Aum Varadarajan

SUB-ID-712601

Batch 3

Batch 3

NUSRL, Ranchi

Document Details

Submission ID

trn:oid:::3618:128563615

Submission Date

Feb 18, 2026, 5:00 PM GMT+5:30

Download Date

Feb 18, 2026, 5:06 PM GMT+5:30

File Name

SUB-ID-712601.pdf

File Size

563.5 KB

11 Pages

2,245 Words

10,936 Characters

7% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Bibliography

Match Groups

17 Not Cited or Quoted 7%
Matches with neither in-text citation nor quotation marks

0 Missing Quotations 0%
Matches that are still very similar to source material

0 Missing Citation 0%
Matches that have quotation marks, but no in-text citation

0 Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

2% Internet sources
3% Publications
5% Submitted works (Student Papers)

Integrity Flags

0 Integrity Flags for Review

No suspicious text manipulations found.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

- **17** Not Cited or Quoted 7%
  Matches with neither in-text citation nor quotation marks
- **0** Missing Quotations 0%
  Matches that are still very similar to source material
- **0** Missing Citation 0%
  Matches that have quotation marks, but no in-text citation
- **0** Cited and Quoted 0%
  Matches with in-text citation present, but no quotation marks

Top Sources

2% Internet sources
3% Publications
5% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

1	Publication	Thomas W. Baumgarte, Stuart L. Shapiro. "Primordial black holes captured by ne...	<1%
2	Submitted works	University of North Florida on 2023-12-06	<1%
3	Submitted works	University of Liverpool on 2022-05-20	<1%
4	Submitted works	Birla Institute of Technology and Science Pilani on 2025-12-08	<1%
5	Publication	Zevin, Michael. "Unveiling the Lives and Deaths of Stars Through Compact Object ...	<1%
6	Submitted works	Curtin University of Technology on 2016-04-26	<1%
7	Internet	astro.kasi.re.kr	<1%
8	Internet	hdl.handle.net	<1%
9	Submitted works	Curtin University of Technology on 2018-04-30	<1%
10	Submitted works	University of Western Australia on 2022-10-28	<1%

11 Submitted works

University of Lincoln on 2024-09-24 <1%

12 Publication

Krishna Prajapati, Snehal Jani, Manisha Singh, Ranjeet Brajpuriya. "Contribution o... <1%

13 Publication

Valeria Ferrari, Leonardo Gualtieri, Paolo Pani. "General Relativity and its Applica... <1%

A Brief Study of Gravitational Waves

By Aum Varadarajan

Index

Abbreviations Used

Abbreviation	Meaning	Value
M⊙	Solar Mass	1.985×10^{30} kg
LIGO	Laser Interferometer Gravitational-Wave Detector	-
BBH	Binary Black Hole	-
BHNS	Black Hole Neutron Star	-
BNS	Binary neutron star	
GW	Gravitational Waves	
SNR	Signal to Noise Ratio	
UTC	Coordinated Universal Time	
GWOSC	Gravitational Wave Open Science Centre	
GWpy	Gravitational Wave Python	

Introduction

Definition

11 Gravitational Waves are caused by highly massive celestial objects like black holes and neutron stars. A gravitational wave can be quite literally be expressed or thought of the fabric of space-time bending and propagating at the speed of light due to the interactions between the masses of these objects. This phenomenon confirms Einstein's theory of relativity and shows how these massive celestial bodies interacted in the early universe.

10 These events are detected by the Laser Interferometer Gravitational-Wave Detector or LIGO detector located at Livingston (known as L1) and Hartford (Known as H1). In summary the detector works by shining a laser at a certain wavelength split by a beam splitter at two mirrors perpendicular to each other. When the detector "feels" the space-time distortion it warps the laser light ever so slightly knocking the two light beams out of phase. This causes the two light beams to destructively interfere with each other, this interference is then measured as a gravitational wave signal.

The gravitational wave events are named in the order GW/YY/MM/DD, for example the event GW150915 is the gravitational wave event detected by LIGO on the year 2015 September 15th

Types of gravitational wave events

There are several types of gravitational wave events depending on what celestial bodies are merging and interacting. The type of Gravitational Wave mergers are:

1. Binary Black Hole Merger (BBH)

As the name suggests this merger occurs when the two bodies are black holes. The first confirmed gravitational event GW150914 was a Binary Black hole merger.

Characteristics

- Binary Black Hole mergers are the most energetic and produce the strongest gravitational waves due to their tiny event horizons and huge masses.
- Due to black Holes not being composed of matter they don't produce any electromagnetic pulses and by extension a supernova, thus release most of their energy through

Gravitational waves with some releasing the energy in the order of 10^{47} Joules of energy or about the energy of 4000 Suns will produce in its entire lifespan at a few hundred milliseconds.

2. Black Hole Neutron Star Merger (BHNS)

This gravitational event is caused when a black hole and a neutron star merge or collide with each other.

Characteristics

- This event results in the black hole “swallowing” the less massive neutron star and leaving behind an accretion disk of matter and a larger Black Hole.
- Due to the neutron star being made of matter this event releases gravitational waves (although not as intense due to the lower mass of the neutron star), Short and intense bursts of gamma rays called gamma ray bursts (GRBs) and producing a kilonova which is essentially like a supernova but far dimmer
- Kilonovae are responsible for all elements heavier than Iron-56 like gold, platinum and so on.

3. Binary Neutron Star Merger (BNS)

This gravitational event is caused when two neutron stars merge or collide with each other. One of the most well known BNS mergers is the event GW170817

Characteristics

- This event results in the two neutron stars merging an forming a larger Black Hole.
- Due to the neutron stars being made of matter this event releases gravitational waves (although not as intense due to the lower mass of the neutron star), Short and intense bursts of gamma rays called gamma ray bursts (GRBs) and producing a kilonova which is essentially like a supernova but far dimmer
- Kilonovae are responsible for all elements heavier than Iron-56 like gold, platinum and so on.

Events Selected for the study:

Attributes	GW250114	GW170817
Type of Merger	Binary Black Hole (BBH)	Binary Neutron star (BNS)
Detector Used	LIGO Livingston (L1)	LIGO Livingston (L1)
GPS Merger Time (s)	1420878141.2	1187008882.4
UTC Merger Time	2025-01-14 at 08:22:03.200	2017-08-17 at 12:41:04.400
Primary Mass ($M_\odot$)	$33.6^{+1.2}_{-0.8}$ $M_\odot$	$1.81^{+0.45}_{-0.45}$ $M_\odot$ (90% probability)
Secondary Mass ($M_\odot$)	$32.2^{+0.8}_{-1.3}$ $M_\odot$	$1.11^{+0.25}_{-0..25}$ $M_\odot$ (90% probability)
Combined Mass ($M_\odot$)	$65.8^{+1.4}_{-1.5}$ $M_\odot$	$2.74^{+0.01}_{-0.01}$ $M_\odot$
Post-Merger Mass ($M_\odot$)	$62.7^{+1.0}_{-1.1}$ $M_\odot$	$2.66^{+0.15}_{-0.13}$ $M_\odot$
Mass Converted into energy ($M_\odot$)	$3.1^{+2.2}_{-2.4}$ $M_\odot$	0.03 $M_\odot$
Energy Released (J) ($E = mc^2$)	9.487 x 10^{47} J to 1.25 x 10^{47} J	5.37 x 10^{45} J
Nature of Released Energy	Gravitational Waves	Gravitational Waves + Electromagnetic Waves + Matter Ejection
Redshift (z)	$0.09^{+0.01}_{-0.01}$	0.0099
Distance (Lyr)	1.14 Billion Lyr	144 Million Lyr
Signal to Noise Ratio (SNR)	80	32.4

These two events are Binary Black Hole mergers (GW250114) and Binary Neutron Star Mergers (GW170817) These two events were specifically selected for their Very high Signal to Noise Ratio or SNR for ease of processing the data. All data except my calculated time and percentage error are pulled from Wikipedia [1].

Steps involved in processing

Step 1

we first begin by initializing and importing the relevant python plugins like GWOSC to obtain all the recorded Gravitational Wave events in order, GWpy to extract the data from the GW event, numpy and matplotlib for normalising and plotting

Step 2

We enter the event name, detector name (L1 or H1) time interval before and after the merger time to extract the data of the event and the merger time is also calculated when the gravitational wave signal is at its highest amplitude. To convert the GPS merger time of LIGO data to UTC time astropy is used. Both these events the use the data from the L1 detector.

Step 3

After extraction of the event time series data we apply a bandpass filter to filter out the extreme ends of the frequency, use the notch function to clip additional frequencies like 60hz which corresponds to the frequency of the current of the instrument to avoid picking up on that and as a final cleanup step we apply a whitening step to essentially separate the instrument noise from the actual GW signal.

Step 4

Now we plot the data in two different charts, the merger chirp signal and the spectrogram

- The Merger Chirp Signal plot shows how spacetime distorted over time as a plot between strain amplitude and time
- The spectrogram is a plot that shows the relation between the frequency of the signal and time using colour coded points, with a brighter square showing a higher intensity and a dimmer square showing a lower intensity

Results

The GW curves and Spectrogram are plotted with the merger time obtained using the python processing workflow below.

1. BBH merger

Event name: GW250114

The plots of the Black hole merger compared to official processed LIGO data are shown below [2]. The obtained merger time was 2025-01-14 08:22:03.218 UTC.

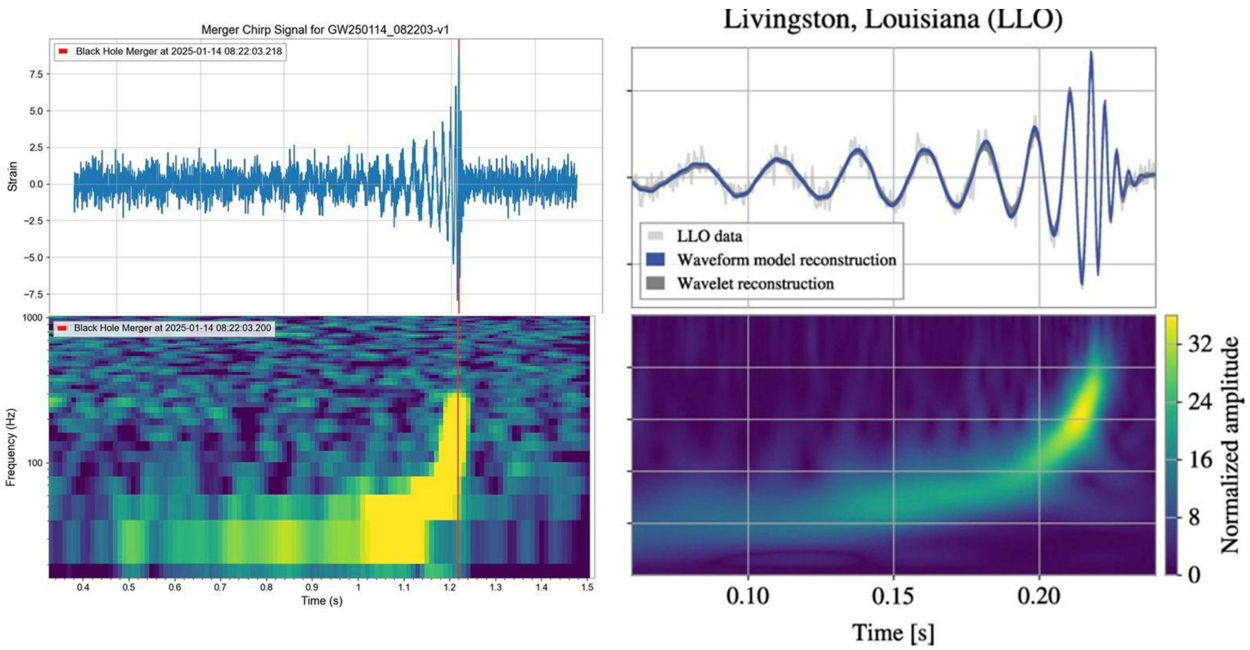

Fig 1: My processed data of GW250114 (Left) vs released data from LIGO (Right)

2. BNS Merger

Event name: GW170817

The plots of the Neutron Star merger compared to official processed LIGO data are shown below. the spectrograms displays a high amplitude but brief glitch of frequencies on both the official LIGO spectrogram and the one processed by me, This is a noise artifact of the L1 detector that occurred right as the neutron stars were merging as discussed and mentioned in LIGO's own news release article of the event [3]. The whitening and bandpass filtering is not a proper substitute for full glitch subtraction which was performed in the official LIGO analysis to clean up the inspiral signal. The obtained merger time is 2017-08-17 12:41:04.400 UTC.

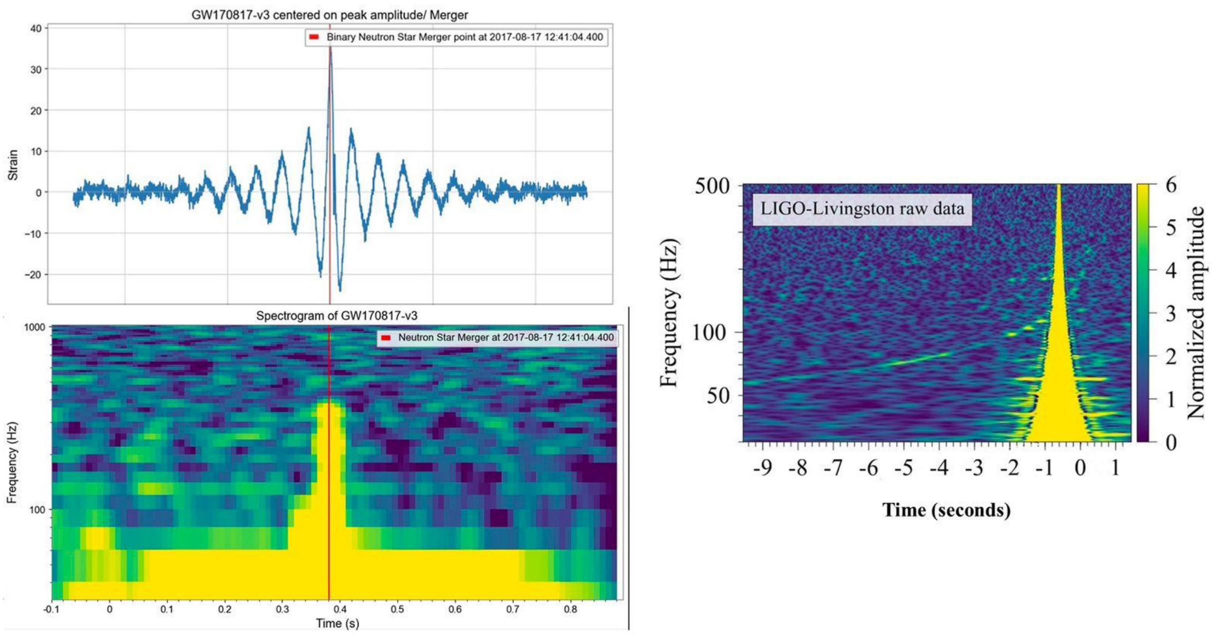

Fig 2: My processed data of the L1 detector glitch a GW170817(Left)
vs released data from LIGO (Right)

Observations

The merger times of the two events are calculated by converting the GPS time system that LIGO uses to UTC or (Coordinated Universal Time) using astropy. Here are the calculated vs actual merger time as per LIGO:

Event	Calculated (UTC)	Official LIGO data (UTC)
GW250114	2025-01-14 08:22:03.218	2025-01-14 08:22:03.200
GW170817	2017-08-17 12:41:04.400	2017-08-17 12:41:04.400

From the amplitude vs time plot of the black hole merger we notice that there are 4 distinct phases as overlaid on the image below they are:

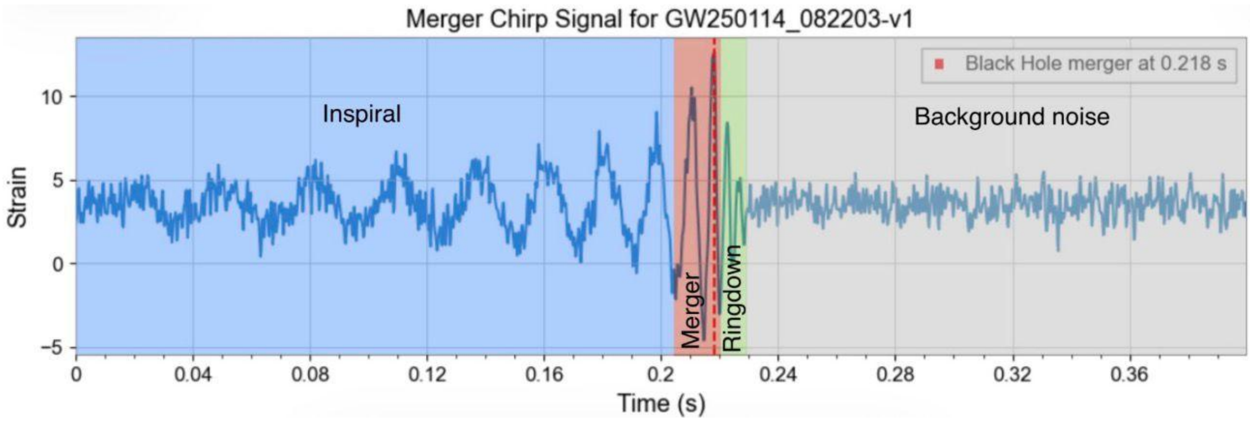

Fig 3: Phases involved in a Black Hole merger

1. **Inspiral Phase**

   In this phase the two black holes start to spiral closer to their shared barycenter due to them radiating energy outward in the form of gravitational waves which pushes the black holes into a lower orbit, this phenomenon is called as orbital decay. Consequently as they spiral closer they also pull on each other exponentially harder causing the decay to accelerate which is why the amplitude stays low and then suddenly spikes with each peak occurring sooner than the previous.

2. **Merger Phase**

   The moment the event horizons or the surfaces come into contact the merger phase begins. due to the black holes and/or neutron stars practically “touching” each other this phase produces the strongest gravitational waves in the universe and where the amplitude of the graph peaks however this phase is extremely short lived and brief only lasting a few milliseconds.

3. **Ringdown Phase**

   Once the merger phase is complete the now larger merged black hole is distorted and asymmetric and as it begins to stabilise and settle down it “rings” like a struck bell and radiates gravitational waves. Over the next few milliseconds the amplitude of said waves rapidly decay and dampen as the black hole stabilises, leading to the formation of a Kerr black hole. To put it simply a kerr black hole is a black hole that rotates and thus possesses angular momentum. Due to angular momentum being conserved the final merged kerr black hole Inherits the angular momentum from its progenitors.

4. **Background Noise**

   At this stage the system goes silent and the gravitational wave signal vanishes leaving just the background noise of the detector. However depending on the type of merger there might be still stuff going on, for binary black hole mergers nothing much happens, no matter or radiation is ejected as the result of a merger but for BNS and BHNS mergers a kilonova and/or a gamma ray burst happens for example the event GW170817 a BNS merger produced a gamma ray burst detected by the fermi telescope 1.7 seconds after the merger of the 2 neutron stars.

Some important points to note are the differences between the behaviours of these mergers

1. In the spectrogram of GW250114 we can see as time passes the higher frequency regions light up in an exponential fashion. The system spends most of its time in a low frequency "hum" and then suddenly spike in frequency and produce a "chirp" signal, the peak of this chirp signal is when the gravitational waves are at their most intense or in other words this phenomenon occurs in the merger phase.

2. Black holes being more massive than neutron stars produce stronger gravitational waves and also release all the energy in the form of gravitational waves unlike neutron stars which are less massive and release energy in the form of GW, Electromagnetic Radiation like gamma ray bursts and kinetic energy of the matter ejected in the kilonova.

3. Due to black holes having a higher mass and smaller sizes (event horizons) their orbits decay quicker and merge faster than neutron stars, in other words their inspiral and merger phase is rapid and brief in black hole mergers.

4. The final merged object's mass is always lower than the sum of the individual masses as a certain fraction of the mass is always converted to energy. In the case of GW250114 the final mass was about 3 solar masses lower than the sum of the progenitor masses. Meaning around 3 solar masses worth of mass was converted into gravitational wave energy.

Conclusion

By using publicly available data from LIGO we can plot the amplitude and spectrogram plots of a GW event to understand the mechanism of the merger and also gain some insight into computational astrophysics like signal cleaning, whitening, band passing and so on. The results were verified by using LIGO's news article and press releases.

References

1. Data such as mass, distance, energy in the table were obtained from Wikipedia
2. The results of GW250114 were verified in the LIGO news article about the same - https://www.ligo-india.in/outreach/detections/gw250114-black-hole-collision-confirms-theories-of-einstein-and-hawking/
3. The L1 detector glitch during the observation of GW170817 was verified to be a glitch of the detector through - https://www.ligo.caltech.edu/news/ligo20171016

Python Plugins used

1. Astropy for GPS time to UTC conversion
2. GWOSC for finding GW events and merger times
3. GWpy for time series plotting of the LIGO data
4. Numpy and matplotlib for graphing values