

- Hak Cipta Dilindungi Undang-undang
1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
 2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

CLUSTERING ANALYSIS OF GRAVITATIONAL WAVE EVENTS FROM NEUTRON STAR AND BLACK HOLE MERGERS OBSERVED BY LIGO AND VIRGO

LUTFI SYAHREZA LUBIS



**STATISTICS AND DATA SCIENCE BACHELOR STUDY PROGRAM
SCHOOL OF DATA SCIENCE, MATHEMATICS, AND INFORMATICS
IPB UNIVERSITY
BOGOR
2025**





STATEMENT REGARDING UNDERGRADUATE THESIS, INFORMATION SOURCES, AND COPYRIGHT

Hereby I declare that the undergraduate thesis with the title “Clustering Analysis of Gravitational Wave Events from Neutron Star and Black Hole Mergers Observed by LIGO and Virgo” is my work with guidance from the supervisory committee and it has not been submitted in any form to any university. Information sources that come or are quoted from published or unpublished work by other authors have been referred to in the text and mentioned in the bibliography. I hereby hand over the copyrights of my undergraduate thesis to IPB University.

Bogor, August 2025

Lutfi Syahreza Lubis
G1401211003

- Hak Cipta Dilindungi Undang-undang
1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
 2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.



ABSTRAK

LUTFI SYAHREZA LUBIS. Analisis Penggerombolan pada Peristiwa Gelombang Gravitasi dari Gabungan Bintang Neutron dan Lubang Hitam yang Diamati oleh LIGO dan Virgo. Dibimbing oleh RAHMA ANISA, AAM ALAMUDI, dan HUSIN ALATAS.

Penelitian ini menganalisis penggerombolan 93 peristiwa gelombang gravitasi (2015–2020) dalam *Gravitational-Wave Transient Catalog 3* (GWTC-3) yang dirilis oleh kolaborasi LIGO-Virgo pada tahun 2021. Dataset terdiri atas kejadian *binary black hole* (BBH), *binary neutron star* (BNS), dan *neutron star–black hole* (NSBH). Studi ini bertujuan mengidentifikasi substruktur pada *compact binary coalescences* melalui penerapan teknik penanganan multikolinearitas dan *unsupervised learning*. Analisis difokuskan pada sembilan parameter, yaitu massa primer, massa sekunder, *chirp mass*, *redshift*, massa total, massa akhir, *signal-to-noise ratio* (SNR), *effective spin*, dan jarak. Dua metode penanganan multikolinearitas, *Principal Component Analysis* (PCA) dan *Uniform Manifold Approximation and Projection* (UMAP), digunakan sebagai tahap praproses data sebelum penggerombolan. Penggerombolan dilakukan menggunakan algoritma K-Means dan DBSCAN, sedangkan evaluasi kualitas gerombol dilakukan dengan *Silhouette Score* dan *Density-Based Clustering Validation* (DBCV). Hasil penelitian menunjukkan bahwa kombinasi UMAP dan K-Means memberikan performa terbaik dengan nilai *Silhouette Score* tertinggi (0,729) yang membentuk tiga gerombol yang terpisah dengan baik. Ketiga gerombol ini secara konsisten dibedakan oleh parameter massa, jarak, SNR, dan *effective spin*, yang dikategorikan sebagai gerombol parameter tinggi, sedang, dan rendah. Temuan ini menegaskan bahwa penanganan multikolinearitas berperan penting dalam meningkatkan performa penggerombolan dan mengungkap pola tersembunyi pada data peristiwa gelombang gravitasi.

Kata kunci: gelombang gravitasi, LIGO, multikolinearitas, penggerombolan, Virgo.

ABSTRACT

LUTFI SYAHREZA LUBIS. Clustering Analysis of Gravitational Wave Events from Neutron Star and Black Hole Mergers Observed by LIGO and Virgo. Supervised by RAHMA ANISA, AAM ALAMUDI, and HUSIN ALATAS.

This study investigates the clustering of 93 gravitational-wave events (2015–2020) in the *Gravitational-Wave Transient Catalog 3* (GWTC-3), released by the LIGO–Virgo Collaboration in 2021. The dataset contains of binary black hole (BBH), binary neutron star (BNS), and neutron star–black hole (NSBH) events. The aim is to uncover substructures in compact binary coalescences using multicollinearity handling techniques and unsupervised learning. The analysis targets nine key astrophysical parameters: primary mass, secondary mass, chirp mass, redshift, total mass, final mass, signal-to-noise ratio (SNR), effective spin, and distance. Principal Component Analysis (PCA) and Uniform Manifold Approximation and Projection (UMAP) were employed as data preprocessing steps prior to clustering. Clustering was performed using the K-Means and DBSCAN algorithms, while cluster quality was evaluated using Silhouette Score and Density-Based Clustering Validation (DBCV). The results indicated that the combination of UMAP and K-Means achieved the best performance, producing the highest Silhouette Score (0,729) and forming three well-separated clusters. These clusters are consistently distinguished by mass, distance, SNR, and effective spin, and can be categorized as high, medium, and low parameter groups. These findings highlighted that handling multicollinearity plays an important role in improving clustering performance and revealing hidden patterns in gravitational wave event data.

Keywords: clustering, gravitational waves, LIGO, multicollinearity, Virgo.



@Hak cipta milik IPB University

- Hak Cipta Dilindungi Undang-undang
1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
 2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

© Copyright IPB University, 2025
Copyrights protected by Law

Prohibited to cite parts or all of this manuscript without referencing its source. Citations are only permitted for educational purposes, research, writing of scientific manuscripts, reports, critiques, or reviews. Citations may not harm IPB University's interests.

Publishing and copying some or parts of this manuscript without authorization from IPB University is prohibited.

CLUSTERING ANALYSIS OF GRAVITATIONAL WAVE EVENTS FROM NEUTRON STAR AND BLACK HOLE MERGERS OBSERVED BY LIGO AND VIRGO

LUTFI SYAHREZA LUBIS

Undergraduate Thesis
To complete the requirement for graduation of
Bachelor Degree in
Statistics and Data Science Study Program

**STATISTICS AND DATA SCIENCE BACHELOR STUDY PROGRAM
SCHOOL OF DATA SCIENCE, MATHEMATICS, AND INFORMATICS
IPB UNIVERSITY
BOGOR
2025**



@Hak cipta milik IPB University

Hak Cipta Dilindungi Undang-undang

1. Dilarang mengutip sebagian atau seluruh karya tulis ini tanpa mencantumkan dan menyebutkan sumber :
 - a. Pengutipan hanya untuk kepentingan pendidikan, penelitian, penulisan karya ilmiah, penyusunan laporan, penulisan kritik atau tinjauan suatu masalah
 - b. Pengutipan tidak merugikan kepentingan yang wajar IPB University.
2. Dilarang mengumumkan dan memperbanyak sebagian atau seluruh karya tulis ini dalam bentuk apapun tanpa izin IPB University.

Title : Clustering Analysis of Gravitational Wave Events from Neutron
Star and Black Hole Mergers Observed by LIGO and Virgo
Name : Lutfi Syahreza Lubis
Student ID : G1401211003

Approved by

Main Supervisor:
Rahma Anisa, S.Stat., M.Si.

First Co-Supervisor:
Ir. Aam Alamudi, M.Si.

Second Co-Supervisor:
Prof. Dr. Husin Alatas S.Si., M.Si.



Acknowledged by

Head of Statistics and Data Science study program:
Dr. Bagus Sartono, S.Si., M.Si.
NIP 19780411 200501 1002



Date of Thesis Defense:
August 8th 2025

Date of Graduation:

PREFACE

Praise to Allah subhanaahu wa ta'ala for His blessings, allowing this scientific work to be completed. This research work, conducted since November 2024 to August 2025 is an undergraduate thesis titled “Clustering Analysis of Gravitational Wave Events from Neutron Star and Black Hole Mergers Observed by LIGO and Virgo”.

The author would like to thank:

1. The author's supervisors, Rahma Anisa, S.Stat., M.Si., Ir. Aam Alamudi, M.Si., and Prof. Dr. Husin Alatas, M.Si., as well as the external examiner, Laily Nissa Atul Mualifah, S.Si., M.Si., who have provided guidance and invaluable advice in completing this scientific work.
2. The author's favorite people on Earth Leo Suhana Simanjuntak, Iin Paradina Lubis, and Nisa Soraya Lubis as the author's family, for their boundless support and prayers.
3. The author's friends from Statistics Batch 58, especially Akmal Basis Jatining Kusumah, Andi Fatihatul Fuadiyah Akbar, Angel Martha, Fedora Ilahi, and Reyzha Siva Dewi, who have accompanied, assisted, and provided valuable advice, input, motivation, support, and encouragement throughout the author's undergraduate studies.
4. The author's friends from Data Analytics of GSB 2022, GSB 2023 and GSB 2024, especially Azra, Diva, Hanifah, Kheni, Much, and Nabil, who have accompanied, assisted, and continuously encouraged the author during the academic journey.
5. Alhur Skuy, especially Angga, Farik, Fajar, and Rafi, who have supported the author throughout the undergraduate studies by helping the author in understanding the lessons in class.
6. IISMA Colorado 2024: Bimo, Fara, Gaby, Nana, Syaki, and Dayu, who were not just fellow fighters during our student exchange at the University of Colorado Boulder, USA, but became a family who stood by the author through every high and low.
7. The author's companion in Boulder, Seungwon Shin and Lauren Ward, as well as to all instructors and teaching assistants at CU Boulder who inspired the author throughout the exchange program and became close friends despite the oceans that separate us, the author expresses heartfelt gratitude.
8. The author's friends at Blibli—Ariqoh, Debo, Gibran, Hamzah, Divia, Kayla, Khania, and Syahla—and to the mentors who colored author's days with laughter, support, and encouragement, thank you for unknowingly becoming such an important part of this thesis journey.

May this scientific work benefit those in need and contribute to the advancement of knowledge.

Bogor, August 2025

Lutfi Syahreza Lubis

TABLES OF CONTENTS

LIST OF TABLES	x
LIST OF FIGURES	x
LIST OF APPENDICES	x
I INTRODUCTION	1
1.1 Background	1
1.2 Research Objectives	2
II LITERATURE REVIEW	3
2.1 Gravitational Wave and Compact Binary Coalescences	3
2.2 Principal Component Analysis (PCA)	4
2.3 Uniform Manifold Approximation and Projection (UMAP)	5
2.4 K-Means	8
2.5 Density-Based Spatial Clustering of Applications with Noise (DBSCAN)	9
2.6 Cluster Evaluation	11
III METHOD	13
3.1 Data	13
3.2 Data Analysis Procedure	13
IV RESULTS AND DISCUSSION	16
4.1 Data Exploration	16
4.2 Multicollinearity Handling	18
4.3 Clustering Analysis	20
4.4 Cluster Comparison between K-Means and DBSCAN	25
4.5 Characteristics of Each Cluster	26
V CONCLUSION AND RECOMMENDATION	32
5.1 Conclusion	32
5.2 Recommendation	32
REFERENCES	33
APPENDICES	35
BIOGRAPHY	42



LIST OF TABLES

1	List of Variables	13
2	Eigenvalues and variance explained by each principal component	19
3	Clusters produced using K-Means	21
4	Clusters produced using DBSCAN with PCA inputs	23
5	Clusters produced using DBSCAN with UMAP inputs	24
6	Comparison of clustering performance	25
7	List of noises of PCA + DBSCAN pipeline	29
8	Mapping table for all BNS and NSBH across clustering pipelines	30

LIST OF FIGURES

1	Schematic illustration of UMAP framework (Oide and Sugita 2022)	6
2	Visualization of core point, border point, and noise in DBSCAN (Ester <i>et al.</i> 1996, modified)	9
3	Example of (a) directly density-reachable, (b) density-connected relationships (Ester <i>et al.</i> 1996, modified)	10
4	Boxplot of all standardized variables	16
5	Pearson correlation matrix among variables	17
6	(a) Elbow Method to Determine Optimal k, (b) Silhouette Score for Different k using PCA Results	20
7	(a) Elbow Method to Determine Optimal k, (b) Silhouette Score for Different k using UMAP Results	21
8	Clusters visualization using K-Means and varying input: (a) PCA with k = 3, (b) PCA with k = 4, (c) UMAP with k = 3, (d) UMAP with k = 4	22
9	Histogram of Pairwise Distance (PCA space)	23
10	Histogram of pairwise distances (UMAP space)	24
11	Clusters visualization using: (a) UMAP + K-Means with k = 3, (b) UMAP + DBSCAN with $eps = 1,32$ and $min_samples = 15$	26
12	Cluster visualization using PCA + DBSCAN with $eps = 2,8$ and $min_samples = 15$	28

LIST OF APPENDICES

1	UMAP embedding with varying parameters	36
2	Summary of each variable	37
3	Clusters profiles identified using PCA + K-Means (k=4)	37
4	Clusters profiles identified using UMAP + K-Means (k=3)	38
5	Clusters profiles identified using PCA + DBSCAN	38
6	Clusters profiles identified using UMAP + DBSCAN	38
	Cluster membership results	39