Public summary

Gravity: The Invisible Architect of the Cosmos

Gravity is the weakest of the fundamental forces, and we experience it every day here on Earth. It's so familiar that we barely notice its effects, as we can easily overcome it by lifting a single finger. However, gravity behaves very differently on a cosmic scale. The universe is a dynamic and violent place, filled with billions of stars born in chaotic and energetic environments. These stars spend their lives producing energy through nuclear fusion—a process that powers the stars—and often end in massive explosions powerful enough to destroy entire worlds. Meanwhile, here on our small home, Earth, we are far removed from these astronomical cataclysms. We are left to wonder what other worlds are dying and what new ones are being born around those distant, shining stars.

Gravity, often referred to as the invisible architect of the cosmos, plays a vital role in shaping the universe. It dictates the orbits of planets, governs the formation of stars, and binds galaxies together. As the force that holds the vast structures of the universe in place, gravity's influence is both subtle and profound. The nature of gravity has intrigued human minds since ancient times, leading to centuries of scientific research.

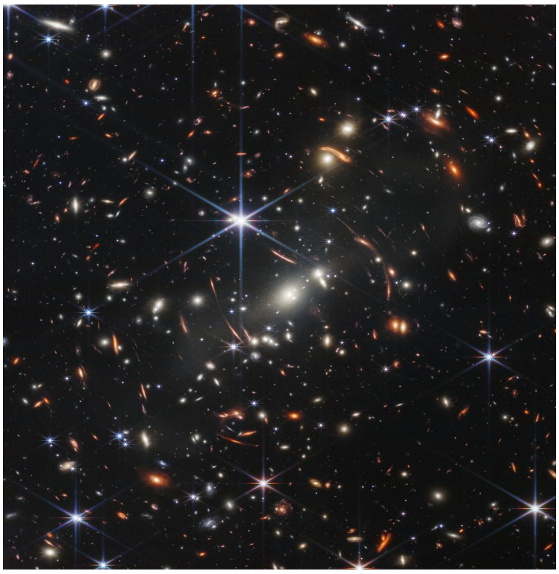

FIGURE S1.1: James Webb Space Telescope image with a large number of lensed galaxies. Credits: NASA, ESA, CSA, and STScI.

In the 17th century, Sir Isaac Newton revolutionized our understanding with his law of universal gravitation, which described how gravity affects objects. However, while Newton's work explained how gravity operates, the true nature of this force remained a mystery. It wasn't until the 20th century that Albert Einstein introduced the theory of general relativity, providing a unified description of gravity and paving the way for modern physics.

According to general relativity, gravity is a geometric property of space-time, the four-dimensional fabric that composes the universe. This fabric includes three dimensions of space and one of time. In this flexible fabric, matter causes space-time to curve, and this curvature dictates how objects move. For example, Earth orbits the Sun because it moves along the curved path generated by the Sun's mass in space-time. A fascinating consequence of these curved paths is the bending of light, known as *gravitational lensing*. This effect is illustrated in Fig. S1.1, captured by the James Webb Space Telescope, where several galaxies appear to have duplicates. In this scenario, a massive object, like a galaxy, acts as a "magnifying glass," allowing us to observe objects located behind it and causing these duplicates as a consequence.

Another consequence of general relativity is that massive astronomical objects can distort the very fabric of space-time. Imagine space-time as a lake of crystal-clear water, so transparent that you can see all the way to the bottom. When a rock is thrown into this lake, it creates ripples on the surface. In this analogy, the lake represents space-time, and the ripples are caused by astronomical cataclysm. These ripples are known as *gravitational waves*, and they travel across the universe at the speed of light. After millions of years, they can reach Earth, where we can now detect them.

Detecting ripples in space-time

Stars, much like humans, are born, age over incredibly long timescales, and eventually die. During their lifetimes, these massive clouds of compressed hydrogen continuously convert hydrogen into helium through a process called *nuclear fusion*, which generates energy. Once they exhaust their hydrogen supply, stars begin fusing heavier elements to produce energy, progressing through the periodic table until they reach iron.

At the end of their lives, very massive stars can no longer support their own weight and collapse inward. This collapse leads to a spectacular outward explosion called a supernova, one of the most powerful events in the universe. In Fig. S1.2, you can see one of the most famous remnants of such an explosion: the Crab Nebula, which was formed by a supernova observed nearly 1,000 years ago in 1054 CE. Even though supernovae are incredibly energetic, the gravitational waves they produce are very weak and hard to detect. Not all supernova explosions leave behind visible remnants like the Crab Nebula. What remains after a supernova depends on the original star's mass. Sometimes, a supernova leaves behind no remnant at all, while other times it forms a compact object like a neutron star or a black

FIGURE S1.2: Hubble Space Telescope image of the Crab Nebula. Credits: NASA and STScI.

In astrophysics, a compact object refers to a massive celestial body that is relatively small. Supernova explosions can form either a black hole or a neutron star. A neutron star is an extremely dense, compact star composed of neutrons, while a black hole is an extremely dense, compact object that deforms space-time itself, absorbing everything that comes near it, including light. For these types of objects, the description of gravity provided by Sir Isaac Newton is no longer valid due to their extreme conditions, and we need to adopt the theory of general relativity.

In nature, stars often form in binary systems, making it common to find pairs such as binary neutron stars, binary black holes, or a neutron star and a black hole. These celestial bodies orbit each other for billions of years, and during this time, their orbits gradually shrink due to the emission of gravitational waves, which are ripples in space-time. Eventually, the two compact objects collide in an astronomical cataclysm, merging to form a larger compact object. The gravitational waves emitted from this collision travel throughout the universe for millions of years, passing by countless galaxies. As they propagate, gravitational waves, like ripples on the surface of a lake, deform space-time, including Earth and everything on it. However, we remain unaware of their effects because the distortions they cause are extremely small.

To measure gravitational waves, scientists have built several detectors forming a network: LIGO Hanford and LIGO Livingston in the USA, Virgo in Italy, and KAGRA in Japan. These extremely complex instruments, known as interferometers, have exquisite precision to be able to detect the tiny distortions caused by gravitational waves, measuring changes in distance as small as $\sim 1/10,000$th the diameter of a proton. You can think of these machines as the most precise seismographs in the world—devices that detect and record waves—but instead of measuring earthquakes caused by tectonic plate movements, they measure ripples in space-time generated by cataclysmic events like supernova explosions and the collisions of black holes or neutron stars. Due to their incredible sensitivity, these detectors can be affected by terrestrial background noise, such as electrical malfunctions, thunderstorms, or even human activity. This background noise can produce artefacts in the data, known as *glitches*, that mimic gravitational wave signals and hinder their detection.

In 2015, the LIGO and Virgo detectors confirmed the existence of gravitational waves from a merger of two black holes, labelled as GW150914, nearly a century after Albert Einstein predicted them in his theory of general relativity. This groundbreaking discovery was awarded the Nobel Prize in Physics in 2017, and, as of this writing, over 90 gravitational wave signals have been detected since then. The immense work of the LIGO-Virgo-KAGRA collaboration has opened a new and exciting way to listen to the symphony of the cosmos and unveil its mysteries. Future research in gravitational wave astronomy promises to deepen our understanding of the universe by probing the densest and most energetic regions of cosmic objects, which were hidden from astronomers' sight up until now.

Exploring the frontier of gravitational wave detection

Just as the soft melody of a street musician's flute can be drowned out by the bustling noise of the city, gravitational waves are incredibly subtle signals often masked by various sources of detector noise. Detecting a gravitational wave signal in current ground-based detectors is like finding a needle in a haystack: we capture only a few seconds of gravitational wave signals amidst approximately $1,296,000$ seconds (two weeks) of detector noise.

Current searches for transient gravitational waves are like finding a needle in a haystack. These searches rely on two main approaches: modeled searches and unmodeled searches. Modeled searches compare theoretical models from general relativity to the detector data to determine if a given signal is of astronomical origin. Unmodeled searches, on the other hand, look for loud signals in the detector data with little to no prior information. However, both methods face challenges because gravitational wave detectors produce glitches that can mimic gravitational wave signals. To overcome this, both types of searches also rely on a key idea: if a signal is observed simultaneously in multiple detectors, it is more likely to have an astronomical origin.

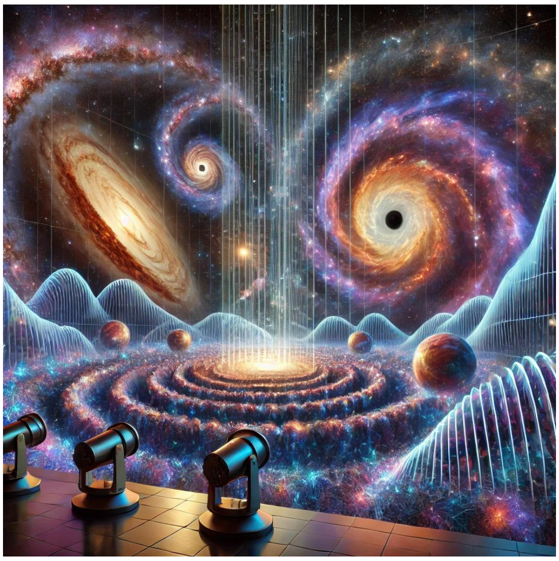

FIGURE S1.3: Interpretation of the cosmic auditorium. Credits:DALL · E 2

As current ground-based detectors are upgraded, they will become more sensitive to gravitational waves. The next generation of detectors, such as the Einstein Telescope, Cosmic Explorer, and LISA, is expected to be even more sensitive, allowing us to access the full symphony of the cosmos. In this scenario, we will enter the cosmic auditorium and need to disentangle the sounds of different instruments. Each gravitational wave source, such as colliding black holes or merging neutron stars, contributes its own unique "note" to the cosmic symphony, much like individual instruments in an orchestra. As we enhance our ability to detect these faint cosmic "notes," we will uncover the rich tapestry of events that shape our universe. However new detectors will pose new data analysis challenges.

Just as the creation of the internet revolutionized our society, the development of artificial intelligence (AI) is shaping it in profound ways every day. In recent years, we have advanced the ability of machines to learn and perceive the world around us in a manner similar to humans. This progress has led to remarkable milestones, including humanoid robots, real-time language translation, autonomous vehicles, and generative algorithms. These AI-driven technologies demonstrate the ability to analyze data and identify patterns at remarkable speeds, offering solutions and insights that were previously unattainable. As an example, in Fig. S1.3 we show the interpretation of the previous paragraph of DALL · E 2, an AI algorithm.

Thanks to the success of artificial intelligence (AI), especially machine learning—a branch of AI—across many fields, scientists in large physics experiments are using these algorithms to find interesting patterns in the data. Gravitational wave research is no exception. Machine learning methods are versatile and can uncover surprising patterns in the data. However, to make these methods flexible, they often become complex, making them hard to understand—a challenge known as the "black box" problem. Additionally, because machine learning algorithms learn from data, they need to be given high-quality data and meaningful features. Finally, humans are needed to evaluate how well these algorithms perform, which is not always easy, especially when discovering new patterns.

Unleashing the power of machine learning

Even though supernova explosions are among the most powerful events in the universe, the gravitational waves they produce are incredibly faint and difficult to detect. Successfully capturing these signals will give us valuable insights into the inner workings of these explosions, helping us understand how they evolve.

We know that supernovae can create black holes that are about 3 to 100 times the mass of our Sun. On the other hand, we observe supermassive black holes that can be millions of times the Sun's mass, like Sagittarius A* at the center of our Milky Way galaxy, as shown in Fig. S1.4. Scientists believe these giant black holes formed over time as smaller black holes merged together. This leaves us with a mystery: the missing link between smaller black holes created by supernovae and the enormous supermassive black holes. These are called intermediate black holes, which have masses between 100 and 1,000 times that of the Sun. Detecting more gravitational waves from intermediate black holes, like those from the event GW190521, could help us piece together the story of how supermassive black holes form and how they shape the galaxies around them.

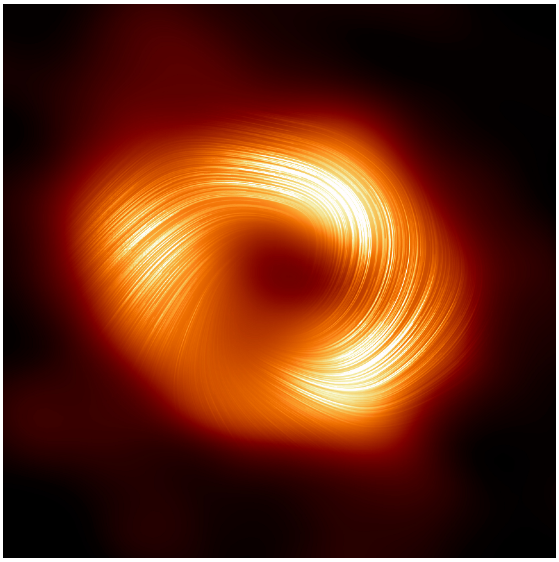

FIGURE S1.4: Sagittarius A, the supermassive black hole at the center of the Milky Way. Credits: EHT.*

Mitigating glitches

Gravitational wave detectors are incredibly complex machines made up of many optical components. These detectors have thousands of sensors that constantly monitor their condition in real time. Due to their high sensitivity, glitches lasting only a few seconds often occur in different parts of the detector and show up in the main data stream. Because we can't predict when a glitch will appear, it's crucial to understand their forms and patterns to identify them and reduce their impact on the data. However, this is a challenging task because glitches happen frequently, about once every second.

A promising way to tackle the issue of glitches in gravitational wave detectors is to categorize them based on their shapes, or "morphologies", in the main stream of the detector. By combining human expertise with machine learning algorithms that are good at finding patterns, we can better identify these glitches, which is the first step toward reducing their impact. However, there are challenges in this approach. One difficulty is determining when a glitch is absent from the data, which makes it hard and time-consuming to fully understand the results of search algorithms. Another issue is that the exact cause of a glitch is often unknown, making it challenging to find effective solutions to prevent them.

In this thesis, we address the first problem by using a generative machine learning algorithm to learn the population of one of the most abundant glitches: Blips. Blips are short lived and affect the frequencies of interest of gravitational wave searches, particularly hindering the searches of supernova and intermediate mass black holes. By creating a synthetic population of these glitches, we can improve our search algorithms in a controlled environment.

We also address the second issue using a machine learning algorithm for anomaly detection. We compress the data of auxiliary channels where these glitches are produce. By compressing this data, the algorithm can identify patterns and learn about the glitches based on their physical processes within these channels. This approach allows us to uncover unexpected patterns and gain a better understanding of the complex nature of these glitches.

Pattern recognition for intermediate-mass black holes and supernovae

Machine learning algorithms are only as effective as the data they are given. To discover interesting patterns, these algorithms require large amounts of high-quality data. So far, we have detected over 90 gravitational waves, but this number isn't sufficient to teach a machine learning algorithm what a gravitational wave looks like. Because of this limitation, we rely heavily on simulations of these astronomical events. We have a good understanding of the physics behind black hole mergers, which allows us to simulate them accurately. However, simulating a supernova explosion is much more complex. A supernova involves several forces and processes, making it difficult to model. Creating a simulation of a supernova is also extremely resource-intensive, often taking months of computation time on a supercomputer.

Machine learning algorithms are excellent at learning patterns and have a remarkable ability to generalize from them. In this thesis, we leveraged this ability by generating signals that are somewhat similar to actual supernova simulations. The key idea is that machine learning algorithms can first learn from these approximate dataset and then refine their understanding using the actual simulations. Additionally, the machine learning method learns that gravitational waves are usually detected in several detectors simultaneously.

Traditional search algorithms for intermediate-mass black holes have been refined over the last 20 years to effectively transform the stream of data from gravitational wave detectors into meaningful features. However, these search algorithms primarily rely on simulations. Machine learning algorithms, on the other hand, can learn directly from both simulations and glitches. However, without the right features, it can be very difficult for machine learning to tell the difference between real signals and noise. In this thesis, we develop a symbiotic relationship between traditional search methods and machine learning algorithms. The machine learning models learn the features generated by the traditional search algorithms, enabling them to better distinguish genuine gravitational waves from background noise.

The work in this thesis aims to enhance the detection of gravitational waves from supernovae and intermediate-mass black holes while reducing the impact of glitches. We have explored the frontiers of transient gravitational wave detection by unleashing the power of machine learning.