ICTS Job Shadow Report

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1 Introduction

I am Pranav and I am a grade 11 IBDP student at One World International School, Sarjapur. Over the summer of 2024, I did a job shadow program under Dr. Vaishak Prasad at the International Center for Theoretical Sciences (ICTS).

A Job shadow program helps students understand being a part of a professional organization. It demonstrates interest in research and serves as an orientation to working in that respective field. As I am interested in pursuing computer/electrical engineering for my further studies, and my hobbies (computing, computer hardware, 3D modeling, and Python programming) revolve around similar disciplines, I nominated ICTS for this experience. The research done here makes use of computation methods extensively and the learning would help with my future endeavors.

During the program, I observed the work done at this research institution, the tools and methods used for that work and understood the process by which the researchers achieve their professional goals. I also attended group meetings, faculty seminars and did some original Python work using the newly acquired skills.

This report highlights my learning throughout the 4 weeks at ICTS.

2 An exploration behind the Physics

This section focuses on the aspects of physics to which I was exposed to during my time here. The following physics terminology is what the research is based on. The Astrophysical relativity group at ICTS focuses their research on compact objects (white dwarfs, neutron stars, and black holes).

2.1 What are Gravitational Waves?

Imagine throwing a stone into a pond. The stone causes ripples that spread outwards on the waters surface, like a wave of influence moving away from the point of impact, in space and time.

2.1.1 Sources of Gravitational Waves

According to Einstein's general relativity theory, massive events like as black hole mergers, supernovae, and colliding neutron stars deform spacetime due to their immense energy. These distortions propagate outward from the source as gravitational waves. By the time these waves reach Earth, they are so feeble that they must be detected by sensitive devices like LIGO.

2.2 LIGO detectors

LIGO (Laser Interferometer Gravitational-wave Observatory) detectors are laser interferometer-based equipment used to detect gravitational waves. These detectors have long arms (4 kilometers) which are enclosed in evacuated tubes, through which a stabilized laser beam is emitted, reflected, and recombined. The interference pattern is detected using sensitive photodetectors that detect minute changes in the relative lengths of the arms caused by a passing gravitational wave. However, the great sensitivity causes noise in the waveform data, which is isolated using sophisticated computational and mathematical techniques. The United States now has two LIGO detectors, which are joined by Virgo, GEO600, and KAGRA, with proposals for a third detector in India.

2.3 Binary Black Holes

A binary black hole (BBH) is a system composed of two black holes that circle each other. BBH systems have three stages: inspiral, merging, and ringdown. During the 'inspiral' stage, the orbit of the black holes reduces, resulting in modest gravitational wave emission. As the black holes approach, the GW emission increases, forcing the binary system to contract more quickly. The "merger" stage occurs when two black holes collide, and GW emission peaks.

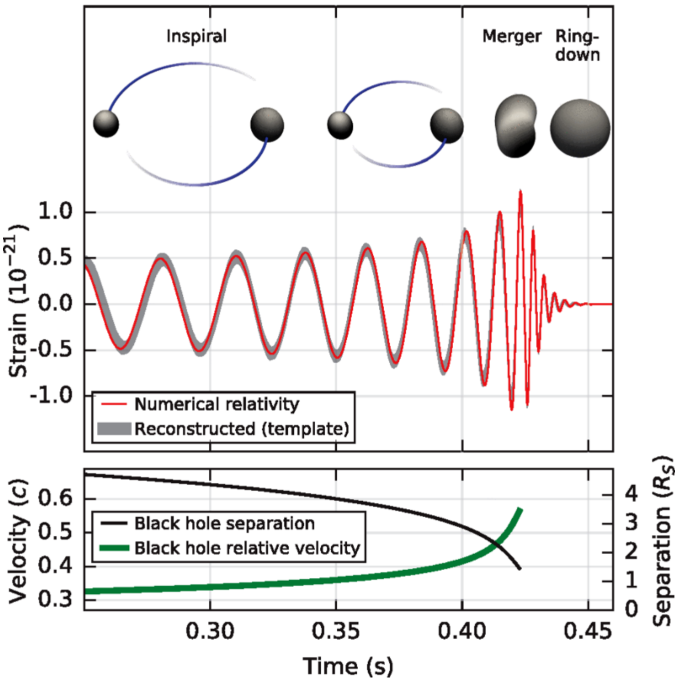

Figure 1: GW150914 Stages of merging

The 'ringdown' step happens when the freshly created black hole rings, resulting in GW emission via a damped sinusoid function.

2.3.1 GW150914

In September 2015, GW150914 was directly observed by LIGO as the first observation of gravitational waves, and our first observation of the merger of a binary black hole. The collision occured approximately 1.3 billion light years away and confirmed one of the key predictions of Einstein's general relativity theory. Such a signal appears for a fraction of a second, and is a testament to how sensitive LIGO is.

2.4 Schwarzschild metric

The Schwarzschild metric is a solution to Einstein's field equations that describes the gravitational field of a non-rotating, spherically symmetric mass distribution in general relativity. It is a fundamental tool in the study of black holes and other compact objects.

$$ds^2 = -(1 - 2GM/r)dt^2 + (1 - 2GM/r)^(- 1)dr^2 + r^2 d\theta^2 + r^2 sin^2\theta d\phi^2 \tag{1}$$

Where:

- G is the gravitational constant
- M is the mass of the object
- r is the radial coordinate
- t is the time coordinate
- θ and ϕ are the angular coordinates

The Schwarzschild radius, rs = 2GM, is a critical parameter in the metric. If r ¡ rs, the metric becomes singular, indicating the presence of a black hole.

2.5 Numerical Relativity

Numerical relativity is a subfield of general relativity that uses numerical techniques to solve Einstein's field equations, which explain the curvature of spacetime in the presence of matter and energy. It is a useful tool to investigate the dynamics of black holes, neutron stars, and other compact objects with strong gravitational fields.

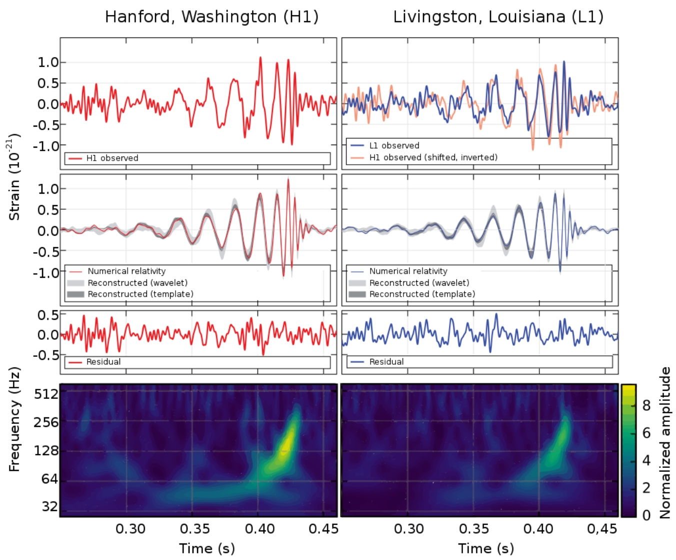

Figure 2: GW150914

2.6 Waveform Generation

Waveform generation in the context of LIGO detectors refers to the process of creating theoretical models of gravitational wave signals that can be compared to the observed data. These models help scientists to identify and interpret potential gravitational wave events.

3 Computational challenges

3.1 Optimization of code

The vast majority of code is built to work on majority of the systems available in the market. If you want to make the most efficient use of the hardware possessed, the code should be specifically tailored to the hardware so that it uses all of the resources available.

For example, Dr. Vaishak was working on optimizing SXS (Simulating eXtreme Spacetime) code to the supercomputers available at ICTS

4 Data Analysis and Parameter Estimation

This section explores the mathematical techniques used in the analysis of gravitational waves (GW) emitted by compact objects in space.

4.1 Minimization

Minimization is a mathematical optimization approach used to get the minimum value of a given function. In the area of gravitational wave data analysis, minimization is frequently used to get the best-fit parameters for a theoretical model that describes the observed data. By minimizing a cost function, such as the sum of the squared residuals between the observed and model waveforms, we may estimate the source's physical properties, including mass and spin.

4.2 Maximum Likelihood Estimation (MLE)

Maximum Likelihood Estimation is a statistical tool for estimating the parameters of a probability distribution using a given dataset. MLE is used in GW analysis to determine the most likely values of parameters, such as merging black hole masses and spins, based on the observed waveform. MLE maximizes the likelihood function, which indicates the chance of witnessing the data given a set of model parameters.

4.3 Bayesian Inference

Bayesian inference is a statistical method that uses previous information and observed data to update probability. It offers a paradigm for combining uncertainty and previous beliefs into data analysis. Bayesian inference is used in gravitational wave research to estimate the posterior probability distribution of merging objects' masses, spins, and distances based on observed data and prior assumptions. This method is particularly beneficial when dealing with ambiguity in model parameters.

4.4 Matched Filtering

Matched filtering is a signal processing method that detects a known signal among noisy data. In gravitational wave analysis, matched filtering is used to find particular waveforms that correlate to gravitational wave occurrences. The approach works by cross-correlating observed data with a template of the predicted signal, enabling for the discovery of weak signals that would otherwise be lost in noise.

4.5 Covariance Matrix

The covariance matrix is a square matrix that calculates the covariances between pairs of parameters. In gravitational wave analysis, the covariance matrix is used to quantify uncertainty in estimated parameters such as merging object masses and spins. The diagonal portions reflect the variance of individual parameters, and the off-diagonal elements show the covariance of several parameters.

4.6 Gravitational Wave Data Analysis

Below are some mathematical terms and their formulae and how they are utilized for compact object analysis.

4.6.1 Dampened Sinusoids

A damped sinusoid depicts a sine wave that decays exponentially. This form describes gravitational waves during the ringdown phase, which happens when two compact objects collide, such as black holes or neutron stars. The ringdown signal reveals details about the freshly generated black hole's characteristics.

4.6.2 Ringdown

The ringdown phase denotes the last step of a GW event. Following the merging of compact objects, the newly generated black hole oscillates and generates gravitational waves before stabilizing. The ringdown signal is crucial to understanding the black hole's mass, spin, and quasinormal modes.

$$f(t) = e^{-\gamma t} \cdot \cos(\omega t) \tag{2}$$

where γ is the damping factor, and ω is the frequency of the oscillation. Taking the logarithm of the function allows for analysis on a logarithmic scale, where γ becomes the slope of the graph when assuming a straight line at the crest of each cycle.

The log-transformed function becomes:

$$\log(f(t)) = \gamma t + \log(\cos(\omega t)) \tag{3}$$

4.6.3 Quasinormal Modes

Quasinormal modes are the oscillations of a black hole during its ringdown phase. These modes are dampened over time, and the frequencies and damping rates reveal information about the black hole's mass and spin.

The function describing the quasinormal mode of a black hole can be written as:

$$h(t) = Ae^{-\gamma t} \cos(\omega t + \phi) \tag{4}$$

Where A is the amplitude of the oscillation, γ is the damping rate, ω is the angular frequency, and ϕ is the phase of the oscillation.

These modes provide important information about the black hole's physical properties. By measuring the quasinormal mode frequencies and their decay rates, we can infer the mass and spin of the black hole, as well as test General Relativity.

4.6.4 Chi-squared Test

The chi-squared test (χ^2) is a statistical hypothesis test that identifies significant differences between observed and predicted data. In gravitational wave analysis, the chi-squared test is used to determine the quality of fit between the observed waveform and the theory.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \tag{5}$$

Where O_i represents the observed data, and E_i represents the expected values based on the theoretical model.

4.6.5 Gaussian Distribution

The Gaussian distribution is a probabilistic distribution that resembles a bell curve. In GW data analysis, noise is frequently represented as a Gaussian process. The probability density function of a Gaussian distribution is defined as:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{6}$$

Where μ is the mean and σ is the standard deviation. Gaussian noise is crucial in analyzing the signal-to-noise ratio in the observed data.

5 Research at ICTS

5.1 Astrophysical Relativity Group

I interviewed researchers who are a part of the Astrophysical Relavity group to get to know more about what they do.

5.1.1 Dr. Vaishak P

Researches the physics of Binary Black hole mergers in highly dynamic scenarios. He focuses on computational physics, particularly in simulating and understanding the complex behaviors of black hole horizons under Einstein's theory of general relativity. He uses supercomputer clusters to manage jobs across multiple nodes, which allows him to run simulations efficiently. This work also involves running and configuring code to optimize resource use on clusters. He has experience with various Linux distributions but primarily uses Fedora as it is similar to the RHEL environments found on supercomputing systems.

Some of his research aims to examine gauge invariance in the context of Einstein's theory - results should remain consistent regardless of coordinate system variations. He is also developing code within the SPEC (Spectral Einstein Code) framework to simulate extreme space conditions. This code relies on spectral methods (methods used for the solution of partial differential equations) which enhances precision and performance for handling complex simulations of black hole behavior. He will be able to give a theoretical basis to match observed GW waves and black hole data by confirming if the phenomena predicted by his Ph.D. study match those from existing simulations in different coordinate systems. If his findings hold true, they might support or contradict Einstein's theories and provide high precision in understanding gravitational waves and black hole dynamics. This research could advance our knowledge of the cosmos and provide fresh approaches to testing the fundamental principles of relativity.

5.1.2 Mukesh Kumar Singh

PhD student researching Early Warning Systems for neutron star-black hole (NSBH) mergers, specifically focusing on improving early warning times through the use of higher-order (subdominant) modes in gravitational waves. These modes provide additional information that enhances the timing and accuracy of early warnings, allowing telescopes to capture crucial electromagnetic (EM) and gravitational wave (GW) data moments before the merger. This research aids in analyzing merging object parameters, such as mass and spin, and contributes to understanding neutron star density, equation of state, and the formation of heavy elements like gold and platinum.

5.1.3 Dr. Prasad R

Involved in multiple projects, one of which focuses on binary neutron stars. His work examines how the magnetic field and the inclination of the poles impact the gravitational wave signals during neutron star mergers. He also does theoretical modeling to predict how gravitational waves would appear if neutron stars have electromagnetic fields. This model is important for scientists needing electromagnetic data from mergers, which allows data analysts to match observational data with theoretical templates that vary based on different parameters, like mass and orientation.

5.1.4 Uddeepta Deka

Studies gravitational lensing, which is the way compact objects with significant density can warp space-time, bending light and electromagnetic (EM) waves. This is similar to how convex lenses converge light to a single point. When gravitational waves and EM waves pass around a compact object, they follow the shortest path due to the warping effect of gravity. As these waves reach Earth, they experience a lot of distortion due to noise and diffraction, deviating from the expected damped sinusoidal model. Udeepta explains that lensing can produce various images or distortions of light emitted by distant stars, resulting in multiple observed images or halos around a lensing object. In the context of GW, the interaction with a lens introduces frequency-dependent modulation to the waveforms. His work involves decoding the modulated signals of GWs to figure out the original waveform and extract the parameters of the lensing object by using "template matching" (similar to how one identifies hybrid dog breeds by comparing them to known templates).

5.1.5 Aditya Kumar Sharma

Focuses on detecting continuous gravitational waves from neutron stars, a different approach than the usual study of compact binary mergers. These waves are emitted by spinning neutron stars with minor deformations which create a time-varying quadrupole moment crucial for emission. Despite the weakness of these waves, their extended observation windows enable detection and aid in the inference of neutron star properties, such deformability, which are linked to the equation of state and contribute to a better understanding of matter under severe circumstances. The present effort looks for signals that could be lensed by supermassive black holes, which makes detection more difficult because of interference and emphasizes how useful Fourier transforms are for filtering out noise and identifying weak signals.

5.1.6 Bhuvaneshwari

Has a B-Tech in Electronics and Communication Engineering, is interested in cosmology and astroparticle physics. She works with GW data at ICTS and specializes in visualizations that promote outreach and theoretical understanding. She creates data and concept representations using Blender, Paraview, and Python. Her long-term objectives include investigating fundamental astrophysics subjects like white holes and baryogenesis, or the universe's imbalance between matter and antimatter. She is also interested in learning more about the origins of the universe, Hubble's constant, and multi-messenger astronomy, which includes neutrinos and gravitational waves. These activities keep her choices open to a variety of specialist subjects and are in line with her goal of obtaining a PhD in astroparticle physics or cosmology.

5.1.7 Dr. Mahesh Chandrasekhar Gandikota

Dr Mahesh is a part of the Statistical Physics and Condensed Matter group at ICTS. He studies the behavior of collections of particles - how active particles, such as bacteria, show non-random motion due to their internal energy sources. His work involves developing theoretical models to understand the dynamics of these particles, especially when they are densely packed. The research explores how these active particles transition from a jammed state to a liquid state through increased activity. By simulating the interactions between these particles, he aims to uncover emergent phenomena, such as flocking behaviors in biological systems. However, practical applications of this research are limited.

5.2 Computational Resources

5.2.1 Laptop

Everyone at ICTS has a laptop running Linux. They are also used to SSH into the supercomputers.

5.2.2 Workstations

Workstations, although not as powerful as the supercomputers, are available, and they are equipped with Intel Xeon CPUs and older Nvidia gt 210 GPUs. Mainly used for smaller, not as demanding tasks.

5.2.3 Supercomputers

There are 2 types of Supercomputers, HPC (High performance computing) and HTC (High throughput computing). HPCs focuses on executing complex computations at high speeds for scientific simulations, and HTCs specialize in completing many tasks over time, such as large-scale data analysis. One of the Supercomputer clusters, *Sonic*, has 14 nodes and is an HPC. It has dual AMD Epyc 7413 24 core CPUs per node and 384gb of ram for compute nodes and 256gb ram for the login nodes. They run the CentOS distribution of linux and are accessed by researchers through secure shell. ICTS recently acquired 2 Nvidia A40 GPUs to accelerate the simulations. *(Since CentOS is discontinued, they may be upgrading to Rocky Linux.).* Dr. Vaishak primarily uses the HPC *Sonic*, where he runs SxS's SPeC numerical relativity simulations. *Sonic* has 40 TFLOPS of computing power, but not all of them are used for the same task. Slurm is a task scheduler on the master node which handles the job queue, assigning nodes to tasks as needed or specified.

5.3 Other Activities

On Wednesdays, the Astrophysical Relativity group meets together and discusses the research papers published over the past week which they find interesting. These papers are published on Arxiv, and one of them is chosen and a detailed presentation about it is given on Fridays.

ICTS also frequently hosts lectures across the various halls. I attended a couple of lectures, covering topics such as Bayesian Inference and Linear algebra. There were also seminars talking about the eROSITA telescope, the development of mathematics in 19th century France, dark energy, and multi messenger cosmology. Notes covering these topics are available on my ICTS repository.

6 Tools and Skills

- **Python**

  Python is a high level object oriented programming language which can be used for a multitude of tasks. I had some experience with Python prior to my time at ICTS, but Dr. Vaishak taught me how to utilize specific libraries to replicate a more simple version of the simulations he conducts. I installed the anaconda distribution of python.

  I started with a new jupyter notebook and used the *matplotlib* and *numpy* libraries to generate simple lines and sinusoidal functions. After testing this, I made a damped sinsoid function and gave it some parameters, added noise onto it so that the original function would be hidden. Then I did a chi-squared test to numerically retrieve the original values I had given the function from the noise. This can be found at my github repository.

- **Dynesty**

  Dynesty is a Python package for Bayesian Inference. I used this library to test if it could retrieve the original parameters of the damped sinusoid hidden in the noise. I followed the tutorial documented on their site, and you can view it here

- **yumcee library by Dr. Vaishak**

  Yumcee is an MPI based Markov Chain Monte-Carlo sampling package for Python, and has a set of tools for carrying out Bayesian parameter estimation.

- **LaTeX**

  LaTeX is a scripting language to make formatting a document easier. It allows the user to focus on the content of the document rather than waste time trying to format it. Overleaf is a free online LaTeX editor, which is what I used to write this document.

- **Windows Subsystem for Linux**

  WSL (Windows Subsystem for Linux) allows you to run a Linux environment on Windows without the need for a separate virtual machine or dual boot. I installed an Ubuntu WSL and installed anaconda, vscode and its shell extensions, and some python packages.

- **Visual Studio Code**

  Visual Studio Code or **VScode** is a code editor, different from an Integrated Development Environment (IDE). It is fast, free and open source and supports many extensions for the various programming language.

- **Obsidian**

  Obsidian is a note taking application that uses the Markdown format. It has a file linking system to better organize thoughts and ideas. These links can be visualized as a graph. I used this software to log my everyday activities at ICTS.

I enjoyed my time job shadowing Dr. Vaishak at ICTS and am very grateful to have had this opportunity. I hope this document has provided insight into the fascinating research and activities taking place at ICTS.

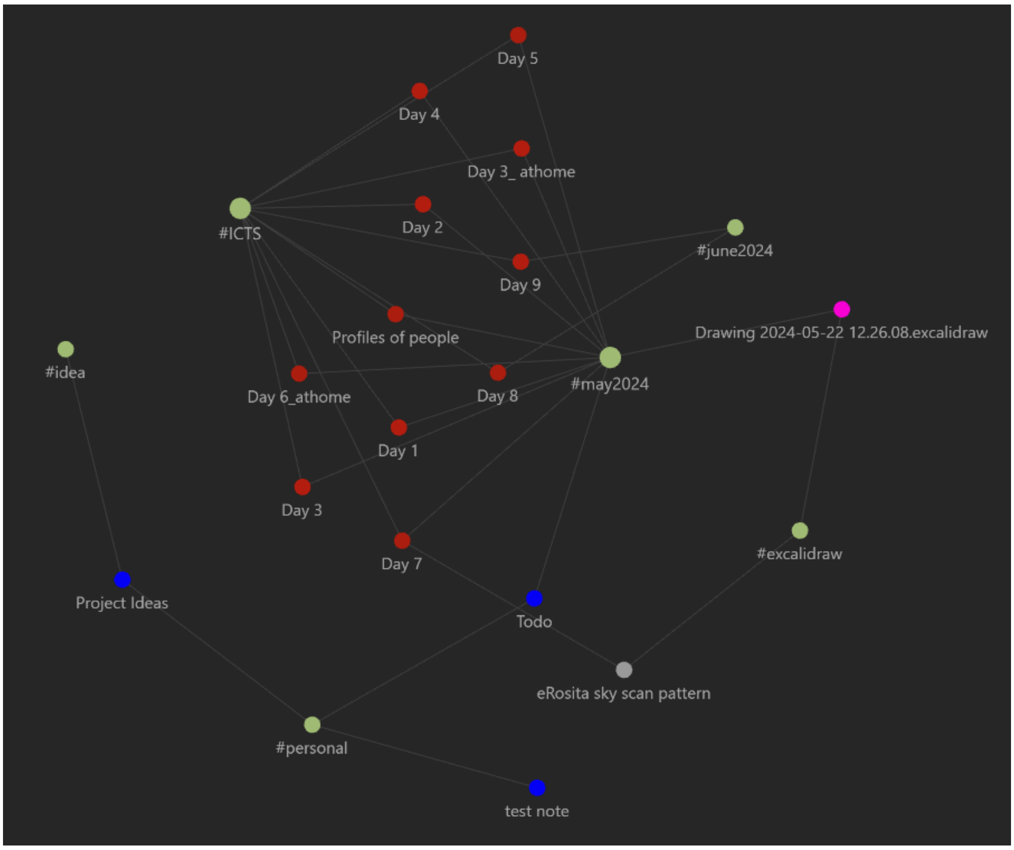

Figure 3: Graph view feature of Obsidian

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