Enhanced Sensitivity Interferometry for Probing Post-Merger Gravitational Waves: Investigating a Novel L-Shaped Interferometer Configuration

Honours Proposal

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Abstract

Gravitational waves, first detected in 2015, have opened new avenues in astrophysics, cosmology, and fundamental physics. Among the various sources of gravitational waves, merging binary neutron stars offer unique insights into the physics of extreme environments and cosmological phenomena. While current ground-based detectors have observed over 90 compact binary merger events, post-merger signals remain poorly understood, particularly regarding the fate of the merging objects and the equation of state for neutron stars. This project aims to investigate a novel L-shaped interferometer configuration, which promises enhanced sensitivity to detect post-merger gravitational wave signals. Building upon previous research, this project will develop an optical model using Finesse in Python to characterise the interferometer's behaviour and assess its potential to extract information about the equation of state for binary neutron star mergers. By simulating the interferometer's performance and estimating event detection rates through Monte Carlo simulations, this study seeks to advance our understanding of post-merger signals and contribute to the development of future and current gravitational wave detectors. The proposed research program outlines a timeline for literature review, model development, testing, and analysis, aiming to yield significant insights into the physics of neutron stars and the broader field of gravitational wave astronomy.

1 Introduction

Gravitational waves were first detected in 2015 from the LIGO-Virgo Collaboration (Abbott et al., 2016). Since then, gravitational waves have provided new possibilities to probe unexplored territories of astrophysics, cosmology, and fundamental physics. Since 2015, over 90 compact binary merger events have been observed by current generation detectors, including Virgo and KAGRA (Zhang et al., 2023).

Gravitational waves from merging binary neutron stars reveal information pertinent to physics and cosmology. The post-merger environment for binary neutron star collisions has yet to be discovered, it is yet unknown whether they form a black hole or a stable neutron star, and over what timescales this occurs. Insights into this environment can be answered by analysing the gravitational wave signals from ground-based detectors and gaining insight into the unknown neutron star equation of state. A post-merger signal provides information of the creation of the object, whether it is a black hole or neutron star. The various ring-downs and potential higher harmonics can help understand the object and optimise the equation of state.

1.1 Neutron Stars

An event detected a binary neutron star merger (GW170817, Abbott et al. (2017a)), in companion with a short gamma ray burst (GRB 170817A, Abbott et al. (2017d)) and joint observations of electromagnetic counterparts (Abbott et al., 2017c) constrained debated astrophysics questions. This multi-messenger discovery confirmed the connection that binary neutron star mergers cause emission of short gamma ray bursts and produce heavy elements via rapid neutron capture (Abbott et al., 2017c). In regards to cosmology, the gravitational wave signal HW170817 allowed for an independent measurement of the Hubble constant (Abbott et al., 2017b). It has also given a unique understanding of the internal structure of neutron stars and their equation of state by restricting their tidal deformability Abbott et al. (2017a), (Abbott et al., 2018), Abbott et al. (2019), Abbott et al. (2020), Chatziioannou (2020), Pan et al. (2020)). The gravitational wave and gamma ray measurements have also led to insights on new constraints and bounds of the speed of gravitational waves and the violation of Lorentz invariance, in addition to a new test of the equivalence principle (Abbott et al., 2017c).

We rely on gravitational waves to extract information on neutron stars as they are inaccessible to experimental laboratories due to their extreme density, ranging from $10^9 - 10^{18}$ kg m^{-3} (Hua, 2022). Observations of neutron stars from sources such as radio pulsars, x-ray binaries, and more (Lattimer, 2010) can constrain the dense matter equation of state, using observable quantities including neutron star masses, radii, rotation rates, radiation radii, redshifts, moments of inertia, temperature and ages. These observable quantities give theoretical limits to the neutron star equation of state, giving insight to the physical mechanisms of the stars. Thus far, the proposed equations of state are entirely theoretically but they can be constrained by gravitational wave observations. However, the current detected binary neutron stars only encapsulates information of the stars at the end of their life cycle, where they experience a strong gravitational force which distorts their observed properties.

1.2 Detector Sensitivity

Current detectors expect a binary neutron star merger event rate of approximately one per few decades (Ackley et al., 2020). Newer design concepts include the Neutron Star Extreme Matter Observatory (NEMO), a proposed gravitational wave interferometer optimised to study nuclear physics with merging neutron stars. To probe these gravitational waves, a detector must be sensitive to the 2-4 kHz regime (Ackley et al., 2020), which current gravitational wave detectors are not sensitive enough to distinguish the post merger signal. This frequency range is set by the various equations of state describing the merger process. However, to maximise the detection probability and optimise target frequency, we need to bridge the modelling of the astrophysical equation of state and the neutron star mass distribution with the modelling of the optical detector configuration.

The first gravitational wave detection was discovered by Advanced Laser Interferometer Gravitational Wave Observatory (aLIGO). It was a laser Michelson interferometer with two arms extending 4km. The beam of light hits a beam splitter, which reflects 50% of the incident light and transmits the other 50%. The incident beam is therefore split into two beams which propagates down the two different arms. The beam is then reflected by the mirror and reflected back to the beamsplitter. They then recombine to be measured at the photodetector (Figure 1). The recombined beams will interfere either constructively or destructively due to the relative changes of the two arms and thus the phase. The relative phase of the two beams when they meet at the photodetector depends on the difference in the length of their optical paths. Gravitational waves cause spacetime to oscillate, stretching one direction whilst compressing in a perpendicular direction, thus causing the LIGO's arms to oscillate in length. When the beams recombine they are no longer in phase and interfere when recombined (Cahillane & Mansell, 2022).

There are currently efforts to create a new generation of detectors that aim to increase the discovery rate of gravitational waves of post merger events, such as the Cosmic Explorer (Evans et al., 2021) and the Einstein Telescope (Maggiore et al., 2020). However, the timeline for constructing and operating these new-age detectors spans decades. Proposed detectors, such as NEMO, aim to be an addition to current-generation detectors that accelerate timelines of operability. The LIGO and Virgo detectors have detected a small number of binary neutron star merger events in their first three observing runs to date. The setup and properties of the interferometer determine the detection of a gravitational wave signal and can infer the properties of the astrophysical source.

Current and next generation gravitational wave detectors operate using a Michelson based interferometer. It has additional cavities in the arms to enhance the phase accumulation due to the gravitational wave. It uses a power recycling mirror to enhance the optical power in the arm cavities, and uses a signal recycling mirror to shape the overall detector response for broadband operations (Cahillane & Mansell, 2022). However, to focus on the 2-4 kHz

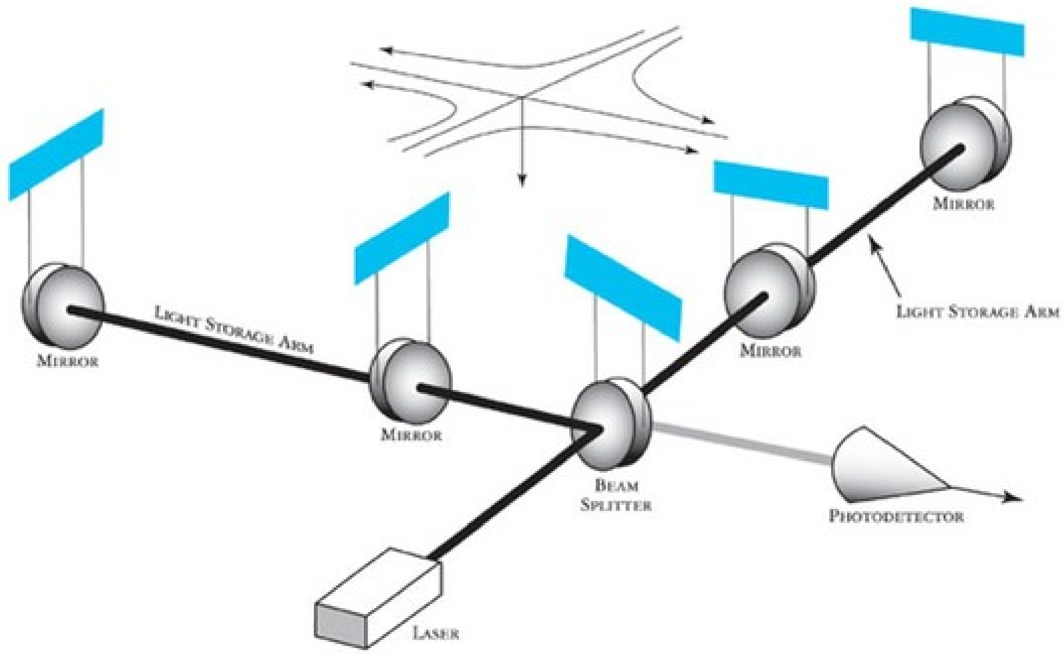

Figure 1: Basic Schematic of LIGO's interferometers with an incoming gravitational wave depicted as arriving from directly above the detector. (Credit: Caltech/MIT/LIGO Lab)

range, other topologies can be explored.

1.3 Problem Statement

My project will investigate the operation of a so-called L-shape interferometer. It is based on a 50 km long linear cavity, which is folded to 90º at the mid-point between the two cavity mirrors. Additional central mirrors will construct a signal input and output path, where a power recycling and signal recycling mirror can be placed. This configuration has the potential to significantly enhance the sensitivity beyond that of the Cosmic Explorer or the Einstein Telescope, as well as bringing insight into current astronomical telescopes, such as VLTI and ALMA. However, as this is a new optical configuration, an understanding of its operation and limits are required to fully characterise its potential.

I will see to develop an optical model to characterise its behaviour, using Finesse in python, and try to evolve that with numerical time domain signals to understand its detector potential to extract the equation of state for binary neutron star mergers.

2 Previous Work

Zhang et al. (2023) investigated an interferometer configuration with a L-shape resonator as the core, which significantly surpasses the loss-limited sensitivity of dual-recycled Fabry-Perot-Michelson interferometers at high frequencies. They provided a broadband design of a 25 km detector with outstanding sensitivity between 2-4 kHz. The new design predicts a detection rate of neutron star postmerger larger than one per year, with the expected rate between $\mathcal{O}(1)$ and $\mathcal{O}(10)$ events per year.

Extra mirrors are introduced in the arms of the Michelson-type design, to form Fabry-Perot cavities which boost both the optical power and the gravitational wave signals. This modification improves the orders of magnitude within the cavity bandwidth, typically from a few hertz to tens of hertz. However, the binary neutron star postmerger signals are mainly between 2-4 kHz, thus Zhang et al. (2023) explores various ideas to improve the high-frequency sensitivity of modern and future detectors. In particular, with the dual-recycled Fabry-Perot-Michelson interferometer by introducing a power recycling cavity at the bright port and a signal recycling cavity and signal extraction cavity at the dark port to further enhance the arm cavity power and adjust the detector response. The interferometer is operated at a dark fringe so that, apart from losses, most of the light is reflected back in the direction towards laser and injection optics, hence this input port is also called the “bright” port of the interferometer, likewise the output port is also called the “dark” port (Bond et al., 2017). Whilst increasing the arm cavity power and becoming more sensitive to high-frequencies, the interferometer idea is contained by the optical losses in the signal extraction cavity. Unfortunately, the signal extraction cavity loss-limited high-frequency sensitivity is independent of the arm length. Thus, a sloshing-type Sagnac configuration can overcome the signal extraction cavity loss limit by adding a filter cavity between two arms and thus shaping coupled-cavity resonances in the absence of a signal extraction cavity. However, the filter cavity loss becomes the new limiting factor as another internal loss. However, the filter cavity loss then becomes the new limiting factor as another internal loss.

In addition, Zhang et al. (2023) also explores the potential advantage of the new detector in its ability to detect dark-matter-induced neutron star collapse. Benefiting from the conspicuous sensitivity between 8-10 kHz, which results from the second resonance of the new interferometer, it gives approximately 30% improvement for neutron stars with around 1.4 solar masses, in comparison to the horizon reach of other configurations.

3 Methodology

This project aims to extend on Zhang et al. (2023)'s work for the case of a 50 km Fabry-Perot-Michelson interferometer.

3.1 Proposed Research Program

For this project, I will see to develop an optical model to characterise its behaviour, using Finesse in python, and try to evolve that with numerical time domain signals to understand its detector potential to extract the equation of state for binary neutron star mergers. First, an understanding of the relevant optical physics will be acquired, in order to critically evaluate the results of the python system, checking to make sure the model is working appropriately. Once an understanding of the python program is developed, I will seek to simulate the Fabry-Perot-Michelson interferometer from the basic Michelson interferometer and then I will add in new components and test whether the system acts as intended. The strain from the final interferometer design will be compared to the strain sensitivity comparison in Fig. 4 (Zhang et al., 2023), comparing against current and future detectors. When the model is confidently calibrated, I plan to use Monte-Carlo simulations, based on current equations of state, to estimate the event detection rate and the signal-to-noise.

3.2 Proposed Timeline

Until the mid semester break in Semester 1, I will be focusing on literature and understanding relevant topics, whilst getting familiar with the python Finesse environment. By the end of semester, I aim to have calibrated the python model and to have a recreated version of the strain sensitivity comparison from Zhang et al. (2023). The semester, I will also focus on my introduction and background information chapters of my thesis. Between semester 1 and 2 will be when my main run of testing will be completed with the model, and implementing Monte Carlo population simulations.

During Semester 2, I will make judgements based on the data trials over the semester break. I will also be focusing on writing the remainder of my thesis.

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