**LIGO SURF 2022 Abstracts**

**Optical Contact Bonding for Mitigating Clamping Losses in Silicon Resonators**

This experiment aims to improve the quality factor of silicon resonators in order to mitigate the thermal noise present in the mirrors and suspension systems in the LIGO Michelson Interferometer. The oscillation of the cantilever is analyzed and used to calculate the mechanical quality factor through the exponential decay of the oscillations in the ringdown method. The clamping losses and thermoelastic sources of loss are studied to understand the intrinsic factors affecting the quality factor. The design of the clamp will use optically contacted layers silicon in order to reduce the acoustic waves radiating away from the resonator into the substrate, which will achieve the effect of improving the quality factor of the cantilever.

**Synergies With WINTER, ZTF, and LIGO for Kilonova Discovery**

During LIGO's fourth observing run (O4), we expect to discover more gravitational wave (GW) events than ever before, including binary neutron star (BNS) and neutron star black hole (NSBH) mergers that produce electromagnetically bright kilonovae. The Zwicky Transient Facility (ZTF) has thus far performed extensive follow-up in the optical regime during LIGO's third observing run, O3. During O4, the Wide-Field Transient Explorer (WINTER), designed specifically for gravitational wave follow-up, will join the campaign in the near-infrared Y, J, and short-H bands. We investigate the potential of combining the resources of both WINTER and ZTF to create an observing strategy suited for joint gravitational wave and electromagnetic discoveries. We use the Nuclear and Multi-Messenger Astrophysics (NMMA) Bayesian Python pipeline to simulate WINTER's observations of kilonovae with different Target of Opportunity (ToO) triggering criteria and observing setups. We draw from a simulated population of LIGO observations and radiative transfer kilonova models. This study begins to assess kilonova parameter recovery with WINTER. In the future, we hope to simulate the the combined WINTER/ZTF observing system to determine the most effective follow-up strategy for a given LIGO gravitational wave alert and integrate it into the campaign starting in O4.

**Implementation of an Inpainting Filter to Mitigate the Effect of Glitches on Gravitational-Wave Parameter Estimation**

Recovering accurate distributions for the source parameters of gravitational-wave signals is essential to confirm current models of general relativity and understand astrophysical properties of the universe. Glitches in gravitational-wave strain data may cause a bias in parameter estimation analyses that use Bayesian inference. We implement inpainting to address this problem in Bilby, one of various parameter estimation pipelines used for gravitational-wave analyses. Using two different methods to obtain inpainted data, we study how each process affects likelihood evaluation times and Bilby's ability to recover accurate posterior distributions. We will also work towards running different PE analyses using inpainted data with injected signals and studying how often Bilby can recover injected parameter values within a specific confidence interval.

**Mode Matching for Triangular Ring Cavity**

In upcoming LIGO designs, a Phase Sensitive Optomechanical Amplifier (PSOMA) will be introduced to help mitigate readout losses in the LIGO interferometer. Though only at the tabletop stage, the PSOMA design is experiencing mode mismatch in its triangular ring cavities. The cause of this discrepancy is assumed to be in the mode matching lenses. Methods of analysis are to model the design with a thick lens, and consider lens aberrations. While a thick lens design is more straightforward to construct, considering lens aberrations is no trivial task. In this project, we take a conceptual idea of the cause and effects of lens aberrations, and apply them to Gaussian beams. The results given may provide much better analysis on how optics play a role in not only the PSOMA cavity, but in the LIGO interferometers.

**Improved Targeted Sub-threshold Search for Strongly Lensed Gravitational Waves With Sky Location Constraint**

Gravitational lensing is an important field in both astrophysics and cosmology as it could provide a large amount of crucial information about our universe unmatched by other phenomena such as the determination of expansion rate of the universe and the distribution of dark matter. Until recently, gravitational lensing had only been applied to the observation of the electromagnetic spectrum. Since the first successful observation of gravitational waves back in 2015, discussions had started to try to find lensed gravitational wave signals. However, in most cases, the lensed image should be much dimmer than the original signal, which might be buried in the noise as it could not pass the normal detection threshold. Our work would be to improve the existing TESLA searching pipeline to suit our need for lensing searches. We hope to recover originally buried sub-threshold lensed signal from the collected data. Our work would be implemented in the TESLA pipeline for future uses.

**Fisher Information Analysis for Emissivity Estimation**

We wish to estimate the emissivities of various test mass barrel coating candidates for the Mariner upgrade of the 40m prototype at Caltech. The cooldown of a sample in our test cryostat has a time constant of several days, making it infeasible to run the experiment multiple times to estimate its emissivity. The methodology involves system identification using Fisher Matrix analysis on the cryostat and finding the optimal experimental configuration and input that minimizes uncertainty on the final emissivity estimate. The Fisher Matrix analysis has shown us a relationship between system design parameters and uncertainty in the test mass emissivity. The optimal heat input is determined using power spectrum optimization, which distributes the total power over various signal frequencies. For a first-order system, this method gives an optimal frequency very close to the one obtained while minimizing the uncertainty of the parameter corresponding to the system's pole. The optimal design parameters and input will be implemented in future measurement runs with silicon wafers.

**Prototype Mirror Suspension for Cryogenic Interferometers**

Gravitational wave astronomy has been a rapid growing field, we use interferometers to detect gravitational waves which give us insight into optically hidden events such as black hole mergers. Since the current noise levels of the Advanced LIGO detectors are reaching to the physical limit, they will soon need detector upgrade. For the successful design of such upgrade, the development of the cryogenic suspension is imperative. The goal of my summer research is to build and test a prototype suspension system. In this article, we will be describing the project "LIGO Voyager" and our goal for the summer to help push the advancement of the current aLIGO to LIGO Voyager by creating a prototype suspension system. This prototype will then be tested in air, vacuum, and at cryogenic temperatures specifically looking at the dynamical and cooling performance. Our Test results are feedback to the modification of the suspension design for Mariner and thus increase the feasibility of the Voyager upgrade.

**Active Monitoring of the Auxiliary Laser System**

The Auxiliary Laser System is used to reduce interferometer locking time, by measuring the difference between the resonance of the cavity and the Pre-Stabilized Laser without locking the cavity to the PSL. Thus we can keep the cavity unlocked while locking the rest of the interferometer to the PSL. The difference between the frequency of the Auxiliary Laser (AUX) and cavity resonance is measured by the Pound-Drever-Hall technique, and minimized by a feedback loop. The gain of this loop is a function of the frequency of the noise entering it. Using a Red Pitaya as a vector network analyzer measuring the AUX laser control loop, we can create an active monitoring system that returns the unity gain frequency (UGF) of the loop, and thus allows us to monitor whether the UGF drifts over time and how frequently recalibration of the loop is necessary.

**Methods of Improving Optical Contacting**

This project will attempt to improve the technique of optical contacting, which is the process of bonding polished, flat surfaces using Van der Waals dispersion forces. It will explore the efficacy of different preparation methods for creating a bond. There will be a focus on the use of heat and pressure to increase the strength of the bond between glass slides and silicon wafers. One of the main goals of the project is to find the best temperature for creating a strong bond. The quality of the bond can be assessed by measuring the shear strength, tensile strength, air gap, and mechanical quality. The eventual goal is to make optical contacting strong enough to be a viable method for conjoining pieces of high precision equipment in space, specifically for the LIGO Voyager.

**Determining the Feasibility of Matched Filter Searches for Core-Collapse Supernovae**

With the efforts of the Laser Interferometer Gravitational-Wave Observatory (LIGO) collaboration, gravitational waves (GWs) have been successfully detected from black hole mergers, neutron stars, and neutron star-black hole binaries. However, there are other violent phenomena, such as core-collapse supernovae (CCSNe), that are potential candidates for gravitational wave studies. CCSNe are of particular interest because they emit other astrophysical messengers such as neutrinos and electromagnetic rays. I will study the feasibility of using matched filter searches for CCSNe with a phenomenological GW model that aims to be representative of CCSNe waveforms. I will examine the impact of stochasticity on the g-mode dominated emission of CCSNe, determine if the randomness of waveforms is manageable for generating a parameter space, design a template bank of CCSNe gravitational waveforms, and compare a search benchmarked against numerical relativity simulations.

**Approximating Simulated Stochastic Gravitational Wave Background BBHs With Broken Splines and Power Laws**

The Stochastic Gravitational Wave Background (SGWB) is the combination of assumed isotropic, stationary, unpolarized, and Gaussian sources of gravitational waves. We expect a large contribution of neutron star and black hole binaries to this unresolved signal. Current LIGO detectors are not sensitive enough to the SGWB strain regime but we anticipate future observing runs to have the required visibility for the SGWB. The promise of future detectors registering the SGWB requires the introduction of detection and fitting algorithms to understand future observation results. A Reverse Jump Markov Chain Monte Carlo (RJMCMC) algorithm permits us to probe the fitting parameters for SGWB signals via spline and power law fittings. The versatility of the RJMCMC can be applied to the astrophysical case of recovering the energy density spectra based on injected mass distributions and merger rates for binary black hole mergers (BBHs). Accurately fitting the SGWB profiles and parametrizing profiles via spline and broken power laws will aid in identifying various components of the SGWB in data from upcoming LIGO observing runs.

**Analyzing the Effective and Component Spin Distributions of Binary Black Hole Mergers**

Gravitational wave (GW) observations of binary black hole (BBH) mergers provide measurements of BBH parameters such as mass and spin, which shed light on the evolutionary history of these systems. We explore the distribution of BBH spin on a population level through looking at different spin parametrizations. LIGO data currently provides strong constraints on effective spin, a mass weighted average of component spin projected in the direction of the angular momentum, but component spin is weakly constrained for individual events. Through a Bayesian hierarchical inference approach, we explore whether we can differentiate synthetic populations with the same effective spin distributions but different component spin distributions. We explore these spin distributions for two different population sizes: one comparable to LIGO's third observing run (O3) and one comparable to the predicted population size after the next observing run (O4). This study demonstrates how current models of spin distribution will improve with O4.

**Supermassive Black Hole Property Determination via Gravitational Radiation From Eccentrically Orbiting Stellar Mass Black Hole Binaries**

The gravitational waveform from a compact inspiraling binary, such as a BBH, can indicate the presence of a nearby massive body, such as an SMBH. The waveform is modulated by de Sitter precession of the BBH’s inner angular momentum and by the time-dependent Doppler phase shift of the BBH in its orbit. The future generation of space-based GW observatories, focused on the millihertz and decihertz band, is uniquely poised to observe these waveform modulations, as the GW frequency from stellar-mass BBHs remains in this band for the months or years over which these modulation effects accumulate. In this work, we apply the Fisher information matrix to estimate how well a decihertz detector can measure properties of BBH+SMBH hierarchical triples. We consider an eccentric orbit of the BBH about the SMBH, extending previous studies which were limited to circular orbits. We find that the uncertainties in measurements of the SMBH mass and semimajor axis can be improved by a factor of a few when the BBH takes a non-circular orbit, but improvement is not universally guaranteed. Furthermore, the eccentricity and argument of periapsis are very well measured.

**Recovering Higher Order Modes in the Ringdown of Binary Black Hole Coalescences**

Disturbances in the curvature of spacetime from the coalescence of binary black holes can be probed by the gravitational waves of radiation emitted by these sources and recorded by Advanced LIGO and Virgo. The merger of such objects allows us to test Einstein's theory of general relativity in the regime of strong and highly dynamical gravity - specifically, the newly formed black hole rings down in a series of quasinormal modes, whose frequencies and damping rates are fully predicted by general relativity. We focus on the ringdown of the remnant black hole, implementing ringdown analysis in the time domain. We demonstrate the ability to fit and recover higher order modes of the ringdown within the simulated IMR signal. Possible deviations of the frequencies and damping times of the ringdown may point to new physics beyond general relativity, such as quantum gravity that we are not yet familiar with.

**Incorporating a Stepping-Stone Sampling Algorithm Into BayesWave**

BayesWave is a library of code used to analyze data from LIGO's gravitational wave detections. BayesWave uses Bayesian statistics to reconstruct signals and determine possible sources. The likelihoods of various models can be compared, such that BayesWave can determine the most likely sizes, locations, and types of sources that could produce a certain detected signal. Currently, BayesWave uses Thermodynamic Integration (TI) to calculate the likelihoods of various models. An alternative method is called Stepping-Stone (SS) sampling. In other fields, SS has been shown to be as accurate as TI while also being less computationally expensive. This project explores the comparison between TI and SS methods when each is applied inside BayesWave, to determine if SS is a viable replacement for TI to be used for analysis of LIGO's fourth detection run in 2023.

**Emissivity Engineering for Radiative Cryocooling**

The Laser Interferometer Gravitational Wave Observatory (LIGO) will undergo the cryogenic Voyager upgrade to increase detector sensitivity, allowing gravitational wave astronomers to learn more information about astronomical events in the field of multimessenger astrophysics. This upgrade will require efficient cooling of the test mass, in part through high thermal emissivity coatings applied to the barrel surface. Testing the emissivity of various coatings is expensive and time consuming, so it is important to find an optimal experimental design and cryogenic test chamber geometry. We used Markov Chain Monte Carlo (MCMC) analysis to observe how errors within the system propagate and to fit the value of the test mass emissivity to noisy data from the system cooldown. This analysis will be applied to emissivity tests of various high thermal emissivity coatings that potentially can be used in the LIGO Voyager upgrade.

**Detecting Non-Power Law Stochastic Gravitational Wave Background**

The Stochastic Gravitational Wave Background (SGWB) is a consistent signal composed of a combination of many unknown sources. Since the SGWB is continuous, there is information on a much larger scale with the hope of included remnants of the early universe in the background. Current models work well to describe SGWB with current detector sensitivity where SGBW can be described by a simple power-law. However, common theories predict a turnover that will be detected with future detectors' sensitivity; this will lead to inconsistencies if current models are used. Since there is so much we do not know yet of the unknown sources it is pivotal to design a general and generic model to detect a SGWB that does not characterize as a simple power law. We use a new method of the Bayes factor along with \code{westley}, to do generic fitting when describing non-power law models, to detect SGWB. We will use splines and Gaussian processes to define this generic model and test with simulated data.

**Characterization and Control of the Auxiliary Laser PZT**

Frequency doubled auxiliary (AUX) lasers in the 40m prototype are used as out-of-loop arm cavity length sensors to help bring the interferometer robustly into resonance with the main laser. To do this, each AUX laser is locked to an arm cavity using the Pound-Drever-Hall (PDH) scheme. To achieve the necessary phase modulation for length sensing using PDH, a piezo electric transducer (PZT) mechanical resonance is exploited. While in this case the single PZT mechanical resonance turns out to be useful, they are generally detrimental to active stabilization of the laser frequency, lowering the gain and with it, the control bandwidth. The aim of this project is to accurately measure the open-loop transfer function of the AUX controller, as well as the PZT actuation transfer function for which a simple analytical model might help predict the shape of PZT mechanical resonances. Having identified several spurious PZT resonances, the inverse actuation transfer function can be found and applied to the system using a digital filter, effectively improving the gain of the system. Our work adds a digital aspect to the AUX laser control system that were previously entirely analog.

**GW Strain Calibration of LIGO Detectors With High Precision and Low Latency**

The detection of gravitational waves (GW) has opened a new era of astrophysical observation, allowing scientists to view and analyze previously unseen phenomena. This process hinges upon measuring the strain $\Delta L/L$ of space over 4 km long baselines, which change by a differential arm (DARM) length on the order of $10^{-20}$ meters when a GW passes. From this information-rich time series, a wealth of astrophysical information may be deduced. In order to produce a reliable estimate of the strain, the Laser Interferometer Gravitational Wave Observatory (LIGO) detectors must be precisely calibrated. Furthermore, the calibration pipeline must produce an associated calibration uncertainty estimate with which to characterize the strain. While uncertainty estimates can currently be produced with low latency, it takes months to investigate the sources of error and verify the quality of calibration. Producing a high precision, low latency uncertainty estimate and a diagnostic monitoring software is therefore crucial for LIGO's fourth observing run (O4). It is this task that forms the basis of this research project. The uncertainty estimation and monitoring software are to be produced using pyDARM, a python package which implements the DARM control loop model and is currently under development. The software must reliably output uncertainty estimates and a suite of diagnostic plots on the timescale of an hour. It will actively be of use in O4.

**Testing Universal Relations Under Non-Parametric Equation-of-State Models**

The equation-of-state (EoS) for the nuclear interactions between particles at very high densities remain a mystery to us. At the moment, our only avenue for exploring the characteristics of matter at these densities is through neutron stars, objects that are extensively studied by LIGO. We aim to test the validity of "Universal Relations", that is, relationships between properties of neutron stars that might hold regardless of the nuclear EoS. We are especially interested in these relationships, as they would be able to tell us more about the nuclear EoS and would further the strength of data gathered by LIGO. To do this, we aim to analyze these relations under many different algorithmically generated EoS models and inspect the variance observed. This is done by generating predictions based on these models through which we are able to evaluate their goodness of fit based on the uncertainty of the models from the prediction.

**Exploring LIGO Sensitivity Across Binary Black Hole Parameter Space**

As we look ahead to LIGO, Virgo and KAGRA (LVK)'s next observational run (O4) and future gravitational wave observatories such as Cosmic Explorer, understanding the sensitivity of the detectors network for compact binary coalescences (CBCs) is important to estimating the merger rate density. The parameter space of CBCs is composed of fifteen parameters, which are used to characterize the binary systems. In this work, we explore how the network sensitivity (space-time sensitive hypervolume) changes according to changes in the CBC population parameter space. Using Monte Carlo simulations, we solve the averaged space-time sensitive hypervolume for different parameter configurations, marginalizing over subsets of the parameter space so that we can compare them.

**Testing Mass Distribution Estimation of Binary Black Hole Mergers**

With ~70 binary black hole merger (BBHs) events detected by the Advanced LIGO and Advanced Virgo Scientific Collaboration, it is possible to infer the overall character of the black hole population in the universe. Specifically, the mass distribution of BBHs provides us with valuable information on stellar evolution and binary formation channel. We here aim to test the current estimation of BBHs population mass distribution based on the third Gravitational-wave Transient Catalog (GWTC-3). The project involves: (1) Examine agreement between the observed data and the fitted mode by conducting goodness-of-fit tests; (2) identifying outliers and examining the impact of non-conventional events with leave-one tests on population parameter estimation; (3) adjusting model to better characterize astrophysical phenomena and describe observed result; (4) compare different theoretical models that may describe the BBHs distribution by fitting observed data to multiple models.