Caltech LIGO SURF 2019 Projects

LIGO Livingston

Clustering algorithm for detector noise sources identification

LIGO is sensitive to environmental vibrations which can couple in via scattered light in the interferometer. This noise limits the sensitivity to the early part of the inspiral as well as to the hypothetical population of black holes of greater than 100 solar masses. The detector complexity makes it such that it is a time intensive task to properly study the behavior of the circa 100 sensors monitoring the ambient noise. Sensors include accelerometers, microphones, magnetometers, seismometers, etc. As part of this project, we will implement an un-supervised learning algorithm (via Keras/Tensorflow) which would find correlations between LIGO noise in certain frequency bands and these sensors. This would help identify areas of the detector which need improvement with the end goal of increasing the LIGO sensitivity.

Knowledge of Python and machine learning algorithms would be useful.

Caltech Experimental Projects

Fabrication of Low Dissipation Mechanical Structures by Optical Contacting

Silicon is a promising material to use for the suspensions and mirrors of gravitational wave detectors, due to its favorable material properties. However, the largest monolithic silicon crystals that can be grown today are at most 45 centimeters in diameter, while future detectors will require mirrors considerably larger than this. Assembly of a composite structure by optical contacting is a way to solve this problem. In principle, it should be possible to enhance the Van der Waals forces through modification of the surfaces and by heat treatments. In this project, we will use optical contacting to bond samples of silicon and study the properties of the product.

Real-time universal transfer function synthesizer

LIGO uses a synchronized networked real-time computing system for data acquisition and interferometer controls. One of its most important features is the ability to implement minimally intrusive changes in the control loop landscape via and in-situ parameter redefinitions such as filter order and coefficients. However, many control loops require bandwidths that far exceed the capabilities of the global real-time system. Using programmable fast-clocked real-time hardware that can interface with the original configuration tools represents a compromise between the flexibility of digital logic with the speed of analog circuits. The goal of this project is to assemble a near-arbitrary transfer function synthesizer with noise-shaping that can be used in control loops and physically instantiate simulated plants for loop analysis. This project will involve the graphical and text-based programming of real-time hardware in Verilog and Simulink, and a limited amount of analog electronics assembly for signal whitening filters.

Familiarity with Python and a basic understanding of control loops is recommended.

Reducing Optical Losses with Actively-Tunable Adaptive Optics

Gravitational wave detectors consist of multiple resonant optical cavities. The laser field exiting one cavity is the input to the next. However, non-idealities in the geometry and positioning of the optics cause the laser mode exiting one cavity to imperfectly match the mode supported by the next, resulting in optical losses which degrade the sensitivity to gravitational waves. Adaptive optics hold the potential to eliminate these losses by actively "canceling" imperfections.

This project will characterize prototype adaptive-curvature mirrors, through simulation and measurement.

Python programming, finite-element analysis, and knowledge of basic optics are recommended.

Image Processing to Track Laser Beam motion

Seismic noise causes the LIGO mirrors to move and thereby, the position of the laser beams on the mirrors. The coupling of laser noise sources from the laser to the gravitational-wave readout is modulated by this beam motion. In this project, we will use the video cameras from a prototype interferometer on the Caltech campus that monitor the interferometer mirrors to determine the beam position as a function of time with high accuracy using a supervised learning approach with convolutional neural networks to reject image noise. This beam spot motion will then be used as an input to nonlinear regression algorithms to improve the LIGO sensitivity.

Knowledge of Python, image processing, and CNNs will be useful.

Extending the reach of gravitational-wave detectors with machine learning

With the advent of gravitational-wave astronomy, techniques to extend the reach of gravitational-wave detectors are desired. In addition to the stellar mass black hole and neutron star mergers already detected, many more are below the surface of the noise, available for detection if the noise is reduced enough. This project applies machine learning algorithms to gravitational-wave detector data and auxiliary channels on-site to reduce the noise in the time-series due to instrumental artifacts. This framework is generic enough to subtract both linear and non-linear coupling mechanisms, and teach us about the mechanisms which are not currently understood to be limiting detector sensitivities. Using realistic assumptions about coupling mechanisms, we seek to reduce the noise floor to lead to sensitivity improvements for binary systems. The expectation is that this work can be generalized to other time series regression analyses in all areas of science.

Interest and knowledge of Python, Machine Learning methods, and FFT / signal processing is recommended.

Understanding interferometer "lock losses" with machine learning

The LIGO interferometers are unstable opto-mechanical systems that require complicated feedback control networks to maintain them in the state at which they are most sensitive to gravitational waves. Occasionally the detectors "lose lock", whereby the feedback systems are not able to maintain the sensitive state, at which point the detectors need to be reset. This is time consuming and reduces detector uptime. In this project we will analyze the data from past lock losses with modern machine learning techniques with the goal of identifying the underlying cause of these lock loss events. The ultimate goal will be to provide useful information to the on-site commissioners to help them make changes to the detectors to reduce the number of these lock loss events in the future.

Interest and knowledge requirements: python, machine learning methods, signal processing.

Optimal non-linear control design for thermal systems

Larger thermal systems in precision experiments are often susceptible to thermal drift that affect the scientific readout. Long time constants, random fluctuations in the environment and the non-linear response of the system under control can make the design of linear control systems difficult. The summer the students will develop a machine based feedback/feedforward system for slow system temperature control. The project is to identify an optimal non-linear controller that achieves optimal temperature stability with minimal settling time.

Strong hands-on experience in lab environment, some knowledge of modeling tools and some practical knowledge about electronics is preferred.

High frequency mechanical scattered light up shifter

Scattered light can be a significant problem for high precision interferometric experiments like Advanced LIGO. Spurious scattered light can bounce off many unintended surfaces and couple back into the experiment. This turns many of the peripheral components of the experiment into a microphone, coupling much unwanted noise into readout from the surrounding environment. In this project the student will develop a PZT driven 10’s kHz mechanical path length modulation device for up-shifting components of scattered light. The project will involve designing and constructing a test rig with a simulated scatter. The up-shifter will be used to diagnose the scatterer characteristics and scheme will be set up to actively remove scatter.

Strong hands-on experience in lab environment, some knowledge of CAD and FEA modeling tools might be handy, enthusiasm for building and testing prototype mechanical-optical devices is also desirable.

Mode spectral content tracking of the input mode cleaner

The periodic resonant structure of an optical cavity encodes information about its geometry. By precisely monitoring the higher-order mode resonances of an optical cavity, information about the optical loss and absorption of the cavity can be backed out, and hence, is an invaluable diagnostic tool for characterizing the many optical cavities of the LIGO interferometers in-situ. This project will involve implementing such a diagnostic system for a single optical cavity of the 40m prototype interferometer, with a focus on applying techniques from Bayesian inference to experimental data analysis.

Experience with optics and python/inference tools are desirable.

Eigen-Mode tracking of a suspended optical cavity

The mirrors of laser interferometer gravitational wave detectors are suspended with thin materials (fiber or wire) made of either glass or metal. This causes the disturbance of the mirror motion at the harmonic frequencies of the string vibrations, so-called "violin mode noise". By precise and continuous measurement of the frequency and amplitude of the violin modes, we will be able to characterize the behavior of the violin modes and eventually damp them down to a harmless level. This project will construct a digital system to monitor and damp the violin modes of the mirror suspensions using the 40m prototype laser interferometer.

Applicants are desirable to be knowledgeable about signal processing, feedback control theory, and python programming.

Environmental coupling diagnostics using Artificial Intelligence

A critical step in improving the sensitivity of the LIGO interferometers to be able to detect astrophysical signals was to identify and mitigate, the coupling of environmental noise sources to the interferometer's readout. These couplings continue to limit sensitivity in some frequency bands of interest. Techniques from machine learning and artificial intelligence are being tested for their noise subtraction potential on interferometer sensor data streams. This project will involve implementing some of these techniques (both deployment of sensors and development of the data analysis framework) at the 40m prototype interferometer, with focus on acoustic and seismic coupling to the Input Mode Cleaner cavity.

Experience with electronics and python/machine learning/NN tools are desirable.

Optimal non-linear control for LIGO interferometers

Fast lock acquisition and high duty cycle operation of the LIGO interferometers relies on hundreds of feedback loops keeping the various subsystems under control. Improving the performance of these feedback loops, particularly extending linear control to non-linear control, could dramatically improve the ease of keeping the interferometers in observing mode. This project will explore the applications of novel machine learning techniques to design and implement non-linear feedback control on a prototype system (inverted pendulum on a cart), and extend it to some of the simpler subsystems of the 40m prototype interferometer.

Experience with mechanics, electronics, and python/machine learning/Neural-Network tools are desirable.

Explorations in Cryogenic High-Q Mechanical Resonators

One limiting source of noise for next generation gravitational wave detectors may be thermal noise, and thermal noise is a limiting source of decoherence in a broad class of optomechanical measurement devices operating at or near their quantum limits. This project uses a recently developed testbed for measuring the internal friction of thin disk resonators to explore open problems in controlling and optimizing such systems, such as:

- Testing candidate materials for low-loss coatings for LIGO optics
- Optimal experimental design for measuring resonators with nonconventional topologies
- New or improved methods for fast, noncontact temperature readout and control

Parametric Instability and Mechanical Loss Engineering

The high circulating optical power in future gravitational wave detectors will provoke numerous parametric instabilities of the vibrational modes of the test mass. These modes must be damped in a targeted manner, so as to quell the instabilities without impairing the sensitivity to gravitational waves. In this project, we will synthesize meta-materials that act as mechanical filters, to tailor thermal noise couplings at acoustic frequencies.

Caltech LIGO Data Analysis & Astrophysics

The descriptions below consist of a list of broad areas of interest within each project topic. To see the descriptions of last years' projects, please refer to page 9 of this document.

LIGO data calibration

In the new era of gravitational wave astronomy, our primary goal is to measure source parameters and draw astrophysical inferences from observed signals. To do this effectively, we require an accurate calibrated estimate of the strain, or relative change in length, due to gravitational waves passing through our detectors. Students who work in LIGO calibration will combine precision controls engineering with computationally efficient signal processing to try to provide such data in real time.

Interest in / experience with signal processing and Python is recommended; students will also learn some techniques from controls engineering.

Understanding LIGO detector behavior

LIGO data is both non-Gaussian and non-stationary. Fourier transformed LIGO data contains strong features at particular frequencies which can pollute searches for gravitational waves from long-duration sources like spinning neutron stars and a stochastic gravitational wave background. LIGO data also contains short bursts of noise called 'glitches' that can confuse searches for transient gravitational waves including black hole and neutron star mergers. This project will investigate sources of detector noise, quantify their impact on the astrophysical searches, and explore methods for improving astrophysical search performance.

Interest in / experience with python and/or signal processing is recommended.

GWs from compact binary coalescences

To date, a technique called 'matched filtering' has identified every LIGO gravitational wave discovery. Matched filtering essentially works by scanning the data stream with a very precise model, looking for signals in the data that match this model. This technique is especially useful in searching for mergers of extraordinarily compact objects, such as neutron stars and black holes, for which we can use general relativity and numerical simulations to make very accurate waveform models. Matched filter searches on LIGO data use hundreds of thousands of waveforms models that span different object masses and spins. Students interested in searching for compact binaries can study the origin, evolution, and morphology of these signals to learn as much as possible about their implications for astrophysics and cosmology.

Interest in / knowledge of Python, signal processing, and statistics is recommended.

GWs from unmodeled bursts

Matched filtering is a powerful tool when we have an accurate model. Current modeled waveforms for the coalescence of neutron stars and black holes are difficult to generate if these objects have extreme spins or eccentric orbits. The Advanced LIGO detectors are also expected to be sensitive to less well-modeled gravitational wave sources such as galactic core-collapse supernovae. For such sources we use model-agnostic transient (or 'burst') gravitational wave searches. Burst searches are particularly useful to explore perhaps the most exciting potential gravitational wave signal of all: the unknown. As these searches are more susceptible to noise sources, current work explores methods to better differentiate astrophysical signals from detector noise.

Interest in / experience with programming in a terminal and/or via a remote connection is recommended.

GWs from continuous sources

This roughly amounts to something like a mountain sitting on the surface of a neutron star, the shape and height of which can teach us about how matter behaves at super-nuclear densities. Students will have the opportunity to look for potential LIGO signals that correlate with known pulsars in frequency and sky location, as well as sources corresponding to neutron stars not observed with light-based telescopes.

Interest in / experience with programming, signal processing, and Bayesian statistics is recommended.

GWs from stochastic sources

It is very likely that echoes of the Big Bang are currently reverberating around the Universe in the form of gravitational waves. We expect the superposition of these echoes with many overlapping, weak compact object merger sources form a detectable stochastic gravitational wave background. A key science goal for Advanced LIGO is to detect this background by searching for long-lasting coherent power between multiple gravitational wave detectors.

Interest in / experience with programming and statistics is recommended.

Measuring source properties from GW signals

Gravitational waves carry information about the astrophysical sources that create them, which can be measured with precision by comparing observed data to models and simulations. In particular, source masses, angular momenta, location on the sky, and distance from Earth (among other things) all affect the amplitude or phase evolution of an observed GW signal. Students who work on parameter estimation will be at the interface between theory and experiment, analyzing LIGO data and developing methods to improve our knowledge of the explosive sources of gravitational waves.

Interest in / knowledge of Python, signal processing, and Bayesian statistics is recommended.

Multi-messenger astronomy

Some of the GW signals that LIGO detects, such as the binary neutron star merger GW170817, will have gamma-ray, X-ray, optical/infrared, radio, or neutrino counterparts. In many ways this can be thought of as witnessing the same event with several different senses. But for most source types LIGO is the one to catch them first, so it's up to us to tell other astronomers where to look. Students who get involved in multi-messenger astronomy will analyze data and develop software to learn as much as possible from joint observations with other telescopes scattered across the world and in space.

Interest in / knowledge of Python, signal processing, image processing, and Bayesian statistics is recommended.

Black hole astrophysics

Numerical relativity is a powerful tool for simulating the gravitational wave signatures of binary black hole mergers, as well as the recoil response of the system after merger. One key direction in current research is using simulations, populations models, and observations of black holes to understand more about the evolution of black hole progenitor stars and binary black hole systems. Another direction is contributing to the body of waveforms that searches for modeled gravitational waves signals in LIGO data can draw on by improving the accuracy of phenomenological models and/or the efficiency of numerical simulations.

Interest in / experience with programming is recommended.

Theoretical astrophysics and general relativity

Breakthroughs in physics are often made at extremes, and the weakest of all interactions -- gravity -- is no exception. General relativity is the prevailing theory of gravity, which describes gravitation as curvature in space and time rather than as a force. Since the early 20th century, tests of general relativity were all done using measurements of Solar System objects where gravitation is relatively weak. However, with every LIGO observation of extremely compact sources such as neutron stars and black holes comes a unique opportunity to test general relativity using extreme spacetime curvature, pushing the theory to its limits. Students who work on such projects will test this foundational principle of modern physics using the cutting-edge LIGO experiment.

Interest in / experience with signal processing and Bayesian statistics are recommended; students will also learn a great deal about general relativity.

Past Projects from Summer 2019

Discovering the Underlying Distributions of Black Hole Populations

The LIGO and Virgo detectors have been observing the cosmos in search of gravitational waves (GW) since 2000. All three detectors were upgraded to Advanced versions, which for LIGO began observing in 2015 and for Virgo in 2017. In Advanced LIGO's first (12 September 2015 to 19 January 2016) and second (30 November 2016 to 25 August 2017) observing runs (O1 and O2, respectively), the detectors found 10 GW signals from binary black hole (BBH) mergers, and 1 from a binary neutron star (BNS) merger, all with high significance, or low probability of being due to instrumental noise fluctuations. Already in the first several months of O3, which began in April 2019, dozens of candidates have been seen with such high significance. The two aforementioned categories, along with neutron star/black hole mergers (NSBH), are collectively known as compact binary coalescence (CBC). In the coming years, as the detectors' sensitivities are improved, we expect to accumulate tens, hundreds, or thousands of CBC events. From such large samples, we expect to be able to infer the underlying population of CBC systems as a function of their masses, component black hole spins, and redshift. This, in turn, will allow us to better understand the astrophysical processes governing the formation, evolution, and final fate of such systems, as tracers of the most massive stars. In this project, we aim to develop tools and techniques to accomplish this through detailed simulation and Bayesian inference.

Digging Deeper: finding sub-threshold compact binary merger events in LIGO data

The LIGO and Virgo detectors have been observing the gravitational wave sky since 2015. In their first and second observing runs (O1 and O2), they detected 10 GW signals from binary black hole (BBH) mergers, and one from a binary neutron star (BNS) merger, all with high significance (low probability of being due to instrumental noise fluctuations). Already in the first two weeks of O3, which began in April 2019, two BBH signals have been seen with high significance. In addition, tens of events were seen with lower significance, as determined by the search pipelines (PyCBC and gstlal). Are they real GW events, or instrumental noise fluctuations? The information obtainable from the search pipelines, which sift through months of data, are insufficient to tell. In this project we explore the use of additional tools, based on Bayesian model selection (which are far too compute-intensive to run on months of data) and signal coherence to better discriminate real signals from instrumental noise backgrounds. We aim to increase the number of significant detected events, in order to better understand the population of BBH systems in the distant universe.

Electromagnetic Follow-up of Gravitational-wave Sources

Many inspiraling and merging stellar remnants emit both gravitational and electromagnetic radiation as they orbit or collide. These gravitational-wave events together with their associated electromagnetic counterparts provide insight about the nature of the merger, allowing us to further constrain parameters about the properties of the binary object. With the start of the third observation run of the Laser Interferometric Gravitational-Wave Observatory (LIGO) and the future launch of the Laser Interferometer Space Antenna (LISA), follow-up observations are needed of both transient objects, like the kilonova counterparts to the gravitational-wave events detected by LIGO, and of ultracompact binary (UCB) systems, as will be detected by LISA. Using instruments including Palomar Observatory's Zwicky Transient Facility and Triple Spectrograph, and Kitt Peak's Electron Multiplying CCD, we observe and analyze light curves and spectra of these UCBs. With collaborators at Northwestern University, we also generate a catalog of gravitational-waveforms for compact white dwarf binaries in decaying orbits informed by Galactic binary population models, and simulate their light curves. These simulations help constrain the range of UCBs we expect to detect with future time domain surveys and follow-up observations.

Optimal Mass, Spin, and Orientation Parameters for Detecting Higher Order Gravitational-wave Modes from Binary Black Hole Mergers

Thus far, the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO) and Advanced Virgo have detected gravitational waves (GWs), or ripples in the curvature of spacetime, from dozens of binary black hole (BBH) and binary neutron star mergers. In order to detect these GWs, aLIGO data are optimally searched against a bank of model waveform templates well-described by General Relativity (GR). These searches only include waveforms for the dominant Y22 mode, neglecting higher order modes (HOMs) which carry important information about the source and its radiation. Furthermore, HOMs are lower in amplitude than the dominant mode, and tend to lie outside of aLIGO's sensitive frequency band for low-mass systems, making their detection very unlikely. Constrained by this strain sensitivity, we use waveforms produced by numerical relativity simulations to assess the capabilities of aLIGO for detecting HOMs, thus paving the way for a powerful test of GR in the strong-field highly dynamical regime. To determine the range of BBH mass, spin, and orbital orientations which optimizes the likelihood of detecting HOM, we therefore calculate the overlap integral between templates with and without HOMs, as well as the maximum effective luminosity distance to the source. We find the following results: the total mass and mass ratio of the merger should be as large as possible, and the aligned spin should be as large and positive as possible. We find the relationship with inclination angle to be more complicated, as it depends on which combination of HOMs are most dominant at a certain mass ratio.

Constructing Echo Waveform from a Kerr-like Background

Gravitational wave (GW) echoes, the GWs reflected from the surface of an exotic compact object (ECO), may provide information about the Planck-scale structure near the horizon. Previous work on GW echoes is mostly done for non-rotating ECOs described by Schwarzschild metric. In more general cases, a theoretical model for GW echoes from spinning ECOs is of importance in the searches for echoes in LIGO/Virgo data. In this project, we derive the echo waveforms for a spinning ECO, incorporate them into current search pipelines, and study the stability of spinning ECOs.

Gravitational Wave Polarizations: a General Relativity Test

This research aims at assessing with software simulations the possibility of inferring the polarization content of gravitational waves (GWs) within a Bayesian framework. The response of a network of GW interferometric detectors will be studied in order to discriminate between different polarizations. Indeed, it is essential to quantify in advance how GW detector configuration choices affect our ability to measure the GW polarization content, as this measurement can place strong, fundamental constraints on theories of gravity.

Analysis of correlations between non-stationary noise and auxiliary channels in LIGO

Noise in LIGO detectors is not stationary. To track the time evolution of the noise we used the Band-Limited Root Mean Square (BLRMS). We analized different frequency bands in different time BLRMS segments for LIGO Livingston and LIGO Hanford O3 data. We used LASSO choosing an appropriate value for the hyper-parameter α to reduce the number of important channels to tens. We will show interesting results for LIGO Livingston in the frequency band 65−76 Hz and for LIGO Hanford for the frequency band 1120−1400 Hz.

Directed search for continuous gravitational waves from a neutron star in LIGO O2 with a hidden Markov model

Searches for continuous gravitational waves from nonpulsating neutron stars in young supernova remnants are computationally challenging because of rapid stellar braking. Most of the searches to date were conducted using data stretches shorter than ~1 month. The semicoherent search method based on a hidden Markov model tracking scheme provides an economical alternative to the coherent search methods. It can track rapid phase evolution from secular stellar braking and stochastic timing noise torques simultaneously without searching second- and higher-order derivatives of the signal frequency. Here we select one source and conduct a semicoherent search using the whole length of LIGO O2 data.

Extending the Reach of Gravitational-wave Detectors with Machine Learning

This proposal presents the idea of using current machine learning techniques and algorithms to reduce the overall noise floor of the LIGO detectors. There will be a hard emphasis on techniques that analyze time series data, such as utilizing long short-term memory and nonlinear regression algorithms. While other sources of noises in the detectors are outlined in the proposal, there will be a focus on using machine learning algorithms to hone in on noise sources coming from the physical attributes of the instrument itself. The goal is to increase the sensitivity of the detectors by subtracting linear and non-linear noise coupling mechanisms.

Data Driven Modeling of Peak Frequency and Luminosity of Black Hole Mergers

During the final moments of LIGO's first detection, more power was radiated than the power radiated in light from all the stars and galaxies in the Universe combined! This remarkable claim is based on models that predict the luminosity of a black hole merger. Current models for the peak luminosity follow a phenomenological approach, which involves making some assumptions based on perturbation theory and intuition and then calibrating free parameters to numerical relativity simulations. In this work, we take a more powerful approach and train our model directly against numerical relativity simulations, without any underlying phenomenological assumptions. We develop a purely data-driven model for the peak luminosity using Gaussian Process Regression and show that our model outperforms existing models by at least an order of magnitude.

Understanding interferometer lock losses with machine learning

The Laser Interferometer Gravitational-Wave Observatory (LIGO) detectors are complex systems that must be extremely stable to detect gravitational-wave signals. Numerous control loops are used to maintain detector stability, or "lock," but a detector can lose lock. A time-consuming lock acquisition process must be undertaken to regain it, reducing the amount of time during which the interferometer is recording data. The causes of some lock losses are unknown. In this project, we use machine learning to analyze time series data from the auxiliary channels in the LIGO Hanford detector, which can indicate changes in the states of various detector components as well as environmental factors such as seismic noise. We first determine features that characterize the data and then perform a regression to identify which of these features can distinguish between data preceding lock losses and data from stable times. We run a clustering algorithm on the predictive features to identify groups of similar lock loss events. The ultimate goal is to minimize the number of lock losses in the future.