LIGO SURF Project Proposals 2016

At LIGO Livingston (Louisiana)

Spectral Line Tracking at LLO

Mentors: Joe Betzwieser, Valera Frolov

The coupling of environmental noise into the LIGO data stream is modulated by slowly varying environmental influences. This project aims to track the frequency and amplitude modulation of many of the narrow peaks visible in the GW channel. The project requires knowledge of Fourier methods, signal processing, and knowledge of Matlab or Python programming.

Fiber-coupled displacement measurement

Mentors: Ryan de Rosa, Valery Frolov

In addition to the test masses, numerous components of the LIGO seismic isolation system must have their motion sensed and controlled. This includes higher stages of the suspensions, done via shadow sensors, and the isolation platforms, done with commercial inertial and position sensors. Sensing noises of these readout systems can couple to the gravitational wave measurement through auxiliary control loops, but installation and operation constraints are tight. A fiber-coupled interferometric sensor could provide an improved sensitivity with minimal operational obstacles. An interest in optics and laboratory techniques is recommended.

Test mass scattering

Mentors: Ryan de Rosa, Joe Betzwieser

Ideally all of the light incident on the LIGO test masses remains in the main beam path, but some is scattered due to surface imperfections, resulting in losses and potentially noise. A comprehensive survey of all available viewing angles during full power interferometer operation, in combination with data from in-vacuum sensors, could provide a detailed model of the angular distribution of scattered power. An interest in optics is recommended.

At LIGO Hanford (Washington)

Development of optical imaging system for LIGO test mass contamination and beam position monitoring

Mentors: Dan Moraru, Rick Savage, Daniel Sigg

The LIGO interferometers employ optical resonators, Fabry-Perot cavities, to enhance the signals induced by gravitational waves. Maintaining low optical losses in these resonators is critical. Beam mis-centering and particulate contamination are key factors that can increase the losses. To monitor these parameters we have designed and procured optical imaging systems that use Nikon D7100 digital SLR cameras and high-magnification Celestron EdgeHD 8” telescopes. This project will involve writing software to enable remote focusing of the imaging systems, recording and evaluating the images to optimize system performance, and calibration of the images to estimate the total losses induced by surface scatter.

LIGO Physical Environment Monitoring

Mentor: Robert Schofield

Advanced LIGO will detect gravitational wave radiation by measuring test mass motions of as little as 1e-20 m/sqrt(Hz). It is important to keep motions resulting from environmental signals, such as acoustic vibrations and ambient magnetic fields from overwhelming the motions produced by astrophysical signals, and of course it is important to be able to distinguish between the two. The student will spend some time maintaining and improving the environmental monitoring system and so will learn about seismometers, accelerometers, magnetometers and other sensors (pem.ligo.org). In addition, the student will be involved in injecting environmental signals to study how the signals couple into the detector, and in attempts to reduce the level of coupling in order to improve the duty cycle or sensitivity of the gravitational wave detector.

Spectral Line Tracking at LHO

Mentor: Greg Mendell

The goal of this project is to help further develop code that monitors LIGO data for narrow spectral lines. These lines can be either calibration lines, in which case measurements of their amplitude and phase is important to calibrating the instrument, or unwanted spectral disturbances that interfere with searches for gravitational waves. Various parts of the code are written in C/C++, Matlab, and Python. The student will learn about signal processing and data analysis, help improve the code and its web interface, and study lines in the data to help better characterize the detector.

Caltech Experimental Projects

Dynamic beam profile shaping for adaptive optics in Advanced LIGO

Mentors: Aidan Brooks, Gabriele Vajente

This project will investigate methods of dynamically shaping the spatial intensity distribution of a laser beam using a MEMS array of reflectors (the same arrays used in video projectors). We will attempt this at a variety of wavelengths and look to characterize the fidelity of the intensity pattern, diffraction from the MEMS device and intensity noise on the output beam. The ultimate goal is to install such a device into the aLIGO adaptive optic system. A good background and interest in optics, programming and experimental techniques is recommended.

Online thermal modeling of Advanced LIGO optics

Mentor: Aidan Brooks, Jamie Rollins

As Advanced LIGO starts to operate at increased laser intensity levels, we will deploy online models that dynamically model the thermal state of the test masses. Using a variety of inputs from sensors and interferometer channels into our state space model, we can use the results to determine various hidden parameters in the detectors, for instance absorption in the test masses. A strong background in programming and modeling is recommended.

Seismometer isolation for noise cancellation at the 40m interferometer

Mentors: Gautam Venugopalan, Koji Arai

LIGO detectors are extremely sensitive to low frequency seismic motion. At the 40 m Prototype Interferometer, we will test new adaptive noise cancellation techniques to reduce seismic noise in the detectors. This technology will be applied to the Advanced LIGO detectors to improve low frequency sensitivity to astrophysical events, and progress made on seismic cancellation will be used to adaptively reduce other noise sources, including audio and magnetic noise. The student will develop enclosures for seismic sensors that isolate the instruments from external electrical and thermal fluctuations, to increase the sensitivity at very low frequencies. Knowledge of Fourier techniques and general laboratory skills is preferred.

Audio Processing for Detector characterization

Mentors: Eric Quintero, Rana Adhikari

The human auditory system has very sophisticated pattern recognition abilities, which we can use to our advantage in understanding noise in gravitational wave detectors: the vibrations of spacetime will be turned into vibrations of our ears. This project will integrate various digital audio processing algorithms with the online data acquisition system, such as filtering, pitch shifting, and (de)modulation. Experience with coding, digital signals processing, and filtering algorithms is recommended.

Google Maps + Large Interferometers = Cosmology

Mentors: Rana Adhikari, Jan Harms

A LIGO detector's low frequency sensitivity is constrained by the environment in which is located. While some mitigation is possible through the use of environmental sensors, the nonlinearity and unpredictability of local seismicity remains an obstacle. One option for future surface detectors may be the utilization of natural features — such as plateaus, mesas, or buttes — to house the end stations, and provide a relatively quiet and predictable seismic environment, and shielding from weather. The student will use large geographical data sets to search for possible locations for extremely large future GW detectors, considering the local geographical features.

Acoustic emissions in metals

Mentors: Gabriele Vajente

Elastic materials such a metals are described with very good accuracy with linear models. However, material defects can introduce non linear behavior that can be the source of excess noise. One important case is the displacement noise generated by the motion of crystal dislocations (crackling) which can be triggered by the external stress applied to the material. A low frequency variation of the stress can modulate the noise level at much higher frequencies. Such effect may be relevant in the suspension system for the advanced gravitational wave detectors being built. A possible approach to study this phenomenon is by direct detection of the energy released by such microscopic events, in the form of acoustic waves propagating in the blades. The successful candidate will collect data using ultrasonic microphones attached to test blades of various materials, loaded at diverse fraction of the yield stress. She/he will analyze the collected data looking for transient acoustic emission correlated to the externally induced motion of the blade. Finally she/he will devise a procedure to calibrate the microphone output signals in terms of physical released energy.

In-vacuum heat switch

Mentors: Zach Korth, Chris Wipf

In many experiments involving cryogenics, it is desirable to have a controllable heat link between the scientific payload and the cold reservoir. For example, one may want a strong thermal link for rapid heat removal during the initial cool-down phase, while the experiment may benefit from being thermally isolated during operation (e.g., if the experiment requires strong mechanical vibration isolation, which is largely incompatible with strong thermal coupling). In this project, the student will investigate several potential designs for creating such a controllable heat link (or "heat switch"). These designs may be active, with a thermal contact being engaged or disengaged via an electro-mechanical actuator, or passive, in which the actuation is replaced by the natural thermal expansion response of the heat switch components as the system evolves in temperature. Additionally, a hybrid scheme may be used in which the thermal expansion effect is used actively by intentional thermal modulation of certain components within the heat switch.

Modeling of Gravitational Wave Detector Suspensions

Mentors: Alastair Heptonstall, Eric Gustafson

The Advanced LIGO gravitational wave detectors use laser interferometry to look for tiny perturbations in space-time associated with extreme astronomical events such as coalescing binary black holes and supernova explosions. The mirrors of the interferometers are suspended in multiple level systems to isolate them from seismic ground noise, with the final two stages being a monolithic fused silica glass structure consisting of a 40kg mirrored test mass fused to four silica fibers, which in turn are fused to a fused silica penultimate mass. This monolithic stage reduces the thermal noise of the suspension by concentrating thermal energy close to resonances and thus reducing off-resonance thermal noise in the measurement band. Thermal noise from coatings, substrate masses and suspensions is the most important noise source in the most sensitive band of the detectors, and must be reduced if we are to further improve the range of future gravitational wave detectors.

The next generation of gravitational wave detectors will most likely use cryogenically cooled mirrors and suspensions to reduce thermal noise. The fused silica material will be replaced with a crystalline one that is compatible with low temperature operation such as silicon or sapphire. Work on designing and modeling these suspensions is critical to successfully implementing an optimized solution. This project involves the use of finite element analysis to model the final stage of a cryogenic silicon suspension system for a proposed detector configuration called Voyager. Based on requirements set for the suspension performance and planned thermal design, Finite Element Analysis (FEA) allows for design of mechanical systems which can be given realistic features, such as internal friction, non-uniform shapes, spatially varying material properties, temperature distributions and heat flow. The model can then be used to analyze dynamics, spatial distribution of elastic energy storage, and gravitational potential energy. We will use FEA along with comparison to analytical models to build up a full model of a suspension system that will eventually allow direct calculation of the mechanical admittance when perturbed by a Gaussian force giving the thermal noise using the Levin technique.

LIGO Caltech Data Analysis / Astrophysics Projects

Improving the stochastic template bank algorithm used for detection of compact binary systems by Advanced LIGO

Mentor: Kent Blackburn

We will research methods to improving the placement and performance in the construction of the template banks used for detection of compact binary systems. If successful in introducing a dramatic speed up, an evaluation of the performance and effectiveness of the new algorithm will be explored across newest waveform approximates incorporating spin effects, and detailed power spectra from Advanced LIGO's first observation run. Skills used and developed in this project will include Linux/Unix (shell), python (numpy, scipy, matplotlib), visualization of data, code writing and optimizations, statistical and data analysis, signal processing and astrophysics.

Observing Gravitational Waves from Failed Core-Collapse Supernovae with Advanced LIGO and Advanced Virgo

Mentor: Sarah Gossan

The formation of black holes from core-collapse supernovae, whether via direct collapse or fall-back accretion, can tell us much about the physical processes driving the explosion. Gravitational wave observations of black hole formation in such systems offer an unparelleled opportunity to probe failed supernova explosions, where no electromagnetic counterpart exists. Using Advanced LIGO and Advanced Virgo, we make quantative estimates on the detectability of gravitational waves from black hole formation from failed core-collapse supernovae, and determine if constraints on the fraction of core-collapse supernova explosions that fail can be made in this way.

Galaxy Catalogs for Locating Gravitational-wave Events

Mentor: Roy Williams

Gravitational wave transients are caused by some of the most energetic events in the Universe, and a precise location would allow deep examination of the counterpart by electromagnetic waves (telescopes collecting light), the combination of GW and EM resulting in very much improved science return. Since the GW detectors do not provide good localization on the sky, the faint counterpart will be very difficult to find. One strategy to help the search is to look first at galaxies, where mass is concentrated, and thus the prior probability of GW events is highest. This project involves the latest and most comprehensive galaxy catalogs, using them to provide guidance to the optical astronomers about where to look first. The successful applicant must have excellent skills with Unix and Python.

Improving detection confidence of binary black holes

Mentors: Rory Smith & Jonah Kanner

The coalescence of two black holes are among the most promising sources of gravitational waves for Advanced LIGO. Inferring the astrophysical properties of black holes from gravitational waves first requires identifying detection candidates from the detector data based on the loudness of the signal, usually from the signal to noise ratio (SNR). Once a candidate is found, one performs "parameter estimation" on the data containing the candidate signal to extract quantities such as the masses and spins of the black holes, and from multiple observations on can combine results from individual measurements to learn about the population of binary black holes in the universe. In principle, one can lower the threshold SNR for detection provided one can compute a more robust detection statistic that better discriminates genuine gravitational-wave signals from statistical fluctuations in the noise. A promising method involves computing the ***probability*** that the data contains a signal vs the probability that it does not. If successful, this could potentially raise the number of gravitational-wave detections and improve the scientific yield of Advanced LIGO. This project will investigate the ability to lower the detection threshold in order to catch quieter gravitational-wave signals. The student should have experience with python and/or C++ and have a knowledge of probability theory and statistics.

Extending a Plotting Application for the LIGO Open Science Center

Mentor: Eric Fries, Jonah Kanner, Roy Williams

Observations of gravitational waves with LIGO must be effectively communicated to the general public via the LIGO Open Science Center. This project will upgrade an existing plotting application to enhance the user experience by introducing interactive capabilities. Experience with Unix and Python is required, and experience with JavaScript is preferred.

Higher modes in black hole waveforms

Mentors: Patricia Schmidt, Rory Smith, Yanbei Chen

The merger of two stellar mass black holes is amongst the most promising gravitational-wave source for the ground-based interferometric detectors such as LIGO. The gravitational waves (GWs) such merging systems emit are their fingerprints carrying important physical information about the GW source such as the masses and the spins of the black holes. In order to understand the nature of the gravitational-wave source, the ability to accurately measure those physical parameters is crucial but this relies heavily on theoretical waveform models. One to make our GW models more realistic is by including more information in the form of “higher modes”. This project aims to understand whether the inclusion of such additional information into our theoretical waveform models helps to improve the measurement of physical parameters. The student is required to have some experience with Linux, C/C++ and Python. It would also be advantageous if the student had undergraduate-level knowledge of general relativity and quantum mechanics.

Measuring black hole masses in noisy data

Mentors: Jessica McIver, Jonah Kanner, & Alan Weinstein
The coalescence of compact binary objects is thought to be a likely source of gravitational waves observed by the Advanced LIGO detectors. The expected waveforms of these sources are well-modeled, making their detection fairly robust to transient noise, or glitches, which occur fairly often in the detectors. However, the impact of glitches on the waveform reconstruction and parameter estimation of these sources is not well understood. This project involves injecting binary black hole waveforms into both Gaussian and glitchy Advanced LIGO data and studying the impact of chance signal coincidence with glitches on our ability to extract the physical parameters of binary black hole mergers.

Noise hunting in Advanced LIGO

Mentors: Jessica McIver and Alan Weinstein
In order to confidently interpret observed gravitational wave signals in Advanced LIGO data, we must first build an understanding of the character of the noise in the instruments. The first observing run has illustrated that there is a population of noise transients in Advanced LIGO data with the potential to impact transient astrophysical searches, particularly for sources like supernovae and black holes. Intense commissioning efforts over the summer in preparation for the second observing run also promise to change the character of the noise. This project would focus on the cutting edge improvements to the instrumentation in evaluating the quality of the data and investigating the most impactful noise sources to searches for transient gravitational waves.

Searching for gravitational waves from the coalescence of high mass black hole binaries

Mentors: Surabhi Sachdev, Kent Blackburn and Alan Weinstein
We aim to detect gravitational wave signals from the coalescence (inspiral, merger and final black hole ringdown) of compact binary systems (neutron stars and/or black holes) with data from the advanced detectors (LIGO, Virgo, KAGRA). The merger signal from the coalescence of Low-mass systems (binary neutron stars) tends to lie above the LIGO frequency band; only the inspiral phase is detectable. For higher mass systems (involving black holes, each of mass greater than 5 solar masses), the merger and final ringdown are also detectable. We search for these signals using analysis pipelines which filter all the data, identify “triggers” of interest, form coincident triggers between multiple detectors in the network, and attempt to optimally separate signal from detector background noise fluctuations. We use simulated signal injections to evaluate the sensitivity of the search pipeline. The analysis pipeline has numerous parameters that can be tuned to improve the sensitivity. In this project, we will run high-statistics simulations to evaluate the search sensitivity as the analysis parameters are tuned, to arrive at optimal settings under different anticipated noise fluctuation conditions. This project will develop experience and skills in statistical analysis, high throughput computing and the Linux/Unix environment. The student will learn about the physics and astrophysics of compact binary coalescence, and gain experience with modern analysis techniques with large data samples.

Parameter estimation of gravitational wave transients

Mentors: Jonah Kanner, Alan Weinstein

Estimating the source parameters of astrophysical systems using gravitational wave data will be an important component of future observations. The case of measuring the mass and spin parameters of merging compact objects has been well studied. However, methods for extracting other astrophysical information or studying other systems remain largely uncertain. For example, gravitational waves may someday inform us about the equation of state of hypermassive neutron stars and the dynamics of supernovae explosions. In this project, we will explore extending the techniques of parameter estimation to these more complex systems.

Understanding and improving the accuracy of Advanced LIGO Calibration

Mentors: Craig Cahillane, Alan Weinstein

The Advanced LIGO detectors have a complex response to gravitational waves. Calibration of that response needs to be as accurate as possible in order to reliably extract the properties of the detected waves and their sources. In this project, we will improve our understanding of the calibration accuracy by carefully comparing measurements made with calibration systems that mimic the effects of real gravitational waves, to detailed models of the detector response. The goal is to develop improved models and correction factors for the calibrated response, then use this information to improve the accuracy of reconstructed gravitational waveforms from astrophysical systems. The student will develop strong skills in numerical analysis and computer modeling of complex systems in both the time and frequency domains. Ability to code in MATLAB preferred.

Detecting Deviations from General Relativity using Gravitational Waves

Mentors: Maximiliano Isi, Alan Weinstein

Gravitational waves offer a unique opportunity to test the strong-field, highly-dynamical regime of Einstein’s theory of General Relativity. In this project we will explore the possibility of detecting deviations from Einstein’s predictions by looking at generic properties the waves, such as their polarization or speed. This could potentially be used to constrain alternative models of gravity, like scalar-tensor theories. We will study both transient and continuous gravitational waves in order to determine whether it will be possible to make a statement about the compatibility of alternative theories with our observations. The student will gain knowledge about the nature of General Relativity and astrophysical sources of gravitational waves. Experience with Python, C++ and, preferably, some familiarity with General Relativity will be needed to complete this project.

Testing General Relativity through measurements of the stochastic gravitational wave background

Mentor: Tom Callister

Distant neutron star and black hole binaries are expected to give rise to a stochastic background of gravitational waves. Far too weak to be directly detected, the stochastic background is instead found by searching for correlated noise in the two Advanced LIGO detectors. So far, searches for the stochastic background have focused only on signals predicted by General Relativity (GR). In this project, we will work to extend the stochastic search to investigate deviations from GR, such as the presence of additional gravitational wave polarizations predicted in alternative theories of gravity. Along the way, the student will learn about gravitational wave astrophysics and gain hands-on experience with the Linux/Unix environment, Matlab, and the signal-processing strategies necessary to uncover the stochastic background.

Caltech TAPIR (theory) Projects

Structure of black holes in theories beyond general relativity

Mentors: Leo C. Stein, Vijay Varma, Maria Okounkova

One of LIGO's science goals is to test the predictions of general relativity. The cleanest setting for testing GR is the merger of black holes, since there is no unmodeled matter around. For an honest test, we need predictions from both GR and alternative hypotheses. This means we need to compute the structure of black holes in theories beyond general relativity. This project will employ numerical methods to solve partial differential equations to find the spacetime geometries of black holes in other theories, and investigate their structures with tools such as numerical ray tracing. The requisite skills for this project are partial differential equations, linear algebra, numerical methods, programming in C++ and Mathematica, and familiarity with the Linux/Unix environment. The student will learn about black holes, different theories of gravity, and numerical methods for solving partial differential equations.

Measuring Kerrness in binary black hole simulation ringdowns

Mentors: Maria Okounkova, Mark Scheel

After a single black hole forms from the merger of a black hole binary, it enters the ringdown phase, radiating away energy in gravitational waves until it settles into a stationary Kerr black hole. However, how soon after the merger does this black hole become close to a Kerr spacetime? Relatedly, how close to the merger phase in a gravitational waveform can LIGO apply data analysis techniques that assume that the remnant black hole is Kerr (or a perturbation thereof)? This project will involve looking at ringdowns of binary black hole simulations, and applying various measures of ‘Kerrness’ such as specialty indices, Mars-Simon tensors, and newer proposed positive-definite measures. The required skills for this project are familiarity with C++ and plotting packages such as Python/Matplotlib and the Linux/Unix environment. While no prior knowledge of general relativity is necessary, the student will learn about black holes, general relativity, and numerical relativity.