Proposed PHYS 590 Research Thesis Topics, 2023

Gunnar Blohm (Gunnar.Blohm@queensu.ca)

The Blohm lab uses a combination of computational models and experimentation to understand sensory-motor processes in the brain - we do neuro-physics (http://www.compneurosci.com/). Proposed projects require knowledge in numerical methods.

1. Design, implement and analyze an artificial neural network that performs multi-sensory integration in a causal fashion. Multi-sensory integration is combining redundant information (e.g. you can localize a dog by hearing it bark and by seeing it; and both). However you don't want to combine unrelated information (e.g. seeing a dog and hearing a meow).
2. Design and implement spiking neural network models to investigate distributed computational principles, such as synchronization in oscillatory sub-nets, entrainment of oscillations, stochastic facilitation, and their consequence for macroscopically measurable electro-magnetic signals, such as measured with Electroencephalography (EEG) or MEG.
3. We are open to suggestions from students with specific other interests feel free to contact me!

Joseph Bramante (joseph.bramante@queensu.ca)

1. **Theory and analysis for heavy dark matter**

   The hunt for dark matter continues at underground experiments, with gamma ray detectors in space, and using rich datasets that catalog the structure and history of our universe. Certain kinds of heavy dark matter present unique signatures and detection opportunities. Projects along these lines include new analyses looking for super-nanoscale dark matter in publicly available data from underground search experiments, studies of dark matter's impact on interstellar gas clouds, and simulation of galaxy formation modified by dark matter that induces white dwarf explosions.
2. **Early universe cosmology and gravitational substructure**

   The coarse gravitational features of galaxies, galactic clusters, and the large scale structure of our universe have been established using myriad tracers of matter in our universe. However, there is the intriguing possibility that there is extra gravitational "substructure," detectable using a number of methods including weak lensing and stellar astrometry. Projects along these lines include developing theoretical models that describe early universe formation of extra substructure, developing new techniques to look for substructure using observation, and modeling the historic transit of dark matter substructures through the earth.

Tucker Carrington (Tucker.Carrington@queensu.ca)

All projects in my group involve using numerical methods to study properties of molecules. All 590 projects are designed to be doable but of interest to experienced researchers.

Possible topics include:

1. A new interpolation-type method for numerically solving the Schroedinger equation. It takes advantage of the near symmetry of the Hamiltonian matrix.
2. A new method for numerically solving a multi-dimensional Schroedinger equation using non-orthogonal basis functions

Mark Chen (mchen@queensu.ca)

1. **The SNO+ Neutrino Experiment**

   The SNO+ experiment studies fundamental neutrino properties using a 780 tonne liquid scintillator target. In particular, we plan to study low energy solar neutrinos; make a precision measurement of neutrino oscillation parameters by detecting anti-neutrinos produced by nuclear reactors; study the composition of the Earth's crust and mantle by measuring the geo-neutrinos; probe the development of a supernova explosion and study neutrino behaviour in high density matter by detecting the neutrinos from a supernova (should one occur while we are running!); and attempt to determine whether or not neutrinos are their own anti-particles and determine the absolute neutrino mass by searching for neutrinoless double beta decay.

   SNO+ is currently taking data in our "pure scintillator" phase. PHYS 590 students have the opportunity to be involved in the analysis of this data, with possible topics including detector simulations, event classification, event reconstruction, and analysis of calibration data.

2. **LiquidO detector development**

   LiquidO is a new particle detection technique that aims to exploit an "opaque" scintillator to localize the light produced by particle interactions in the medium. This allows the pattern of energy deposition to be "imaged" by collecting and reading out the light using an array of wavelength-shifting optical fibres coupled to SiPM detectors. Possible projects for students include: building and testing a prototype mini LiquidO detector; testing novel formulations of liquid scintillator; simulating and studying different classes of events, including employing machine-learning techniques to classify various signals using their different event patterns.

Stéphane Courteau (courteau@queensu.ca)

1. **Modelling Astronomical Images**

   Infante-Sainz, Trujillo, and Roman (2020) measured an extended point spread function for stars by combining a variety of tools to do sky subtraction, masking, cutouts, aligning, and stacking in an iterative process that is labour intensive. However, this could be more simply executed with the AutoProf software in a single pass. Rather than cutting out clean star images for stacking, one would just model the stars and any other objects in the astronomical (FITS) image simultaneously. Each star could have an independent position and brightness, but its shape parameters (radius, concentration, etc. depending on the model) would be shared for all stars. The end result of such an exercise is a model for all stars and other extended objects in the astronomical image. The student will first fit one-dimensional Gaussians to stellar profiles in deep extragalactic fields (using UNIONS/DESI images), and then explore more complex profiles such as the Nuker law and full Zernike polynomial fits plus diffraction spikes. This analysis will greatly benefit current and future investigations of galaxy structure with the AutoProf software.

   This study involves Python programming, numerical methods (e.g., non-linear fits, Bayesian methods), and some understanding of galaxy structure and astronomical observations. This project is partly motivated by the papers:

   The Sloan Digital Sky Survey Extended Point Spread Functions (Infante-Sainz el 2020, MNRAS, 491, 5317)

   AutoProf-I. An Automated non-parametric light profile pipeline for modern galaxy surveys (Stone et al 2021, MNRAS, 508, 1870)

2. **Spiral Structure within Elliptical Galaxies**

   This project takes advantage of an extensive sample of deep multi-band images of elliptical galaxies. We use image smoothing and techniques of high contrast imaging with the image analysis facility AutoProf to tease out signatures of spiral structure in elliptical galaxies. Detailed studies of galaxy formation require clear definitions of the structural components of galaxies. It is generally assumed that elliptical galaxies are generally smooth and relatively featureless spheroidal galaxies, even though they result from the merger of more structured systems such as spiral galaxies. Are elliptical galaxies truly distributed according to simplistic models, or can we detect evidence of remnant (spiral/shell-like?) structures from a more troubled past? This project uses light and stellar mass profiles from DESI (and possibly HSC/UNIONS/JWST) images to test if the commonly assumed (smooth) density distributions of elliptical galaxies apply and what might be the fraction of elliptical galaxies with underlying spiral structure and embedded disks? Conclusive results could also be tested on cosmological simulations of galaxy formation (e.g., Illustris TGN).

This study involves Python programming, numerical methods (e.g., non-linear fits, Bayesian methods), and some understanding of galaxy structure and astronomical observations. This project is partly motivated by the papers:

Embedded disks in Fornax dwarf elliptical galaxies (De Rijcke et al 2003, A&A, 400, 119)

AutoProf-I. An Automated non-parametric light profile pipeline for modern galaxy surveys (Stone et al 2021, MNRAS, 508, 1870)

3. **The Structure of Galaxies in the Stephan's Quintet**
   The new James Webb Space Telescope produced exquisite infrared images of a quintessential group of interacting galaxies called the "Stephan's Quintet." This project will provide the most accurate structural decompositions for these interacting galaxies in order to understand how galactic interactions may have driven galaxy evolution in the early universe. The new image analysis facility AutoProf will be used to extract these decompositions. These can then help understand how interacting galaxies trigger star formation in each other, how gas in galaxies is being disturbed, and constrain outflows driven by a black hole in a level of detail never seen before. When the observations are broken down by galaxy and their respective sub-components (bulge, disk, nucleus), one can identify the contrasting characteristics of the galaxies and the relationships with their neighbours. With AutoProf, we can assess the stellar mass and star formation rates in each member of the Stephan's Quintet and ideally (with other multi-wavelength information and orbital modelling) characterize their star formation history and initial trajectories.

   This study involves Python programming, numerical methods (e.g., non-linear fits, Bayesian methods), and some understanding of galaxy structure and astronomical observations. This project is partly motivated by the papers:

   The gas about Stephan's Quintet reveals a history of collision (Blue Bird, J. 2022, Nature 610, 458)

The JWST Early Release Observations (Pontoppidan et al 2022, ApJ, 936, 14)

AutoProf-I. An Automated non-parametric light profile pipeline for modern galaxy surveys (Stone et al 2021, MNRAS, 508, 1870)

James Fraser (james.fraser@queensu.ca)

1. **Photonics at the Nanoscale**

   The new Nanophotonics Research Centre aims to explore photonics of nanoscale materials, with the goal of understanding new physics and developing new applications. We need help in designing, implementing, and testing new optical set-ups for the Centre. This is an in-lab research project that will help you develop your experimental optics, data collection, computer integration, and/or analysis skills. Your schedule will need to be sufficiently flexible that you can meet weekly with the team and supervisor. You will also need to follow university-mandated safety training to become a laser worker.

Jun Gao (jungao@queensu.ca)

1. **Polymer-based light-emitting devices** and **polymer solar cells** are attractive candidates for display, lighting and energy harvesting applications. Semiconducting polymers offer interesting electrical and optical properties, solution processibility, chemical tenability and mechanical flexibility that are unrivaled by conventional inorganic semiconductors. These 590 projects aim to explore the design, performance, and physics of these polymer photonic devices through fabrication and testing and/or modelling and simulation.

Guillaume Giroux (gg42@queensu.ca)

1. **The search for dark matter with the PICO bubble chamber**

   PICO is an international collaboration working at searching for dark matter at SNOLAB using superheated liquid detectors, or bubble chambers. The most recent iteration of the experiment, PICO-40L, is now taking data and will allow the exploration of new dark matter models. PICO-500 is the next-generation, ton-scale bubble chamber, to be constructed at SNOLAB. Research topics are available in the fields of data analysis (dark matter search data and calibration data), detector simulation, detector design and R&D.

2. **The search for dark matter with the NEWS-G spherical proportional counters**

   NEWS-G is an international collaboration aiming at the detection of low-mass dark matter particles using spherical proportional counters (SPCs) installed in the deep underground laboratories of LSM in France, and SNOLAB in Canada. A 140-cm SPC made from ultrapure copper is now installed at SNOLAB and will have unprecedented sensitivity to low-mass dark matter particles. Research topics include data analysis, detector simulation, and detector calibration using SPCs located at Queen's.

The GeRM Lab (Contact Ryan Martin: ryan.martin@queensu.ca)

1. Our group has a number of research interests, and we can work with motivated students to develop a project that is aligned with our research, the student's interests, and the skills that the student wishes to develop. Fundamentally, we are work in the field of particle astrophysics with a focus on understanding the true nature of the neutrino. Our lab is aimed at developing and modeling high purity germanium point-contact detectors that are used in particle astrophysics, particularly in the context of the LEGEND experiment. A number of hardware or analysis projects can be developed around this work.

2. Our group is specialized in the development of machine learning tools that can be used in particle astrophysics and beyond. This has included developing algorithms to process data from the SNO+ detector, as well as algorithms with broad applications in removing electronic noise and processing electronic signals. We are also interested in further exploring generative machine learning tools to develop particle physics simulation tools.

3. Our group also collaborates on a project to use agent-based Monte Carlo modelling techniques to simulate the spread of COVID-19. This work is primarily conducted within an interdisciplinary group of undergraduate students. A thesis project would involve developing the CV-19 simulation to examine one aspect of the pandemic (e.g., the effect of a specific public health policy) or developing a similar agent-based model to simulate other systems, such as an economy.

4. Finally, our group is also interested in physics education research. Past projects in physics education research have examined implementing machine learning to predict student grades as well as developing tools to measure acquisition of laboratory skills.

Nahee Park (nahee.park@queensu.ca)

1. **Cosmic Ray Propagation studies with HELIX and future magnet spectrometers**

   Cosmic rays are high-energy charged particles arriving at Earth from sources throughout our Galaxy and beyond. A better understanding of particle propagation through our Galaxy is the key to understanding new features of the cosmic ray flux (such as an unexpected excess of anti-matter) recently discovered by space-based experiments. HELIX, a long-duration balloon-borne experiment that will fly 40 km above sea level for several days, aims to provide detailed measurements of cosmic-ray isotopes needed to explain these puzzling observations. To achieve its scientific goals, HELIX requires precisely measuring the trajectories and velocities of the particles. The HELIX instrument comprises a 1 Tesla superconducting magnet, gas drift chamber, time-of-flight system, and a ring Cherenkov counter. HELIX aims to have its first flight in 2024 summer from Kiruna, Sweden. PHYS 590 students will remotely participate in the integration and performance tests of the HELIX payload to ensure the payload will be ready for flight in 2024 summer. This work will include data analysis, analysis tool development, and running and evaluating the detector simulations.

2. **Detector developments for future neutrino telescopes**

   The IceCube neutrino telescope, a cubic kilometre-sized detector array located under the South Pole, has opened a new window to the Universe by discovering the high-energy astrophysical neutrino flux. The origin of these neutrinos is still unclear. Studying the properties of this neutrino flux requires building larger detectors than IceCube with better optical sensors. Given the limited resources to fill a detection volume larger than a cubic kilometre, a cost-efficient and innovative detector design is necessary. PHYS 590 students will explore potential photon detection methods other than traditional photon detection with photomultipliers, perform detector simulation and develop an evaluation process to compare different designs. The project is suitable for a student with interest in hardware development.

3. **Probing dynamics of high-energy particles in our Universe with the VERITAS very-high-energy gamma-ray observatory**

   VERITAS is an array of imaging atmospheric Cherenkov telescopes designed to measure gamma rays with energies higher than 100 GeV (photons with hundreds of billions of times higher energies than visible light.) VERITAS detects gamma rays by observing Cherenkov light generated by the particle interactions in the atmosphere. Fully operating since 2007, VERITAS has been one of the major collaborations leading the very-high-energy gamma-ray communities with many discoveries. The science objectives of VERITAS cover a wide range of studies, including probing the particle dynamics around Galactic and extragalactic astrophysical objects, indirect searches for dark matter signals, and multi-messenger observations. PHYS 590 students will have the opportunity to improve the data analysis methods of the highest-energy gamma rays and most energetic events detected by VERITAS. They may also choose to explore how gamma rays are distributed around the astrophysical sources in order to better understand the complicated physics at work in extreme systems in our Galaxy.

Sarah Sadavoy (sarah.sadavoy@queensu.ca)

1. **Topics in Star Formation and Planet Formation**

   Students can choose from numerous projects related to the formation of stars and planets. These projects utilize astronomical data from telescopes all over the world (or in space) and across multiple wavelengths. Students can work with observations of dust grains, molecular line emission, or polarization on the scales of individual star-forming clouds or planet-forming disks around young stars. Projects can be focused on data processing, modeling, statistical methods, or analysis tools, depending on preference.

Bhavin Shastri (bhavin.shastri@queensu.ca)

1. **Real-time optimization of quantum photonic networks**

   Linear-optical processors are a promising option for realizing quantum computing. These processors are networks of interferometers, optical devices which couple light beams from two adjacent waveguides and apply phase shifts to the beams. This configuration gives rise to the challenge of optimizing the required phase shifts to achieve the desired information processing functionality. Optimization of the interferometers on a chip gets increasingly complex as the number of interferometers increases, especially in the presence of losses, an unavoidable consequence of the real-world construction of photonic processors. This thesis will study how large-scale quantum photonic networks can be optimized in real-time using algorithm implemented with neural networks.

2. **Cryogenic compatible photonic network for computing**

   Quantum and superconducting single flux quanta (SFQ) computing platforms operate at cryogenic (4K) temperatures. Signals from these platforms are small (mV), ultrafast (GHz), and can decohere easily. Processing these signals for tasks such as qubit readout classification or dimensionality reduction poses a severe challenge—as such tasks are most effectively performed with machine learning algorithms implemented on neural networks. However, processing these high bandwidth and small signals ex-situ in real-time is impossible with the latency associated with getting these signals out. The objective of this thesis will be to propose a low-temperature neural network enabled by nanophotonics (optical physics) and 2D materials like graphene. Specifically, this thesis will study devices such as graphene-based optical modulators as neurons and how they can be interconnected to form a cryogenic-compatible network.

Kristine Spekkens (kristine.spekkens@rmc.ca)

1. **Probing Galaxy Evolution with Star-Forming Gas**
   How do galaxies like the Milky Way evolve? Where and how do they get their gas? How is their dark matter distributed? What is the fate of the smallest galaxies in the universe? All of these outstanding astrophysical questions can be probed using observations of the star-forming gas in nearby galaxies. This PHYS590 project will focus on one aspect within this broad theme, with the specific project tailored to the student's interest. Example projects include constraining the atomic gas content in the smallest and faintest known galaxies, searching new survey data for the ionised gas shreds of colliding galaxies, or writing code to derive the orbital velocities of the gas in Milky Way-like systems to measure dark matter.

Greg van Anders (gva@queensu.ca)

1. **Robust Distributed Systems Design**
   One of the challenges in distributed systems design is understanding the interactions between whole systems and consituent elements. One example of this is in the context of transportation networks. For example, how an airline manages traffic volumes and routes between destinations affects the design of individual aircraft components. State-of-the-art approaches to this problem attempt to optimize aircraft component design for fixed traffic, but it is difficult to understand how changes traffic lead to changes in component specifications. This project address this problem by using statistical physics techniques to understand how systems-level changes in network traffic exert forces on aircraft design.
2. **Lock-and-Key Design**
   Because living things are divided into cells, that organization means lot of different, functionally orthogonal chemical pathways need to play out in the same tiny, cellular reaction vessel. One of the ways that nature solves this problem is via Fischer's lock-and-key principle. This principle describes the interaction specificity between, enzymes and substrates, hormone and receptors, and drugs and various targets, among others. One of the things that make the lock-and-key principle work is geometric complementarity, but we don't have a complete understanding of how that works because complementarity coexists with chemical specific interactions (moeties in chemistry language) that also affect interactions. In this project we want to understand how to leverage purely geometric realizations of the lock-and-key mechanism to understand isolate the role of geometric complementarity in the molecular machinery of biochemical processes.
3. **Flashpoints in Land Use Change**
   The United Nations has reported that two key challenges humanity will face in this century are climate change and urbanization. A key problem in meeting

both of these challenges is finding ways to address how people will change the way they use land. People typically approach land allocation via optimization techniques, however, optimization only works for problems that have a closed form where everyone agrees on the relative importance of all of the different forms of land use, which is never the case in practice. This project will use statistical physics techiques to study tradeoffs among priorities for land use to identify potential flash points where different desired uses are likely to come into contact.

4. **Artificial Intelligence: Shining Light into Black Boxes**

   Artificial intelligence provides an important set of algorithms for automating tasks that have typically been done by people. This can save human labour, however, evaluations done by machines can reproduce the discrimination exercised by human decision makers, which raises serious questions for applying machine learning to evaluate resumes, assess parole eligibility, screen graduate school admissions, etc. Figuring out how to remove these biases is difficult because part of the power of artificial intelligence is its black-box approach to achieving optimal behaviour. This project will use techniques from statistical physics to interrogate the ways that biased training data get encoded in artificial neural networks with the goal of working toward methodologies to reduce discriminatory outcomes.

5. **Nanoparticle self-assembly: Are good stabilizers good crystallizers**

   Self-assembly is an approach to nanomaterials development where basic material building blocks spontaneously form a target structure in solution without needing to be guided. Getting robust self-assembly requires two things: getting the building blocks to form the structure (kinetics), and then getting the structure to be stable once it has formed (thermodynamics). Recent work from our group has demonstrated how to solve the stability problem. However, getting the particles into the target structure is a separate problem. This project aims understand whether there is a relationship between nanoparticle designs that are good for thermodynamic stability and ones that are good for self-assembly kinetics. This project will involve computational work using industry-leading, open-source molecular simulation software.

Gregg Wade (Gregg.Wade@rmc.ca)

1. **Convection-driven decay of fossil magnetic fields in cool main sequence stars**

   Fossil magnetic fields - present at the surfaces of about 10% of main sequence A, B and O type stars - decline precipitously in frequency around spectral type F0 before being quickly replaced by dynamo fields at cooler temperatures. What is the origin of this abrupt transition in the qualitative character of stellar magnetism? We are testing the hypothesis that the hydrogen convection zone, growing with decreasing effective temperature, results in the systematic decay of fossil fields. This project will involve the analysis of new magnetic field measurements, as well as a systematic examination of TESS photometry and high resolution spectroscopy, to determine the magnetic and surface convective properties of a sample of cool magnetic A stars. Ultimately the results will be used to confront predictions of a new model of the interaction between fossil magnetic fields and convection.

Aaron Vincent (aaron.vincent@queensu.ca)

1. My research encompasses many aspects of astroparticle phenomenology and cosmology, with emphasis on the particle nature of dark matter, and the search for novel ways to identify it. I am particularly interested in the effects of dark matter on stars like the Sun, along with its interactions with other messengers including neutrinos and the cosmic microwave background. Another active research area is the interpretation and possible scientific uses of the high-energy astrophysical neutrinos recently seen by the IceCube Neutrino Observatory located at the South Pole. Research in my group involves some theoretical calculations (pencil & paper or Maple/Mathematica), statistical analysis, and a good amount programming. Most can be done in Python, but some specialty software is written in Fortran and C++.

Larry Widrow (widrow@queensu.ca)

1. **Galaxic Dynamics with Gaia**
   In June 2022, Gaia, a space telescope operated by the European Space Agency, will release astrometric data giving estimates for positions and velocities for 35 million stars in the disk of the Milky Way. Further data releases in the coming years will bring the number of stars with position and velocity information to 1 billion or about 1% of the stellar content of the galaxy. The Gaia phase space maps provide an unprecedented opportunity to probe the dynamics of our galaxy and test models for interactions between the stellar disk and the dark matter halo. The 590 project will use numerical N-body simulations and statistical modelling, including machine learning methods, to explore this data set. The project is suitable for a student with a strong interest in computational and mathematical physics. Course work in astrophysics, while useful, is not essential.

Alex Wright (awright@queensu.ca)

1. **The SNO+ Neutrino Experiment**

The SNO+ experiment studies fundamental neutrino properties using a 780 tonne liquid scintillator target. In particular, we plan to study low energy solar neutrinos; make a precision measurement of neutrino oscillation parameters by detecting anti-neutrinos produced by nuclear reactors; study the composition of the Earth's crust and mantle by measuring the geo-neutrinos; probe the development of a supernova explosion and study neutrino behaviour in high density matter by detecting the neutrinos from a supernova (should one occur while we are running!); and attempt to determine whether or not neutrinos are their own anti-particles and determine the absolute neutrino mass by searching for neutrinoless double beta decay.

SNO+ is currently taking data in our "pure scintillator" phase. PHYS 590 students have the opportunity to be involved in the analysis of this data, with possible topics including detector simulations, event classification, event reconstruction, and analysis of calibration data.

2. **The Scintillating Bubble Chamber Experiment**

The Scintillating Bubble Chamber (SBC) experiment is a new liquid argon based bubble chamber experiment. Liquid argon is a scintillating medium, and the combination of scintillation light in a bubble detector allows SBC to operate with extremely low thresholds and provides interesting possibilities for background discrimination. This will allow SBC to carry out a competitive search for low mass dark matter particles and potentially study neutrino properties through a coherent neutrino scattering measurement near a nuclear power reactor.

Potential PHYS 590 projects include studies of the physics potential of a SBC coherent neutrino scattering measurement, and molecular dynamics studies to better understand the interaction between bubble nucleation and scintillation light production in liquid argon.