Proposed PHYS 590 Research Thesis Topics, 2025

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. Design and implement an analysis pipeline for directed functional brain connectivity based on magnetoencephalography (MEG) recordings using methods such as partial directed coherence. Then devise a novel visualization method to analyze task-related changes in functional connectivity.
4. Neuro-robotic performance: design and implement EEG analytics / decoding for brain-driven online robotic control and generative visuals/music with the ultimate goal of developing a performance arts show. This project will be in collaboration with Ingenuity Labs and the School of Drama.
5. 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 searches for dark matter in ancient minerals like mica, 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 dark matter structure**

   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 dark matter is a large state with an extended structure, detectable using a number of methods including lensing and stellar astrometry. Projects along these lines include developing theoretical models that describe early universe formation of dark matter structures, 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.

Philippe Di Stefano (philippe.distefano@gmail.com)

1. **Potassium-loaded scintillators:** student will investigate how to load scintillators with as much potassium as possible, looking out for light yield, as well as for chemical and aging effects
2. **A setup to measure thermal contraction at cryogenic temperatures:** After a literature review, the student will design a setup based around an existing 10 K cryostat to measure thermal contraction of materials, including polymers, from room temperature down to 10 K. Methods may include laser triangulation and image metrology.
3. **Simulations to optimize the design of the KDK+ experiment using Geant4:** KDK+ seeks the elusive b+ decay of 40K, and will use a liquid scintillator loaded with 40K, and surrounded by an efficient gamma tagger.
4. Build a model to determine CdA in cycling based on power and speed. Compare to data.
5. Trigger rate calculation for vacuum surface alphas in the DEAP 3600 dark matter search.

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.

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

Our group (the GeRMLab) 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. Our research is in the field of experimental particle astrophysics with a focus on neutrinoless double-beta decay and dark matter searches. We participate in the NEWS-G experiment to search for dark matter and the SNO+ and LEGEND experiment to search for neutrinoless double-beta decay. Our focus is on developing machine-learning based techniques to analyze data from these experiments as well as extending their applications to other fields.

1. **Denoising autoencoders** We use deep neural networks in an autoencoder configuration to remove electronic noise from time-series data as well as for anomaly detection. We can propose projects to improve the technology and/or to expand it to other applications, for example in astrophysics. The specific project would be developed based on the student's interests.
2. **Machine-learning based position fitter for SNO+** We have developed machine-learning based methods to infer the position of events in the SNO+ detector based on the pattern of photomultiplier hits. We can propose a variety of project around improving and characterizing different machine-learning based position fitters.
3. **Physcs education** We are generally interested in physics education research. Past projects have included using machine learning to predict grades and identify students in need, quantifying the effects of imposterism in physics students, and developing laboratory instruction that is focused on skill development.
4. **Large Ge detector characterization** Our lab hosts a very large high-purity germanium particle detector prototype for next generation searches in neutrinoless double-beta decay. We are interested in characterizing how well one can infer the position of energy depositions based on the signals that are recorded from the device. This project would involve a component of modelling detector signals as well as data collection to then test the model.

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 had a successful first flight in 2024 summer from Kiruna, Sweden, and preparing for a second flight from Antarctica in the near future. HELIX plans to continuously improve its detector for future flight to extend the measurements toward higher energies.

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.

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. **Photonics for Artificial Intelligence, Neuromorphic Computing, and Quantum Machine Learning**

   A central theme of our research is studying photonic physics for photonic computing, neuromorphic photonics, and quantum neuromorphic photonics by unifying nanophotonics (study of light at small scales) and complex systems (e.g., neural networks) on emerging substrates (e.g., compound semiconductors on silicon). Our interdisciplinary research focuses on the design and experimental demonstration of integrated photonic devices and systems for applications to neuromorphic computing, artificial intelligence (AI), and quantum machine learning.

   Please contact Prof. Shastri to discuss potential topics before signing up. Students are expected to propose their own topics based on their interests, recent papers (listed below), and the Shastri Lab website.

   1) J. Ewaniuk, J. Carolan, B. J. Shastri and N. Rotenberg, "Realistic quantum photonic neural networks," arXiv:2208.06571 [quant-ph]

   2) B. J. Shastri, A. N. Tait, et al. "Photonic for artificial intelligence and neuromorphic computing," Nature Photonics 15, 102–114 (2021).

Kristine Spekkens (kristine.spekkens@queensu.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.

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 to determine the magnetic 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.

2. **Magnetic fields of evolved stars**

   The modern exploration of stellar magnetism across the H-R Diagram have revealed populations of evolved stars with peculiar and unexplained magnetic properties. These range from the Blue Supergiant stars, to the classical Cepheid variables, to AGB stars. This project aims to understand the interrelationships of the magnetic properties of this evolved stars and those of their main sequence progenitors, and will involve analysis of new magnetic observations of selected evolved stars and stellar types to infer their magnetic properties and origins.

3. **Spectroscopic and photometric variability of massive stars**

   Massive O-type stars are hot, young stars with masses tens of times that of the sun. While massive stars are rare stellar objects, they significantly influence their stellar environments through strong stellar winds and their end-of-life explosions as supernovae. A small subset of massive stars are known to host strong dipolar magnetic fields which channel the star's wind into a dense magnetosphere. The signatures of physical processes are observed in the spectra and light curves of massive stars including magnetic fields and stochastic-low frequency variability. It is predicted that magnetic fields can inhibit O star stochastic variability which is believed to arise from sub-surface convective layers or deep in the stellar core. Therefore, magnetic O stars provide unique laboratories to probe massive star interiors. The successful applicant will analyze existing spectroscopic and photometric data sets of massive stars to answer research questions related to massive star magnetism and variability. The successful candidate will have the opportunity to work with diverse data sets including high cadence photometry from the Transiting Exoplanet Survey Satellite (TESS) and spectra from ground based telescopes such as the Canada-France-Hawaii Telescope (CFHT).

4. **Spectroscopic modeling of classical Cepheids**

   Classical Cepheids are young, evolved stars that pulsate radially with periods of days to weeks. Cepheids famously obey the Leavitt Law, a strict period-luminosity relation making them instrumental in setting the cosmic distance ladder. As "cosmic yardsticks" Cepheids are used to measure extra-galactic distances and the expansion rate of the Universe. However, many aspects of Cepheids remain poorly understood including their evolutionary history, atmospheric dynamics and magnetic properties. During pulsation Cepheid atmospheres can move at speeds up to 100,000 km/h, covering distances several times the diameter of the sun. As a result, Cepheid pulsation distorts the morphology of observed spectra and magnetic signatures, providing a complicated modelling problem. The successful applicant will perform spectroscopic analysis and modelling on existing data sets to infer Cepheid atmospheric properties such as velocity gradients, shocks, turbulence and rotational velocities.

5. **Infrared studies of evolved magnetic stars with Spirou**

   Magnetic fields impact the evolution and behaviour of stars across a wide range of spectral types. Over the past decade large spectropolarimetric studies have provided a wealth of information about the magnetic properties of core hydrogen-burning stars on or near the main sequence. However, little is known about the magnetic properties of evolved stars in the transitionary stages between the main sequence and the red-giant branch. During this stage of evolution, the star's radius will increase by an order of magnitude, leading to a substantial decrease in the magnetic flux. This makes surface magnetic fields in evolved stars challenging to detect using traditional optical spectropolarimeters. Future large-scale magnetic studies of evolved stars will need to make use of alternative instrumentation. One possible solution is to perform observations at near-infrared wavelengths where the stellar flux is higher and spectral line transitions are more magnetically sensitive. The successful applicant will perform a feasibility study to determine the suitability of using the SPIRou near-infrared spectropolarimeter at CFHT to perform large monitoring studies of evolved stars. The work may include identifying suitable targets from diverse stellar classes (e.g. Supergiants, classical Cepheids, Type II Cepheids and RR Lyraes), synthesizing polarized spectra with existing codes, conducting exposure time calculations and designing an observing program.

6. **Interaction in massive binaries as a pathway to stellar magnetic field generation**

   Recent observations and modeling of massive stars lead to the inescapable conclusion that the classical theory of stellar evolution - envisioning single stars evolving in an isolated fashion - is fundamentally wrong in many, and quite possibly most, cases. A majority of massive stars are known to form in binary or higher-order multiple systems, and as these stars evolve they expand to fill their Roche Lobes, resulting in mass and angular momentum exchange. The resultant stripped star mass donors and rejuvenated mass recipients are characterized by masses, rotational properties, and surface chemistry that are entirely at odds with evolution models of single stars.

   The rapid and violent evolution resulting from mass transfer and merger events also provide fertile grounds for the generation of powerful magnetic fields. This project will explore recent examples of massive binaries in which magnetic fields are proposed to have been generated via mergers or mass transfer, and will exploit new and existing observations to identify new examples to understand the relevance of binary field generation pathways.

Larry Widrow (widrow@queensu.ca)

1. **Galactic Dynamics with Gaia**

   Gaia, a space telescope operated by the European Space Agency, is measuring positions and velocities for 1 billion stars in the Milky Way or about 1% of the total number of stars. Gaia's 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. Possible projects will use simulations, theoretical astrophysics, and statistical modelling to explore this data set and various problems in galactic dynamics. 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 are studying low energy solar neutrinos; making a precision measurement of neutrino oscillation parameters by detecting anti-neutrinos produced by nuclear reactors; studying the composition of the Earth's crust and mantle by measuring the geo-neutrinos; probing 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 attempting 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, with the transition to double beta decay phase anticipated during the winter of 2025. 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.