PHYSICS HONOURS PROJECTS FOR 2025

This document lists a number of potential honours research projects within the School of Physics, together with supervisor contact details and a paragraph describing each of the projects. These are only some of the opportunities available, and *you are welcome to explore other possibilities with potential supervisors*. If you are free, please also join us for the **Honours Information Session at 12:00 on Tuesday 24th September**.

It is important to choose a project and supervisor to suit your interests and skills. *You are encouraged to have discussions with several possible supervisors before making a decision.* Speaking to honours and postgraduate students will also give you valuable feedback. The Web of Science (accessible from the Library website) will give you information on the research activity of the School's academics. You should also read the School's Research pages (https://sydney.edu.au/science/schools/school-of-physics.html) for more information on areas of active research.

You must arrange a supervisor and project prior to applying for honours. When you have reached agreement with a supervisor, please ask them to send you a formal email agreeing to take you on as a student, with cc to physics.honours@sydney.edu.au. Note that you should aim to start work on your research project *three weeks before the start of lectures*. This will enable you to get your project underway before lectures and assignments compete for your time. You should also make certain that your proposed supervisor will not be absent for protracted periods during semester, unless an associate supervisor is also involved. These issues will need to be formally settled when you submit your Research Plan, two weeks after the start of your first semester as an honours student.

Thank you for your interest in physics honours.

Bruce Yabsley, Honours Coordinator (physics.honours@sydney.edu.au), 20th September 2024

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Grand Challenge Projects

Lightsail dynamics and Doppler damping

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The Alpha Centauri system is the closest star system to the Sun. Since it is more than 4 light years away it would take 1000's of years to get there using current technology. Breakthrough Starshot is an exciting and ambitious project that aims to shorten this long timeframe. The plan is to accelerate sails with a surface area of 10 m^2 and mass of 1 gram (including payload) to 20% of the speed of light using a 100 GW Earth-based laser. At this speed it would take about 25 years to reach the Alpha Centauri system and to send signals back to Earth. There are many practical and conceptual challenges that must be overcome for this to become a reality. One of these challenges is sail stability. The laser beam is never perfect so acceleration of the sail by the laser unavoidably lead to sideway motion and to torques which will cause the sail to veer off. This must be overcome by sail designs that are self-correcting, thus leading to a stable motion towards the target. We recently carried out a theoretical analysis of two-dimensional motion and established a proof-of-principle and are now in the process to make this fully three-dimensional. We have a number of theoretical and numerical projects available that require the method of theoretical mechanics, special relativity, optics and electromagnetism, and that aim to determine the detailed optical properties of the sail's surface, its motion, and the conceptual design of the sail structure.

These projects are supported by a special Grand Challenge Grant from the Physics Foundation.

Applied physics and plasma surface engineering

Synthesis and collection of nanoparticles in a plasma reactor for use in nanomedicine

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Nanomedicine promises a range of therapeutic functions including targeted drug delivery and new diagnostic techniques, due to the ability of nanoparticles to carry molecules into cells. We are developing the technology to engineer nanoparticles capable of delivering drugs to specific targets, such as tumours, whilst being monitored non-invasively. These nanoparticles are synthesised in our lab from organic materials using radio frequency capacitively coupled plasma. Strict control of the plasma properties is necessary to produce nanoparticles with the desired properties, whilst an effective method to collect the nanoparticles from the reactor gases is also critical. For students with a sufficient foundational knowledge of plasma physics, this project will offer the opportunity to investigate the relationship between the reactor control parameters and the plasma parameters using passive and active plasma diagnostic techniques. Students will have the opportunity to learn a variety of methods to diagnose plasma such as electrostatic probes, energy analysers and optical spectroscopy and develop new understanding of the process physics. An intermediate level of Python skills and also knowledge of or interest to learn multivariate statistics would be desirable as this project also offers the opportunity to modify and develop code for real-time monitoring of plasma for process control purposes.

Atmospheric plasma processes for biofunctionalization in additive manufacturing

Supervisor: Prof. Marcela Bilek
Co-supervisors: Dr Khadijeh Alavi, Dr. Kosta Tsoutas
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3D bioprinting, also known as biofabrication, promises highly patient-specific disease models and personalised biomedical implants. However, an ability to tailor surface biocompatibility and interfacial bonding between printed components, such as polymers and hydrogels, is currently lacking. We are developing atmospheric pressure plasma jet processes that can locally activate polymeric surfaces for the reagent-free covalent attachment of proteins and hydrogels in a single-step process at desired locations throughout the printed structures. This work extends to biofunctionalising the plasma treated surfaces with chemically synthesised DNA as a platform for guided self-assembly of environmentally responsive materials. To develop the process further we need a deep understanding of the mechanisms that underpin the surface activation we observe. This project will offer students the opportunity to diagnose the atmospheric pressure plasma jet using various diagnostic methods including optical emission spectroscopy and imaging. Such techniques are required to investigate the physiochemical characteristics of the atmospheric plasma jet.

Biosensor with On Board Neuromorphic Processor

Supervisor: Prof. David McKenzie
Co-supervisor: Dr G Pandejee, Ms S Cottam, Dr CT Tran, Prof. MM Bilek
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Biosensors are devices that detect and monitor pathogens or markers associated with disease or environmental management. The detection step is usually made by a targeting molecule with specific binding to its target antigen. Detection needs to be specific and sensitive, and increasingly this requires some processing of the output of a sensor device to prevent false negative and false positive detection. In this project we are examining the potential for simple neuromorphic circuits to carry out the on-board processing of multiple sensory inputs with a simple low cost technology based on biomimetic principles. The freshwater polyp Hydra is able to make simple detection decisions with an elementary neural net formed in two layers in the animal. We will carry out a simulation study in which we will combine a computer simulation study of the behaviour of the 1000 neuron network of Hydra with the first steps toward implementation in an all-carbon technology based on memristor networks, to emulate the elementary unit of neuromorphic computing in biological networks, termed a perceptron.

Advanced tissue culture platforms

Supervisor: Dr Aaron Gilmour
Co-supervisor: Dr Clara Tran, A./Prof. Stuart Fraser, Prof. Marcela Bilek
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Polystyrene and glass cover slips are fundamental materials for tissue culture due to their optical transparency allowing microscopy studies. However, the native surfaces of these materials poorly facilitate cell adhesion and growth without the use of exogenous extracellular matrix proteins (EMC). ECM proteins dynamically interact with cells as they develop and proliferate and thus influence the cell behaviour. An ideal platform to enable observation of cell behaviour will promote cell attachment and migration but also retain ideal optical properties to enable microscopic observation through the material. Transformation of the surface chemistry of these cell culture materials using plasma technologies (plasma immersion ion implantation and plasma polymerization) will be the main aim of this project. The functionalized materials will be used for tissue culture in comparison with commercial products. Students will have opportunities to learn surface characterization techniques as well as tissue culture, biochemical assays and be introduced to advanced microscopy techniques. This research will evaluate and identify plasma surface modification parameters which promote cell attachment and or differentiation whilst maintaining ideal optical properties.
Active projects for advanced tissue culture platforms that this project will interface with include:

- Development of covalently attached cell instructive ECM and biomolecule cocktails for stem cell differentiation (cardiomyocytes, neurons, and glia)
- Evaluating surface chemistry dependent competitive (Vroman effect) protein attachment and biofunctionality on plasma activated coatings using mass spectrometry.

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Plasma-assisted functionalisation of additively manufactured porous structures for biomedical implants

Supervisor: Prof. Marcela Bilek
Co-supervisor: Dr Khadijeh Alavi, Dr. Roberto Sangines de Castro
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Conventional implantable biomedical devices suffer from poor long-term stability in the body, along with suboptimal material properties such as stiffness. Additive manufacturing has enabled the production of porous implants with mechanical properties that can be tuned to match the host environment. Nonthermal plasmas can be used to functionalise the surfaces of these materials for the immobilisation of cell adhesion and signalling proteins and/or antimicrobials, thereby enabling cell attachment and tissue integration for robust biocompatibility. Careful control of the plasma treatment process, which is dependent on local gas pressure and electric field strength throughout the porous matrix, is critical to ensure consistent surface functionalisation. This project will offer students the opportunity to investigate this process using a range of diagnostic techniques including plasma spectroscopy, imaging and electrical diagnostics. The improved understanding of the plasma physics gained will enable us to fine tune the treatment process for various scaffold designs.

Plasma treatment on gauze for wound healing

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Co-supervisor: A./Prof. Stuart Fraser, Prof. Marcela Bilek
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Wound healing is a critical process with several specific phases including hemostasis, defence, proliferation, and maturation. Gauze wound dressings have played critical roles in this process for over 100 years with relatively little change, by stopping bleeding, absorbing exudates, preventing bacteria growth and promoting healing. To transform ordinary cotton gauze into a powerhouse of healing potential, we will use plasma surface functionalisation to covalently attach antibiotics, antimicrobial peptides, growth factors and extracellular matrix onto gauze to enhance the healing process. As a student on this project, you will receive hands-on training in low pressure plasma ion implantation and atmospheric pressure plasma treatment processes as well as surface characterisation techniques and cell biological / microbiological analytical systems.

Improving electrochemical biosensor interfaces with plasma activated coatings

Supervisor: Dr Clara Tran
Co-supervisor: Prof. Marcela Bilek, Ms Sophie Cottam
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This project focuses on developing a highly sensitive electrochemical biosensor device that requires a low sample volume and can be miniaturized for point-of-care applications. Recognition biomolecules attached on the electrodes selectively bind to the analytes, triggering detectable changes in the electrical signals for detection. However, conventional conductive materials used for electrodes often lack the ability to robustly attach and hold functional biomolecules, compromising biosensor performance. To address this, we will apply plasma-activated coatings to modify carbon electrode surfaces, enabling reagent-free covalent attachment of recognition biomolecules by means of embedded unpaired electrons. We anticipate dramatic improvements in sensitivity and specificity of the sensing. This project will investigate how the plasma coating affects the electric double layer formed at electrode interface and the charge transfer resistance through electrical impedance spectroscopy (EIS). Students will gain practical experience with plasma surface treatment technology, EIS and biosensor design and operation.

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Optically clear microelectrode arrays

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Microelectrode arrays (MEAs) are powerful tools for high-throughput electrophysiological studies, drug discovery, and biosensing in neuroscience. They consist of tiny, precisely fabricated electrodes on a substrate to measure electrical activity of cells such as neurons and cardiomyocytes to understand how they communicate and interact. Traditional MEA electrodes, however, are made of opaque metals, blocking light transmission and hindering cell observation. This limitation disconnects electrical information from visual biochemical observation of cell behaviour, thereby restricting research outcomes. In addition, these materials do not support cell adhesion and growth, requiring significant effort to functionalize their interfaces to cultivate and maintain longevity of the cell growth for effective measurements.
This project will explore our recently patented conducting and transparent plasma coatings as a platform to fabricate transparent patterned electrodes. Students will gain hands-on experience with plasma deposition and laser treatment as well as surface characterisation techniques, electrochemical impedance spectroscopy, electrical stimulation and recording using the MEA.

Stem cell differentiation to neuronal cell types for the study and treatment of neurological conditions

Supervisor: Prof. Marcela Bilek
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Materials that can support stem cell culture and stimulate differentiation to desired cell types hold great promise for disease modelling, drug screening and personalised medicine. For example, fine control of local differentiation into various neuronal cell types would represent a major advance in the study and treatment of neurological conditions. This project will assess the effectiveness of culturing neural stem cells on multiwell plates, plastic Petri dishes and chamber slides that have been treated in a plasma reactor leading to the formation of a plasma-activated coating (PAC) on the bottom surface of the plates, dishes, and slides. Since this PAC allows almost instant covalent attachment of biomolecules without any additional chemistry, growth factors and extracellular matrix molecules can be fixed in position to simulate desired cell responses at each location throughout the time of the cell culture. This project will assess neurogenesis in vitro with covalently and non-covalently bound signalling molecules and the outcomes compared with those of cell culture on non-functionalised materials. Encompassing the disciplines of biology, chemistry, physics, engineering, and medicine, this multidisciplinary project will involve plasma treatment, stem cell culture, neural differentiation and characterisation of differentiated cells, towards developing an innovative platform for further research and translation. The project will be undertaken in the Applied Physics and Plasma Surface Engineering laboratory at the University of Sydney and the Arto Hardy Family Biomedical Innovation Hub laboratory at Chris O'Brien Lifehouse comprehensive cancer centre.

Biofunctionalised microcarriers for stem cell expansion

Supervisor: Prof. Marcela Bilek
Co-supervisor: Dr Khoon Lim, Dr Kosta Tsoutas, Dr Giselle Yeo, Dr Clara Tran
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Clinical applications of mesenchymal stem cells (MSCs) require billions of cells and traditional two-dimensional (2D) cell culture platforms cannot be scaled up cost effectively. Three-dimensional (3D) culture techniques present a promising approach to achieve a scalable number of undifferentiated MSCs for cell transplantation and tissue engineering applications. Large-scale 3D culture of adherent cells requires a substrate for cell attachment and access to nutrients in media. Microcarriers, such as tiny beads of size ranging from 100 – 300 microns, with surface properties that enable attachment of adherent cells would facilitate cell adhesion and suspension inside bioreactors. This project will fabricate microcarriers using a xeno-free and degradable tyraminated poly(vinyl alcohol) (PVA-Tyr) hydrogel system. Although the PVA-Tyr has tuneable physical properties (stiffness, swelling ratio, degradation profile), it does not possess any cell-adhesive motifs to support cell attachment. Therefore, we will use plasma technology to biofunctionalise the surface of these microcarriers with cell-adhesive peptides (RGD sequence) to enhance cell-attachment of MSCs. Plasma treatments will be carried out on and optimised for the microcarriers, using bespoke atmospheric plasma processes and subsequent surface characterisation to detect changes in surface chemistry and associated biomolecule functionalisation capability. MSC expansion efficacy including cell proliferation and preservation of stem cell characteristics will be determined in cell culture experiments in collaboration with collaborators at the Charles Perkins Centre.

Lightning and the chemical origin of life

Supervisor: Prof. Marcela Bilek
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What are the early steps in the chemical origin of life on Earth, prior to the existence of complex organic molecules and biology? Could Earth have relied on fallen meteorites carrying alien species, or could lightning storms have turned an inorganic Earth and its inert atmosphere into chemically reactive building blocks for early life to emerge, survive, and evolve? This project will test the “Frankenstein” scenario, experimentally simulating lightning strikes under a prebiotic Earth-like environment on the bench top. We explore reaction pathways uniquely enabled by plasma- and radical- chemistry, as well as the role of reactive interfaces (e.g., mineral surfaces or volcanic aerosols) in electrochemical synthesis, under geologically plausible conditions.

Plasma Deposition of High Entropy Alloy coatings for satellite applications

Supervisor: Prof. Marcela Bilek
Co-supervisor: Dr Kosta Tsoutas
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The design of thin film coatings for satellites must account for the harsh conditions of space, where materials must withstand high energy radiation, extreme temperature fluctuations, and potentially impact degradation. With the introduction of electric propulsion for microsatellites, managing heat generated by thrusters becomes an additional operational challenge. In the absence of active cooling systems, materials with controlled emissivity can be utilised. High entropy alloys (HEA) present a promising material class capable of addressing all these issues. Despite being composed of five or more atomic species, HEAs are metallurgically unique, as they exist as a single crystalline phase and have tuneable properties based on their composition. This project will explore various plasma methods for synthesising HEA thin films and evaluate their mechanical, electrical, and chemical material properties using a range of advanced characterisation techniques.

Deposition of graded films via reactive High-Power Impulse Magnetron Sputtering

Supervisor: Prof. Marcela Bilek
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Magnetron sputtering is a thin film deposition process where energetic ions from a plasma impinge on a target located at the discharge cathode and, because of a collisions cascade, atoms (M) are sputtered out from the target to be condensed afterwards at the substrate. If a reactive gas (R) is introduced to the deposition chamber during the sputtering process, a compound (MR) deposition can be achieved. The presence of R within the chamber results in a reactions with the atoms at the target surface producing so-called target poisoning, which changes the deposition rate and affects the film composition. This project seeks to investigate the synthesis of graded thin films containing compounds of nitrogen and oxygen. A graded film is defined as a film with a continuously changing composition along the direction of growth, in this case, perpendicular to the substrate surface. This is achieved by changing the mixture of the reactive gases within the chamber. Correlations between different compositions of the thin film and the plasma properties, as measured by optical emission spectroscopy, will allow for the monitoring and control of the deposition process, in spite of the confounding effects of target poisoning.

Multifluid plasma modelling of magnetoplasmadynamic thruster physics

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Magnetoplasmadynamic (MPD) thrusters are promising candidates for high-efficiency, high-thrust space propulsion. Traditional single-fluid magnetohydrodynamics (MHD) models provide a macroscopic view of plasma behavior but often overlook the detailed interactions between different plasma species. Multifluid plasma models, which treat electrons, ions, and neutrals as separate fluids, offer a more nuanced understanding of these interactions, though at increased numerical expense. This research aims to investigate the multifluid plasma effects in the operation of MPD thrusters. The work involves high-performance computing, some code development, and plasma simulation using fluid models e.g. multifluid plasma and magnetohydrodynamics.

Reading the mechanical stresses in transparent materials

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Co-supervisor: Prof. David McKenzie
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Have you ever looked at the rear window of a car through your sun glasses on cloudy day and seen arrays of round spots? It is due to the stress differences in the tempered glass used in the rear window. Would it be possible to measure these stresses in the glass? One of the effects of stress on materials is to change the optical constants of materials so that they become optically biaxial with two different principal refractive indices. In this project we will explore this phenomenon with ellipsometry. The stress in silica glass will first be examined and then we will examine the stress distribution in tempered glass. Silica glass is used in our research on protein attachments and tempered glass has a compressively stressed surface that makes it extremely tough against fracture. We will use the information from this project to make advances in both areas. The purpose of this project is to find new non-destructive method to measure stresses in materials.

Lasers and Plasma Technologies for Energy Efficient Glazing

Supervisor: Dr Cenk Kocer
Co-supervisor: Prof. David McKenzie
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This project is concerned with a novel glazing technique, developed by our group in Sydney, which has the potential to revolutionize energy efficient buildings. Windows are responsible for a high proportion of the heat loss in buildings, and therefore, a large carbon footprint. Our research group is the acknowledged international leader in this field having developed a technology currently being manufactured and sold in Japan. We are now working with several of the world's biggest glazing manufacturers to develop the next generation vacuum insulating glazing. We are offering several projects which will look at the physics of laser and plasma processes on glassy materials. For example, the application of a laser process to produce a hermetic glass-to-glass seal. The laser process must be optimized for well-defined special heat absorption and reduced thermal shock. Furthermore, the plasma processes can be used to treat glassy surfaces to reduce contamination and increase adhesion. Samples will be treated using a dielectric barrier discharge over very short times: 1 – 10 sec. These processes will reduce energy use in production and increase the quality of the vacuum insulating glazing unit.

We have several projects and key aspects to be addressed in these projects are the physical process surrounding surface vacuum degradation, thermomechanical performance, energy embodiment, and mechanics, using laboratory techniques of laser and plasma processes, surface coating production, and the use of numerical simulations through high-performance computing.

The mechanics of Vacuum Insulating Glazing: a study of failure processes

Supervisor: Dr Cenk Kocer
Co-*supervisor:* Prof. David McKenzie
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Vacuum insulating glazing is a unique low weight, highly insulating, technology for insulating commercial and residential buildings. The glazing consists of two flat sheets of glass, separated by an array of high strength spacers, and hermetically sealed at the edges. The glazing provides thermal insulation better than conventional double glazing at only a fraction of the thickness, allowing retrofit installation to single glazed windows. Since there is a highly evacuated space, the atmospheric pressure acting on the surfaces of the glazing is extremely high: about 10,000 $kg.m^{-2}$. Even though current vacuum insulating glazings are produced to withstand these static surface pressures, the glazing must also exhibit a high resistance to breakage when under dynamic external loading. In order to understand the deformations and strain energies in a vacuum insulating glazing under dynamic loading, a parallel investigation using numerical analysis techniques and experiment is essential. This project will involve producing finite element models to simulate the affects of dynamic loading. The data from the models will be validated and extended using high speed photography. Vacuum insulating samples will be subjected to various dynamic loads, and the subsequent deformations and fracture process will be captured using high speed cameras. The behavior of vacuum insulating glazing fabricated from annealed and tempered glass will be studied.

This project will involve experimental and computational methods to study the vibrational response of a vacuum glazing to an impact. Using this data, design changes will be determined that may lead to a high strength vacuum glazing product. Prototypes will be tested in a purpose built pendulum impact tester, to obtain high speed cameras at 1,000,000 frames per second to capture fracture processes.

Astronomical and space science

The impact of super-massive black holes on their host galaxies

Supervisor: Scott Croom
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Supermassive black holes sit at the centres of most galaxies. When gas falls onto these black holes it forms a luminous accretion disk and the radiation from the disk can profoundly change the galaxy it sits in. In this project we will identify active supermassive black holes using state of the art X-ray observations from the eROSITA telescope and combine this with spatially resolved spectroscopy from the SAMI Galaxy Survey. The spectroscopy can be used to measure the state of the gas in the galaxies and to determine if there has been recent star formation. There could be one or more projects in this and related areas. Some expertise in programming (e.g. in Python) would be an advantage.

Searching for the Milky Way's missing baryonic matter with the Australian Square Kilometre Array Pathfinder

Supervisor: Dougal Dobie
Co-supervisor: Yuanming Wang (Swinburne University of Technology)
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The Australian Square Kilometre Array Pathfinder (ASKAP) will observe the entire Southern sky to unprecedented sensitivity over the next 4 years. Wang et al. (2021) used a small set of ASKAP observations to detect an enormous Galactic plasma filament by searching for the "twinkling" effect they had on background galaxies, formally known as scintillation. The origin of these filaments is unclear, and they may make up a significant fraction of the "missing" baryonic matter in the Milky Way. We will use the latest ASKAP data to search for more scintillating galaxies across the entire sky in order to map these plasma filaments to determine their origin and potentially resolve the missing baryon problem. In this project you will use brand new data that is yet to be explored. You will improve your coding skills by developing new techniques to search for and analyse the properties of rapidly scintillating galaxies, and interpret their spatial distribution across the sky.

Cathodic Arc Rocketry: A prototype pulsed plasma thruster for microsatellites

Supervisor: Prof. Marcela Bilek
Co-supervisor: Dr Kosta Tsoutas
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With the number of satellites in low earth orbit now surpassing 3000 units, research has shifted towards propulsion technologies to control thrust and overcome the effects of atmospheric drag. Electric propulsion (EP), using solid metal fuel electrodes, is an excellent candidate for small satellite thrusters. EP is advantageous over traditional combustion or gas engines as it reduces satellite mass by removing liquid and gas fuel from the payload. Due to the relative simplicity of using metal as the propulsion fuel, it is foreseen that the electrodes could be produced in orbiting space forges, using collected metallic space debris as the raw material. Using so called "space junk" as fuel would help eliminate the problems it causes in space as well as bringing significant energy savings by reducing the launch mass. This project will engage a student to work on the engineering and physics of a prototype pulsed plasma thruster (PPT) device, including laboratory based experimental assessment with capacity of computer simulation and modelling. Students will learn about the physics of cathodic discharge, plasma diagnostics and aerospace engineering principles.

How to feed gas into galaxies to make stars

Supervisor: Julia Bryant
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Galaxies need gas to make stars and build mass. How galaxies accrete gas affects how they look (their morphology) and their dynamics. Using the new Hector Galaxy Survey data, this project will use resolved maps of stellar rotation and gas rotation to understand how the accretion of gas drives the physics in galaxies. There are several projects in this area. Skills in python programming would be an advantage. As the Hector Galaxy Survey is the largest and best of its type in the world, not only will this project have use of the brand new, unique data, but may be a lead into the new PhD projects with Hector.

Revealing explosive star formation

Supervisor: Scott Croom
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Star formation is central to the growth of galaxies. This star formation in controlled by feedback from young hot massive stars. Winds from the stars as well as supernovae explosions can heat and accelerate the gas in galaxies, suppressing further star formation. In this project, we aim to directly identify the locations where star formation feedback is happening, by studying the motion of the gas and measuring its turbulence. The project will make use of spectroscopic data from the new Hector Galaxy Survey, led from the University of Sydney.

Advanced computer simulations of the Lower--Hybrid Drive Process for Electron Acceleration

Supervisor: Iver Cairns
Email contact: iver.cairns@sydney.edu.au

Lower-hybrid drive involves two parts, first the generation of lower hybrid waves by an ion instability and, second, acceleration of electrons parallel to the magnetic field by the lower hybrid waves. It is believed relevant to the 2-3 kHz radio emissions observed by the Voyager spacecraft beyond the heliopause and also to solar flares. This project will involve setting up the open source 3D particle-in-cell simulation code VPIC and using VPIC to simulate the physics of lower-hybrid drive, seeking to answer whether this process should be quantitatively important in these applications.

Plasma depletion layers throughout our solar system and beyond

Supervisor: Iver Cairns
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The solar wind interacts with the local interstellar medium and planets through shocks and boundary layers, the latter sometimes known as “plasma depletion layers” (PDLs) since the plasma density is decreased and the magnetic field increased. Recently Voyager 1 has crossed into the local interstellar medium and observed the associated PDL. This project will analyse NASA spacecraft data to assess the detailed characteristics of the PDL beyond the heliopause. It will also determine and compare the waves and plasma properties of PDLs as functions of heliocentric distances, and then interpret the results using plasma theory.

Prediction of type II solar radio bursts for the Sun and other stars

Supervisor: Iver Cairns
Co-supervisor: A./Prof. Joe Khachan
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Type II solar radio bursts are associated with shock waves in front of coronal mass ejections leaving the Sun. These shocks accelerate and reflect electrons, which then produce Langmuir waves and radio emission. A new and improved theory exists for these processes for Earth's bow shock, a shock wave standing in the solar wind flow. This project will involve modifying the numerical code to predict the radio emission of a shock moving through the solar wind plasma and magnetic field structures for a model corona and solar wind, either from a simulation or from a model. This will lead to predictions of type II radio bursts from the Sun to the orbit of Earth. Similar calculations will be performed for model shocks in the coronas of other stars and assessed for their observability by the Murchison Widefield Array and the Square Kilometer Array.

Tomographic reconstruction of the 3D ionosphere using GPS, radio, and in situ satellite data

Supervisor: Iver Cairns
Co-supervisor: Associate Professor Joe Khachan
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Earth's ionosphere varies with time of day, latitude, and space weather events. This multi-part project involves calculating the change in phase of GPS signals (and so the derived path-integrated electron density or TEC) from the GPS signals to a satellite or the ground for existing analytic ionospheric models, tomographic reconstruction of the 3D ionospheric electron density from a set of TEC data for multiple GPS satellites and observers, and evaluating the improvements obtained from fusing both in situ satellite measurements of electron density with tomographic reconstructions. In addition, density information from refraction of astrophysical radio sources, such as measured by the Murchison Widefield Array, may also be used. The observability of modelled transient disturbances and other space weather events might also be considered. The project will involve a mix of analytic theory and computation.

Biological, biomedical and medical physics

The Ingham Institute, associated with Liverpool Hospital, is offering scholarships for honours students. Each Honours scholarship is worth $5,000 for 12 calendar months. Any student that is considering a medical physics project and would be interested in applying for the scholarship is welcome to discuss with Professor Annette Haworth: annette.haworth@sydney.edu.au

Complex systems; Data science

Sleepless in Pacific

Supervisor: A/Prof Svetlana Postnova
Co-supervisor: Prof Corinne Caillaud (Digital Health, Faculty of Medicine and Health)
Email contact: svetlana.postnova@sydney.edu.au

Motivation: More than 70% of school students do not get enough sleep on school nights, which results in chronic sleepiness, poor memory consolidation, underperformance, and disease. This can be avoided by either changing school times (often unfeasible in the short term) or evidence-based interventions to improve sleep. Objective: This project will combine biophysical modelling of brain dynamics with experimental data from hundreds of high-school students in the South Pacific islands where school starts as early as 7 AM to (i) investigate the effects of school start/end times on accumulating chronic sleep debt and disturbances of circadian rhythms of students in urban, rural, and tribal populations; and (ii) develop model-based interventions to improve students' sleep and performance. If successful, the interventions will be implemented as part of the program to improve students' health and well-being.

Understanding Brain Diseases through modelling of sleep

Supervisor: A/Prof Svetlana Postnova
Co-supervisor: Dr Elie Matar (Faculty of Medicine and Health, Royal Prince Alfred Hospital)
Email contact: svetlana.postnova@sydney.edu.au

Motivation: Brain disorders, including different types of dementia, are associated with sleep disturbances. Sleep changes often precede other symptoms and may appear years before cognitive changes. However, it is unclear how the brain networks involved in sleep are affected by the diseases and whether they contribute to cognitive decline. Objective: This project aims to understand the potential mechanisms responsible for changes in cognition and sleep in patients with Parkinson's disease and Lewy Body Dementia. This will be achieved by applying a validated biophysical model of the ascending arousal system in the brain to experimental data from the clinical populations to identify physiological parameters that differ between healthy and diseased conditions. The supervisory team includes modelling and clinical experts, providing a unique opportunity for interdisciplinary research with potential real-world impact.

Quantitative modelling of cognitive performance

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Co-supervisor: Dr Federica Conti
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Motivation: The ability to focus and solve complex and simple tasks fluctuates over the 24-hour cycle and is affected by prior sleep. New experimental data from the National University of Singapore (NUS) shows that split sleep is more beneficial for cognitive performance than a consolidated sleep episode of the same duration. However, existing theoretical models fail to explain these findings, and an improved model is required. Objectives: In this project, we will collaborate with the research team from NUS to develop a new biophysical model to explain the changes in dynamic processes underpinning cognitive performance in teenagers following split sleep schedules. This model is expected to redefine our understanding of the mechanisms underlying the effects of sleep on cognition and replace the existing models for prospective predictions in various applications.

Inferring canonical statistical signatures of nonlinear dynamics

Supervisor: Ben Fulcher
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Complex dynamics patterns are found in physical systems all around us. But what are the best ways of detecting and quantifying patterns indicative of interesting underlying dynamical properties (like low-dimensional chaos) from less interesting ones (like stochastic linear dynamics)? Scientists have developed a range of tools for detecting and quantifying such structures, but they remain disjoint; it thus remains unclear what types of statistical properties allow us to best characterize the interesting dynamics we care about detecting and studying. In this project, the student will start with a large library of candidate analysis methods (the hctsa library) and reduce it down to a minimal but powerful subset, enabling major practical applications for analyzing real-world systems from a nonlinear physics perspective. The student should have an interest in numerical simulation, data science, and machine learning.

Detecting misinformation on a social network

Supervisor: Tristram Alexander
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The quantities of data shared on a social network are immense, and it is often difficult to tell if a particular piece of content is misinformation or not. In this project you will explore the nature of information spreading on a social network and develop automated techniques for the detection of misinformation based only on the network connectivity surrounding a piece of information. The developed approaches will then be validated against manually coded data, including manually coded sources. Applications will include the identification of misinformation prevalence in different domains, such as discussions related to climate science, or vaccines.

Network models of language dynamics

Supervisor: Tristram Alexander
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The statistical properties of language show remarkably consistent behaviour, however these properties have been predominantly studied in environments where language changes slowly. Social networks are becoming a more and more important means to share information, and the language dynamics on these networks appears to show strikingly different behaviour. There is a fundamental interplay between the nature of the network and the language evolution, but this has not been explored. In this project you will develop models for language evolution on a network, and validate these models against social network data. Key language characteristics will be identified and compared to results from non-social media data.

What makes a community on a social network?

Supervisor: Tristram Alexander
Co-supervisor: Prof. Eduardo Altmann (Mathematics)
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Community is an important social construct, but what makes a community on a social network? Members of a social network can interact widely with other members, some of whom may be ideologically distant. Is a community defined by who members contact? Ideology? Or shared behaviours? The nature of community is essential for understanding how information spreads on a social network, but this most fundamental unit of the network is still poorly defined. In this project you will use computational techniques to identify what it is that makes a community on the network. You will work with real social media data, and test community detection methods on artificially created data. These fundamental developments will then allow the treatment of applied problems, such as the identification of opinion echo chambers and network "super-spreaders".

Brain vortices: new pathways to understanding brain dynamics

Supervisor: A/Prof Pulin Gong
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Cortical neural circuits are complex, non-equilibrium systems whose collective dynamics cannot be described solely by oscillations or low-dimensional aperiodic (chaotic) dynamics. Recently, we have developed a method that enables us to uncover new physical principles of neural circuits. For example, we have identified dynamic coherent patterns, such as vortices, that coordinate the spatiotemporal dynamics of cortical circuits (see our paper on this topic: https://www.nature.com/articles/s41562-023-01626-5). This exciting discovery draws a parallel between brain dynamics and those observed in turbulent fluids, where a hierarchy of vortices is also embedded within stochastic spatiotemporal processes. This project will involve further refinement of this innovative method, including the analysis of neural data gathered by our collaborators at Imperial College London. Additionally, the project will involve expanding the neural circuit models developed by our research group to simulate brain vortices. The outcome of this project will significantly advance our understanding of the physical principles of brain dynamics. Students participating in this project will have the opportunity to acquire essential skills in big data analysis and modelling.

How does the brain compute? Distributed dynamical computation in neural circuits

Supervisor: A/Prof. Pulin Gong
Email contact: pulin.gong@sydney.edu.au

One of the most fundamental questions regarding the brain is how it performs computation. To address this, we have developed the concept of distributed dynamical computation (DDC), in which neural computation and information processing occur through the interactions of propagating wave packets. DDC serves as a bridge, integrating the previously disconnected perspectives of brain dynamics and computation. Recently, we demonstrated that within the DDC framework, wave packets can efficiently implement sampling-based probabilistic computations [Qi and Gong, Nature Communications 2022; Chen and Gong, Science Advances 2022; Wardak and Gong, Phys Rev Lett 2022]. This project will focus on establishing further connections between neural dynamics and computation, including an in-depth study of the neural circuit models developed by our research group. The goal of this exploration is to uncover the physical principles underlying key brain functions, such as visual processing and attention, laying the foundation for the development of brain-inspired artificial intelligence.

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The physics of deep learning in artificial intelligence

Supervisor: A/Prof. Pulin Gong
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Deep learning networks, widely used in artificial intelligence (AI), can be trained to effectively solve a variety of real-world problems, including speech recognition, object detection, and drug discovery. However, our understanding of why they are so effective remains incomplete. Recently, we discovered that the learning processes within deep learning networks exhibit complex diffusion dynamics [Chen and Gong, Neural Networks 2022], which contrasts with the conventional assumption of normal diffusion (i.e., Brownian motion). These complex dynamics involve intermittent large jumps that prevent the learning process from becoming trapped in local minima, thereby enabling the attainment of optimal solutions. This finding offers a new explanation for the effectiveness of deep learning networks. This project will involve further investigation into the physical mechanisms underlying these complex learning dynamics. Specifically, the project will explore how the fractal, self-similar geometric structures of loss function landscapes within deep learning networks interact with gradient descent to give rise to these intricate learning dynamics. Students participating in this project will have the opportunity to learn essential models and algorithms used in AI.

Exploration-Exploitation with Stochastic Resetting

Supervisor: Wave Ngampruetikorn
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Stochastic resetting is a relatively young field in statistical physics (see, Evans, Majumdar & Schehr arXiv:1910.07993). It has attracted much attention owing to its wide-ranging applications from stochastic processes to nonequilibrium physics to many-body physics to optimization. This project will explore recent developments in this exciting field. We will use analytical and numerical approaches as well as simulations to investigate the exploration-exploitation tradeoff in systems with stochastic resetting, focusing on biological and machine learning systems. The student will enjoy a high degree of freedom to choose the research directions that most interest them and will have the opportunity to join an international collaboration. This project requires the student to possess good mathematical and analytical skills with a strong interest in learning numerical and computational methods as needed.

Condensed matter physics; Materials physics

From Defects to Devices: Designing atomic defects for quantum technologies

Supervisor: Catherine Stampfl
Co-supervisor: Oliver Conquest
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The aim of this project is to explore and identify materials for quantum emitters with improved brightness and stability through defect and strain engineering of low-dimensional (low-D) semiconductors and insulators using first-principles quantum mechanical calculations. Atomic defects in solids are one of the most promising single-photon sources for quantum technologies. In order to design improved quantum emitters, a fundamental understanding of their optical and electronic properties, as well as defect formation energies, is essential. The theoretical knowledge gained in the project will lead to a better understanding of the behavior of defects in low-D materials and potentially aid in the design of atomic defects systems for tailored applications as quantum emitters. The student will gain experience with high-performance computing and materials simulation methods.

CO2 – From a Problem into a Solution

Supervisor: Catherine Stampfl
Co-supervisor: Oliver Conquest
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There is little question that the sustainable reductive transformation of carbon dioxide is one of the most important scientific and technical challenges of the 21st century. In this way, CO_2 can serve as a raw material for Power-to-X technologies. The major obstacle in meeting this challenge is the lack of low-cost, highly active, efficient, selective and stable catalysts. With increasing computer resources and the development of more accurate methods and efficient algorithms, computational condensed matter and materials physics now plays an active and predictive role in catalyst design. Low-dimensional materials are at the forefront of materials research. This is due to their enormous variety of structures, unique properties and tunability for a wide range of technological applications. For catalysts, they have the advantage of large surface/volume ratio and electron confinement, as well as the ability to readily tailor the properties through composition and structure. This project will use high-performance computing, together with state-of-the art quantum mechanical simulations, to investigate potential catalyst materials for active and selective carbon dioxide reduction (CO2R). The new knowledge gained in the project will lead to a better understanding of what characteristics are important for the design of improved CO2R catalysts.

Artificial Intelligence and Quantum Mechanics: Cutting-edge Approach to CO2 Catalysis on Au Particles

Supervisor: Marco Fronzi
Co-supervisor: Catherine Stampfl
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The catalytic reduction of carbon dioxide (CO2) on gold (Au) particles has received significant attention given its potential to address carbon emission challenges.[1,2] Ab-initio Molecular dynamics calculations provide a fundamental approach for understanding the effect of structural parameters, substrate composition and thermodynamic conditions, on catalytic efficiency. However, while accurate, they are extremely time-consuming. Using density functional theory calculations and machine learning models, we generate interatomic potentials that accelerate molecular dynamics simulations without compromising the accuracy of ab-initio calculations. This acceleration enables the analysis of chemical reactions involved in the process over extended periods, which is the bottleneck of ab-initio methods.[3,4]

This project not only contributes to the deeper understanding of CO2 catalysis on Au particles but also showcases the power of integrating machine learning with quantum mechanical calculations to accelerate the discovery and optimization of catalytic systems. The findings from this project are expected to have a substantial impact within the scientific community working on catalysis and environmental sustainability.

1) Peter, Sebastian C. ACS Energy Letters 3.7 (2018): 1557-1561.
2) Birdja, Yuvraj Y., et al. Nature Energy 4.9 (2019): 732-745.
3) M. Fronzi, R. D. Amos, R. Kobayashi Nanomaterials 13(12), 1832, (2023)
4) M. Fronzi, R. D. Amos, R. Kobayashi, N. Matsumura, K. Watanabe and R. Morizawa Nanomaterials 12(21), 3891 (2022)

Exploring 2D Heterostructures: A Computational Approach using Quantum Mechanics and Artificial Intelligence

Supervisor: Marco Fronzi
Co-supervisor: Catherine Stampfl
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Van der Waals heterostructures, formed by layering two-dimensional (2D) materials, are revolutionizing material science and technology due to their unique properties and the large number of crystals possible from 2D combinations.[1] The analysis of the electronic structure gives important information to understand fundamental properties of this novel class of materials, which is crucial for performance optimization of devices.[2,3] This project leverages quantum mechanics and artificial intelligence to explore the extensive heterostructure space (millions of novel bilayers), focusing on calculating their functional properties.[4,5] Initially, density functional theory will compute the target property of a selected set of heterostructures. The resultant database will then use to build machine learning models that will efficiently and accurately estimate the target property across all heterostructures. This approach aims to significantly accelerate material screening, expanding the range of potential hybrid materials for the scientific community. The combination of quantum mechanics and machine learning presents an innovative pathway for discovery novel materials.

1) Novoselov, K. S., et al Science 353.6298 (2016): aac9439.
2) Li, Peicheng, and Zheng-Hong Lu. Small Science 1.1 (2021): 2000015.3)
3) Biswal, Bubunu, et al. Applied Physics Letters 120.9 (2022).
4) Fronzi, Marco, et al. Advanced Intelligent Systems 3.11 (2021): 2100080.
5) Fronzi, Marco, et al. Advanced Theory and Simulations 3.11 (2020): 2000029.

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Particle physics

Development of data quality cuts for dark matter searches with the LZ Experiment

Supervisor: Theresa Fruth
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The LZ Experiment is one of the most sensitive direct detection searches for dark matter ever performed. Its recently published first science result set world-leading limits for Weakly Interacting Massive Particles (WIMPs).

As data taking is continuing, it is critical to further our understanding of the detector. As a rare event search, it is essential that any period of detector instability is vetoed and removed from the data before the final analysis. A suite of monitoring sensors (electromagnetic, acoustic, temperature) have been installed in the detector for this purpose.

The student on this project will work on understanding the signals from these sensors further by analysing data from LZ and additionally performing test measurements in the lab in Sydney. The student will have the opportunity to integrate their analysis in the LZ data quality procedure. There will be opportunity to use machine learning algorithms for this project.

Novel probes of ultralight dark matter

Supervisor: Yevgeny Stadnik
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Models of dark matter involving ultralight fields coupled to standard-model fields predict variations in the fundamental “constants” of Nature (which include, e.g., the fundamental particle masses and parameters describing the strengths of the fundamental interactions), as well as time-varying phenomena coupling to particles’ spins (including electric dipole moments, which provide tests of the CP symmetry). This project explores novel phenomenological aspects of such models, including precision measurements in the laboratory, as well as astrophysical probes.

Dark matter waves

Supervisor: Ciaran O'Hare
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We know that dark matter exists in abundance in our universe, however we do not know anything about its fundamental nature. Many popular theories for dark matter predict that it should be made of a particle that is many orders of magnitude lighter than any other particle we know of currently. If this is the case, then there must be enormous numbers of dark matter particles around us in the galaxy right now. So many, in fact, that the dark matter would become a collective phenomenon like a fluid and exhibit wave-like rather than particle-like behaviour. This project would seek to explore some of this behaviour through mathematical models and simulations, and determine the implications for experiments that are searching for dark matter right now.

Advanced Particle Detector Development for Environmental and Cosmic Ray Studies

Supervisor: Laura Manenti
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This project focuses on developing Front-end Electronics for Silicon Photomultipliers (SiPMs) to create a new particle detection system. You'll be involved in building the detector from scratch, including circuit design and signal processing. Depending on your interests, there will also be an option to develop a microcontroller. The detector will have practical applications in environmental radiation measurements and cosmic ray detection, with a focus on correlating results with weather conditions. This hands-on project offers experience in hardware development, data acquisition, and analysis techniques essential for modern physics instrumentation. Additionally, you will have an independent small budget to manage, as I believe this will give you valuable experience in managing project costs.

Mapping Sydney's radioactivity profile

Supervisor: Laura Manenti
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Ever wondered about the radioactive exposure in Sydney? Radiation surrounds us as a natural part of our environment, from cosmic rays to radioactive elements in the ground. But how much radiation are we exposed to, and what types are present in the city?

In this project, you'll use a gamma detector called Radiacode (https://www.radiacode.com/eur) to map Sydney's radioactivity . The detector connects to your smartphone (iPhone or Android), allowing you to track real-time counts per second and analyze radiation spectra as you move around the city. By studying these spectra, we will identify the types of ambient radiation in different locations. You'll also collect environmental samples from various parts of Sydney, analyzing them with a germanium detector and mass spectrometry to measure natural levels of uranium and thorium. Additionally, you'll build your own gamma-ray spectrometer using a SiPM and a scintillating crystal, gaining hands-on experience with the underlying technology behind the Radiacode. This project transforms Sydney into your laboratory, allowing you to apply nuclear physics to real-world data and reveal the city's hidden radioactive profile. A publication is expected from the findings of this work.

Firmamento: Discovering multi-messenger cosmic emitters using machine learning and generative AI

Supervisor: Laura Manenti
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Firmamento (https://firmamento.hosting.nyu.edu) is a web-based, mobile-friendly scientific platform designed to discover and analyze multi-messenger cosmic emitters, particularly blazars and radio galaxies. Originally built for a citizen science project, Firmamento now serves as a valuable tool for professional researchers by offering efficient access to a wide range of open data, combining both classical and cutting-edge multi-frequency and multi-messenger imaging, spectral, and timing data. The platform is used to identify high-energy sources detected by observatories like Fermi-LAT, IceCube, and eROSITA, and will be key for upcoming facilities such as CTA, ASTRI, LHAASO, KM3NeT, and IceCube-Gen2.

In this project, you will leverage Firmamento to create new catalogues of blazars, contributing to the discovery of new astrophysical sources. You will also develop expertise in machine learning techniques and AI to analyze and classify data. This hands-on project will give you practical skills in multi-messenger astronomy and data science, while your findings are expected to lead to a publication.

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Weak mixing angle using solar neutrino measurements in the low momentum transfer regime

Supervisor: Tarak Nath Maity
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Solar neutrinos have been measured with high precision by experiments such as Borexino,[1] the Sudbury Neutrino Observatory (SNO),[2] and SNO+.[3] One of the channels through which these neutrinos are observed is neutrino-electron scattering, an interaction governed by the weak mixing angle, a key Standard Model parameter. The primary aim of this project is to measure the weak mixing angle using results from Borexino, SNO, and SNO+, while also identifying potential degeneracies with neutrino oscillation parameters. In contrast to reactor neutrino detection via neutrino-nucleus scattering (as with COHERENT), these experiments are expected to probe the weak mixing angle in a lower momentum transfer regime.

1) https://inspirehep.net/literature/1700565
2) https://arxiv.org/abs/1109.0763
3) https://arxiv.org/abs/2407.17595

Search for Top-Philic Exotic Particles with the ATLAS Experiment

Supervisor: Dr. Harish Potti
Co-supervisor: A/Prof Bruce Yabsley and Prof. Kevin Varvell
Email contact: harish.potti@sydney.edu.au

This project aims to search for exotic particles that preferentially decay into a pair of top quarks, known as top-philic particles, using data from the ATLAS experiment at the Large Hadron Collider (LHC). These particles are predicted by various new physics frameworks, such as composite Higgs models and extra-dimensional theories. The discovery of such exotic particles would provide crucial insights into addressing many open questions in particle physics. In this project, the student will first analyse ATLAS simulations to identify the signature of these exotic particles. Then, machine learning based techniques, using frameworks like PyTorch Lightning, will be developed to optimise the sensitivity of the search. These techniques will be then applied on ATLAS data to report any excess that is consistent with the signature of the exotic particles. Prior basic knowledge of Python or C++ would be useful for this project, but it is not required.

Precision measurements of Higgs boson properties with the ATLAS experiment

Supervisor: Dr. Harish Potti
Co-supervisor: A/Prof Bruce Yabsley and Prof. Kevin Varvell
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The Higgs boson plays a central role in the Standard Model of particle physics, as well as in many new physics theories. It was experimentally observed by the ATLAS and CMS experiments at the LHC in 2012. Since its discovery, precision measurements of the Higgs boson's properties have become one of the primary objectives of the LHC physics program. In this project, the student will measure the strength of the Higgs boson's interaction with the top quark using data collected by the ATLAS experiment. By analysing the kinematic and topological properties of the top quark and the Higgs boson, the student will develop selection criteria to distinguish signal events containing the Higgs boson and top quarks from background events. Special relativity principles and advanced statistical methods will also be applied in this project. Prior basic knowledge of Python or C++ would be useful for this project, but it is not required.

Rare D-meson decays at Belle II as a unique window on new physics

Supervisor: Bruce Yabsley
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Rare particle decays provide a window on "new physics" beyond the Standard Model, and the search for rare decays is an important part of the programme at the Belle II experiment in Japan. Rare decays of B-mesons and τ-leptons are being actively studied (including at Sydney), but less work has been done on D-mesons. In particular, the decay $D \to e\,\tau$ has never been studied. It provides unique access to certain beyond-Standard-Model effective operators: a search at Belle II could exceed the sensitivity of the Large Hadron Collider for some operators. Reconstruction of $D \to e\,\tau$ events is also technically interesting. A student doing this project will have the opportunity to work with real and simulated Belle II data to help develop a $D \to e\,\tau$ search. This work would be suitable both for standalone honours projects and for projects leading into subsequent PhD research.

Track-driven clustering as a tool for the reconstruction of rare-decay events at Belle II

Supervisor: Bruce Yabsley
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Grand Challenge: Fundamental laws & the Universe

Rare particle decays, which are important in the search for new forces of nature and other new physics, are challenging to reconstruct: one must "look for a needle in a haystack". Most rare decay searches at the Belle II experiment in Japan rely on some kind of comprehensive reconstruction of all of the particles in an "event" (the debris from a single electron-positron annihilation). These techniques, which can be quite sophisticated, allow for ambiguous events to be suppressed, driving down background levels. But all the techniques currently in use are built on a one-size-fits-all procedure for reconstructing energy deposits in the Belle II electromagnetic calorimeter, one of the key detectors: energy deposits are formed into clusters, and then matched to the tracks left by charged particles. We are examining an alternative approach where the energy deposits by reconstructed tracks are clustered first, exploiting information from other detectors and allowing a true global reconstruction of the event. In this project you will help to develop this procedure, and test it on rare decay events and their competing backgrounds. This project would suit a student with an interest in learning about the interactions of particles with matter, and in development of algorithms.

Photonics and optical science

Thermally invisible materials through passively cooling nanostructures

Supervisor: Boris Kuhlmey
Co-supervisor: Martijn de Sterke, Alex Song
Email contact: boris.kuhlmey@sydney.edu.au

In many situations, how much an object can be cooled is limited by how much heat radiation it can emit: this is the case for probes in space, where radiation is the only heat exchange mechanism, delicate scientific equipment in vacuum, but also for a body beneath clothing – where the balance of incoming sunlight to outgoing infrared radiation greatly contribute to thermal comfort. What you were taught in first year thermodynamics, that emissivity and absorption are the same and are a property of a substance is not entirely true: these properties can in fact be altered substantially through nanostructuring, to the point where in principle a very absorbing material can be made entirely transparent to infrared radiation, while remaining completely reflective to the sunlight's or a laser's radiation. Such a thermally invisible material could revolutionise clothing for hot climates, but could also find applications in many situations where radiative cooling is important. This theoretical and numerical project will use electromagnetic theory in structured matter to find new ways of achieving such thermal invisibility.

Solitons on the cusp

Supervisor: Martijn de Sterke
Co-supervisor: Antoine Runge
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We have developed a laser which is ideally suited for the generation of a wide variety of solitons because it allows us to program any dispersion relation, the relation between the frequency ω and the wavenumber β in the cavity. Solitons balance the effect of this dispersion with nonlinear effects by which the refractive index depends on the light intensity. Since none of these solitons have been investigated previously, we also need to develop the theoretical framework to describe and understand them as well as their governing equations. Most recently we have become interested in dispersion relations with a cusp. The aim of this theoretical and numerical project is to investigate these solitons theoretically, i.e. their shape, their stability, their governing equations, to guide subsequent experimental work.

Pattern formation in high dimensional systems

Supervisor: Tristram Alexander
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Pattern forming systems occur in a wide range of physical systems, and the models describing these dynamics are often universal. However, guided by physical principles, these models have been limited to second-order spatial derivatives. Recent developments in optics, in which higher-order derivatives become physically relevant, open up fundamental questions about the universal models. What happens if the dimensionality of the phase space is increased? What patterns become possible? The fundamental investigation of this project will inform experimental work in the Institute of Photonics and Optical Science, however the results will be generalisable to other physical systems, such as Bose-Einstein condensates.

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Frequency combs from a Fabry-Perot cavity

Supervisor: Martijn de Sterke
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Frequency combs are light beams that consist of equally spaced spectral lines with a fixed phase relation. They are of great importance in metrology and spectroscopy, as well as in optical communications. Over the last two decades it has become possible to generate combs in microresonators. These can emit combs with hundreds of optical lines and lend themselves to chip-scale integration. The most common cavity is the ring cavity, which has been extensively explored, both experimentally and theoretically. Recently, initial demonstrations of comb emission in microresonators based on a Fabry-Perot cavity have been reported. These differ from ring cavities since the light propagates forward and backward inside the same structure leading to interactions which are absent in rings. Though the study of this novel system is still in its early stages, it is important to understand the differences compared to ring cavities. In this project, you will focus on the theory and modelling of these Fabry-Perot microresonators, and whether they have advantages over rings. Specifically you will examine the degree to which specifically designed mirrors affect the comb properties.

Soliton with fractional dispersion

Supervisor: Martijn de Sterke
Co-supervisor: Antoine F. J. Runge; Van Thuy Hoang
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Optical solitons are pulses that propagate while maintaining their shape, by balancing nonlinear and dispersion effects. This feature has made solitons central in numerous modern photonics applications including telecommunications, ultrashort pulse generation in lasers, and frequency combs. Mathematically, the propagation of optical solitons is governed by the nonlinear Schrödinger equation, where the effect of the dispersion of order n is described by a nth order derivative of the electric field, with respect to time, and where n is an integer. However, we recently discovered that optical solitons can also form if the dispersion order n is a fractional number. These solitons are therefore described by a corresponding fractional nonlinear Schrödinger equation with a fractional derivative. In this project, you will study theoretically, numerically and experimentally this novel class of optical solitons using our home-built laser system. This unique setup allows us to program any arbitrary dispersion profile, that is not achievable in conventional optical systems. During this project, you will acquire skills in state-of-the-art numerical modelling (solving advanced nonlinear partial differential equations) and experimental photonics (measuring ultrashort pulses using phase-sensitive spectro-temporal techniques). We expect the applications of these novel nonlinear pulses to range from laser physics to quantum system analogy.

Hypersound surface waves on a photonic chip

Supervisor: Dr Moritz Merklein
Co-Supervisor: Prof. Benjamin Eggleton
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Surface acoustic wave devices are widely used for signal processing and filtering (including your mobile phone), as well as mechanical, chemical, and biological sensing. Currently, these acoustic waves that propagate along a surface of a material are induced and detected electronically which limits their frequency range, material platforms and use cases. Our team found recently a method to excite and detect surface acoustic waves optically, using a laser, in a photonic integrated circuit on a chip. The discovered surface acoustic wave oscillates at a very high frequency, placing it in the hypersound regime.

Based on our proof-of-principle discovery this project will aim to create a deeper understanding of these novel waves. How long do they live? How far can the propagate? How strong is the interaction with the light field? Are they sensitive to the surrounding of the waveguide? Can we tailor their properties by changing the waveguide design? The project will incorporate all aspects of an integrated photonics project, from modelling optical and acoustic waves, to designing an optimized photonic integrated circuit and, excitingly, experimental measurements of the circuit in the lab. You will learn how to use state-of-the-art modelling tools and test and measurement equipment to characterize photonic chips – microchips that guide light instead of electronic signals. Optically exciting and detecting surface acoustic waves offers a lot of rich physics to be studied and explored but also has great potential for many applications, including sensing, signal processing, and even potential applications as quantum transducers.

Interplay of optical frequency combs and hypersound waves?

Supervisor: Dr Moritz Merklein
Co-Supervisor: Prof. Benjamin Eggleton
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Optical frequency combs are a revolutionary technology awarded the Nobel Prize in 2005 and the theme of a new ARC Centre of Excellence in Australia, called COMBS (Centre of Excellence in Optical Microcombs for Breakthrough Science). A frequency comb consists of equally spaced optical "laser lines" in the spectral domain. The periodicity acts as a precise ruler for frequency and time measurements, and furthermore frequency combs are deemed to revolutionize spectroscopy and telecommunication (where data could be transmitted in parallel channels encoded on the individual frequency comb teeth). However, there are at least still two major challenges that require more research: One is to shrink the frequency comb from an expensive and bulky lab bench setup into a photonic chip. The second challenge is to control and manipulate the frequency comb for its particular use case, in particular, controlling individual comb teeth.

In this project you will work on finding ways to manipulate frequency combs on a line-by-line basis, as required for many applications in telecommunication, sensing, and detection and ranging. You will set up your own frequency comb in the lab and we will study the intricate interplay between Brillouin scattering – a coherent light-sound interaction – and the frequency combs. You will work in a state-of-the-art optics lab and learn how to use the latest optical and microwave test and measurement equipment.

Interplay of light and hypersound at low temperature

Supervisor: Dr Moritz Merklein
Co-Supervisor: Prof. Benjamin Eggleton
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Optical fibers made out of silica glass are underpinning the internet and any long-haul communication today. Long before the development of optical fibers and the invention of the laser, it was predicted that optical waves of high intensity will interact with thermal density fluctuations – sound waves – and hence cause backscattering of the light. This effect is called stimulated Brillouin scattering and is the center of exciting research for many decades. Surprisingly only very little work was done on investigating the interaction between light and high-frequency acoustic waves at different temperatures, including cryogenic temperatures. This project will study experimentally Brillouin scattering at different temperatures. You will build your own setup using state-of-the-art test and measurement equipment. The temperature of the medium (optical fiber) can be cooled down to below 4K in a cryostat. This study will aim to provide a better understanding of the interaction of thermal vibrations with optical signals that is crucial for characterizing noise in telecommunication applications as well as providing fundamental physical insights central for future quantum experiments that rely on single-photon and phonon interactions.

Neuromorphic computing using light

Supervisor: Dr Moritz Merklein
Co-Supervisor: Prof. Benjamin Eggleton
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Machine learning and AI is currently rapidly increasing in its impact on our daily live. The underpinning compute, however, is intense, at times slow, and extremely power hungry. Optical circuits that perform analog signal processing are a potential alternative route. This project aims to explore the field of optical neuromorphic computing, which relies on photons and nonlinear optical interactions to emulate neural processes in a highly parallel and energy-efficient manner. This alternative approach to neuromorphic computing has potential to dramatically increase speed and reduce power consumption compared to traditional electronic systems. The project will explore different optical computing architectures and look into proof-of-principle demonstration of an optical nonlinear transfer function that can form the basis of a neural network.

Storing light as hypersound on a photonic chip

Supervisor: Dr Moritz Merklein
Co-Supervisor: Prof. Benjamin Eggleton
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Light travels fast – sometimes a little too fast when it comes to data processing. We recently showed that we can slow down the flow of information carried by optical data pulses via transferring the information to slow traveling acoustic waves – phonons. The difference in velocity of optical and acoustic waves is around a factor of 100 000. After the information accumulates a delay in the acoustic domain we transfer it back to an optical signal. This is achieved on a photonic chip that is designed to guide light as well as acoustic waves. In this project, you will experimentally investigate the physical limitations of this delay technique. What are the shortest pulses we can store as acoustic waves and how does the dynamic of the process change on very short time scales (nanoseconds). The second questions we are aiming to answer is for how long we can hold the information in the soundwave and still retrieve it back to the optical domain. You will use state-of-the-art test and measurement equipment and will work with photonic chips – microchips that guide light instead of electronic signals

Ultra-broadband Signal Synthesis using Optical Frequency Comb

Supervisor:	Prof. Benjamin Eggleton
Co-*Supervisor:*	Mr Ziqian Zhang
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Optical fibers made out of silica glass are underpinning the internet and any long-haul communication today. Long before the development of optical fibers and the invention of the laser, it was predicted that optical waves of high intensity will interact with thermal density fluctuations – sound waves – and hence cause backscattering of the light. This effect is called stimulated Brillouin scattering and is the center of exciting research for many decades. Surprisingly only very little work was done on investigating the interaction between light and high-frequency acoustic waves at different temperatures, including cryogenic temperatures. This project will study experimentally Brillouin scattering at different temperatures. You will build your own setup using state-of-the-art test and measurement equipment. The temperature of the medium (optical fiber) can be cooled down to below 4K in a cryostat. This study will aim to provide a better understanding of the interaction of thermal vibrations with optical signals that is crucial for characterizing noise in telecommunication applications as well as providing fundamental physical insights central for future quantum experiments that rely on single-photon and phonon interactions.

Plasma Physics

Thermal waves in magnetized and unmagnetized plasmas

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The moving charged particles in a thermal plasma produce thermal levels of the plasma's natural modes. Measurement of the power spectrum of thermal Langmuir waves in a plasma, for instance by a satellite, allows extraction of the plasma's number density and temperature. This project involves calculating the power spectrum of other thermal waves in a plasma, in particular ion acoustic waves for an unmagnetized plasma and then for upper hybrid waves in a magnetized plasma. These results will be used to interpret the observations in a laboratory plasma device and then for the CUAVA-2 CubeSat in Earth's ionosphere.

Nonlinear wave-wave processes in Earth's ionosphere

Supervisor:	Iver Cairns
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Recent TRICE-2 rocket observations show the existence of upper hybrid waves and lower hybrid waves engaged in various nonlinear wave-wave processes. The first part of this project will involve a detailed examination of the constraints on the participating waves posed by kinematics, meaning conservation of energy and momentum for the participating wave quanta. The second part will be to calculate the nonlinear rate for the wave processes. The results will then be compared with the TRICE-2 data to assess whether the new theory is consistent with the available observations.

THE UNIVERSITY OF SYDNEY

Quantum physics and quantum information

Space-time quantum error-correction

Supervisor:	Campbell McLauchlan
Co-supervisor:	Stephen Bartlett
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Large-scale quantum computing will require the correction of errors that are common in quantum devices. The common strategy for achieving this utilises redundancy – we encode a small amount of quantum information in a large system, using a "quantum error-correcting (QEC) code". Recently, we have begun to understand that QEC codes ought to be thought of as existing both in space and in time. The codes that take advantage of this extra temporal dimension are called Floquet, or dynamical, codes. These can have counter-intuitive properties that require the generalisation of our notion of QEC codes. Indeed, when examined non-dynamically, they may seem to store no quantum information at all, yet their error-correction properties emerge as the system evolves in time. Beyond their theoretical interest, these codes can benefit from certain practical advantages for implementation, including requiring only two-qubit measurements. While there exist several examples of non-trivial dynamical codes, we are only beginning to understand the best ways to compute with the information they can store. In this project, we will develop new theoretical protocols for fault-tolerantly computing using dynamical codes. In doing so, we will develop new examples of topological defects in these systems which will aid our understanding of dynamical codes and their potential.

Testing topological quantum error correcting codes on real hardware

Supervisor:	Georgia Nixon
Co-supervisor:	Stephen Bartlett
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Quantum computers are highly susceptible to noise, which can invalidate the results of quantum algorithms. To address this, we use quantum error-correcting codes. These codes utilise large numbers of physical qubits to encode a smaller number of more stable logical qubits. One promising method involves encoding logical qubits to the system's topology, leveraging global properties that are more resistant to disruption. In this project, the student will design, develop and test error-correcting codes that are tailored to real-world devices. Specifically, the project will utilise real noise data obtained from state-of-the-art IBM cloud quantum devices to produce error-correcting codes that are specialised to quantum hardware. The student will learn about topological quantum error correction and develop numerical models to interrogate their performance on quantum devices. The project is numerically intensive and is suggested to students with some coding experience.

Generating states of light for error-robust quantum computation

Supervisor: Sahand Mahmoodian
Co-supervisor: Andrew Doherty
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A key roadblock in developing quantum technologies is decoherence which destroys fragile quantum states of information. Generating quantum states of light that are robust to these decoherence processes is an important milestone in quantum computation and communication. In this project you will work on developing protocols to generate photon states that are robust to decoherence processes. Such states of light require strong nonlinear interactions to be produced. You will model the nonlinear interaction between photons and atoms at the quantum level. The project work will involve a mix of numerical computational work and analytic pen-and-paper theory.

Quantum control of hybrid trapped ion systems

Supervisor: Christophe Valahu
Co-supervisor: Ting Rei Tan
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Quantum computers have mainly focused on using discrete variables – qubits – to perform computations. Recent proposals and experiments have shown that using additional continuous variables – bosonic modes – can dramatically enhance computational capabilities. Hybrid systems that use qubits and bosonic modes together can, for example, perform efficient simulations of chemical reactions, or create hardware-efficient error-correction codes. Trapped ions make an excellent platform for this hybrid architecture, as they contain qubits and bosonic modes with high coherences. The goal of this project is to come up with new quantum control protocols and algorithms targeted for a hybrid trapped-ion system. The project is theoretical, and will involve numerical simulations, optimizations, quantum control design and algorithm construction. The student will also work very closely with the experimental trapped ion team, such that the theoretical results can be incorporated in the lab.

Building next-generation superconducting quantum circuits

Supervisor: Dr. Xanthe Croot
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In this project you will work at the frontiers of superconducting qubit development, exploring the relatively new field of "protected" superconducting qubits to design, build and characterise novel qubits in a state-of-the-art cryogenic laboratory. Superconducting circuits are a mature technology used extensively in academic and industrial efforts to build quantum processors and simulators. In traditional superconducting qubits, there is a fundamental trade-off between minimizing different types of errors – one type of error is minimized at the expense of increasing another. Fortunately, the versatility of superconducting circuits gives us incredible flexibility to design and engineer new, multi-mode qubits that are intrinsically robust against error – these qubits are known as "protected" qubits. This project will involve (but is not limited to) (a) the design, simulation, fabrication and characterisation of new superconducting protected qubits, (b) device engineering to expand the parameter space of traditional superconducting circuit elements to improve access to the "protected" regime, and (c) developing scalable protocols to couple and control protected qubits.

Harnessing the power of cQED in hybrid platforms for quantum computing

Supervisor: Dr. Xanthe Croot
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The long-range interactions superconducting circuits enable are powerful tools for scalable quantum architectures. Devices which integrate both semi- and superconducting technology allow us to harness the "best of both worlds" – the excellent coherence times of semiconductor qubits with the long-range interactions enabled by superconducting resonators. Without these interactions, entanglement between semiconducting qubits would be limited to very short length-scales and would make building a large-scale semiconductor quantum processor challenging.

In this project you will work on hybrid semi-superconducting devices, engineering qubit architectures where distant semiconducting qubits can be entangled on-demand via dispersive interactions with a superconducting resonator. An important aspect of this project will be developing a scalable approach, paving the way to all-to-all connectivity of registers of semiconducting qubits. The project will involve nanofabrication, device design and simulation, cryogenic measurement and characterization, as well as the development of materials technology.

On-chip Quantum Levitodynamics

Supervisor: Robert Wolf
Co-*supervisor:* Cyril Laplane
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The development and deployment of quantum technologies has become one of the paramount tasks for science in the 21st century. Quantum systems are characterized by their coherence. In order to preserve this coherence, the systems need to be extremely well isolated from their environment and cool down to extremely low temperatures. Levitated nanoparticles are exquisite mechanical oscillators with no mechanical clamping to the environment. As such, they are close-to-ideal quantum mesoscopic systems. They present a promising avenue to reach force sensitivities beyond current state-of-the-art sensors. These massive particles made of billions of atoms makes them particularly suited for studying macroscopic quantum physics and to probe the boundaries between quantum and classical physics. Thanks to active feedback on their motion, the levitated particle can be cooled down to its motional quantum ground state without the need of a cryostat. In this project you will engineer a novel integrated design of an on-chip hybrid optical (optical tweezer) and electrodynamic trap (Paul trap). This design will allow for exquisite control, robustness and scalability while ultimately allowing for the integration of future new components such as magnetic or mechanical actuators. The developed platform will be used to simultaneous cool down all the mechanical degrees of freedom to their motional quantum ground states and explore schemes to bring the particle into more complex quantum states from squeezed states to ultimately motional quantum superpositions. You will build a strong expertise in theoretical and experimental quantum physics, optomechanics and atomic physics in addition to developing a range of technical skills in optical design, nanofabrication, vacuum engineering, CAD modelling, physical simulation and programming.

Investigating materials for a quantum internet

Supervisor: John Bartholomew
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Background: Machines that capitalise on the quantum behaviour of light and matter have the potential to dramatically accelerate advances in science and technology. However, the development of powerful quantum machines is restricted because each machine is isolated: there is no quantum internet to connect them to one another. The quantum technology sector needs researchers like you to create the quantum internet and this project aims to develop materials and knowledge to take on that challenge.

Project: This project will focus on crystals embedded with the rare-earth ion erbium (an element that is essential to today's classical internet infrastructure). The project will develop experiments to test the quantum optical and spin properties of erbium ions and probe interactions at the atomic scale. You will work in the new Quantum Integration Laboratory housed in the Sydney Nanoscience Hub, and have the opportunity to interact with other quantum research groups from Australia and around the globe. You will gain experience in fields including experiment design, quantum light-matter interactions, cryogenic systems, and magnetic resonance.

Quantum integration of light and atomic spins in a crystal

Supervisor: John Bartholomew
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Background: A key challenge within quantum science and technology is to create strong interactions between light and atomic spins at the quantum level. Experiments targeting this goal have long been instrumental in developing our understanding of the quantum world. Today, these same experiments form the basis for quantum internet technology, which aims to link up quantum computers and create entanglement on a global scale. However, these are significant challenges that require researchers like you to help make important breakthroughs.

Project: This project will focus on designing and fabricating optical cavities from crystals containing the element erbium. The project will develop microscale optical cavities that have very narrow resonances, and build up an experimental system to measure the cavities at room temperature and in a dilution refrigerator at <100 mK. These cavities can then be used to couple light to erbium atoms embedded within them. You will work in the new Quantum Integration Laboratory housed in the Sydney Nanoscience Hub, and have the opportunity to interact with other quantum research groups from Australia and around the globe. You will gain experience in fields including experiment design, crystal machining, optical fibres, quantum light-matter interactions, and cryogenic systems.

Trapped Ion Crystals and Large-Scale Entanglement

Supervisor: Robert Wolf
Co-supervisor: Ting Rei Tan
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Trapped atomic ions are a leading candidate system for experiments in quantum simulation and quantum-enhanced sensing. In quantum simulation, we attempt to realize a controllable quantum system capable of simulating more complex, uncontrolled quantum systems, e.g. for material discovery and design. Quantum-enhanced sensing can be used to perform ultra-sensitive force detection, as e.g. proposed for dark matter detection. This project will focus on the development of these types of experiments using large ion crystals in a Penning trap. This effort will build on successful experimental demonstrations of quantum control of hundreds of qubits and will leverage new insights into the manipulation and application of quantum systems. This project will be conducted within the new Sydney Nanoscience Hub. This project will incorporate experience in experimental atomic physics, charged-particle trapping, custom experimental system design, and electromagnetic simulation. Multiple projects are on offer within this heading.

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Renewable Energy and Sustainability

Making Green Ammonia from Water and Air: Nitrogen vacancy engineering for N_2 dissociation

Supervisor: Catherine Stampfl
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Owing to ammonia's significant contribution as a fertilizer and building block for the synthesis of various pharmaceutical products, it is recognized as one of the chemical mainstays of the modern world. As a fuel, ammonia has an energy density by volume that is twice that of liquid hydrogen and it is easy to transport. The predominant method for ammonia production has huge fossil-energy consumption and significant greenhouse gas emission. The urgency of replacing fossil fuels and mitigating the global climatic change motivates the global effort for the development of a sustainable energy system; crucial to this effort is the interconversion of small molecules such as CO_2 and N_2. The current big challenge in achieving a sustainable energy system is the lack of low-cost, highly active, efficient, selective and stable catalysts. It has been proposed that nitrogen vacancies on the surface of a nitride material, have the ability to bind and activate the N_2 molecule, weakening the strong N-N bond. The adsorbed N atoms are then able to react with hydrogen atoms that are generated through the dissociation of H_2 at metal clusters on the nitride surface and form ammonia. This project will use density-functional theory calculations on high performance computers to investigate the atomic scale dynamics of nitrogen dissociation at nitride surfaces. The new knowledge obtained will be valuable for the development of new catalysts with optimized chemical compositions and designed structures.

Quantifying dynamical processes by analyzing the response of driven physical systems.

Supervisor: Ben Fulcher
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Methods to understand the dynamical structure of time-varying systems are important for applications across science, from understanding communication patterns in brain to detecting animal species from microphones embedded in a forest. We have recently developed a range of useful methods for quantifying time-series structure by driving a physical system and analyzing its response. For example, we have found a class of physical systems that are sensitive to subtle changes in the waveform of speech from patients with Parkinson's Disease. In this project, the student could develop the theory and applications of this method, which is likely to yield powerful new methods for diverse scientific applications. The student should have an interest in numerical simulation, data science, and machine learning.

Plasma-electrochemical synthesis for a clean future

Supervisor: Prof. Marcela Bilek
Co-supervisor: Dr. Haihui Joy Jiang, Dr Kostadinos Tsoutas
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Synthetic nitrogen fertilizer produced by the Haber-Bosch process provides food security for half of the global population (4 billion people) today. However, this industrial process accounts for 1.4% of global CO_2 emissions, 1-2% of the world's total energy consumption, and nearly 40% of world's hydrogen fuels every year. Inspired by lightning strikes in nature, we uses electrical discharge to drive radical reactions at gas-liquid-solid interfaces. Our group designs green and scalable methods to electrify chemical synthesis and simplify synthetic routes that are otherwise energy intensive or pollutive. This project will focus on utilising plasma pathways for the synthesis of nitrogen fertilizers, fuels, and sanitation products from air and water, while examining the cross-coupling, aromatic functionalization, and olefin oxidation reactions.