Physics Honours Projects: 2023

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 15:00 on Monday 12th 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), 8th September 2022

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Grand Challenge Projects

Algorithmic Rules for Nanoscale Brain Navigation

Supervisor: Ben Fulcher
Co-supervisor: Shelley Wickham
Email contact: ben.fulcher@sydney.edu.au
Grand Challenge: Artificial Intelligence and Physics; Physics in Medicine & Biology; "Nanoscale Brain Navigation" Grand Challenge Grant

In the past several years, high-throughput neuroscience methods have yielded a comprehensive blueprint of the entire brain. These data have revealed strikingly low-dimensional spatial patterns in the brain's molecular patterning. In this project, the student will use numerical simulation to investigate how this gradient-like spatial structure can be exploited by nanoscale sensing rules to locate itself in an arbitrary location in the brain. The student will work with whole-brain neuroscience datasets, and use methods from statistical learning and physics to develop optimal sensing rules required for accurate and efficient brain navigation. This project is part of the School of Physics Grand Challenge in Nanoscale Brain Navigation, and could pave the way for innovative new targeted treatments for brain diseases.

Lightsail dynamics and Doppler damping

Supervisor: Boris Kuhlmey
Co-supervisor: Martijn de Sterke
Email contact: boris.kuhlmey@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe; "Starshot" Grand Challenge Grant

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 m2 and mass of 1 gram (including pay load) 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.

Astronomical and space science

Emission line diagnostics of star-forming regions from ultraviolet to optical

Supervisor: Madusha Gunawardhana
Co-supervisor: Scott Croom
Email contact: madusha.gunawardhana@sydney.edu.au

The project will focus on emission line diagnostics of star-forming regions from ultraviolet to optical. For this, we will use datasets drawn from various spectroscopic and multi-wavelength surveys (e.g. Sami, Hector and MUSE surveys), covering a large range of stellar metallicities, and compare the observations with stellar population and photoionisation models representing star-forming regions. The project aims to gain insights into the physical processes within these regions, which will allow us to understand their emission line spectra.

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

Supervisor: Scott Croom
Email contact: scott.croom@sydney.edu.au

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.

The Life and Time of Satellite Planes

Supervisor: Geraint Lewis
Email contact: geraint.lewis@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Strange planes of satellite galaxies orbiting large galaxies have presented a challenge to cosmology. In this project, we will explore the stability of these satellite planes by dynamically integrating orbits in the dark matter potentials of large galaxies. We will determine the impact of the shape and clumsiness of dark matter on the survivability of satellite planes and whether they represents a true challenge to cosmology. This is a computationally-based project, and familiarity with python would be an advantage.

Visualising the view from orbits in a Schwarzschild black hole

Supervisor: Geraint Lewis
Email contact: geraint.lewis@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

What do you see when you orbit a black hole? In this project, we will calculate the view from a spacecraft orbiting close to a black hole. This will require understanding the relativistic equations governing the orbit of the spacecraft and the paths of light rays, including the concept of observable in relativity. The goal will be to combine this to produce a physically realistic movie (that can be experienced in VR) of what you would see in such an orbit. This will require programming in python, so experience would be beneficial.

What happens to double white dwarf binaries after they merge?

Supervisor: Courtney Crawford
Co-supervisor: Tim Bedding
Email contact: courtney.crawford@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Millions of years after their birth, stars in binary systems sometimes become close enough to merge. For many stars, this merger process can be explosive, likely igniting into a brilliant supernova. However, for the lowest mass stellar remnants—for example two white dwarfs whose total mass is less than the Chandrasekhar limit—the merger process results in a new, exotic type of star with its own unique evolutionary path. For this project, you will model and study the evolution of such a post-merger star using the stellar evolution code Models for Experiments in Stellar Astrophysics (MESA). We will be investigating different masses of the progenitor white dwarfs and their effects on the post-merger star's evolution and surface abundances. Prior experience with any programming language will be helpful, but is not required.

Tracing the Effects of Dust Production in Multiple Wavelengths

Supervisor: Courtney Crawford
Co-supervisor: Tim Bedding
Email contact: courtney.crawford@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

It is very common for a star at the later stages of its life to begin producing dust. In the case of the exotic variable class known as R Coronae Borealis (RCB), this dust production is so extreme that it causes the star to dim up to 8 magnitudes, nearly a million times dimmer. We can trace the production of this dust using near-infrared wavelength observations, and track its effects on the visible brightness of the star. In this project, you will compare the near-infrared and optical light curves of these rare RCB variables and discern the effect of dust production on the star's brightness—for example learning whether an increase in the infrared brightness can foretell an optical dust decline or a change in the star's pulsation period.

Accretion in active galactic nuclei

Supervisor: Helen Johnston
Co-supervisor: Roberto Soria
Email contact: h.johnston@sydney.edu.au

Quasi-periodic eruptions (QPEs) are short duration flares seen in a few low-luminosity active galactic nuclei (AGN). These bursts are exceptionally sharp for an AGN, with a luminosity going up by an order of magnitude in an hour. Similar bursts have been observed in the intermediate-mass BH HLX-1. The problem is that the timescales are different: from few hours to a year (in HLX-1). Are the phenomena related, or do they arise from completely unrelated mechanisms in different sources?

The two main competing explanations are:

- an instability in the disk surrounding the AGN, or

- partial tidal disruption events of a white dwarf, that passes very close to the nuclear BH on an eccentric orbit, and loses an outer layer at each periastron passage.

Neither model completely explains the observations. The aim of this project would be to look for new patterns in the known sources, such as peak luminosity, duration of the flare, total fluence, interval between flares, as well as patterns in the types of galaxies in which these flares have been seen. You would then try see which model (if any) best fits the observations.

Automated identification of solar flares

Supervisor: Michael Wheatland
Co-supervisor: Tara Murphy
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Grand Challenge: Artificial Intelligence and Physics

Solar flares are explosive events on the Sun which affect our local space weather. Flares and associated coronal mass ejections (CMEs) create space weather storms which can damage satellites, disrupt power grids, and produce radiation hazards to humans in space, or on polar aircraft flights. This project will develop improved methods for identifying solar flares (and characterising their properties) based on automated processing of soft X-ray light curves from the Sun. Standard flare event-identification methods based on soft X-ray observations date to the early 1970s, and have not improved since then, despite generational advances in time series analysis, statistical methods, and the advent of machine learning. This project will attempt the state-of-the-art in event identification and characterisation.

Black holes in the distant Universe

Supervisor: Professor Elaine Sadler
Co-supervisor: Dr Elizabeth Mahony (CSIRO)
Email contact: elaine.sadler@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

In this project, you will use CSIRO's ASKAP radio telescope to study the synchrotron radiation arising from supermassive black holes in distant galaxies at a lookback time of 5 to 8 billion years, or about half the age of the Universe. Galaxies at this early cosmic epoch were more 'active' than those we see around us today, in the sense that star formation was more vigorous and relativistic radio jets emanating from black holes at the centres of these galaxies were both more common and more powerful. The reasons for this 'cosmic evolution' are still not well understood, and ASKAP observations of the 21cm spectral line of neutral hydrogen can provide new insights. Several different projects are possible depending on the interests of the student, and we would be happy to discuss these in person or by email.

GECKOS - Turning galaxy evolution on its side with deep observations of edge-on galaxies

Supervisor: Dr Jesse van de Sande
Co-supervisor: Prof Joss Bland-Hawthorn
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Grand Challenge: Fundamental laws & the Universe

How galaxies assemble their mass and angular momentum is one of the fundamental questions in Astronomy. In recent years we have gained enormous insights in how our Milky Way was formed. However, the Milky Way is only one galaxy, and to assume all galaxies follow the same formation path is perhaps naive. GECKOS is a brand new large survey that aims to better understand our own Milky Way Galaxy's unique evolutionary history by comparing it to its extragalactic cousins. GECKOS uses an instrument called MUSE on the Very Large Telescope that can take 90,000 spectra a single observation run. It allows us to build a three-dimensional map of the individual colours present in the captured light from the target galaxy. From this we can determine the chemical composition of its stars and gas, with the side-on viewpoint also giving them a chance to study vertical outflows of gas and detect faint signatures that were left behind by small galaxy mergers a long time ago. In this project you will learn to use spatially-resolved optical spectroscopic observations of galaxies from the GECKOS project to study their formation history in exquisite detail. We will explore the stellar archaeology, dynamics, and dark matter content of nearby Milky Way-like galaxies to place our own Galaxy in its proper cosmological context.

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.

Deciphering the assembly history of galaxies through their high-order stellar kinematic signatures

Supervisor: Dr Jesse van de Sande
Co-supervisor: Prof Scott Croom
Email contact: jesse.vandesande@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

There are many ways astronomers try to understand how galaxies have formed an evolved. Detailed dynamical studies of stars in present-day galaxies provide a fossil-record of their individual assembly history. Traditionally, only the stellar velocity and velocity dispersion measured from galaxy spectra have been used to trace the ordered and random motions of stars. Recently, our team has successfully employed a technique that uses the skewness and kurtosis in spectra to get a more precise picture of the orbital motions in galaxies. However, these measurements were done in the present-day Universe, whereas with a new survey called MAGPI we can now determine whether the high-order kinematic signatures evolve or whether the orbital structure was already set 4 Gyr ago. In this project you will work with state-of-the-art integral field spectroscopic data from the SAMI and MAGPI survey to reveal the true dynamical evolution of galaxies.

Asteroseismology: probing inside stars using stellar oscillations

Supervisor: Tim Bedding
Co-supervisor: Courtney Crawford
Email contact: tim.bedding@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Asteroseismology involves using the oscillation frequencies of a star to measure its internal properties. Measuring stellar oscillations is a beautiful physics experiment: a star is a gaseous sphere and will oscillate in many different modes when suitably excited. The frequencies of these oscillations depend on the sound speed inside the star, which in turn depends on density, temperature, gas motion and other properties of the stellar interior. This analysis, called asteroseismology, yields information such as composition, age, mixing and internal rotation that cannot be obtained in any other way and is analogous to the seismological study of the interior of the Earth. Many stars, including the Sun, are observed to oscillate. Asteroseismology is a new and rapidly developing field and there are several possible Honours projects, depending on the preference of the student. These include using observations from NASA's highly successful Kepler and TESS spacecraft, as well as theoretical modelling.

Electrical Design and Testing for a Satellite Tether

Supervisor: Xueliang Bai
Co-supervisor: Iver Cairns
Email contact: iver.cairns@sydney.edu.au
Grand Challenge: Physics & Society

A wire or “tether” deployed from a satellite in orbit around the Earth can be used to de-orbit the satellite: an EMF is induced along the tether, thereby driving a current and causing a Lorentz force with a component opposite to the satellite's velocity across the Earth's magnetic field lines to act on the tether and so the satellite. This project involves designing, building, and testing an electronics package to measure the current and voltage where the tether enters the satellite, to assess how to charge a battery or otherwise use this electrical energy, and how to electrically isolate the tether from the satellite. Other aspects such as the tether deployment mechanism could also be part of the project if desired.

Identifying galactic disks like our Milky Way

Supervisor: Professor Scott Croom
Co-supervisor: Dr Jesse van de Sande, Dr Nic Scott
Email contact: scott.croom@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Our galactic home, the Milky Way, is likely to be a relatively typical disk galaxy. A current hot topic in astrophysics is trying to identify Milky Way-like galaxies (or Milky Way analogues), to see how typical our galaxy really is. This can be done in a number of ways, such as comparing visual appearance, mass and colour. What is more challenging is to test whether these Milky Way analogues have similar dynamics (i.e. orbits of stars) compared to our galaxy. In this project we will use data for Milky Way analogues drawn from the Sydney led SAMI Galaxy Survey (http://sami-survey.org/). We will develop new methods to extract higher resolution dynamical measurements. This will allow us to reach the precision required to see whether the stars in these galaxies have motions typical of those seen in the Milky Way. Some coding experience, preferably in Python, would be valuable for this project, although not a requirement.

Interferometry with the JWST space telescope

Supervisor: Peter Tuthill
Co-supervisor: Anthony Soulain
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Grand Challenge: Fundamental laws & the Universe

When it launches in 2021, the James Webb Space Telescope will inherit the mantle of the Hubble Space Telescope as the pre-eminent astronomical observatory of the 21st century. With a primary mirror more than 6 meters in diameter, this mission will fly to the L2 Lagrangian point to begin a unique mission of discovery. Flying aboard is a unique interferometric imaging experiment designed, built and led from the University of Sydney. This aperture masking interferometer in the NIRISS instrument will empower the JWST to make the finest and most sensitive surveys for the presence of faint structures in the environment of forming stars that have ever been achieved. This opens an entirely new window on the origins of stars and planets, informing our own origins and place in the universe as well as expectations for the ubiquity and diversity of life in the Galaxy. Your role will be to bring this powerful new instrument to its first observations.

The TOLIMAN space telescope

Supervisor: Peter Tuthill
Email contact: peter.tuthill@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

he TOLIMAN space telescope is a Sydney University led initiative to detect and characterize Earth analog planets within the immediate solar neighborhood. Our mission will exploit astrometric detection - the registration of the minute deflection of the star's position as it is perturbed by gravitational reflex motion due to a rocky planet in orbit in a temperate orbit. The primary target is our nearest stellar neighbor: the Alpha Centuri system. The project forms a key stepping stone in the audacious Breakthrough Starshot initiative which aims to send humanity's first high speed robotic probe to interstellar space. The year 2021 will see the major components of the spacecraft designed and fabricated. Your role will be to participate in flight design, hardware and software for this audacious mission.

Imaging Newborn Exoplanets

Supervisor: Peter Tuthill
Co-supervisors: Barnaby Norris, Marc-Antoine Martinod
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Grand Challenge: Fundamental laws & the Universe

This project aims to separate the faint mote of light betraying a newborn planet from the powerful glare of its host star. Our group are world leaders in pioneering new technologies for this technically demanding field, recently delivering the first resolved images of exoplanets at birth. We have built innovative instruments now in operation at the world's largest telescopes including the Keck, Subaru, Large Binocular Telescope, Gemini and VLT. One particularly exciting new instrument is VAMPIRES at the Subaru telescope, which is now delivering unique polarized-light imaging of dusty disks and stellar halos and is able to discriminate faint structures against the (unpolarized) glare of the photosphere. Your role will be to work with hardware (for example at Mauna Kea in Hawaii) and data taken to witness the birth of new planetary systems.

Optical Fibre Bundles for Hyperspectral Coherent Imaging

Supervisor: Christopher Betters
Co-supervisor: Sergio Leon-Saval
Email contact: christopher.betters@sydney.edu.au

Multi-spectral imaging (e.g. images with several colours instead of just red, green blue) sensors are used in remote sensing /earth observation to extract valuable information in a variety of fields including agriculture, geology, and coastal and marine sciences. These may be deployed in the laboratory, on vehicles and UAVs or even in satellites. In the ARC Training Centre for CubeSats UAVs and their Applications (CUAVA) we want to build these devices as small as possible, specifically for small UAVs and CubeSats. In this project, you will help design and build a novel multi-spectral imager that uses multiple coherent optical fibre bundles to allow a single detector to take an image in various colours simultaneously. This could include optical-design, mechanical CAD, handling real optics to build the device and eventually testing in the lab and time permitting on a small UAV.

Plasma depletion layers throughout our solar system and beyond

Supervisor: Iver Cairns
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Grand Challenge: Fundamental laws & the Universe

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
Email contact: iver.cairns@sydney.edu.au

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.

Black Holes, Polarization and Microlensing

Supervisor: Geraint F. Lewis
Email contact: geraint.lewis@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

The presence of stars and black holes along the light-of-sight to distant sources can produce a magnification through gravitational lensing. In this project, will explore this for polarized emission from the inner regions of quasars, some of the most luminous objects in the universe. By determining the complex magnification patterns, we will determine the impact on polarization by decomposing the source into its Stokes vectors, reconstructing the observed polarization as a source is micrlolensed. Given the highly non-linear nature of the problem, this project will be based on numerical programming, so familiarity with programming is desirable.

THE UNIVERSITY OF SYDNEY

Biological, biomedical and medical physics

A Neurophotonic Platform as Universal Nerve Interface - II

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Dr Anai Gonzalez-Cordero, Dr Cathal O'Connell
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Grand Challenge:	Artificial Intelligence and Physics,Physics in Medicine & Biology

We have assembled a team of experts whose combined expertise is essential to develop a universal neural interface (UNI). It is well known that genetically modified photoactive neurons can be differentiated from pluripotent embryonic stem cells (ESC). In this project we will progress this further. Furthermore, we will tackle and solve challenges which will lead to develop a micropatterning technique to bond the photoactive neurons onto a biocompatible film. We will replicate a method, based on photolithography, already published in the literature. We will advance this further, since we need to fabricate the film on our photonic chips and characterise it. We will also test it with photoactive neurons generated at the CMRI. You will collaborate with the Team at the CMRI who prepares the neurons, and the team at the RMIT School of Engineering, who will help with the biomolecules. It involves photonics and fabrication.

This project could be the precursor of a novel neuromorphic platform as well as a universal neural interface which could solve the majority of disabilities.

Navigating the brain along its spatial gradients using DNA nanorobots

Supervisor:	Shelley Wickham
Co-supervisor:	Ben Fulcher
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Grand Challenge:	Physics in Medicine & Biology

Recent high-throughput neuroscience methods have revealed spatial patterns in the brain's molecular structure. In this project, we will use a combination experiment and theory to build a nanoscale machine that is able to navigate to an arbitrary location in the brain using stored information of these patterns. The student will work with DNA to construct programmable molecular logic gates that perform sophisticated information processing. These molecular DNA circuits will be designed to compare local chemical gradients to stored threshold values, which represent a molecular ‘postcode’ of the destination address. By combining multiple gradient inputs into a consensus output, the nanorobot will be able to determine its location in the brain. UV lithography surface patterning will be used to build a ‘brain-map-on-a-chip’, which will serve as a controlled in vitro ‘maze’ in which to train and test these nanorobots experimentally. This work could ultimately lead to targeted drug delivery to specific parts of the brain.

Complex systems

Modelling brain clearance during sleep

Supervisor: Svetlana Postnova
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Grand Challenge: Physics in Medicine & Biology

Sleep is crucial for clearance of toxic neuro-metabolites from the brain. This process is driven by a brain-wide fluid transport system that moves waste products out of the brain. Poor clearance, e.g., due to disturbed sleep, is associated with cognitive decline and neurodegenerative disorders. In this project we will use biophysical modelling to understand how brain clearance of metabolites with different production and degradation rates depend on sleep-wake patterns. If successful, this new knowledge will contribute to new models and algorithms for prediction and analysis of brain clearance which, ultimately, aim to reduce the health burden of cognitive and sleep disturbances in society. This project will suit those who are familiar with numerical techniques in Matlab/Python or similar.

Biophysical modelling for personalised predictions and interventions to improve alertness and sleep.

Supervisor: Svetlana Postnova
Email contact: svetlana.postnova@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

Important next frontiers in modelling the brain are (i) predictions of an individual's future dynamics and (ii) estimation of an individual's parameters that can't be measured empirically. One application of such individualised brain modelling is in sleep and cognition fields, e.g., to evaluate an individual's sleepiness and their risk of developing a disease like Alzheimer's. In this project we will use quantitative modelling, machine learning, and large experimental datasets to develop and validate algorithms for personalised prediction of future sleep patterns and cognitive outputs. This project is expected to contribute to understanding mechanisms of individual variability and development of real-world tools for monitoring brain states and prevention of disease. This project will suit those who are familiar with numerical techniques in Matlab or similar.

The physics of deep learning in artificial intelligence

Supervisor: A/Prof. Pulin Gong
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Grand Challenge: Artificial Intelligence and Physics,Physics in Medicine & Biology

Deep learning networks widely used in artificial intelligence can be trained to effectively solve many real-world problems such as speech recognition, object detection, and drug discovery. However, our understanding of why they are so effective is lacking. Recently, we have found that rather than being a normal diffusion process (i.e., Brownian motion) as conventionally assumed, learning processes in deep learning networks exhibit complex diffusion dynamics [Chen and Gong, Neural Networks 2022]. Such complex dynamics possess intermittent big jumps that prevent the learning process from being trapped in local minima, thus enabling it to reach good solutions. This finding offers a novel explanation of the effectiveness of deep learning networks. This project will involve further investigations of the physical mechanism underlying the complex learning dynamics. Particularly, the project will involve studying how fractal, self-similar geometry structures of loss function landscapes of deep learning networks interact with gradient descent to give rise to the complex learning dynamics. For this project, students will have the opportunity to learn essential models and algorithms used in artificial intelligence.

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

Supervisor:	Pulin Gong
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Grand Challenge:	Artificial Intelligence and Physics,Physics in Medicine & Biology

One of the most fundamental problems about the brain is how it computes. To answer this question, we have developed a concept of distributed dynamical computation (DDC), in which neural computation or information processing is carried out by interactions of propagating wave packets. DDC can merge dynamical and computational perspectives of the brain, which used to have great gaps between each other. Recently, we have demonstrated that in DDC, wave packets can efficiently implement sampling-based probabilistic computations [Qi and Gong, Nature Communications 2022; Chen and Gong, Science Advances 2022]. The project will involve making further links between neural dynamics and computations, including studying the neural circuit models developed by our group to reveal the physical principles of key brain functions such as visual processing and attention.

Googling the brain: Search of associative memory

Supervisor:	A/Prof. Pulin Gong
Email contact:	pulin.gong@sydney.edu.au
Grand Challenge:	Artificial Intelligence and Physics,Physics in Medicine & Biology

Human memory has a vast capacity, storing all the knowledge, facts and experiences that people accrue over a lifetime. Given this huge repository of data, retrieving any one piece of information from memory is a challenging computational task. In fact, it is the same problem faced internet search engines that need to efficiently organize information to facilitate retrieval of those items relevant to a query. It is therefore of fundamental and practical importance to understand dynamical mechanisms underlying memory searching in the brain. Very recently, we have developed a biologically plausible neural circuit model, which can quantitatively reproduce salient features of memory retrieval. This project will involve further developing the model based on latest experimental results to unravel principled dynamics of memory searching. These dynamics will then be used to develop a novel searching algorithm applicable to the huge repository of data as used by the Google search engine.

Inferring a computational logic of scientific time-series analysis algorithms

Supervisor:	Ben Fulcher
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Grand Challenge:	Artificial Intelligence and Physics

Time-varying systems are all around us, and scientists love to measure and understand them: from the oscillations in our heart, spiking of neurons in our brains, and the complex pulsing of distant astrophysical objects. Methods to understand the structure of the dynamics produced by these systems have wide-ranging consequences for science (e.g., understanding communication patterns in brain) and in diverse industries (e.g., detecting faults on a production line). We have recently developed a library containing thousands of time-series analysis methods, which holds the key to developing a concise interdisciplinary toolkit for understanding real-world dynamics. In this project, students will infer the computational logic of this library by applying it to a diverse range of simulated systems, including linear stochastic and nonlinear chaotic physical systems. This will allow us to deduce the empirical structure of a literature encapsulating decades of human creativity in a way that could be pioneering for the automated analysis of dynamical systems. The student should have an interest in numerical simulation, data science, and machine learning.

What makes a community on a social network?

Supervisor: Tristram Alexander
Co-supervisor: Prof. Eduardo Altmann (Mathematics)
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Grand Challenge: Physics and Society

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'.

Network models of language dynamics

Supervisor: Tristram Alexander
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Grand Challenge: Physics and Society

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.

Complex systems; Data science

Brain vortices: new pathways to understanding brain dynamics

Supervisor:	A/Prof Pulin Gong
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Grand Challenge:	Artificial Intelligence and Physics,Physics in Medicine & Biology

Cortical neural circuits are complex, non-equilibrium systems whose collective dynamics cannot be described solely in terms of oscillations or low-dimensional aperiodic (chaotic) dynamics. Recently, we have developed a method that enables us to make new discoveries regarding the physical principles of neural circuits; for instance, we have found dynamic coherent patterns such as vortices that organize spatiotemporal dynamics of cortical circuits. This new finding therefore makes brain dynamics analogous to that observed in turbulence fluids, in which a hierarchy of vortices are similarly embedded in stochastic spatiotemporal processes. This project will involve further developing this new method, analysing neural data collected by our collaborators at Imperial College London and Fudan University, and modelling brain vortices by extending the neural circuit models developed by our group. The results of this project would significantly advance our understanding of the physical principles of brain dynamics. For this project, students will have the opportunity to learn essential skills for big data analysis and modelling

Detecting misinformation on a social network

Supervisor:	Tristram Alexander
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Grand Challenge:	Physics & Society

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

Condensed matter physics; Materials physics

Thermodynamic properties of atomic defects for quantum technologies

Supervisor: Carla Verdi
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Grand Challenge: The Nano and Quantum world

Atomic defects in solids are one of the most promising single-photon sources for quantum technologies. In order to design and engineer better quantum emitters, a fundamental understanding of their optical and electronic properties, as well as defect formation and migration, is essential. In this project, first-principles quantum mechanical calculations combined with machine-learning techniques are used to provide a detailed understanding of key properties such as defect dynamics, formation mechanisms, free energies and stabilities at room and elevated temperatures. The computational tools and theoretical insights developed in the project aim to inform 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, in particular first-principles methods and machine-learned potentials.

Direct Epitaxy of All Inorganic Halide Perovskites for X-ray Detectors

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Co-supervisor: Feng Li
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Grand Challenge: The Nano and Quantum world; A Sustainable Future

X-ray detectors are widely used in medical diagnostics and therapy, safety screen and inspection, and scientific equipment. Halide perovskites are the potential game changer due to their (i) strong X-ray attenuation, (ii) exceptional optoelectronic properties, and (iii) low-cost raw materials and crystal growth. The commercialisation is currently hindered by three challenges: (i) large dark current, (ii) integration with read-out circuitry, and (iii) poor stability. This project aims to solve all the main challenges simultaneously by direct epitaxial growth of allinorganic halide perovskite single crystal films on read-out circuitry. The outcomes from this project could lead to the replacement of existing X-ray detection technologies.

Plasma treatment of substrates with complex geometry

Supervisor: Marcela Bilek
Co-supervisor: Clara Tran
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Grand Challenge: Physics in Medicine & Biology

Surface treatment of cell culture plates using plasma to enable covalent binding of biomolecules onto the plate surface significantly improves the performance of biological assays. The plasma treatment can take the form of either ion bombardment to activate the surfaces of culture plates or thin film deposition to form optically transparent coatings on the surfaces. Commercial culture plates vary in the number of wells, ranging from 6 wells up to 384 wells, and the well size varies accordingly. When the well size increases, plasma dust, an undesirable result of the plasma process, forms aggregates and settles on the inside of the wells during the treatment. These aggregates do not only adversely influence the optical properties of the wells, but they may also detach from the well plate and interfere with the biological assays. This project aims at understanding the formation of plasma dust and parameters that can be used to minimize/eliminate aggregates to obtain strong and uniform coatings for different cell culture plates, which would pave the way for the commercialization of plasma-treated cell culture plates. Students will have access to our new plasma labs in the J03 Engineering and Technology Precinct and learn to use both plasma deposition and surface characterization equipment

Creating nano-scale surface roughness using plasma-enhanced chemical vapour deposition

Supervisor: Marcela Bilek
Co-supervisor: Clara Tran
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Grand Challenge: Physics in Medicine & Biology

Surface topography plays in important role in cell-surface interactions including cell adhesion, cell growth and signalling. Plasma-enhanced chemical vapour deposition (PECVD) has been demonstrated to create radical-rich surfaces and thin films. Nano-scale roughness can be induced through the deposition of aggregates created in the plasma into the growing film or through removal of material by sputter etching. This project will investigate different strategies/parameters to control the surface topography of materials including plasma etching and plasma deposition. Students will have the opportunity to experiment with plasma treatment processes and will be trained in surface characterization techniques such as secondary electron microscope (SEM), tensiometry, spectroscopic ellipsometry and atomic force microscopy (AFM).

Developing new methods to characterise ultra-thin hydrogel layers on solid-hydrogel hybrid materials for biomedical applications

Supervisor: Marcela Bilek
Co-supervisor: Aaron Gilmour, Clara Tran
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Grand Challenge: Physics in Medicine & Biology

The Bilek group has developed methods to form covalently bound, ultra-thin hydrogel layers on the surface of organic and inorganic solid materials through the use of Plasma Immersion Ion Implantation (Piii) and Plasma Activated Coatings (PAC).

The use of hydrogels to alter the interfacial stiffness of biomaterials for implants and in vitro cell culture applications is of significant interest to improve performance and reduce implant rejection. However, the classical methods for characterising the mechanical properties (stiffness and elasticity) of free-standing hydrogels are inadequate for ultra-thin (< 100μm) surface bound hydrogels layers.

The focus of this project is to develop new or modify existing methods to evaluate these ultra-thin surface bound hydrogel layers. This will enable us to not only better understand the materials we are creating but to tune the hydrogel properties to optimise it for a range of biomedical applications. In this project you will learn the following techniques: Plasma deposition and characterisation of resultant materials, including tensiometer, ellipsometry, mechanical testing with an Instron and AFM.

Flexible optoelectronic devices based on halide perovskites

Supervisor: Feng Li
Co-supervisor: Rongkun Zheng
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Grand Challenge: The Nano and Quantum world

Intrinsically large absorption coefficient and high carrier mobility endow halide perovskites with great potential for high-performance optoelectronic devices. More interestingly, recent researches have also demonstrated the high stability nature of halide perovskite devices after the extended bending, holding significant promise for the high-performance flexible devices and the wearable applications. The Project will focus on the realization of flexible optoelectronic devices via using halide perovskites. Specifically, the device interface's influence on device performance will also be investigated in detail.

Plasmas for capturing carbon dioxide from air in spacecraft and space missions

Supervisor:	Professor David R McKenzie
Co-supervisor:	Dr Georgio Katsifis, Professor Cathy Stampfl
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Grand Challenge:	The Nano and Quantum world,A Sustainable Future

This project will use plasmas to create reactive species in a gas to form aggregates and ultimately solid materials. In this project, we will use plasmas to form useful solids from gases containing hydrocarbon and carbon dioxide precursors. Analytical techniques and diffraction methods will be used to investigate the nature of the solid phases created. Density functional theory will be used to model the structure of the supramolecular aggregates formed in gas phase collisions. The application we envisage is the cleansing of captive atmospheres in space missions.

Nanoscience

Upconverting nanoparticle in DNA-linked plasmonic dimer for biosensing

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Dr Hien Duong
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Grand Challenge:	The Nano and Quantum world

In this project we want to engineer and study a plasmonic dimer, constituted by a gold nanorod coated with a thin glass film, an upconverting nanoparticle, a DNA link bonded to a gold nanopshere. In this way the upconverting nanoparticle (UPN) is sandwiched in the middle between a nanorod and a nanoparticles. In this conditions the nanoparticle should be quenched by the gold nanosphere. Only when this system interacts with a specific molecule of interest, then one of the DNA links is broken and the upconverting nanoparticle will fluoresce. The gold nanorod serve as an enhancer of the fluorescence signal. This can be used as background free biosensing method. We have already prepared the UPNs and tested their emission. We are currently attaching them to Au nanorods to probe the enhanced luminescence. This project could also have applications in organic solar cell enhancement as well as a potential new method for LED TVs.

Optical nose: a revolution in mobile sensing

Supervisor:	A/Prof Stefano Palomba
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Grand Challenge:	The Nano and Quantum world

The Holy Grail in molecular sensing, is the capability to detect and identify any individual molecule in a mixture, like pollutants in air (CO2, CH4) or water (hydrocarbons, nitrides), biomarkers for diseases in body fluids (DNA, exosomes), very small pathogens in air/breath (coronaviruses, influenza). This project aims to develop an integrated plasmonic (metal) slot waveguide to act as a molecular sensor. You will optically characterise the structure and help with the fabrication. These measurements aim also to confirm a theoretical paper we published in the past. You will also probe gas molecules by the working and optimised chip. This project can be the precursor of a revolutionary on-chip platform for developing a molecular sensor, i.e. an optical nose.

Novel nanolasers: a brighter future for photonic integrated devices

Supervisor:	Stefano Palomba
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Grand Challenge:	The Nano and Quantum world

All the plasmonic nanolasers published in the literature since 2009, follows two specific configurations, i.e. metal-insulator-semiconductor-air (MISA) or metal-insulator-semiconductor-insulator-metal (MISIM). We realized that these configurations are not optimal. Based on our published work (DOI 10.1039/C8NR04898C) we realized that adding a high index material as insulator would allow a gain threshold increase of 45%. In this project, we want to proof that our novel platform can enhance Perovskite-

based plasmonic nanolasers performance. The project could remove the impasse that this field is bearing and potentially be fed into the market of integrated nanolasers. Currently we have been able to measure the fluorescence from these nanowires but not lasing yet.

Molecular Nanorobotics

Supervisor: Shelley Wickham
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Grand Challenge: Physics in Medicine & Biology

The biological polymer DNA can be used by physicists and material scientists as a molecular building block for self-assembling nanoscale structures and devices. In this project, the student will build molecular nanorobots, autonomous and programmable nanomachines self-assembled from DNA, to improve diagnosis of heart disease. The focus of this project is on using the experimental technique 'DNA origami', to build the nanorobot core. This core will need to be complex enough to bring together the many functions of the robot, and stable enough to survive the high flow environment of blood vessels. The student will work on experiments with DNA nanorobot assembly and testing in microfluidic devices that simulate blood flow, and perform fluid and DNA simulations. This work will lead to improved diagnosis of early-stage heart disease.

Heterostructuring hybrid perovskites for improving optoelectronic device performance

Supervisor: Feng Li
Co-supervisor: Rongkun Zheng
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Grand Challenge: The Nano and Quantum world

Hybrid perovskites are the fast-rising star in photovoltaic and other optoelectronic applications, because of their excellent merits including large light-absorption coefficients, adjustable bandgaps, and cost-effectiveness. It is well acknowledged that heterostructured systems offer an additional degree of freedom to tune the band alignments and control charge transport and recombination for more promising optoelectronic devices. This project aims to develop the rationally engineered halide perovskite-based heterostructures, targeting at enhancing the optoelectronic device performance and exploring the interesting physical behaviors that are otherwise inaccessible to single-perovskite systems.

Atomic-scale understanding of the degradation of halide perovskites

Supervisor: Rongkun Zheng
Co-supervisor: Feng Li
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Grand Challenge: The Nano and Quantum world; A Sustainable Future

High-efficiency and low-cost perovskite solar cells have achieved remarkable progress over the last few years, but there is still a lack in understanding of why and how they degrade over time. This project aims to understand the instability of halide perovskites by revealing the changes in microstructure and electronic structure at the atomic scale. The expected outcomes of this project will advance our knowledge of the instability of perovskite solar cells and provide critical guidance for future development and optimisation. This will then help the local and global energy sector transition to sustainable energy and so benefit both the economy and the environment.

In-situ STEM investigation of photocatalysis for water splitting

Supervisor:	Rongkun Zheng
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Grand Challenge:	The Nano and Quantum world; A Sustainable Future

Water splitting by means of photoelectrochemical cells, is regarded as the most economical way to acquire the clean and renewable fuels principally hydrogen. However, long-lasting issues such as low sunlight to hydrogen conversion rate, photocorrosion of the catalysts, inadequate knowledge of the photocatalytic mechanism and expensive noble metal decoration, restrict the development of efficient water splitting system for spontaneous hydrogen/oxygen reaction evolution. This project aims to clarify the fundamentals of these problematic issues via in-situ STEM investigation and the outcome will provide new conception and knowledge to address the long-lasting issues within the community in terms of instability and efficiency.

Particle physics

Quantum anomaly and the Hawking radiation of black holes

Supervisor:	Archil Kobakhidze
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Black holes in quantum theory radiate thermal radiation first discovered by Hawking. This radiation contains on average an equal number of particles and antiparticles, as the process does not distinguish between the two. In this project, we investigate how Hawking radiation is modified due to the phenomenon known as a quantum anomaly that segregates particles and antiparticles.

Casimir effect as a probe of new physics

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Grand Challenge:	Fundamental laws & the Universe

In this project, we compute a macroscopic force that originates from subtle quantum vacuum fluctuations in a theory with the Higgs mechanism. We analyse the feasibility to measure this force as a probe of new short-ranged forces that are not feasible to discover by means of high-energy experiments.

Studying rare B-meson decays at the Belle II experiment

Supervisor:	Kevin Varvell
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Grand Challenge:	Fundamental laws & the Universe

The Belle II experiment at the SuperKEKB electron-positron collider in Japan has so far accumulated data from over 400 million pairs of B-meson decays. Belle II primarily aims to study rare decays of B mesons in order to search for physics beyond the Standard Model of Particle Physics. A student doing this project will have the opportunity to collaborate with scientists from around the world working on Belle II, and examine real and simulated data from the experiment in order to help search for rare decays which include leptons and missing neutrinos amongst the decay products. Such decays can be sensitive probes of new physics. There is scope for projects for more than one student, and the work would be suitable both for standalone honours projects and for projects leading into subsequent PhD research.

Investigations of processes involving top quarks at the Large Hadron Collider

Supervisor:	Kevin Varvell
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Grand Challenge:	Fundamental laws & the Universe

The Large Hadron Collider is designed to produce exotic particles such as the Higgs boson, top quark, and W and Z bosons by colliding protons together, using gigantic detectors like ATLAS to examine the debris. The LHC has recently commenced its “Run 3” after an extended shutdown, and now collides protons at a centre-of-mass energy of 13.6 TeV. By comparing data collected by ATLAS to predictions made by the Standard Model, the model which describes all fundamental interactions of elementary particles, we can study a number of processes, for example those that produce multiple top quarks, and perform tests of the Standard Model. A student doing this project will have the opportunity to collaborate with scientists based at CERN and elsewhere, and will be involved in statistical analysis of LHC data. There is scope for projects for more than one student, and the work would be suitable both for standalone honours projects and for projects leading into subsequent PhD research.

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CYGNUS: a directional dark matter detector

Supervisor: Ciaran O'Hare
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Grand Challenge: Fundamental laws & the Universe

The quest for the mysterious dark matter that makes up most of the mass in the Universe has inspired some of the most sensitive physics experiments ever performed. These giant detectors are often located underground or inside of mountains and are some of the quietest places in the Universe. Nevertheless, dark matter has still not been detected. To assist in the global search for dark matter, the Australian particle physics community has endeavoured to construct the first underground lab in the southern hemisphere, to be located in a working gold mine in Stawell, Victoria. One of the flagship detectors to be situated at Stawell is one node of a planned network of experiments known as CYGNUS. The experimental principle behind CYGNUS sets it apart from all currently running experiments. CYGNUS aims to detect not just the incoming dark matter particles themselves, but also their directions. This enables far superior background rejection capabilities, as well as the potential to more precisely study the nature of dark matter and its behaviour in our galaxy. This project will be centred around finding the optimal running configurations of CYGNUS to detect and study dark matter. The work will involve a mixture of theoretical particle physics calculations, statistical analyses, as well as detector simulations.

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

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

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

A Neurophotonic Platform as Universal Nerve Interface - I

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Co-supervisor:	Dr Anai Gonzalez-Cordero
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Grand Challenge:	Artificial Intelligence and Physics,Physics in Medicine & Biology

We have assembled a team of experts whose combined expertise is essential to develop a universal neural interface (UNI). It is well known that genetically modified photoactive neurons can be differentiated from pluripotent embryonic stem cells (ESC). In this project we will progress this further. Furthermore, we will tackle and solve challenges which will lead to developing an integrated photonic device, constituted by a light guide and a grating to couple light in/out of it, embedded inside a polymeric film; this will serve as a light source/collector for the photoactive neuron. In this project we need to experimentally prove that the chip can send/collect light to/from the photoactive neurons. you will collaborate with the Team at the CMRI who prepares the neurons, and develop the process to perform the measurement. This project could be the precursor of a novel neuromorphic platform as well as a universal neural interface which could solve the majority of disabilities.

Photonics to the Rescue! A novel sensor for greenhouse gases

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Co-supervisor:	Peter Tuthill, Sergio Leon-Saval
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Grand Challenge:	A Sustainable Future

Methane is the second most important greenhouse gas with a per-molecule about 80 times more potent than CO2. Making a real impact with methane is much more tractable than CO2 which is an unavoidable byproduct from fossil fuel energy production. However enforcing limits on Methane release is problematic: effective wide-area remote surveillance is not technically feasible. In this project you will lead the development of a major innovation in optical sensing that targets Methane gas. Our group has recently patented world-leading photonic technology that employs bespoke Fibre Bragg Gratings to sense any gas with projected levels of sensitivity well beyond any existing competing technology. Your task will be to build this University of Sydney photonic innovation into a working instrument to be tested both in the lab and in the field with deployment and flight in unmanned aerial vehicles.

Thermal management, passive cooling and atmospheric water capture by nanostructuring

Supervisor:	Martijn de Sterke
Co-supervisor:	Alex Song (electrical engineering)
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Grand Challenge:	A Sustainable Future

It has been shown in the last decade that the thermal properties of objects can be manipulated by nanostructuring, which allows the design of the wavelength-dependent reflection, transmission and absorption of thermal radiation. In this way it is possible to create materials that spontaneously cool by radiating heat into space, and textiles that keep you cool in summer. However, the detailed design of such materials is challenging and requires a combination of rigorous numerical techniques, deep understanding and experiments. We are offering several projects in this general area. Some of these will be carried out in collaboration with a recent start-up company in this area that aims to use the spontaneous cooling to capture humidity from the atmosphere.

New families of solitons—meet the relatives

Supervisor: Martijn de Sterke
Co-supervisor: Antoine Runge
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Optical solitons are stable light pulses that are unchanged upon propagation by balancing nonlinear effects (refractive index depends on intensity) and dispersion (refractive index depends on wavelength). They are intriguing in their own right and have applications as wide as medical diagnostics and telecommunications. We have recently predicted and discovered entirely new classes of solitons in a laser in which the dispersion can be programmed in at will over a wide wavelength range. One such class requires modest optical power thus bringing novel applications a step closer. Others are of fundamental importance and exemplify key physical concepts. We have a number of projects available in this general area that can be theory, numerics, experiments, or a combination of these.

Black and white holes in an optical fibre

Supervisor: Martijn de Sterke
Co-supervisor: Dawn Tan (Singapore University of Technology and Design)
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Grand Challenge: Fundamental laws & the Universe

A black hole is a region of space from which no waves can escape; similarly, a white hole is a region which waves cannot enter. Although best known in the context of general relativity, the phenomenon is more general and can be observed elsewhere. In optical fibres, for example, light pulses can interact with each other via the nonlinear response of the glass. Combined with the dispersion of the glass, which describes the frequency-dependence of the refractive index, this leads to phenomena that are similar to black and white holes. We are collaborating on this with an experimental group in Singapore. They are interested not only in the underlying physics, but also at the novel opportunities this provides to manipulate light pulses. This is a theoretical and numerical project that will be carried out collaboratively with the colleagues in Singapore. In the first instance we require a simple theory to provide back-of-the-envelope estimates for the key parameters, which can be tested against rigorous numerical simulations. This will be followed by thorough simulations to understand and optimise experimental conditions.

High-energy solitons in microresonators

Supervisor: Dr Antoine Runge
Co-supervisor: Prof. Martijn de Sterke
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Grand Challenge: A Sustainable Future

Optical frequency combs, also known as rulers of light, are light sources with spectra consisting of perfectly equidistant, ultra-narrow laser lines. This technology, for which its pioneers received the Nobel prize in 2005, revolutionized fundamental science by allowing frequency measurements with unprecedented precision, enabling applications in communications, medical spectroscopy, and astronomy. These frequency combs can now be generated in photonic resonators smaller than a fingertip. Such “microcombs” rely on the generation of special type of solitons, which provide high stability and coherence. However, these solitons, and therefore the microcombs are limited to low energy. A recent discovery in the School of Physics has shown that pure-quartic solitons a novel type of soliton, can carry a much higher energy, which would be greatly beneficial for microcombs. The aim of this project is to design a micro-resonator that supports the generation of these solitons and to study their properties using a combination of analytical and numerical techniques. Following the fabrication of the designed microresonator by our collaborators in Melbourne, generation and characterization of the novel microcomb could be performed at the University of Sydney.

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Pattern formation in high dimensional systems

Supervisor: Tristram Alexander
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Grand Challenge: Fundamental laws & the Universe

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.

Photonics processor in Silicon

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Dr. Alvaro Casas Bedoya
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Microelectronics technology has transformed the way human being communicate, exchange information and process data in real life, enabling key units such as integrated processors that empower mobile phones, tablets, autonomous vehicles and even air/space crafts. To radically handle the explosively-increasing requirements of upload/download network speeds, big data processing and connections with data clouds, integrated photonics processor have been conceived as the revolutionary technology for the next generation of information and communication technologies. In this project, you will reach out to the cutting-edge integrated photonic chips which incorporate optical encoder, interconnect optical link, optical nano-wires and optical decoders in centre-meter-square footprint, similar sizes as finger nails. You will study how lights are guided, transmitted, processed and detected in nano-scale, and program the way how the photonic processor functions for high-performance signal processing and neural network simulations.

Vibrations in silicon at MIR

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Dr. Alvaro Casas Bedoya
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Strong optical beams can literally shake the material at the nanoscale. These vibrations result in hypersound waves – phonons – which can be harnessed for several exotic applications on a photonic integrated circuit (IC). Silicon is the most widely used electronic platform and was the basis of the electronics revolution of the 20th century. A multi-trillion dollar industry is based on this material and we are moving towards the next revolution: a photonic-phononic revolution! In this project, we will explore the development of optical and phononic circuits in silicon at Mid-Infrared (MIR) wavelengths. The MIR wavelengths are exciting since they allow efficient photonic-phononic interactions in silicon and are also of interest for sensing applications. In this project there will be opportunities to model, design, characterize, and fabricate photonic-phononic circuits. The state-of-the-art cleanrooms at the Sydney Nano Institute will allow the student to fabricate their own devices and test them in our photonics labs. At the end of the project, the first-ever MIR circuit with both photonic and phononic components will be demonstrated. This will be a crucial step towards the long-term vision of integrating photonic-phononic circuits with electronics on a single chip. This project is suitable for 2 students.

Storing light as hypersound on a photonic chip

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Moritz Merklein
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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 can we 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.

Interplay of light and hypersound at 1Kelvin?

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Dr. Moritz Merklein
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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 cryogenic temperatures. This project will study experimentally Brillouin scattering at low temperatures. You will build your own setup using state-of-the-art test and measurement equipment. The fiber will 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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Co-supervisor:	A./Prof. Joe Khachan
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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

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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.

Quantum physics and quantum information

Optimising trapped-ion experiments through machine learning

Supervisor: Robert Wolf
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Grand Challenge: Artificial Intelligence and Physics,Fundamental laws & the Universe,The Nano and Quantum world

Ion traps have established themselves as a leading platform for quantum computing, simulation, and sensing. Furthermore, they are key instruments for high-precision measurements in fundamental physics, for example for the test of quantum electrodynamics, test of matter-antimatter symmetry, and as ultra-high precision clocks. At the Quantum Control Laboratory we are operating different types of ion traps for quantum science. To advance measurement performance by increasing precision and sensitivity the technical complexity of these instruments increases continuously. However, tuning these experimental systems manually is often inefficient and tedious and should be automated. This project will focus on developing and implementing machine-learning-based online optimisers at our Penning ion trap for quantum simulation and sensing. The overall aim is to enhance experimental capabilities by using the existing resources most efficiently. This project is targeted at a student with a strong motivation for machine learning and experimental control systems development. The student's programming experience in python is recommended but not essential. The student will have the possibility to collaborate with other ion trap experiments for fundamental physics research, e.g., at CERN, and implement the developments in a subsequent PhD project.

Trapped Ion Crystals and Large-Scale Entanglement

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Grand Challenge: The Nano and Quantum world

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.

Fermion condensing defects in the surface code

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Grand Challenge: The Nano and Quantum world

Quantum spin lattice models for topological quantum field theories and their boundaries form the basis of the popular surface code approach to quantum error correction, which is currently being pursued by leading industry groups including Google, AWS and IBM. Adding physical fermions to the surface code allows for new boundaries and defects where fermionic anyons can be locally created and condensed. These defects have applications in experimental realizations of the surface code that involve physical fermions.

Fault-tolerant measurement-based quantum computation by shuffling Rydberg atoms

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Grand Challenge: The Nano and Quantum world

Remarkably, universal fault-tolerant quantum computation can be achieved by making single spin measurements on an entangled quantum many-body state. Rydberg atoms have recently jumped to the forefront of quantum simulation, with new techniques allowing for the creation of entangled states of many particles. Here we aim to take advantage of experimentally feasible operations on Rydberg atoms to lay out a theoretical roadmap for the implementation of a fault-tolerant measurement-based Rydberg quantum computer.

A Wannier function-based approach to topological quantum error correction

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Grand Challenge: The Nano and Quantum world

A crucial step in building a quantum computer is to store information in a quantum system in such a way that the errors caused by the system's interactions with its environment can be corrected. Thus, designing experimentally feasible protocols for correcting such errors is a grand challenge in the field of quantum computation. A class of exotic systems known as “topological systems” have emerged as the leading candidates for realizing error-corrected quantum memories. This project will focus on developing error correction protocols for previously unexplored parameter regimes of an experimentally feasible topological system known as “Kitaev's honeycomb model”. A combination of analytical and numerical tools from the theory of Wannier functions in condensed matter physics as well as quantum information theory will be used for the development of these protocols. Apart from guiding future experiments for implementation of these protocols, this project will provide pathways to answering fundamental questions about the physics of topological systems.

Building better qubits

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Grand Challenge: The Nano and Quantum world

Quantum computers are hard to make; performing a quantum computation requires very precise control over many fragile quantum systems. However, finding a system that is easy to control but resilient to noise has proven to be tricky. One of the most successful systems for quantum computation has been in superconductors; both Google and IBM are in a race to build quantum computers out of superconducting qubits.

In recent years, proposals have emerged for “next-gen” superconducting qubits, which promise to be much more resilient to noise than current devices. Since nothing comes for free, these qubits are going to be much more challenging for experimentalists to engineer. Since such qubits are more highly protected from noise they are also typically more difficult to control.

Our goal for this research project is to determine if the extra effort is worth it. The challenge is to simulate logical operations on next-gen qubits with realistic models for the experimental noise. This will allow us to understand when such protected qubits work better than the existing approaches.

This project is theoretical in nature, but exists at the interface between theoretical analysis and experimental device physics. It will involve numerical simulation of proposed qubits as well as analytical calculations.

Quantum computing with continuous variables: Exploring new codes via continuous symmetries

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Grand Challenge: The Nano and Quantum world

Full-fledged quantum computers could efficiently run algorithms tackling tasks that are considered out of the reach of current classical machines, including supercomputers. Quantum computers, at some level, will run on “qubits”, a very delicate building block. A large part of quantum computing research is dedicated to overcoming this inherent fragility using error-correcting schemes. Different architectures rely on different physics and are affected by different types of errors. In this project, we will be exploring error correction with “bosonic codes”, whose underlying state space is much richer than products of 2-level systems. There is a large “zoo” of qubit codes, whereas bosonic codes are a rather unexplored field (https://errorcorrectionzoo.org/). A bosonic code mimics a qubit while at the same time introducing a layer of error correction. It has become increasingly clear that a bosonic code can be characterised in terms of continuous symmetry transformations acting upon its codewords, but this realisation has yet to be used to either generate new bosonic codes or give categorizations of the current ones that point to the existence of new classes. Do there exist more bosonic codes, or did we in some sense exhaust all the possible useful representatives thereof? We will use the correspondence between continuous symmetry groups and continuous-variable error-correcting codes to formalise this question as well as work towards an answer. Finally, we will use what we learned to present and benchmark the new bosonic codes we have constructed.

A classical model for quantum computing

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Grand Challenge: The Nano and Quantum world

What gives quantum computers their power? We don't know, but non-classical aspects of quantum physics such as superposition, entanglement, Bell nonlocality, and contextuality suggest possible answers to this question. In this project, we will investigate a recent “hidden variable” model that, on the one hand, appears to be entirely classical but, on the other hand, provides a way of modelling any quantum computing circuit. The classical state space is extraordinarily large, which might explain its apparent power. We will use methods from linear algebra and convex optimization to characterise the classical state space of this model, and to understand how this “classical” model is able to describe uniquely quantum effects.

Spin-qubit quantum computing

Supervisor: Stephen Bartlett
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Grand Challenge: The Nano and Quantum world

Electron spins trapped in semiconductor quantum dots make for very good qubits - the building blocks for quantum computers. Spin qubits have been shown to possess long coherence times, high-fidelity 1- and 2-qubit quantum logic gates and high fidelity readout. This project will investigate how to best design quantum architectures for these spin qubits, using up to 100 qubits to implement the basic operations of quantum error correction. This project is theoretical in nature, but offers the opportunity to collaborate with experimental groups at Microsoft Sydney and UNSW.

Building next-generation superconducting quantum circuits

Supervisor: Dr. Xanthe Croot
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Grand Challenge: The Nano and Quantum world

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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Grand Challenge: The Nano and Quantum world

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.

Designing a protocol for optically linking superconducting qubits

Supervisor: John Bartholomew
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Grand Challenge: The Nano and Quantum world

Background: Superconducting qubit systems are one of the leading quantum computing platforms. Superconducting qubits operate at microwave frequencies and need to be maintained at temperatures near absolute zero to avoid thermal noise swamping the quantum signals. The consequence is that superconducting quantum computers cannot be connected in a network beyond the refrigerator in which they are housed. Researchers like you are needed to take up the challenge to build an optical network to transfer quantum signals between superconducting qubits.

Project: This project will focus on designing and characterising a protocol to create entangled pairs of photons. One photon will be at microwave frequencies and the other photon will have a wavelength in the infrared telecommunication band. The protocol will be based on ensembles of erbium ions embedded in crystals that are coupled to optical and microwave cavities. You will develop approximate analytical models and numerical models of the photon pair source and use these models to test the performance of the protocol. You will work within the new Quantum Integration Laboratory team based 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 cavity QED, theory of emitters in crystals, collective atom dynamics, and quantum light-matter interactions.

Investigating materials for a quantum internet

Supervisor:	John Bartholomew
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Grand Challenge:	The Nano and Quantum world

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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Grand Challenge:	The Nano and Quantum world

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.

Generating states of light for error-robust quantum computation

Supervisor:	Sahand Mahmoodian
Co-supervisor:	Andrew Doherty
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Grand Challenge:	The Nano and Quantum world

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.

Renewable Energy

Plasmonic-induced water splitting: the green hydrogen revolution

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Grand Challenge:	The Nano and Quantum world, A Sustainable Future,Physics & Society

At the 2021 UN Climate Change Conference (COP26), 197 countries signed the Glasgow Climate Pact, committing to reduce the use of coal. But the targets will be hard to fulfill, and currently we are on track for a catastrophic 2.7°C increase by the end of the century. The overarching aim of the project is to combine our expertise in nanophotonics, photocatalysis, materials science, and micro/nanofluidics to deliver proof-of-concept of an integrated nanophotonic platform that induces efficient water splitting, producing only green hydrogen and oxygen. It will also be completely passive,

i.e. it will use only sunlight and water. You will help with the fabrication of the fundamental building block of the photonic chip and characterise it, proving its optical efficiency as well as its capability to produce enough photocurrent. This project could revolutionise the way of producing green hydrogen, solving the current fossil fuel based energy production issue.

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

Supervisor:	Ben Fulcher
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Grand Challenge:	Artificial Intelligence and Physics

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.