Physics Honours Projects: 2021

This document lists a number of potential honours research projects within the School of Physics, together with supervisor contact details and a paragraph describing each of the projects. These are only some of the opportunities available, and *you are welcome to explore other possibilities with potential supervisors*. If you are free, please also join us for the **Honours Information Session at 12:00 on Monday 21st 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), 14th September 2020

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Astronomical and space science

Gravitational Microlensing and Photon Correlations

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

Gravitational microlensing by stars produces multiple images of distant sources, each seen with a small time delay. This small delay offers the prospect of detecting correlations between the arrival rate of photons, an effect known as Hanbury-Brown-Twiss correlations. In this project, we will use numerical techniques to explore these correlations in binary stellar lensing systems, in particular the case where images merge as caustics are crossed. If detectable, these correlations will offer new clues to the nature of the lensing systems. This project will suit those who are familiar with numerical techniques in python/matlab.

The Entropy of the Universe

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

The low entropy at the birth of the universe remains a mystery, although it is commonly thought that this is a result of low gravitational entropy due to smoothly distributed matter. Recently, Rovelli suggests that the low entropy is due to the universal expansion moving away from equilibrium at the early stages, leaving baryonic matter in the form of primarily hydrogen. In this project, we will explore this using a numerical code (AlterBBN) to explore nucleosynthesis in the early stages of the universe, examining the elemental outcome due to differing expansion histories. AlterBBN is written in C, so some experience with programming is desired.

The Orbits of Andromeda's Globular Clusters

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

Recently, we found that the outer globular clusters of Andromeda orbit in two distinct, perpendicular populations, something quite unexpected from our models of galaxy evolution. In this project, we take a look at the inner population of globular clusters, to explore their kinematic properties. Through considering various models, we will explore whether the inner globular clusters represent a single population, or possess significant substructure. This project will use Bayesian approaches to relatively assess the success of differing models. Experience with Matlab/python is desirable.

Galactic seismology: what excites the giant waves crossing the Milky Way?

Supervisor: Joss Bland-Hawthorn
Co-supervisor: Thorsten Tepper-Garcia
Email contact: jbh@physics.usyd.edu.au
Grand Challenge: Fundamental laws & the Universe

The ESA Gaia satellite made the extraordinary discovery of giant waves crossing the Milky Way. Already there are several theories to explain this remarkable phenomenon. The most likely explanation is that the Galaxy was hit by a large object, say a dwarf galaxy, that set the Galaxy wobbling. We have run the most advanced supercomputer simulations to date to understand just how and when this must have taken place. We can also explore the impact of different dark matter models in our analysis. The student will be asked to work with the supervisor on analysing these new simulations with a view to publication in the Astrophysical Journal.

Asteroseismology: probing inside stars using stellar oscillations

Supervisor: Tim Bedding
Co-supervisor: Tim White
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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.

Inflows and Outflows in Milky Way Analogues with MUSE

Supervisor: Dr Jesse van de Sande
Co-supervisor: Dr Nic Scot & Prof Joss Bland-Hawthorn
Email contact: jesse.vandesande@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

The Milky Way is by far the best-studied galaxy in the Universe and is considered a benchmark for understanding galaxy formation. However, the Milky Way is only one galaxy, and by studying "Milky Way Analogues" we can challenge the existing paradigm that our Galaxy is the Rosetta Stone of galaxy formation. In this project we will study the inflow and outflow of ionised gas in such a Milky Way Analogue. Characterising the rates of gas flow is crucial for understanding the details of the "galactic fountain" model, where gas is first blown out of the disk by exploding stars and eventually cools and rains back down. The state-of-the-art spatially-resolved optical spectroscopic observations of UGC 10738, an edge-on Milky Way Analogue, will provide unique insights in this galactic fountain model from an extragalactic perspective. Other possible projects in this area include exploring the stellar archaeology, dynamics, and dark matter content of nearby Milky Way-like galaxies to place our own Galaxy in its proper cosmological context

Machine and Deep Learning Applied to Galaxy Morphology and Kinematics

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

The taxonomy of galaxies determined from their visual morphological properties has been a powerful tool to advance our knowledge on the processes that shape galaxies, with Hubble's classification scheme from 1926 still in active use today. Machine and Deep Learning applied to galaxy morphology is becoming increasingly popular and effective to accurately classify galaxies. Besides the morphology of galaxies, resolved stellar kinematic measurements now provide a unique look into the dynamical properties of galaxies. In this project, we will use traditional machine learning algorithms as well as Deep Learning to combine the information from visual and kinematic morphology to obtain the most insightful classification of galaxies. We will use data from the SAMI Galaxy Survey, a project pioneered at the University of Sydney, and investigate in detail the properties of ~3000 galaxies to unravel the formation and evolution of galaxies.

Extreme Events: Exploring the Dynamic Radio Sky with ASKAP

Supervisor: Tara Murphy
Email contact: tara.murphy@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Some of the most extreme events in the Universe occur when black holes form as a massive star collapses, or when neutron stars merge. When this happens strong bursts of electromagnetic radiation are released as shocks travel into the interstellar medium and are detected on Earth as transient radio emission. Not only are these events interesting in their own right, they also serve as an astronomical laboratory for exploring physics in extreme conditions. Until now we have had a limited ability to find and study these objects as they appear and disappear on short timescales. In this project you will work with data hot off the press from the Australian SKA Pathfinder (ASKAP) telescope. You will have access to these unique (and completely unexplored) datasets to look for transient and highly variable radio sources, and then draw on multi-wavelength data and observations from other telescopes to identify what these sources are. Python programming skills would be useful - but not essential: this is something you will learn or build on during the project.

Carbon under Extreme Pressure

Supervisor: Professor David McKenzie
Co-supervisor: Professors Dougal McCulloch and Nigel Marks
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Carbon is one of the most common elements in the Universe and forms interesting structures when placed under pressure. For example, ordinary graphite becomes transparent and electrically insulating. Proposed structures formed under pressure are related to diamond and its allotropes including the mysterious material called Lonsdaleite or "hexagonal diamond", found in many carbonaceous meteorites. We are examining meteorites under the microscope and have gained evidence for the formation of these forms of carbon. In this project computer simulations and experiments in a diamond anvil cell will be done where we explore how these materials are formed by compression. We are currently exploring a mechanism whereby a phase change propagates in a miniature example of vein formation of minerals. The project is related to deep seated earthquakes in subduction zones in the earth.

Interferometry with the JWST space telescope

Supervisor: Peter Tuthill
Co-supervisor: Anthony Soulain
Email contact: peter.tuthill@sydney.edu.au
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 Riddle of the Red Square

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

The "Red Square" is a spectacular, newly-discovered bipolar nebula (Tuthill et al, Science 2007). Using cutting-edge imaging techniques such as Adaptive Optics and Optical Interferometry implemented at some of the worlds largest observatories (e.g. Keck, Gemini), we have revealed beautiful and startlingly detailed structures. A striking set of rungs crossing the nebula imply the existence of a highly regular series of nested bicones: possibly a relic of previous episodes of eruption or instability in the host star MWC 922 at the heart of the system. What is particularly compelling about this object is the correspondence between the sharp rung structures we see in The Red Square, and the beautiful polar rings now exhibited by the only naked-eye supernova since the invention of the telescope: SN 1987A. The origin of these mysterious rings stands out as one of the foremost unsolved problems in Supernova astronomy, and in the Red Square, we may have found the best example of a candidate progenitor for these structures. For this project, you will unravel the physics of this fascinating target and participate in new observing programs for the Keck telescopes (Hawaii) and VLT telescopes (Chile). In revealing the true nature of the enigmatic star MWC 922, we hope to solidify the links between this new nebula and the relic structures around SN 1987A.

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
Email contact: peter.tuthill@sydney.edu.au
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.

Machine-learning applied to solar flare prediction

Supervisor:	Michael Wheatland
Co-supervisor:	Tara Murphy
Email contact:	michael.wheatland@sydney.edu.au
Grand Challenge:	Artificial Intelligence and Physics

Solar flares are enormous magnetic explosions on the Sun. Large flares and associated coronal mass ejections produce hazardous space weather conditions, which can cause damage to satellite electronics and electricity grids on the surface of the Earth, and pose radiation risks for space travellers and crews on polar flights. Accurately predicting solar flares is critical to reduce these risks, but it is not currently possible due to a due to a lack of understanding of the physical details of flare triggering and the energy-release process. Recent work uses machine learning classifiers to categorise active regions on the Sun based on vector magnetic field data, however, the accuracy of the results is still poor. In this project you will investigate a different approach, using not only magnetic field data but also the past history of flaring to estimate the future rates for small flaring events, which are much more numerous than the (more dangerous) large ones. You will analyse data from the Solar Dynamics Observatory and use machine learning to see whether the new approach gives improved outcomes. The project will involve data analysis, machine learning and visualization of results. Some programming skills (preferably in Python) are required.

The hidden Galaxy with GAIA

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

2021 marks the release of the first major raw data catalog from one of the most successful astronomy missions in history - ESA's audacious GAIA mission. GAIA has recovered exquisitely precise data on a billion stars: with this release comes exact positions and motions of our evolving galaxy. This project will prospect for subtle patterns in this enormous data volume, signatures of unseen gravitating bodies in the local universe. The pathway to discovery of new physics here will require you to master advanced algorithms in machine learning and pattern inference from large datasets.

Extreme Imaging: exploring stellar mass loss and planet formation with VAMPIRES

Supervisor:	Barnaby Norris
Co-supervisor:	Peter Tuthill
Email contact:	barnaby.norris@sydney.edu.au

The processes behind both the turbulent birth of new planetary systems and the last gasps of dying stars present two of the biggest puzzles in astronomy. To understand these mysteries, one needs to directly observe the very heart of these systems, at extreme resolutions far beyond that achievable with conventional telescopes and instruments. In this project you will use data from VAMPIRES – a high resolution, polarimetric imaging instrument developed by our group and deployed at the Subaru Telescope in Hawaii – to help answer these questions. You will be involved in performing new observations, and we also have several beautiful data-sets that are yet to be explored. By analysing these data to produce images (using existing software as well as developing your own), you will perform a study of one of these processes, culminating in a deeper understanding of the physical mechanisms involved.

Deeper imaging of distant stars through polarisation of light

Supervisor: Barnaby Norris
Co-supervisor: Peter Tuthill
Email contact: barnaby.norris@sydney.edu.au

Making high quality images of distant astronomical objects, such as extra-solar planets and giant stars, is at the heart of many areas of astronomy. One key method is to exploit the polarisation of light to detect the faint signal of an exoplanet from the overwhelmingly brighter signal of its host star. Our group has built an instrument – called VAMPIRES - to do exactly this, and is deployed at the 8 metre Subaru telescope in Hawaii. In order to realise the ultimate in sensitivity, we need to understand the polarisation signals produced by the telescope and instrument itself, which mask the true scientific signals. In this project you will produce a model of the polarisation properties of the telescope and instrument. Drawing on physical optics, linear algebra, coding and data inference, your model will allow the received data to be transformed into accurate measurements and images of these distant objects. You will test and refine your model using the latest data from the instrument to produce new images, and also be involved in performing new observations.

THE UNIVERSITY OF SYDNEY

Atomic, molecular and plasma physics

Deposition of robust functionalized coatings on pulse-biased substrates

Supervisor: Dr Behnam Akhavan and Prof. Marcela Bilek
Email contact: behnam.akhavan@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Plasma polymerization is a versatile surface engineering process capable of depositing ultra-thin functionalized films for a range of applications such as biomaterials for cell attachment and immobilization of enzymes and proteins. In this technology, the desired monomer is initially converted into vapour under a low pressure, and it is subsequently excited into the plasma state using an electric field. The recombination of active species takes place on any surface exposed to the plasma, thus forming a thin layer of functionalized plasma polymer coating. Production of plasma polymer films that are high in functional group(s) yet stable in body fluids is, however, challenging. This research will be focused on the production of robust functionalized plasma polymer films through judicious choice of plasma deposition parameters. The student will obtain experience in laboratory experiments including both fabrication and characterization of novel engineered surfaces.

Understanding and managing residual stress in hard protective coatings for high-tech applications

Supervisor: Prof. David McKenzie and Prof. Marcela Bilek
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Grand Challenge: A Sustainable Future

Wear and corrosion are the most important failure mechanisms in industry and in our daily lives. As an example, the cost of corrosion, wear and other materials deterioration in the USA in 2013 exceeded $1 trillion US$ (6.1% of the GDP). Wear imposes very large economic loss in the transportation industries, in particular in aerospace. In response, further advances in the field of protective coatings (PC), through coating materials development as well as the related fabrication technologies and testing methodologies, are highly important from economic, societal, and sustainability (environment-related) points of view. However, despite the progress in PC fabrication, the acceptance of the deposition processes is frequently limited by high residual stress (RS) in the coating systems. This is particularly related to the lack of fundamental knowledge of the stress-generating mechanisms, their complex relation to the microstructure, and the availability of pathways to mitigate it. In response to the technological challenges and goals with respect to further progress in PC, this project proposes to investigate new approaches for stress management using high energy ion bombardment. Specifically, it focusses on the study of the effect of ion energies and ion fluxes during the deposition of hard metal nitride films using plasma immersion ion implantation deposition (PIIID) on the microstructure and on the mechanical and tribological properties [1]. The student will benefit from the fact that this project is performed as part of an international collaboration with Polytechnique Montreal, the largest engineering school and Canada. [1] G. Abadias, E. Chason, J. Keckes, M. Sebastiani, G.B. Thompson, E. Barthel, G.L. Doll, C.E. Murray, C.H. Stoessel, and L. Martinu, “Stress in thin films and coatings: Current status, challenges and prospects”, J. Vac. Sci. Technol. A, 36 (2018) 020801.

Plasma ion implantation treatment of porous materials

Supervisor: Prof. Marcela Bilek and Dr Behnam Akhavan
Email contact: behnam.akhavan@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Plasma immersion ion implantation (PIII) is a plasma treatment process that creates highly reactive radicals on carbon-based materials. These reactive radicals are excellent sites for the immobilization of functional molecules. Membranes and porous materials treated via this technique are of interest for a number of applications including sensing, separation, purification, cell culture and tissue engineering. For such applications, reactive sites must be generated not only onto the surface of a membrane, but also onto the entire internal network of pores. The development of suitable processes will uncover new plasma physics about how the porous structures interact with and regulate the plasma through surface charging and modulation of electric fields and pressure in the pores. The student can choose from projects focused on laboratory experiments including fabrication and characterization of novel engineered materials, and/or plasma diagnostics or theoretical modelling projects aimed at gaining fundamental understanding.

High Entropy Alloys - Understanding the performance of a new category of materials synthesized by pulsed plasma technologies

Supervisor: Prof. Marcela Bilek
Co-supervisor: Prof. Zongwen Liu, Dr. Behnam Akhavan
Email contact: marcela.bilek@sydney.edu.au
Grand Challenge: A Sustainable Future

High entropy alloys (HEA) is a new category of multicomponent materials not dominated by one or a combination of two components, but by a complex mix of amorphous structures, typically away from the boundaries of a compositional phase diagram. HEA are thus becoming a new research field that focuses on the development of promising new multifunctional materials systems with improved performance that makes them potentially suitable for numerous applications, such as tools, molds, dies, mechanical parts and furnace parts, they can be applied in chemical plants, semiconductor foundries and marine applications, typically in situations that require high strength and thermal stability, as well as wear, erosion and oxidation resistance. As such, the HEA offer much promise for the fabrication of novel devices and surface engineering solutions with a high potential of use in different industrial sectors. The proposed projects aim to focus on new and innovative approaches to the synthesis of HEA films and coatings using High Power Impulse Magnetron Sputtering (HiPIMS) and Pulsed Cathodic Arc. The student will have an opportunity to analyse the effect of varying plasma-surface interactions during synthesis on microstructure on the nanoscale, and its impact on the mechanical and tribological performance of the coatings. Promising materials will be tested for their suitability for protective coating on aircraft engine components and for other applications. In particular, the project and the student will benefit from the synergies of expertise in the participating applied physics, plasma processing, electron microscopy and functional coating laboratories, as well as from an international collaboration with Polytechnique Montreal, the largest engineering school in Canada.

Plasma coatings of pharmaceutical agents for controlled and sustained release

Supervisor: Dr Maliheh Ghadiri, Dr Behnam Akhavan and Prof. Marcela Bilek
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Grand Challenge: Physics in Medicine & Biology

Conventional coating methods use organic solvents to prepare coated particles that provide controlled-release medications. However, this approach has disadvantages in that it can cause particle agglomeration, reduce pharmaceutical stability, and leave residual organic solvents. Plasma polymerization is a versatile surface engineering process capable of depositing ultra-thin film on the particles. Therefore, using plasma polymerization as a one step and dry process for encapsulation and control of the release rate of pharmaceuticals is the focus of this project. Student will learn laboratory experiments including both fabrication and characterization of coated pharmaceutical particles as well as characterization of drug stability and release.

Biological, biomedical and medical physics

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.

Atmospheric pressure discharges to activate tissue engineering scaffolds during additive manufacturing

Supervisor: Prof Marcela Bilek
Co-supervisor: Dr Behnam Akhavan and Prof David McKenzie
Email contact: marcela.bilek@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

Additive manufacturing (commonly also known as 3D printing) holds great promise in medicine where it can be used to create arbitrarily complex scaffolds for tissue and organ repair/ replacement. The thermoplastic materials optimised for use with these manufacturing processes typically suffer from poor biocompatibility. Our group has developed a number of low-pressure plasma processes that can render such materials not only biocompatible but positively biologically active in that they stimulate and direct desirable cell proliferation. This project aims to develop and characterise localised discharges that can be used to render scaffolds and implantable devices biocompatible during their additive manufacture. The work builds on a prior honours project in which capillary discharges compatible with the additive manufacturing processes were created and their ability to activate polymeric surfaces to enable covalent attachment of biomolecules was demonstrated. In this project, the fundamental mechanisms unpinning the biomolecule immobilisation will be explored. Experiments conducted in controlled atmospheres in which certain atmospheric gas constituents are absent and pretreatment with chemicals that inactivate radicals and other reactive species will be used to eliminate various hypotheses. The physical and chemical characteristics of the plasma-activated scaffolds will be studied using X-Ray photoelectron spectroscopy (XPS) and infrared spectroscopy (FTIR). The project is highly interdisciplinary and will involve a continuous collaboration with the Charles Perkins Centre, where the biocompatibility of the plasma-modified scaffolds will be studied using in-vitro and in-vivo techniques.

Bioactive interfaces for implantable biomedical devices using plasma discharges

Supervisor: Prof Marcela Bilek and Dr Behnam Akhavan
Email contact: marcela.bilek@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

In this project you will develop and characterise biocompatible plasma activated interfaces for medical implants using state-of-the-art plasma discharge technologies. The work will develop novel High Power Impulse Magnetron Sputtering (HiPIMS) and Plasma Immersion Ion Implantation processes, aiming to synthesise thin films for improving the biocompatibility of biomedical devices so that they integrate optimally into the host tissue.

Precursors for the films can be delivered as sputtered vapour or dip-coated natural materials such as Shellac. Electrical and optical diagnostics will be used to explore the most relevant plasma parameters during the process. The physical and chemical characteristics of the thin-films will be studied using electron microscopy techniques (TEM, SEM, EDS and EELS), nano-indentation, X-Ray photoelectron spectroscopy (XPS), infrared spectroscopy (FTIR) and ellipsometry. The project is highly interdisciplinary and will involve a continuous collaboration with biomedical colleagues, where the biocompatibility and mechanical stability of the plasma coated devices will be further studied using in-vitro and in-vivo techniques.

Developing an antimicrobial coatings from highly dense immobilized quaternary ammonium salts

Supervisor: Dr Clara Tran, Prof Marcela Bilek and Dr Das Ashish Kumar
Email contact: clara.tran@sydney.edu.au and marcela.bilek@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

Most hospital infections are associated with biofilm formation on medical implants and devices. Antimicrobial coatings for medical device surfaces are a simple and effective solution to combat the bacterial pathogen. Quaternary ammonium salts (QASs) have been widely used as disinfectants in household products due to their active action against microorganisms. It has been proposed that QASs penetrate bacteria cell membranes via electrostatic interactions, inducing intracellular leakage and cell death. High surface density of immobilized QAS containing polymers greatly contribute to the antimicrobial activity. This project will investigate the covalently attachment of QAS containing polymers on plasma functionalized surfaces. By manipulating an applied external electric field during the immobilisation process, surface density and orientation of the immobilized QAS containing polymers will be controlled to understand their influence on antimicrobial activity of the surface. Students participating in this project will develop skills in plasma surface treatment, surface characterisation and bacterial assays.

Microfluidic devices for analysis of blood materials interactions

Supervisor: Prof Marcela Bilek and Dr Anna Waterhouse
Email contact: marcela.bilek@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

Blood clots present major and often fatal problems for virtually all implantable blood contacting devices, such as cardiovascular stents, as well as imposing limitations on the processing of blood products from donors. Materials that can make contact with flowing blood without initiating clotting or thrombosis are needed but an understanding of how blood flow in contact with the surfaces of synthetic materials causes clotting or thrombosis is currently lacking. This project aims to create microfluidic devices that can be used to study the clotting behaviour of blood in contact with various materials under a range of flow conditions. Lithographic processing will be used to make microfluidic structures that will be tested with blood in the Charles Perkins Centre together with thrombosis expert, Dr Anna Waterhouse. The surfaces of these devices will be modified using a variety of plasma treatments ranging from low pressure to atmospheric and the effects on thrombosis quantified. The physical and chemical characteristics of the plasma-modified surfaces will be studied using contact angle goniometry, ellipsometry, X-Ray photoelectron spectroscopy (XPS) and infrared spectroscopy (FTIR) to reveal new understanding of the effects of various surface properties on the formation of blood clots.

Next generation hybrid materials for biomedical applications

Supervisor: Professor Marcela Bilek
Co-supervisor: Dr Behnam Akhavan and Dr Giselle Yeo
Email contact: marcela.bilek@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

Hydrogels are cross-linked fibrous materials that incorporate large amounts of water and provide environments for cells that mimic the native aqueous environments of cells in living tissues. Existing technologies allow the creation of a variety of hydrogels that incorporate biological signalling molecules but they lack the structural stability and mechanical strength required for many applications in biomedical implantable devices and sensing. This project will investigate the potential of using plasma surface activation to create hybrid hydrogel materials in which the hydrogel is robustly bonded to a stronger polymeric scaffold. Plasma parameters with a focus on gas flow dynamics and electric field distributions will be tuned to achieve uniform activation of complex scaffold structures. We have already demonstrated that such treatments are possible and that they make the polymer surfaces more hydrophilic and capable of direct covalent binding to hydrogels. The hydrophilic surfaces facilitate easy hydrogel incorporation and the embedded radicals facilitate covalent bonding of the hybrid structures. The physical and chemical characteristics of the plasma-activated scaffolds will be studied using X-Ray photoelectron spectroscopy (XPS) and infrared spectroscopy (FTIR). Together with our colleagues in Chemical and Biomolecular Engineering, mechanical properties of the hybrid materials will be assessed for suitability for applications in implantable medical devices and microfluidic sensors. Parallel projects together with our collaborators in the Charles Perkins Centre (CPC) and Heart Research Institute (HRI) will verify the biocompatibility and efficacy in biological applications.

Plasma immersion ion implantation for controlled drug release and biodegradation

Supervisor:	Prof Marcela Bilek and Dr Behnam Akhavan
Email contact:	marcela.bilek@sydney.edu.au
Grand Challenge:	Physics in Medicine & Biology

Local delivery of drugs and biological agents from coatings on biomedical implants to prevent infections, mitigate adverse immune responses and facilitate optimal tissue integrations suffers from high initial release rates leading to toxicity and lower than therapeutic release rates thereafter. Biocompatible coatings with tuneable degradation and release rates could solve these problems. Shellac, a fundamentally biocompatible resin secreted by the female lac bug, can be dissolved in ethanol, combined with drugs or biological agents and brushed or dip coated onto arbitrarily complex structures as used in biomedical devices. In this project, we plan to explore the use of ion implantation from a plasma to control the degradation rates of such coatings in aqueous environments and study the effects on drug release rates over time. Ions accelerated by high voltages in a plasma sheath deposit energy tens of nanometers below the coating surface breaking chemical bonds and forming new cross-links in polymeric materials. We have evidence that shows that release of agents loaded into the treated surface layers is inhibited, eliminating the initial toxic burst and that the cross-linking can slow the biodegradation leading to a sustained therapeutic delivery in the long term. An in-depth study of the changes in microstructure, cross-linking and degradation rates is required to allow the production of controlled drug release devices. The physical and chemical characteristics of the ion implanted coatings will be studied using contact angle goniometry, ellipsometry, X-Ray photoelectron spectroscopy (XPS) and infrared spectroscopy (FTIR). Elution assays will be used to study changes in drug elution rates and biodegradability. Biological testing will be carried out together with colleagues at the Heart Research Institute and colleagues in China.

Covalent attachment of extracellular matrix protein for stem cell attachment and differentiation for neural network chips

Supervisor:	Dr Clara Tran and Prof Marcela Bilek
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Grand Challenge:	Physics in Medicine & Biology

Neural network chips will be developed based on localised differentiation of stem cells for studying neural interactions and drug screening in vitro. Locally stimulated differentiation allows the formation of physiological-like hetero cellular structures. The differentiation depends largely on signalling from interactions between specific signalling proteins where the stem cells are attached. For this purpose, protein micropatterns strongly attached to a substrate surface (eg: glass coverslip) with a uniform density and a controlled composition present relevant biological environments that can induce differentiation into various types of neuronal cells. Covalent bonding of proteins to plasma treated polymeric coatings have been proven to be superior than physical adsorption with low cross-contamination and high stability in culture medium. In this research, we will use plasma deposition to produce a radical-rich thin coating on glass surfaces for protein binding. Tested signalling proteins will be stamped into the glass surface to form micropatterns. This platform will be used to investigate stem cell differentiation into neural cell types, such as neurons and astrocytes, to create a platform

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for rapid screening of drugs for pain suppression and for the study of neurodegenerative disease. Students with strong interest in surface characterisation and/or stem cells will find this project highly stimulating and rewarding.

Functionalized coatings of pharmaceutical agents for targeted drug delivery

Supervisor:	Dr Maliheh Ghadiri, Dr Behnam Akhavan and Prof. Marcela Bilek
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Grand Challenge:	Physics in Medicine & Biology

Plasma polymerization is a versatile surface engineering process capable of depositing ultra-thin film on the particles. Therefore, using plasma polymerization as a one step and dry process for encapsulation and control of the release rate of pharmaceuticals is the focus of this project. In the past decades, polymeric coating of drugs has emerged as a most promising and viable technology platform for targeted and controlled drug delivery. As vehicles, ideal particles are obliged to possess high drug loading levels, deliver drug to the specific pathological site and/or target cells without drug leakage on the way, while rapidly unloading drugs at the site of action. In this project, various "intelligent" polymeric moieties that release drugs in response to an internal or external stimulus such as pH, redox, temperature, magnetic and light will be studied. Student will learn laboratory experiments including both fabrication and characterization of coated pharmaceutical particles as well as characterization of drug stability and release.

Complex systems

Inferring brain networks from data

Supervisor: Oliver Cliff
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Grand Challenge: Artificial Intelligence and Physics; Physics in Medicine & Biology

The brain is capable of remarkable feats due to its distributed architecture, sharing the same emergent properties as other complex systems such as swarms, flocks, or entire ecosystems. The physical substrates and communication channels that form cognition are often described by a network of nodes and edges abstracted from structural or functional measurements of the brain. Representing an individual's brain in this unified framework allows researchers to capture important characteristics like the early detection of neurodegenerative diseases or fundamental signatures of human thought. For instance, the networks of Alzheimer's patients are far more disconnected than control subjects, whereas epilepsy is characterised by overly integrated circuitry causing sporadic synchronisation of neuronal activity. Even the leading theory of human consciousness, at its core, hinges on global networks that emerge from interactions of local neurons in different physical states. The benefits of network neuroscience are boundless; however, the field relies on accurate network inference and it remains unclear whether the commonly-used approaches are suitable for such a task. Indeed, recent research has suggested that many network inference techniques fail to reconstruct relatively simple neuronal networks from simulated fMRI data. This project aims to overcome this hurdle by applying state-of-the-art network inference algorithms developed within the University to the problems of network neuroscience. The student will have the chance to work with techniques that have previously been validated for a variety of complex systems, applying them to both simulated and real recordings of brain dynamics. In doing so, we hope to transform our understanding of the connection between human mental faculties and physical processes in the brain, moving towards better diagnoses and the theoretical underpinnings of our most important resource.

Modeling brain dynamics with hierarchical spatial gradients

Supervisor: Ben Fulcher
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Grand Challenge: Artificial Intelligence and Physics; Physics in Medicine & Biology

A central aim of neuroscience is to understand how the brain, with its staggering complexity of 100 billion neurons, makes sense of the world around it. Large-scale global initiatives have measured the brain in intricate detail, but have given limited physical understanding of how the brain's microscopic properties shape the whole-brain dynamics that underlie cognition. In this range of projects, we will develop, constrain, and validate a new generation of physiologically based brain models that tightly integrate large-scale neuroscience data. Datasets of microscopic structure and macroscopic brain dynamics in both mouse and human will allow us to develop models that will allow us to quantitatively assess the uniqueness of human brain organization.

Modeling the mechanisms of brain stimulation

Supervisor: Ben Fulcher
Co-supervisor: Nigel Rogasch
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Grand Challenge: Artificial Intelligence and Physics; Physics in Medicine & Biology

Despite the growing use of new technologies like transcranial magnetic stimulation (TMS), that allow us to causally manipulate brain activity in humans, we do not yet understand how it works. We have recently shown how a mathematical model that describes interactions between neural populations in the cortex can reproduce the complex brain responses to stimulation, opening up an exciting new research avenue that uses quantitative analytical methods to guide groundbreaking new clinical applications. In this project, the student will develop a neural field model of how cortical circuits respond to brain stimulation to inform the development of the next generation of personalised TMS treatments.

Scale invariance of activity fluctuations in insomnia

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

Many physiologic variables in healthy humans and other animals show scale-invariant or ‘fractal’ properties, manifested in temporal structures that are similar across different timescales, from minutes to 24 hours (Gu et al., 2015, PNAS). Several diseases have recently been linked to reduction of this scale invariance in 24-hour motor activity patterns including Alzheimer’s disease and suprasellar tumors. Insomnia is one of the most prevalent sleep disorders affecting 10% of the general population in Australia at any given time and characterised by difficulty to initiate or maintain sleep. It is manifested in reduced sleep time over extended periods of time (≥2 weeks) and leads to daytime sleepiness, increased risk of accidents, mood disturbances and overall reduction of wellbeing and health. This project aims to test whether scale invariance of activity fluctuations is preserved in insomnia compared to healthy people. The answers will provide new information about potential brain mechanisms of insomnia.

Quantitative modelling to uncover brain mechanism of vulnerability to sleep loss

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

Insufficient and disturbed sleep are widespread phenomena in modern society with nearly 7.4 million Australians affected daily. Sleep loss induces adverse changes in alertness resulting in accidents and loss of life, e.g., contributing to 20-30% of fatal car crashes each year. Impaired alertness is unavoidable in occupations with shiftwork like healthcare, police, and fire and rescue service. The degree of impairment, however, is highly variable across individuals with the most vulnerable being at highest risk of accidents. Identifying vulnerable vs. resilient individuals and predicting an individual’s alertness is critical to minimising accident risks and improving safety. To address this major problem, this project will use a quantitative ODE-based model of alertness (Postnova et al., 2018, J Biol Rhythms) to investigate the brain mechanisms underpinning differences in alertness dynamics. This will allow us to make predictions of an individual’s alertness and design interventions to avoid low alertness (high accident risk) conditions.

Global dynamics of sleep and circadian rhythms: how human-made time zones affect our health?

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

Before discovery of electricity, human circadian (~24 hour) rhythms, e.g., sleep-wake cycles, were driven by the solar light-dark cycle which is dependent on the geographical location and seasons. In the modern world, however, access to artificial light, human-made time zones, social norms (e.g., work hours), and transitions between daylight saving time and standard time change our timing of light exposure and can result in chronic circadian misalignment in large proportion of population. Such circadian misalignment is associated with increased risk of obesity, diabetes and cancer (e.g., Gu et al., 2017, Cancer Epidemiol) but it can be prevented by optimising exposure to environmental time cues, including light. In this study we use quantitative modelling of sleep and circadian rhythms (Abeysuriya et al., 2018, J Pineal Res) to investigate the effects of natural and human-imposed changes of environmental light timing on sleep and circadian synchronization. We will interpret results in view of existing experimental data and develop potential solutions for better organization of time zones.

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

Supervisor: A/Prof 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 presented a concept of distributed dynamical computation (DDC), in which neural computation or information processing is carried out by interacting, propagating neural waves. This concept can merge dynamical and computational perspectives of the brain, which used to have great gaps between each other. 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.

The physics of deep learning in artificial intelligence

Supervisor: A/Prof Pulin Gong
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Grand Challenge: Artificial Intelligence and Physics

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. 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 the gradient descent learning algorithm 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.

Turbulence in the brain: Detection and analysis of dynamic coherent structures in collective neuronal activity

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

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 wave packets in the population activity of neurons. This new finding therefore makes cortical spatiotemporal dynamics analogous to that observed in turbulence fluids, in which a hierarchy of coherent activity patterns 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 modeling the dynamic wave packets 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 modeling.

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 life time. 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.

Condensed matter physics and materials physics

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

Supervisor:	Rongkun Zheng
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.

3D printed Metamerials

Supervisor:	Professor David McKenzie
Co-supervisor:	A/Prof Natalka Suchowerska
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Grand Challenge:	Fundamental laws & the Universe; The Nano and Quantum world; Physics in Medicine & Biology

3D printing has opened up new opportunities for creating structures that were previously very difficult, or even impossible to create using conventional machining methods. "Metamaterials" is a field of research where new topologies for the microstructure of materials are invented that may give physical properties on the macroscale that are rare or at the limits of what theory considers possible. Some of these have already been found in Nature but not yet built synthetically. Examples are negative refractive index and negative Poisson's ratio. This project combines theory with experiment where we aim to build very strong materials with many applications in medicine and manufacturing. Emphasis will be placed on the idea of "critical links" in 3D printed structures where the impact on macroscopic properties is large. The student will have access to a range of innovative 3D printers in the University and its affiliated laboratories.

Data science

Inferring the dimensionality of physical systems from their empirical dynamics

Supervisor: Ben Fulcher
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Grand Challenge: Artificial Intelligence and Physics

Finding simple principles that can explain the complexity of the world around us is a hallmark of physics. Hints that simple principles may capture the behavior of diverse real-world systems can be found from the observation that collections of high-dimensional data often lie on lower-dimensional manifolds in measurement space. However, we still lack the ability to automatically infer interpretable parameters that capture a system's dynamical freedoms. In this project, the student will investigate how this can be achieved in a model-free way (from data alone) using a new highly comparative machine learning framework, hctsa. The framework will be validated on a range of simulated and real-world datasets. The student should have an interest in numerical simulation, data science, and machine learning.

Untangling the web of influence on social media

Supervisor: Tristram Alexander
Co-supervisor: Ben Fulcher
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Grand Challenge: Physics & Society

Social media is leading to an increased fracturing of public opinion, through the ease with which extreme opinions and misinformation can be spread. For instance, the scientific evidence pointing to the accelerating pace of climate change is unequivocal, yet any discussion of solutions is mired in partisanship, and opposed by powerful voices claiming a "climate hoax". This project seeks to disentangle the different communities active on social media, using automated methods to classify members of a community and so determine the nature, size, and interconnectedness of climate action, climate denier, and regular user networks. How much information flows between the networks? How do the networks of activists and extremists connect to regular users? And where are the networks of the extremists geographically based? This project uses tools of data science, network science, information theory and physical modelling techniques.

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Nanoscience

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 atomicscale. 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.

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.

Multi-functional nanocarriers for targeted therapeutics and imaging

Supervisor: Prof Marcela Bilek and Dr Behnam Akhavan
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Grand Challenge: Physics in Medicine & Biology

Nanoparticles hold great promise in medicine. In the size range 50-200 nm they can enter cells and deliver cargo including drugs, imaging and targeting agents. An optimum nanocarrier would be able to find a specific target (eg a malignant tumour), deliver a drug and be externally detectable with convenient medical imaging modalities to allow effective monitoring of the treatment. Although there has been a great deal of research on the development of nanoparticles globally, nanoparticles that can be easily functionalised with multiple agents are not available. In recent research, our group has developed and patented a new type of nanoparticle that contains reactive species that enable linking of a wide range of cargo molecules on contact. The attachment of the cargo is achieved through a spontaneous reaction with radicals embedded in the surface of the particle during its synthesis in plasma. We are in discussion with industry partners about the commercial translation of these particles and are conducting a number of engineering, biomedical and basic physics studies to gain a deeper understanding of the mechanisms unpinning their plasma synthesis / extraction, behaviour in aqueous solution when mixed with cargo to be attached, mechanisms of reaction, charge-charge interactions that can be used to orient immobilised bioactive molecules and their biological interactions in vitro and in vivo. This work enables many interesting honours projects and can be tailored to student interests.

Particle physics

Theoretical projects:

Dilaton as dark matter

Supervisor: A/Prof Archil Kobakhidze
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Grand Challenge: Fundamental laws & the Universe

The approximate invariance of fundamental laws of nature under scaling transformation provides a new insight into the mechanism of mass generation for elementary particles, including the Higgs boson. A class of scale invariant models predicts the existence of a new, very light scalar particle, known as the dilaton. In this project, we will study the properties of this particle with the aim to determine whether the dilaton can be sought as the prime constituent of the observed, yet mysterious, dark matter in the universe.

Electroweak monopoles

Supervisor: A/Prof Archil Kobakhidze
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Grand Challenge: Fundamental laws & the Universe

Does an isolated magnetic charge exist? While within the classical Maxwell theory the answer is negative, in a more complete quantum description, known as the electroweak Standard Model, the existence of magnetic monopoles is a theoretical possibility. The goal of this project is to provide a new quantum description of electroweak monopoles using the coherent state formalism. The project involves mastering some advanced topics in quantum field theory and will appeal to students with analytical skills from mathematics and theoretical physics.

Quantum gravity, asymptotic symmetries and gravitational instantons

Supervisor: A/Prof Archil Kobakhidze
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Grand Challenge: Fundamental laws & the Universe

Instantons are Euclidean classical solutions in field theories, which describe quantum tunneling between topologically inequivalent vacua. In this project we study gravitational instantons within Einstein's theory of General Relativity and asymptotic symmetries in Eucledian curved spacetimes with the aim to describe physical meaning of quantum tunnelings in gravity. The projects involves some advanced topics in mathematics and physics and will appeal to mathematically inclined students interested in fundamental physics.

Cosmological phase transitions in a model of parallel Universes

Supervisor: A/Prof Archil Kobakhidze
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Grand Challenge: Fundamental laws & the Universe

We investigate the theoretical possibility of the existence of a parallel world which interacts with the observable one through yet undetected feeble interactions. During the cosmic evolution these two worlds may carry different temperatures and influence each other through thermal effects. In this project we study potentially observable manifestations of such interactions.

Primordial black holes from cosmic phase transitions

Supervisor: A/Prof Archil Kobakhidze
Email contact: archil.kobakhidze@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Small inhomogeneities in the otherwise homogeneous expanding universe may collapse under the force of gravity into black holes. These black holes can survive to present days as a dark matter. In this project we study the production of such primordial black holes during the cosmological phase transition

Numerical simulations of the early Universe: cosmic strings and dark matter

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

The physics that governs the very early Universe, before the formation of the first atomic nuclei, is a hotly debated topic in the particle physics and cosmology community. One possibility that has been pondered for many decades, but has enjoyed resurgence in interest recently, is the formation of cosmic strings. These are a kind of "topological defect" which can be formed when the Universe undergoes a phase transition; they can be thought of in a similar way to cracks in a sheet of ice. They are extremely thin, but with lengths that can extend across the size of the observable Universe. The resurgence in interest recently is because such cosmic strings are a prediction of a candidate for dark matter that is extremely popular right now: the axion. This project will involve setting up a numerical simulation of the very early Universe to study how cosmic strings form and decay, and make predictions about the resulting dark matter.

Experimental projects:

Investigations of Standard Model processes at the Large Hadron Collider

Supervisor: Prof 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. 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.

Studying rare B-meson decays at the Belle II experiment

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

The Belle II experiment at the SuperKEKB electron-positron collider in Japan commenced data-taking for physics in early 2019, and has so far accumulated data from some 75 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.

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

Supervisor: A/Prof 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 rare decays of D-mesons. In particular, the decay $D \to e\,\tau$ has never been studied. This decay provides unique access to certain beyond-Standard-Model effective operators: a good search at Belle II would rival the sensitivity of the Large Hadron Collider for some operators, and exceed it for others. The particle-reconstruction properties of $D \to e\,\tau$ events are 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.

Graph Neural Networks as a tool for discovery in particle physics

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

Experimental particle physics makes widespread use of machine learning techniques as an aid in deducing the underlying physics processes taking place in particle collisions at colliders such as the Large Hadron Collider at CERN in Europe and the SuperKEKB collider at KEK in Japan. Finding rare signals of interest in very dirty data containing large amounts of background requires sophisticated techniques. The latest deep learning techniques from data science are informing methods used in particle physics, and in this project the aim is to explore one such technique, graph neural networks (GNNs). These are gaining a lot of interest in their application to particle physics. This project will explore whether graph neural networks can offer improvements over some specific, currently deployed techniques for detecting rare processes used by the ATLAS experiment at CERN and/or the Belle II experiment at KEK.

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Development of new detection techniques:

Discovering new forces in quantum interference experiments

Supervisor: A/Prof Archil Kobakhidze
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Grand Challenge: Fundamental laws & the Universe

There are good theoretical reasons to speculate about the existence of new gauge interactions beyond those already discovered within the standard model of particles physics. These extra gauge theories are assumed to be massive and hence the corresponding charges are screened at distances larger than the Compton wavelength of the associated massive gauge bosons. Therefore, to detect the effect of new interactions one must resolve very small distances which represent a significant challenge. Currently, the search for new forces is conducted at particle colliders, such as the Large Hadron Collider. In this project, we study the feasibility of detecting new forces via topological interactions, such as the Aharonov-Bohm scattering, in relatively simple tabletop experiments.

Extending the reach of dark matter detectors

Supervisor: Ciaran O'Hare
Email contact: ciaran.ohare@sydney.edu.au
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 the recent rapid advancements of 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. The project will be in anticipation of the first underground lab opening in the southern hemisphere, located in Victoria, Australia. One aim of the project will be to develop new techniques to give existing detectors the sensitivity to search for brand new dark matter theories that have still not been tested. Another aim will be to find potential physics discoveries a dark matter detector could make “for free” by detecting neutrinos. Sources of neutrino from the Sun, supernovae, cosmic rays and from geological processes will all be additional signals a dark matter detector could see if - but only if we set them up in the right way. This project will involve mostly computational and numerical work, but will be based on multidisciplinary physics: from particle theory and detectors, to astrophysics and geophysics. So it will be an excellent opportunity to develop computational skills while in the context of broad and exciting physics.

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Photonics and optical science

Soliton physics — molecules of light

Supervisor: Martijn de Sterke
Co-supervisor: Antoine Runge
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One of the key features of light is that, unlike, electrons which are charged, photons do not interact with each other. This makes them ideal for carrying information through optical fibres. It is therefore perhaps surprising that we are carrying out experimental work on soliton molecules—complicated optical pulses consisting of different frequencies but coincident in time, that are, somehow, bound together and propagate as a single unit. We can achieve this because light interacts, although weakly, in nonlinear media, media in which the refractive index depends on the intensity of the light. In fact we have built a laser that emits a wide variety of such pulses. These include molecules in which the two constituent atoms are the same, and heteronuclear molecules, in which they are fundamentally different. This is a brand new area that has only barely been explored, with application that have yet to be unlocked. We have a number of projects in this area that can be experimental, theoretical, numerical or a combination of these.

Black and white holes in an optical fibre

Supervisor: Martijn de Sterke
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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 too. 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, according to which the velocity of the light pulses varies with frequency, this leads to phenomena that are similar to that of black and white holes. We are collaborating on this with an experimental group in Singapore, who require theoretical support. 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.

Extreme nonlinear optics with a mobile phone

Supervisor: Alessandro Tuniz
Co-supervisor: Martijn de Sterke
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Grand Challenge: The Nano and Quantum world

Imagine a material for which the dielectric constant is zero, i.e., $\varepsilon=0$. In such a material the wavelength of light would be infinite and the phase velocity would diverge: it would have weird properties. In fact such a material – indium tin oxide – exists, and is contained in the screen of your mobile phone. It was recently shown to have extreme nonlinear optical properties, larger than almost any other known material, as the intensity inside the material is extremely high. These very unusual features throw much of the conventional wisdom of nonlinear optics in disarray, so that the underlying physical mechanism is still a matter of debate. Since this material promises to enable ground-breaking all-optical signal processing, it would certainly be advantageous if an existing and ubiquitous technology (namely, the mobile phones in our pockets!) already contained the necessary ingredients for this kind of technology. This project aims to perform a systematic analysis of the nonlinear properties of the indium tin oxide inside a mobile phone. (We will provide the mobile phone, though you can bring your own!) This is an experimental-based project for students interested in hands-on experience in a state-of-the-art optics laboratory.

One million times smaller: the topology of terahertz waves at the nanoscale

Supervisor:	Alessandro Tuniz
Co-supervisor:	Boris Kuhlmey
Email contact:	alessandro.tuniz@sydney.edu.au
Grand Challenge:	The Nano and Quantum world; Physics in Medicine & Biology

Terahertz frequencies are at the heart of several enabling multidisciplinary technologies, including security, telecommunications, and medical diagnostics. These frequencies contain information on the slow, long-range, inter-molecular interactions that no other frequency can provide, promising to unlock a wealth of very important but currently unavailable bio-molecular information. However, because terahertz waves have millimeter scale wavelengths, it has been challenging to use them to characterize nanoscale molecular events: they are too small to be measured using existing optical systems. We have recently shown a method to conveniently concentrate light at a 10 nm metal nanotip on a photonic chip: this approach can straightforwardly be extended to terahertz frequencies. However, the extreme difference in the scales involved imply that such designs will rely on a delicate balance of the complex and subtle topologies that govern the participating Eigenmodes. This project aims at designing, fabricating, and measuring THz radiation on a nano-tip integrated on a silicon micro-chip, and is suitable for students interested in hands-on experience in state-of-the-art experimental facilities.

A Neurophotonic Interface – I

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Prof Marcela Bilek and Prof Stuart Fraser
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Grand Challenge:	Artificial Intelligence and Physics; Physics in Medicine & Biology

We are developing a universal neural interface. In this project we will develop a micropatterning technique to bond the photoactive neurons onto a biocompatible film, treated to covalently bond biomolecules. We will use an optical microscope equipped with an nanopositioner in order to accurately position a plasma-treated biocompatible film with biomolecules on a PDMS mask; here photoactive neurons will be grown and their activities probed. We will need to output the ideal pattern geometrical parameters to make the neuron form/not form a neural network maintaining their photoactivity.

A Neurophotonic Interface – II

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Prof Martijn de Sterke, Dr Alessandro Tuniz and A/Prof Stuart Fraser
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Grand Challenge:	Artificial Intelligence and Physics; Physics in Medicine & Biology

The vision of this project is to develop a universal neurophotonic interface. 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. 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 addressing photoactive neurons. In this project we need to model high-index waveguides with in- and output gratings to send/collect light to/from the immobilised photoactive synapses by simulating the most efficient and appropriate materials. We will also test the fabricated device.

DDMEBT-polymer composite: a new nonlinear material

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Dr Alessandro Tuniz and Prof Martijn de Sterke
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Grand Challenge:	Artificial Intelligence and Physics; The Nano and Quantum world

An empirical rule, called Miller's rule, suggests that the nonlinear optical properties of any material increase with its own index of refraction. However, for certain efficient waveguide-based devices, this is not ideal; a material with high nonlinearities and low refractive index, the opposite of Miller's rule, is sought. A few years ago a new organic film was created, exhibiting exactly these characteristics, called DDMEBT, which is very difficult to manufacture. One of our collaborators in Tokyo has synthetised the polymeric version of this materials, way easier to and handle. In this project, we want to measure the DDMEBT-polymer nonlinear optical properties by using an ultrasensitive nonlinear technique we developed. You will learn how to use a fs laser source and our technique to perform these measurements on this new material. The material will play a central role for future integrated optical chips for nonlinear and quantum optical applications.

Novel nanolasers: a brighter future for photonic integrated laser sources

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Prof Martijn de Sterke and Alessandro Tuniz
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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 recently realized that these configurations are not optimal. Based on our latest 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 prove that our novel platform can enhance Perovskite-based plasmonic nanolasers performance. The project could remove the impasse that this field is currently bearing and potentially be fed into the market of integrated nanolasers. You will first test their lasing capabilities on a bare substrate and then into the configuration we predicted to enhanced their performance. The project could lead to publications and patents.

Plasmonic-enhanced upconverting nanoparticles: a path toward point-of-care paper-like biosensors

Supervisor:	A/Prof Stefano Palomba
Co-supervisor:	Dr Hien Duong (Pharmacy) and Dr Reza Behi (Engineering)
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Grand Challenge:	The Nano and Quantum world

In this project we will engineer and test 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 these conditions the nanoparticle is quenched by the gold nanosphere. Only when this system interacts with a specific molecule of interest, then one of the DNA links breaks and the upconverting nanoparticle emits strong light that can be detected. The gold nanorod serve as an enhancer of the luminescence. This system can be used as background free biosenor. This project could also have applications in organic solar cell enhancement as well as a potential new method for LED TVs.

Waveguide-coupled 2D materials for spontaneous parametric down conversion (SPDC): a cornerstone for future quantum optical chips

Supervisor: A/Prof Stefano Palomba
Co-supervisor: Prof Dragomir Neshev (ANU), Dr Alexander Solntsev (UTS)
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Grand Challenge: The Nano and Quantum world

The future quantum optical information processing (QOIP) field doesn't have a "winning" platform yet. One of the approaches is to generate single photons on demand, identical (spectral purity) and in high quantity. One potential solution to this problem is to use nonlinear optical phenomena, such as spontaneous parametric down conversion (SPDC), i.e. pumping the material at low optical wavelength (such as 750 nm) and observe the generation of correlated (produced at the same time and with correlated properties) photon pairs. These can then be entangled on-chip and used for modern QOIP. However, the ideal source of correlated photon pairs has to be demonstrated yet. Here we want to detect the SPDC from a 2D material deposited on a Si integrated waveguide. In this way we hope to increase the light-matter interaction and enhance the production of correlated photon-pairs which will be already couple into the waveguide and ready to be entangled and used directly on-chip. The project could revolutionise quantum optical photon pair generation on-chip.

Dark solitons in the presence of higher-order dispersion

Supervisor: Tristram Alexander
Co-supervisor: Martijn de Sterke
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Grand Challenge: Fundamental laws & the Universe

Dark solitons are self-guided intensity notches sitting on a bright background, existing due to a balance between nonlinear and linear effects. These exotic nonlinear waves have proved to be highly robust, due to their topology, and have appeared in numerous fields in physics. However, in all cases considered, it has been the nonlinearity that has been the focus of attention. Recent work in the School of Physics has shown that we can carefully control the linear properties experienced by a nonlinear wave, and that these linear properties fundamentally alter the nature of the resulting solutions. So far this research has focused on a class of solutions known as bright solitons. This project will study the much more mysterious dark soliton, using a combination of analytical and numerical techniques.

Photonics processor in Silicon

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Dr. Alvaro Casas Bedoya
Email contact: alvaro.casasbedoya@sydney.edu.au

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
Email contact: alvaro.casasbedoya@sydney.edu.au

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
Email contact: moritz.merklein@sydney.edu.au

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.

High-efficiency and low-noise single photon detectors

Supervisor:	Prof. Benjamin Eggleton
Co-*supervisor:*	Dr. Shouyi Xie
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Highly sensitive single-photon detector is an enabling technology and vital in optical quantum communication, LIDAR, and biological and medical imaging. Conventional solid-state single-photon detectors are based on avalanche process in crystalline semiconductors at high reverse bias voltage which is inherently noisy, low-efficiency and power demanding. We aim to overcome these disadvantages by utilising a different signal amplification mechanism, namely cycling excitation process, in highly disordered semiconductor materials. In this project you will gain understanding on the carrier excitation and transport mechanisms in semiconductors that contributes to the electrical performances of the single-photon detectors. You will design and optimise the structures and fabrication processes of the detectors through simulation. You will also collaborate with the team members to incorporate the optical performances of the detectors. The optimised structure will be fabricated into real devices at Sydney Nanoscience Hub.

Physics education

The measure of things

Supervisor: Manjula Sharma
Co-supervisor: Tom Gordon
Email contact: tom.gordon@sydney.edu.au
Grand Challenge: Physics and society

In this project, you will compare different measurement devices against the measurement capabilities of a smart phone or tablet device. You will compare the reliability, validity and accuracy of these devices against common measurement devices used in the laboratory environment either at secondary or tertiary settings. This project is suited to those interested in education and engagement in Physics. The project may also include development and integration of measurement devices, applications and techniques. This project is part of a government funded project on improving school science. The findings from these projects are being used in workshops with school teachers and students across the country, from Darwin to Armidale. They have the potential to be published in journals.

Science inquiry: From demos, recipes to open investigations

Supervisor: Manjula Sharma
Co-supervisor: Tom Gordon
Email contact: manjula.sharma@sydney.edu.au
Grand Challenge: Physics and society

The Australian Government has funded a $2M national project to improve school science education by researching 'how to make better use of investigations' to engage and excite students as well as improve understanding. Your project will entail examining issues ranging from:

- How often are investigations used?
- What is the nature of investigations carried out in school classrooms?
- Developing and evaluating experiments.
- Involvement in workshops across the country.
- Many other questions you can design

The findings from this project will being used in workshops with school teachers and students across the country, from Darwin to Armidale. They have the potential to be published in journals.

Physics of neuromorphic systems

The neuromorphic nose for medical diagnostics

Supervisor: Professor David McKenzie
Co-supervisor: Mr E Guo and Dr James Partridge
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Grand Challenge: Artificial Intelligence and Physics

Human and animal noses are amazingly powerful sensors with a lot to teach us about sensing and detection. We have a funded ARC project that is using ideas derived from the biology of the nose to make new types of parallel sensors combined with neuromorphic neural networks for pattern recognition. One disease, motor-neurone disease, is being targeted for detection using the new methods, in partnership with a medical start-up company. The project will combine experiment with theory of neuromorphic pattern recognition to design and develop parts of the detection system. The emphasis in the project work will to some extent be customised to the interests of the student, as this is a large project with several aspects.

Quantum physics and quantum information

Quantum Control and Quantum Computation with Trapped Ytterbium Ions

Supervisor: Prof. Michael J. Biercuk
Co-supervisor: Dr Ting Rei Tan
Email contact: Tingrei.tan@sydney.edu.au
Grand Challenge: Artificial Intelligence and Physics; The Nano and Quantum world

The Quantum Control Laboratory is an experimental research group focused on developing new techniques in quantum computation using trapped-ions - one of the most advanced technologies for quantum computing globally. In particular, we are interested in studying new techniques to improve the performance of quantum computing hardware and creating novel operating paradigms for the application of quantum computers to problems in chemistry (known as quantum simulation). This project will combine insights from experimental atomic physics with the most advanced techniques in machine learning in order to solve major problems in the field. This project will be conducted within the Sydney Nanoscience Hub and make use of both the most advanced quantum computing hardware in Australia and cutting-edge software tools. Students will have the opportunity to engage with world-leading industry partner Q-CTRL as well as international partners through participation in global collaborative research. Experience gained in this project will cover atomic physics, magnetic resonance, microwave systems, quantum computing, and quantum control. Multiple projects are on offer within this heading.

Quantum Computing with Trapped Ytterbium Ions

Supervisor: Prof. Michael J. Biercuk
Co-supervisor: Dr Ting Rei Tan
Email contact: tingrei.tan@sydney.edu.au
Grand Challenge: The Nano and Quantum world

The Quantum Control Laboratory is an experimental research group focused on developing new techniques in quantum computation using trapped-ions - one of the most advanced technologies for quantum computing globally. In particular, we are interested in studying new techniques to improve the performance of quantum computing hardware and creating novel operating paradigms for the application of quantum computers to problems in chemistry (known as quantum simulation). This project will combine insights from experimental atomic physics with the most advanced techniques in machine learning in order to solve major problems in the field. This project will be conducted within the Sydney Nanoscience Hub and make use of both the most advanced quantum computing hardware in Australia and cutting-edge software tools. Students will have the opportunity to engage with world-leading industry partner Q-CTRL as well as international partners through participation in global collaborative research. Experience gained in this project will cover atomic physics, magnetic resonance, microwave systems, quantum computing, and quantum control. Multiple projects are on offer within this heading.

Overcoming Barren plateaus for near-term quantum algorithms

Supervisor: Isaac Kim
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Grand Challenge: Artificial Intelligence and Physics; The Nano and Quantum world

Recently, there has been a surge of interest in using near-term quantum computers to simulate classically intractable quantum many-body systems. The dominant approach is to use a parametrized circuit to prepare physical states of interest, by variationally minimizing the energy with respect to this circuit. A major bottleneck in this direction is the Barren plateau, a phenomenon in which the gradient of the energy with respect to the parameters vanish, stymying the variational optimization. In this project, the student will investigate methods to overcome this phenomenon.

Spin-qubit quantum computing

Supervisor: Stephen Bartlett
Email contact: stephen.bartlett@sydney.edu.au
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.

Trapped Ion Crystals and Large-Scale Entanglement

Supervisor: Michael J. Biercuk
Co-*supervisor:* Robert Wolf
Email contact: michael.biercuk@sydney.edu.au
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.

Investigating materials for a quantum internet

Supervisor: John Bartholomew
Email contact: john.bartholomew@sydney.edu.au
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
Email contact: john.bartholomew@sydney.edu.au
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.

Designing a protocol for optically linking superconducting qubits
Supervisor: John Bartholomew
Email contact: john.bartholomew@sydney.edu.au
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.

Matter Wave Electronics
Supervisor: Professor David McKenzie
Co-*supervisor:* Dr James Partridge
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: The Nano and Quantum world

Recently we have shown that some phenomena taking place at junctions between materials require the wave nature of the electron to be taken into account. In a recent paper "Antireflection coating of barriers to enhance electron tunnelling: exploring the matter wave analogy of superluminal optical phase velocity" we showed how electron wave reflections at a boundary between materials can be controlled to enhance transmission in an unexpected and novel manner. We showed that physical intuition based on experience with antireflection coatings in optics can be misleading so that the best opportunities have so far been missed. In this project, we will extend our method based on one dimensional solutions of the time-dependent linear Schrodinger equation to allow the modelling of potentials for realistic interfaces found in common electronic devices. The implications of the technology are wide reaching with the possible opportunity to reduce ohmic loss in many common devices and thereby increase their efficiency.

THE UNIVERSITY OF SYDNEY

Renewable Energy

Polymer Free Glass Bonding for Solar Glazing

Supervisor: David McKenzie
Co-supervisor: Anita Ho-Baillie
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: The Nano and Quantum world; A Sustainable Future; Physics & Society

The multi-billion worldwide building integrated photovoltaics market is predicted to rise by 20% annually in the next 5 years. There is vast solar energy resource on the facades of high rise buildings in modern cities which is currently not utilised. The aim of the project is to develop glass bonding with electrical feedthroughs as an enabling technology for energy generating, aesthetically pleasing glazings. Diffusion bonding is a form of bonding where intimate mixing occurs at an interface. We will develop a form of diffusion bonding using an intermediate layer. The challenge is to make a fully hermetic bond at low temperature which is compatible with next generation photovoltaic technology. We will be exploring material options and examining the interface using electron microscopy and atomic force microscopy. This project is suitable for an entrepreneurial student interested in industry relevant science for a translatable outcome.

Characterising defects in perovskite materials and solar cells

Supervisor: Anita Ho-Baillie
Co-supervisor: David McKenzie
Email contact: anita.ho-baillie@sydney.edu.au
Grand Challenge: The Nano and Quantum world; A Sustainable Future

One of the exciting attributes of perovskite solar cell research is the ability to tailor and engineer material systems to achieve the desirable opto-electronic and material properties for durability and high energy conversion efficiency. It is important that we have the capabilities of quantifying and visualising the transport properties of and defects in perovskite materials using impedance spectroscopy and photoluminescence imaging. Identifying defects because these are the limiting factor in producing record high efficiencies. This project is suitable for a student interested in semiconductor physics and instrumentation and being part of the development of new generations of perovskite cell technology in the School of Physics for higher efficiency and durability.

Durable perovskite tandem solar cells

Supervisor: Anita Ho-Baillie
Co-supervisor: David McKenzie
Email contact: anita.ho-baillie@sydney.edu.au
Grand Challenge: The Nano and Quantum world; A Sustainable Future

Si-perovskite tandem solar cells show huge potential given the rapid improvement in performance from 14% (uncertified) in 2015 to 29% (certified) in 2020 in only 5 years surpassing the efficiency record of single junction Si solar cells. However, for tandems to be cost effective, not only must the increase in cost be matched by an increase in efficiency, the lifetime of the perovskite component must match that of the Si component. This project aims to improve the durability of the Si-perovskite tandem by studying the stability and failure modes of various cell designs and encapsulation options. This study will involve solar cell testing enabled by real time solar cell measurement during accelerated environmental exposure. The aim of this project is to analyse electrical characteristics of multiple cell measurement to identify key drivers that lower performance and to elucidate weak spots in cell design and encapsulations. The knowledge is important for future improvements in cell design and encapsulation schemes.

Metal halide perovskites for solar cells in space

Supervisor: Anita Ho-Baillie
Co-supervisor: Iver Cairns and David McKenzie
Email contact: anita.ho-baillie@sydney.edu.au
Grand Challenge: The Nano and Quantum world; A Sustainable Future

Metal halide perovskites have excellent properties, enabling high energy conversion efficiency solar cells in thin film form for light weight and flexibility. There have been reports about the excellent resistance of perovskite solar cells to high energy electrons and protons. In addition, these cells can be fabricated at relatively low cost, making it possible for wide-spread use in space. This project conducts research on perovskite solar cell designs that can withstand environmental conditions in space including launch shocks, hard vacuum, thermal cycles, high ultraviolet radiation, atomic oxygen, electron and proton radiation, and plasma bombardment. There will be an opportunity for students to take part in the development of new generations of perovskite cell technology for space.

Physics of the hydrogen economy

Supervisor: David McKenzie
Email contact: Anita Ho-Baillie
Grand Challenge: The Nano and Quantum world; A Sustainable Future; Physics & Society

This project will look at some aspects of the production of hydrogen by electrolysis of water. The power is intended to come from renewable resources. We will consider the possibility of lowering the barrier for the creation of hydrogen from water by low voltage electrolysis, at lower voltages than currently used. In this method electrons are transferred to hydrogen ions in solution by quantum mechanical tunnelling through a barrier rather than over the barrier. We aim to do some simple experiments as part of the project to demonstrate hydrogen production in this way.

THE UNIVERSITY OF SYDNEY

Starshot Grand Challenge

Lightsail dynamics

Supervisor: Martijn de Sterke
Co-supervisor: Mohammad Rafat and Boris Kuhlmey
Email contact: martijn.desterke@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

The Alpha Centauri system is the closest star system to our own Sun. It is located at a distance of 4.37 light years from the Sun and it would take 75,000 years for the Voyager 1 spacecraft (if it was pointing in the right direction) to reach while travelling at its current speed of 17 km/s. This is far too long on the scale of the lifetime of human beings. Breakthrough Starshot is an exciting and ambitious project that aims to rectify this unacceptable time-frame! The plan is to attach probes with mass of about one gram to sails of similar mass and with surface area of 10-20 square meters and accelerate them to 20% of the speed of light (or 60,000 km/s) using an Earth-based laser array of 100 gigawatt power. At 3,500 times the speed of Voyager 1, it would take about 30 years for the probe to reach the Alpha Centauri system and send a signal back to Earth. There are many practical and conceptual challenges that must be overcome for this dream to become a reality. One of these challenges is sail stability. The acceleration of the sail by the laser will lead to generation of torques which will cause the sail to veer off. This must be overcome by sail and laser beam designs that lead to a stable motion of the sail towards the intended target. We offer theoretical and numerical projects in this area that involve theoretical mechanics, optics and electromagnetism.

Lightsail thermal management

Supervisor: Boris Kuhlmey
Co-supervisor: Martijn de Sterke and Mohammad Rafat
Email contact: boris.kuhlmey@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

The Alpha Centauri system is the closest star system to our own Sun. It is located at a distance of 4.37 light years from the Sun and it would take 75,000 years for the Voyager 1 spacecraft (if it was pointing in the right direction) to reach while travelling at its current speed of 17 km/s. This is far too long on the scale of the lifetime of human beings. Breakthrough Starshot is an exciting and ambitious project that aims to rectify this unacceptable time-frame! The plan is to attach probes with mass of about one gram to sails of similar mass and with surface area of 10-20 square meters and accelerate them to 20% of the speed of light (or 60,000 km/s) using an Earth-based laser array of 100 gigawatt power. At 3,500 times the speed of Voyager 1, it would take about 30 years for the probe to reach the Alpha Centauri system and send a signal back to Earth. There are many practical and conceptual challenges that must be overcome for this dream to become a reality. One of these challenges is thermal management of the sail. Thermal management goes far beyond simple thermal engineering, as heat transport between close thin layers of sail is insufficiently explained by the usual black body radiation laws. Instead, heat transport through evanescent waves needs to be taken into account, as well as how the sail structure affects photonic and thermal properties. We offer theoretical and numerical projects in this area that involve optics, electromagnetism and thermal physics.

Sustainability

Atmospheric water capture

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Grand Challenge: A Sustainable Future

One of the grand challenges of the 21st century is the provision of clean water. Although we have had rain in recent months, most of us remember that it is not long ago that almost the entire state of NSW was drought-declared. Now at 70% humidity and at 20^{o} C, a cubic meter of air contains 12 grams of water and at 30^{o} C it is as much as 21 grams! Is it possible to harvest this moisture in a sustainable way? In an interdisciplinary project with colleagues in chemistry, biology, engineering, architecture, we are developing a technology that does exactly this. The water condenses on a cool surface where it forms droplets and which can then be collected in a bucket. The process relies on passive cooling, the cooling of a surface below the ambient, by thermal radiation, through the atmosphere, into space, which has a temperature just below absolute zero. This type of cooling requires no energy input and has no moving parts—it is therefore perfect for remote, off-the-grid locations where maintenance is difficult. We have a number of projects in this area that can be experimental, theoretical, numerical or a combination of these.

Development of plasma activated coatings on particulate surfaces

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A plasma activated coating (PAC) is deposited onto substrates via excitation of a precursor gas, e.g. acetylene, in a plasma deposition system consisting of an RF electrode and a pulsed voltage source. PAC facilitates the immobilization of bioactive molecules on the surface owing to highly reactive radicals generated in the coating. While we have successfully fabricated such surfaces onto 2-D substrates, there is great potential to further develop this knowledge for the coating of particulate materials. In comparison with 2-D substrates, plasma polymer-coated 3-D surfaces are of more interest in real-world applications such as protein adsorption/separation and removal of toxic matter from water. This project will utilise an agitation system to retrofit an existing plasma deposition system followed by the deposition of plasma activated coatings onto model particulate substrates. The student will obtain experience in laboratory experiments including both fabrication and characterization of novel engineered surfaces.