

# Physics Honours Projects: 2020

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 in your field of interest with potential supervisors*. If you are free, please also join us for the **Honours Information Session at 12:00 on Wednesday 11<sup>th</sup> September, in SNH Lecture Theatre 3003**, followed by lunch from 13:00.

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](mailto: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](mailto:physics.honours@sydney.edu.au)), 6<sup>th</sup> September 2019;  
final project list update 7<sup>th</sup> November

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## Interdisciplinary projects on the Grand Challenge Grants

### **Mission to $\alpha$ -Centauri—sail stability**

*Supervisor:* Martijn de Sterke  
*Co-supervisor:* Tristram Alexander, Mike Wheatland, Chris Poulton (UTS)  
*Email contact:* martijn.desterke@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe

This project is part of a School of Physics “Grand Challenge” that aims to propel an object to the stars closest to Earth. It is based on radiation pressure, the phenomenon that causes comet tails to stream away from the Sun. The plan is to use an intense laser beam to exert radiation pressure on a highly-reflective “sail”. The aim of this part of the project is to study the motion of the sail in an inevitably non-uniform laser beam, and to investigate how stability can be achieved. It has been suggested that including a grating on the bottom of the sail, which reflects some of the light in a sideways direction, would help achieve this. This project, which uses the techniques developed in theoretical mechanics, consists of a combination of pen-and-paper calculations and numerical modeling.

### **Mission to $\alpha$ -Centauri—materials**

*Supervisor:* David McKenzie  
*Co-supervisor:* Sergio Leon-Saval, Martijn de Sterke  
*Email contact:* David.McKenzie@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe

This project is part of a School of Physics “Grand Challenge” that aims to propel an object to the stars closest to Earth. It is based on radiation pressure, the phenomenon that causes comet tails to stream away from the Sun. The plan is to use an intense laser beam to exert radiation pressure on a highly-reflective “sail”. As a precursor study to an experimental program, we will identify the critical challenges of finding strong refractory materials from which to construct a sail of the highest possible reflectance, tuned to the laser frequency with allowance for the Doppler effect. The forces arising from differential temperature distributions will be studied together with the forces of interaction with a Gaussian laser beam. This will require simulation of the fields in and around a multilayer construct of high and low refractive indices and its net force of interaction with the field. Student will gain skills in thermal physics, in electromagnetic wave simulation and in the design of optical multilayer devices.

### **Development of suitable and reliable metrics on modern slavery**

*Supervisor:* Joy Murray  
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*Grand Challenge:* Physics and Society

Modern Slavery affects around 43 million people, more than at any time in recorded history. A media and civil society focus on this evil has prompted governments and businesses to act. Australia’s Modern Slavery Act came into force at the end of 2018. Global companies and NGOs working at the centre of the ‘combatting modern slavery’ agenda have identified a profound lack of knowledge on what constitutes a supply chain, how to identify modern slavery and what to do if modern slavery is found. To fill this knowledge gap we need to develop suitable and reliable metrics on modern slavery that are fit to be linked to a global trade database. The student’s role will be to collect bottom-up process data on slavery-related indicators and incorporate those data into the Global IELab platform to generate heat-maps of a global MRIO table linked with those slavery indicators. This is part of a larger project to integrate small (local) data into a big data highly-detailed global economic trade framework.

## **Astronomical and space science**

### **The TOLIMAN space telescope**

*Supervisor:* Peter Tuthill  
*Co-supervisor:* Barnaby Norris  
*Email contact:* Peter.tuthill@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe

The 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.

### **Imaging Newborn Exoplanets**

*Supervisor:* Peter Tuthill  
*Co-supervisor:* Marc-Antoine Martinod  
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*Grand Challenge:* Fundamental laws & the Universe

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

### **Are solar flare sizes and waiting times correlated?**

*Supervisor:* Michael Wheatland  
*Co-supervisor:* Donald Melrose  
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*Grand Challenge:* A Sustainable Future

Solar flares are giant magnetic explosions in the solar atmosphere, which influence our local space weather. Flares occur in the strong magnetic fields around sunspots. The statistics of flare occurrence give information on the flare mechanism, which is incompletely understood. Flares follow a power-law size distribution, and appear to occur randomly in time in a given sunspot region. Recently evidence has been presented for a correlation in waiting times between flares and flare size. This project will examine soft X-ray flare and other flare data, to investigate further the claimed correlation. The project has scope for data analysis, computation, and theory.

### **A new perspective on the Milky Way**

*Supervisor:* Nic Scott  
*Co-supervisor:* Jesse van de Sande & Sanjib Sharma  
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*Grand Challenge:* Fundamental laws & the Universe

The Milky Way is by far the best-studied galaxy in the Universe, but because of our unique position inside the Galaxy it is difficult to compare to other galaxies. This project will overcome this challenge by using state-of-the-art models of the Milky Way to produce the first ever mock "observations" of our galaxy from an external perspective, allowing direct comparison to spatially resolved spectroscopic observations of nearby galaxies with the MUSE and SAMI instruments. These mock observations will provide a brand new perspective on our Galaxy, letting us accurately place the Milky Way in a cosmic context.

### **Asteroseismology: probing inside stars using stellar oscillations**

*Supervisor:* Tim Bedding  
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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 completely 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 Mission and the recently-launched TESS spacecraft.

### **Interferometry with the JWST space telescope**

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

The James Webb Space Telescope stands to 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. When it does so, it will deploy a unique interferometric imaging mode designed, built and led from the University of Sydney. This aperture masking interferometer is aboard the NIRISS instrument, and 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 structure from stars to brown dwarfs to planets, informing our own origins and place in the universe as well as expectations for the ubiquity and diversity of exoplanets in the Galaxy.

### **Exploring galaxy transformation with the MAGPI Survey**

*Supervisor:* Dr Caroline Foster  
*Co-supervisor:* Prof Scott Croom  
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*Grand Challenge:* Fundamental laws & the Universe

The Middle-Ages Galaxy Properties with Integral field spectroscopy (MAGPI) Survey is a new observational campaign on the European Southern Observatory's Very Large Telescope to observe galaxies at intermediate redshift (i.e. 4 billion years ago) using the popular MUSE instrument. Galaxies in the universe's middle-ages (redshifts  $z \sim 0.3$ ) underwent important morphological and dynamical transformations, the causes of which are still under debate. MAGPI will be the first to comprehensively probe this important transition and unveil the processes responsible for creating the organised galaxy systems we see today and live in: from grand design spirals to smooth ellipticals. There will be lots of data and plenty of scope for varied scientific interests, please contact Caroline Foster or Scott Croom if you'd like to explore various or specific possibilities.

### **The Riddle of the Red Square**

*Supervisor:* Peter Tuthill  
*Co-supervisor:* Barnaby Norris  
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*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.

### **Accretion in triple star systems**

*Supervisor:* Helen Johnston  
*Co-supervisor:* Roberto Soria  
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*Grand Challenge:* Fundamental laws & the Universe

Accretion processes in binary star systems are well understood, but how does the presence of a third star affect the accretion flow and outflow? Theory predicts that there should also exist triple system, with a donor star transferring mass to a binary system of compact objects. This project involves developing simple phenomenological models to predict the accretion disk structure and observational appearance of triple systems, for a range of physical parameters (such as mass ratio and and separation of the compact objects, accretion rate, etc). This will involve calculating particle orbits numerically, and calculating the spectrum from the accretion disk analytically. You will then compare your predicted properties with those observed in X-ray binaries and ultraluminous X-ray sources, and consider whether some of them may indeed be triple star systems.

### **In search of stellar acceleration**

*Supervisor:* Joss Bland-Hawthorn  
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*Grand Challenge:* Fundamental laws & the Universe

Galactic archaeology is the study of stars in the Milky Way, how they are born and how they evolve with cosmic time. Stars move around with complex orbits and tell us about the shape and structure of the Galaxy, particularly the distribution of the mysterious dark matter. In current research, we use positions and velocities to infer how the Galaxy evolves with time. But with a new-technology, very accurate spectrograph, we may be able to detect a star's acceleration in the Milky Way. Accelerations are more informative than velocities because they tell us about forces. In this project, we will explore how many stellar accelerations are needed to detect the presence of local and global dark matter in the Galaxy.

**Murchison Widefield Array observations of solar radio bursts**

*Supervisor:* Prof. Iver Cairns  
*Co-supervisor:* Dr Joachim Schmidt  
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*Grand Challenge:* Fundamental laws & the Universe ; Physics & Society

Multiple types of solar radio bursts are observable with the Murchison Widefield Array (MWA). These include type II and III bursts, associated with streams of semi-relativistic electrons produced by solar flares and shock waves in front of coronal mass ejections (CMEs), respectively. The MWA produces novel images of the radio sources, using analysis codes developed by our group. Several projects are available to image and quantify the radio sources and to compare the results with theory, including unusual radio emissions associated with CMEs, detailed analyses of type II bursts, and the source areas and temporal decay of type III bursts.

**Plasma depletion layers throughout our solar system and beyond**

*Supervisor:* Prof. Iver Cairns  
*Co-supervisor:* Dr Joachim Schmidt  
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*Grand Challenge:* Fundamental laws & the Universe

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

## Atomic, molecular and plasma physics

### **Deposition of robust functionalized coatings on pulse-biased substrates**

*Supervisor:* Dr Behnam Akhavan and Prof. Marcela Bilek  
*Co-supervisor:* Dr Behnam Akhavan and Prof. Marcela Bilek  
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*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  
*Co-supervisor:* Prof. Marcela Bilek and Dr Behnam Akhavan  
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*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  
*Co-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.

### **Radio emission from bolides and conducting structures entering Earth's atmosphere**

*Supervisor:* Prof. Iver Cairns  
*Co-supervisor:* Dr Joachim Schmidt  
*Email contact:* iver.cairns@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe ; Physics & Society

Meteorites and other bolides, as well as spacecraft and human space stations, often enter Earth's ionosphere and atmosphere. A shock is expected in front of the object as it enters, with an associated magnetic barrier for a suitably electrically-conducting object. This magnetic barrier can reflect electrons upstream, leading to the

growth of plasma waves and radio emission. This project will model the build-up of the magnetic barrier, the electron reflection, and the generation of radio waves, Langmuir waves, and other diagnostics, all as functions of properties of the object and the local ionosphere. The predictions will be compared with certain mysterious radio emissions observed in the last few years and with historical records for re-entering space objects. In brief, we will determine whether asteroids, bolides, and re-entering objects like the International Space Station should produce observable radio signals and can explain recent observations.

### **Liouville's Theorem and single particle motions**

*Supervisor:* Prof. Iver Cairns  
*Co-supervisor:* A/Prof. Joe Khachan  
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*Grand Challenge:* Fundamental laws & the Universe

Electrons moving along magnetic field lines in Earth's magnetosphere are responsible for the aurora and several important radio emissions, including Auroral Kilometric Radiation and planetary continuum radiation. Assuming conservation of energy and magnetic moment, characteristic changes in the electron velocity and temperatures are predicted as the magnetic field strength changes. Space observations support these predictions, at least sometimes. Liouville's Theorem appears to contradict these predictions and observations, yet should hold. The project will address these apparent contradictions by explicitly mapping the distribution function and reconsidering the existence or not of electric fields in the region and the conditions for Liouville's Theorem to hold. The results will be applied to space phenomena at Earth and the outer heliosphere.

### **Electrical Tether for a CubeSat**

*Supervisor:* Prof. Iver Cairns  
*Co-supervisor:* A/Prof. Joe Khachan  
*Email contact:* iver.cairns@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe ; A Sustainable Future ; Physics & Society

An electrical wire connected to a satellite moving through the ionosphere and across Earth's magnetic field experiences an induced electromotive force, a current, and a drag force. The current in the "tether" is drawn from the plasma. It is possible in principle to drive a current the opposite way down the tether and to thereby generate lift. This project involves several of the following steps: a) Developing a robust electrical design to allow the current to be directed either way along the tether and explicitly addresses how electrons are drawn from and released into the plasma. b) Developing a detailed model for the plasma physics of the system, including the satellite, tether, and plasma. c) Implementing and testing the electrical design in a plasma chamber.

### **Plasma Wave Receiver for a CubeSat**

*Supervisor:* Prof. Iver Cairns  
*Co-supervisor:* A/Prof. Joe Khachan  
*Email contact:* iver.cairns@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe ; A Sustainable Future ; Physics & Society

Plasmas consist of electrons and ions plus plasma waves. These waves contain information on the number densities and temperatures of the plasma constituents, plus the local magnetic field. A plasma wave receiver can detect the waves' electrical and magnetic fields, providing a much simpler means to characterise a CubeSat's plasma environment than a thermal plasma detector. A plasma wave instrument consists of an antenna, an amplifier subsystem, an Analog to Digital Converter (ADC), a subsystem to calculate and appropriately average the power spectrum, and a subsystem to report these power spectra and selected waveforms to an external processor. The project is to develop a working prototype of a plasma wave receiver to fly on a CubeSat.

## Biological, biomedical and medical physics

### **Material systems for regenerative nerve growth**

*Supervisor:* Maryanne Large  
*Co-supervisor:* Syamak Farajikhah , Simon Fleming, Marcela Bilek, Stuart Fraser (Physiology)  
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*Grand Challenge:* Physics in Medicine & Biology

Nerve damage can be devastating and remains challenging to treat due to limited capacity of nerves to regenerate. In this project you will explore novel ideas for materials, interfaces and structures that control and guide stem cell differentiation into specialized neural cells. Specifically the project builds on two novel techniques developed in the School of Physics and expertise in stem cells in the School of Medical Science. The novel physical techniques are the ability to fabricate microstructured nerve conduits in bioresorbable materials, and to modify the surface properties through plasma treatment to encourage stem cell differentiation into nerve cells.

### **Molecular nanorobotics for Health**

*Supervisor:* Shelley Wickham  
*Co-supervisor:* Anna Waterhouse  
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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.

### **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, the student will use experimental methods from nanoscience 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  
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*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  
*Co-supervisor:* Dr Clara Tran, Prof Marcela Bilek and Dr Das Ashish Kumar  
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*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  
*Co-supervisor:* Prof Marcela Bilek and Dr Anna Waterhouse  
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*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  
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*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  
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*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 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.

**Composite media theory for design of bone scaffolds for replacing lost bone in cancer patients**

*Supervisor:* Professor DR McKenzie  
*Co-supervisor:* Associate Professor Natalka Suchowerska  
*Email contact:* david.mckenzie@sydney.edu.au  
*Grand Challenge:* Physics in Medicine & Biology

This project is about finding the best design of a porous bone scaffold to help patients who have lost bone to cancer or serious injury. We will use composite media theory combined with diffusion theory to optimise the layout of pores in a 3D printed polymer structure to allow bone cells to optimally penetrate the structure while retaining the most strength in the scaffold. The project will be supported by VectorLAB at Chris O'Brien Lifehouse, the ETOPIIM fund and will be collaborative with a major international 3D printing company.

**Spatial and Temporal Modulation of Radiation Beams for Improved Radjotherapies**

*Supervisor:* Professor David R McKenzie  
*Co-supervisor:* A/Professor Natalka Suchowerska  
*Email contact:* david.mckenzie@sydney.edu.au  
*Grand Challenge:* Physics in Medicine & Biology

This project is about the use of time and spatial modulation of high energy (MeV) X-ray beams as well as proton beams to improve radiation therapy for treating cancer. We will develop mathematical models based on the physics of molecular diffusion which are benchmarked against experimental studies of cell survival after exposure. These models will assist in the treatment planning for patients in future planned clinical trials. We will also use a range of diagnostic studies (NMR, mass spectroscopy) to identify the types of molecular agents responsible for any observed increase in cancer cell death.

## Complex systems

### **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 core 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 (including the brain's response to external stimulation), will allow us to develop models that will allow us to quantitatively assess the uniqueness of human brain organization.

### **Individual variability in body clocks: from theory to applications**

*Supervisor:* Svetlana Postnova  
*Co-supervisor:* Tahereh Tekieh, Vincenzo Muto  
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*Grand Challenge:* Artificial Intelligence and Physics ; Physics in Medicine & Biology

Circadian (~24 h) rhythms affect every aspect of our physiology (e.g., sleep and alertness) and correct alignment between the body circadian clocks and the environmental time cues (e.g., light) are essential to healthy body functioning. Knowledge of individuals' circadian time allows to prevent fatigue-related accidents, optimize times of drug treatments, and even prevent disease development. However, so far there is no practical way to measure circadian phase for individuals under real world conditions. We use biophysical modelling and machine learning approaches alongside large experimental data sets to understand biological mechanisms behind individual variability and enable real-world prediction of circadian rhythms. Projects in this area involve biological data analysis, physically based modelling of brain dynamics, and development of artificial neural network models to predict individual dynamics.

### **Fighting Jetlag with Physics**

*Supervisor:* Svetlana Postnova  
*Co-supervisor:* Yu Sun Bin, Susan Ledger  
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*Grand Challenge:* Physics in Medicine & Biology

Long-haul flights are a norm for Australians, and ultra-long-haul ~20h flights are planned by Qantas to launch in 2022, directly connecting Sydney and Melbourne with New York, London, and Rio ("Project Sunrise"). However, transmeridian travel and flying lead to jetlag which can last from days to weeks depending on individual, time zones crossed, direction and time of travel, and strength of environmental time cues (symptoms including disturbed sleep, fatigue, irritation, indigestion, and others). We use cross-disciplinary approaches, including physical modelling, computation and experiment, to advance our understanding of jetlag and develop solutions to minimize impact of transmeridian travel. Projects in this area involve developing and applying physically-based models of brain dynamics, developing new research tools, work with experimental data, and collaboration with scientists across variety of disciplines.

### **Googling the brain: Search of associative memory**

*Supervisor:* A/Prof. Pulin Gong  
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*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.

#### **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, recently 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 computation, including studying the neural circuit models developed by our group to reveal the physical principles of key brain functions such as pattern recognition and attention. These principles will be applied for creating new brain-inspired AI models.

#### **Nanorobotic navigation along the brain's intrinsic coordinates**

*Supervisor:* Ben Fulcher  
*Co-supervisor:* Shelley Wickham, Mac Shine (Brain and Mind Centre)  
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*Grand Challenge:* Artificial Intelligence and Physics ;Physics in Medicine & Biology

In the past several years, high-throughput neuroscience methods have yielded a comprehensive blueprint of the entire brain. These data have revealed strikingly low-dimensional spatial patterns in the brain's molecular patterning. In this project, the student will use numerical simulation to investigate whether this gradient-like spatial structure can be exploited by a nanoscale machine to navigate to an arbitrary location in the brain. The student will work with whole-brain neuroscience big data, and implement chemically realistic navigation rules to determine the number and type of chemical brain gradients required for accurate brain navigation. The new science generated could pave the way for innovative new targeted treatments.

#### **The physics of working memory in the brain**

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

Working memory, a core cognitive function, is responsible for the transient holding, processing, and manipulating information. Its neural correlate (persistent firing activity of neurons), as shown in latest experimental studies, has great variability and is topographically organized in the form of spatial gradients. These properties along with the power-law forgetting behaviour of working memory can't be explained by conventional models with homogenous stable states. In this project, a new physical mechanism of working memory, which is based on interacting, localized Turing-like activity patterns, will be studied. Particularly, the collective subdiffusive dynamics emerging from these interacting patterns will be used to account for key dynamical properties and coding accuracy of working memory.

### **Turbulence in the brain: Detection of dynamic wave packets in collective neuronal activity**

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

Cortical neural circuits are complex, non-equilibrium systems whose collective dynamics cannot be described solely in terms of oscillations or low-dimensional aperiodic (chaotic) dynamics. Recently, we have developed a method that enables us to make new discoveries regarding the physical principles of neural circuits; for instance, we have found dynamic coherent patterns such as 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 modelling 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.

### **Quantifying information transfer using a basis set of features**

*Supervisor:* Ben D. Fulcher  
*Co-supervisor:* Joe Lizier (Engineering)  
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*Grand Challenge:* Artificial Intelligence and Physics ;Physics in Medicine & Biology

Complex webs of interacting dynamical systems exist all around us, from the microscale interactions between networks of neurons in the brain, through to the macroscale communication dynamics between a swarm of bees. The emergent dynamics of these physical systems can be understood using the tools of information theory, which allows us to quantify these natural phenomena in terms of how information is processed and transferred. Applying these powerful techniques to real-world systems has been complicated by the need for long streams of high-precision data, as data is conventionally represented in measurement space. This project will investigate a feature-based reduction of time series, which will allow us to represent information storage and transfer dynamics in terms of a set of interpretable features (using the recently developed toolbox, catch22). The methods developed have the potential to transform the application of information theory to diverse physical systems. The student will develop and simulate new models of feature-based information transfer to design new methods that will be evaluated on real-world data streams, including neural dynamics.

### **Fighting the spread of misinformation**

*Supervisor:* Tristram Alexander  
*Co-supervisor:* Ben Fulcher  
*Email contact:* tristram.alexander@sydney.edu.au  
*Grand Challenge:* Physics & Society

Science denial is growing as the challenges facing the planet grow. The use of misinformation by vested interests has a long history, however the advent of social media has vastly increased the power wielded by those bent on introducing confusion into debate. However, while social media brings unprecedented reach, it also allows for accountability, as the connections between players in the network are visible. This project will use the tools of network analysis to quantify the nature of information flow within, and between, the networks of scientists, the general public, and key influencers (such as politicians and media organisations). This quantitative analysis will give a measure of the extent to which influencers are relying on misinformation, and provide the keys needed to fight back against science denial.

## Condensed matter physics

### **Computational Materials Discovery**

*Supervisor:* Prof Catherine Stampfl  
*Co-supervisor:* Dr Peng Zhang  
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*Grand Challenge:* The Nano and Quantum world ;A Sustainable Future

We have numerous potential projects available. All are based on using quantum mechanical ab initio (density functional theory) calculations on high performance computers, to explore, discover, predict and design new materials and structures for applications in a range of high technology applications, including nanoelectronic devices (e.g. spintronic, topological, superconducting, single-photon emitters), sensors and catalysis.

### **Next Generation Photovoltaic Cells for Improving Energy use in Cities**

*Supervisor:* Professor DR McKenzie  
*Co-supervisor:* Professor Anita Ho-Baillie  
*Email contact:* david.mckenzie@sydney.edu.au  
*Grand Challenge:* A Sustainable Future;Physics & Society

We have support for this project from the Australian Research Council. We will carry out research into encapsulating new types of metal-halide perovskite high efficiency solar cells into hermetic glass enclosures using a newly developed low temperature sealing process. We will be using a newly installed controlled atmosphere glove box to manufacture the cells and enclose them, then measure their performance in a solar simulator. The application is to improve the use of energy in cities and reduce unwanted warming of the local environment.

## Data science

### **Employing organic single crystal semiconductors for spintronic devices**

*Supervisor:* Rongkun Zheng  
*Co-supervisor:* Feng Li  
*Email contact:* rongkun.zheng@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world ;A Sustainable Future

Organic semiconductors, including organic small molecules and pi-conjugated/aligned polymers, show a variety of tunable chemical and physical properties and are relatively inexpensive as compared to inorganic semiconductors. In particular, many organic semiconductors hold long spin relaxation time, support ambipolar charge transport and are sensitive to the change of external parameters such as light, magnetic field and temperature. Furthermore, the charge and spin transport characteristics in organic semiconducting devices can be tuned by engineering the hybrid device interfaces. In this project, organic single crystals without grain boundaries that have relatively high carrier mobility will be employed as the spin transport layer for fabrication of spintronic devices, expecting to obtain the optimized device performance and realize the novel device applications for logic operations. In addition, ferromagnetic materials with high chemical resistance and robust magnetic properties even at high temperatures will be sought.

### **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.

### **The computational logic of time-series analysis**

*Supervisor:* Ben Fulcher  
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*Grand Challenge:* Artificial Intelligence and Physics

Time-varying systems are all around us, and scientists love to measure and understand them: from the oscillations in our heart, spiking of neurons in our brains, and the complex pulsing of distant astrophysical objects. Methods to understand the structure of the dynamics produced by these systems have wide-ranging consequences for science (e.g., understanding how the brain works) and in diverse industries (e.g., predicting credit-card fraud). We have recently developed a library containing thousands of time-series analysis methods, which holds the key to developing a concise interdisciplinary toolkit for understanding real-world dynamics. In this project, students will infer the computational logic of this library by applying it to a diverse range of real-world systems. This will allow us to deduce the empirical structure of a literature encapsulating decades of human creativity. The results could be pioneering for the automated analysis of dynamical systems.



**Language dynamics on social media**

*Supervisor:* Tristram Alexander  
*Co-supervisor:* Eduardo Altmann (Mathematics), Monika Bednarek (Linguistics)  
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*Grand Challenge:* Artificial Intelligence and Physics

What is happening on social media? Who is speaking to whom? The language of social media is rapidly evolving, but we don't know how or why. The enormous quantities of data available from Twitter allow for a real-time investigation of the exchanges occurring on this platform. By focusing on specific elements of this data, such as hashtags, this project will quantify the rate of evolution, identify the drivers of this evolution, and develop a model for the language dynamics. This project will use information theory and techniques from machine learning and Natural Language Processing for the quantitative analysis.

## Nanoscience

### **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.

### **A Neurophotonic Platform as Universal Nerve Interface - II**

*Supervisor:* A/Prof Stefano Palomba  
*Co-supervisor:* Prof Marcela Bilek  
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*Grand Challenge:* Physics in Medicine & Biology

We have assembled a team of experts whose combined expertise is essential to develop a universal nerve interface (UNI). It is well known that genetically modified photoactive neurons can be differentiated from pluripotent embryonic stem cells (ESC). In this project we will progress this further. Furthermore, we will tackle and solve challenges which will lead to develop a micropatterning technique to bond the photoactive neurons onto a biocompatible film, treated to covalently bond biomolecules. We will use an optical microscope equipped with a nanopositioner in order to accurately position a plasma-treated biocompatible film with biomolecules which after being pressed onto the film will form a micropattern ready to be bonded to photoactive neurons.

### **Light-Matter interactions for fabricating neuromorphic structures for pattern recognition**

*Supervisor:* Professor David R McKenzie  
*Co-supervisor:* Professor Marcela Bilek  
*Email contact:* David.McKenzie@sydney.edu.au  
*Grand Challenge:* Artificial Intelligence and Physics

This Project is about light-matter interactions for creating nanostructures useful for neuromorphic networks for artificial intelligence applications. We have shown how heat converts an electrically insulating carbon film into a conducting one by reconfiguring the bonding arrangement of the atoms. We will use electromagnetic theory to calculate the temperature rise isotherms in a film subjected to a laser pulse and we will convert these into a temperature-time profile to assist experimental implementation of neuromorphic networks in an all-carbon technology. The student undertaking this project will learn the COMSOL Multiphysics package, will gain skills in nanofabrication techniques, will learn about switching technologies and will learn about neuromorphic computing strategies.

### **Atomic-scale Tomography of Functional Nanoparticles**

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

Laser-assisted atom probe tomography (APT) is a powerful technique, offering the opportunity to investigate the positional and compositional information of chemicals within various samples from metals to insulators, with up to ~100 ppm detection capacity. Though APT has already had very good practice on bulk materials such as metal block, semiconductor thin film, free standing nanowires and quantum dot, the application of APT on particle samples is dissatisfied due to the difficulty of preparing a needle shape APT specimen from Micro/Nano particle samples, which restrict the application APT on the catalysis where most of the samples are particle---shaped. This project is aiming at developing effective specimen preparation method for particle samples with different size.

### **Flexible optoelectronic devices based on halide perovskites**

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

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

### **Spin transport dynamics in hybrid perovskites**

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

Hybrid perovskites are the fast-rising star in photovoltaic and other optoelectronic applications, because of their excellent merits including large light-absorption coefficients, adjustable bandgaps, and cost-effectiveness. However, prior research centered on photo-induced charge transport, and few studies have focused on spin transport in hybrid perovskites. In this new domain of research, several key questions remain unanswered regarding quantitatively evaluating the mechanism of spin relaxation in such hybrid materials. In this regard, clarification of the spin-dynamics and spin-transport properties within hybrid perovskites is essential for fundamental science. The project is also expected to have significant impact on spintronic devices and storage applications with multifunctionality.

### **Collective behaviour in synthetic molecular motors**

*Supervisor:* Shelley Wickham  
*Co-supervisor:* Anna Waterhouse  
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*Grand Challenge:* Physics in Medicine & Biology

We are building autonomous, programmable nanorobots to navigate through the body to detect and treat early disease. Nature uses swarming to achieve complex behaviour from the interaction of many simple units. Army ants link themselves together to form rafts and bridges, and neurons in a brain fire off signals that collectively create intelligence. We have made molecular robots out of DNA, which can navigate a maze (Nat. Nanotech. 2012, 7, 169). In this project the student will design and test DNA walkers that can work together, and use them to explore greater complexity in function through collective behaviour. This will lead to sophisticated nanorobot swarms that can interact to diagnose disease in the body.

## 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's 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 advance 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  
*Email contact:* archil.kobakhidze@sydney.edu.au  
*Grand Challenge:* Fundamental laws & the Universe

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

### *Experimental projects:*

#### **Investigations of Standard Model processes at the Large Hadron Collider**

**Supervisor:** Prof Kevin Varvell  
**Email contact:** kevin.varvell@sydney.edu.au  
**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 fitting 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 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 semileptonic B-meson decays in early data from the Belle II experiment**

**Supervisor:** Prof Kevin Varvell  
**Co-supervisor:** Dr Chia-Ling Hsu  
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**Grand Challenge:** Fundamental laws & the Universe

The Belle II experiment at the SuperKEKB electron-positron collider in Japan completed a commissioning run in 2018, and started data-taking for physics in early 2019. Belle II will primarily aim to study rare decays of B mesons. In this project, Belle II data from the first year of data-taking will be examined to study “semileptonic” decays of B mesons, where the products of the decay are a lighter meson than the B, a charged lepton such as an electron, muon or tau, and a corresponding neutrino. Decays of this type enable us to probe fundamental parameters of the Standard Model of particle physics (SM), and to search for possible evidence for the SM breaking down.

#### **Improving the measurement of rare decays at Belle II through track-driven clustering**

**Supervisor:** A./Prof. Bruce Yabsley  
**Email contact:** bruce.yabsley@sydney.edu.au  
**Grand Challenge:** Fundamental laws & the Universe

Rare decays of B mesons provide sensitive probes of new physics. The Belle experiment, at KEK in Japan, recorded several billion events over its long data-taking run (1999-2010) and broke new ground in rare decay measurement. The new Belle II experiment, which started data-taking for physics in 2019, will take a sample fifty times larger than Belle; it also includes many improvements to the detector, its electronic readout, and its reconstruction algorithms. One of the sub-detectors, the electromagnetic calorimeter, is particularly important for rare decays, and recent development work in Canada, Germany, and here in Sydney aims to give the calorimeter new capabilities. In this project you will have the opportunity to apply this work to improve rare decay searches at Belle II, using a published Belle analysis (2010) as a template, and a basis for comparison. Rare decays are an important part of the Belle II physics programme, and this project will allow you contribute to this ongoing work.

### *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 ; The Nano and Quantum world

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 to detect new forces via topological interactions, such as the Aharonov-Bohm scattering, in relatively simple tabletop experiments.

#### **Detecting dark matter with DNA**

*Supervisor:* Prof Céline Boehm

*Co-supervisor:* Dr Cíaran O'Hare, Prof Zdenka Kuncic

*Email contact:* ciaran.ohare@sydney.edu.au

*Grand Challenge:* Fundamental laws & the Universe ; The Nano and Quantum world

Decades of observational evidence have confirmed that the bulk of the mass in the universe is comprised of dark matter. The quest to experimentally measure the particle properties of this mysterious substance is now one of the most important in modern physics and is being driven by an extremely active research community. Given the vast array of candidate particle models for dark matter and the great difficulty in detecting any one, new and novel types of detector are increasingly being investigated. One of these new ideas exploits recent advances in biological technology to construct an experiment consisting of a large number of strands of sequenced DNA. Particles, such as dark matter from our galaxy, that interact inside the detector will cause a sequence DNA strands to break. Since the sequence of bases in each strand in the detector can be carefully selected, we can immediately identify which strands were broken, and then locate and reconstruct particle tracks to nanometer precision. The idea is interdisciplinary and highly novel. While there are initial suggestions that the experiment would work, a full feasibility study is still required.

This work will be primarily computational in nature, but with background theory containing elements of particle physics, biophysics and astrophysics. The project would initially involve running simulations of particles interacting with a network of DNA strands and analysing the resulting tracks. The feasibility study would need to determine how the track of DNA strand breakings could be used to 1) identify which type of particle interacted, 2) measure the particle's energy, and 3) determine its incident direction. This study would be the first of its kind, and of great interest to the wider dark matter detection community.

## Photonics and optical science

### **Self-similar laser pulse propagation**

*Supervisor:* Martijn de Sterke  
*Co-supervisor:* Antoine Runge  
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*Grand Challenge:* The Nano and Quantum world

Self-similarity is a generic phenomenon in optics, according to which light pulses may propagate without changing their basic shape, even though the pulse length and energy may change. A well-known example is propagation of parabolic pulses, which become increasingly narrow and more energetic, but which retain their parabolic shape. This pulse shape depends on the detailed properties of the dispersion, the way in which the refractive index depends on frequency. We are interested in optical fibres with very unusual dispersion properties, which are likely to have unusual self-similar pulses. This project can have elements of laboratory work, mathematical analysis of the pen-and-paper variety, and numerical simulations. The weights of each of these can be adjusted to suit the student.

### **Short adiabatic tapers with loss**

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

A basic and very important functionality in optics is to transfer light from one waveguide to another. Though this sounds easy, in fact it is not. The two waveguides may have wildly different cross sections and impedances, both of which lead to strong reflections. Adiabatic couplers may act as bridges that efficiently connect the two guides, but the problem is that adiabatic implies “long,” and that is not always realistic. We have several theoretical and numerical projects in this general area. There are fantastic claims about very short adiabatic couplers, which merit investigation. These were developed in atomic physics for transferring electrons between levels, which, surprisingly, is described by the same equation as light in a waveguide. We are also interested in the effect of absorption losses, which has no analogy in atomic physics.

### **DDMEBT-polymer composite: a new nonlinear material**

*Supervisor:* A/Prof Stefano Palomba  
*Co-supervisor:* Dr Alessandro Tuniz, Prof Martijn de Sterke  
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*Grand Challenge:* 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 synthesised the polymeric version of this material, which is easier to handle. In this project, we want to measure the DDMEBT-polymer nonlinear optical properties by using the z-scan technique. However, our z-scan currently is not performing as expected. We think that it requires the installation of a reference arm which will reduce enormously the background generated by the laser fluctuations. Hence, we need to install and test the reference arm and demonstrate the expected performance. At this point we would be able to measure the new material nonlinear optical properties.

### **Nanostructured light trapping for single photon detectors**

*Supervisor:* Shouyi Xie  
*Co-supervisor:* Benjamin Eggleton  
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*Grand Challenge:* The Nano and Quantum world

Highly sensitive single-photon detector is an enabling technology and vital in optical quantum communication, LIDAR, and biological and medical imaging. Single photon avalanche diodes (SPAD) based on Si are widely used in practical applications due to their advantages of small size, low cost and room temperature operation but suffer from relatively low photon detection efficiency. This project aims to improve the efficiency of SPAD by enhancing the light absorption in Si with the aid of nanostructures. In this project you will gain understanding on the interaction of light with nanostructures and Si. You will design and optimise the size, material and pattern of nanostructures through simulation, and then fabricate them on SPADs in the state-of-the-art cleanroom at Sydney Nanoscience Hub. The performances of the nanostructured SPADs will be characterised to demonstrate the impact of light trapping on the photon detection efficiency. You will build up your experimental, simulation and programming skills from this project.

### **Novel soliton-based fibre lasers**

*Supervisor:* Martijn de Sterke  
*Co-supervisor:* Antoine Runge  
*Email contact:* martijn.desterke@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

Fibre lasers have many advantages over conventional lasers, including a superior beam shape and robustness. This makes this the laser of choice for many applications, ranging from material processing, to sculpting the shape of the cornea. Fibre lasers based on solitons have the additional advantage that the temporal pulse shape is intrinsically optimal, and therefore does not require additional tuning. However, current soliton fibre lasers are limited in energy, which in turn limits their applications. In this laboratory-based project you will characterise and develop a novel type of soliton fibre laser, which promises all advantages of conventional soliton fibre lasers, but can also operate at high power. In addition to experiments you will also learn about nonlinear physics, and the properties of solitons.

### **Novel nanolasers: a brighter future for photonic integrated devices**

*Supervisor:* A/Prof Stefano Palomba  
*Co-supervisor:* Prof Martijn de Sterke  
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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. Currently we have been able to measure the fluorescence from these nanowires but not lasing yet.

### **Upconverting nanoparticle in DNA-linked plasmonic dimer for biosensing**

*Supervisor:* A/Prof Stefano Palomba  
*Co-supervisor:* Dr Hien Duong (Pharmacy)  
*Email contact:* stefano.palomba@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

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

### **Waveguide-coupled 2D materials for spontaneous parametric down conversion (SPDC) generation and collection**

*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 coupled into the waveguide and ready to be entangled and used directly on-chip. The project will first entail a linear and nonlinear characterization of the samples which are produced at ANU.

### **Sensitive Nonlinear Optical Measurements of Ultra-Thin Media**

*Supervisor:* Alessandro Tuniz  
*Co-supervisor:* Martijn de Sterke, Stefano Palomba  
*Email contact:* alessandro.tuniz@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

In recent years, a wide range of materials have shown extremely large optical nonlinearities when their thickness approaches the atomic scale, with massive implications in ultra-compact quantum optics and nonlinear signal processing. However, measurements of nonlinear properties have been extremely poor, due to the lack of sensitive techniques – at times yielding discrepancies of more than two orders of magnitude for nominally identical samples! In the Nanophotonics and Plasmonics Advancement Lab, we have recently developed an extremely sensitive technique for measuring nonlinearities. This project aims for a systematic and consistent experimental analysis of the nonlinear properties of several emerging materials using this new technique, including two-dimensional materials, highly nonlinear polymers, and noble metals. This is an experimental project for students interested in hands-on experience in a state-of-the-art optics laboratory.

### **Solitons with complex phase**

*Supervisor:* Martijn de Sterke  
*Co-supervisor:* Tristram Alexander  
*Email contact:* martijn.desterke@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

Media with dispersion (i.e., refractive index depends on frequency) and nonlinearity (i.e., refractive index depends on intensity) exhibit all kinds of wonderful properties, which are still being investigated and even discovered. The recent discovery of solitons supported by the interplay of nonlinearity and higher-order dispersion has led to an explosion of new directions for nonlinear wave research. Understanding the implications of precisely controlled linear wave properties in nonlinear waves is still in its infancy, however one recent finding is that self-localised waves with a complex internal structure may exist. The properties of these solutions are currently unknown, and some look to be of forms never seen before. Significant new physics in this field appears to have been missed due to the previous focus on nonlinear rather than linear properties.

### **A Neurophotonic Platform as Universal Nerve Interface - I**

*Supervisor:* A/Prof Stefano Palomba  
*Co-supervisor:* Prof Martijn de Sterke  
*Email contact:* stefano.palomba@sydney.edu.au  
*Grand Challenge:* Physics in Medicine & Biology

We have assembled a team of experts whose combined expertise is essential to develop a universal nerve interface (UNI). It is well known that genetically modified photoactive neurons can be differentiated from pluripotent embryonic stem cells (ESC). In this project we will progress this further. Furthermore, we will tackle and solve challenges which will lead to developing an integrated photonic device, simply constituted by a light guide and a grating to couple light in/out of it, embedded inside a polymeric film; this will serve as a light source/collector for the photoactive neuron. In this project we need to 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.

### **Improving transmittance of polycaprolactone fibres**

*Supervisor:* Professor Simon Fleming  
*Co-supervisor:* Dr Ivan Rukhlenko and Dr Syamak Farajikhah  
*Email contact:* ivan.rukhlenko@sydney.edu.au  
*Grand Challenge:* Physics in Medicine & Biology

Polycaprolactone (PCL) fibres fabricated using the standard fibre drawing technique are indispensable in tissue engineering but can hardly be used for light guiding applications, because of the strong natural opacity of PCL ( $>50$  dB/m) at room temperature. It is possible to overcome this limitation and significantly reduce the optical losses in PCL by rapidly cooling it down to avoid crystallization and preserve its amorphous structure. This project aims at enhancing the transmittance of PCL fibres by their rapid cooling using liquid nitrogen, and exploring the optical, mechanical, and structural properties of the thus prepared polymer fibres. You will fabricate, post-process, and characterise PCL fibres at our fibre draw facility at the Institute of Photonics and Optical Science (IPOS). This project is likely to result in a high-impact publication in a peer-reviewed physics or material science journal.

### **How do light and sound interact at low temperatures?**

*Supervisor:* Professor Benjamin Eggleton  
*Co-supervisor:* Dr Moritz Merklein and Dr Atiyeh Zarifi  
*Email contact:* moritz.merklein@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

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.

### **Storing light as sound on a chip**

*Supervisor:* Professor Benjamin Eggleton  
*Co-supervisor:* Dr Moritz Merklein  
*Email contact:* moritz.merklein@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

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 optical information to slow traveling acoustic waves – phonons. The difference in velocity of optical and acoustic waves is around 5 orders of magnitude. 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. 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.

### **Non-hermitian Adiabatic Systems: A Coupled Mode Approach**

*Supervisor:* Alessandro Tuniz  
*Co-supervisor:* Martijn de Sterke  
*Email contact:* alessandro.tuniz@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

Hermitian systems can describe a wide range of physical phenomena (e.g., propagation in a waveguide) to predict the evolution of eigenstates via unitary operations with real Eigenvalues. Recently, coupled non-Hermitian systems, i.e. which are lossy and have complex Eigenvalues, have received much attention. While the properties of lossless coupled systems are well known, their non-Hermitian counterparts exhibit rich physics that is not yet understood. We are interested in plasmonics, where metals (which are lossy) enable deep-subwavelength confinement, accompanied by huge field enhancements. This project dives into a complete description of coupled non-Hermitian photonics for efficient energy transfer to deep subwavelength volumes. It would suit those interested in pen-and-paper theory combined with state-of-the-art numerical modelling.

### **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.

## 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 be used in workshops with school teachers and students across the country, from Darwin to Armidale. They have the potential to be published in journals.

## Quantum physics and quantum information

### *Experimental projects:*

#### **Ground-state cooling and high-fidelity detection of large ion crystals in a Penning trap for quantum simulations**

*Supervisor:* Robert Wolf  
*Co-supervisor:* Michael J. Biercuk  
*Email contact:* robert.wolf@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

Trapped atomic ions are a leading candidate system for experiments in quantum simulation, through which we attempt to realize a controllable quantum system capable of simulating more complex, uncontrolled quantum systems. This project will focus on the development of quantum simulation experiments using large ion crystals in a Penning trap. This effort will build on successful experimental demonstrations of quantum simulation using 300 qubits, and will leverage new insights into the control 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 Control of Trapped Ytterbium Ions**

*Supervisor:* Cornelius Hempel  
*Co-supervisor:* Michael J. Biercuk  
*Email contact:* cornelius.hempel@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

The Quantum Control Laboratory is an experimental research group focused on the control and manipulation of the internal states of trapped ions as model quantum systems. In particular, we are interested in studying new techniques to perform quantum logic operations in a manner that is robust against errors. This can be accomplished through the application of a special sequence of control operations designed to counteract the buildup of error due to uncontrolled environmental coupling. The project will focus on the implementation of such control protocols using a novel, ultra-low-noise microwave system that permits arbitrary manipulation of a ytterbium atom's quantum state. This project will be conducted within the new Sydney Nanoscience Hub. Experience gained in this project will cover atomic physics, magnetic resonance, microwave systems, and quantum control. Multiple projects are on offer within this heading.

### **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.

### **Quantum Simulation for Quantum Chemistry**

*Supervisor:* Cornelius Hempel  
*Co-supervisor:* Michael J. Biercuk  
*Email contact:* cornelius.hempel@sydney.edu.au  
*Grand Challenge:* The Nano and Quantum world

The Quantum Control Laboratory is an experimental research group focused on the control and manipulation of the internal states of trapped ions as model quantum systems. We have developed new experimental capabilities allowing the trapping and coherent manipulation of chains of ions in a RF Paul trap. We are seeking to leverage new theoretical concepts developed by our group in order to realize the simulation of chemical reactions using real quantum coherent hardware. This project will be conducted within the new Sydney Nanoscience Hub. Experience gained in this project will cover atomic physics, laser-atom interactions, microwave systems, and quantum control.

### **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.

### *Theoretical projects:*

#### **Exotic Quantum Many-Body Systems for Quantum Computing**

*Supervisor:* Stephen Bartlett  
*Co-supervisor:* Steven Flammia  
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*Grand Challenge:* Fundamental laws & the Universe ;The Nano and Quantum world

Quantum computers are potentially much more powerful than the computers we use today, but building a quantum computer is a huge challenge. Most proposals to construct one involve building it from scratch “atom by atom”. What we have shown is that certain materials, when cooled down to a very low temperature, will naturally form a quantum computer on their own. This way, we may be able to get nature to build our quantum computers for us: we just have to find (or synthesize) the right material, then put it in the fridge. This theory project will be to investigate the zero- and low-temperature quantum phases of some promising spin lattices, and develop techniques for quantum computation that are robust against variations in the Hamiltonian, thermal errors, or other deleterious effects. It will make extensive use of techniques from quantum theory, statistical mechanics, and linear algebra, and will appeal to students with an interest in analytical techniques from mathematics as well as theoretical physics.

#### **The Power of Quantum Computing**

*Supervisor:* Stephen Bartlett  
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*Grand Challenge:* Fundamental laws & the Universe ;The Nano and Quantum world

What gives quantum computers their power? We don't have a good answer to this question. One approach to answering it involves developing (classical) simulation methods for quantum processes. If we can efficiently simulate a quantum circuit on a classical computer, then clearly it's not 'quantum powerful'. This theory project will involve coding up a new approach to simulating quantum circuits by using 'negative probabilities', and testing how well these simulations run, with a goal of isolating the key quantum resources.

#### **Quantum computing with Majorana fermions**

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*Grand Challenge:* The Nano and Quantum world

Majorana fermions are exotic particles that exist in certain one-dimensional quantum systems. One of their most fascinating properties is that they can be used as carriers of quantum information in a quantum computer. It is, however, largely an open question how to best enact a quantum computation using Majorana fermions, and several competing proposals are currently investigated by the research community. In this theory project we will develop new quantum computing schemes with Majorana fermions and attempt to quantify their potential. The project will include close interactions with Microsoft Quantum — Sydney, who are working on realizing Majorana fermions in the lab.

#### **Practical quantum error correction**

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*Grand Challenge:* The Nano and Quantum world

Quantum computers exploit exotic properties of quantum mechanics such as entanglement and superpositions to perform computational tasks that are impossible for conventional computers. Given that quantum states are very fragile and superpositions only survive for fractions of a second in real systems, it might seem that quantum computers are an impossible dream. One of the most surprising scientific discoveries of the last few decades is that this is, in fact, not the case, thanks to two basic ideas: quantum error correction and fault-

tolerance. In this theory project we will develop practical error correction schemes for quantum information encoded into bosonic modes. An example of a bosonic mode is a standing wave of the electromagnetic field between two mirrors, or the electromagnetic field in a quantum LC circuit. This is currently one of the most promising approaches to quantum error correction and a very active area of both theoretical and experimental research. There are several possible student opportunities within this, with a mix of numerical and analytical work.

### **Circuit quantum electrodynamics**

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*Grand Challenge:* The Nano and Quantum world

When electrical circuits are cooled down to milli-Kelvin temperatures, the metal becomes superconducting and currents and voltages start to behave quantum mechanically. It is essentially a circuit realisation of quantum electrodynamics. This gives us an ideal playground for both exploring light-matter interaction at a very fundamental level, and developing new technology based on “quantum electronics.” In fact, this platform is arguably the most promising approach to quantum computing today, and several tech companies (e.g., Google, IBM and Rigetti Computing) have recently decided to invest heavily in this technology. In this theory project we will think outside the box and investigate new ways to both store and manipulate quantum information in superconducting quantum circuits. There are several possible student opportunities within this project.

### **Quantum interference phenomena to improve transmission probability of electrons through barriers**

*Supervisor:* Professor David R McKenzie  
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*Grand Challenge:* The Nano and Quantum world

This project is about the use of quantum interference to improve electronic devices such as CMOS logic gates, solar cells and light emitting diodes. In recent work we have applied the time dependent Schrodinger equation implemented in a one dimensional simulation to create the matter wave analogy of an optical antireflection coating, in which wave reflection from an interface between two materials can be suppressed, causing enhanced tunnelling probability. Specifically, a new barrier in front of an existing barrier can increase the transmission probability of electrons. We will explore this approach for improving the efficiency of solar cells and other devices as well as extending the understanding of how disorder in an array of potential wells can give rise to localised electronic states in a solid .

(This project is predominantly theoretical, but has opportunities for a strategic experiment in nanofabrication.)

## Sustainability

### **Development of plasma activated coatings on particulate surfaces**

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*Grand Challenge:* A Sustainable Future

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.

### **Optimizing and demonstrating passive radiative cooling**

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*Grand Challenge:* A Sustainable Future

A surprising consequence of the theory of black body radiation is that surfaces with appropriately designed properties may cool without energy input, even when placed in the full sun. The cooling power of approximately 100 W/m<sup>2</sup> arises because the surface reflects sunlight (which peaks in the visible part of the spectrum), and so it is unaffected by it. The surface is also designed to act as a black body at wavelengths around 10 μm, where the Earth's atmosphere is transparent—the surface can therefore dump energy directly into deep space, which has a temperature of a few Kelvin. Surfaces that are suited for this are invariably complicated: they have different constituents and are non-uniform. We have several different projects in this area, which can be numerical (determining the radiative properties), surface design and fabrication, or experimental (measuring their properties), or combinations of these.

### **Turning air into water**

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*Grand Challenge:* A Sustainable Future

Water is becoming an increasingly precious, and scarce, resource. A recently funded Sydney Nano Grand Challenge proposes to tackle this problem by capturing water directly from the atmosphere. However, there are significant theoretical challenges to be overcome before any successful implementation. Heat exchange occurs between the water-laden air and any water capture surface, and this will depend on local flow conditions, while the ability to cool a surface will depend on the atmospheric conditions, and also on how the water is captured. This project will examine the interplay of these effects, and ultimately determine how best to optimise water capture. This will inform the experimental investigations in the Grand Challenge, and open up a new pathway for harvesting water in dry conditions.