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Physics Honours Projects: 2022

This document lists a number of potential honours research projects within the School of Physics, together with supervisor contact details and a paragraph describing each of the projects. These are only some of the opportunities available, and *you are welcome to explore other possibilities with potential supervisors*. If you are free, please also join us for the **Honours Information Session at 12:00 on Monday 6th September**.

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

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

Thank you for your interest in physics honours.

Bruce Yabsley, Honours Coordinator (physics.honours@sydney.edu.au), 1st September 2021

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Grand Challenge Projects

Algorithmic Rules for Nanoscale Brain Navigation

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

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

Positronium Interference in the magnetic field of a PET-MR scanner

Supervisor: Dr Yaser Gholami
Co-supervisor: Prof. Annette Haworth, A./Prof. Bruce Yabsley, Prof. Steven Meikle (Medical Imaging), Dr Georgios Angelis (Health Sciences)
Email contact: yaser.gholami@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology; Positronium and Cancer Grand Challenge Grant

PET-MR multimodal imaging is becoming an important diagnostic tool in cancer imaging and has rapidly progressed from the prototype stage to systems that are increasingly being used in clinics.

In **positron emission tomography**, as much as 40% of positron annihilation occurs through the production of positronium (Ps) atoms (i.e. a hydrogen-like positron–electron complex) inside the patient's body. The decay of these Ps atoms is sensitive to physical (e.g. magnetic field) and biological (e.g. metabolism) factors. These factors can impact the PET imaging quality (e.g. spatial resolution). Positronium has two ground states, the zero spin para-positronium (pPs) with antiparallel (↑↓) orientation of the positron and electron spins, and the ortho-positronium (oPs) triplet state with parallel spins (↑↑). In theory in a PET/MR scanner, the MR magnetic field can mix the states of p-Ps and o-Ps with a zero spin projection onto the direction of the field. This can impact the spatial resolution of PET-MR images due to the residual momentum of p-Ps and o-Ps at the time of decay (i.e. the lack of collinearity of the annihilation photons).

The aim of this project is to perform a series of in-vitro/silico studies to investigate the interference of Ps states in the MR magnetic field. Simultaneous PET-MR (with different MR sequences) and PET-only (with the PET scanner outside the MR magnetic field) images will be acquired with a pre-clinical PET-MR scanner in the Brain and Mind Center. The spatial resolution of the PET images will be measured, and to study the Ps statistics, PET images will be analysed in LIST mode.

Students will preferably have experience in using a modern computing language (Python, MATLAB), good physics knowledge (PET/MR), and a solid understanding of medical imaging.

Lightsail dynamics

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

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

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Astronomical and space science

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

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

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

Asteroseismology: probing inside stars using stellar oscillations

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

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

Dissecting the assembly history of Milky Way Analogues with MUSE data from the Very Large Telescope

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

How galaxies assemble their mass and angular momentum is one of the fundamental questions in Astronomy. In recent years we have gained enormous insights in how our Milky Way was formed. However, the Milky Way is only one galaxy and to assume all galaxies follow the same formation path is perhaps somewhat naive. Nonetheless, the Milky Way remains by far the best-studied galaxy in the Universe and is considered a benchmark for understanding galaxy formation. By studying "Milky Way Analogues" we can challenge the existing paradigm that our Galaxy is the Rosetta Stone of galaxy formation. In this project we will use the state-of-the-art spatially-resolved optical spectroscopic observations of seven Milky Way Analogues to study their formation history in exquisite detail. We will explore the stellar archaeology, dynamics, and dark matter content of nearby Milky Way-like galaxies to place our own Galaxy in its proper cosmological context.

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Inflows and Outflows in Milky Way Analogues with MUSE data from the Very Large Telescope

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

The Milky Way is by far the best-studied galaxy in the Universe and is considered a benchmark for understanding galaxy formation. However, the Milky Way is only one galaxy, and by studying "Milky Way Analogues" we can challenge the existing paradigm that our Galaxy is the Rosetta Stone of galaxy formation. In this project we will study the inflow and outflow of ionised gas in such a Milky Way Analogue. Characterising the rates of gas flow is crucial for understanding the details of the "galactic fountain" model, where gas is first blown out of the disk by exploding stars and eventually cools and rains back down. The state-of-the-art spatially-resolved optical spectroscopic observations of edge-on Milky Way Analogue (such as UGC10738), will provide unique insights in this galactic fountain model from an extragalactic perspective.

Machine and Deep Learning Applied to Galaxy Morphology and Kinematics

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

The taxonomy of galaxies determined from their visual morphological properties has been a powerful tool to advance our knowledge on the processes that shape galaxies, with Hubble's classification scheme from 1926 still in active use today. Machine and Deep Learning applied to galaxy morphology is becoming increasingly popular and effective to accurately classify galaxies. Besides the morphology of galaxies, resolved stellar kinematic measurements now provide a unique look into the dynamical properties of galaxies. In this project, we will use traditional machine learning algorithms as well as Deep Learning to combine the information from visual and kinematic morphology to obtain the most insightful classification of galaxies. We will use data from the SAMI Galaxy Survey, a project pioneered at the University of Sydney, combined with the MaNGA Galaxy Survey and investigate in detail the properties of ~13000 galaxies to unravel the formation and evolution of galaxies.

Extreme Events: Exploring the Dynamic Radio Sky with ASKAP

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

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

Carbon under Extreme Pressure

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

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

Interferometry with the JWST space telescope

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

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

The Riddle of the Red Square

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

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

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The TOLIMAN space telescope

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

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

Imaging Newborn Exoplanets

Supervisor:	Peter Tuthill
Co-supervisors:	Barnaby Norris, Marc-Antoine Martinod
Email contact:	peter.tuthill@sydney.edu.au
Grand Challenge:	Fundamental laws & the Universe

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

Machine-learning applied to solar flare prediction

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

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

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

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

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

Deeper imaging of distant stars through polarisation of light

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

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

Developing a photonic technology to image distant exoplanets

Supervisor:	Barnaby Norris
Co-supervisor:	Sergio Leon-Saval, Christopher Betters
Email contact:	barnaby.norris@sydney.edu.au
Grand Challenge:	Fundamental laws & the Universe, Artificial Intelligence and Physics

Directly imaging a habitable, Earth-like exoplanet is a massive goal in exoplanet science, as the observed light can yield information on the distant planet's orbit, surface structure, weather and even the presence of life (biosignatures). But this is not yet achievable by even this biggest telescopes, due largely to the blurring caused by peering through the Earth's turbulent atmosphere.

In this project you will help develop a pioneering technology to tackle this problem, which uses novel photonic technologies (such as the Photonic Lantern) combined with advanced data processing to undo the blurring of the astronomical image and extract the faint light of the planet signal contained within. There are multiple aspects to this endeavour including photonics development, laboratory experiments, simulation and data analysis software development, and deep learning, providing scope to customise the project according to your interests.

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Unravelling the history of the Milky Way's halo with Gaia

Supervisor:	Ciaran O'Hare
Email contact:	ciaran.ohare@sydney.edu.au
Grand Challenge:	Fundamental laws & the Universe

The European Space Agency's revolutionary astrometry mission Gaia has mapped almost 2 billion stars in the Milky Way with unprecedented accuracy. This huge dataset is enabling us to deconstruct the components of the Milky Way and trace out the major events that took place in its 13 billion year history. One of the most surprising discoveries was a vast structure that is invisible to the naked eye, but has left a unique dynamical imprint on our galaxy's stellar halo. The object, known as the Gaia Enceladus-Sausage, is believed to be the debris from one of the Milky Way's last major collisions with a smaller galaxy. This project would involve collating and analysing data from Gaia, as well as other spectroscopic surveys, to map the extent of this structure around our galaxy and determine its kinematics and chemistry. It would also be interesting to consider the implications of this structure for ongoing searches for the elusive dark matter.

How metal is your galaxy?

Supervisor:	Dr. Sam Vaughan
Co-supervisor:	Professor Scott Croom
Email contact:	sam.vaughan@sydney.edu.au
Grand Challenge:	Fundamental laws & the Universe

As stars evolve, they fuse light elements like Hydrogen and Helium into heavier ones. The amount of heavy elements in a galaxy's stars (which astronomers call its 'metallicity') is a key quantity to measure, since it gives us clues about the galaxy's history. Even more information is contained in how the metallicity varies at different locations within a galaxy. Does the centre have a higher metallicity than the outskirts? Is one side more metal-rich than the other? Is there a simple relationship between the metallicity and radius from the centre? Recent advances in instrumentation have allowed us to make these measurements for thousands of different galaxies and build up a statistically powerful data set. You will use observations from the SAMI galaxy survey to investigate and characterise how metallicity varies within different types of galaxies. You will then correlate your findings with the extensive additional data available for our targets, hoping to understand why some galaxies show such different metallicity behaviour to others. Experience with python would be useful for this project but definitely not essential.

Optical Fibre Bundles for Hyperspectral Coherent Imaging

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

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

Black holes around active galactic nuclei

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

The LIGO gravitational wave detector has found evidence of stellar black holes with (pre-merger) masses > 40 solar masses (Abbott et al. 2021: https://ui.adsabs.harvard.edu/abs/2021ApJ...913L...7A/abstract). Models of stellar evolution and core collapse suggest that such massive remnants are very difficult to form from the collapse of individual stars at non-zero metallicity, even including the effect of accretion from a companion star. One scenario to get around this problem is that the most massive BHs were formed from stars embedded in the accretion disk of an AGN. Accretion from the surrounding disk material may have caused those stellar BHs to grow to a size a few times higher than their birth mass after a stellar collapse (in the same way that planetesimals grow via accretion from a proto-planetary disk).

A few references to learn more about this process:

Yi et al 2018: https://ui.adsabs.harvard.edu/abs/2018ApJ...859L..25Y/abstract

Tagawa et al 2020: https://ui.adsabs.harvard.edu/abs/2020ApJ...898...25T/abstract

Kaaz et al 2021: https://ui.adsabs.harvard.edu/abs/2021arXiv210312088K/abstract

Wang et al 2021: https://ui.adsabs.harvard.edu/abs/2021ApJ...916L..17W/abstract

Current gravitational wave detectors do not have the spatial resolution to test whether the events are associated with AGN. However, if AGN disks provide a growth environment for stellar BHs, we should find electromagnetic evidence of this population of fast-accreting BHs around nearby AGN. The radiative output of an AGN will, in general, be much higher than the emission from stellar-mass BHs around it; however, in some energy bands or from time variability studies, it may be possible to separate the two contributions. Starting from the known properties (radiation and outflows) of fast-accreting stellar-mass BHs, and from analytic models of accretion disk structure (eg, Frank et al 2002), the student will explore which ranges of AGN mass and accretion rate ranges offer the best chance to detect embedded stellar BHs, and which regions of the AGN accretion disk may be significantly affected by the emission of those BHs.

Location, location, location: how does the environment of the most massive galaxies influence their structure?

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

Most galaxies are rotating disks, like our own Milky Way. However, many of the most massive galaxies (at least 5 times more massive than the Milky Way) are made up of stars on random orbits, and are rotating slowly, if at all. These "slow rotators" are thought to be formed through a variety of violent galaxy-galaxy mergers that randomise and redistribute the orbits of the stars. The slow rotators appear more likely to occur in high density environments (galaxy groups and clusters). However, the exact pathway to form these galaxies is unclear. The SAMI Galaxy Survey (http://sami-survey.org/) has identified many new slow rotators. In this project we will combine the results from SAMI with new ultra-deep imaging from the Subaru Telescope on Hawaii to precisely measure the number and distribution of low mass galaxies surrounding slow rotators. The aim is to compare the environments of the slow rotators to regular rotating galaxies to help us understand exactly what is special about their environment.

Identifying galactic disks like our Milky Way

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

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

How well do galaxies hold onto their dark matter?

Supervisor: Professor Scott Croom
Co-supervisor: Dr Sam Vaughan
Email contact: scott.croom@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

One of the earliest indications that dark matter was present in the Universe was from measuring the rotation curves of galaxies and seeing that they rotated faster than expected given the visible matter present. Dark matter now forms a fundamental part of our current cosmological model. All galaxies are thought to form within dark matter halos. Over time both the halos and the galaxies within them can merge. We see galaxies merge, but it's much harder to see the impact of mergers on dark matter halos. In this project we will use measurements of galaxy rotation curves from the Sydney led SAMI Galaxy Survey (http://sami-survey.org/) to compare galaxy rotation at large radius in different environments. We will compare the rotation curves of galaxies that are isolated to those in groups and clusters. This will allow us to explore how much of the dark matter halo is removed when galaxies fall into the groups and clusters. We will compare the observational results to predictions for numerical galaxy formation simulations.

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

Supervisor: Prof. Iver Cairns
Co-supervisor: A./Prof. Joe Khachan
Email contact: iver.cairns@sydney.edu.au

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

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Plasma depletion layers throughout our solar system and beyond

Supervisor: Prof. Iver Cairns
Email contact: iver.cairns@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

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

Analysis of space weather data from the CUAVA-1 CubeSat

Supervisor: Prof. Iver Cairns
Co-supervisor: A./Prof. Joe Khachan
Email contact: iver.cairns@sydney.edu.au

The CUAVA-1 CubeSat recently launched to the International Space Station and is expected to be deployed into space. Once there it should measure the radiation environment of the CubeSat as a function of time, position, and space weather events at much lower altitudes than for standard international satellites. Using a GPS instrument it should also measure the position of the satellite as a function of time, allowing assessment of the satellite's orbital decay due to both the average ionosphere and also transient atmospheric changes due to space weather events. These two data sets will be compared with other satellite data and used to assess the effects of space weather at the satellite's altitude.

Life on the lightcone: Hunting for Kardeshev III Populations?

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

"Where is everybody?" This question, asked by Enrico Fermi, has been the basis for many arguments about life in the universe. In this project, we will explore the detectability of Kardeshev III populations over the life of the Universe. These are galactic spanning civilisations who harvest the light of the majority of stars in their galaxies, processing stellar light into infra-red waste. We will use the cosmological equations to model the apparent number of such civilisations apparent in surveys of galaxies, firstly for idealised models, and then using realistic scenarios for the evolution of galaxies. This project will involve some analytic work, and numerical analysis using python code, so some experience with programming would be beneficial.

Black Holes, Polarization and Microlensing

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

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

Dark Matter and new physics signatures in the sky

Supervisor: Prof. Céline Boehm
Email contact: celine.boehm@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Understanding the nature of dark matter is one of the last bastions of cosmology and particle physics. Its very existence highlights the need for new physics and could lead to a conceptual revolution in our understanding of fundamental principles. In this project, we will study the signatures of specific dark matter models in the sky (and new physics in general) in light of forthcoming experiments such as CTA and the SKA. This project is at the frontier of particle physics, cosmology and astronomy. Not much prior knowledge is needed but please do expect to code in python.

Mass modelling in clusters of galaxies and dark matter constraints

Supervisor: Prof. Céline Boehm
Email contact: celine.boehm@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Clusters of galaxies are prime targets to study the properties of the invisible matter (the so-called dark matter) that makes up most of the matter in the Universe. In this project, you will model the mass distribution of the dark matter in a distant cluster using HST data (as well as other Astronomy survey data) and constrain dark matter microscopic interactions using their corresponding signatures in the electromagnetic spectrum.

Atomic, molecular and plasma physics

Deposition of robust functionalized coatings on pulse-biased substrates

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

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

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

Supervisor: Prof. David McKenzie and Prof. Marcela Bilek
Email contact: marcela.bilek@sydney.edu.au
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 coatings of pharmaceutical agents for controlled and sustained release

Supervisor: Dr Maliheh Ghadiri, Dr Behnam Akhavan and Prof. Marcela Bilek
Email contact: maliheh.ghadiri@sydney.edu.au
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.

Plasma ion implantation treatment of porous materials

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.

Power-to-X and plasma catalysis: Opportunities for greening emissions-intensive industries, exporting renewable energy, and enabling self-sufficient settlements on Mars

Supervisor: Dr Mark Baldry and Prof. Marcela Bilek
Email contact: mark.baldry@sydney.edu.au
Grand Challenge: A sustainable future

Power-to-X (P2X) describes a suite of technologies that use electricity to drive chemical processes. The simplest example is storing renewable energy by using solar or wind power to electrolyse water, producing hydrogen and oxygen gases. Electrocatalytic and plasma-based P2X technologies can activate stable molecules such as atmospheric carbon dioxide and nitrogen, transforming them into commodities such as net-zero emissions fuels and synthetic fertilisers. In space, P2X technology has the potential to greatly expand our capabilities of in-situ resource utilisation, enabling astronauts and future Martian settlements to be self-sufficient. In this project you will use multiphysics modelling to simulate the interaction of cold plasma with 3D printed catalyst support structures, and design reactors that maximise conversion and selectivity of important chemical processes.

Thermal waves in magnetized and unmagnetized plasmas

Supervisor: Prof. Iver Cairns
Co-supervisor: A./Prof. Joe Khachan
Email contact: iver.cairns@sydney.edu.au

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

Nonlinear wave-wave processes in Earth's ionosphere

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

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

Liouville's Theorem and single particle motions

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

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.

THE UNIVERSITY OF SYDNEY

Biological, biomedical and medical physics

Navigating the brain along its spatial gradients using DNA nanorobots

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

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

Use of machine learning and advanced imaging techniques for biologically optimised radiotherapy

Supervisor: Prof. Annette Haworth
Co-supervisor: Dr Hayley Reynolds, Dr Yu Sen, Dr Rob Finnegan, Dr Jonathan Sykes, Dr Michael Jameson
Email contact: annette.haworth@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

Radiotherapy is a treatment for cancer involving radiation. To significantly improve radiotherapy treatments, the Biofocussed RadioTherapy (‘BiRT’) team is developing predictive models to extract biological information from advanced imaging methods such as multi-parametric MRI, so that quantitative imaging data can be used to optimize radiotherapy treatment planning and follow-up. Our team of researchers are based at the University of Sydney, University of Auckland and at multiple hospitals in NSW. Within our group we have a range of projects on offer including:

(1) predictive model development (using machine learning techniques)
(2) image processing
(3) treatment planning and
(4) magnetic resonance linear accelerators.

Projects may be theoretical and/or experimental. Projects involving the development of predictive models using state-of-the-art methods provide opportunities to develop skills in medical physics, programming, statistics, mathematics and deep learning/ machine learning which can be applied in other domains. Prior experience of Python programming is preferred. Projects involving image processing may include the analysis of multiparametric MRI, PET and other imaging methods for a range of clinical sites including prostate, liver and breast.

THE UNIVERSITY OF SYDNEY

Atmospheric pressure discharges to activate tissue engineering scaffolds during additive manufacturing

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

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

Bioactive interfaces for implantable biomedical devices using plasma discharges

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

In this project you will develop and characterise biocompatible plasma activated interfaces for medical implants using state-of-the-art plasma discharge technologies. The work will develop novel High Power Impulse Magnetron Sputtering (HiPIMS) and Plasma Immersion Ion Implantation processes, aiming to synthesise thin films for improving the biocompatibility of biomedical devices so that they integrate optimally into the host tissue. Precursors for the films can be delivered as sputtered vapour or dip-coated natural materials such as Shellac. Electrical and optical diagnostics will be used to explore the most relevant plasma parameters during the process. The physical and chemical characteristics of the thin-films will be studied using electron microscopy techniques (TEM, SEM, EDS and EELS), nano-indentation, X-Ray photoelectron spectroscopy (XPS), infrared spectroscopy (FTIR) and ellipsometry. The project is highly interdisciplinary and will involve a continuous collaboration with biomedical colleagues, where the biocompatibility and mechanical stability of the plasma coated devices will be further studied using in-vitro and in-vivo techniques.

Developing an antimicrobial coatings from highly dense immobilized quaternary ammonium salts

Supervisor: Dr Clara Tran, Prof Marcela Bilek and Dr Das Ashish Kumar
Email contact: clara.tran@sydney.edu.au
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.

THE UNIVERSITY OF SYDNEY

Microfluidic devices for analysis of blood materials interactions

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

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

Functionalized coatings of pharmaceutical agents for targeted drug delivery

Supervisor: Dr Maliheh Ghadiri, Dr Behnam Akhavan and Prof. Marcela Bilek
Email contact: behnam.akhavan@sydney.edu.au
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.

Next generation hybrid materials for biomedical applications

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

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

Plasma immersion ion implantation for controlled drug release and biodegradation

Supervisor:	Prof Marcela Bilek and Dr Behnam Akhavan
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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.

Complex systems

Modeling the mechanisms of brain stimulation

Supervisor: Ben Fulcher
Co-supervisor: Nigel Rogasch
Email contact: ben.fulcher@sydney.edu.au
Grand Challenge: Artificial Intelligence and Physics; Physics in Medicine & Biology

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

Inferring a computational logic of scientific time-series analysis algorithms

Supervisor: Ben Fulcher
Email contact: ben.fulcher@sydney.edu.au
Grand Challenge: Artificial Intelligence and Physics

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

Brain clearance and sleep

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

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

THE UNIVERSITY OF SYDNEY

Personalised modelling for precision-based medicine

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

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

Fractals and health

Supervisor: Svetlana Postnova
Co-supervisor: Chris Gordon (Woolcock Institute)
Email contact: svetlana.postnova@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology; Artificial Intelligence and Physics

Many physiologic variables in healthy humans and other animals show scale-invariant or 'fractal' properties, i.e., patterns that do not change with increasing observation time. One such variable is motor activity, which is commonly recorded using an accelerometer over many days at a time. Several diseases have recently been linked to reduction of scale invariance in motor activity, which can be used for monitoring, diagnosis, and intervention. This project will use numerical and machine learning approaches to investigate differences in scale invariance in accelerometry of healthy people and patients with sleep disorders. The project is expected to contribute to advanced understanding of sleep disorders and development of diagnostic tools that can be integrated in smartwatches for day-to-day monitoring.

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

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

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

Googling the brain: Search of associative memory

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

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

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

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

One of the most fundamental problems about the brain is how it computes. To answer this question, we have presented a concept of distributed dynamical computation (DDC), in which neural computation or information processing is carried out by interacting, propagating neural waves. This concept can merge dynamical and computational perspectives of the brain, which used to have great gaps between each other. The project will involve making further links between neural dynamics and computations, including studying the neural circuit models developed by our group to reveal the physical principles of key brain functions such as visual processing and attention.

The physics of deep learning in artificial intelligence

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

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

What makes a community on a social network?

Supervisor: Tristram Alexander
Co-supervisor: Prof. Eduardo Altmann (Mathematics)
Email contact: tristram.alexander@sydney.edu.au
Grand Challenge: Physics and Society

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

Network models of language dynamics

Supervisor: Tristram Alexander
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Grand Challenge: Physics and Society

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

Condensed matter physics and materials physics

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

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

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

3D printed Metamaterials

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

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

Metal-doped two-dimensional monolayers as electrochemical catalysts for CO2 reduction: A first-principles study

Supervisor: Catherine Stampfl
Co-supervisor: Oliver Conquest
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Grand Challenge: The Nano and Quantum world; (Sydney Nano:) CO_2 Zero

With increasing environmental and energy-related concerns, the efficient use of CO_2 has received considerable attention. Converting CO_2 into a chemical fuel is particularly meaningful for reducing the influence of the greenhouse effect. However, the CO_2 molecule is stable, and its electro reduction reaction (CO_2 ERR) requires a considerable overpotential. Therefore, tremendous effort has been devoted to developing effective electrocatalysts. Recently, borophene, a two-dimensional (2D) material, and 2D alloys, namely transition metal dichalcogenides (TMDCs), have recently been shown to exhibit promising catalytic properties for this purpose. In this project, the effectiveness of such 2D materials will be investigated using ab initio quantum mechanical calculations, performed on the national supercomputer, to determine the reaction energetics and pathways and thus to identify potential new candidate catalysts and to understand the underlying physical and chemical properties (structure-property relationships) that are responsible for the predicted improved performance.

Twistronics: First-principles investigations of twist dependent properties and transport in 2D heterobilayers

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Grand Challenge:	The Nano and Quantum world; (Sydney Nano:) Computational Materials Discovery

Two-dimensional (2D) mono-component bi-layer or hetero-bi layer structures have been explored recently due to their novel electronic, photonic, optical and transport properties. Such properties have been identified through a concerted effort of both theorists and experimentalists by analyzing a variety of different multi-layer structures of potential relevance for future nano-electronic devices. The weakness of the van der Waals interaction, the principal force that binds the layers, makes the change in stacking angle of 2D materials feasible. This is in contrast to the strong chemical bonding involved in the interfaces between bulk materials. Therefore, a large variety of new 2D hetero-structures can be fabricated. The variation of the twist angle in these heterostructures has given rise to various phenomena such as moiré excitons, topological superconductivity and non-conventional superconductivity. This project will explore the impact of twisting (rotational stacking) on the physical properties, e.g. vertical charge transfer and electron transport, in graphene/boron-nitride bilayer, with/without intercalants/dopants using density functional theory (DFT), and the non-equilibrium Greens function approach, respectively. It will examine the bilayers for a number of twist angles that introduce minimal strain to the system. Identification of twist-induced changes in the properties could have an impact on enhancing the applications of two-dimensional twisted structures in nano electronics.

Sensing signature of disease in the human body: Quantum mechanical Electron transport calculations

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Co-supervisor:	El-Abed Haidar
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Grand Challenge:	The Nano and Quantum world; (Sydney Nano:) Computational Materials Discovery

Two-dimensional (2D) nanomaterials display a spectrum of new and exotic properties that are not found in their three-dimensional analogues. However, many of technical hurdles in the utilization of such low-dimensional nanomaterials in target devices still exist, and many of them originate from our lack of fundamental understanding. These atomically thin, 2D structures hold promise for a variety future technologies including nanoelectronics, photonics, sensing, energy storage and opto-electronic devices. The most well-known of such structures being graphene. Recent advances have been made in many "beyond graphene" materials, e.g. transition metal dichalcogenides, borophene, phosphorene etc, are attracting attention as potential next-generation low-cost transistor biosensors that may permit single-molecule detection. In this project, we will use quantum mechanical first-principles calculations to investigate the sensing capability of a number of 2D nanoribbons, via change in the electron transport and resulting current-voltage characteristics, of small molecules (e.g. hydrogen peroxide, nitric oxide) which can be a signature of disease in the human body.

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Data science

Detecting misinformation on a social network

Supervisor: Tristram Alexander
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Grand Challenge: Physics & Society

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

Neuromorphic AI

Supervisor: Zdenka Kuncic
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Grand Challenge: Artificial Intelligence and Physics

A new physically-motivated neural network algorithm has been developed based on the physics of electrical switching junctions with memory, mimicking synaptic weights that self-adapt to dynamically changing input signals. This is in stark contrast to weights in abstract neural network AI algorithms, where weights need to be trained for a particular task and are not adaptive, resulting in "catastrophic forgetting" and the inability to multi-task. In Neuromorphic AI, only the output weights need training, which can be achieved with very computationally efficient linear methods (because the network transforms the input signals into a higher dimensional feature space, where the signals are linearly separable). Neuromorphic AI has demonstrated transfer learning, prediction of chaotic signals and image classification using basic machine learning datasets. This project aims to demonstrate the potential of Neuromorphic AI as an efficient compact AI technology operating at the extreme edge – in space. The project will involve developing an application for efficient image and video classification on board satellites, i.e. without access to cloud-based resources.

Nanoscience

Atomic-scale understanding of the degradation of halide perovskites

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

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

In-situ STEM investigation of photocatalysis for water splitting

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

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

Molecular Nanorobotics

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

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

Multi-functional nanocarriers for targeted therapeutics and imaging

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

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

Neuromorphic Nanowire Networks

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

Nanowire networks exhibit intriguing neuromorphic properties, including a complex neural network-like structure, memory and emergent higher-order functionality arising from their synapse-like electrical nano-junctions (see Adv. Phys. X Review). Two promising research directions for nanowire networks are:

(i) **Neuro-inspired information processing**: with their recurrent connections, neuromorphic nanowire networks can be implemented in a reservoir computing framework, where only output weights are trained, thus vastly improving efficiency over conventional neural network methods (see Physics Dialogues YouTube video). Basic machine learning tasks have already been demonstrated, paving the way to demonstrate more complex, signal processing tasks.

(ii) **Neural interface bioelectronics**: due to the high interconnectivity and synthetic synapses, nanowires can mimic neuron action potential "spikes", suggesting they could be used as a neural "bridge" to restore communication between damaged or dysfunctional neural regions; one application currently in progress is a retinal interface, where the nanowire network augments a microelectrode chip to produce neuromorphic electrical signals that can aid the visual cortex to better reconstruct images for the blind or visually impaired (see Sydney Nano Grand Challenge Unlocking the Neural Interface).

Projects are available in each of these research areas. Both involve experimental and computational modelling and data analysis methods.

Particle physics

Experimental projects:

Investigations of Standard Model processes at the Large Hadron Collider

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Grand Challenge: Fundamental laws & the Universe

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

Studying rare B-meson decays at the Belle II experiment

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

The Belle II experiment at the SuperKEKB electron-positron collider in Japan commenced data-taking for physics in early 2019, and has so far accumulated data from some 200 million pairs of B-meson decays. Belle II primarily aims to study rare decays of B mesons in order to search for physics beyond the Standard Model of Particle Physics. A student doing this project will have the opportunity to collaborate with scientists from around the world working on Belle II, and examine real and simulated data from the experiment in order to help search for rare decays which include leptons and missing neutrinos amongst the decay products. Such decays can be sensitive probes of new physics. There is scope for projects for more than one student, and the work would be suitable both for standalone honours projects and for projects leading into subsequent PhD research.

Graph Neural Networks as a tool for discovery in particle physics

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

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

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

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Grand Challenge: Fundamental laws & the Universe

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

Utilising Deep Learning in Rare B-meson decays at the Belle and Belle II experiments

Supervisor: Dr Chia-Ling Hsu
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Grand Challenge: Fundamental laws & the Universe

Rare decay processes in B-meson decays provide a unique opportunity to explore "new physics" beyond the Standard Model of particle physics. This is the primary aim of both the Belle and Belle II experiments. So-called charmless B-meson decays to two hadrons, e.g. $B^+ \to \eta' K^+$, are some of the most interesting cases, because they provide good probes to search for new sources of matter-antimatter asymmetry, which is the key to explain the matter-dominance of the universe. Searching for rare events of interest from data containing a large amount of background is very challenging and requires sophisticated approaches to suppress the background level. This project will explore how much advanced machine learning techniques, such as Deep Learning, can improve the significance of measurements in rare B-meson decays.

Development of new detection techniques:

CYGNUS: a large-scale directional dark matter detector

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

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

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

Supervisor:	A/Prof Bruce Yabsley
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Grand Challenge:	Fundamental laws & the Universe

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

Theoretical projects:

Discovering new forces in quantum measurements

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Grand Challenge:	Fundamental laws & the Universe

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

Electroweak monopoles

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Grand Challenge:	Fundamental laws & the Universe

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

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Cosmological phase transitions in a model of parallel Universes

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

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

Primordial black holes from cosmic phase transitions

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

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

Quantum gravity, asymptotic symmetries and gravitational instantons

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

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

Informing the search for dark matter using galaxy simulations

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

We have extremely strong evidence that our galaxy is embedded in a vast halo made up of an invisible material called dark matter. The quest to uncover the particle identity of this substance has driven the development of some of the most sensitive particle physics experiments ever performed. Nevertheless, dark matter remains undetected. As this has been going on, in the astrophysics community, decades of extensive computational work has resulted in the extraordinarily sophisticated numerical simulations needed to understand the complex processes involved in the formation of galaxies. The outputs of these simulations are fake galaxies that look remarkably like our own Milky Way. As well as normal luminous matter, these simulations must also track the dark matter halos of their galaxies. We therefore have a unique opportunity to gain insight into what terrestrial dark matter experiments should be seeing by analysing the dark matter halos surrounding these Milky Way analogues. This project would be a blend of astrophysics and particle physics. The work would involve manipulating data from large hydrodynamic simulations, extracting the dark matter distribution around the "fake" Earth's location, and using this to predict the particle physics signals for a range of hypothesised dark matter particle candidates.

Photonics and optical science

Enhancement nonlinear optical effects—solitons on a (power) budget

Supervisor: Martijn de Sterke
Co-supervisor: Antoine Runge, Tristram Alexander
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Saying that something is linear is a well-defined statement; saying that some is nonlinear is everything else. Nonlinear optical effects come in many variations, one of which is that the refractive index depends on the light intensity. Even though nonlinear optical effects are weak, nonlinear optics has evolved into a huge field with applications such as in medical diagnostics, communications and lasers. However, these applications could be much more widespread if the nonlinear effects can be enhanced, somehow. We recently discovered a novel way to do so and demonstrated this in the lab; the solitons that we generated require 3.5x less energy than conventional solitons—a substantial reduction. However, this was just the first step. This is a theoretical and numerical project that aims to better understand this novel phenomenon, to investigate its limits, and to see how it can be pushed further.

Black and white holes in an optical fibre

Supervisor: Martijn de Sterke
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Grand Challenge: Fundamental laws & the Universe

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

High-energy solitons in microresonators

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

THE UNIVERSITY OF SYDNEY

How exceptional: nonlinear topological photonics

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

Nonlinear optics plays a pivotal role for in many of applications, including high-resolution microscopy, all-optical signal processing, and quantum information. Unfortunately, most materials possess a weak optical nonlinearity, which limits practical applications, requiring large power consumption and long propagation lengths. Overcoming these limitations requires an enhancement of the interaction between light and matter. In parallel, it was recently observed that the topology of "open" photonic states (i.e. which can lose or gain the total energy) can be very sensitive to the environment, near the so-called exceptional point. We believe that these states' topology also provides a pathway for large optical nonlinearities. This work aims at elucidating how the topology of these photonic states is related to their nonlinear response, and will inform next-generation compact integrated photonic circuit designs. This project is suitable for students who are interested in theoretical and numerical analysis.

A few-atom terahertz source

Supervisor: Alessandro Tuniz
Co-supervisor: Antoine Runge
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Grand Challenge: The Nano and Quantum world

Terahertz frequencies are at the heart of several enabling multidisciplinary technologies, including security, telecommunications, and medical diagnostics. However, they are quite challenging to produce, and typically require large, complicated, and expensive opto-electronic setups. Terahertz frequencies can also be generated using nonlinear optics using optical rectification, which is a second order nonlinear effect. Recent years have shown that two-dimensional materials – which are only a few atoms thick – exhibit extreme second order nonlinear effects. This project aims at experimentally constructing a terahertz source using recently fabricated two-dimensional materials, in collaboration with the Fraunhofer institute (Germany). This project is suitable for students interested in hands-on experience in state-of-the-art experimental facilities.

Optical fibers enhanced with two-dimensional material

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Grand Challenge: The Nano and Quantum world

The last years have shown increased effort to unveil and understand the electronic and photonic properties of monolayers materials, known as two dimensional materials. These materials exhibit a number of amazing properties, e.g., extreme nonlinearity, spin-valley-coupling, and excitons with unprecedented binding energy, which make them appealing for a whole range of possible applications in photonics. We have recently grown high quality layers of two-dimensional materials on the exposed core of an optical fiber: the field at the core surface can thus interact with the two dimensional material over long lengths, as opposed to over a few atoms. This project will experimentally investigate the nonlinear properties of such monolayer-enhanced fibers, with particular attention to nonlinear frequency conversion. This project is suitable for students interested in hands-on experience in state-of-the-art experimental facilities.

A Neurophotonic Interface – I

Supervisor: A/Prof Stefano Palomba
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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. We will use an optical microscope equipped with a nanopositioner in order to test a photonic implant by which we can control photoactive neurons. The chip will be fabricated by our collaborators at ANU and needs to be tested in Sydney.

In this project, we aim to deliver the proof of concept of a working photonic chip which can bidirectionally communicate with photoactive neurons.

A Neurophotonic Interface – II

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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. We will use commercial laser scanning confocal system located at the CMRI (Westmead), to probe that our genetically modified neurons are photoactive as expected. In this project, we aim to deliver the proof of concept of our ability to prepare permanently photoactive neurons.

Optical nose: a revolution in mobile sensing

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

The Holy Grail in molecular sensing, is the capability to detect and identify any individual molecule in a mixture, like pollutants in air (CO2, CH4) or water (hydrocarbons, nitrides), biomarkers for diseases in body fluids (DNA, exosomes), very small pathogens in air/breath (coronaviruses, influenza).

Raman scattering is the ideal physical phenomenon for the detection and identification of any type of individual molecule. However, it is very difficult to harness due to its low efficiency. Hence, it needs to be enhanced. This is conventionally achieved by immobilising the molecule to a metallic nanoparticle or substrate, via a molecule-specific binding compounds ("labelling").

We will use a nanoscale gap between two metal films, the metal-dielectric-metal (MDM) configuration, where the light intensity is tightly confined and strongly increased. This will lead to a large, uniform, reproducible and deterministically enhanced Raman scattering signal. In this project we will use two gold nanorods as an MDM platform and as a precursor and proof of concept for a fully integrated version. We aim to prove that the MDM nanorods act as a waveguide for Enhanced Raman Scattering.

THE UNIVERSITY OF SYDNEY

Novel nanolasers: a brighter future for photonic integrated devices

Supervisor: A/Prof Stefano Palomba
Co-supervisor: Prof Anita Ho-Baillie
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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 proof 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.

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

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Grand Challenge: The Nano and Quantum world; Physics in Medicine & Biology

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 nanosphere. 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 nanosphere. Only when this system interacts with a specific molecule of interest, such as a specific biomarker, e.g. cancer biomarker, then one of the DNA links is broken and the upconverting nanoparticle will emit visible light. The gold nanorod serves as an enhancer of the light emission. This system can be used as background-free biosensing method. 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) and 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. Once of the approaches is to generate single photons on demand, identical (spectral purity) and in high quantity. One potential solution to this problem is to use nonlinear optical phenomena, such as spontaneous parametric down conversion (SPDC), i.e. pumping the material at low optical wavelength (such as 750 nm) and observe the generation of correlated (produced at the same time and with correlated properties) photon pairs. These can then be entangled on-chip and used for modern QOIP. However, the ideal source of correlated photon pairs has to be demonstrated yet. Here we want to detect the SPDC from a 2D material deposited on a Si integrated waveguide. In this way we hope to increase the light-matter interaction and enhance the production of correlated photon-pairs which will be already couple into the waveguide and ready to be entangled and used directly on-chip. The project will first entail a linear and nonlinear characterization of the samples which are produced at ANU.

THE UNIVERSITY OF SYDNEY

Pattern formation in high dimensional systems

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

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

Photonics processor in Silicon

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

Vibrations in silicon at MIR

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

THE UNIVERSITY OF SYDNEY

Storing light as hypersound on a photonic chip

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

Interplay of light and hypersound at 1Kelvin?

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

Enabling laser communications in space with multimode photonics

Supervisor: Sergio Leon-Saval
Co-supervisor: Christopher Betters
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NASA is developing a trailblazing, long-term technology demonstration of what could become the high-speed internet of the sky. Laser communications, also known as free-space optical communications, encodes data onto a beam of light, which is then transmitted between spacecraft and eventually to Earth terminals. SAIL labs have recently partnered with NASA Goddard Space Flight Centre to investigate the use of multimode photonics and mode converters known as photonic lanterns coupled to a 1 metre diameter telescope as the earth-based link optical receivers. The aim of the project will be to model, design, fabricate and test a new generation of photonic lanterns multimode to few-mode convertors for this project in direct collaboration with our partners in NASA Goddard Space Flight Centre and NASA Glenn Research Centre.

Photonic Lantern Adaptive Optics Coherent Combiner

Supervisor: Sergio Leon-Saval
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Photonic lanterns - efficient multimode to single-mode convertors devices are a very fascinating technology currently used in Astronomy and Telecommunications. Those optical devices convert light from a set of co-propagating optical modes with different spatial electromagnetic distributions into a set of identical optical modes at different fibre ports and vice versa. The unique properties of photonic lanterns also enable dynamic control of the beam intensity and phase, which has enormous potential for advanced highspeed adaptive optics beam shaping and adaptive optics. This project will study an alternative approach to coherently combine a multimode signal into one single-mode optical fibre -hence, achieving an all-fibre based AO system for the first time. This project will have a strong experimental laboratory component.

Physics of neuromorphic systems

The neuromorphic nose for medical diagnostics

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Grand Challenge: Artificial Intelligence and Physics

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

Quantum physics and quantum information

Quantum Control and Quantum Computation with Trapped Ytterbium Ions

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

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

Spin-qubit quantum computing

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

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

Trapped Ion Crystals and Large-Scale Entanglement

Supervisor: Robert Wolf
Co-supervisor: Michael J. Biercuk
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Grand Challenge: The Nano and Quantum world

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

THE UNIVERSITY OF SYDNEY

Investigating materials for a quantum internet

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

--- Background: --- Machines that capitalise on the quantum behaviour of light and matter have the potential to dramatically accelerate advances in science and technology. However, the development of powerful quantum machines is restricted because each machine is isolated: there is no quantum internet to connect them to one another. The quantum technology sector needs researchers like you to create the quantum internet and this project aims to develop materials and knowledge to take on that challenge. --- Project: --- This project will focus on crystals embedded with the rare-earth ion erbium (an element that is essential to today's classical internet infrastructure). The project will develop experiments to test the quantum optical and spin properties of erbium ions and probe interactions at the atomic scale. You will work in the new Quantum Integration Laboratory housed in the Sydney Nanoscience Hub, and have the opportunity to interact with other quantum research groups from Australia and around the globe. You will gain experience in fields including experiment design, quantum light-matter interactions, cryogenic systems, and magnetic resonance.

Quantum integration of light and atomic spins in a crystal

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

--- Background: --- A key challenge within quantum science and technology is to create strong interactions between light and atomic spins at the quantum level. Experiments targeting this goal have long been instrumental in developing our understanding of the quantum world. Today, these same experiments form the basis for quantum internet technology, which aims to link up quantum computers and create entanglement on a global scale. However, these are significant challenges that require researchers like you to help make important breakthroughs. --- Project: --- This project will focus on designing and fabricating optical cavities from crystals containing the element erbium. The project will develop microscale optical cavities that have very narrow resonances, and build up an experimental system to measure the cavities at room temperature and in a dilution refrigerator at <100 mK. These cavities can then be used to couple light to erbium atoms embedded within them. You will work in the new Quantum Integration Laboratory housed in the Sydney Nanoscience Hub, and have the opportunity to interact with other quantum research groups from Australia and around the globe. You will gain experience in fields including experiment design, crystal machining, optical fibres, quantum light-matter interactions, and cryogenic systems.

Simulating tunable quantum magnets using light and atoms

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

Computing the ground state or the dynamics of quantum systems composed of many spins is a formidable task. For this reason, there is significant interest in building a quantum system where such spin dynamics can be simulated. In this project you will analyse the interactions between atoms via the emission of photons when atoms are placed in an environment where the photon emission can be controlled. Such environments can be realised by placing atoms near a photonic nanostructure or by placing atoms near a periodic array of other atoms. By tuning the photon emission, one can control the coupling between atoms which can be used to simulated tunable interactions between spins. A quantum simulator using this principle can be potentially realized in microwave circuit QED systems or using cold atoms.

Designing a protocol for optically linking superconducting qubits

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

--- Background: --- Superconducting qubit systems are one of the leading quantum computing platforms. Superconducting qubits operate at microwave frequencies and need to be maintained at temperatures near absolute zero to avoid thermal noise swamping the quantum signals. The consequence is that superconducting quantum computers cannot be connected in a network beyond the refrigerator in which they are housed. Researchers like you are needed to take up the challenge to build an optical network to transfer quantum signals between superconducting qubits. --- Project: --- This project will focus on designing and characterising a protocol to create entangled pairs of photons. One photon will be at microwave frequencies and the other photon will have a wavelength in the infrared telecommunication band. The protocol will be based on ensembles of erbium ions embedded in crystals that are coupled to optical and microwave cavities. You will develop approximate analytical models and numerical models of the photon pair source and use these models to test the performance of the protocol. You will work within the new Quantum Integration Laboratory team based in the Sydney Nanoscience Hub, and have the opportunity to interact with other quantum research groups from Australia and around the globe. You will gain experience in cavity QED, theory of emitters in crystals, collective atom dynamics, and quantum light-matter interactions.

A classical model for quantum computing

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

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

Renewable Energy

Polymer Free Glass Bonding for Solar Glazing

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

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

Characterising defects in perovskite materials and solar cells

Supervisor: Anita Ho-Baillie
Co-supervisor: David McKenzie
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Grand Challenge: The Nano and Quantum world; A Sustainable Future

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

Durable perovskite tandem solar cells

Supervisor: Anita Ho-Baillie
Co-supervisor: David McKenzie
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Grand Challenge: The Nano and Quantum world; A Sustainable Future

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

Metal halide perovskites for solar cells in space

Supervisor: Anita Ho-Baillie
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Grand Challenge: The Nano and Quantum world; A Sustainable Future

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

Physics of the hydrogen economy

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

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

Sustainability

Atmospheric water capture

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Co-supervisor: Alex Song (electrical engineering)
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Grand Challenge: A Sustainable Future

One of the global grand challenges of the 21st century is the provision of clean water. Although we have had rain in recent months, not long ago almost the entire state of NSW was drought-declared. At 70% humidity and at 20° C, a cubic meter of air contains 12 grams of water and at 30° C it is as much as 21 grams! Is it possible to harvest this moisture in a sustainable way? In an interdisciplinary project with colleagues in chemistry, biology, engineering, architecture, we are developing a technology that does exactly this. The water condenses on a cool surface where it forms droplets and which can then be collected. The process relies on passive cooling, the cooling of a surface below the ambient, by thermal radiation, through the atmosphere, into space, which has a temperature just above absolute zero. This type of cooling requires no energy input and has no moving parts—it is therefore perfect for remote, off-the-grid locations where maintenance is difficult. Suitable materials for this require strong reflection of sunlight and strong emission of IR radiation. This is a numerical modelling project of the optical properties of materials the aim of which is to identify materials that are suitable for this purpose.

Development of plasma activated coatings on particulate surfaces

Supervisor: Prof Marcela Bilek and Dr Behnam Akhavan
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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.

Probabilistic Disaggregation and Downscaling of Economic Material Flows

Supervisor: Dr Arunima Malik
Co-supervisors: Dr Richard Scalzo (DARE), Dr Mengyu Li
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Grand Challenge: A Sustainable Future

Understanding of whole-of-economy environmental impacts and material flows is path-critical for shifting transitioning linear economies towards sustainability and/or into circularity. Datasets on material flows are not only very large, but span a wide range of geographic scales; detailed data at small scales are often missing or inferred. These missing data give rise to uncertainties that, unless fully quantified, incurs risk on policy or business decisions made with reference to them. This project will develop a probabilistic modelling framework for uncertainty quantification of economic flows using hierarchical Bayesian techniques, capturing causal structure among material flows that might include waste, energy, water, and/or carbon. Problems to be addressed within this framework might include disaggregation of flows where small-scale data are unavailable; downscaling of flows to finer-grained economic areas; and prediction where data are wholly unavailable, including forecasting.