Physics Honours Projects: 2024

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 11th 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), 7th September 2023

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Grand Challenge Projects

Lightsail dynamics and Doppler damping

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

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

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Astronomical and space science

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

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

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

Characterizing Exoplanets with the NASA TESS Mission

Supervisor: Dan Huber
Email contact: daniel.huber@sydney.edu.au

Planets orbiting stars other than the Sun can be detected through a periodic decrease in brightness (transits) as planets move across the disc of the host star in the line of sight of an observer. The depth of the transit depends on the size of the planet relative to the size of the star, while the frequency of observed transits yields the orbital period. The characterization of transiting planets relies on our knowledge of the host stars: if the stellar size and mass are precisely known, the size of the planet and the orbital separation from its host star can be measured.

The NASA TESS mission has collected brightness measurements of hundreds of thousands of stars to detect transiting planets. TESS data are also uniquely suited to measure stellar oscillations, which can be used to precisely constrain the mass, radius, and age of planet host stars. The project will involve analyzing TESS light curves using Fourier transforms to detect transits and measure stellar oscillations, which can be combined to characterize exoplanets.

Asteroseismology: probing inside stars using stellar oscillations

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

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

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Chasing Stellar Fireworks: Unveiling the Secrets of Radio Stars with ASKAP

Supervisor: Laura Driessen
Co-supervisor: Tara Murphy
Email contact: laura.driessen@sydney.edu.au

Radio stars are active, magnetic stars that have explosive flares many times larger than the flares from our Sun. Exploring the behaviour and properties of flares and bursts from radio stars is important for understanding plasma physics, magnetic dynamos and more. For example, a star with extreme space weather events would make any planets it hosts uninhabitable. Until now, astronomers have only been able to investigate the flares of individual stars, but new telescopes mean we can survey the sky for hundreds of stars at a time.

In this project you will explore cutting-edge data from the new ASKAP telescope to investigate a new sample of radio stars detected for the first time. This work will be the first large-scale study for stellar radio flares, and will give you the opportunity to learn skills in astronomy, data analysis and Python coding (previous programming experience is not required).

Application of the Gauss separation theorem to vector magnetograms

Supervisor: Michael Wheatland
Email contact: michael.wheatland@sydney.edu.au

Electric currents in the solar corona provide the energy for solar flares. However, the determination of coronal currents depends on coronal magnetic field models constructed from vector magnetic field values determined for the low solar atmosphere (the photosphere), and there is considerable uncertainty in the results. Although it is well-known in the fields of terrestrial and planetary magnetism, the Gauss separation theorem has only recently been applied in solar physics (Schuck et al. 2022). This technique allows identification of which components of the field in the photospheric boundary are due to the currents in the corona. In principle this additional information can be used to improve coronal field models, and better determine the coronal currents. This project will investigate the application of the Gauss separation theorem to vector magnetic field data for solar active regions, and to coronal magnetic field models.

Black holes in the distant Universe

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

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

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.

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

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

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

Plasma depletion layers throughout our solar system and beyond

Supervisor:	Iver Cairns
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.

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

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

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

Earth. Similar calculations will be performed for model shocks in the coronas of other stars and assessed for their observability by the Murchison Widefield Array and the Square Kilometer Array.

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

Supervisor: Iver Cairns
Co-supervisor: Associate Professor Joe Khachan
Email contact: iver.cairns@sydney.edu.au

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

The Life and Time of Satellite Planes

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

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

Testing the Cosmological Principle

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

Our cosmological models are built on the idea that the universe is homogeneous and isotropic. But is it? In this project, we will develop new tests of this cosmological principle, exploring whether the large-scale distribution of distant objects is truly homogeneous as expected, or if the foundations of cosmology are on shaky ground. We will approach this through the generation of synthetic catalogues of galaxies and the application of Bayesian hypothesis testing considering spherical harmonics over the sky. In the project, you will learn the concepts of modern cosmology and key statistical approaches. Some experience with programming would be beneficial but not essential.

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.

Interferometry with the JWST space telescope

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

With its launch in 2021, the James Webb Space Telescope inherited 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, and ideally placed at the L2 Lagrange point, the JWST has begun a unique mission of discovery. Flying aboard is a unique interferometric imaging experiment designed, built and led from the University of Sydney. This aperture masking interferometer in the NIRISS instrument will empower the JWST to make the finest and most sensitive surveys for the presence of faint structures in the environment of forming stars that have ever been achieved. This opens an entirely new window on the origins of stars and planets, informing our own origins and place in the universe as well as expectations for the ubiquity and diversity of life in the Galaxy. Your role will be to bring this powerful new instrument to its first observations.

The TOLIMAN space telescope

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

The TOLIMAN space telescope is a Sydney University led initiative to detect and characterize Earth analog planets within the immediate solar neighborhood. Our mission will exploit astrometric detection — the registration of the minute deflection of the star's position as it is perturbed by gravitational reflex motion due to a rocky planet in orbit in a temperate orbit. The primary target is our nearest stellar neighbor: the Alpha Centuri system. The project forms a key stepping stone in the audacious Breakthrough Starshot initiative which aims to send humanity's first high speed robotic probe to interstellar space. 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
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.

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Biological, biomedical and medical physics

Developing and applying deep learning methods in medical imaging data

Supervisor: Annette Haworth
Co-supervisor: Yu Sun, Erin Wang, Joel Poder
Email contact: annette.haworth@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

SAM (Segment Anything Model) is an open source model published by Meta. It's trained on Meta's large natural image dataset (SA-1B, with 1.1 billion masks) and has a strong ability to comprehend edges and objects. It can be used as a zero/few-shot learning model, i.e. requiring very little fine tuning to adapt to a new environment. While SAM is not directly related to medical data, its output provides a potential stepping stone to achieve segmentation of tumours and organs efficiently. This is because most segmentations in medical imaging data are based on boundaries such as the interfaces between normal and malignant tissues. Hence one can pick the segments from SAM's output to match with the ground truth when ground truth data is available. Since ground truth data, such as tumor sub-volume delineation, is not always available, the development of AI-based models for automated segmentation using these data is challenging. Clustering is a form of unsupervised learning can be performed on the imaging data. Clustering neighboring voxels into relevant subvolumes offers an important first step for downstream tumor segmentation. Typically, the signal intensity of each voxel with spatial information (e.g., the coordinate of the voxel) is used in the clustering. However, this approach doesn't make use of the additional rich features available in the imaging data. Therefore, within this study the value of radiomics features and deep features in the context of clustering will be investigated. Multiple patient data sets collected by the University of Sydney BiRT team (https://birt.sydney.edu.au/) will be made available for this study, the aim of which is to investigate the value of SAM in segmenting subvolumes in medical images when ground truth data is available, and clustering when ground truth is not available.

Navigating the brain along its spatial gradients using DNA nanorobots

Supervisor: Shelley Wickham
Co-supervisor: Ben Fulcher
Email contact: shelley.wickham@sydney.edu.au
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.

Simulating the Production of Reactive Species in Water for Cancer Therapy

Supervisor: Prof. Davd McKenzie
Co-supervisor: A./Prof. Ann Kwan (SOLES)
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

New software approaches are becoming available that can simulate how radiation interacts with water molecules to produce short lived reactive species that we use in our bodies to generate energy from the oxygen in air that we breathe. In a new development, we have discovered how these species can help make better treatments for cancer. This project will add to our knowledge of the behaviour of such interesting species as: individual electrons dissolved in water ("hydrated electrons"), the radical anion made from an oxygen gas molecule by adding an electron ("superoxide anion") and the radical obtained by tearing off one of the hydrogen atoms from a water molecule ("hydroxyl radical"). These species are easy to make by mixing ionised gases from a plasma with water and will be examined using density functional theory, computer simulation (GEANT4-DNA) and experimental synthesis methods specialised to produce and examine the properties of radical species.

The Physics of Dynamic Double Layers in Aqueous Electrolytes for Biosensing

Supervisor: Prof. David McKenzie
Co-supervisor: Mr Enyi Guo
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: Physics in Medicine & Biology

When a conductive electrode is placed in an ionic liquid and has an electric potential applied to it that differs from that of the body of the electrolyte, a double layer forms in a time-dependent manner that reflects the conditions occurring at the surface of the electrolyte. We will study the dynamics of double layer formation and relaxation using a finite element method. We will show how the detailed time response enables the detection of a binding event when a molecule tethered on the surface binds to another targeted molecule. This is a new type of sensitive biosensor that will be trialled to detect the presence of antibodies in blood, using as an example the antibody generated in motor-neurone disease. The student taking this project will become familiar with finite element methods for studying physical problems and learn about the emerging science of biosensing using nanotechnology.

Molecular Nanorobotics

Supervisor: Shelley Wickham
Email contact: shelley.wickham@sydney.edu.au
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.

Complex systems; Data science

Modelling brain clearance during sleep

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

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

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

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

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

Inferring canonical statistical signatures of nonlinear dynamics

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

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

Detecting misinformation on a social network

Supervisor: Tristram Alexander
Email contact: tristram.alexander@sydney.edu.au
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.

Network models of language dynamics

Supervisor: Tristram Alexander
Email contact: tristram.alexander@sydney.edu.au
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.

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".

THE UNIVERSITY OF SYDNEY

Brain vortices: new pathways to understanding brain dynamics

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

Cortical neural circuits are complex, non-equilibrium systems whose collective dynamics cannot be described solely in terms of oscillations or low-dimensional aperiodic (chaotic) dynamics. Recently, we have developed a method that enables us to make new discoveries regarding the physical principles of neural circuits. For instance, we have found dynamic coherent patterns, such as vortices, which orchestrate spatiotemporal dynamics of cortical circuits (see our paper on this topic: https://www.nature.com/articles/s41562-023-01626-5). This exciting discovery likens brain dynamics to those observed in turbulent fluids, where a hierarchy of vortices is likewise embedded within stochastic spatiotemporal processes. This project will entail further refinement of this innovative method, encompassing the analysis of neural data gathered by our collaborators at Imperial College London. Additionally, the project will involve expanding the neural circuit models developed by our research group to model brain vortices. The outcome of this project would significantly advance our understanding of the physical principles of brain dynamics. For this project, students will have the opportunity to acquire essential skills in big data analysis and modelling.

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

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

One of the most fundamental questions regarding the brain is how it carries out computation. To answer this question, we have formulated a concept of distributed dynamical computation (DDC), in which neural computation and information processing occur through interactions of propagating wave packets. DDC serves as a bridge that integrates the previously disjointed perspectives of brain dynamics and computation. Recently, we have demonstrated that within the framework of DDC, wave packets can efficiently implement sampling-based probabilistic computations [Qi and Gong, Nature Communications 2022; Chen and Gong, Science Advances 2022; Wardak and Gong, Phys Rev Lett 2022]. The project will involve establishing further connections between neural dynamics and computations, which will include an in-depth study of the neural circuit models developed by our research group. The goal of this exploration is to unveil the underlying physical principles governing crucial 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

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

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 possesses a vast capacity, encompassing all the knowledge, facts, and experiences accumulated over a lifetime. With this extensive store of information, retrieving any specific piece of data from memory presents a formidable computational challenge. Indeed, this mirrors the challenge encountered by internet search engines, which must adeptly organize information to facilitate the retrieval of relevant items in response to queries. Consequently, understanding the dynamic mechanisms that underlie memory searching within the brain is of both fundamental and practical significance. Recently, we have developed a biologically plausible neural circuit model capable of quantitatively replicating key aspects of memory retrieval. This project will entail further refinement of the model, integrating the latest experimental findings to unravel the principled dynamics of memory searching. These dynamics will subsequently serve as the foundation for the development of a pioneering search algorithm applicable to the extensive data repository, analogous to the one utilized by the Google search engine.

Condensed matter physics; Materials physics

From Defects to Devices: Designing atomic defects for quantum technologies

Supervisor: Catherine Stampfl
Co-supervisor: Oliver Conquest
Email contact: catherine.stampfl@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

CO2 – From a Problem into a Solution

Supervisor: Catherine Stampfl
Co-supervisor: Oliver Conquest
Email contact: catherine.stampfl@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

THE UNIVERSITY OF SYDNEY

Quantum Mechanics Enables Efficient Electrolysis for the Hydrogen Economy

Supervisor: Prof. David McKenzie
Co-supervisor: Mr Kevin Sun
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: The Nano and Quantum world

We are researching the pathways by which electrons make the journey between a platinum metal electrode and ions in water solution, motivated by more efficient ways of producing hydrogen as a medium for transporting and storing energy. There is still much to learn about the subject of water electrolysis which straddles physics and chemistry, and we have an active program underway that is revealing interesting new roles for quantum mechanical tunnelling in solution and challenging existing ideas about how thermodynamics applies to nanoscale phenomena. The student undertaking this project will learn about the ways in which quantum ideas can be applied to electrochemical reactions. There are opportunities for both theory and experimental work to increase our understanding of how to make hydrogen with the best use of energy available in the environment.

Associations of Light Elements in Carbonaceous Cosmic Dust

Supervisor: Prof. David McKenzie
Co-supervisor: Ms Linda Losurdo
Email contact: david.mckenzie@sydney.edu.au
Grand Challenge: The Nano and Quantum world

The light elements carbon, hydrogen, oxygen and nitrogen are the most common chemically active elements in the Universe. Their condensation from gases produces dust that undergoes aggregation to form larger bodies of comets, meteors and ultimately planets. In this project we will investigate the formation of solid network structures of these elements by carrying out first principles molecular dynamics simulations to predict their structure and infrared spectra for comparison with observational data from the James Webb space telescope and laboratory synthesised dust. Some of the questions we seek to answer are: what are the most common groups of atoms that form naturally by condensation from the gas phase as a function of the initial composition? Can we use composition to select for certain chemical groups in a synthetic process using electronic excitation of the gases to make useful products? The student undertaking the project will learn skills and methodologies of wide applicability in physical science.

THE UNIVERSITY OF SYDNEY

Particle physics

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

Supervisor: Theresa Fruth
Email contact: theresa.fruth@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

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

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

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

Sustainability in Particle Physics: The carbon footprint of dark matter searches

Supervisor: Theresa Fruth
Email contact: theresa.fruth@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Particle physics investigates the most fundamental constituents of matter, trying to enhance our understanding of the world around us. These endeavours often involve building large, bold experiments. In a world, where climate change is a reality, it is essential that particle physics is aware of its own carbon footprint and moves towards more sustainable practises to stay in play.

The aim of this project is to calculate the carbon footprint of the LUX-ZEPLIN experiment, a current world-leading dark matter search and identify the main sources of emissions. The results will inform the ongoing planning of the next generation dark matter experiment. The student on this project will analyse the different components of LZ's circulation, cryogenic and high voltage systems, and gain a thorough understanding of the detector technology in the process.

Novel probes of dark matter and dark energy

Supervisor: Yevgeny Stadnik
Co-supervisor: Archil Kobakhidze
Email contact: yevgeny.stadnik@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Models of dark matter and dark energy involving ultralight fields coupled to standard-model fields predict variations in the fundamental "constants" of Nature (which include, e.g., the fundamental particle masses and parameters describing the strengths of the fundamental interactions). This project explores novel phenomenological aspects of such models, including precision experiments in the laboratory, as well as astrophysical and cosmological probes.

THE UNIVERSITY OF SYDNEY

Investigation of integrating Neural-Network-based algorithms into Level I Trigger system at the Belle II experiment

Supervisor: Chia-Ling Hsu
Email contact: chia-ling.hsu@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

Real-time processing on data from the detector at the Belle II experiment is challenging due to the luminosity increase achievable with the SuperKEKB electron-positron collider. The real-time Level-I Trigger System at the Belle II experiment, based on FPGA chips, is indispensable in extracting physics-oriented data from the continuous data flow. In this project, we will study the development of Neural-Network algorithms based on a topology trigger using information on K-long clustering and muon tracking in Belle II's KLM sub-detector. The work would suit students with an interest in getting fundamental knowledge of detector physics, developing an algorithm for high energy experiments from scratch, and implementation of algorithms in FPGAs.

Utilise Deep Learning in Rare B-meson decays at the Belle II experiment

Supervisor: Chia-Ling Hsu
Email contact: chia-ling.hsu@sydney.edu.au
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 one of the primary aims of the Belle II experiment.

B-meson decays via charmless processes into two hadrons are one 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-dominant 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.

Studying rare B-meson decays at the Belle II experiment

Supervisor: Prof Kevin Varvell
Email contact: kevin.varvell@sydney.edu.au
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 400 million pairs of B-meson decays. Belle II primarily aims to study rare decays of B mesons in order to search for physics beyond the Standard Model of Particle Physics. A student doing this project will have the opportunity to collaborate with scientists from around the world working on Belle II, and examine real and simulated data from the experiment in order to help search for rare decays which include leptons and missing neutrinos amongst the decay products. Such decays can be sensitive probes of new physics. There is scope for projects for more than one student, and the work would be suitable both for standalone honours projects and for projects leading into subsequent PhD research

THE UNIVERSITY OF SYDNEY

Investigations of processes involving top quarks at the Large Hadron Collider

Supervisor: Kevin Varvell
Email contact: kevin.varvell@sydney.edu.au
Grand Challenge: Fundamental laws & the Universe

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

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

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

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

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

Supervisor: Bruce Yabsley
Email contact: bruce.yabsley@sydney.edu.au
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.

THE UNIVERSITY OF SYDNEY

The last electron-proton interactions and their possible imprint in the radio sky

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

This project will explore the fate of the Bremsstrahlung photons associated with the last electron-proton interactions during the epoch of recombination. In particular, we will investigate whether they survive absorption processes in the Universe and if they can leave a visible imprint in the radio sky which could be detected eventually by radio experiments (such as the SKA). Extension to dark matter interactions with standard model particles may be considered depending on the progress. This project requires knowledge of Cosmology and Particle Physics. You will need to compute cross sections, numerically solve the evolution of energy distributions, as well as (if time allows) perform a spherical harmonics decomposition of the signal across the sky. The work is based on https://arxiv.org/pdf/2204.13711.pdf

A new theory of modified gravity and implications for the growth of large-scale-structures in the Universe

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

An alternative to Dark Matter particles is to modify the theory of general relativity. However this is quite difficult to achieve and only one theory of modified gravity have successfully reproduced observations of the Cosmic Microwave Background so far, namely AeST (see https://arxiv.org/abs/2007.00082). This project aims to understand how large-scale-structures (galaxies etc) form in such a theory based on the results from https://inspirehep.net/literature/2650533. The project will require a lot of coding and a definite taste for Cosmology and theoretical concepts.

THE UNIVERSITY OF SYDNEY

Photonics and optical science

Dynamic biomolecular nanomaterials with optical and magnetic functions

Supervisor: Shelley Wickham
Email contact: Shelley.wickham@sydney.edu

Biological organisms have developed comprehensive molecular machinery for adapting and reconfiguring their states, for example to change shape or colour. Inspired by biology, we aim to build new material systems that can be reconfigured with nanoscale precision to achieve custom responsive optical and magnetic functions. The ability to reconfigure new materials at the level of molecules and nanoscale objects has potential to modulate optical, biological, catalytic and mechanical properties, for applications in optical information storage and processing. The overall approach of this project is to design and build addressable 3D biomolecular frameworks out of DNA and incorporate inorganic nanoparticles (gold, iron oxide, quantum dots). Micro- and nanofabrication techniques will be used develop substrates to scale-up nanoparticle systems. Microfluidic systems will be developed to observe dynamic biomolecule assembly and reconfiguration in real-time. Techniques involved include: DNA origami and self-assembly, electron microscopy, microfluidics, super-resolution microscopy, and plasma surface modification and characterisation.

Enabling laser communications in space with multimode photonics

Supervisor: Sergio Leon-Saval (Director SAIL labs)
Co-supervisor: Chris Betters
Email contact: christopher.betters@sydney.edu.au

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. This technology offers data rates that are 10 to 100 times better than current radio-frequency (RF) communications systems. The Laser Communications Relay Demonstration (LCRD) project will help NASA understand the best ways to operate laser communications systems. SAIL labs has 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.

Photonics to the Rescue! A novel sensor for greenhouse gases

Supervisor: Maryanne Large
Co-supervisor: Peter Tuthill, Sergio Leon-Saval
Email contact: maryanne.large@sydney.edu.au
Grand Challenge: A Sustainable Future

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

Understanding the wavelength dependence of photonic lanterns and modal excitation in multicore fibres with optical fibre couplers

Supervisor: Sergio Leon-Saval
Co-supervisor: Chris Betters, Barnaby Norris
Email contact: sergio.leon-saval@sydney.edu.au

The project aims to revolutionize the field of optical communications and photonics by leveraging the advancements in Multicore Fibres (MCFs). Initially designed for high-capacity communications, sensing, and astronomy, MCFs have now reached a level of quality that allows for telecom-grade performance. In conjunction with photonic lanterns, this project seeks to explore multimode photonics and achieve complex functionalities, such as sensing and filtering. A groundbreaking addition to the project's objectives is the study of the wavelength dependence of photonic lantern-based spectroscopy. This will involve investigating how different wavelengths interact with photonic lanterns and MCF cores, thereby enhancing the efficiency and precision of spectroscopic systems. The project will also delve into the first-ever study of hybrid optical fibre couplers between MCFs and single-core fibres, aiming to realize selective excitation of higher-order modes in MCF cores. This research is expected to pave the way for innovative multicore fibre devices applicable in lasers, communication systems, and advanced optical sensing. The project offers both theoretical and experimental avenues, allowing students the flexibility to focus on either aspect.

New families of solitons—meet the relatives

Supervisor: Martijn de Sterke
Co-supervisor: Antoine Runge, Chris Lustri (Mathematics & Statistics)
Email contact: antoine.runge@sydney.edu.au

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

Pattern formation in high dimensional systems

Supervisor: Tristram Alexander
Email contact: tristram.alexander@sydney.edu.au
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, Dr Moritz Merklein
Email contact: alvaro.casasbedoya@sydney.edu.au

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

Vibrations in silicon at MIR

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

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

Ultra-broadband Signal Synthesis using Optical Frequency Comb

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Mr Ziqian Zhang
Email contact: ziqian.zhang@sydney.edu.au

Terahertz (THz) technology, encompassing a broad frequency band and high-resolution capabilities, is set to transform radar sensing with unprecedented resolution and communication through extraordinarily high and resilient data throughput. One key to unlocking this potential is generating ultra-broadband signals, achievable through optical frequency comb (OFC) technology.

The primary objective of this project is to utilise an OFC to synthesise ultra-broadband and stable signals for radar sensing. You will explore diverse OFC techniques to produce ultra-wideband THz radar signals, ensuring sensing precision and accuracy. The project offers an integrative exploration into microwave photonics, optical frequency comb, and radar sensing, amalgamating theoretical insights with experimentations. Simultaneously, it facilitates experiential learning through hands-on interactions with advanced optical and electronic components, state-of-the-art laboratory equipment, and applying foundational principles to address real-world challenges.

Storing light as hypersound on a photonic chip

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Moritz Merklein
Email contact: moritz.merklein@sydney.edu.au

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

Interplay of light and hypersound at 1Kelvin?

Supervisor: Prof. Benjamin Eggleton
Co-supervisor: Dr. Moritz Merklein
Email contact: moritz.merklein@sydney.edu.au

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

Plasma Physics

Thermal waves in magnetized and unmagnetized plasmas

Supervisor: 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: 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.

THE UNIVERSITY OF SYDNEY

Quantum physics and quantum information

Optimising trapped-ion experiments through machine learning

Supervisor:	Robert Wolf
Co-supervisor:	Ting Rei Tan
Email contact:	robert.wolf@sydney.edu.au
Grand Challenge:	Artificial Intelligence and Physics; Fundamental laws & the Universe; The Nano and Quantum world

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

A Wannier function-based approach to topological quantum error correction

Supervisor:	Prof. Andrew Doherty
Co-supervisor:	Dr. Abhijeet Alase
Email contact:	abhijeet.alase@sydney.edu.au
Grand Challenge:	The Nano and Quantum world

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

Generating states of light for error-robust quantum computation

Supervisor:	Sahand Mahmoodian
Co-supervisor:	Andrew Doherty
Email contact:	sahand.mahmoodian@sydney.edu.au
Grand Challenge:	The Nano and Quantum world

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

Building better qubits

Supervisor: Thomas Smith
Co-supervisor: Andrew Doherty
Email contact: thomas.b.smith@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

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

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

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

Scalable ion trap architectures for quantum computing

Supervisor: Tomas Navickas
Co-supervisor: Ting Rei Tan
Email contact: tomas.navickas@sydney.edu.au
Grand Challenge: The Nano and Quantum world

Quantum computing will require miniaturised ion traps to store and move quantum bits between different computational zones. This project involves designing electromagnetic fields that confine ions above the trap surface, investigating the most optimum microwave emitter configuration for fast quantum gates, and building a library of ion-shuttling operations under the quantum charged-coupled-device architecture. Furthermore, this project will explore using machine learning to achieve robust and fast shuttling operations. Finally, the project involves numerical simulation of the trapping potentials and shuttling operations, modelling of EM field for microwave delivery, assembly of experimental systems, and performing experiments.

Characterisation of noise correlations in noisy quantum devices

Supervisor: Robin Harper
Co-supervisor: Stephen Bartlett
Email contact: robin.harper@sydney.edu.au
Grand Challenge: Artificial Intelligence and Physics,The Nano and Quantum world

The ability to characterise the noise in current near term quantum devices is an essential component in the push towards making universal fault-tolerant quantum computers. Recent data take from one of Google's super-conducting devices and some of IBM's super-conducting devices have shown unexpected measurement correlations between the qubits. It will be essential to have some way of identifying, measuring, and modelling such noise. This project involves looking at ways to identify and model such correlations in the data. Initially we will analyse whether we can use convex programming techniques to fit sparse two-dimensional, transversal Ising models from data. This will allow us to identify any hidden close range correlations. Moving on we will then try and identify non-Markovian effects e.g. hidden two-level systems, perhaps by using using restricted Boltzmann machines models (or any hidden node network). This will involve using various machine learning techniques to fit the noise, with a view to seeing if we can help identify the likely causes of such noise effects.

Building optical systems for an ion trap quantum computer

Supervisor: Christophe Valahu
Co-supervisor: Ting Rei Tan
Email contact: christophe.valahu@sydney.edu.au
Grand Challenge: The Nano and Quantum world

Quantum computers based on trapped ions require stable, high-powered, and tightly focused laser beams to implement high-quality quantum gates enabled by light-atom interactions. This project will design and construct optical systems to shape and deliver tightly focused laser beams to a trapped-ion quantum computer. Furthermore, this project will also involve assembling and characterising high-speed electronics for the stabilisation of the laser systems. The project will involve numerical simulations of light propagations, designing optical systems such as telescopes, and experimentally assembling and demonstrating the setup. The student will validate the new optical system by running experiments on a trapped-ion quantum computer.

Building next-generation superconducting quantum circuits

Supervisor: Dr. Xanthe Croot
Email contact: xanthe.croot@sydney.edu.au
Grand Challenge: The Nano and Quantum world

In this project you will work at the frontiers of superconducting qubit development, exploring the relatively new field of "protected" superconducting qubits to design, build and characterise novel qubits in a state-of-the-art cryogenic laboratory. Superconducting circuits are a mature technology used extensively in academic and industrial efforts to build quantum processors and simulators. In traditional superconducting qubits, there is a fundamental trade-off between minimizing different types of errors – one type of error is minimized at the expense of increasing another. Fortunately, the versatility of superconducting circuits gives us incredible flexibility to design and engineer new, multi-mode qubits that are intrinsically robust against error – these qubits are known as "protected" qubits.

This project will involve (but is not limited to) (a) the design, simulation, fabrication and characterisation of new superconducting protected qubits, (b) device engineering to expand the parameter space of traditional superconducting circuit elements to improve access to the "protected" regime, and (c) developing scalable protocols to couple and control protected qubits.

Harnessing the power of cQED in hybrid platforms for quantum computing

Supervisor: Dr. Xanthe Croot
Email contact: xanthe.croot@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

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

Investigating materials for a quantum internet

Supervisor: John Bartholomew
Email contact: john.bartholomew@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

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

Quantum integration of light and atomic spins in a crystal

Supervisor: John Bartholomew
Email contact: john.bartholomew@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

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

Designing a protocol for optically linking superconducting qubits

Supervisor: John Bartholomew
Email contact: john.bartholomew@sydney.edu.au
Grand Challenge: The Nano and Quantum world

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

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

Trapped Ion Crystals and Large-Scale Entanglement

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

Trapped atomic ions are a leading candidate system for experiments in quantum simulation 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.

Renewable Energy and Sustainability

Plasmonic-induced water splitting: the green hydrogen revolution

Supervisor: A/Prof Stefano Palomba
Email contact: stefano.palomba@sydney.edu.au
Grand Challenge: The Nano and Quantum world; A Sustainable Future; Physics & Society

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

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

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

Supervisor: Catherine Stampfl
Email contact: catherine.stampfl@sydney.edu.au
Grand Challenge: A Sustainable Future

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

THE UNIVERSITY OF SYDNEY

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

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

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

Thermal management by nanostructuring

Supervisor: Martijn de Sterke
Co-supervisor: Boris Kuhlmey, Alex Song (electrical engineering)
Email contact: martijn.desterke@sydney.edu.au
Grand Challenge: A Sustainable Future

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