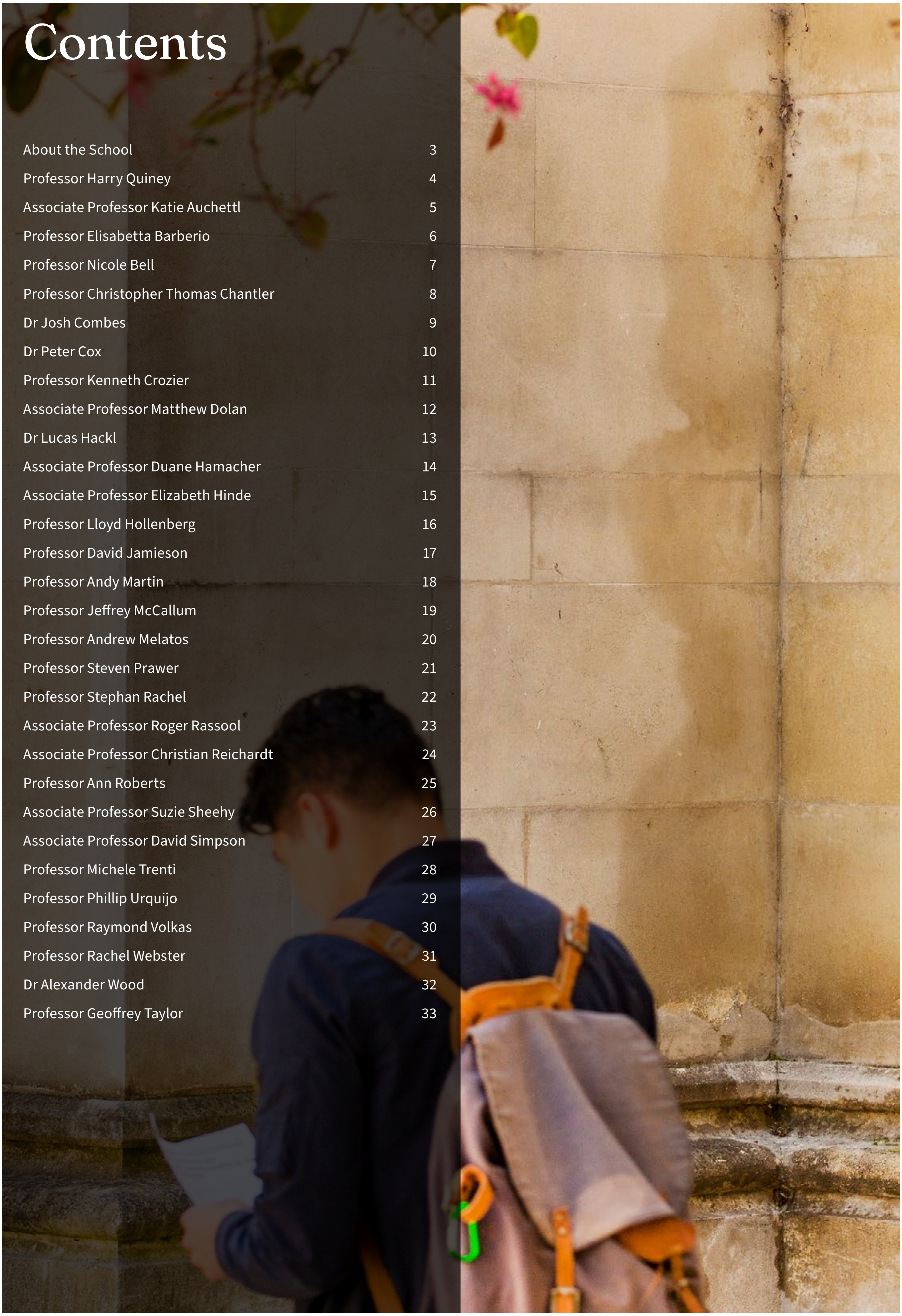
THE UNIVERSITY OF MELBOURNE

Faculty of Science

School of Physics
Research Prospectus

Contents



About the School

The School of Physics at the University of Melbourne is one of the leading physics departments in Australia.

Physics is an enabling science that expands our knowledge of the universe and underpins new technologies that benefit our society. Our programs in astrophysics, theoretical particle and experimental particle physics explore questions relating to the origin, evolution and fate of our universe.

Our School studies matter and light interactions, particularly in advanced materials utilising diamond and silicon, quantum information science, photonics, nanoscale imaging and nanoelectronics, and hosts interdisciplinary teams of physicists, biologists and chemists studying biological molecules.

The University of Melbourne's Faculty of Science acknowledges the Traditional Owners of the lands on which we work: the Wurundjeri Woi-Wurrung and Bunurong peoples (Burnley, Fishermans Bend, Parkville, Southbank and Werribee campuses), the Yorta Yorta Nation (Dookie and Shepparton campuses), and the Dja Dja Wurrung people (Creswick campus). We pay respect to their Elders, past and present. We also acknowledge and respect that Aboriginal and Torres Strait Islander people are this country's first scientists, with deep and enduring knowledge of the land, waters and skies.

Professor Harry Quiney

Head of the School of Physics

Professor Harry Quiney

- Atoms
- Molecules
- Photons
- Physics
- Biology

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My research works towards a first principles understanding of complex electronic systems for the development of new materials.

The electronic structures of atoms, molecules and solids and their interactions with light provide the theoretical foundations of chemistry and structural biology and open a window to the discovery of new physics through precision measurements. These frontiers include searches for electric dipole moments of elementary particles and insights into the nature of dark matter. We develop sophisticated computational models of electronic structures and their interactions with light, especially X-rays.

Structural biology and free-electron lasers

Most of what is known about structural biology comes from either crystallography or cryo-electron microscopy. These approaches provide static molecular structures, but they do not have the capacity to capture the transient time-dependent processes involved in biochemical reactions. Free-electron lasers are large international research facilities that first became available a decade ago. These intense pulsed X-ray sources have the potential to record molecular movies with femtosecond time resolution, but many challenges remain to be solved before this can be achieved. We are members of international research collaborations that are working to overcome the challenges of recording time-resolved images of biomolecular processes with atomic spatial resolution.

Relativistic quantum electrodynamics

Atoms and molecules exhibit a range of physical effects that are attributable to both special relativity and quantum electrodynamics. These effects become more significant as the nuclear charges in these systems are increased. The associated electric fields inside these systems are huge and have the potential to amplify the experimental signatures of physics beyond the standard model of elementary particles. Precision measurements on atoms and molecules are currently underway in several international laboratories, providing a low-energy approach to detecting as-yet-unknown high-energy phenomena of particle physics. We have developed the theoretical and computational machinery to model these processes, which include the possible existence of electric dipole moments in elementary particles and the physics behind current efforts to detect dark matter particles.

Complexity and the many-body problem

The familiar structure of the periodic table of the elements can be explained by simple physical and chemical concepts, such as the filling of atomic shells and the pairing of electron spins. These models capture the average behaviours of electrons, but quantitative treatments of atoms and molecules usually require a detailed description of the statistical correlations of electrons. This is a statement of the 'many-body problem', which is a major bottleneck in developing new technologies by computational modelling based on fundamental physical principles.
Formally, the complexity of these electron correlations grows exponentially with the number of electrons, and an accurate treatment becomes impossible, even for small systems. We are developing methods to deal with many-body problems that involve an increase in complexity that has a polynomial scaling with the number of electrons. This may make possible tractable computational treatments of large, complex electronic systems.

Associate Professor Katie Auchettl

Associate Professor Katie Auchettl

- Time domain astronomy
- Multi-wavelength astronomy
- Stellar astrophysics
- Black hole and neutron star physics
- Binaries

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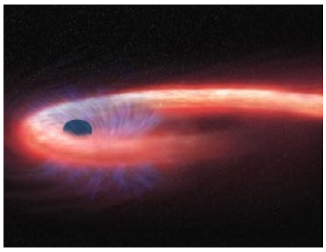
My research focuses on using multi-wavelength (optical/UV/X-ray/gamma-ray) and time-domain observations to better understand the physical processes and observational signatures related to the extreme death of stars. My research has two main aims. First, it studies the demographics, emission properties and processes, and environments of both active and quiescent accretion systems? Second, it asks how do stars explode, and what are the resulting stellar outcomes (observable supernova explosion, supernova remnant, compact objects) and properties of these explosions and their stellar remnants?

The supernova remnant W49B as observed using the Chandra X-ray Telescope. This remnant resulted from a core-collapse of a star more than eight times the mass of our sun, that died long ago.

Connecting supernovae and their remains: probing the life and death of massive stars

The majority of my research aims to understand the endpoint of stellar evolution. I investigate this through its link with its progenitor, the resultant explosion type and outcome of stellar collapse (ie formation of a black hole, neutron star and/or an observable supernova explosion). I focus on studying the properties of supernovae located in nearby galaxies and supernova remnants in the Milky Way and nearby galaxies. Furthermore, I seek to understand the physics of neutron stars and stellar mass black holes, especially those in binary systems. These objects are the sources of gravitational waves. Their mass distributions also provide unique insight into the physics of core-collapse supernova explosions, the structure of the massive stars, and the effect that environmental characteristics have on the properties of these objects. By studying the nearby compact objects and binaries within the Milky Way, we can better understand these objects and accretion onto them in detail and better quantify the demographics of this population.



An artist's illustration of a tidal disruption event (TDE). A TDE is a luminous multiwavelength flare that results from a star that wandered too close to a black hole and is ripped apart.

Accretion in the extreme - understanding the properties and nature of black holes found at the heart of galaxies

Accretion of material onto a black hole plays a crucial part in the evolution of these sources. Black holes undergoing regular, long-term accretion have been well documented and studied yet provide only a small window into a subset of the total supermassive black hole (SMBH) population. However, while we expect most galaxies to host an SMBH, only a fraction of galaxies host an active black hole called an AGN. Quiescent, weakly or non-accreting SMBHs are thus one example of a population of black holes that cannot be studied without some other observation method. Rare transient accretion events give us the ability to study these otherwise inaccessible populations of black holes, both in their individual properties (eg masses, environments) and their population characteristics (ie What are the mass and spin demographics of black holes throughout the Universe, are they correlated, and do they evolve with redshift?). I have used tidal disruption events (TDEs) —luminous, multi-wavelength accretion powered flares from a disrupted star — as a probe of black holes that would otherwise be inaccessible. I also study extreme accretion events from changing look AGN and other types of AGN galaxies.

Professor Elisabetta Barberio

Professor Elisabetta Barberio

- Physics
- Particle physics
- Dark matter direct detection

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While astrophysical observations study the macroscopic properties of the universe to infer the existence of dark matter, terrestrial physics experiments are essential to study the fundamental laws of nature associated with dark matter. We are yet to determine the precise nature of dark matter, and it remains one of the biggest questions in contemporary physics. I am researching what is the fundamental nature of dark matter.

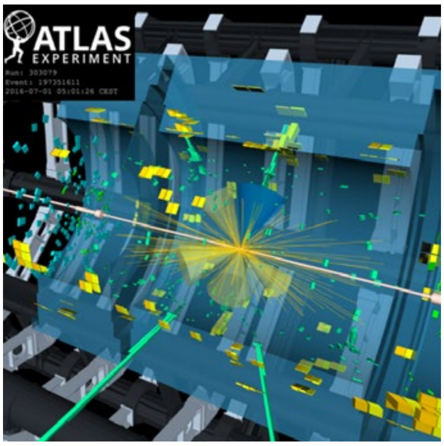
Dark matter direct detection

Around 80 per cent of the matter of the universe is a mystery made of dark matter. One leading hypothesis is that dark matter is made up of exotic particles that don't interact much with ordinary matter. My research focuses on building terrestrial experiments to uncover the fundamental nature of dark matter. These scientific instruments need to be placed 1 km underground to shield them from cosmic rays. My ongoing research focuses on the SABRE experiment: the first dark matter direct detection experiment in Australia located 1 km underground in the Stawell Underground Laboratory. The SABRE experiment will start data collection in 2024 and deliver the first results in 2025.

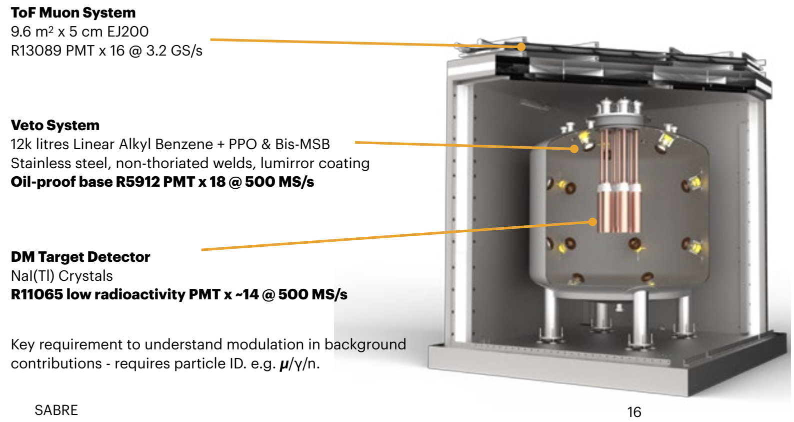
Matter-antimatter asymmetry

The Big Bang created an equal amount of matter and antimatter in the early universe. But today, everything we see is made almost entirely of matter. Something must have happened to tip the balance; one of the greatest challenges in physics is to figure out what happened to the antimatter.

My research at the Belle experiment at KEK in Japan and at the ATLAS experiment at CERN (Switzerland) aims to uncover the mechanism that produced this imbalance by performing very precise measurements of some of the properties of the Higgs particle and one other fundamental matter particle called the b-quark. My research in ATLAS and in KEK, respectively, has directly contributed to two Nobel prizes: Higgs and Englert in 2013 resulting from the Higgs discovery, and Kobayashi and Maskawa in 2008 resulting from the confirmation of CP violation in the b-quark system.



Searching for matter antimatter asymmetry with the ATLAS experiment: event displays where the Higgs boson is produced in association with top quarks. Image credit: CERN.



The SABRE experiment and its component. Sabre is 4 m high and 4 m wide.

Professor Nicole Bell

Professor Nicole Bell

- Dark matter
- Neutrinos
- Matter-antimatter asymmetries
- Astroparticle physics
- Particle physics

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What are the fundamental building blocks of which the universe is made and what are the laws which govern them? Understanding nature at the most basic level is the ultimate goal of my research. As a theoretical physicist working at the intersection of particle physics and astrophysics, I use clues from high energy particle physics experiments, astrophysical observations and beyond to understand the fundamental interactions and matter of the subnuclear world.

Dark matter

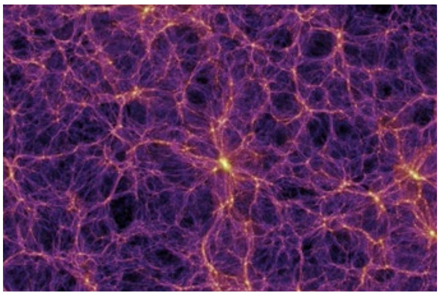
Most of the matter in the universe consists of dark, unknown particles and is the strongest direct evidence that our knowledge of elementary particle physics is incomplete. The quest to identify this cosmological dark matter is one of the foremost goals of modern science. My research looks for clues using high energy particle collider experiments, underground direct detection experiments or astrophysical signals from regions of high dark matter density, such as the galactic centre. Ultimately, we aim to develop the theoretical framework to describe dark matter particles and their interactions, incorporating dark matter into a new fundamental theory of nature.

Neutrino physics

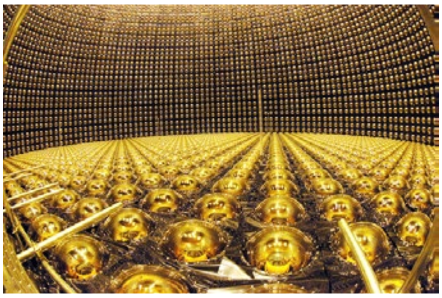
Neutrinos are the least understood of the known elementary particles. Yet they hold the key to some of the most fundamental open questions in physics. Chief among the open questions is whether the neutrino is its own antiparticle and whether they are responsible for the creation of the matter-antimatter asymmetry of the universe. Neutrinos are produced in copious amounts by nuclear fusion processes in the sun and serve as unique cosmic messengers from astrophysical systems such as supernova and from the universe itself. They also contribute a background signal in dark matter detectors — the so-called ‘neutrino-floor’. My research aims to investigate the fundamental particle properties of neutrinos and use neutrinos to probe astrophysics.

New particles and interactions

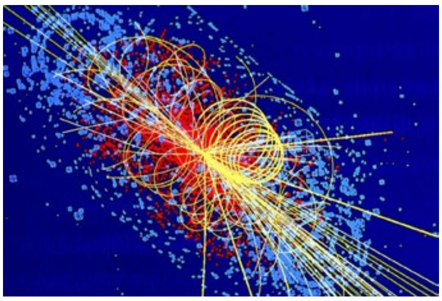
There are a number of clues that the so-called Standard Model of particle physics is incomplete. For example, in addition to open questions about dark matter and neutrinos, new particles and interactions are required to explain the cosmological matter-antimatter asymmetry. These new particles could take a variety of forms, eg additional Higgs bosons or extra heavy neutrinos. In order to find these new particles, we typically need to access high energy scales either by accelerating particles in collider experiments or studying the physics of the early universe (ie the Big Bang). By combining such clues, we aim to develop a more complete understanding of fundamental physics.



Dark matter distribution in the universe.
Image credit: V. Springel, Max-Planck-Institute for Astrophysics, Germany.



The Super-Kamiokande neutrino detector.
Image credit: Getty images.



Particle collision. Image credit: Lucas Taylor/CMS.

Professor Christopher Thomas Chantler

Professor Christopher Thomas Chantler

- X-ray optics and synchrotron science
- Relativistic atomic physics
- X-ray absorption spectroscopy
- Experimental and theoretical condensed matter science
- Quantum electrodynamics

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What is the interaction between light and matter? It drives society, our technology and nanotechnology, and involves lasers, infrared, x-rays and other frequencies of light. But it originates in our fundamental understanding of relativistic quantum mechanics and electromagnetism, currently based on the theory of Quantum ElectroDynamics.

New fields and technology in x-ray spectroscopy at synchrotrons

I was awarded the Lawrence Bragg medal for developing new fields of spectroscopy at synchrotrons.

We ask, 'how can we get structural information from an isolated quantum system — a molecule, gas or non-crystalline solid?' We are world leaders in extracting structural and quantum information from atomic, molecular and organometallic (ie biophysical) systems with advanced experiments and analysis, advancing techniques used by 30 per cent of all synchrotron researchers. This includes my X-ray Extended Range and Hybrid Techniques for synchrotron nanostructure, some 100x more accurate than earlier work. We also lead in theories of electron scattering, the Finite Difference Method for XAS and new software packages. Recent doctoral students have developed new fields of non-destructive nanoroughness measurement, electron inelastic scattering experiment and theory or made major developments in dominant fields of x-ray science or relativistic quantum mechanics.

Relativistic atomic physics theory and experiment

Our relativistic atomic theory and tabulation is the most successful currently available in terms of agreement with experiment. Honours students have developed new theories and computational tools for condensed matter science, including the first extended XAFS solution avoiding 'muffin-tin' approximations and the largest (organometallic) XAFS modelled without this assumption, with major implications for biological science.

Tests of Quantum ElectroDynamics (QED)

Quantum Electrodynamics is one of the two best-tested theories in physics and science and the most trusted example of a Quantum Field Theory. Yet people like Roger Penrose conclude that there are fundamental flaws yet to be discovered. QED is the primary explanation of the interaction of light and charge, fundamental to most physics we assume and rely on today. We are the only group to test QED in Australia and have had breakthroughs reported in Physical Review, Physics Today and New Journal of Physics.

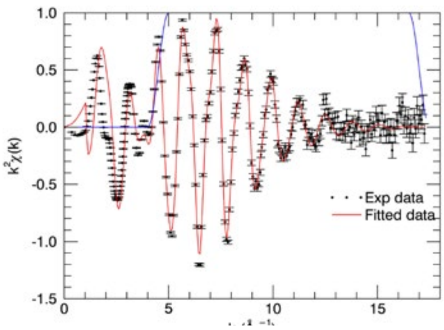
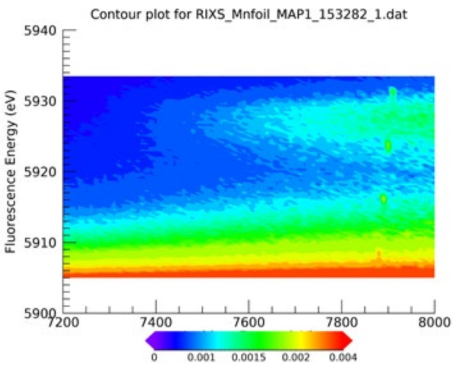


Fig. 5. Experimental data (black) with absolute uncertainties and the fitted model (red) across $k = 4.5 Å^{-1}$ to $17 Å^{-1}$ for zinc K-edge. Data was fitted over a Hanning window.

Outstanding data quality in the first implementation of our new technology (XERT) at the Australian Synchrotron. The quantum interference seen here allows measurement and imaging of the dynamic nanostructure of many materials and especially dilute and non-crystalline systems.



A new (relativistic) process discovered during COVID, on a run remotely at Diamond Light Source, UK, 2021. Despite this novel RIXS technology (Resonant Inelastic X-ray Scattering) source operating for some 20 years now, there are many exciting discoveries to be made.

Dr Josh Combes

Dr Josh Combes

- Quantum computing
- Quantum error correction
- Quantum sensing and metrology
- Quantum hardware modelling
- Quantum foundations

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I aim to advance reliable quantum technologies to solve problems beyond the reach of today's computers and enable sensors with unprecedented precision.

Quantum computing

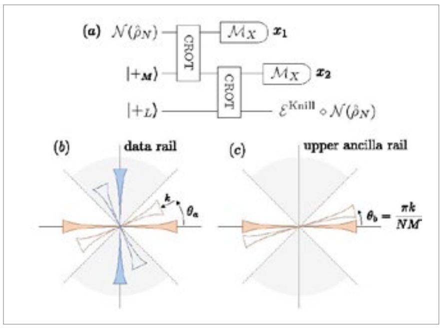
From theory to device-level modelling, my research group collaborates closely with experimental teams, with the goal of making scalable, practical quantum computing a reality. We design low-error hardware architectures, fault-tolerant logic gates, and novel quantum error-correcting codes.

Quantum sensing and metrology

We are developing error-corrected sensors, pioneering nonlinear metrology techniques, and devising fundamentally new types of quantum measurements to enable advances from fundamental physics to precision engineering.

Quantum foundations

We explore the theory of quantum measurement and the boundary between classical and quantum physics. This includes developing classical simulations of quantum systems to test our understanding of quantum mechanics and guide the design of quantum technologies.



A quantum circuit implementing error correction for a rotation code.

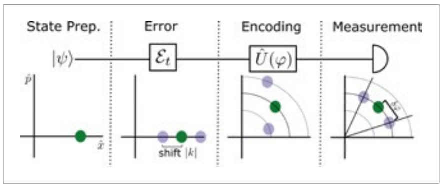
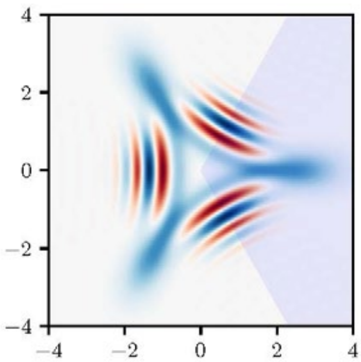


Illustration of noisy nonlinear metrology in harmonic oscillator phase space.



A new error-correcting code with applications in quantum computing and quantum sensing.

Dr Peter Cox

Dr Peter Cox

- Particle and astroparticle physics
- Dark matter
- Beyond the Standard Model

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To better understand the observed universe – including dark matter – I investigate the fundamental laws of nature that govern elementary particles and their interactions.

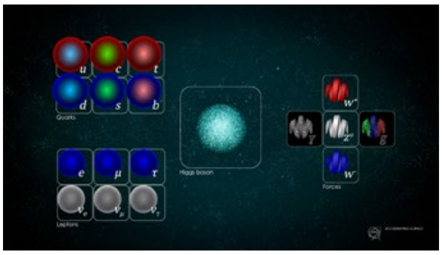
Beyond the Standard Model

The Standard Model of particle physics describes elementary particles and their interactions. But there are phenomena that it cannot explain, such as the masses of neutrinos, the dominance of matter over anti-matter, and the dark matter of the universe. To address these issues, I explore extensions to the Standard Model and how they can be tested experimentally – for example, using particle accelerators and colliders such as the Large Hadron Collider.

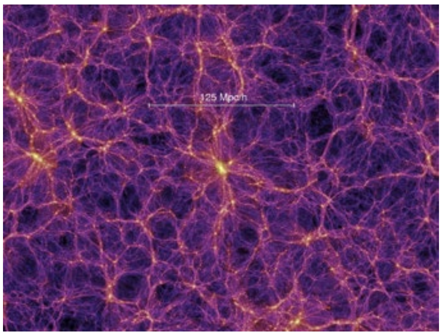
Dark matter

Atoms and molecules comprise only 15 per cent of the matter in the universe, leaving 85 per cent 'dark matter', which we have observed solely through its gravitational effects on ordinary matter, in galaxies and in the very early universe. The identity of dark matter remains unknown, but the most likely candidate is a new fundamental particle.

I explore particle physics models for dark matter, investigating how dark matter was produced in the early history of the universe. I also research methods for directly detecting dark matter using extremely sensitive detectors that are usually located deep underground to shield them from background radiation.



Particles of the Standard Model of particle physics. (Image credit: Daniel Dominguez/CERN)



The large-scale distribution of dark matter in the universe. (Image credit: VIRGO Consortium)

Professor Kenneth Crozier

Professor Kenneth Crozier

- Plasmonics
- Metamaterials
- Photodetectors
- Optoelectronics

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It is an exciting time to be working in optics. Previous generations of researchers were largely limited to the use of naturally occurring optical materials, such as glass and crystals. Recent advances in fabrication made by the integrated circuit industry have dramatically improved our ability to produce nanostructured materials. Recent years have also seen an explosion in computing power. These two developments have made it possible to design and fabricate nanostructured materials ('metamaterials') with optical properties not present in natural materials. We use these and related concepts to realise new optical devices, including photodetectors based on nanomaterials, advanced holograms, optical nanotweezers and lightweight infrared microspectrometers.

Advanced Holograms

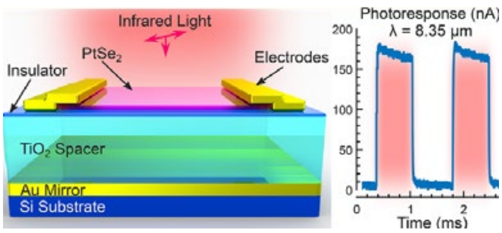
Holograms use diffraction to produce three-dimensional light fields used for document security (eg credit card security features), sensors, and data storage, and there is also much interest in employing them in advanced displays. We are developing new types of holograms based on nanostructured materials. A hologram records the wavefront of light from an object, but it is usually not an image itself and looks unintelligible under diffuse ambient light. We have recently developed a new paradigm to encode a colour hologram onto a colour-printed image. The printed image can be directly viewed under white light illumination, while a low-crosstalk colour holographic image can be seen when the device is illuminated with red (R), green (G), and blue (B) laser beams. The device is a dielectric metasurface that consists of titanium dioxide cones on a glass substrate.

Metasurface-enabled photodetectors (infrared wavelengths)

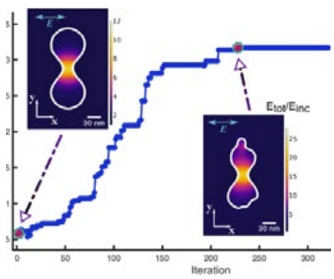
Mid-wave infrared (MIR) radiation is characterised by low photon energy, and is thus usually detected by semiconductor materials with small band gaps. At room temperature, charge carriers are thermally generated in such materials at very high rates. Cooling the detector mitigates this yet adds significantly to size, weight, power consumption and cost. This has prompted research into room temperature MIR detectors. Much of this work has concerned materials that are incompatible with silicon technology. We aim to harness recent breakthroughs in nano-optics and in two-dimensional materials to realise photodetectors for high-performance, large-format and low-cost MIR imaging at room temperature. We have demonstrated MIR photodetectors from a variety of advanced materials, including graphene, black phosphorous-moylbdenum disulphide, tellurium and platinum diselinide.

Optical nanotweezers

Optical tweezers are an important scientific tool in many fields: they use the forces exerted by focused laser beams to trap and manipulate particles. Conventional optical tweezers employ lenses to focus laser beams, but due to the diffraction limit, these can only focus light to spots no smaller than roughly half the wavelength. This sets a limit to the force that can be exerted by conventional optical tweezers on a particle of a given size with a given laser power, making it challenging to trap very small particles. We've overcome this limitation by using nanostructures rather than lenses to concentrate light. These include gold nanostructures and silicon nanoantennas.



Left: schematic of infrared photodetector based on two-dimensional material (platinum diselenide) on TiO2/Au optical cavity substrate. Right: photocurrent vs time measured from photodetector when subjected to mid-infrared light pulses.



We used an algorithm to design plasmonic apertures for optical nanotweezers. The apertures were fabricated using a helium ion microscope and were characterised by cathodoluminescence and optical trapping experiments. It was shown that at every laser intensity, an algorithm-designed structure can outperform a conventional plasmonic aperture.

Associate Professor Matthew Dolan

Associate Professor Matthew Dolan

- Dark matter
- Collider physics

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We know that the Standard Model of particle physics is incomplete: it cannot explain dark matter, neutrino masses, the matter-antimatter asymmetry of the universe or the lightness of the Higgs boson. My research focuses on identifying the particle nature of dark matter and the detailed properties of the Higgs boson.

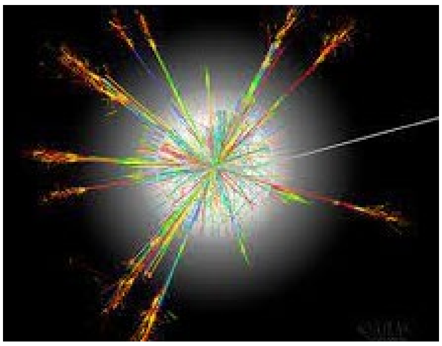
I am a theoretical particle physicist who proposes new searches and measurements to uncover new particles and forces and re-interpret and apply current data in innovative ways to constrain the properties such hypothetical particles may have.

Dark matter

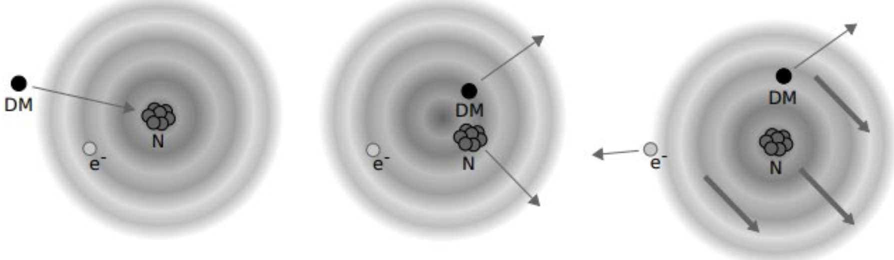
Dark matter constitutes most of the universe and is well-established through astrophysics and cosmology, but its fundamental properties remain deeply mysterious. However, there are a number of ways in which we can probe the existence of dark matter terrestrially. For example, I have worked extensively on searches for dark matter at particle colliders such as the Large Hadron Collider (LHC) near Geneva. I have a particular interest in light dark matter, and have set important constraints on the interactions between light dark matter and normal matter. Recently, I have also studied the early universe cosmology of a particular form of dark matter called axions and demonstrated how gravitational micro-lensing can be used to search for dense 'clumpy' structures it forms at late times galaxy clusters.

Collider Physics

Particle collider experiments form one of the most powerful probes of the Standard Model (SM) of particle physics and the existence of physics beyond the SM. The discovery of the Higgs boson in 2012 was the final SM particle to be discovered. I have written a number of papers on experimental proposals searching for the production of di-Higgs production, a rare process with unique sensitivity to a key parameter of the SM. I also lead a research program centred around the development of machine learning methods applicable to physics at particle colliders such as the LHC. Finally, I have an enduring interest in searches for axion-like particles at colliders such as Belle-II, and in rare meson decays.



A depiction of an event at the LHC.



Dark matter scattering off a nucleus, leading to atomic ionisation.

Dr Lucas Hackl

Dr Lucas Hackl

- Quantum Information
- Fundamental theory
- Entanglement entropy
- Variational methods
- Gaussian states

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I develop mathematical tools to understand and model the quantum information properties of physical systems, ranging from quantum matter probed in particle accelerators to cosmological observations in spacetime. I also collaborate on applications in quantum technologies.

My research program rests on three pillars: (i) entanglement theory, (ii) variational methods and (iii) Gaussian states, which are all interconnected.

Entanglement theory

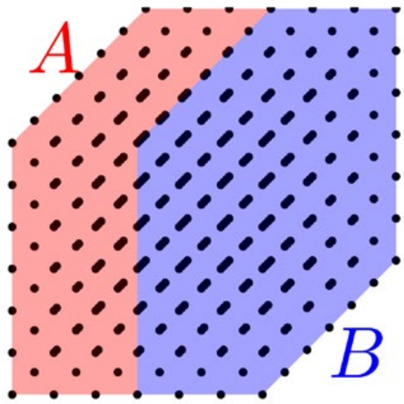
I am using quantum information quantities (such as the bipartite entanglement entropy) to explore properties of quantum systems, such as their dynamics, chaotic behaviour, and longtime averages of physical observables. Related work also explores how to extract entanglement from quantum systems to be used as a resource in quantum information processing.

Variational methods

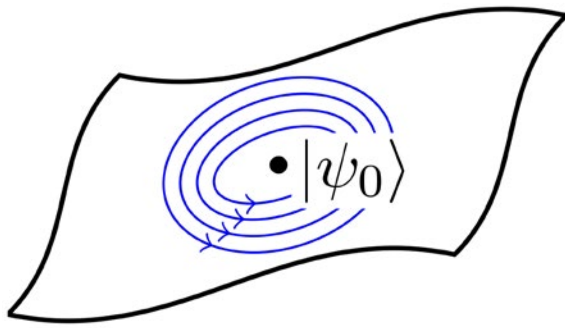
I have used tools from differential geometry to develop a systematic theory on how to approximate ground states, low excited energy eigenstates, time evolution and linear response based on the choice of a variational family.

Gaussian states

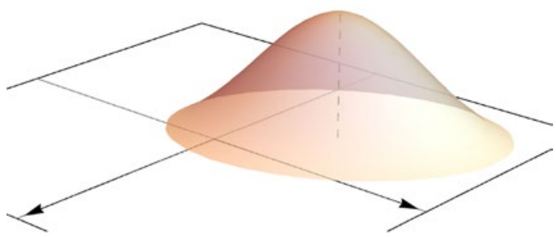
Research in this field has provided a unified mathematical framework to describe bosonic and fermionic Gaussian states based on group theory and representation theory. I apply this to the study of entanglement in Gaussian state ensembles and as a variational family for variational calculations. It also enables construction of new variational families, such as generalised Gaussian states or Gaussian state superpositions, and provides the required tools to compute expectation values of physical observables efficiently for such states.



Entanglement theory. We illustrate a lattice system divided into subsystems A and B, whose entanglement (quantum correlations) we quantify.



Variational methods. We illustrate a family of variational states with approximate ground state (black dot) and time evolution (blue).



Gaussian states. We illustrate a Gaussian state as positive distribution in the classical phase space.

Associate Professor Duane Hamacher

Associate Professor Duane Hamacher

- Cultural astronomy
- History of astronomy
- Dark sky studies
- Philosophy of science
- Astronomical heritage

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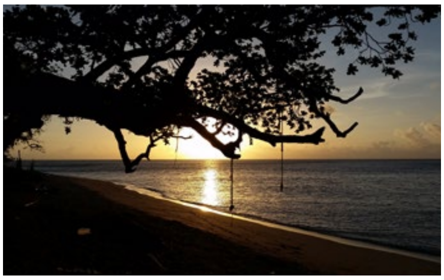
My aim is to develop social understandings of science and culture with respect to astronomy. I do so by elevating voices and profiles, doing my part to build up the profiles and careers of Indigenous people, women, and the Queer/GLBTI+ communities. You lift yourself by lifting others.

My research focuses on the intersection of astronomy, culture, history, heritage, and society. I primarily work for Indigenous communities to document, record, and reconstruct fragmented star knowledge with applications to education, community service, and scholarship. My work in dark sky studies focuses on safeguarding traditional star knowledge through heritage efforts to lower light pollution, protect tangible heritage sites, and reconnect people with the night sky.

Surveying the Carnac standing stone in Brittany.



Sunset on Mer in the eastern Torres Strait.

Associate Professor Elizabeth Hinde

Associate Professor Elizabeth Hinde

- Fluorescence
- Microscopy
- Biophysics
- Nucleus
- DNA

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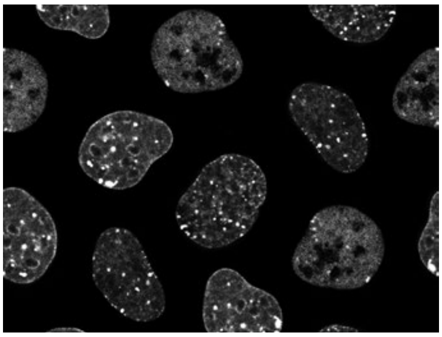
Nucleus architecture has emerged as a key player in genome function. Thus, with the molecular machinery responsible for DNA replication, transcription and repair having been defined by biochemical analysis, and with dramatic advances in complete genome sequencing providing snapshots of chromatin network architecture, we now need to understand how the genome and its regulators operate in their natural environment — the nucleus of a living cell. To do just this, we are developing live cell microscopy methods to probe nuclear architecture with super-resolution and from the point of view of the proteins exploring this complex environment. We aim to use this technology to understand how nuclear structure maintains genome integrity and faithful transmission of the genome.



Confocal image of cell nuclei.

Inside the nucleus of a living cell the human genome is much more than a linear DNA sequence. Our DNA is organised into a multi-layered three-dimensional (3D) structure termed chromatin that continuously undergoes real-time rearrangement to spatiotemporally regulate what genetic information is available to the proteins that read and copy the DNA template. Our research aims to uncover how exactly these chromatin network dynamics facilitate genome function.

To investigate this, we are developing microscopy methods based on fluorescence lifetime and spatiotemporal correlation spectroscopy to quantitatively image live cell chromatin density and the impact this structural framework has on the diffusive route of nuclear proteins adopt during DNA target search at the single-molecule level. Using this technology, we have discovered nanoscale rearrangements in DNA packaging (chromatin compaction) promote repair machinery arrival at DNA damage sites and regulate transcription factor access to specific nuclear locations.

This body of work suggests chromatin architecture to serve as a 'road map' for DNA-binding proteins to navigate the nucleus and modulate real-time access to the genome.

Professor Lloyd Hollenberg

Professor Lloyd Hollenberg

- Quantum computing
- Quantum sensing

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Stemming from a deep interest in fundamental quantum physics, we seek to develop new quantum technology for sensing and computing powered by uniquely quantum effects. In quantum computing, as global state-of-the-art improves rapidly we are increasingly interested in how these devices can solve real-world problems. In quantum sensing, we are interested in how this technology can improve imaging in biology and new atomic-level condensed matter systems.

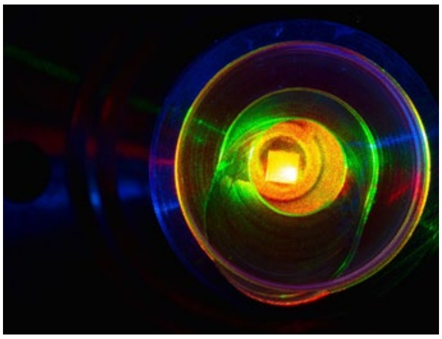
Quantum computing

Our group conducts research into many areas of quantum computing, including the physics of quantum devices, architecture designs, quantum algorithms, quantum error correction and fundamentals of quantum information. With our group linked to the IBM Quantum Hub at the University of Melbourne, we are able to experimentally explore the implementation of our concepts on state-of-the-art quantum computers and develop new algorithms for real-world applications. Our team built the Quantum User Interface (QUI), a quantum computing programming and simulation environment which underpins teaching and research at the University of Melbourne. For quantum computers based on donors in silicon, our team in the Centre for Quantum Computation and Communication Technology has achieved a critical milestone towards the implementation of accurate quantum computer designs by enabling the exact pinpointing of qubit spatial locations in silicon-based scanning tunnelling microscope imaging techniques. Another part of our work explores innovative quantum computing architectures. In particular, we have recently proposed a surface code quantum computer based on a two-dimensional lattice of donor spin qubits in silicon, providing a new pathway for large-scale quantum information processing in this platform.

Quantum sensing

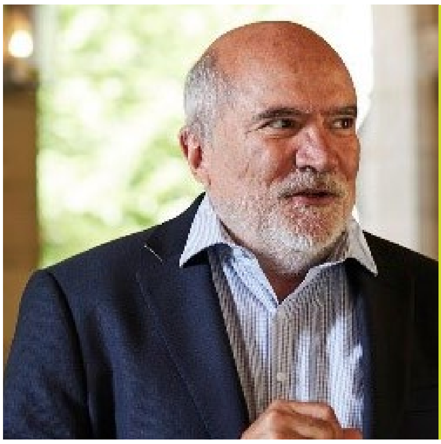
We develop novel quantum sensing and imaging techniques based on spins in diamond and explore applications to biology, chemistry and condensed matter physics. The physical system we use is the nitrogen-vacancy (NV) centre in diamond: an atomic defect that acts as a spin qubit embedded in a solid matrix. Importantly, the electrons trapped in the NV centre possess a spin that can be optically polarised, manipulated and read-out, even at room temperature. This allows spin resonances of a single NV centre to be detected by optical means, which forms the basis for quantum-sensing protocols designed to detect minute magnetic fields, electric fields, or temperature variations. Our group theoretically and experimentally explores new quantum sensing and imaging techniques, with a focus on real-world applications across physical and life sciences.

The Quantum User Interface (QUI) developed by the Hollenberg group at the University of Melbourne is a programming and visualisation system integrated into the teaching of quantum computing.
Image credit: L. Hollenberg et al.



Quantum sensing technology based on colour defects in diamond have promising applications in improving imaging and analysis in life and physical sciences contexts. Image credit: D. Simpson et al.

Professor David Jamieson



Professor David Jamieson

- Ion beam physics
- Quantum technology
- Electronic and magnetic properties of condensed matter
- Semiconductors

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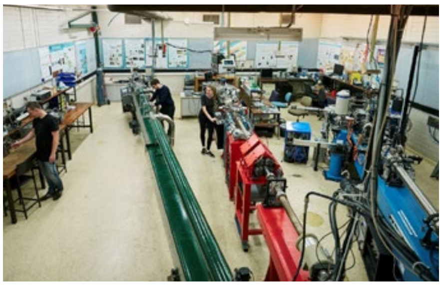
My aim is to discover new ways of applying fundamental principles of physics to solve problems that are difficult or impossible with present approaches. If we are successful with our quantum computer project, a quantum computer with a billion quantum bits (qubits) could have revolutionary potential for quantum mechanical drug design or discovering new pathways to fusion power. These capabilities are well beyond the capacity of even the most powerful classical computers. My research expertise in the field of ion beam physics was applied to test some of the key functions of a revolutionary quantum computer constructed in silicon in the Australian Research Council Centre of Excellence for Quantum Computation and Communication Technology.

I direct the ion beam program in this Centre and collaborate with overseas colleagues on investigating new ways of storing and processing information in quantum states of single atoms in silicon and other materials. My research group perform experiments with the ion beam accelerators in our laboratories to configure semiconductor chips with few or single dopant atoms and explore the quantum states of these atoms in nanoscale electronic devices.

I devote a lot of time to advocacy for physics and its important role in our society. I am interested in how to inspire young people to engage in studies in physics, and I have presented numerous public lectures on fundamental issues in physics.



Professor Andy Martin

Professor Andy Martin

- Rotating quantum systems
- Quantum gases

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Understanding the fundamental properties of quantum systems underpins much of the technology we use today. Our theoretical and experimental research aims to push this understanding to new areas and limits which may enable potential future technological applications.

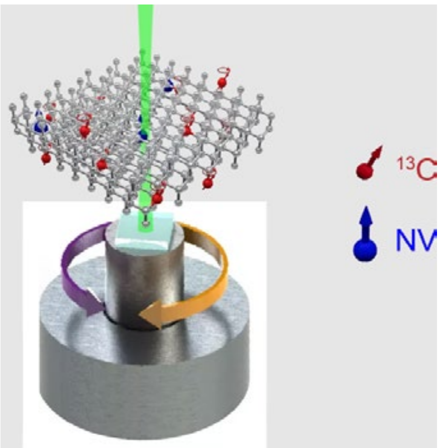
Rotating qubits

We theoretically and experimentally investigate the properties of rotating nitrogen-vacancy defects in diamond. Such a system can be thought of as qubits (nitrogen-vacancy defects) embedded in a rotating diamond lattice. To our knowledge, we are the only group in the world that can coherently initialise, quantum mechanically manipulate and readout spin qubits at room temperature whilst they are physically rotating. This research program has enabled us to:

1. Develop the means to quantum mechanically address single atom-scale qubits and ensembles of qubits at rotational frequencies comparable with the decoherence time of the qubits
2. Demonstrate that physical rotation can be used to control the interactions of qubits with the local environment and hence control their coherence, and
3. Apply rotation to yield enhanced sensitivity for diamond magnetometers.

Quantum gases

Over the last decade, we have made several significant theoretical contributions to the understanding of quantum gases. Such systems are extremely pure and controllable in terms of the interactions between the particles in the gas. Ultimately, the theoretical understanding of such interacting many-body quantum systems relies on analytical and computational approaches to determining the stationary and dynamical properties of such systems. Using such approaches, we have studied the collapse dynamics of dipolar condensates; dynamical instabilities in rotating dipolar condensates; collective excitations in trapped dipolar condensates; how quantum gases interact with surfaces, and the dynamical properties of such systems in the limits of small and large particle numbers.



Schematic of a diamond containing quantum sensors (nitrogen-vacancy centres in blue) on a rotating spindle. The grid pattern represents the atomic structure of the diamond. The diamond is mostly non-magnetic carbon-12 atoms but contains a small number of magnetic carbon-13. A green laser is used to both create and read the quantum state.

Professor Jeffrey McCallum

Professor Jeffrey McCallum

- Semiconductor devices
- Electronic materials
- Quantum devices
- Nanoelectronics

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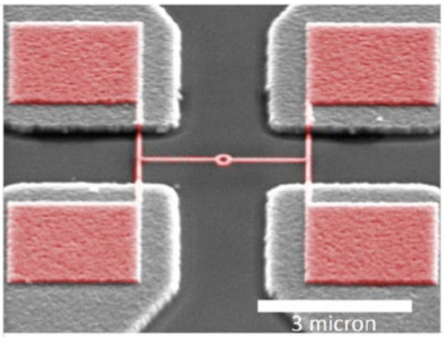
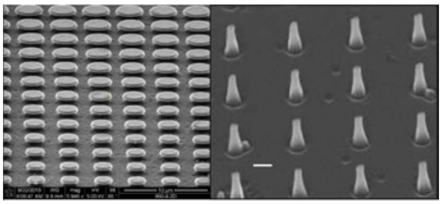
Development of quantum devices has enormous potential for pushing the boundaries of what is currently possible in a broad range of fields including metrology and computing and hence to contribute to human development in ways that we are only beginning to imagine. Being able to contribute to this is my aim.

Being able to harness the laws of quantum mechanics in electronic devices is very exciting because it provides direct access to this unfamiliar world and provides confirmation that, at the fundamental level, the world interacts by quantum mechanical (and not classical) rules. The fragility of quantum states means that they are easily influenced by their surroundings, and this makes them both difficult to maintain and control but also very sensitive to their environment. This fragility can, for example, be used to make extremely good sensors. And, where the quantum states can be maintained and controlled, the challenge is to use the extra degrees of freedom that are available to perform operations that are not available in classical devices.

My research work investigates the development of nanoscale semiconductor devices in which some aspect of the behaviour of the device depends on the laws of quantum mechanics. That may include the transport of electronic charge in the device or the manner in which the device absorbs or emits light, or it may involve quantum interference effects in a superconducting loop in the device. Such devices are not constrained by the classical laws of physics, and the quantum degree of freedom in these devices can greatly enhance device performance, for example, in sensing or even in computing applications. Being able to build, measure and understand these quantum devices is an exciting challenge that has the potential for enormous payoff in terms of being able to produce devices that will enhance our ability to sense, communicate.



A superconducting quantum interference devices fabricated on a silicon substrate.



Arrays of quantum emitters fabricated by our team.

Professor Andrew Melatos

Professor Andrew Melatos

- Gravitational waves
- Neutron stars
- Complex systems
- Signal processing

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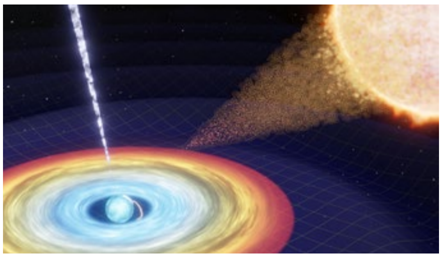
The true nature of space and time is one of the deepest mysteries confronting humanity. As layers of the mystery are peeled away, revealing deeper layers, humanity comes closer to understanding reality. It is an extraordinary privilege to contribute to this shared adventure.

In 1915, Einstein predicted the existence of gravitational waves: tiny vibrations in the fabric of space and time produced by cataclysmic cosmic events like the merger of two black holes. One hundred years later, these vibrations were detected directly for the first time by the Laser Interferometer Gravitational Wave Observatory (LIGO), a historic discovery that was awarded the 2017 Nobel Prise in Physics. Members of my research group and I were privileged to be co-authors on the LIGO discovery paper and to share in the 2016 Special Breakthrough Prise for Fundamental Physics with our LIGO colleagues.

The University is a leader in combining sophisticated algorithms and supercomputing to detect tiny signals in LIGO data. My research group in physics works with colleagues in electrical engineering to design new, cross-disciplinary mathematical approaches to gravitational wave data analysis. For example, we deploy hidden Markov models to detect and track signals with randomly wandering frequencies, drawing on techniques used in radar, mobile telephony, and speech recognition.

My research group is also a leader in developing theories of signals from black holes based on Einstein's theory of gravity and signals from neutron stars based on the quantum mechanics of nuclear matter under extreme densities, temperatures, and electromagnetic fields. We study the fascinating dynamics of vortex avalanches and magnetic field penetration in this exotic material, drawing on fundamental condensed matter physics, and make predictions about how these processes emit gravitational waves.



Artist's impression of one potential source of continuous gravitational waves — asymmetric accretion onto a spinning neutron star. Image credit: Mark Myers, Ozgrav, Swinburne University.

Artist's impression of a black hole about to collide with a neutron star. Image credit: Carl Knox, OzGrav, Swinburne University.

Professor Steven Prawer

Professor Steven Prawer

- Diamond
- Quantum devices
- Medical devices
- Implantable electronics
- Nanotechnology

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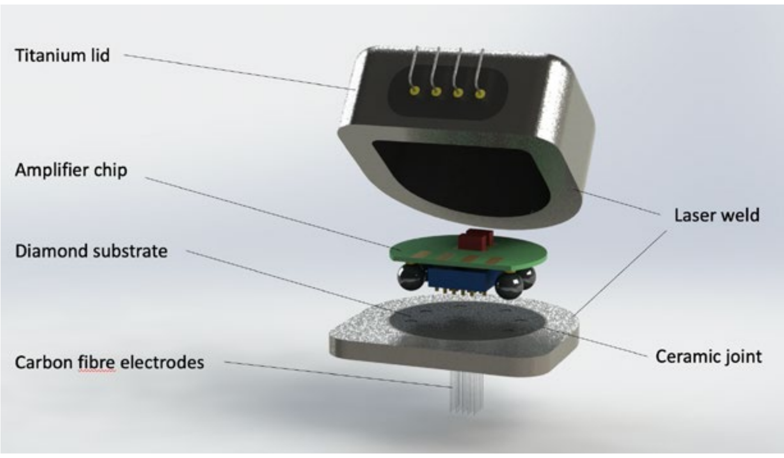
I endeavour to use our knowledge of physics (including materials, electronics and quantum mechanics) to solve real-world problems in neuroscience, medicine and defence. Our vision for electric medicine is a future in which safe, smart, miniature, implantable devices enable the widespread deployment of therapies based on electric stimulation and recording for improved health and diagnosis to provide revolutionary new treatments where pharmaceutical solutions are inadequate.

Bionics

At the boundary of physics and medicine, we have discovered ways of building a revolutionary brain-machine two-way interface using the unique properties of diamond and carbon fibres. We call this 'carbon cybernetics', and our interdisciplinary team of physicists, neuroscientists, clinicians and engineers are developing compact implantable devices to treat epilepsy, mitigate pain and restore vision.

Quantum technologies

We have developed the toolkit for the fabrication of practical, diamond-based quantum devices, such as single-photon sources for secure communications, integrated quantum photonic chips for magnetic sensing and for imaging neural networks.



Professor Stephan Rachel

Professor Stephan Rachel

IBM Quantum Hub

- Quantum physics
- Condensed matter theory
- Topological quantum computing
- Superconductivity

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My quantum matter group specialises in (i) topological quantum computing, (ii) quantum simulations on IBMQ and (iii) quantum materials more broadly. Prominent examples of quantum simulations on the IBM Quantum Computers includes our work on Discrete Time-Crystals. Our interest in quantum materials ranges from semiconductors and superconductors to quantum magnets.

Topological quantum computing

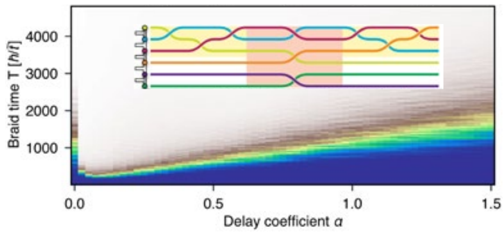
Future techology will rely on fault-tolerant i.e. error-free, quantum computers. We investigate such future concepts based on exotic Majorana particles which can be stabilised in topological superconductors. We perform unprecedented time-dependent simulations to investigate the interplay of multiple Majorana particles performing quantum computation tasks while being immune to errors.

Quantum Materials

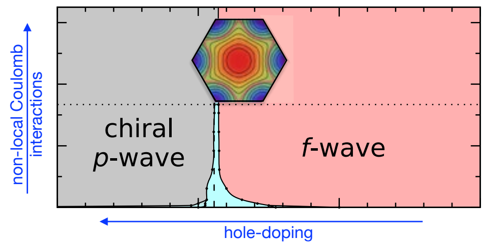
Systems and materials with show strong quantum effects are our main focus. As a recent example, we are interested in the quantum many-body ground states of material Sn/Si(111) where we predicted chiral topological superconductivity. Currently we investigate the competition of more exotic phenomena in this material class.

Time Crystals

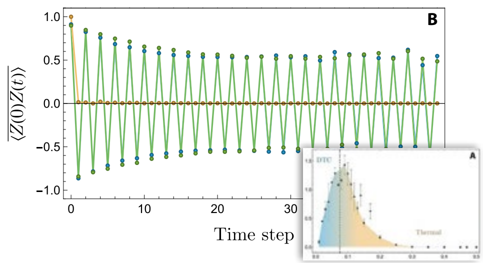
We are amongst the first researchers who make use of the potential of the IBM quantum computers (accessed through the IBM Quantum Hub at the University of Melbourne). Our recent success in observing a discrete time crystal on a quantum computer is the first realization of a non-equilibrium phase of matter. Our research is considered to be one of the first examples where a quantum computer outperforms classical computers.



Performance of a topological quantum bit: white region corresponds to a successful quantum gate operation. Inset shows the worldlines of six Majorana particles.



Quantum phase diagram of Sn/Si(111): over a wide range of possible interactions and electron densities, we predicted the material to realise a chiral topological superconductor (as latter confirmed in experiments).



Time crystal: periodic pattern in time. Traditional wisdom predicts that such an oscillating pattern must vanish over time. A time crystal evades, however, the laws of thermodynamics and features persistent oscillations.

Associate Professor Roger Rassool

Associate Professor Roger Rassool

- Medical oxygen
- Pneumonia
- COVID-19 accelerators
- Cancer

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We believe every child has the right to breathe, live and thrive. Our mission is to enable access to oxygen to save lives and reduce inequalities in health.

Did you know that pneumonia continues to be the single largest infectious cause of death in children worldwide, claiming more than 700,000 lives per year? Ninety-nine per cent of these deaths occur in the developing world.

A key medicine that will reduce this death toll is oxygen — in the air around us. COVID-19 shone a spotlight on the crucial role that oxygen plays in treating deadly highly contagious respiratory conditions and how the lack of access to medical oxygen in low-resource countries is one of the biggest health inequities of our time. While COVID-19 challenged health systems all over the world, communities in sub-Saharan Africa were more exposed than ever because they did not have reliable continuous medical-grade oxygen — the most basic medicine for people with pulmonary conditions.

I lead the FREO2 Group within the School of Physics, which combines expertise in physics, problem solving and innovation to design a portfolio of products that directly respond to this challenge.

Nico Snellen and Abigail Neave prepare oxygen systems for Uganda (2021).

Associate Professor Christian Reichardt

Associate Professor Christian Reichardt

- Cosmology
- Cosmic microwave background
- Inflation
- Dark energy
- Neutrinos

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I study the beginnings and inner workings of the universe to figure out how the cosmos works. I hope to leave us with a better understanding of the world around us and the majesty of the great unknowns in space.

Our group focuses on making precision measurements of the Cosmic Microwave Background (CMB) using world-leading international CMB experiments in Chile and the South Pole. The CMB is our first image of the infant universe — when the universe was a mere 0.003 per cent of its current age — and provides stringent tests of our understanding of how the universe began and how it has evolved. We work on all stages of the analysis of these Petabyte-sized data sets, from experimental characterisation to cosmological interpretation.

The South Pole Telescope observing during the winter of 2020. Image credit: Allen Foster.

Professor Ann Roberts

Professor Ann Roberts

- Optics
- Nanophotonics
- Imaging
- Meta-optics

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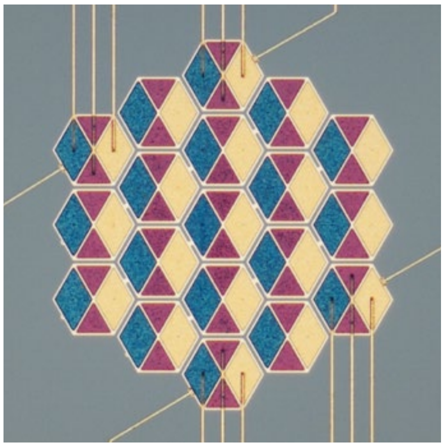
The interaction of light with matter on the nanoscale underpins complex physics, giving rise to the capacity to control light using devices that are much more compact than conventional optical components such as lenses. My group's research is aimed at developing a fundamental understanding of novel aspects of nano-optics and developing new theoretical and computational tools to study the properties of these intriguing systems. Furthermore, we are realising the next generation of ultracompact devices that can generate, manipulate and detect light.

Structural colour

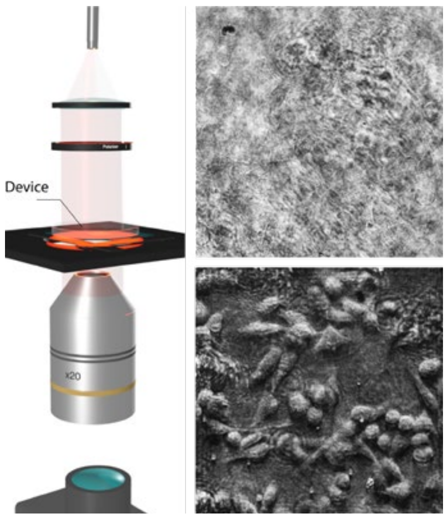
Central to being able to control light is the capacity to filter its optical spectrum. This is associated with the generation of colour which is normally produced using pigments and dyes. This traditional approach adds additional materials to the manufacturing process and is vulnerable to fading over time. We are investigating methods to create colour from metals and transparent material where the colouration derives from nanostructure introduced into the surface. Not only do these structures have potential applications in manufacturing, but the fact that these are much thinner than conventional filters makes them attractive for incorporation into camera sensors. Furthermore, in collaboration with researchers in the School of BioSciences, we are interested in expanding our understanding of structural colour in nature, such as the vivid appearance of beetles and butterflies.



Microscope image of an array of colour pixels seen in reflection where the colour derives from the geometry and arrangement of nanostructures embedded in the device.

Imaging using nanostructures

One of the intriguing aspects of planar nanostructured surfaces is they can be tailored so that the transmission through them depends on the angle of incidence at which they are illuminated. Harnessing this aspect of these meta-optical devices provides an avenue to modify images obtained with cameras in real time without the use of computational post-processing nor introducing complex bulk optics. We have shown that it is possible to generate pseudo-three-dimensional images of transparent cells using ultracompact nanostructured films opening the way to their integration into microfluidic and electronic devices.



Transparent cells (upper right) can be placed on a suitably tailored nanostructured device to create, in real time, a pseudo-3D intensity contrast image (lower right).

Associate Professor Suzie Sheehy

Associate Professor Suzie Sheehy

- Particle accelerators
- Particle therapy
- Radiotherapy
- Beamlines
- X-band RF

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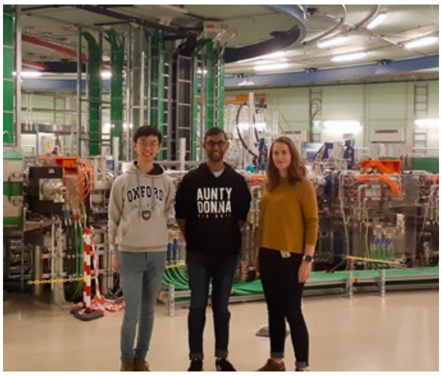
Our group vision is to undertake world-leading research in accelerator physics in order to create positive societal impact — in Australia and globally. We will achieve this through international collaborations, multi-disciplinary research, experimental and computational expertise and strong industrial connections. Our group values diversity, creativity and curiosity. Together we are creating physics through to experimental demonstration pathways to take concepts from simulation to reality.

Particle accelerators are an enabling technology of significant and growing importance. There are now around 50,000 accelerators in the world operating in industrial and medical applications in high-tech factories, hospitals, ports and mining sites. Applications abound from radiotherapy to the production of nuclear medicine isotopes to materials processing and security scanning. The development of particle accelerators for fundamental physics research has created the technology used in these highly varied applications and has revolutionised many areas of science, not just in physics but also in chemistry, biology, engineering, environmental science and cultural heritage.

This research area uses advanced accelerator physics concepts and approaches – from non-linear beam dynamics and high gradient 'X-band' radiofrequency technology through to advanced simulation and machine learning. With an experimental approach, we aim to design, build and test novel particle accelerators for next-generation societal applications.



MedAustron particle therapy centre near Vienna, Austria.

Celebrating the arrival in January 2021 of the X-LAB equipment from CERN.

Associate Professor David Simpson

Associate Professor David Simpson

- Diamond
- Quantum sensing
- Magnetic fields
- Electric fields
- Biotechnology

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Quantum sensors provide a new and unique view of the world, and can be used to solve long-standing problems in medicine, biology, and physics.

Our research is focused on the development of novel quantum-based sensors that can provide solutions to longstanding scientific challenges, such as imaging electrical activity in the brain, establishing more sensitive and accurate clinical assays and developing precision sensors that push the limits of detection.

Diamond-based quantum sensors

Diamond is a fascinating material that is at the forefront of the current quantum technology revolution. Diamond can be engineered to host atomic defects that act as near perfect quantum systems that can be used to sense very small changes in magnetic and electric fields. Our interdisciplinary group studies the material properties of diamond and applies diamond quantum sensors to a range of problems in physics, biology and chemistry. We collaborate with a broad range of medical institutions, government and industry partners to translate research into real-world solutions.

Medicine and healthcare

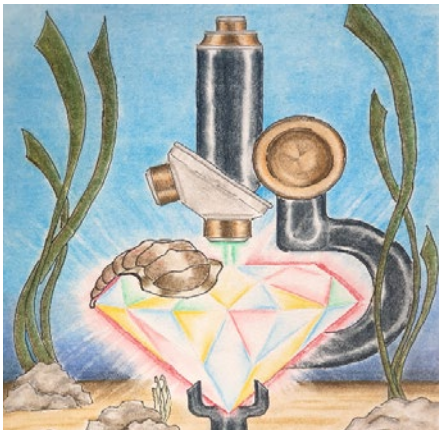
Understanding how our brains communicate and process information is a grand challenge in science made difficult by the shared number of neurons that make up complex networks and the challenges of reporting from each. To tackle this grand challenge, our group has developed a novel voltage imaging platform using defect centres in diamond that can image electrical activity at sub-cellular resolution. Our aim is to apply this non-invasive quantum technology to study cardiovascular disease and neurodegenerative disorders.

Iron deficiency affects approximately one third of the world's population. Using cutting-edge diamond magnetic sensing technology, we aim to establish a new clinical test that will provide fundamentally new information about how iron is regulated within our body. Our hope is that the insights will lead to improved diagnosis, treatment and management of iron-related disorders.

Precision sensing

Diamond quantum sensors are unique in that they can operate at room temperature in ambient conditions and with sensitivities that surpass their classical counterparts. Our group is exploring methods to build precise diamond-based vector magnetic field sensors for applications in geo-surveying, magnetic navigation, biomimetics, communications and object detection and classification. This technology drive will serve broader application areas in medical imaging and chemical detection and analysis.

Precision sensing with a quantum-based diamond magnetometer.



Diamond-based magnetic microscopy applied to study the magnetic properties of iron biomineral in chiton teeth.

Professor Michele Trenti

Professor Michele Trenti

- Galaxy formation and evolution
- Space telescopes
- Nanosatellite instrumentation
- Infrared remote sensing

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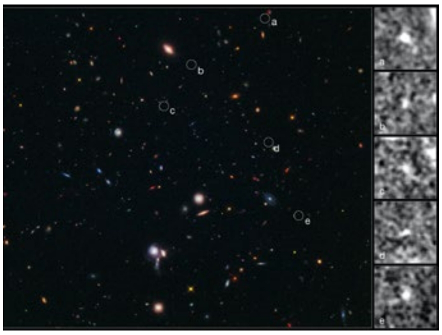
I aim to explore the cosmos through the lens of telescopes and understand how the universe grew in complexity across cosmic time and led to the formation of stars like the Sun and galaxies like our Milky Way that can host sentient life. By carrying out fundamental research, we are fostering critical thinking and problem-solving skills that can be applied effectively to a wide range of social and economic issues, offering a strong return on investment to society.

I am an astrophysicist with broad research interests and expertise, primarily studying the formation and evolution of stars and galaxies in the infancy of the Universe. I am a heavy user of the Hubble Space Telescope, having been awarded about three months of time (1400 Hubble orbits) to date as Principal Investigator on this multibillion-dollar facility. In addition to observations of the most distant galaxies, I am interested in theoretical modelling and computer simulations of galaxy formation, in understanding the connection between gamma-ray bursts and star formation, and in the dynamics of self-gravitating stellar systems such as globular clusters.

I also have a keen interest in contributing to the growth of the emerging Australian space sector in the area of innovative and high-performing nanosatellites for Earth and space observation. I am the director of the Melbourne Space Laboratory and Principal Investigator of the SpIRIT satellite, funded by the Australian Space Agency International Space Investment: Expand Capability scheme. SpIRIT is the first space mission selected by the Australian Space Agency. It aims to demonstrate the maturity and international competitiveness of the national space sector through a made-in-Australia advanced nanosatellite. SpIRIT will also contribute to multi-messenger astrophysics thanks to a gamma and X-ray detector provided by the Italian Space Agency.

Artist impression of the Space Industry Responsive Intelligent Thermal (SpIRIT) satellite, the first space mission funded by the Australian Space Agency. Image credit: M. Trenti, S. Barraclough and the SpIRIT team. Background image: NASA.



Composite (visible and near-infrared) image acquired with the Hubble Space Telescope as part of the Brightest of Reionizing Galaxies (BoRG) survey, showing in the insets five objects identified as a group of galaxies seen when the universe was less than 650 million years old (more than 13 billion years ago). Image credit: NASA, ESA, M. Trenti, L. Bradley and the BoRG team.

Professor Phillip Urquijo

Professor Phillip Urquijo

- Dark matter direct detection
- Experimental particle physics
- Flavour physics

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My research addresses why matter particles have mass, why nature has three generations of matter particles with different masses, why the universe contains matter and not antimatter and how dark matter interacts with matter particles. As an experimental particle physicist, I build discovery machines and develop data analysis and simulation techniques to describe the phenomena of the interactions of fundamental particles.

Matter-antimatter asymmetry and flavour physics

The Big Bang should have created equal amounts of matter and antimatter in the early Universe. But today, everything we see from the smallest life forms on Earth to the largest stellar objects is made almost entirely of matter. Comparatively, there is not much antimatter to be found — something must have happened to tip the balance. One of the greatest challenges in physics is to figure out what happened to the antimatter and why we see an asymmetry between matter and antimatter.

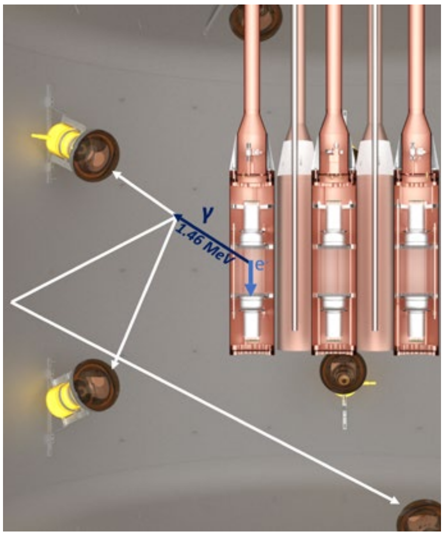
My research program with the Belle II experiment at the SuperKEKB electron-positron collider aims to understand this asymmetry through the study of heavy quark interactions. I am also using Belle II to investigate quark and lepton interaction strengths in an effort to uncover new fundamental interactions.

Dark matter direct detection

Results from astronomical observations provide overwhelming evidence for the existence of a large amount of dark matter in the Universe. The majority of the mass in our universe is composed of this type of matter, yet its particle nature remains unknown.

My research is on building and operating dark matter detectors in Australia. The first Australian dark matter experiment, SABRE (Sodium Iodide with Active Background Rejection Experiment), will be located at the Stawell Underground Physics Laboratory in Victoria. A fundamental model-independent signature for dark matter particles interacting with earth-based detectors is the annual modulation of the expected interaction rate. SABRE aims to detect the annual modulation with an array of high radio-purity thallium-doped sodium iodide (NaI(Tl)) scintillating crystals deployed in a liquid scintillator, which works as an active anti-coincidence veto.

The SuperKEKB accelerator and the Belle II detector in Tsukuba, Japan. Image credit: KEK/Belle II.



The SABRE dark matter experiment. This diagram depicts the detection of potassium-40 background using the liquid scintillator veto system.

Professor Raymond Volkas

Professor Raymond Volkas

- Beyond the Standard Model
- Dark matter
- Neutrinos
- Baryogenesis

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My research is about helping to uncover a more complete theory than the current Standard Model of particle physics, especially in relation to the nature of dark matter, the origin of neutrino and other elementary particle masses, and the origin of the cosmological matter-antimatter asymmetry.

Beyond the standard model of particle physics

My research is about extending or going beyond the Standard Model (SM) to understand more about the fundamental laws of the universe. While the SM provides a very successful description of elementary particles and their interactions, it is known to be incomplete. The existence of nonzero neutrino masses, dark matter and the cosmological matter-antimatter asymmetry establishes the need for a more complete theory. The SM also has theoretical shortcomings that motivate the existence of new particles and interactions.

Neutrino masses

Neutrinos are electrically neutral particles that are produced through the weak interaction in conjunction with the electron and its more massive cousins the muon and the tau. In the SM, the three neutrinos are exactly massless, but experiments have now proven that neutrinos, in fact, have mass, though those masses are extremely small. How neutrinos gain their masses and why they are so much smaller than those of related particles the electron, muon, tau and the quark, is unknown.

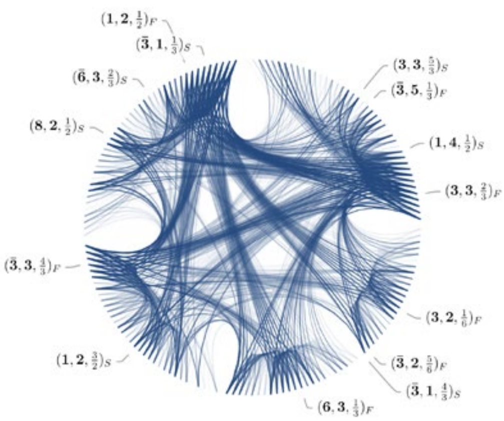
My research program concerns proposing theories for how neutrino masses arise, and especially for why they are so tiny. I am also very interested in rigorously testing whether or not the SM mechanism for generating the other quark and lepton masses is correct.

Dark matter

Most of the mass density of matter in the universe comprises the mysterious 'dark matter'. The existing evidence points strongly to dark matter being composed of a stable, or very long-lived, electrically neutral particle or set of such particles. Existing research has shown that massive neutrinos do not work as dark matter candidates, which means that the dark matter particle(s) go beyond the SM particle zoo. My work is about developing theories of what dark matter might be and elucidating in each case what the experimental, astrophysical and cosmological signatures could be.

The matter-antimatter asymmetry of the universe

In the early stages of the Big Bang, the universe was full of both matter and antimatter. Today's universe, however, is almost entirely populated by matter. What must have happened is that, at some stage during cosmological evolution, a slight preponderance of matter over antimatter was dynamically generated. As the universe expanded and cooled, all the antimatter was annihilated with matter to produce radiation, leaving the excess matter to form all the galaxies, stars and planets we see today. The SM is unable to explain how this happened. I develop theories that extend the SM to include possible explanations, and I am especially interested in connecting the question of the cosmological origin of ordinary matter with the origin of dark matter.



Professor Rachel Webster

Professor Rachel Webster

- Epoch of Reionisation
- Quasars
- First stars
- Gravitational lensing
- Cosmology

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My astrophysical research program has been inspired by a deep appreciation of the beauty and complexity of the universe, and the excitement of using physics and mathematics to understand a little more of how it has formed and evolved. As a physical scientist, I believe we have an obligation to use these tools to understand the evolution of our planet, to educate, and to contribute to the changes that will be required to avert catastrophic changes.

The Epoch of Reionisation (EoR)

The EoR is the period early in the history of the universe when the first stars re-ionised the neutral hydrogen that resulted from the Big Bang. The sequence of structure formation during this period is still to be determined. An observational program to detect these first stars uses low-frequency radio telescopes to measure a signal in the distribution of neutral hydrogen, but so far only limits have been obtained. The EoR project collects massive datasets that need to be meticulously analysed to remove all the instrumental and foreground signatures to uncover the underlying EoR signal. The next 5-10 years will be an exciting period, with a likely detection either from the current generation of instruments or the new SKA-Low telescope in Western Australia.

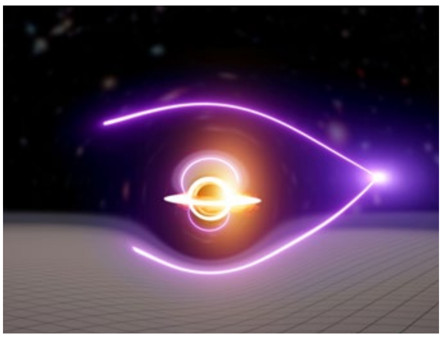
Quasars

Quasars are luminous sources powered by supermassive black holes at the centres of galaxies. The accretion of matter onto these black holes and the outflow of a disk wind are ubiquitous and broadly understood. However, despite over 50 years of observations and theoretical modelling, there is still no consensus about the detailed physics and kinematics, particularly of the disk wind. The observed characteristics of the disk wind are used to measure many of the physical parameters of the system, eg the black hole mass. Thus, an accurate physical understanding of the diskwind is key to understanding the birth and evolution of supermassive black holes in the early universe. This project uses new techniques, in particular gravitational lensing, to develop a physical picture of the disk wind of a quasar.

Renewable energy

The release of the 2021 IPCC report on the impact of climate change on our planet has made clear the critical need for harnessing new forms of renewable energy. In the Latrobe Valley in Victoria, we have substantial geothermal resources near the surface which are readily accessible. A series of projects are being developed to harness this resource both to support large-scale district heating within the communities in the Valley and importantly to develop new industries particularly associated with food production that can ensure long-term prosperity for these communities.

An artist's impression of gravitational lensing by a black hole, in this case a Gamma Ray Burst. This depicts the first lensed Gamma Ray Burst. Image credit: Carl Knox.



An artist's impression of gravitational lensing by a black hole, in this case a Gamma Ray Burst. This depicts the first lensed Gamma Ray Burst. Image credit: Carl Knox.

Dr Alexander Wood

Dr Alexander Wood

- Quantum sensing
- Quantum optics
- Atomic physics
- Magnetometry
- Inertial sensing

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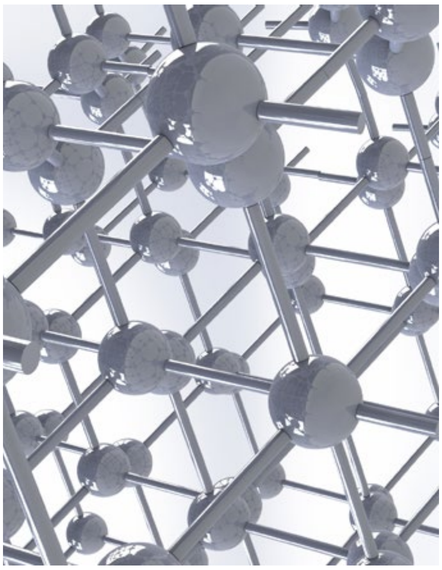
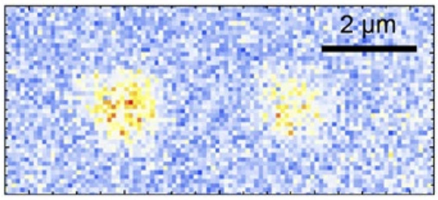
The quantum properties of matter are intrinsically fascinating and inherently useful, and we are constantly searching for new handles on a quantum system. My research uses quantum objects to understand how quantum angular momentum and classical rotation are intertwined at nano-to-microscopic length scales and in complex spin systems like magnets. We also seek to exploit these quantum oddities that appear in a rotating frame to make better sensors and quantum information platforms.

Quantum sensing with spinning spins

Angular momentum plays a central role in quantum mechanics, where we describe gate operations in terms of rotations in abstract Hilbert space. But what about ordinary classical rotation? How does that affect a quantum object? My research makes use of fluorescent colour centres in diamond, such as the nitrogen-vacancy (NV) centre, to explore how classical physical rotation at quantum-relevant timescales affects a coherent quantum object.

We have built a machine that rotates ultrapure diamonds to speeds of up to 500,000 rpm, fast enough that the qubits inside the diamond remain coherent over the period of rotation. Highlights of this research include measurement of ultrafast rotating single spins, quantum phases from classical rotation, fictitious rotationally-induced magnetic fields that tune the coherence of a quantum sensor, and a novel technique to enhance the sensitivity of a quantum magnetometer by spinning a qubit.





Two single NV centres imaged rotating at 3.3kHz

Professor Geoffrey Taylor

Professor Geoffrey Taylor

- Particle physics
- Particle detectors

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My work addresses critical questions in the field of particle physics, with a primary focus on determining the properties of the Higgs boson.

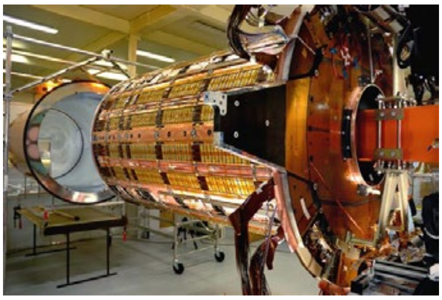
Particle beam collisions

In the first fraction of a second after the Big Bang, high-energy particle beams collided. Recreating these collisions gives us the best glimpse of the very early universe. The ATLAS Experiment uses CERN's Large Hadron Collider to cause high-impact, head-on collisions between high-energy particle beams, so we can probe matter at the finest scale. Discoveries of new particles produced in these collisions – like the 2012 discovery of the Higgs boson – build our understanding of the most basic building blocks of matter and the fundamental forces of nature.

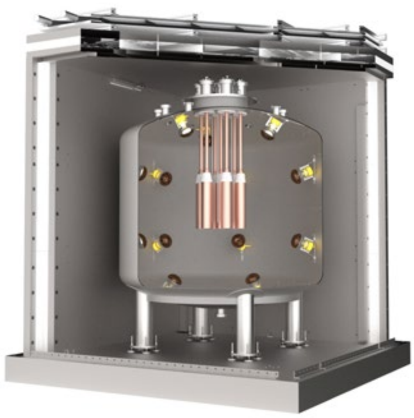
Dark matter

Most (around 85 per cent) of the matter of our universe interacts with gravity but does not absorb, reflect or emit electromagnetic radiation – it is 'dark' matter. We are searching for evidence of dark matter particles being produced at the Large Hadron Collider. We are also preparing the new Stawell Underground Physics Laboratory (located one kilometre underground in a goldmine) and a new experiment (SABRE) to search for direct evidence of dark matter in our solar system and galaxy.

We have a well-advanced, long-term proposal to build a 'Higgs Factory' – the International Linear Collider. This electron-positron collider will enable cleaner, closer study of the Higgs boson to seek out tiny deviations from its expected properties, offering a portal to 'new physics' including dark matter particle candidates.



The SCT particle detector during installation.



Schematic of the SABRE dark matter search experiment being built for installation in the SUPL underground laboratory at Stawell, Victoria.

Schematic of proposed Higgs the factory - the ILC. (Illustration - Rey.Tori)

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