What do quantum physicists know about gravitational waves and dark matter?

Did you know that dark matter makes up over 85% of the Universe's mass, but scientists have never been able to detect it? And that some gravitational waves are proving just as elusive? At **The University of Western Australia**, quantum physicists **Dr William Campbell** and **Emma Paterson** are aiming to solve these mysteries.

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Field of research
Quantum physics

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Detecting gravitational waves and dark matter using quantum technologies

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PROFILES

Talk like a ...

quantum physicist

Axion — a hypothetical particle which is believed to be part of dark matter

Black holes — regions in space where gravity is strong and nothing, not even light, can escape

Cavity resonator — a space that confines electromagnetic waves by reflecting them back and forth between the cavity's walls

Cryogenic — relating to the branch of physics that deals with very low temperatures

Dark matter — a form of hypothetical matter which does not interact with the electromagnetic field

Electromagnetic wave — a wave created by the interaction of an electric field with a magnetic field

Electron — a subatomic particle with a negative electric charge

Electron volt (eV) — a unit of energy in particle physics, which can also be a unit of mass

Gravitational wave — an invisible ripple through space that travels at the speed of light

In-spiral — when two things spiral towards each other

Kelvin (K) – a scale for measuring temperature

Photon — a particle of light

Piezoelectricity — the electric charge that builds up in solid materials

Quantum — the smallest amount or unit of something

Quantum physics — the branch of physics relating to how everything works at the smallest scale

"Quantum technology is at an exciting stage where we are starting to see how it can be used in real-world applications," says Emma Paterson, a quantum physics PhD student at The University of Western Australia. "The current level of technological advancement in quantum physics means we are on the cusp of seeing real breakthroughs," says her colleague, Dr William Campbell. As


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quantum physicists, Emma and Will are using quantum technology for different applications: while Will is hoping to discover new gravitational waves, Emma is focusing on detecting dark matter.

What are gravitational waves?

Gravitational waves are invisible waves that travel through space at the speed of light. "These are generated by large energetic events in the Universe, such as two black holes orbiting each other until they eventually in-spiral and collide into one another," says Will. "These astronomical events send ripples in space and time, much like stones being thrown into a pond sending out water waves."

High-frequency gravitational waves

Gravitational waves were first discovered in 2013 – a discovery that changed the world of physics forever. However, that was only the detection of low-frequency gravitational waves; Will's research is trying to detect high-frequency gravitational waves.

"While low-frequency gravitational waves are formed by large objects that don't orbit around each other very rapidly, high-frequency gravitational waves are thought to be formed by objects that spiral at much faster frequencies," explains Will. Objects that can spiral faster would be much smaller, such as micro black holes.

The Multi-mode Acoustic Gravitational wave Experiment

To detect high-frequency waves, Will has created the 'multi-mode acoustic gravitational wave experiment', also known as MAGE, using a quartz crystal. "Quartz is a special material because when it vibrates at its natural frequencies, it generates an electric charge on its surface," explains Will. "This phenomenon is known as piezoelectricity."

Due to this phenomenon, when a high-frequency gravitational wave passes by the quartz crystal, the crystal starts to vibrate. "This is much like how the plucking of a guitar string causes the string to ring out," says Will. When the quartz vibrates, a tiny electric charge is created on its surface.

Will then uses a device called a superconducting quantum interference device, or SQUID, which amplifies the electric charge enough that the tiny vibration of the crystal is detectable.

What does MAGE involve?

The MAGE needs to be kept extremely cold to detect small vibrations from far away gravitational events. "We keep it in a cryogenic tank at 4 K or -269.15 °C," says Will. The colder the detector is kept, the smaller the gravitational wave it can search for from events further away in space.

"A typical day in the lab involves looking after the set-up by working with cryogenics, as well as collecting large amounts of data and searching through large data sets for potential signals from gravitational waves," says Will.

The team has to be extremely precise when searching through data for these signals. "Recently, we found two super strong and rare signals in our data," says Will. "Over 153 days of observation, these signals only lasted for about one second each!"

If Will can successfully detect a high-frequency gravitational wave, it would have significant impacts on what we know about the Universe. "It would help us to answer questions about how the Universe was formed and the composition of a mysterious form of 'dark' matter, and address many other hypothetical theories," says Will.

Dark matter detection

Dark matter is a hypothetical component of space. "It makes up 85% of the Universe's mass and is everywhere," says Emma. "We can't see it because it doesn't interact with light or other forces, but we know it's there due to its gravitational effect on stars, planets and galaxies."

Despite there being a lot of evidence that dark matter exists, researchers are still trying to detect it. "Scientists think dark matter is made of particles that feel gravity but don't interact much with other forces," says Emma. "One interesting candidate for these particles is the axion."

The axion is thought to be an extremely lightweight particle and was first suggested to exist in 1977. It has no electric charge, but it might be detectable because, under certain conditions involving electric and magnetic fields, axions can (theoretically) turn into photons, which are particles of light.

"The smallest axion mass we can detect with current technology is about 10^{-7} electron volts (eV)," says Emma. This leaves a lot of smaller dark matter particles undetectable. However, to solve this problem, Emma has helped build the Anyon Cavity Resonator, which is able to search for particles with as low a mass as 10^{-24} eV.

"These resonators have the potential to detect the difficult-to-search-for axion due to a unique electromagnetic mode they can create through a mechanism called 'photonic magneto-electric coupling'," explains Emma. The cavity resonator reflects electromagnetic waves back and forth between its walls and creates a special twisted light. It had to be made with 3D printing techniques, as traditional methods could not handle the complexity of the design.

What else can the resonator do?

When studying the special twisted light created in the cavity resonator device, Emma discovered a surprising application that has nothing to do with dark matter, but instead benefits the medical industry.

Have you ever noticed the flipped image of yourself when looking in a mirror or taking a selfie? There are similar mirror images of molecules too, caused by them having left-handed and right-handed versions.

It is very important for scientists in the medical industry to be able to differentiate between the two, as different versions of medical drugs can have very different effects. "Take thalidomide, for example," says Emma. Thalidomide was a drug developed in the 1950s, which caused one of the biggest medical disasters of all time. While its right-handed version helped fight cancer, its left-handed version led to thousands of miscarriages and birth defects after being given to pregnant women to reduce nausea.

"Currently, the pharmaceutical industry uses expensive and slow equipment, costing around $100,000 per device, to separate these mirror-image forms of drug molecules," says Emma. "They produce only a few milligrams of each drug per day from each device."

When working on the new cavity resonator device, Emma discovered that the special twisted light created by the device can manipulate large amounts of molecules. It can even separate left-handed molecules from right-handed ones much more effectively and efficiently than current methods.

"Our devices cost just $10,000 each and can handle larger volumes," says Emma. "This breakthrough is crucial because there's a high demand for faster, more cost-effective ways to produce safe medicines in large quantities."

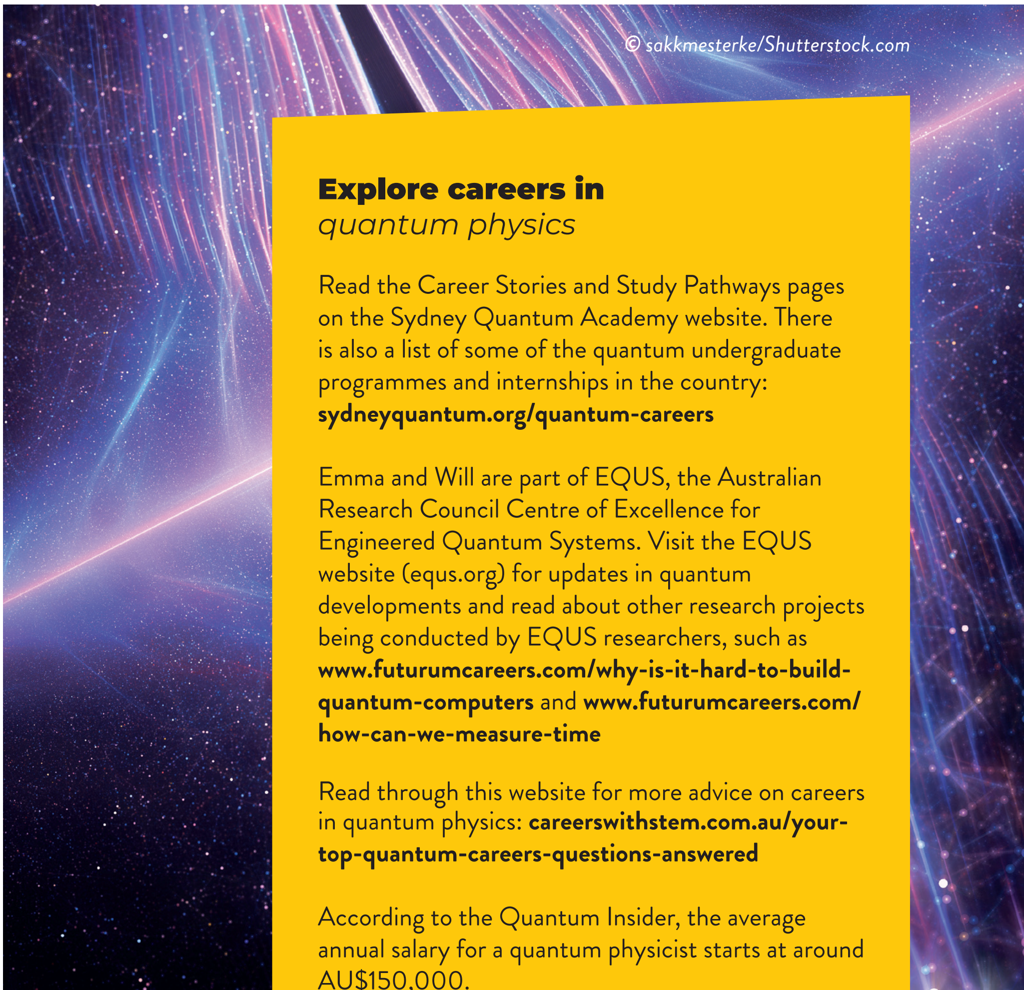
What's next?

Emma is focusing on the exciting healthcare applications of her work for now. "We want to improve how we separate these molecules to make them purer, more efficient, and easier to do on a larger scale," says Emma. She hopes to have the Anyon Cavity Resonator available for use within the next five years, and possibly even able to sort up to grams of molecules at a time. This would have an incredible impact on the healthcare industry, with the benefits for dark matter detection yet to come too!

About *quantum physics*

Quantum physics explains how things work at the smallest level and involves studying how subatomic particles and forces interact with each other. It is a rapidly expanding field that is becoming a more important area of research all the time – the Australian Government, for example, recently invested AU$ 18.4 million dollars to create a new national quantum physics centre.

"The next generation of quantum physicists will shape the way quantum technology benefits society," says Emma. "Tomorrow's physicists will harness the power of the quantum realm to generate new innovations and technologies that help people in different ways, from advanced computing and communication to medical breakthroughs."



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Explore careers in *quantum physics*

Read the Career Stories and Study Pathways pages on the Sydney Quantum Academy website. There is also a list of some of the quantum undergraduate programmes and internships in the country: **sydneyquantum.org/quantum-careers**

Emma and Will are part of EQUS, the Australian Research Council Centre of Excellence for Engineered Quantum Systems. Visit the EQUS website (equs.org) for updates in quantum developments and read about other research projects being conducted by EQUS researchers, such as **www.futurumcareers.com/why-is-it-hard-to-build-quantum-computers** and **www.futurumcareers.com/how-can-we-measure-time**

Read through this website for more advice on careers in quantum physics: **careerswithstem.com.au/your-top-quantum-careers-questions-answered**

According to the Quantum Insider, the average annual salary for a quantum physicist starts at around AU$150,000.

Meet *Emma*

The experiences that have shaped my career in quantum science started with a research project I did at the Quantum Technologies and Dark Matter Research Lab at The University of Western Australia. This opportunity gave me valuable experience in the field and connected me with an academic network I needed to start my career. One of the most exciting moments for me was realising that my work could lead to new discoveries and technologies that might change the world.

Reflecting on my journey so far, I'm incredibly proud of several achievements that have shaped my career in research. One of the biggest milestones for me was being accepted onto a PhD programme, receiving a scholarship from the Australian Government and a higher degree student research grant from the Defence Science Centre, which allowed me to pursue my passion for quantum science. Another highlight was seeing my first academic paper published in a journal. Winning the oral presentation award at the ANZCOP-Australian Institute of Physics Summer Meeting was another exciting accomplishment.

I aim to continue being involved in cutting-edge research, whether that be through a job in industry or an academic position.

Emma's *top tip*

Focus on your love of research and physics, and make that your number one priority. The PhD opportunities and research output will follow.

Meet *Will*

The mysteries and wonder of science, as well as the wacky world of quantum mechanics, inspired me to consider a career in physics. There are so many unanswered questions that I can work on and explore as an early career scientist. Working in science and discovering something new every day is the dream for me.

Last year, I travelled to Geneva, Switzerland, to visit the Large Hadron Collider at CERN and give a talk on my work at a conference. Doing a PhD and then further work in physics will give you plenty of opportunities to travel the globe, meet like-minded people and discuss all the exciting work happening around the world. If you like travelling and seeing new things, this could be the career for you!

In physics, there is a lot of room for different types of people, with different passions, in experimental as well as theoretical fields. Do you like taking apart old electronics and building new things? Do you like reading, critical thinking and solving problems? Do you like working with people as a team?

Will's *top tip*

Find out what it is you love doing, and do it! Taking the right science classes always helps, but the most important ingredient is finding your passion and forgetting any external voices telling you that you can't do it because of X, Y and Z.

Pathway from school to *quantum physics*

Study physics and maths at school and college. "At university, major in physics and consider the benefits of an honours programme," says Emma. "However, it should be noted that there are many different pathways to a career in physics, and the most important asset is the enjoyment of learning and discovering new things."

To do research in quantum physics, you will need to complete an honours or master's degree and a PhD.

The National Quantum and Dark Matter Road Trip (**www.qdmroadtrip.org**) travels around Australia each year. The road trip includes a team of quantum scientists and science communicators delivering presentations, hands-on activities and information about quantum physics across the country, with the hope of inspiring the next generation of physicists.