CAS HONOURS PROJECT LIST 2020

1. Do the laws of gravity depend on cosmological environment?

Supervisor: Prof Chris Blake
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Project description: As the large-scale structure of the Universe is shaped by the competing forces of gravity and cosmic expansion, the distribution of galaxies forms a network of clusters, filaments, sheets and voids. A key test of the nature of gravity on cosmological scales is whether the laws of gravity are the same in all these environments. The results of this test have significant implications for the nature of the dark energy which is driving the expansion of the Universe to speed up.   In this project, we will map the cosmic environments traced by the largest available galaxy redshift dataset, the Baryon Oscillation Spectroscopic Survey, which contains over a million galaxies spanning a volume of 10 cubic giga-parsecs (that's $10^{77} \, m^3$!) We will use the resulting topological map to search for differential signatures of lensing and galaxy clustering as a function of environment. The project will utilise and develop your skills in programming, statistics and mathematics.

2. Gravitational waves from a population of colliding black holes and neutron stars

Supervisor: Dr Simon Stevenson
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Project description: Gravitational waves have now been observed from colliding neutron stars and black holes by Advanced LIGO and Virgo, with the number of observations rising almost daily. As the size of the observed population grows, we shift from being in a regime where each individual event is interesting on its own, to a regime where information is encoded in the population (e.g. the rate, the shape of the mass and spin distributions, etc). A key open astrophysical question is how these merging binaries are formed: they can be formed dynamically from neutron stars and black holes in dense stellar environments such as globular clusters, or from the evolution of a binary of two massive stars. In this project we will investigate what can be learned from the current catalogue of gravitational wave observations by building population models to compare with observations.

Further reading:
- Current catalogue of gravitational-wave events: LIGO/Virgo Collaborations 2019 https://arxiv.org/abs/1811.12907
- COMPAS population synthesis suite: Stevenson et al 2017 https://arxiv.org/abs/1704.01352

3. Estimating parameters of black hole binary gravitational wave signals detected with LIGO and Virgo

Supervisors: Dr Jade Powell
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Project description: The Advanced LIGO and Advanced Virgo gravitational-wave detectors have made the first direct detections of gravitational waves from compact binary neutron stars and black holes. The waveforms of the gravitational-wave signals can tell us information about the parameters of the source, such as the masses and spins of black holes and neutron stars. The mass and spin measurements of a population of gravitational-wave signals can inform our understanding of their formation. The goal of this project is to develop methods that can enable us to determine the formation mechanism of black holes from the mass and spin measurements of a population of gravitational-wave sources. This can then be applied to simulated gravitational-wave data for testing, and real gravitational-wave detections made during the Advanced LIGO and Advanced Virgo observing runs.

Further reading:
- J Veitch et al. Robust parameter estimation for compact binaries with ground-based gravitational-wave observations using the LALInference software library. Phys. Rev. D 91, 042003 (2015)

4. Black planets as dark matter

Supervisor: A/Prof Alan Duffy and Prof Jeremy Mould
Contact: aduffy@swin.edu.au

Project description: We aim to measure the fraction of the dark matter in our Galaxy in the form of sub-stellar-mass primordial black holes (PBH). If they exist, such objects brighten background stars when they pass between the star and Earth, in a process known as gravitational microlensing. Astronomical camera technology now allows a microlensing experiment in our Galaxy's halo to decrease the detected event time to 10 seconds from its limit in the MACHO experiment two decades ago of 1 day, reaching PBH masses of a billionth of a solar mass, hypothetically known as "black planets".

Our student will pipeline 5 Tb of Cerro Tololo DECam data through existing photometry software and produce a million light curves. The detection of PBH candidates will be automated, and a student with some coding experience will have the opportunity to be creative in this phase. Expected outcomes include the mass range and density of these objects in the Galaxy. If this is not a detection but an upper limit, it will redirect the search for a quarter of the mass of the Universe towards other candidates.

5. How do ionizing photons leak through the interstellar medium?

Supervisor: A/Prof Emma Ryan-Weber and Dr Rob Bassett
Contact: eryanweber@swin.edu.au

Project description: The transmission of photons with sufficient energy to ionize Hydrogen is a critical process in astrophysics. Understanding how these photons escape their birth places holds implications for both local galaxies and the high redshift Universe. The ionizing photons are produced by massive O and B-type stars that illuminate the surrounding gas producing nebula emission lines, such as $H\beta$ and [OIII], which can be observed using spectroscopy with optical telescopes. The ionization nebulae are also known as HII regions. The neutral Hydrogen gas, HI, in the immediate neighbourhood can be measured in the 21-cm emission line using radio telescopes.

The main goal of this project is to compare the escape fraction of ionizing photons from HII regions with the density and kinematics of HI in same vicinity. We know that only a few percent of the ionizing photons escape. How does that few percent leak through the interstellar medium? Does the HI data hold any clues? Do HII regions with high levels of leaking photons correspond to holes or velocity offsets in the HI?   This project will appeal to a student who is interested in working with multi-wavelength spectroscopic data and with the curiosity to try new ideas.

Further reading:
- Bassett et al. 2019, MNRAS, 83, 5223
- Borthakur et al. 2014, Science, 346, 216
- Pellegrini et al. 2012, ApJ, 755, 40

6. Gas flows in and out of extreme star bursting galaxies

Supervisor: Dr Deanne Fisher
Contact: dfisher@swin.edu.au

Project description: In this project the student will work with data from the new, cutting-edge instrument on the Keck telescope to study the gas flows in extreme star-forming galaxies. Shortly (10-50 Myr) after stars form, a small fraction of them will explode in violent supernova events. Supernovae, as well as intense radiation from young stars, inject energy and momentum into the surrounding gas. This arrests future star formation and provides outward pressure preventing galaxies from collapsing under their own gravity. We call this process "stellar feedback". Without stellar feedback, cosmological simulations cannot explain the bulk properties of galaxies. Measuring the gas flows that come from these supernovae is therefore a critical aspect of galaxy evolution, which in the past has been extremely difficult to observe. However, with the recent commissioning of the Keck Cosmic Web Imager, we can now make point-to-point measurements of gas flows within galaxies. The student will join a team of researchers working on many details of studying outflows and how they affect the galaxy that contains them.

7. Calibrating the chemical content of galaxies near and far

Supervisor: Dr Sarah Sweet
Contact: ssweet@swin.edu.au

Project description: Chemical content is an important signature of a galaxy's lifecycle, as the build-up of elements from hydrogen and helium to heavier "metals" is intimately linked to its history of star formation. There are two equally-justifiable methods for measuring chemical content based on regions of active star formation within galaxies, but the methods are not properly calibrated, so they do not agree. Moreover, they are valid in different regimes, so that we cannot accurately compare distant galaxies with those nearby, or massive galaxies with smaller ones. We are using the tiny bundles of optical fibres of the Sydney-AAO Multiple Integral field unit (SAMI) on the Anglo-Australian Telescope to obtain a complete three-dimensional picture of star-forming regions in nearby galaxies, and recalibrate the chemical content measurements.

This project involves working with 3D spectroscopic data from SAMI of approximately one hundred star-forming regions in nearby galaxies, and the derived maps of their key properties such as temperature, ionization and emission line strength. Key questions to be addressed include: What are the conditions in super star clusters, thought to be the dominant mode of star formation at high redshift? What is the impact of stellar winds on the HII region properties? What is the full range of ionization parameter across HII regions, and what causes the variations? These are important contributions towards recalibrating the methods, which will enable more accurate comparison of galaxies near and far.

8. Machine learning for finding rare gems in a deluge of astronomical spectroscopic data

Supervisor: Dr Edward Taylor
Contact: entaylor@swin.edu.au

Project description: The big idea of this project is to use machine learning techniques to classify astronomical spectra, with the particular goal of identifying rare, interesting, or even unexpected astronomical phenomena. This is part of a larger programme to develop a data classification and outlier identification pipeline for the 4MOST spectroscopic survey facility, which will collect as many as 100,000 spectra each night; well over 20 million spectra in its first 5 years of operations. With such an extreme data rate, two things are assured: 1.) 4MOST will observe many, many rare and even unexpected astronomical sources or events, and 2.) without effective automated pipelines to find and flag them, these high-value data will end up unnoticed and forgotten in a data archive somewhere. For this project, you will use the 300,000 spectra from the Galaxy And Mass Assembly (GAMA) survey as a testbed for one or more machine learning approaches to sorting and classifying spectra, with the genuine prospect of discovering new phenomena in this established dataset.

9. Probing Cosmological Variability of Fundamental Constants with Quasar Spectra

Supervisor: Prof Michael Murphy
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Project description: Distant galaxies, seen in silhouette against bright, background quasars, imprint a characteristic pattern of absorption lines onto the quasar light as it travels to Earth. This pattern is determined by the fundamental constants of nature. Using spectra taken with the largest optical telescopes in the world (e.g. Keck and Subaru in Hawaii, VLT in Chile), this pattern can be compared with laboratory spectra to determine whether the fundamental constants were indeed the same in the distant, early universe as we measure them on Earth today. Several different avenues are available for exploration in this project. For example, one option is to analyse new spectra taken from the Keck and/or VLT with the aim of measuring the variability of the fine-structure constant (effectively, the strength of electromagnetism). Another option is to improve the methods used to make these exacting measurements so that we can make the best use of a new instrument being built on the VLT specifically for such work. These and other options will be discussed with the candidate.

Further reading:
- Evans T.M., Murphy M.T., Whitmore J.B. et al., 2014, Mon. Not. Roy. Astron. Soc., 445, 128
- Murphy M.T., Malec A.M., Prochaska J.X., 2016, Mon. Not. Roy. Astron. Soc., 461, 24613

10. Searching for Rare Metals in the Distant Universe with Quasar Spectra

Supervisor: Prof Michael Murphy
Contact: mmurphy@swin.edu.au

Project description: How the heavy elements originated in stars is an enduring problem in astrophysics, as is the question of how exploding stars polluted the gaseous surroundings of galaxies. This project will draw upon a large database of the highest-quality spectra of quasars in the distant universe, the lines-of-sight to which probe gas around foreground galaxies. The aim is to combine these spectra to search for absorption lines from heavy elements not previously seen outside our own galaxy. Identifying these rare metals can help diagnose the physical and nucleosynthetic origins of the absorption clouds, and may greatly improve future measurements of the fundamental constants in the distant universe.

Further reading:
- Prochaska J.X., Howk J.C., Wolfe A.M., 2003, Nature, 423, 57

11. The nature of the first stellar populations in the Universe

Supervisor: Prof Karl Glazebrook
Contact: kglazebrook@swin.edu.au

Project description: The forthcoming launch of the James Webb Space Telescope (JWST) (https://www.jwst.nasa.gov) will dramatically open up the possibilities for learning about the first billion years of cosmic history (redshifts $z > 4$). JWST is a 6.5m space telescope, significantly larger than the 27-year-old 2.5m Hubble Space Telescope, and will extend much further into the infrared due to its cold location, one million km from the Earth.

Especially significant is that JWST spectroscopy will enable the first detailed measurements of the stellar populations of early galaxies (Hubble has not had a high-resolution spectrograph and has not been able to reach the long wavelengths needed). This will lead to new discoveries on topics such as the Initial Mass Function (IMF), rate of formation, elemental abundances and the presence of exotic populations. These studies will probe the fundamental physics of galaxy formation at $z > 4$ in detail previously not possible. Recent discoveries of massive evolved galaxies (stellar masses $> 10^{11} \, M_\odot$) in such an early Universe point to an epoch of extremely fast star-formation followed by just as rapid quenching.

A variety of next-generation spectral synthesis codes have been developed in the past few years, which allow more sophisticated treatment of emission lines, binary populations, abundances, complex star-formation histories and the IMF. In this Honours project, we will test the ability of neural networks to "learn" the solutions to models with complex star-formation histories using the Prospector code, and speed up the results for fitting individual spectra. This project is part of Professor Glazebrook's Laureate Fellowship (starting at the end of 2019) and so there may be further opportunities to continue this research after Honours.

Further reading:
- Hezaveh Y. D., Levasseur L. P., Marshall P. J., 2017, Fast automated analysis of strong gravitational lenses with convolutional neural networks, Nature, 548, 555
- Leja J., Johnson B. D., Conroy C., van Dokkum P. G., Byler N., 2017, Deriving Physical Properties from Broadband Photometry with Prospector: Description of the Model and a Demonstration of its Accuracy Using 129 Galaxies in the Local Universe, ApJ, 837, 170

12. Machine Learning for discovering High-Redshift and Exotic Objects

Supervisor: Prof Karl Glazebrook
Contact: kglazebrook@swin.edu.au

Project description: The forthcoming launch of the James Webb Space Telescope (JWST) will dramatically open up the possibilities for object discovery in the $z > 4$ Universe. Dozens of imaging bands from 2-28 microns will suddenly become available, and sensitive enough, to

find diverse types of early galaxies, and potentially new populations of exotic objects that may appear in the early Universe. Traditional colour selection (2-3 photometric bands) is not optimal for this new data, and traditional photometric-redshift selection requires highly specific models of what to look for. In this Honours project, we will test the potential of neural networks to measure photometric redshifts and deliver spectral energy classifications of galaxies using data from deep multi-band surveys in a flexible and robust approach. This project is part of Professor Glazebrook's Laureate Fellowship (starting at the end of 2019) and so there may be further opportunities to continue this research after Honours.

Further reading:
- Jacobs C., Glazebrook K., Collett T., More A., McCarthy C., 2017, Finding strong lenses in CFHTLS using convolutional neural networks, MNRAS, 471, 167
- Hezaveh Y. D., Levasseur L. P., Marshall P. J., 2017, Fast automated analysis of strong gravitational lenses with convolutional neural networks, Nature, 548, 555

13. Interstellar scintillation as a tool for studying pulsars and fundamental physics

Supervisor: Dr Daniel Reardon
Contact: dreardon@swin.edu.au

Project description: Pulsars are some of the most extreme objects in the universe. They are incredibly dense and rapidly rotating stars that we use as tools to study fundamental physics. They provide unique opportunities for testing theories of gravity in the strong field, searching for low-frequency gravitational waves from supermassive black hole binaries, and exploring the fundamental behaviour of matter at supranuclear densities. Pulsars are commonly timed like a precise clock using a detailed model of their rotation, binary orbit, and interstellar plasma that disturbs their radio emission. However, an emerging method for improving pulsar models is the study of the pulsar's scintillation, or "twinkling", caused by scattering by this plasma.

In this project, you will work with the ~15 year dataset of the Parkes Pulsar Timing Array (PPTA) collaboration to study the long-term behaviour of pulsar scintillation. This dataset includes ~20 of the most rapidly rotating pulsars and the most stable natural clocks in the Galaxy. Using a combination of pulsar scintillation and timing data, you will be able to solve the geometries of pulsar orbits, understand sources of noise in timing data, and identify extremely dense and turbulent structures in the interstellar plasma. This work will help constrain the pulsar masses for studies of dense matter, and improve the sensitivity of the PPTA to gravitational waves. You will also have opportunities to conduct pulsar observations using the famous 64m Parkes radio telescope!

Further reading:
- Reardon D., 2018, PhD thesis, "*Precision radio-frequency pulsar timing & interstellar scintillometry*": https://figshare.com/articles/Precision_radio-frequency_pulsar_timing_interstellar_scintillometry/7056602

14. UV upturn in early-type galaxies

Supervisor: Prof Duncan Forbes
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Project description: Strong ultra-violet (UV) colours are seen at the centre of many early-type (E and S0) galaxies. The origin of this upurn is debated. It may be due to the destruction of metal-rich, UV-bright globular clusters (GCs). Goudrooij (2018, ApJ, 857, 16) showed a strong correlation between FUV-UV colour and S_N (a measure of the number of metal-rich GCs per host galaxy luminosity). However, the number of galaxies in this sample is small.

The purpose of this Honours project is to extend the sample size and see if the correlation holds up. A secondary aim is to investigate whether the size of the UV emission correlates in any way with the size of the GC system in each galaxy.