CAS HONOURS PROJECT LIST 2021

Unveiling the nature of dark matter with galaxy-galaxy strong gravitational lensing

Supervisor: Dr Dorota Bayer
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Project description: One of the major unsolved puzzles in the fundamental physics is to unveil the nature of dark matter. While a direct detection of the dark-matter particle remains very challenging, it might be possible to constrain the nature of dark matter indirectly. One of the most promising avenues in this respect is the study of the abundance and properties of dark-matter substructures in the mass distribution of observed galaxies, and a subsequent comparison with predictions from phenomenological dark-matter models, such as the cold, warm or hot dark matter. The phenomenon of galaxy-galaxy strong gravitational lensing provides a unique opportunity to search for gravitational signatures of such substructures in lens galaxies beyond the local Universe. Recent astronomical surveys, such as the Kilo-Degree Survey (KiDS) or the Dark Energy Survey (DES), and the upcoming facilities, such as the James Webb Space Telescope (JWST), the Euclid Mission, the Nancy Grace Roman Space Telescope (WFIRST) or the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), are expected to increase the number of known galaxy-galaxy strong gravitational lens systems by at least two orders of magnitude. In this project, we will develop novel machine-learning techniques that will allow us to automate the search for substructures in such large datasets of strong gravitational lens systems.

Further reading:

- Vegetti S., Lagattuta D. J., McKean J. P., Auger M. W., Fassnacht C. D., Koopmans L. V. E., 2012, Gravitational detection of a low-mass dark satellite galaxy at cosmological distance, Nature, 481, 341
- Hezaveh Y. D., Levasseur L. P., Marshall P. J., 2017, Fast automated analysis of strong gravitational lenses with convolutional neural networks, Nature, 548, 555

Transfer learning for neural network lens hunting

Supervisor: Dr Colin Jacobs
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Project description: Strong Gravitational Lensing is a rare and beautiful phenomenon that can teach us much about gravity, matter and cosmology. Lensing occurs when a massive body such as a galaxy or cluster of galaxies bends the light of more distant objects, resulting in distinctive magnified arcs, rings and multiple images from our viewpoint here on Earth. Studying strong lensing has many scientific applications, including understanding the distribution of dark matter, constraining cosmological parameters, and observing distant galaxies that would otherwise be too faint to study; however, finding strong lenses is a challenge due to their rarity. In recent years, deep learning techniques have become the state of the art in lens finding. However, they need large training sets to achieve good accuracy, a challenge for very rare objects. In this project we will explore the benefits of using transfer learning - taking a deep neural network trained on one data set or for one problem domain and applying it to another after retraining with a new, smaller training set. If we can efficiently re-train a network trained on images suitable for one photometric band or astronomical survey for another with only minimal retraining, future lens-finding will be much more rapid and efficient. The goal of the project is to quantify the effects of different bands, resolution, and seeing conditions on the network accuracy and how efficiently these can be mitigated with transfer learning using images with different parameters. We will also explore the benefits of training with a small number of real lens images versus simulations. The student will utilise and expand skills in python programming, machine learning, Linux and high-performance computing.

Further reading:

- *A brief history of gravitational lensing* https://www.einstein-online.info/en/spotlight/grav_lensing_history/
- *Finding strong lenses in CFHTLS using convolutional neural networks* https://ui.adsabs.harvard.edu/abs/2017MNRAS.471..167J/abstract
- *Transfer Learning in Astronomy: A New Machine-Learning Paradigm* https://arxiv.org/abs/1812.10403

Local globular clusters as a ground truth for galaxy stellar population analysis methods

Supervisor: Dr Themiya Nanayakkara
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Project description: Understanding the properties of the stars in the early Universe is driven by the analysis of integrated light of galaxies. Even with the best telescopes these galaxies are merely observed as small blobs in the sky. Using spectrophotometric data from these galaxies, a variety of theoretical stellar population models and bayesian inference methods are used by astronomers to make crucial assumptions about the properties of the stars and gas from *cosmic dawn* to *cosmic noon*. The accuracy of such fitting routines to reproduce the observables and thus the conditions of the galaxies are generally quantified via mock observables. Application to real observed data where these properties are independently measured is often overlooked. In this project, you will address this issue by looking into local globular clusters as a benchmark for stellar population properties of galaxies. You will use a sample of globular clusters, whose properties are well constrained through colour-magnitude diagram analysis and through spectroscopy of individual stars, to create observables as inputs for a variety spectral energy distribution fitting softwares. Previous experience in programming (e.g. python) and some knowledge in statistics would be beneficial for this project.

Further reading:

- Spectroscopic ages and metallicities of stellar populations: validation of full spectrum fitting, Koleva et al. 2008, MNRAS https://ui.adsabs.harvard.edu/abs/2008MNRAS.385.1998K

3D foetal brain ultrasound: help brain development studies and improve prenatal clinical care

Supervisor: Dr. Jielai Zhang
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Project description: The human brain is the most complex organ of the human body, and its link to human behavior, memory, decision making and consciousness is tantalizingly elusive. One key outstanding question in the study of the human brain is what healthy development looks as the brain is forming in utero, development that will give rise to the full complexity of the human experience. What is the extent of variability in what is considered healthy, and when does that variability veer into states that are associated with disease? This has huge implications not only for understanding human brain development, but also in foetal health monitoring throughout pregnancy. Early brain development in utero has been difficult to study because of a lack of tools. While ultrasound is the primary point of care tool for foetal health monitoring throughout pregnancy, it has not been widely adopted for scientific investigation of foetal brain development. The reason for this is routine clinical practice uses 2D ultrasound, but 2D slices of the brain does not allow accurate measurements and population studies. 3D ultrasound is preferred for scientific study, but there is a lack of standardised tools for analysing 3D foetal ultrasound brain data. Over the last decade, many software tools have been developed for processing and analysing 3D foetal ultrasound brain data by engineers and image processing experts, but access to said software and using it is outside the skill domain of medical researchers. You will work on creation of a software GUI toolkit that allows people without coding skills to use these tools, helping to make the use of 3D foetal brain ultrasound data for medical research pervasive. The tools you will include in this GUI were developed by the Oxford Ultrasound NeuroImage Analysis Group (http://users.ox.ac.uk/~some2959/index.html).

Dust in the interstellar medium: what is it like really?

Supervisor: Dr. Jielai Zhang
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Project description: Dust is a critical component of the interstellar medium (ISM) and plays an important role in galactic evolution. It can serve as a catalyst for the formation of molecular hydrogen, heat the ISM via the photoelectric effect in the presence of UV light, help dense regions cool, and impart radiation pressure to gas. For those who do stellar or extragalactic observations, dust in the Milky Way is a source of extinction, and so must be characterized to measure the intrinsic color and brightness for a source of interest. For those who study cosmology, dust polarizes the signal coming from the cosmic microwave background (CMB), and so must be characterized to measure the polarization of the CMB due to cosmological effects. Suffice to say, understanding the physical and radiative properties of dust is a critical element in many areas of astronomy. However, measurements of the amount (column density) of gas and dust, as well as properties of the dust are very nuanced. Many parameters required to ascertain the column density of dust or its properties are interdependent and need to be assumed. One novel method that sidesteps many complications to determining the properties of dust and test dust models is to study it using two different radiative processes simultaneously. You will test dust models by observing dust scattered light images from the Dragonfly Telephoto Array (https://www.dragonflytelescope.org), and thermal dust emission images from the Herschel Space Observatory. You will learn advanced image processing techniques, including how to remove stars from your images to enable analysis of the diffuse dust.

Deeper, Wider, Faster: Discovering the fastest bursts in the Universe

Supervisor: Dr. Jielai Zhang
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Project description: The Deeper, Wider, Faster (DWF) program is the first program able to detect and study the fastest bursts in the Universe (on millisecond-to-hours timescales), such as fast radio bursts, supernova shock breakouts, kilonovae, all types of gamma-ray bursts, flare stars, and many others. DWF coordinates over 50 major observatories on every continent and in space (gamma-ray through radio), including particle and gravitational wave detectors, with a number of these multi-messenger facilities coordinated to observe the target fields simultaneously. DWF performs real-time supercomputer data processing and transient identification within minutes of the light hitting the telescopes. Fast identification and localisation enable rapid-response spectroscopic and imaging follow up before the events fade using 10m-class telescopes like Keck in Hawaii, Gemini-South and the VLT in Chile, SALT in South Africa, as well as Parkes, ASKAP, Molonglo, and ATCA radio telescopes and 4m AAT optical telescope in Australia and the NASA Swift and Chinese HXMT space telescopes. Finally, our network of over thirty 1-10m telescopes worldwide provide follow-up imaging and spectroscopy at later times. Depending on the interests and experience of the student, the project will involve (1) cross-matching multi-wavelength (radio, optical, UV, x-ray, and gamma-ray) data to discover new transients, (2) creating a system to coordinate and schedule observatories for DWF runs, and (3) enhancing and accelerating transient discovery by progressing data visualisation and data sonification techniques. Participation in DWF observing runs is encouraged and, in some cases, will help test the results of the student project.

Reconstructing the expansion history of the Universe

Supervisor: Prof Chris Blake
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Project description: Astronomers have long known that the Universe is expanding. However, over the past two decades evidence has grown that this expansion is actually accelerating, driven by a mysterious dark energy which seems to comprise around 70% of the current matter-energy density of the Universe. This result is obtained by fitting a specific empirical model, known as the "ΛCDM cosmological model", to the data. However, we do not yet have a convincing theoretical justification of this model, because we do not understand the origin of dark energy. In this Project we will test if we can measure the accelerating cosmic expansion independently of the ΛCDM model, by reconstructing non-parametric expansion curves of the recent Universe using standard candles and standard rulers, such as Type Ia supernovae and Baryon Acoustic Oscillations, using statistical model-fitting techniques. Can we directly see the accelerating expansion today, thereby confirming the existence of dark energy?

In dust we trust! Or do we?

Supervisor: Dr Michelle Cluver
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Project description: Star formation rate (SFR) indicators are an indispensable tool in astrophysics, but usually present a troublesome situation where multiple tracers do not agree. This is a consequence of both the assumptions made in using the tracer, and limitations of the tracer and the data. One popular method is using the warm dust continuum at 23/24 microns (i.e. in the mid-infrared), pioneered by the Spitzer Space Telescope. Another is using the 12micron band of the WISE survey, which samples a combination of small grain dust continuum and molecular PAH (polycyclic aromatic hydrocarbon) emission, which are both associated with star formation (Cluver+2017). Differences in the SFRs determined by the 12micron and 23micron bands of the WISE space telescope could be influenced by several factors, one being that the dust continuum is shaped by the geometry of the dust in relation to its star formation. This project will make use of the WISE Large Galaxy Atlas (Jarrett+2019), selecting nearby star-forming galaxies with different morphologies and orientations in order to compare their spatial star formation rates using 12 and 23 micron maps. In combination with mass maps from the 3.4 micron and 4.6 micron WISE imaging, we can additionally track the SFR-Mass scaling. This will give us insight into why we see differences, and also when we should be trusting one indicator over another. Where available, we will also compare to optical and/or UV SFRs.

Further Reading:

- Jarrett, T.H., Cluver, M.E., et al. 2019, ApJS, 245, 25
- Cluver, M.E., Jarrett, T.H., et al. 2017, ApJ, 850, 68

The distribution of gas and metals around galaxies, from low to high redshift

Supervisor: Prof Darren Croton
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Project description: The hydrogen gas content of a galaxy, from which new stars form, is an excellent probe of its future, while the metal content within that gas, produced in supernova during the death of old stars, is a similarly valuable probe of its past. *The goal of this project is to make predictions for the distribution of gas and metals around galaxies from low to high redshift, for different galaxy types and in different environments, and compare these against observations. We will build a map of the hidden baryons in the universe.*

The project has 5 parts: (1) undertake a literature review of our current understanding of gas and metals in galaxies; (2) to review the theory of how galaxies form and evolve across cosmic time, with a focus on the relevant physical processes; (3) to construct a model universe with the (existing) SAGE galaxy formation code run on the OzStar supercomputer at Swinburne; (4) using this model, to reproduce the current observations of gas and metals in and outside of galaxies out to the redshifts for which it's been measured; and (5) explore the model beyond this baseline to make predictions for future observational surveys. Additional goals will be to develop a solid understanding of galaxy evolution and cosmology, become familiar with supercomputer simulations and models, and the technical skills required to create and use them for science.

Probing the star formation main sequence of galaxies across cosmic time.

Supervisor: Prof Darren Croton
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Project description: Galaxies in the local universe appear to follow what has come to be called the star formation main sequence. This sequence reveals a strong correlation between a galaxy's stellar mass and its star formation rate, with only small scatter across the entire mass range probed. The sequence is known with confidence to extend out to z~1, with studies underway to probe it to even earlier times.

This project has 5 goals: (1) to review the literature about the current state and understanding of the star formation main sequence; (2) to review the theory of how galaxies form and evolve across cosmic time, with a focus on the relevant physical processes; (3) to construct a model universe with the (existing) SAGE galaxy formation code run on the OzStar supercomputer at Swinburne; (4) using this model, to reproduce the current observations of the star formation main sequence out to the redshifts for which it's been measured; and (5) to extend the exploration of the sequence using the model to earlier times that have yet to be observed so as to make predictions for future observational surveys.

Our main goal is to understand when and why the sequence first arises in the early universe. Additional goals will be to develop a solid understanding of galaxy evolution and cosmology, become familiar with supercomputer simulations and models, and the technical skills required to create and use them for science.

Cyber-human discovery systems for enhanced Earth observation data analytics

Supervisor: Prof Chris Fluke
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The volume, velocity and variety of Earth Observation data from space systems, satellites, unmanned aerial vehicles (UAVs), and terrestrial sensor solutions continues to grow rapidly. New data-driven solutions are required that provide an integrated yet flexible coupling between human visual analysis and automated methods (e.g. artificial intelligence and machine learning), in order to support discovery and decision-making. We refer to these approaches as *Cyber-Human Discovery Systems*. Within Australia's rapidly growing Space Industry, these solutions have application in domains as diverse as public health, agriculture, mining, disaster management, and defence.

Current and future Earth Observation data includes combinations of images, hyperspectral data cubes (i.e. two spatial and one spectral or frequency channel), and an assortment of derived data products from ground-based, UAV, and space-based programs. The dynamic and strongly time-based nature of Earth Observations means that datasets are collected over multiple observing epochs, often with varying spatial/spectral resolutions and observing cadences (i.e. time between successive observations of the same region).

Through a new Swinburne research focus on Space System Data Fusion, Integration and Cognition supported by the SmartSat Cooperative Research Centre (https://smartsatcrc.com), opportunities to develop new knowledge, and prototype real-world applications for Australia's Space industry, include:

1. ***Enhanced visual analytics***: The creation of new workflows and work scenarios to support comparative and collaborative insight and knowledge discovery for Earth Observation data. This will be achieved by adapting, integrating and translating existing, tested solutions for terabyte-scale hyperspectral analysis and visualisation from their original domain of data driven astronomy to Earth Observation data. This project will provide students with experience using the OzSTAR supercomputer. Swinburne's Remote Telescope Operations Centre and Discovery Wall will be utilised as a test laboratory for human interaction with automated systems through in situ and simulated decision-making scenarios.

2. ***Balancing human and automated discovery***: Finding the balance between automated discovery and human-centred insight that maximises the potential for discovery from data. For Earth Observation data (images, hyperspectral data products and fusion with other datasets), this will be achieved by designing and evaluating user experiences that integrate visual discovery and decision making with automated discovery and classification workflows for 2D images, 3D data cubes (hyperspectral or multispectral data products), and fused data products over single and multiple time-based epochs.

3. ***Understanding the human in the design of Cyber-Human Discovery Systems:*** With the increased reliance on automated and autonomous discovery and decision-making

workflows, there is a need for an improved understanding into how people currently make visual discoveries from data. Starting with a detailed investigation of the impact of expertise and skill in performing visual discovery tasks in astronomy, this knowledge will be transferred to relevant Space Industry contexts. Potential applications to arise from this work include: (1) supporting just-in-time coaching and training; (2) enabling talent identification; and (3) designing user interfaces for data exploration and visualisation that automatically respond to the skill level and needs of the users.

This is nuts: (peanut-shell)-shaped structures in face-on disk galaxies

Supervisor: Prof Alister Graham
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Project description: A growing number of galaxies with a bar-like feature - residing within the galaxies' flattened disk of stars - are known to additionally display a (peanut-shell)-shaped pattern. It is commonly thought that the stellar bar wobbles and buckles above and below the disk plane to form these "peanuts". We have recently developed a new method for quantifying these bar+peanut structures in terms of the 6th-order Fourier Harmonic deviation from purely elliptical isophotes. However, unbeknown to most astronomers, and rarely observed, this bar-buckling phenomenon can also occur within the plane of the disk. In 2018, we provided the first measurement of such an in-plane peanut in a galaxy whose disk is orientated face-on to us. We have identified ~10 more such galaxies and wish to measure their physical structure for comparison with the peanuts already measured in galaxies whose disks are orientated edge-on to us, yielding insight into the relative strength of the vertical (out of plane) and horizontal (in plane) bar-instability.

Further Reading:

- https://astronomynow.com/2016/05/08/astronomers-detect-double-peanut-shell-galaxies/
- https://arxiv.org/abs/1603.00019
- https://arxiv.org/abs/1712.00430

Galactic candy: quantifying the ansae of galaxies

Supervisor: Prof Alister Graham
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Project description: Galaxies possess a range of features, including discs, bulges, bars, rings, and more. Partial rings, known as "ansae", are located at the ends of galactic-bars. Collectively, with the other galaxy components, the isophotal structure, i.e. the contours of equal intensity, in these galaxies can resemble the silhouette of a candy wrapper, or a TIE fighter from Star Wars. Perhaps surprising, given the long history of astronomy, such features have never been quantified. Using Fourier harmonics, we have developed a technique which quantifies the departure of a galaxy's isophotes from pure ellipses, possibly enabling us to measure such features via the 8th order Fourier harmonic term. This project will work with ground and/or satellite images of roughly 10 galaxies possessing a bar and ansae in an effort to quantify and better understand these structures.

Further reading:

- https://arxiv.org/abs/1507.02691
- https://arxiv.org/abs/1603.00019
- https://arxiv.org/abs/1712.00430

Discovering morphological substructure in early-type galaxies

Supervisor: Prof Alister Graham
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Project description: This project will carefully measure the distribution of light in a sample of (20-30) early-type galaxies imaged with the Hubble Space Telescope (Ferrarese et al. 2006). Sometimes obvious, and sometimes subtle, changes in the shape of a galaxy's isophotes, as a function of galaxy radius, can be used to establish the presence of different physical structures, such as discs, bars, rings and more, in what at first glance appear to be rather simple, amorphous, elliptical-looking galaxies. Using Fourier harmonics, we have developed a technique which quantifies pear-shaped (B_3 Fourier term), boxy/discy-shaped (B_4), plus 5- and 6-humped (B_5 & B_6) galaxy features, with the latter related to unstable stellar bars. This project will focus on the "pears" and "boxes", thought to be associated with galaxy mergers, and establish the frequency of these particular substructures, possibly discover unknown galaxy components and trends, and thereby help to better understand the evolution of early-type galaxies.

Further reading:

- B. Ciambur (former Swinburne PhD student), 2015, The Astrophysical Journal, 810, 120 (https://arxiv.org/abs/1507.02691)
- Graham, 2019, Monthly Notices of the Royal Astronomical Society, London, 487, 4995 (https://arxiv.org/abs/1907.09791)

Asteroid-mass primordial black holes

Supervisors: Prof Jeremy Mould & Prof Alan Duffy
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Project description: Formed in the cauldron of the inflationary Universe, these objects are candidates for the 24% of everything that is Cold Dark Matter. They may have already been detected in our observing run this year on the Blanco 4m telescope, sister of the Anglo Australian Telescope. The Honours student is going to find them in our gravitational microlensing data. Your python skills will be handy, as we are using the Ozstar supercomputer to find these needles in our terabyte haystack.

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

Searching for rare metals in the distant universe with quasar spectra

Supervisor: Prof Michael Murphy
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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