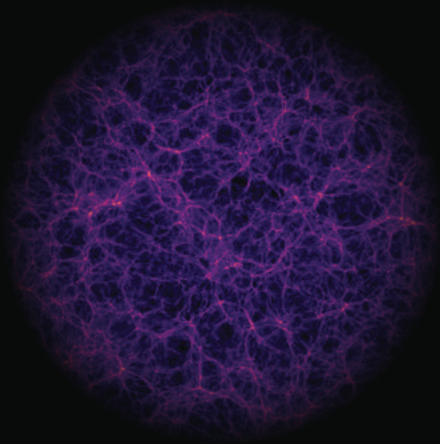
Astronomy PhD Projects at Durham

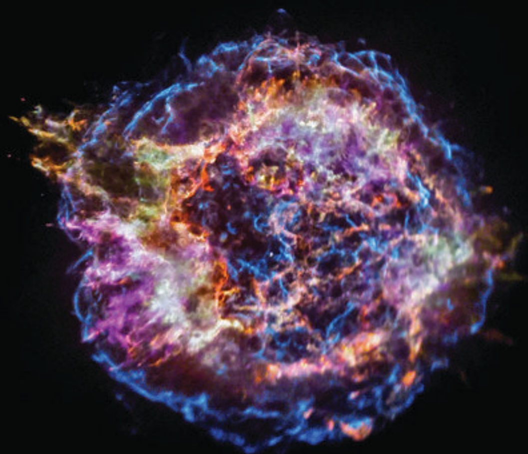
2021

Durham University

ICC



Durham Centre for Extragalactic Astronomy



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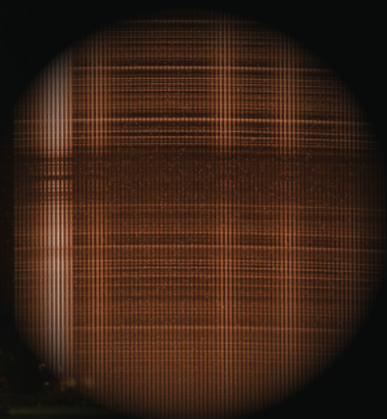


PHD PROJECTS IN ASTRONOMY FOR AUTUMN 2021 START

Introduction

List of STFC/FLF fundable PhD Projects

Brown: Studying the most energetic accelerators in the Universe: γ-ray astronomy and CTA

Done: Understanding Quasars across cosmic time: structure of accretion flow around SMBH

Frenk: The identity of the dark matter

Jauzac: Galaxy Clusters to Reveal the Nature of Dark Matter

Mcleod: - Resolved stellar populations in nearby galaxies
- Stellar feedback at low metallicities
- Synthetic observations of star formation and galaxy evolution simulations

Morabito: - Particle Acceleration in High Redshift AGN
- Outflows in active galactic nuclei: what is driving the radio emission?

Scaringi: - Exploiting the Gaia/TESS synergy: using ML to build a novel discovery tool
- Eavesdropping on accretion disks: using TESS to unravel the physics of accretion

Swinbank: Galaxy Evolution over the last 10 billion years

List of additional PhD/MScR Projects with other funding opportunities

Alexander: - Tracing the cosmic growth of black holes with the NuSTAR X-ray observatory
- Why are (some) quasars special? Towards an understanding of the evolution of quasars

Chadwick: Surveying the Extreme Universe with the Southern Wide-field Gamma-ray Observatory

Edge: Infrared Dust Reverberation from Space

Landt-Wilman: Machine Learning Algorithms for Time-domain Astronomy

O'Brien: A new era of astronomy with Kinetic Inductance Detectors

Smith: Lensing and Cosmology with HARMONI at the ELT

INTRODUCTION

Durham University is a UK-leading centre for astronomical research with world-class groups working in a wide range of fields covering the observational, theoretical and instrumentation aspects of astronomy. Durham has been ranked ranked Number One in Europe and sixth in the world for our research into Space Science (which covers research into astronomy and astrophysics) over the decade 2002–2012, according to Thomson Reuters.

There are 33 academic staff across the combined astronomy groups, with over 100 people involved in astronomy research, which includes postdocs, postgraduate students and support and technical staff. Our main areas of expertise are extragalactic astronomy and cosmology (observational and theoretical), advanced instrumentation, and high-energy astrophysics. Astronomy in Durham is split over three closely connected groups within the Physics Department and which are now all located to a large extent within the newly built Ogden Centre for Fundamental Physics. The three groups consists of the Centre for Advanced Instrumentation (CfAI), the Centre for Extragalactic Astronomy (CEA) and the Institute for Computational Cosmology (ICC).

We are seeking now graduate students to undertake research within our PhD and MSc by Research programmes, starting from October 2021.

Fully Funded PhD Studentship Options

This booklet outlines primarily PhD projects for which we can provide full funding (fees plus a stipend) over 4 years typically, but not exclusively. For those project with funding associated, we provide brief details on the funding below.

Science and Technology Facilities Council (STFC) studentships. These 4-year PhD studentships are available to any student meeting the qualification criteria thanks to financial backing from Durham University. We note that there are quotas on the number of international students that can be funded. We refer candidates to enjoy the clarity of the information and eligibility rules that applies to STFC studentships. We expect to offer 6 STFC-funded studentships this year, based on previous years STFC allocations, which according to the rules in place at the time of writing could imply up to 2 international studentships.

Future Leader Fellow (FLF) funded PhD studentship. This 4-year PhD studentship has nominally the same eligibility criteria as the STFC studentships, but with the quota on international studentships currently in place the current understanding is that it is limited to UK students and/or students with settled status only. We offer 1 FLF studentship this year.

Other PhD Studentship Options

We can offer an even broader range of PhD projects and supervisors for graduate students that have obtained their own funding or are in the process to apply for funding. For details of other potential projects and a full list of potential supervisors, please see the Postgraduate Opportunities link off of our web page. Some specific projects have been included in this booklet.

Two potential funding routes are provided by Durham University through the **Durham Doctoral Studentships (DDS)** and **China Scholarship Council (CSC)** schemes. The application deadline for DDS and CSC scholarships is such that nomination letters by staff based on the applicant's submitted material needs to be in place by Wednesday January 6$^{\text{th}}$ 2021, for an autumn 2021 start. We note that by the deadline we need to have received reference letters in support of your application, something we request directly from your referee once you have submitted your application. Therefore we encourage interested graduate students to contact us well in advance of this deadline to ensure maximum success, as well as to explore other potential sources of funding. Hence we recommend DDS/CSC applications to be submitted by **mid/late December 2020** to receive full consideration.

Bell Burnell Graduate Scholarship Fund. The IOP and leading physicist Professor Dame Jocelyn Bell Burnell launched the Bell Burnell Graduate Scholarship Fund to encourage greater diversity in physics. It is a scholarship fund to support full or part-time graduates who wish to study towards a doctorate in physics and are from groups that are currently under-represented in physics. As host university, Durham can put forward a maximum of two students for the Fund. To be considered, candidates needs to have applied and be nominated by a staff member by the internal physics deadline of January 6$^{\text{th}}$ 2021. Hence we recommend applicants interested to be considered for the *Bell Burnell Graduate Scholarship Fund* to submit their application by **mid/late December 2020** to receive full consideration.

In past years prospective PhD students have been successful in securing funding from various national and international funding bodies with support from academic staff in Durham, including *Van Mildert College Trust*, *Team Durham Graduate Programme*, *CONACYT* and *CONICET* PhD scholarships. For more details, please see the Postgraduate Opportunities link off of our web page.

PhD application process

PhD studentships are awarded on the basis of academic record and research aptitude, which are assessed via an on-line application and an interview (in person in Durham or remotely depending on the situation). We expect to interview shortlisted candidates for funded studentships from mid-February through to mid-March (see our web-pages for up-to-date information regarding possible interview days and effective deadlines to meet).

We recommend you to indicate several projects for which you wish to be considered, or your general area of interest (simulations, observations, etc), to help us identify potential supervisors for the interview days. Your application is not expected to include an original research proposal, but rather to indicate which of the described projects you wish to pursue. In practice, these descriptions provide a starting point for each project; the ongoing direction of your research will adapt naturally over the course of study.

MSc by Research Studentship Options

We can offer an equally broad range of MSc by Research (MScR) projects and supervisors for graduate students that have their own funding. For details of other potential projects and a full list of potential supervisors, please see the Postgraduate Opportunities link off of our web page. Currently there is no funding available for MScR projects, but for residents in England the UK government has a scheme to apply for post-graduate loans. For more specific details of the scheme, please consult the UK government webpages https://www.gov.uk/postgraduate-loan.

Follow the post-graduate opportunities link from our web site or contact our astronomy post-graduate administrator (Dr. Peder Norberg; peder.norberg@durham.ac.uk; Ogden Centre West 129) for further details.

STUDYING THE MOST ENERGETIC ACCELERATORS IN THE UNIVERSE: GAMMA RAY ASTRONOMY AND THE CHERENKOV TELESCOPE ARRAY

Main Supervisor:	Dr. Anthony M. Brown	anthony.brown@durham.ac.uk
Office:	Rochester 125d	
2nd Supervisor:	Prof. Paula Chadwick	p.m.chadwick@durham.ac.uk
Funding:	STFC and all other funding schemes	

Description:

Over the last 10 years, very high energy (VHE) gamma ray astronomy has opened a new window on the extreme universe. The catalogue of known VHE-emitting objects has grown by an order of magnitude and includes many different classes of objects - supernova remnants, pulsars, binary star systems, star formation regions and active galaxies - while other objects remain a mystery. The VHE radiation from these systems is produced by non-thermal particle acceleration, but the mechanisms by which this occurs have not been established. Observations of the more distant objects provide us with a probe of the extragalactic background light, of intergalactic magnetic fields and even of the structure of space-time itself. VHE gamma rays may also be one of the ways in which we detect the presence of dark matter in the Universe.

However, we have really opened this new window only a little way, and so some 1450 scientists and engineers from 31 nations are joining together to create a new instrument: the Cherenkov Telescope Array (CTA). Consisting of a 100-telescope array in the southern hemisphere and a 20-telescope array in the north, CTA will have sensitivity around 10 times better than any gamma ray telescope now in operation, will cover 4 orders of magnitude in energy and have better angular resolution than anything we have built before. Prototyping of telescopes and instrumentation has already begun; the first telescope of the northern array is already in place, and construction of the southern array is expected to start in 2021.

As founder members of CTA, the Durham group is involved in many different aspects of the telescopes. Students can choose from a range of possible projects, including science studies relating to active galactic nuclei, multi-messenger (gamma-ray/neutrino) studies, dark matter etc. in preparation for CTA (primarily using data from the Fermi Gamma-ray Space Telescope), telescope calibration using UAVs, simulations of array performance, the development of new analysis algorithms and the design and testing of instrumentation. We are particularly involved in the construction of cameras for the small telescopes of the array and lead CTA's UAV work package. Students can also expect to be involved in work on preliminary data from pre-production telescopes, which are expected to go on the final site of the southern array in Chile.

The CTA Project homepage: https://www.cta-observatory.org/
The CTA Science Case: https://arxiv.org/abs/1709.07997
UAV-based calibration feasibility study: https://arxiv.org/pdf/1711.01413.pdf

UAV-calibration of CTA. Left: first light data of the technique. Centre: Schematic showing approach. Right: features in gamma-ray spectra, the science use-case for the UAV calibration.

Notes:

UNDERSTANDING QUASARS ACROSS COSMIC TIME: THE STRUCTURE OF THE ACCRETION FLOW AROUND A SUPERMASSIVE BLACK HOLE

Main Supervisor: Prof Chris Done chris.done@durham.ac.uk
Office: Ogden Centre West 132
Funding: STFC and all other funding schemes

Description:

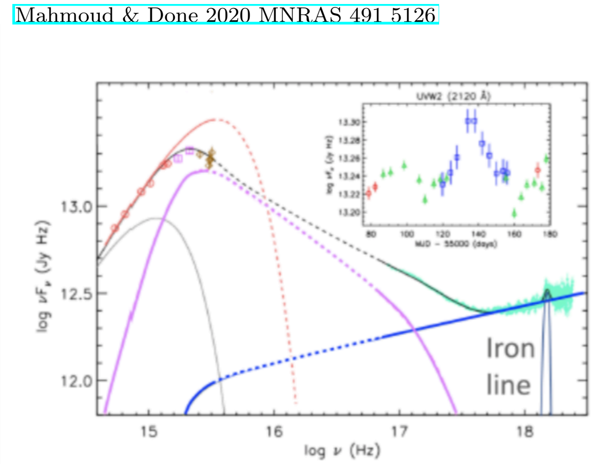
Black holes are the simplest possible objects, characterised only by mass and spin. We see them most easily via accretion, where the enormous gravitational potential energy released by the infalling material transforms these darkest objects in the Universe into the brightest. Hence there is another parameter which controls the observable appearance of an accreting black hole, namely the mass accretion rate, along with viewing angle for any non-spherical flow. Fundamentally, these parameters must determine the majority of the properties.

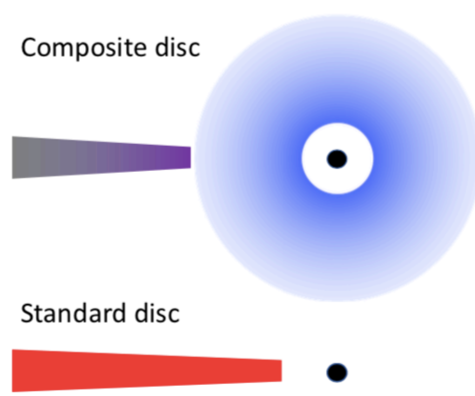
Standard disc models seem to mostly work in stellar mass black holes at high luminosities, accreting material from a binary companion star. But some very different structures are seen for similarly high luminosities in the supermassive black holes powering the Active Galactic Nuclei (AGN). A standard accretion disc in a luminous AGN with mass $10^8\ M_\odot$ has peak temperature of $\sim 10^5$K, making a very blue optical/UV continuum (red line in Fig 1). Such continuua are seen, though they are often not as blue as expected (e.g. data in Fig 1). There is a downturn in the UV emission which appears to connect to an upturn in the X-ray emission below 1 keV (the soft X-ray excess, magenta, Fig 1). The optical/UV is also variable, typically showing changes of more than 10% on timescales of weeks (inset), yet a standard disc can only respond to changes in mass accretion rate on a timescale of $> 10^4$ years (e.g. Noda & Done 2018). The hot X-ray corona (blue, Fig 1) is variable on even faster timescales (days), but again its nature is not well understood.

Instead of a standard disc (bottom schematic) the data can be fit by models where the accretion flow structure changes (top schematic). This composite geometry predicts the emission spectrum of the AGN based on mass, mass accretion rate and spin, and predicts the relative geometry of the UV and X-rays (Kubota & Done 2018).

These models are testable, as they completely specify the geometry. The variable X-rays can illuminate the soft X-ray excess and outer disc, producing a variable UV component from reprocessing which is a lagged and smoothed version of the illuminating X-ray flux (Mahmoud & Done 2020). The project will calculate this response, and use this on intensive monitoring data to explore the inner structure of AGN accretion discs, where the majority of their vast luminosity is emitted. This will give us a physical model to understand AGN across cosmic time.

Noda & Done 2018 MNRAS 480 3898
Kubota & Done 2018 MNRAS 480 1247
Mahmoud & Done 2020 MNRAS 491 5126





Notes:

THE IDENTITY OF THE DARK MATTER

Main Supervisor: Prof. Carlos Frenk CBE FRS c.s.frenk@durham.ac.uk
Office: Ogden Centre West 225
2nd Supervisor: Prof. Adrian Jenkins a.r.jenkins@durham.ac.uk
Funding: STFC and all other funding schemes

Description:

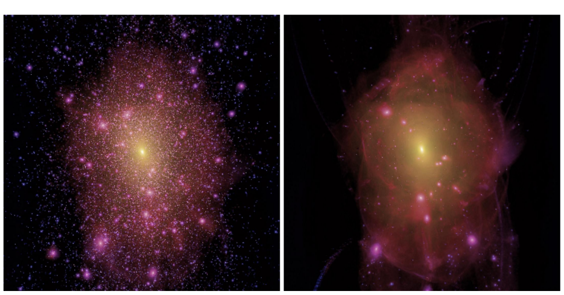
Ever since the idea that the dark matter could consist of non-baryonic particles was put forward in the early 1980s, identifying its nature has been a prime target of physics research. The best studied hypothesis (extensively explored by ICC theorists) is that the dark matter is a cold, collisionless particle, such as the lightest particle in supersymmetric theories of particle physics, or an axion. This hypothesis lies at the core of the singularly successful "ΛCDM" model, developed in the 1980s and early 1990s, whose predictions have been shown to match microwave background data from, most famously, COBE, WMAP and Planck, and from surveys of the large-scale structure, particularly the 2dFGRS and the SDSS. In spite of these successes, which have enshrined ΛCDM as the "standard model" of cosmogony, the stark reality is that we have no direct evidence to support the key assumption of the model - that the dark matter is indeed a cold, very weakly interacting particle.

Cold dark matter particles have negligible thermal velocities at early times. These, however, are not the only kind of particles that could have been produced in the early universe. For example, sterile neutrinos, if they exist, would have appreciable thermal velocities at early times, and thus behave as warm, rather than cold dark matter. These particles could also explain observed neutrino oscillation rates and baryogenesis, making them attractive candidates for the dark matter. Warm particles free-stream out of small initial density perturbations and this affects the way in which galaxies build up. On scales larger than individual galaxies, however, the formation of structure procedes in very similar ways whether the dark matter is cold or warm and so current astronomical observations on those scales cannot distinguish between these diffferent types of dark matter particles. However, on smaller scales, the differences between the two are large (see figure).

The goal of this project is to uncover astrophysical observables that might constrain, or perhaps even reveal the identity of the dark matter. It will focus on two key diagnostics: dwarf galaxies and stellar halos. Dwarf galaxies are relevant because they are mostly made of dark matter and are expected to have different properties if the dark matter is cold or warm. Stellar halos are relevant because the are the fossil record of the assembly of galaxies by the merger of smaller galaxies - their properties too might depend on the nature of the dark matter. The project is primarily theoretical but some analysis of real astronomical data may be required. It will rely heavily on cosmological simulations, both using N-body simulations that follow the evolution of the dark matter and gasdynamic simulations that follow, in addition, the evolution of baryonic (or ordinary) material. The simulations are technically challenging but we have a revolutionary new code, SWIFT, developed at Durham, that will enable cosmological simulations an order of magnitude larger than is possible today.

The student will make use of the ICC's large supercomputer (the "Cosmology Machine"), as well as resources provided by the "Virgo consortium", Europe's premier collaboration for cosmological simulations, which is based at the ICC. The results of the simulations may suggest observational strategies that the student might wish to pursue. For example, we are members of the international DESI project, a spectro-photometric survey that will acquire spectra for tens of millions of galaxies and also for hundreds of thousands of stars in the Milky Way. The particle models that we will consider have predictive power and are disprovable. This programme has the potential to rule out many dark matter particle candidates, including CDM.

Frenk, C. S. & White, S. D. M, 2012, Dark matter and cosmic structure Annalen der Physik, vol. 524, 507
Sawala, T. et al. 2015, The APOSTLE simulations: solutions to the Local Group's cosmic puzzles, arXiv:1511.01098
Li, R. et al 2016, Constraints on the identity of the dark matter from strong gravitational lenses, arXiv:1512.06507



Images of a cold (left) and a warm (right) dark matter galactic halo from large N-body simulations carried out at the ICC. Image intensity indicates the line-of-sight projected density squared, and hue the projected density-weighted velocity dispersion, ranging from blue (low velocity dispersion) to yellow (high velocity dispersion). Each box is 1.5 Mpc on a side. Note the sharp caustics visible at large radii in the WDM image, several of which are also present, although less well defined, in the CDM case.

Notes:

GALAXY CLUSTERS TO REVEAL THE NATURE OF DARK MATTER

Main Supervisor: Dr Mathilde Jauzac mathilde.jauzac@durham.ac.uk
Office: Ogden Centre West 126
Funding: STFC and all other funding schemes

Description:

Dark matter is one of the most mysterious constituents of our Universe, and constitutes up to 80% of its matter content. Most particle physics theories predict dark matter to interact so weakly with standard model particles that it will remain fundamentally undetectable in terrestrial experiments. If correct, dark matter can only be studied where it gathers in sufficient quantities for its gravity to affect things around it we can see. With this PhD project, we will track the behaviour of dark matter in galaxy clusters (the most massive structures in the universe), to constrain its particle nature.

Different dark matter models make different testable predictions for the rate at which structures, assemble compared to the standard cold dark matter (CDM). For example, warm dark matter inhibits the initial seeding of dark matter structures in the early Universe, while self-interacting dark matter (SIDM) predicts interactions between dark matter particles at late times that prevent the densest regions from growing.

Galaxy clusters are ideal laboratories in which to study its properties because they are still forming through mergers of smaller clusters and galaxy groups, commonly called substructures, and every merger acts like a gigantic particle collider. The decoupling of baryons (stars and gas) and dark matter during mergers in massive substructures provides an important constraint on the non-gravitational forces acting on dark matter particle. If SIDM, we expect variation of a few percent (between 3 and 5%) of substructures' stellar and gas density compared to CDM, as well as frictional forces that cause dark matter to gradually separate from stars and gas.

With this project, one will independently 'follow' the dark matter, stellar and gas contents in massive clusters, by mapping their distributions, weighing them, and identifying any differences/similarities (distribution peaks, quantities, etc). For this one will exploit observations obtained by the *Hubble Space Telescope* in the context of the large treasury programme, BUFFALO (https://buffalo.ipac.caltech.edu/), and follow-up spectroscopy from the largest telescope on Earth (VLT). BUFFALO observations were designed to map clusters' dark matter via the effect of 'gravitational lensing', which distorts and magnifies objects behind the cluster. The results obtained will be interpreted within the theoretical framework of state-of-the-art Durham's simulations of our universe.

This image shows the galaxy cluster MACS J0416.1–2403, one of six clusters targeted by the BUFFALO programme. The varying intensity of blue haze in this image shows the dark matter revealed by the magnifying power of gravitational lensing.

Notes:

RESOLVED STELLAR POPULATIONS IN NEARBY GALAXIES

Main Supervisor: Dr. Anna McLeod anna.mcleod@durham.ac.uk
Office: Ogden Centre West 120

Funding: STFC and all other funding schemes

Description:

The life cycle of star-forming galaxies is very complex: cold gas is turned into stars; the formed stellar populations stir, mix, enrich, heat, and expel the gas via stellar winds, radiation, and supernova explosions; the gas can then fall back onto the galaxy, cool, and form new generations of stars (e.g., Fig. 1). While we qualitatively understand the physical processes involved in governing the galactic gas recycle, we still do not have a clear *quantitative* description of them. As a consequence, constraining how galaxies turn their gas into stars, how feedback from these stars disrupts the gas and regulates the growth of galaxies, and how these processes have changed with galactic environment across cosmic time, is one of the fundamental problems in modern astrophysics.

With this project you will address a key part in solving this problem by revealing and studying resolved stellar populations in nearby galaxies. Indeed, nearby galaxies are our best laboratories to study the interplay between stars and gas: they provide the necessary numbers to study star formation across many different environments and, crucially, on the small and resolved scales at which the relevant physics happens. The simultaneous study of both the individual stars and the gas has only recently become possible, thanks to observations from integral field spectrographs (which combine imaging and spectroscopy into a single instrument), and novel analysis methods that allow us to combine these data sets with high-resolution imaging from e.g. the *Hubble Space Telescope* (*HST*). With data from the integral field spectrograph MUSE on the Very Large Telescope and data from *HST*, you will study the stellar population of the nearby galaxy NGC 300 at unprecedented levels of detail, and directly connect the stars to the gas reservoir in the galaxy. Once in place, the developed analysis methods can then be applied to other nearby galaxies (e.g. from the SIGNALS survey, see link below), therefore providing a framework to quantify the galactic life cycle of gas and stars.

More about this topic:
Stellar Feedback and Resolved Stellar IFU Spectroscopy in the Nearby Spiral Galaxy NGC 300
SIGNALS: the Star formation, Ionized Gas, and Nebular Abundances Legacy Survey

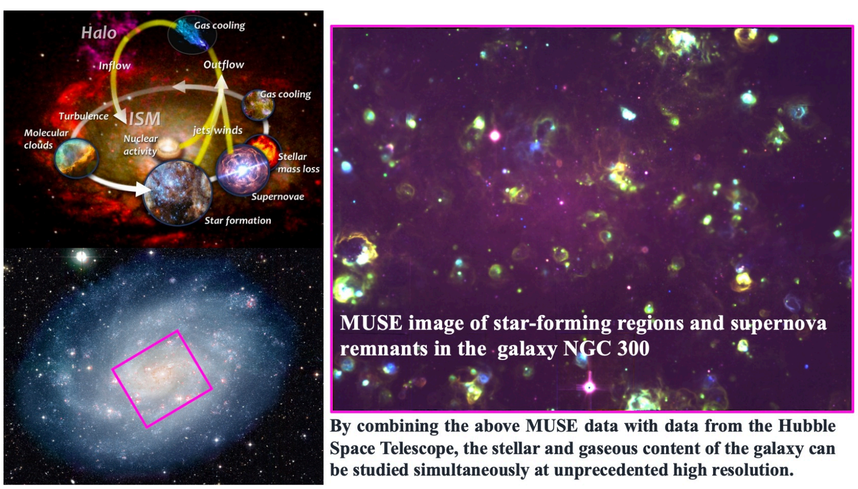


Fig. 1. Upper left. *The galactic life cycle: cold molecular clouds form stars; the combined feedback from these stars (together with feedback activity from the nuclear region) disrupts the gas and drives galactic outflows; the feedback-affected gas can then cool and form new generations of stars (credit: SPICA collaboration).* **Lower left.** *ESO/WFI image of the nearby star-forming galaxy NGC 300 (credit: ESO). The magenta region is the footprint of the MUSE image shown on the right.* **Right.** *MUSE integral field mosaic of the central part of NGC 300 tracing regions in which gas is being ionised by star-formation and supernova events. This data is the central focus of this PhD project.*

Notes:

STELLAR FEEDBACK AT LOW METALLICITIES

Main Supervisor: Dr. Anna McLeod anna.mcleod@durham.ac.uk
Office: Ogden Centre West 120
Funding: STFC and all other funding schemes

Description:

Throughout their short lives, massive stars (> 8 solar masses) have a deep impact on their surroundings via e.g. protostellar outflows, strong stellar winds, ionising radiation, and supernova explosions. These so-called feedback mechanisms drive the evolution of galaxies: the energy and momentum produced by massive stars can disrupt entire star-forming regions, control how galaxies turn their gas into new generations of stars, deposit heavy elements into their surroundings, and even facilitate the destruction of planetary systems as they are forming.

Yet, despite a qualitative understanding of feedback from massive stars, our quantitative knowledge of stellar feedback is severely lacking. For example, we know that these feedback mechanisms not only depend on which types and how many massive stars are present, but also on the characteristics of the environment the massive stars form in, like the location within the galaxy, the gas and dust content, or the amount of metals in the interstellar medium. Studying how the environmental properties influence the effects of feedback from massive stars is crucial to our understanding of star formation and galaxy evolution. Of particular interest are low-metallicity environments: here, stars are hotter, stellar winds are weaker, and the chemical composition is similar to the conditions of the earlier Universe.

In this project you will use data from the integral field instrument MUSE on the Very Large Telescope (VLT), as well as a variety of data sets ranging from the X-Rays to the infrared and millimetre regime, to characterise massive stars and quantify stellar feedback in low-metallicity environments such as the Magellanic Clouds and other nearby dwarf galaxies. Additionally, you can lead observing proposals to obtain more data from facilities like the VLT and the *James Webb Space Telescope*. The results from this thesis will be compared to Milky Way conditions, and serve as important empirical benchmarks for state-of-the-art numerical simulations of star (cluster) formation and galaxy evolution.

More about this topic:
Feedback from massive stars at low metallicities: MUSE observations of N44 and N180 in the Large Magellanic Cloud
ESO press release "Bubbles of Brand New Stars"

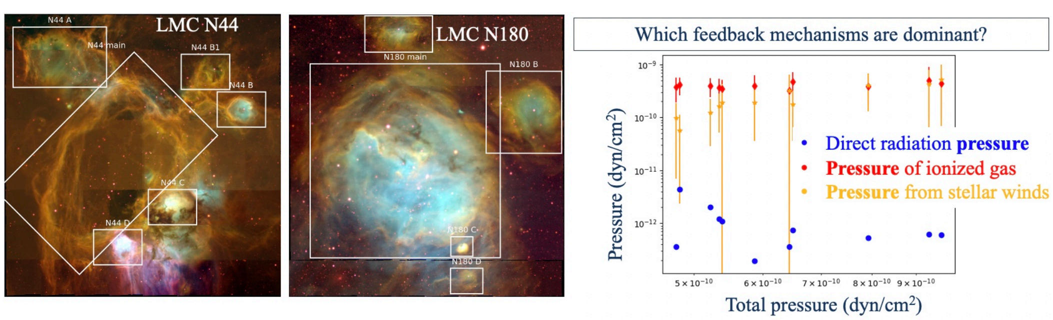


Fig. 1. *Star-forming regions in the Large Magellanic Cloud observed with the VLT MUSE instrument. The two images are mosaics of 64 individual telescope pointings each, amounting to a total of about 12 million spectral pixels! By identifying and classifying the feedback-driving massive stars and simultaneously characterising the feedback-driven gas, these data can be used to quantify stellar feedback. This is shown on the right, where three feedback-related pressure terms are compared to each other to evaluate which ones are dominant in these regions. In this project you will use similar data to extend this kind of analysis to other types of environments at low metallicities.*

Notes:

SYNTHETIC OBSERVATIONS OF STAR FORMATION AND GALAXY EVOLUTION SIMULATIONS

Main Supervisor: Dr. Anna McLeod anna.mcleod@durham.ac.uk
Office: Ogden Centre West 120
Funding: STFC and all other funding schemes

Description:

Throughout their short lives, massive stars (> 8 solar masses) have a deep impact on their surroundings via e.g. strong stellar winds, ionising radiation, and supernova explosions. These so-called feedback mechanisms drive the evolution of galaxies: the energy and momentum produced by massive stars can disrupt entire star-forming regions, control how galaxies turn their gas into new generations of stars, deposit heavy elements into their surroundings, and even facilitate the destruction of planetary systems as they are forming. Stellar feedback is also the key ingredient required to connect the observed galaxy population to cosmological theories and simulations: indeed, the outcome of simulations critically depends on the adopted prescription of feedback.

While so-called integral field instruments like MUSE on the Very Large Telescope (VLT; left panel in Fig. 1) are currently observing a large number of galaxies at high spatial resolution, and novel computer simulations are producing more and more realistic galaxies with comparable resolution, with this project you will drive progress in understanding feedback by directly linking the observational results to simulations. Specifically, you will produce synthetic observations of computer simulations, as well as meaningful methods to compare these to real observations.

The methods you develop in this project will be used to answer two broad classes of questions: (i) how accurate are the analyses commonly applied to genuine observations (for example, to infer star formation rates) when used on the synthetic data (for which the quantities of interest are known in advance)?; (ii) in what ways do the simulations agree and disagree with the observations, and hence, how can the simulations be improved upon? At Durham University you will have the opportunity to closely collaborate with members of the ICC who developed EAGLE, a world-leading suite of cosmological simulations.

More about this topic:
Synthetic observations of star formation and the interstellar medium
Optical integral field spectroscopy observations applied to simulated galaxies: testing the fossil record method

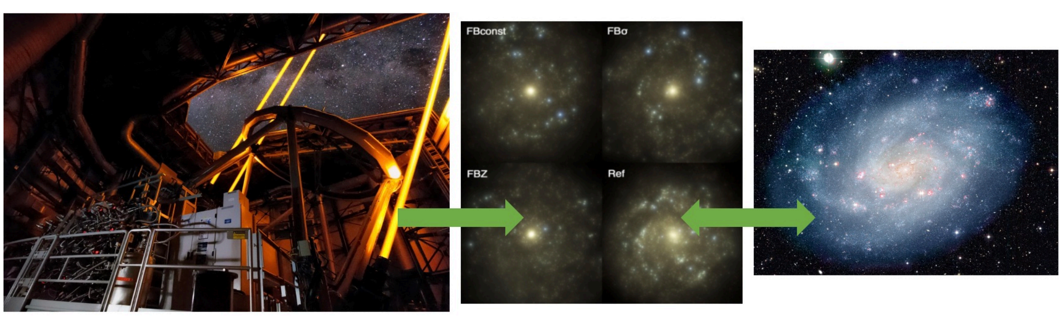


Fig. 1. *With computer simulations we can produce galaxies with varying amounts of feedback (like the EAGLE simulations shown in the middle panel, from Crain et al., 2015), and study how feedback affects the characteristics and evolution of these galaxies. In this project, you will produce synthetic observations of simulations like these, for example as we would observe them with the VLT MUSE instrument (left panel), together with meaningful ways of quantitatively comparing the mock observations to real ones (e.g. observations of the nearby galaxy NGC 300 shown in the right panel).*

Notes:

OUTFLOWS IN ACTIVE GALACTIC NUCLEI: WHAT IS DRIVING THE RADIO EMISSION?

Main Supervisor: Dr. Leah Morabito leah.k.morabito@durham.ac.uk
Office: Ogden Centre West 124
Funding: FLF studentship and other non-STFC funding schemes

Description:

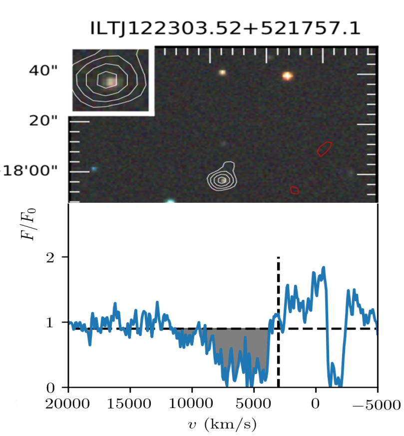
Active Galactic Nuclei (AGN) are actively accreting super-massive black holes which produce powerful outflows such as winds or jets, with observational signatures from X-rays to the radio. The winds can vary in strength and velocity, from colder and slower material to ultra-fast outflows. In the radio regime we see jets that range from galaxy scale to cluster scale, with a wide range of morphologies. These outflows are all potential means for the AGN to feed energy back into its host galaxy, driving the tight relations we see between super-massive black holes and host galaxy properties (e.g., the $M_\bullet$-σ relation). What we don't know yet is the details on how all this happens, and how all of these different kind of outflows interact with each other. Making advances in this area is key to understanding how AGN can shape the evolution of their host galaxies.

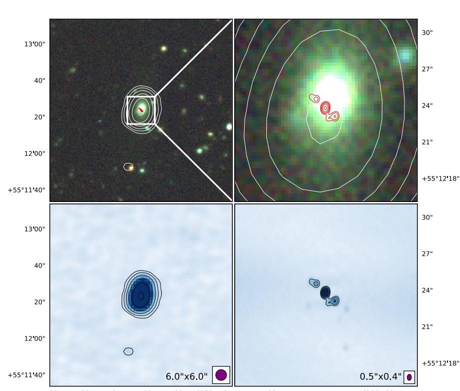
One element that is often overlooked is the radio emission. While it is fairly easy to classify AGN as either radio-loud or radio-quiet (a crude way to separate sources with cluster-scale jets and those without), large-area radio surveys typically have had limited resolution and sensitivity. In particular, it is interesting to explore whether the radio emission in radio-quiet AGN is linked to the outflows. We see hints of this in a special class of quasars which show broad, blue-shifted absorption in their optical spectra (which implies strong, fast outflows) where the likelihood of radio detection increases strongly as a function of outflows strength (Morabito et al. 2019). **But what about other types of outflows?** Are they connected somehow to the radio as well? How might they be connected, and on what physical scales?

You will explore these questions using new data from the LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2019). You will **construct your own sample** of AGN with outflows using existing catalogues and/or multi-wavelength data, deciding on what types of outflows interest you, while working in a team dedicated to related topics. Starting with the largest radio catalogue ever made (LoTSS data release 2), you will explore their radio properties using science-ready catalogues, and follow this up by re-processing LOFAR data at sub-arcsecond resolution (using new imaging techniques providing 20× improvement!) to determine on what scales this radio emission operates.

You will learn transferable skills such as dealing with large data sets, computing in a cluster environment, and how to translate physical laws into programming language. You will also have a chance to prepare proposals for telescope time and potentially go observing if the time is granted.

More reading: The LOFAR Two-metre Sky Survey, The Origin of Radio Emission in Broad Absorption Line Quasars
Meet the team: https://lmorabit.github.io





__Left:__ : A quasar with strong outflows. The r,g,b image is from optical bands with radio emission overlaid as contours. Beneath this you can see the broad, blue-shifted absorption in the optical spectrum that implies a strong outflow. ***Right:*** *The power of resolution: The white contours are from radio data with the same resolution as the quasar on the left, but by re-processing the data we can improve the resolution by over a factor of 20 to see the small-scale radio emission.*

Notes:

PARTICLE ACCELERATION IN HIGH REDSHIFT AGN

Main Supervisor: Dr. Leah Morabito leah.k.morabito@durham.ac.uk
Office: Ogden Centre West 124
Funding: FLF studentship and other non-STFC funding schemes

Description:

Luminous high-redshift radio galaxies (HzRGs) are unique laboratories for studying the formation and evolution of rich clusters, massive galaxies and black holes when the Universe was less than half its age. HzRGs are among the most massive known galaxies in the early Universe, and their radio luminosities and radiative lifetimes imply total energies in excess of 10^{60} ergs, placing them among the most energetic objects in the Universe. One of the most intriguing properties of HzRGs is the strong correlation that exists between the radio spectral index (slope of the power-law synchrotron emission) and the redshift of the associated optical galaxies (see Figure below). Most known HzRGs have been discovered by measuring the redshifts of radio sources with the steepest radio spectra. However, the nature of this relation remains a mystery: is it driven by observational effects? Does it have to do with higher ambient density at high redshift? Higher Inverse-Compton losses at high redshift? Or is there something intrinsically different about accretion processes at high redshift? Crucially, has selecting HzRGs using spectral index alone provided us with a biased picture?

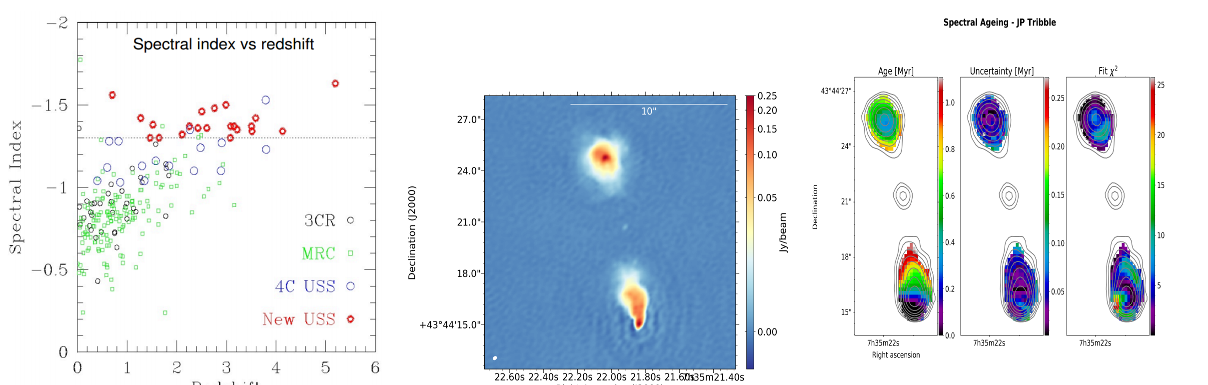
To answer these questions, we must determine the particle acceleration mechanisms in HzRGs. To do this requires high-resolution imaging across a broad range of radio frequencies (MHz to GHz) to perform spectral modelling, and it is critical to include MHz frequencies. This is only now possible thanks to new high-resolution imaging techniques developed for the new LOw Frequency ARray (LOFAR), which operates at ∼10 - 200 MHz.

In this project, we will initially conduct a pilot program to constrain the particle acceleration mechanisms for a sample of 10 HzRGs (data in hand). We will use spectral modelling to constrain the ages and magnetic fields in our sample, compare these to low-redshift sources, and identify the main cause(s) of the spectral index – redshift relation. Using this information, we will design better criteria to select a complete sample of HzRGs from the LOFAR Two-metre Sky Survey, and study their general properties. We will use this larger sample to address the following questions:

- Are high-redshift radio galaxies fundamentally different from their low-redshift counterparts?
- How numerous are high-redshift radio galaxies in the early Universe?
- How massive are the galaxies / super-massive black holes associated with high-redshift radio sources?

This is an observationally-driven PhD project. The successful student will use new and archival radio data, with the possibility for follow-up observations using other facilities. The PhD will join the international LOFAR Surveys collaboration and have the opportunity to travel around the world to present their work. The PhD will provide training in data reduction and analysis, and imaging techniques, along with statistical methods for handling big data.

More reading: Investigating the cause of the α-z relation, LOFAR-VLBI studies at 55 MHz of 4C 43.15
Meet the team: https://lmorabit.github.io



Left: *The observed relation between radio spectral index and redshift, showing that steeper spectral indices tend to be associated with higher redshift sources (de Breuck et al. 2000).* ***Centre:*** *A high resolution image at 150 MHz of 4C 43.15 (z=2.4; Sweijen et al. in prep).* ***Right:*** *The ages of the radio jets in 4C 43.15. This is the only HzRG for which spectral modelling has ever been done.*

Notes:

EXPLOITING THE GAIA/TESS SYNERGY: USING MACHINE LEARNING TO BUILD A NOVEL DISCOVERY TOOL

Main Supervisor: Dr Simone Scaringi simone.scaringi@durham.ac.uk
Office: Ogden Centre West

Funding: STFC and all other funding schemes

Description:

The launch of the *TESS* space-based observatory and the release of *Gaia* Data Release 2 have truly revolutionised the way we explore and learn about Galactic sources and populations. Through the use of full-frame images (FFIs) *TESS* provides the opportunity to generate lightcurves of most targets in the sky with *TESS* magnitudes brighter than ≈17. Coupled with the parallax, brightness, and proper motion information provided by *Gaia*, this dataset is allowing the discovery of specific populations of objects which would not have been promptly identified if not for the *TESS/Gaia* synergy.

Over the past 2 years, *TESS* has surveyed over 85% of the full sky, while at the same time *Gaia* has released five-parameter astrometric solution (positions on the sky, parallaxes, and proper motions) for more than 1.3 billion sources. This enormous dataset now allows us to locate sources in calibrated colour-magnitude diagrams, determine their kinematic properties, and at the same time explore their variability properties in unprecedented detail (see e.g Fig. 1).

At first, this project will exploit existing tools, as well as develop new ones, to extract over 12 million lightcurves from the *TESS* FFIs. These targets will be cross-matched with *Gaia* to obtain their astrometric and photometric measurements. The project will then exploit the *Gaia/TESS* dataset to a) build a robust mapping through regression that will map *TESS* lightcurves onto the calibrated *Gaia* colour-magnitude plane. For this several machine learning algorithms will be used and tested, including Deep Learning, Convolutional Neural Networks and Transformer Networks. Having trained the regression network the project will then exploit this to search for a) data-driven clusters of objects in order to improve the census of specific stellar populations and b) identify "outliers" that require additional follow-up for identification.

This project is also bound to exploit other datasets that are to be either incorporated into the regression algorithm or used as validation for object identification. These include the spectroscopic LAMOST survey and WEAVE in future, as well as multi-wavelength photometry from other surveys (e.g. WISE, GALEX, PanSTARRS and eRosita). Merging these heterogeneous datasets (lightcurves, spectra, photometric and astrometric measurements) will involve the development of novel data-fusion techniques.

TESS Guest Investigator Website
Gaia Website

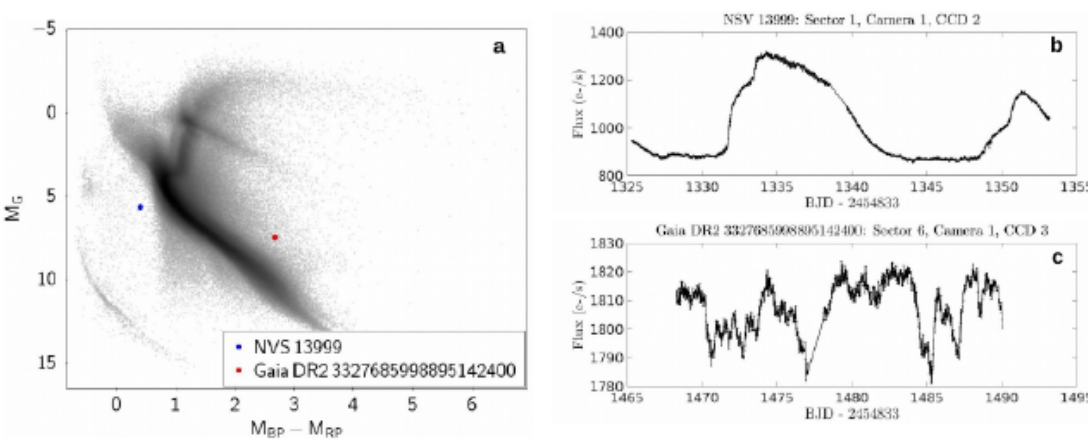


Fig. 1. *Colour-magnitude diagram obtained using Gaia and example lightcurves from TESS. Panel (a) shows the colour-magnitude diagram from Gaia of over 3.6 million targets that reside in the TESS field-of-view for Sectors 1-7. On the right-hand side are two TESS lightcurves of previously unidentified targets. Given their position in CMD space and their variability properties, panel (b) is moist likely associated to an accreting white dwarf, while panel (c) is most likely an accreting young stellar-object.*

Notes:

EAVESDROPPING ON ACCRETION DISKS: USING TESS TO UNRAVEL THE PHYSICS OF ACCRETION

Main Supervisor: Dr Simone Scaringi simone.scaringi@durham.ac.uk
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Funding: STFC and all other funding schemes

Description:

Accretion is the process that drives and regulates the growth of most objects in the Universe: from the birth of stars to the feeding of supermassive black holes, from the evolution of galaxies over cosmological time scales to the life cycles of interacting binary stars in the Solar neighbourhood. Accretion requires angular momentum to be lost from the in-falling material, usually resulting in the formation of a so-called accretion disk. Accretion discs are ubiquitous in astrophysics, found in young-stellar objects (YSOs), interacting binary stars with a compact object accretor (white dwarf, WD; neutron star, NS; or black hole, BH) and the central engines of active galactic nuclei (AGN). Remarkably, the accretion process is generally unstable in all of these environments, with systems cycling between long-lasting low states ("quiescence") and short-lived high states ("outburst"). The accretion rate through the disk and onto the central object ($\dot{M}_{acc}$) is much higher in outburst than in quiescence, and the time-averaged accretion rate is therefore dominated by the mass that is accreted during these outbursts. The classical equations of disk structure (e.g. Pringle & Rees 1972) and more modern magneto-hydrodynamics approaches (e.g. Blaes & Balbus 1994) suggest that the basic physics of the accretion process should work through the same processes for all types of accretion disks. Nonetheless, although the importance of accretion disks have been recognised for many years and that they may be considered scale-invariant also from observations (see Fig. 1), the detailed physics and dynamics of accretion is still poorly understood, and pivotal questions remain yet to be answered.

The successful student will analyse variability data mostly from the space-observatory *TESS* and apply timing tools to study the variability properties of a large sample of systems, with particular emphasis on accreting white dwarfs, to further test the idea that accretion physics is scale-invariant across mass and size scales. Some of the questions that will be explored will be:

1. What are the major viscous mechanisms allowing matter to lose angular momentum and propagate inwards?
2. How does the geometry of accretion disks relate to different mass accretion rates?
3. How do accretion disks react to different radiation environments?
4. What are the secular changes in mass transfer rates, especially in binary systems?

References: Pringle & Rees 197; Blaes & Balbus 1994; Scaringi et al. 2015; TESS Guest Investigator Website

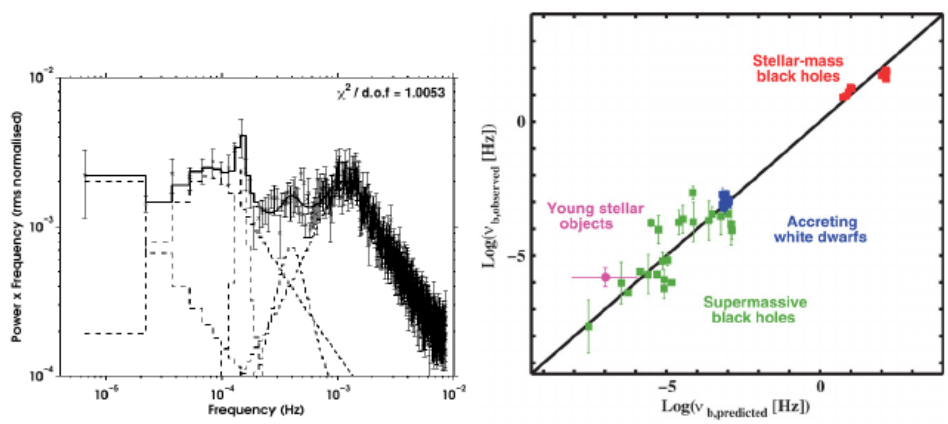

Fig. 1. *Example of a power-spectral density (PSD) for the accreting white dwarf MV Lyrae (left-panel). The characteristic high-frequency break in the PSD in a common feature of most accreting systems. Although this break happens at different frequencies depending on the accretor type, it appears that a universal scaling relation can be found linking accreting systems on a wide range of mass and size scales. The right-panel shows the so-called accretion variability plane linking masses (M), radii (R), and mass accretion rates ($\dot{M}$) to the PSD breaks (ν_b) of accreting systems on a wide range of mass and size scales. Figure taken from Scaringi et al. (2015).*

Notes:

GALAXY EVOLUTION OVER THE LAST 10 BILLION YEARS

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Funding: STFC and all other funding schemes

Description:

The Hubble-Sequence of galaxy morphologies remains one of the defining characteristics of galaxies, and provides one of the key constraints that galaxy formation models strive to reproduce.

Dynamical studies of local galaxies have shown that the Hubble Sequence of galaxy morphologies follows a sequence of increasing angular momentum at a fixed mass. In the cold dark matter paradigm, galaxies form at the centres of dark matter halos. As the gas collapses within the dark halo, the baryons can both lose and gain angular momentum. If the angular momentum of the baryons is (weakly) conserved during collapse, they will form a centrifugally supported disk with an exponential light profile (e.g. a spiral galaxy). If the angular momentum is redistributed (due to mergers and/or strong outflows), the morphology of the galaxy is more likely to represent a early-type or elliptical galaxy.

While the role of angular momentum in locating galaxies along the Hubble-Sequence is well constrained at $z \sim 0$, how the baryonic angular momentum evolves with cosmic time, and results in the emergence of the Hubble-Sequence at high redshift has not been established. Observations from the *Hubble Space Telescope (HST)* have shown that the transition from a galaxy population dominated by clumpy, irregular morphologies to smoother, disk-like galaxies appears to occur around $z \sim 1.5$, and this has been heralded as the epoch when the Hubble Sequence "emerged",

In this project, we will conduct an observational program to measure the spatially resolved gas dynamics and star formation in a large sample of star-forming galaxies at $z \sim 1$–2 (i.e. lookback times of 7–10 billion years). We will measure the role of baryonic angular momentum, dark matter, disk turbulence, and gas inflows and outflows in defining the formation of the Hubble-Sequence of galaxy morphologies. We will address the following inter-related questions:

1. How does the angular momentum of high-redshift galaxy disks result in the emergence of the Hubble-Sequence?

2. How do the dark matter fractions of galaxies evolve with mass and redshift?

3. What physical processes control the formation and evolution of star-forming clumps?

4. Where do star-forming winds originate and how much mass and angular momentum do they carry?

This is an observationally-driven PhD project. The successful student will use a range of observational facilities, potentially including travel to Chile, Hawaii or Europe to obtain data for their thesis. The PhD will provide training in the reduction and analysis of imaging, integral field spectroscopy and interferometry There will also be opportunities to relate the observational results to theoretical models being developed at Durham.

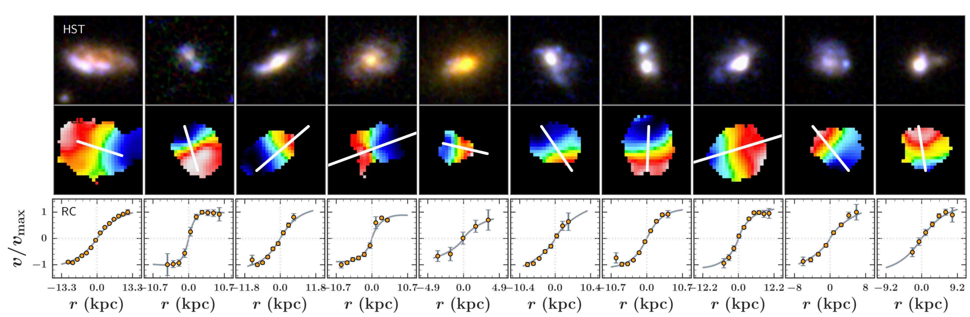

Fig. 1. *Images and dynamical maps of star-forming galaxies at $z \sim 1.5$ from our ongoing KMOS survey. We show the* HST *colour image (top row), velocity field (middle row), and galaxy rotation curve (bottom row). We will exploit maps like these to measure the dynamics, rotation curves, total baryonic angular momentum and dark matter properties in a large sample. See also:* http://www.astro.dur.ac.uk/~ams/kmos *and* http://www.astro.dur.ac.uk/£\sim£ams/kmos/

Notes:

TRACING THE COSMIC GROWTH OF BLACK HOLES WITH THE NUSTAR X-RAY OBSERVATORY

Main Supervisor: Prof. David Alexander d.m.alexander@durham.ac.uk
Office: Ogden Centre West 119
Funding: DDS, CSC and other non-STFC funding schemes

Description:

The cosmic X-ray background (CXB) was first discovered in the early 1960's (Giacconi et al. 1962), several years before the cosmic microwave background (CMB). Unlike the CMB, which is truly diffuse in origin, the CXB is dominated by the emission from high-energy distant point sources: Active Galactic Nuclei (AGNs), the sites of intense black-hole growth (see Brandt & Alexander 2015). X-ray surveys with *Chandra* and *XMM-Newton* have resolved $\approx$ 70–90% of the CXB at low energies (< 10 keV) into AGNs at $z < 5$–6. However, the CXB peaks at 20–30 keV and, until recently, observatories in this energy range had only resolved $\approx$ 1–2% of the CXB. A great breakthrough in resolving the peak of the CXB is *NuSTAR* (Harrison et al. 2013). *NuSTAR* is the first orbiting > 10 keV observatory with focusing optics, which provide 1–2 orders of magnitude improvement in sensitivity and angular resolution over previous non-focusing missions. Importantly, the high energy 3–79 keV coverage of *NuSTAR* means that it selects AGNs almost irrespective of the amount of obscuration towards the AGN. This has opened up the possibility to construct a complete census of distant X-ray emitting AGNs.

We have been leading the *NuSTAR* serendipitious survey (Alexander et al. 2013; Lansbury et al. 2017; Klindt et al. in prep), which is the most powerful component of the overall extragalactic survey program undertaken by *NuSTAR*. Through a combination of deep and shallow wide-area coverage, the *NuSTAR* serendipitious survey fills out the L_{X}–z plane of AGN and detects *intrinsically rare* AGN populations not otherwise identified; see the figure below. For example, our latest 80-month catalog contains $\approx$ 1300 AGNs over 35 deg^2 (Klindt et al. in prep). As shown in the figure below the *NuSTAR* serendipitous survey pushes to higher redshifts than previously possible at these X-ray energies.

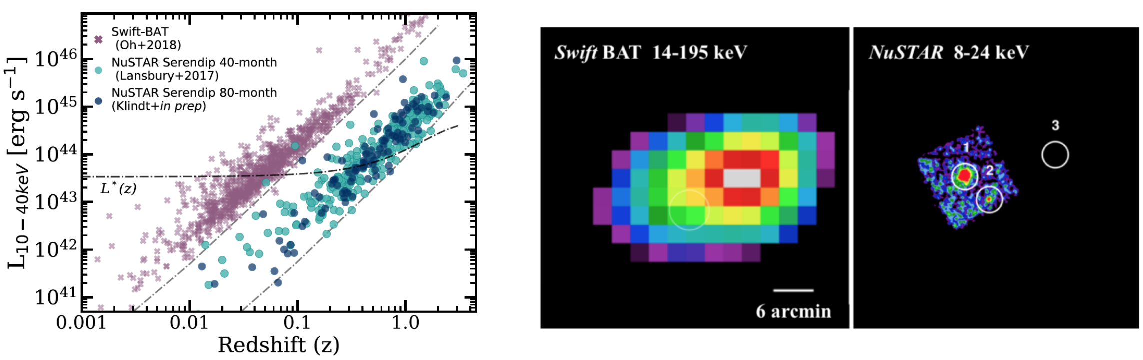

Figure: (left) X-ray luminosity ($L_{10-40\mathrm{keV}}$) versus redshift for the AGNs spectroscopically identified in the 80-month NuSTAR serendipitous survey as compared to the shallower Swift-BAT survey. The evolving knee of the X-ray luminosity function ($L_*(z)$) of AGNs is indicated. Taken from Klindt et al. (in prep). (right) imaging comparison between the previous-generation hard X-ray observatory Swift-BAT and NuSTAR within the same region of the sky. This demonstrates the significantly improved resolution and sensitivity of NuSTAR: the single Swift-BAT source is actually revealed as two AGN with NuSTAR.

I am looking for a student to analyse the data from the *NuSTAR* serendipitious survey to provide the most complete X-ray selection of AGNs to date. During your PhD you will use the *NuSTAR* survey to identify new AGN and utilise softer X-ray *Chandra* and *XMM-Newton* observations to characterise their overall X-ray emission to allow for measurements of the amount of absorption towards the AGN. You will also follow up the newly identified AGN with optical spectroscopy to obtain source redshifts and emission-line classifications using a slew of telescopes around the world (the VLT in Chile; SALT in South Africa; Palomar in California; Keck in Hawaii). Exploiting multi-wavelength observations available for sources detected in the *NuSTAR* serendipitious survey you will characterise the emission and measure the properties of the AGN to construct the most complete census of AGN activity.

Notes:

WHY ARE (SOME) QUASARS SPECIAL? TOWARDS AN UNDERSTANDING OF THE EVOLUTION OF QUASARS

Supervisor:	Prof. David Alexander	d.m.alexander@durham.ac.uk
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Funding:	DDS, CSC and other non-STFC funding schemes	

Description:

Quasars are the most luminous subset of the overall population of Active Galactic Nuclei (AGN) and can be seen out to the edge of the observable Universe. They are powered by mass accretion onto a super-massive black hole, the same basic power source for all AGN, and are thought to have had a profound impact on the overall formation and evolution of galaxies. However, despite being discovered over half a century ago, we still have limited knowledge on how different subsets of the quasar population are related to each other; e.g., the connection between obscured and unobscured quasars.

The relationship between less powerful obscured and unobscured AGN appears to be due to the orientation of an optically and geometrically thick structure (often referred to as the "dusty torus") towards our line of sight. An AGN is observed to be obscured when the "torus" intercepts the line of sight while the AGN is unobscured when the "torus" is orientated away from the observer. This model is known as the "unified model of AGN" (see Netzer 2015 for a recent review). However, although referred to as a "unified model", we have recently found that this model does not apply to all quasars.

We have found that red quasars, a subset of the quasar population obscured by dust and gas, have fundamentally different radio and X-ray properties to normal quasars (Klindt et al. 2019; Fawcett et al. 2020; Rosario et al. 2020; Igo et al. in prep). This evidence points towards red quasars being a phase (probably early in the life of a quasar) in the evolution of quasars rather than being normal quasars aligned away from our line of sight. However, although our results are clear and conclusive, we lack details about this phase such as the duration, whether it is episodic, and the trigger mechanism. The leading model for the evolution quasars is shown in the figure below; however, we do not know whether it is correct.

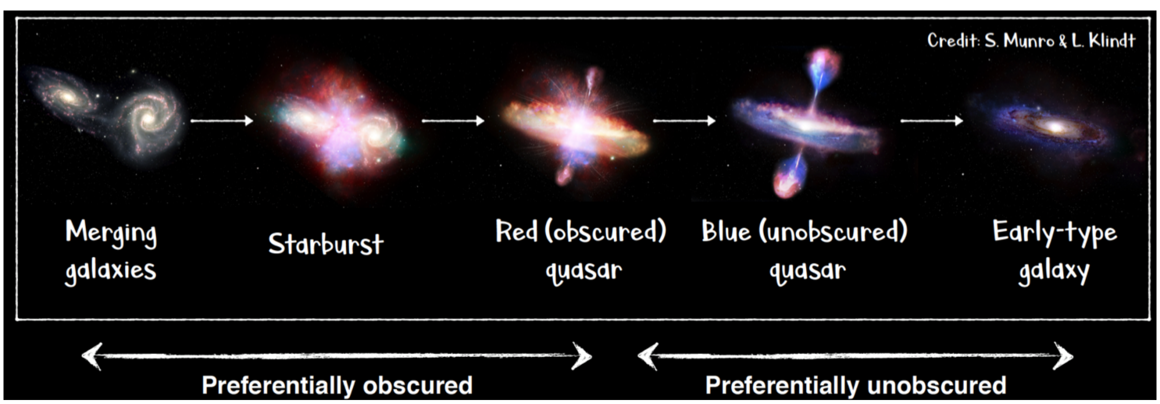

Figure: The leading evolutionary model for quasars. The sequence is triggered by huge amounts of gas inflow (potentially from a merger of two galaxies) which leads to a burst of dust-obscured star formation and a heavily buried (i.e., obscured) quasar. As the quasar ages it drives out energetic winds which blows away the obscuring dust, revealing a red quasar and then ultimately revealing an unobscured quasar (see Alexander & Hickox 2012 and Hickox & Alexander 2018 for reviews). Eventually the huge amount of energy formation and forms a "red and dead" early type galaxy. Schematic produced by S. Munro and L. Klindt.

I am looking for a student to extend our understanding of the evolution of quasars . This research will exploit our membership of the on-going 4-year Dark Energy Spectroscopic Instrument (DESI) survey (Dey et al. 2019) and the future 4-year AGN survey using the 4MOST instrument (Merloni et al. 2019). Each of these surveys will detect over 1 million quasars and AGN, pushing deeper than current surveys and extending to more extreme systems. You will undertake systematic analyses using a variety of multi-wavelength datasets to quantify the differences between normal and red quasars. For example, utilising the previous Sloan Digital Sky Survey (SDSS) you will investigate how often quasars change from normal to red (and vice versa) over a decade-long timescale, providing key insight on whether the red-quasar phase is episodic and providing the first constraints on the duration of the red-quasar phase. You will also analyse deep multi-wavelength observations to measure the physical properties of red quasars such as the amount of obscuring dust, the black-hole mass, and the black-hole accretion rate.

Notes:

SURVEYING THE EXTREME UNIVERSE WITH THE SOUTHERN WIDE-FIELD GAMMA-RAY OBSERVATORY

Main Supervisor: Prof. Paula Chadwick p.m.chadwick@durham.ac.uk
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2nd Supervisor: Dr. Anthony M. Brown anthony.brown@durham.ac.uk

Funding: DDS, CSC and other non-STFC funding schemes

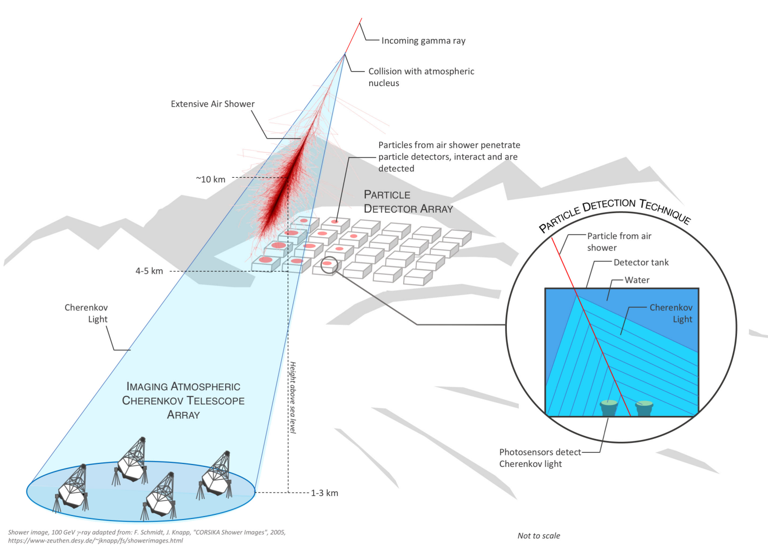
Description:

Over the last 10 years, very high energy (VHE) gamma ray astronomy has opened a new window on the extreme universe. The catalogue of known VHE-emitting objects has grown by an order of magnitude and includes many different classes of objects - supernova remnants, pulsars, binary star systems, star formation regions and active galaxies - while other objects remain a mystery. The VHE radiation from these systems is produced by non-thermal particle acceleration, but the mechanisms by which this occurs have not been established.

The telescopes that have done this important work are designed to point at a small region of sky. However, some gamma-ray objects cover large areas of the sky and many are transient - sudden, bright events that are very difficult, if not impossible, to predict. We need an instrument that is able to survey the sky over a wide area and at all times, even when the Sun is above the horizon. This is why the international SWGO project was founded in 2019. This will be a gamma-ray observatory based on ground-level particle detection, located in South America at a latitude between 10 and 30 degrees south and at an altitude of 4.4 km or higher. It will cover an energy range from 100s of GeV to 100s of TeV, and aims to provide survey and wide-angle capability to complement observatories like the Cherenkov Telescope Array. Its science topics include unveiling galactic and extragalactic particle accelerators, monitoring the transient sky (including gravitational wave events) at very high energies, probing particle physics beyond the Standard Model, and the characterization of the cosmic ray flux.

SWGO is in its design stages at present, and students will be able to choose from a range of projects in science simulations and instrumentation for SWGO.

The SWGO (formerly SGSO) Science Case: https://arxiv.org/abs/1902.08429
The SWGO homepage: https://www.swgo.org/SWGOWiki/doku.php



The SWGO concept.

Notes:

INFRARED DUST REVERBERATION FROM SPACE

Main Supervisor: Prof. Alastair Edge alastair.edge@durham.ac.uk
Office: Ogden Centre West 126
2nd Supervisor: Dr. Hermine Landt-Wilman hermine.landt@durham.ac.uk
Funding: DDS, CSC and other non-STFC funding schemes

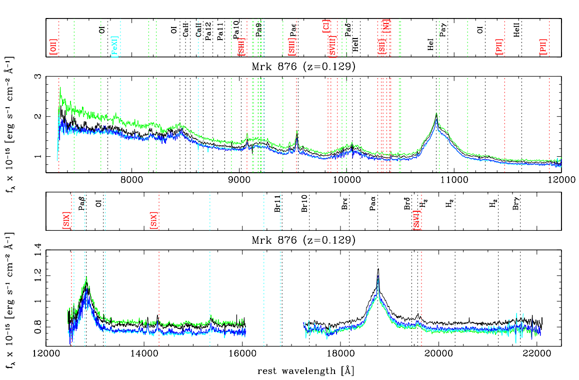
Description:

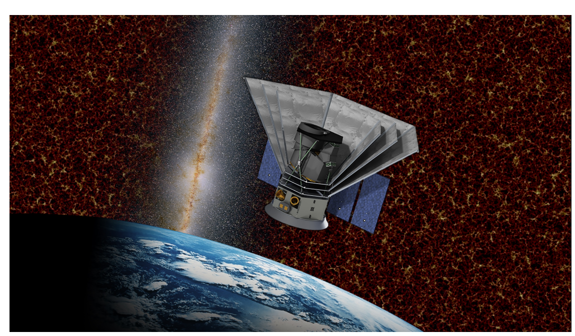
Scales too small to be resolved by direct imaging can be measured out using the time the light takes to travel across them. This is the basic idea behind the method of reverberation mapping. Components around supermassive black holes at the centres of the most massive and luminous galaxies are such small structures and their complexity is mainly revealed by spectroscopy. A near-infrared spectrum shows broad emission lines from clumps of gas orbiting the black hole with 5%–10% the speed of light that are illuminated by ultra-violet light from the accreting material. The accretion disc also heats dust in a compact structure that produces the near-infrared continuum radiation (Fig. 1, left panel). By monitoring simultaneously the ultra-violet/optical light from the accretion disc and the near-infrared light from the dust we can measure the delay between peaks in their light-curves. This dust response time, which translates directly to a scale since light has a finite speed, was measured so far only with photometry and was found to be of the order of light-months.

We have pioneered the technique of infrared dust reverberation in active galaxies using spectroscopy obtained at NASA's Infrared Telescope Facility (Landt et al. 2019). Spectroscopy, unlike photometry, can measure also the dust temperature. Assuming thermal equilibrium, we can then calculate the expected dust radius for different grain sizes and types and compare it to the dust response time - a powerful way to constrain the astrochemistry of the dust around supermassive black holes.

Your PhD project will extend this program to space. You will use spectroscopic data delivered by NASA's space mission SPHEREx due to launch in 2024 (Fig. 1, right panel). In preparation for this mission, you will assemble the optical light-curves of suitable candidates in the southern hemisphere using the Legacy Survey of Space and Time (LSST; LSST Science Collaborations et al. 2017) that will be delivered from 2021 by the Vera C. Rubin Observatory, an 8.4 m telescope currently being built in Chile by a large consortium including the UK. For northern candidates, you will have access to monitoring with the Las Cumbres Observatory network of 1 m and 2 m robotic telescopes. You will actively write observing proposals for near-infrared spectroscopy at major telescopes, such as the Very Large Telescope, Chile, and the 8 m Gemini telescopes, Hawaii, and lead the observing preparation and data reduction. In addition, you will be the main observer for our continuing dust reverberation program with NASA's Infrared Telescope Facility. These observing runs are usually conducted remotely from Durham, but we expect that you will occasionally visit the telescope in Hawaii.

Landt et al. 2019, MNRAS, 489, 1572
SHEREx: An All-Sky Spectral Survey
LSST Science Collaborations et al. 2017
Talk at Conference "Galaxy Formation and Evolution in the Era of the Nancy Grace Roman Space Telescope", October 2020





Left panel: *A series of near-infrared spectra of the luminous nucleus in the active galaxy Mrk 876 taken with the GNIRS instrument on Gemini North 8 m telescope, Hawaii.* **Right panel:** *An artist's impression of the SPHEREx space mission due for launch by NASA in 2024 (credit: NASA).*

Notes:

A NEW ERA OF ASTRONOMY WITH KINETIC INDUCTANCE DETECTORS

Main Supervisor: Dr Kieran O'Brien kieran.s.obrien@durham.ac.uk
Office: Ogden Centre West 029
Funding: DDS, CSC and other non-STFC funding schemes

Description:

Many of the most important discoveries in astronomy over the last decades have been driven by technological advances that have enabled researchers to open up new avenues of research. This includes advances in telescope design, such as with the upcoming Extremely Large Telescope (ELT), modes of operation such as Adaptive Optics and perhaps most importantly, through developments in the detector technologies used, such as moving from photographic plates to electronic imaging. At Durham, we are part of a world-leading collaboration to develop and exploit Kinetic Inductance Detectors (KIDs) for optical and near-infrared astronomy. KIDs could potentially drive the next revolution in astronomy as they enable incredibly sensitive 3D spectroscopy. They are made from super-conducting materials that use the kinetic inductance effect to measure the energy of individual photons (to better than 10%) and their arrival time to better than 1 microsecond. By making arrays of 1000's of such detectors, we are able to open areas of research impossible with other technologies.

The first optical/IR KID camera was demonstrated in 2011 by a team from the University of California, led by Prof. Ben Mazin and including Dr. O'Brien. The photon counting capability and spectral resolution of a KID array is capable of making a unique contribution to a wide range of fields, including exoplanet science, time domain astronomy, gravitational wave follow-up and the high red-shift Universe.

This project represents an exciting opportunity to join our team (currently myself, a post-doc and 3 PhD students) and be involved in a novel instrumentation project from an early stage. We are looking for a highly motivated student to work on instrument development in the Centre for Advanced Instrumentation. No prior knowledge of KIDs is expected and all necessary training will be given. The project would suit students interested in experimental physics from a wide range of backgrounds, including astronomy, low temperature physics, optics, and superconductivity. The exact focus of development could be chosen to match those interests, but potential areas include cryogenic device testing and digital readout design. Projects in each area could also include some observational astronomy alongside the instrumentation element.

Web pages: Durham KIDs homepage Homepage of Mazin Lab at UCSB
Introduction to KIDs: Introduction to KIDs by Ben Mazin Example research paper: KIDspec paper

Left, Microscope image (~ 0.3×0.5mm) of pixels in a KID array, from Mazin Lab website. Right, photo of the KID development lab at Durham University.

Notes:

LENSING AND COSMOLOGY WITH HARMONI AT THE ELT

Main Supervisor: Dr Russell Smith russell.smith@durham.ac.uk
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Funding: DDS, CSC and other non-STFC funding schemes

Description:

Strong gravitational lensing – the distortion and splitting of a background source image by the presence of a massive galaxy along the line of sight – has become a standard tool for probing the distribution of dark and luminous mass in and between galaxies, as well as testing for deviations from general relativity, and measuring the cosmological components of the Universe.

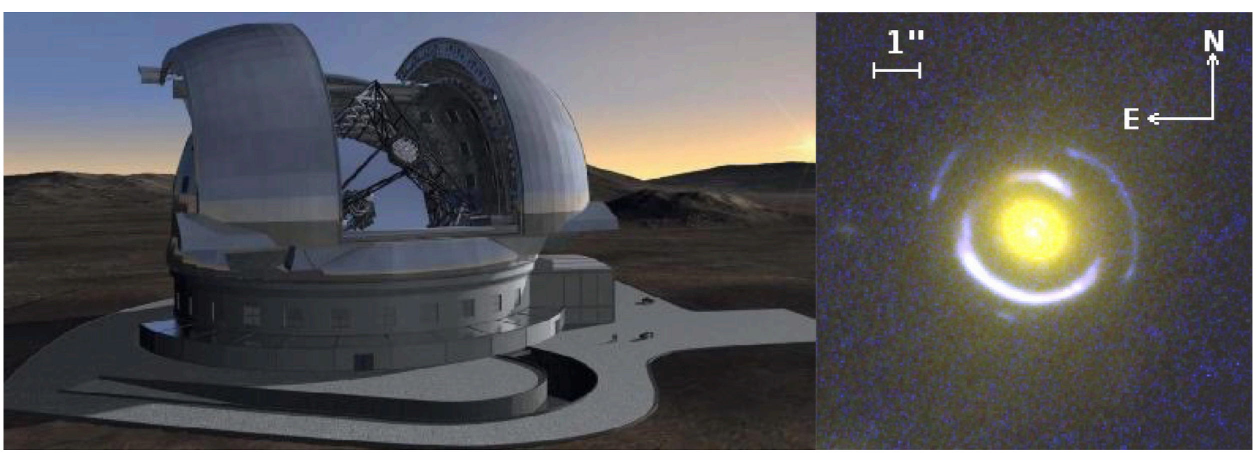
Lensing is often considered to be a *rare* event, because the two galaxies must be very closely aligned along a single line of sight. For example, a search based on looking for blended spectra in the Sloan Digital Sky Survey found only $\sim$100 lenses from $\sim 10^6$ observed targets. However, this method is limited by the rarity of *bright* background sources. As we observe deeper, the Universe presents an increasingly rich screen of potentially-lensed faint sources behind *every* massive galaxy. Integral-field unit (IFU) spectrographs can isolate the emission lines for these sources even in the presence of a bright foreground galaxy.

The arrival of enormous telescopes like the 39m ESO ELT from the mid-2020s opens up a new regime: *any* sufficiently massive galaxy observed for $\sim$1 hour with an IFU on such a telescope should be surrounded by faint strongly-lensed line-emitters. In the case of already-known lenses, we will be able routinely to find *additional* distant background sources, converting them into "double-source-plane" systems. Such lenses are extremely powerful as cosmological probes, because their configurations (e.g. the relative size of the Einstein rings) are sensitive to ratios of the distances between the lens and the two sources. In particular, double-source-plane lenses can be used to measure the equation-of-state parameter, w, which can distinguish a standard cosmological constant from "quintessence" or other dynamical models for the mysterious dark energy.

Recent observations with MUSE at the VLT confirm that converting known lenses to multiple-source systems is possible for individual galaxies (e.g. Collett & Smith 2020, MNRAS, 497, 1654). However, to measure w with interesting precision will require the analysis of a large sample of lens systems, which will only be feasible through huge sensitivity gain of the ELT.

In this PhD project, you will develop a survey to construct and exploit double-source-plane lenses with the ELT, using the HARMONI IFU. The first steps will be to generate "mock" HARMONI observations of gravitational lenses, with realistic source and lens properties, informed by deep observations, e.g. with MUSE. Later you will use end-to-end survey simulations to optimise the sample selection and observational strategy, and maximise the cosmological sensitivity. The end goal is to design a scientifically compelling and technically feasible survey for HARMONI in time for first light, currently projected for 2024–25.

Durham is now a full partner in the HARMONI instrument consortium, and so will have access to guaranteed observing time, as well as a wealth of local instrument expertise. This project is an opportunity to help shape the first scientific exploitation of the new generation of giant telescopes, and to gain experience with the leading optical facility of the next decade.



Left: Expected appearance of the completed the 39m ESO ELT at Cerro Armazones, Chile. Right: a double-source-plane strong lens, with two partial Einstein rings formed by background galaxies at different redshifts. Currently very rare, with HARMONI at the ELT we will routinely discover more such systems, whose configurations can be used to probe the nature of dark energy.

Notes:

MACHINE LEARNING ALGORITHMS FOR TIME-DOMAIN ASTRONOMY

Main Supervisor: Dr. Hermine Landt-Wilman hermine.landt@durham.ac.uk
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Funding: none defined (MScR project)

Description:

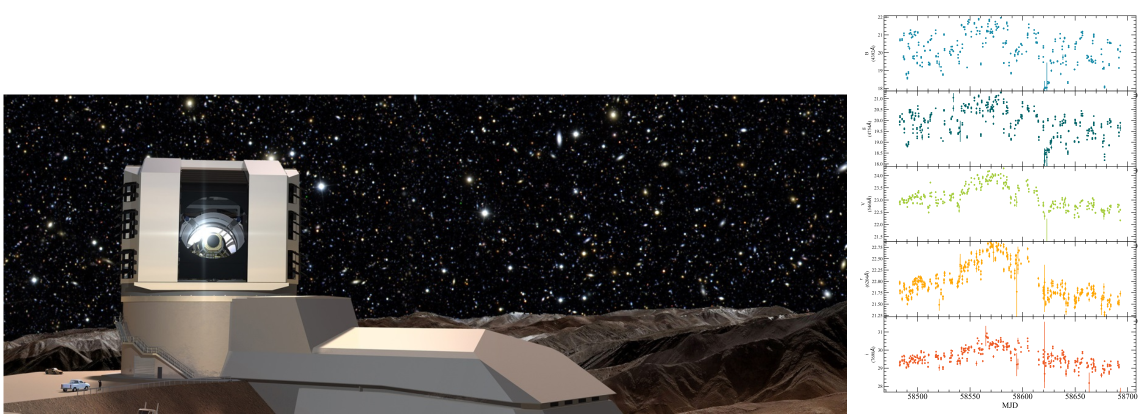
We are now starting the new era of time-domain astronomy. Large sums of money are currently being invested in astronomical facilities that can continuously survey the sky in order to detect and study interesting variable and transient sources. The largest ground-based facility for time-domain astronomy will be from next year the Vera C. Rubin Observatory, an 8.4 m telescope currently being built in Chile by a large consortium led by the USA and including also the UK. It will have the sole purpose of imaging the transient sky every few nights, a survey now referred to as the Legacy Survey of Space and Time (LSST; LSST Science Collaborations et al. 2017; Fig. 1, left panel). Future optical and infrared space missions are also being designed to support time-domain astronomy. ESA's Euclid and NASA's SPHEREx space missions, due for launch in 2022 and 2024, respectively, will weekly monitor certain sky fields. NASA's next flagship, the Nancy Grace Roman Space Telescope, due for launch in 2025, will then monitor large fields almost daily.

Machine Learning is now not only at the forefront of astronomy but also at the forefront of Computer Science. Large databases have become the norm in all areas of life and in order to exploit the (known and unknown) information that they might hold great efforts are being invested in designing Machine Learning algorithms. These are very different from regular computer coding where the information to be extracted from the database needs to be known a priori. Rather the machine learns from trial-and-error in a supervised or unsupervised way. So access to suitable data to train efficient Machine Learning algorithms rather than access to observing facilities will determine the quality and amount of research output in the future.

Your MScR project will apply known Machine Learning algorithms suitable for time-series analysis and develop new ones. You will use astronomical data sets, such as light-curves (Fig. 1, right panel), to train the algorithms and explore their application to other scientific areas (e.g. biology). For your work you will have easy access to the COSMA 5 supercomputer, owned by the Durham astronomy group, and you will be able to apply also for computing time on NICE, UK's new Northern Intensive Computing Environment, which is hosted by Durham University.

As well as travels within the UK, you will travel for collaborative visits to Uppsala, Sweden. Uppsala University is a major strategic partner for Durham University and host to an IT department specialised in Machine Learning. This project could be combined with an industry placement at Intogral Ltd., a company specialised in Image Analysis Solutions.

LSST Science Collaborations et al. 2017
Nancy Grace Roman Space Telescope
Intogral Limited



Left panel: *An artist's impression of the Vera C. Rubin observatory expected to have first light in 2021 (credit: LSST Corporation).* **Right panel:** *The multi-wavelength light-curve of the quasar 3C 273. Such astrophysical time-series are interpolated and analysed using Machine Learning algorithms, e.g., Gaussian processes.*

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