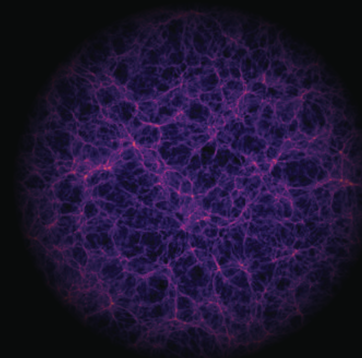
Astronomy PhD & MScR Projects at Durham

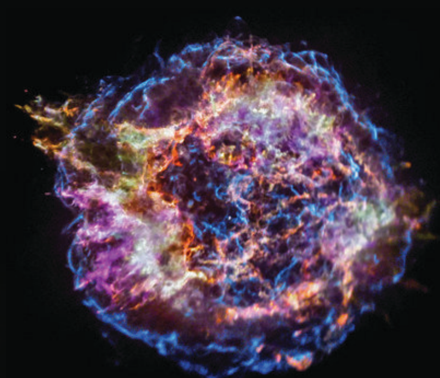
2025

Durham University

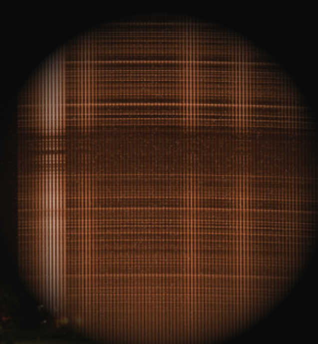
ICC



Durham Centre for Extragalactic Astronomy



CfAI



PHD & MSCR PROJECTS IN ASTRONOMY FOR AUTUMN 2025 START

Introduction

List of STFC/Durham funded PhD Projects

Baugh: Machine Learning Galaxy Formation

Brown: Ultra High Energy Neutrino Astronomy with Trinity

Brown: Improving the Accuracy of Drone Based Remote Sensing with Astronomical Instrumentation

Cole: Beyond the Galaxy-Halo Connection

Deason: Near-Field Cosmology with Destroyed Dwarf Galaxies

Edge: Constraining the Accretion History of the Most Massive Black Holes

Harris: Developing the Multi Core Integral Field Unit

Jauzac: Galaxy Clusters with JWST to Reveal the Nature of Dark Matter

Li: Dark Energy and Gravity in the Era of Euclid

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Li: Dark Energy and Gravity: When Science Meets Supercomputing

Morabito: Finding Hidden Active Galactic Nuclei Using Novel Observational Modelling Methods

Pontzen: Comparing Observed and Simulated Dwarf Galaxies

Pontzen: Non-linear Gravitational Dynamics of Dark Matter

Pontzen: Accelerating Simulation Analysis

Smith: Science Project Development for HARMONI on the ESO Extremely Large Telescope (Gravitational Lensing or Stellar Populations)

Reeves: Optimising Free Space Optical Communications in Strong Turbulence Conditions with Machine Learning

Wilson: Characterising and Correcting Atmospheric Turbulence Effects to Enhance Ground Based Astronomy

List of additional PhD Projects that require applications for funding

Alexander: Why are (Some) Quasars Special? Towards an Understanding of the Evolution of Quasars

Bose: Fundamental Cosmology with Large-Scale Structure

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 the top institution 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. In 2014 we were ranked 5th in the world (1st in Europe) in terms of research impact in space sciences. The Clarivate Analytics Highly Cited Researchers 2018 list puts Durham's astronomers and cosmologists first in the UK, second in Europe and sixth in the world for the quality and influence of their research in space science.

There are roughly 35 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 2025. We particularly encourage applications from members of the community that are under-represented in physics.

Fully Funded PhD Studentship Options

This booklet outlines primarily PhD projects for which we can provide full funding (fees plus a stipend) over 3.5 to 4 years typically, but not exclusively. For those projects with funding associated, we provide brief details on the funding below.

Science and Technology Facilities Council (STFC) studentships. These up to 4-year long 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 expect to offer up to 6 STFC-funded studentships this year, based on previous years STFC studentship allocations. According to the rules in place at the time of writing this could imply up to 2 international studentships.

Durham funded PhD studentship. We offer up to three Durham funded PhD studentship this year for a duration of up to 4 years.

European Research Council (ERC) studentships. These 4-year PhD studentships are available to any student irrespective of domicile. We offer up to 3 ERC studentships 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 need to be in place typically by the end of December or start of January, for an autumn 2025 start. We note that by the deadline we need to have received reference letters in support of the application, as well as relevant language certificates. Therefore we encourage interested graduate students to contact us well in advance of this deadline to allow appropriate assessment, as well as to explore other potential sources of funding. Hence we recommend DDS/CSC applications to be submitted by **early/mid- December 2024** to receive full consideration.

Bell Burnell Graduate Scholarship Fund. The Institute of Physics (IOP) and leading physicist Professor Dame Jocelyn Bell Burnell launched the Bell Burnell Graduate Scholarship Fund (BBGSF) 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 need to have applied and be nominated by a staff member by the internal physics deadline in early January. Hence we recommend applicants interested to be considered for the BBGSF to submit their application by **early/mid- December 2024** 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 the *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 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 guaranteed 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 web pages https://www.gov.uk/postgraduate-loan.

Follow the post-graduate opportunities link from our web site or contact our astronomy post-graduate coordinators, Prof. Ryan Cooke (ryan.j.cooke@durham.ac.uk) and Dr. Dimitri Gadotti (dimitri.a.gadotti@durham.ac.uk) for further details.

MACHINE LEARNING GALAXY FORMATION

Main Supervisor:	Prof. Carlton Baugh	c.m.baugh@durham.ac.uk
Office:	Ogden Centre West 122	
Funding:	STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)	

Description:

Many of the processes involved in galaxy formation remain poorly understood. The differential equations used to model these processes contain parameters whose values must be chosen to produce a fully specified model. The resulting model parameter space can have many dimensions. The model itself can take a large amount of computer time for one set of parameters, making a search of the parameter space expensive or even infeasible.

The aim of this project is to apply techniques from machine learning to speed up and fully automate the parameter search. The first step is to train a machine learning emulator to mimic running the full calculation. The second step is to devise an efficient way to optimize the model (find the best fitting set of parameters) and to characterize the parameter space so that we can quote acceptable ranges of models. The aim is to do this whilst taking full account of the uncertainty on the data used to calibrate the model parameters. The pipeline developed to explore the parameter space and optimize the model could be applied to any scientific model that contains parameters and is computationally expensive to evaluate.

Notes:

ULTRA HIGH ENERGY NEUTRINO ASTRONOMY WITH TRINITY

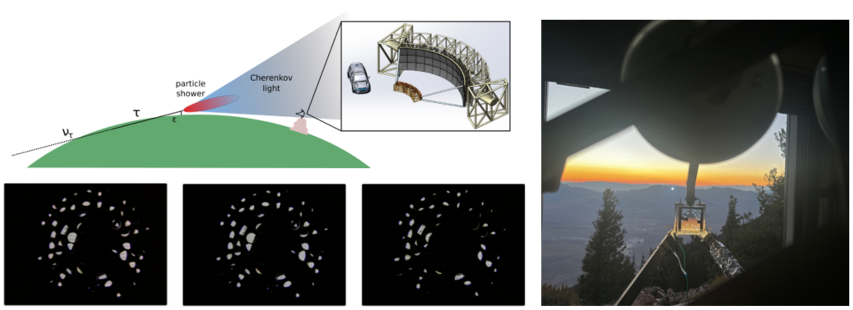
Main Supervisor: Dr. Anthony M. Brown anthony.brown@durham.ac.uk
Office: Ph125B

Funding: Durham, STFC and other funding schemes (Bell Burnell, DDS, CSC)

Description:

The Trinity telescope is a new and unique approach to observing the neutrino Universe. Trinity will indirectly observe Ultra-High-Energy (UHE) tau neutrinos by detecting the Cherenkov radiation emitted by an upwards going air shower that appears out of the ground. This air shower is the result of a tau neutrino skim through the Earth's crust, interacting with matter to produce a tau particle, which decays as it comes out of the Earth. By placing a bespoke wide-field-of-view telescope on a mountain, and pointing it below the horizon, Trinity will observe these upwards travelling flashes of light (see Figure 1 below). Essentially, Trinity is translating expertise in gamma-ray astronomy to UHE neutrino astronomy, which allows us to minimise the observed background, whilst maximising the energy and angular resolution of the observations.

In your PhD, you'll be joining the Trinity collaboration, exploiting the Trinity demonstrator telescope to open up the UHE neutrino window to the Universe. Supervised by Dr Anthony Brown, and interacting closing with international collaborators in the USA, the PhD post will make significant contributions to several key operational aspects of Trinity. Your tasks will include developing new (drone-based) hardware to calibrate Trinity, quantifying the sensitivity of Trinity and interpreting Trinity observations to place sensitive flux limits on UHE neutrino emission from astrophysical sources.



Caption *Images outlining key aspects of the position. Top left: schematic outlining key components of Trinity's detection technique. Right: photo of drone-based light source illuminating the Trinity demonstrator telescope (for a variety of calibration requirements). Bottom left: first data of drone-based mirror alignment (September 2024).*

Notes:

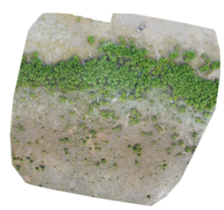
IMPROVING THE ACCURACY OF DRONE BASED REMOTE SENSING WITH ASTRONOMICAL INSTRUMENTATION

Main Supervisor: Dr. Anthony M. Brown anthony.brown@durham.ac.uk
Office: Ph125B
Funding: Durham, STFC and other funding schemes (Bell Burnell, DDS, CSC)

Description:

The recent advances in UAV capability has given the remote sensing community a number of exciting possibilities. Unfortunately, in the context of plant ecology, the realization of this potential has focused on monitoring crop health where the species of plant is known. Furthermore, this monitoring is usually restricted to a small number of wavelengths, resulting in a noisy dataset that is not able to differentiate between plant species or identify pathogens. As such, UAVs have not realised their full potential in UAV-based remote sensing of plants. This unrealised potential also applies to other areas of UAV-based remote sensing such as atmospheric content where UAV technology affords us the possibility of mapping out temporal and spatial variations in atmospheric gas and dust content.

This PhD position will look to combine astronomical instrumentation, UAV technology and machine learning, with a sensor-fusion approach to improve remote sensing capability. To achieve this, your tasks will include developing new imaging capability to mount to UAVs, apply machine learning analysis to remote sensing data sets to improve remote sensing accuracy and conduct simulations to quantify the accuracy of the new remote sensing capability.



Left: image of UAV-based calibration system above a telescope array in Namibia. Centre: UAV imagery of a wheat field with different pathogens. Right: UAV-imagery of a mangrove forest in Suriname.

Notes:

BEYOND THE GALAXY-HALO CONNECTION

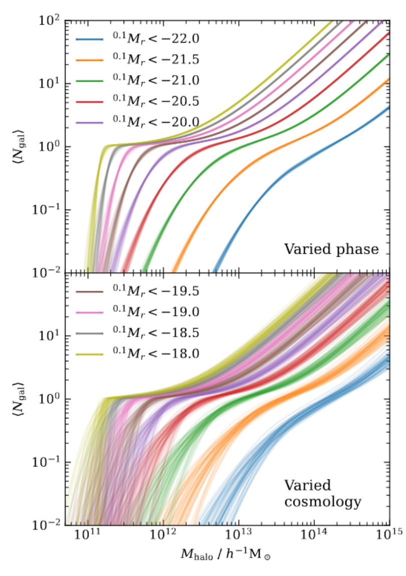
Main Supervisor: Prof Shaun Cole shaun.cole@durham.ac.uk
Office: Ogden Centre West 211
2nd Supervisor: Prof Peder Norberg peder.norberg@durham.ac.uk
Funding: STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)

Description:

In this project, we will make use of both the latest generation of cosmological simulations of galaxy formation run on the COSMA supercomputers at the ICC and data from the unprecedentedly large DESI galaxy redshift survey. The DESI galaxy redshift survey which will be completed during the course of this project is an order of magnitude larger than previous surveys.

The connection between the dark matter cosmic web of voids, sheets, filaments, and knots produced in cosmological simulations and the large-scale galaxy distribution mapped in large galaxy redshift surveys has been made very successfully through statistical descriptions of the galaxy-halo connection. For instance, the Halo Occupation Distribution (HOD), which quantifies the mean number of galaxies of a given luminosity hosted by a halo of a given mass, has been well-constrained by fitting the clustering (2-point correlation function) of galaxies in the SDSS galaxy redshift survey (Zehavi ey al. 2011) and by early DESI data (see figure).

In this project, we will aim to go beyond this statistical connection between galaxies and dark matter and probe the way in which physical processes modelled in the simulations affect galaxy clustering. Using the Bright Galaxy Survey (BGS), which we have been involved in since its inception, we will be able to determine the galaxy 2-point correlation function with higher accuracy than ever before and also be able to explore more novel clustering statistics. In this way, we envisage being able to determine how galaxy properties not only depend on halo mass, but also on other parameters such as their formation history, internal structure, and local environment. Furthermore, by analysing the simulations, in which we have full knowledge of the formation history of each galaxy, we will seek explanations for the correlations we uncover and hence shed light on what processes are important in shaping the observed galaxy distribution.



Top: Best-fitting HODs of the 25 simulations with the same Planck cosmology, but with different random phases. Each line represents a single HOD fit. The HOD curves are highly consistent with one another for all the samples, with significant differences emerging only at the low mass tails. Bottom: Variation of the best-fit HODs for simulations with different cosmologies. Each line represents a single HOD fit. The HOD variation is larger than the case where cosmology is held constant as in the upper panel.
From Smith et al. (2023).

Notes:

NEAR-FIELD COSMOLOGY WITH DESTROYED DWARF GALAXIES

Main Supervisor: Prof. Alis Deason alis.j.deason@durham.ac.uk
Office: Ogden Centre West 216
Funding: STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)

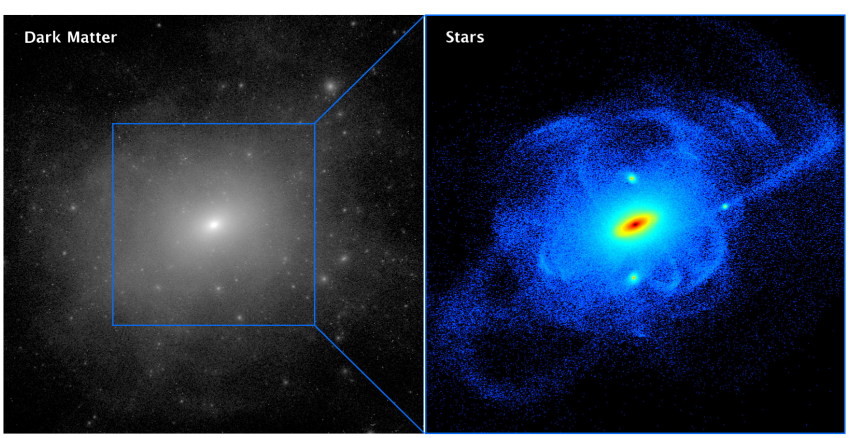
Description:

The Milky Way galaxy is a cannibal; throughout its lifetime it devours hundreds of dwarf galaxies. Observable memories of this eating habit are splayed out in a vast stellar halo, which extends out to tens of kpc from the Galactic centre. These halo stars provide a unique insight into the lowest luminosity dwarfs in the Universe, and the dark matter halo of the Milky Way. Dwarf galaxies play a major role in our understanding of dark matter and galaxy formation; while the dwarf satellites continue to challenge our cosmological theories, their destroyed analogues have rarely been used to address the same fundamental questions.
We are currently witnessing a surge in the number of observational surveys of the Milky Way halo. This data boon is spearheaded by the *Gaia* mission which is mapping the structure of the Milky Way to unprecedented detail. The combination of wide-field spectroscopic surveys (e.g DESI, WEAVE, 4MOST) and *Gaia* astrometry has provided us with a rich dataset of stellar halo with 6D phase space (3 spatial dimensions, 3 velocity dimensions) plus chemical information.

This project will use this game-changing 6D+ dataset to quantify the dissolved dwarfs in the halo of our Galaxy. A multicomponent chemo-dynamical method will be developed and applied to both the observational dataset and mock observations to construct the observed destroyed dwarf luminosity function. These measurements, in combination with the surviving satellite population, will be used to provide a critical test of our standard cosmological model, and will be used to constrain the epoch of reionization — a pivotal phase in the history of the Universe, which signifies the end of the dark ages.

The project is intended to have both observational and theoretical elements, but the student can choose to focus more on one aspect if they wish.

Chemo-dynamical modeling using globular clusters
Measuring the dwarf galaxy luminosity function using metallicity distributions
A recent review article on Galactic Archaeology



Simulation showing dark matter (left) and stars (right). Image adapted from Rashkov, Pillepich, Deason et al. (2013). Most of the luminous material resides in the dense, inner region of the galaxy – in the disc and bulge. The low density streams of stars in the outer parts of the Galaxy are the remains of dwarf galaxies that have been destroyed by the massive host galaxy.

Notes:

CONSTRAINING THE ACCRETION HISTORY OF THE MOST MASSIVE BLACK HOLES

Main Supervisor: Prof Alastair Edge alastair.edge@durham.ac.uk
Office: Ogden Centre West 109
Funding: STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)

Description:

This mass of the central black hole in galaxies appears to correlate with the mass of the whole galaxy across the full range of mass. This correlation implies that the most massive black holes ($> 10^{10} M_\odot$) will be found in the most luminous galaxies. The galaxies at the centre of clusters of galaxies are by far the largest stellar systems and there is growing evidence for exceptionally massive black holes in these systems.

The effect of these supermassive black holes on their host galaxy and local environment is particularly strong and strongly truncates the number of stars formed in the galaxy through a process refered to as AGN Feedback. This process can be constrained through the measurement of the current activity due to accretion onto the black hole, through the power of radio jets launched in the past 10 Myr from the black hole or by determining how these jets inflate bubbles in the hot gas surrounding the galaxy.

By studying a large, statistically complete sample of X-ray selected clusters from the eROSITA survey and combining it with the multiple radio, optical and infrared surveys it is possible to estimate the accretion history of these black holes over the past 10 Gyrs. With addtional JWST observations of a few of the more extreme systems, we can match the energy output to the amount of cold gas available to fuel this activity.

Suggested reading McNamara & Nulsen 2007 Annual Reviews article

A multi-wavelength view of the Perseus cluster and its central galaxy NGC1275. The optical image is in greyscale, the X-ray emission in blue and radio emission in red.

Notes:

DEVELOPING THE MULTI CORE INTEGRAL FIELD UNIT

Main Supervisor:	Dr. Robert J. Harris	robert.j.harris@durham.ac.uk
Office:	Ogden Centre West 030	
2nd Supervisor:	Dr. Kieran O'Brien	kieran.s.obrien@durham.ac.uk

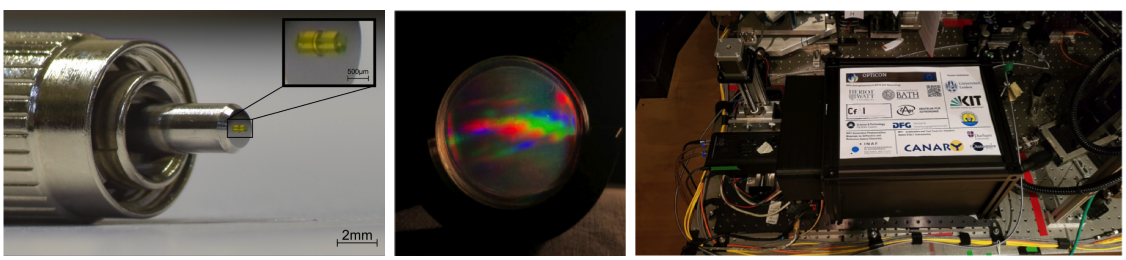
Funding:	STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)	

Description:

The Multi Core Integral Field Unit (MCIFU) is a technology demonstrator for the Planetary Camera and Spectrograph (PCS) of the Extremely Large Telescope and will be used to validate technology allowing direct imaging spectroscopy of exoplanets. Once complete the MCIFU will be installed at the Magellan telescope in Chile (on sky commissioning due 2026). Here it will be used to evaluate the technology and complement the MagAO-X system by taking spectra of close companion systems.

In your PhD, you'll be joining the team developing the MCIFU. You'll be joining Dr. Robert Harris and team in Durham and you'll interact with with international collaborators in the USA, Germany and Italy. Your tasks will include modelling, developing the hardware in the laboratory and validation for future use. You'll develop plans for observations using the instrument and evaluate its capabilities.

As a side project, you'll also investigate how future technologies being developed by the group in Durham can be integrated into the MCIFU and eventually PCS. This could for instance be combining fibre technologies with MKID detectors, which can resolve energy and hence reduce the need for bulk optics whilst also improving efficiency.



Images of the components of the original MCIFU system. Left) Two-photon Polymerised microlenses in yellow sit on a fiber ferrule. The lenses are roughly 400 um high, slightly larger than a human hair. Middle) A triple stacked volume phase holographic grating allowing high efficiency dispersion. Right) The original spectrograph system, sitting on the CANARY bench at the William Herschel Telescope in 2019. Your PhD will be to investigate how a small demonstrator can be used to validate technologies for the ELT.

Notes:

GALAXY CLUSTERS WITH JWST 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 other funding schemes (Bell Burnell, DDS, CSC, ...)

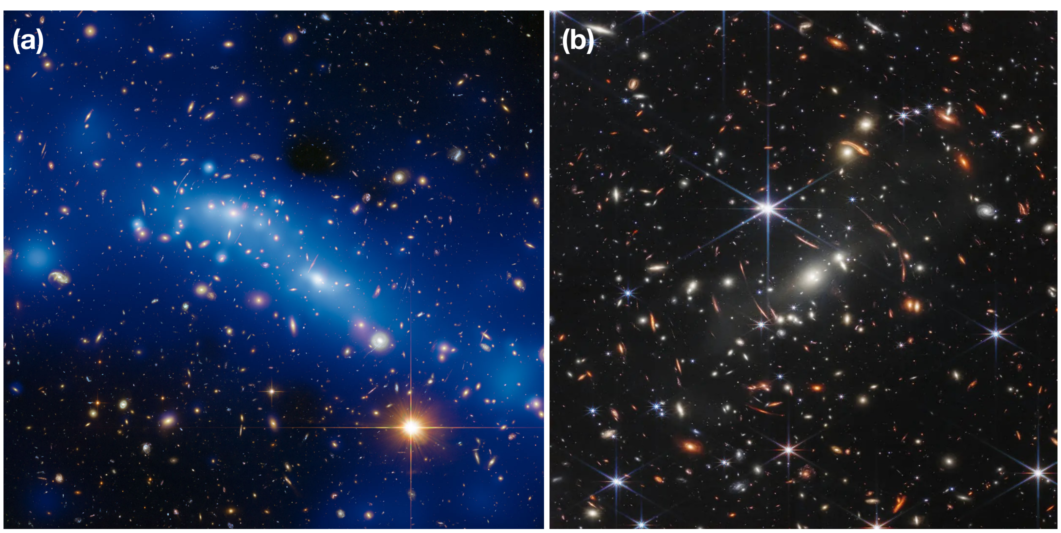
Description:

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 SLICE survey programme, a *James Webb Space Telescope* survey started over the summer 2024, and follow-up spectroscopy from the largest telescope on Earth (VLT). SLICE 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.



***(a)** The galaxy cluster MACS\J0416.1–2403, one of six clusters targeted by the BUFFALO programme with the Hubble Space Telescope. The varying intensity of blue haze in this image shows the dark matter revealed by the magnifying power of gravitational lensing. **(b)** The galaxy cluster SMACS J0723, the first cluster observed by the JWST, released on 12 July 2022. SLICE observations will have similar resolution and allow for amazing detailed analyses of the physics of galaxy clusters and dark matter.*

Notes:

DARK ENERGY AND GRAVITY IN THE ERA OF EUCLID

Main Supervisor: Prof. Baojiu Li baojiu.li@durham.ac.uk
Office: Ogden Centre West 218
2nd Supervisor: Prof. Carlton Baugh c.m.baugh@durham.ac.uk

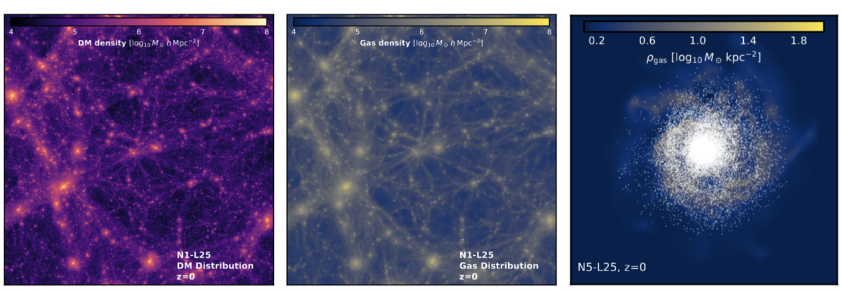
Funding: ERC

Description:

The European Space Agency's *Euclid* satellite, successfully launched in 2023, is one of human being's most advanced and ambitious endeavours to explore the Universe, following a long chain of successful space and ground-based telescopes that have defined the precision era of cosmology studies. By mapping the space distribution and time evolution of cosmological large-scale structures, it aims to shed new light on the origin of the mysterious accelerated Hubble expansion, be it due to some unknown matter species known as dark energy or a need for a new theory of gravity beyond General Relativity.

This PhD project is broadly designed to explore the scientific potential of *Euclid* to test models of dark energy and modified gravity models. However, following the past practices of the two supervisors, it will be open-ended, to allow the student to develop their own interest and ideas from early stage. Possible directions include: explorations of *Euclid*'s data on galaxy clustering, weak gravitational lensing or clusters of galaxies to constrain models of new physics, improving our understanding of galaxy formation in the models through semi-analytic models or state-of-the-art hydrodynamical simulations, developing new summary statistics and cosmological probes to test models in general, or employing AI tools in the above aspects, or some mixture of the above possibilities. The student will learn both analytical and (super)computing skills from this project, as well as connections with observational data via model tests.

Reference 1: Galaxy formation simulations in modified gravity models 1
Reference 2: Galaxy formation simulations in modfiied gravity models 2
Reference 3: Systematic cosmological simulations of new physics 1
Reference 4: Systematic cosmological simulations of new physics 2
Reference 5: FORGE-A-BRIDGE: machine learning and gravity simulations



Galaxy formation simulation of a gravity model with a universe that is 5-dimensional, showing the distributions of dark matter (left), gas (middle) and stars (right; zoomed-in to a single galaxy).

Notes:

COSMOLOGY IN THE ERA OF DESI

Main Supervisor: Prof. Baojiu Li baojiu.li@durham.ac.uk
Office: Ogden Centre West 218
2nd Supervisor: Dr. Sownak Bose sownak.bose@durham.ac.uk
Funding: ERC

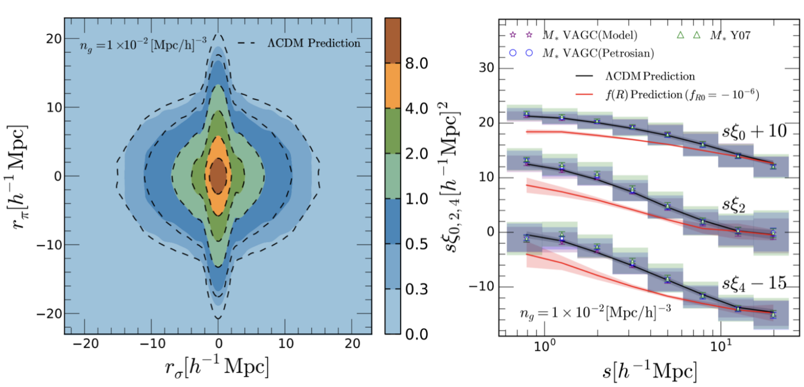
Description:

We are witnessing an exciting period when our understanding of the Universe is being changed, potentially revolutionised, by the advent of large, state-of-the-art, galaxy surveys, such as *Euclid*, *Vera Rubin* and DESI. A key objective of these surveys is to precisely measure the parameters of the Universe and to help solve the enigma of cosmic acceleration, but they will also play an important role in deepening our understanding of gravitation and particle physics, such as dark matter candidates and neutrinos. Early analyses of DESI data appear to favour a dynamical dark energy—instead of a cosmological constant Λ as in the standard ΛCDM model—as the driving force of the accelerated Hubble expansion.

In this PhD project, the student will work on galaxy-clustering observables, including but not exclusive to baryonic acoustic oscillations, galaxy power spectrum, redshift-space distortions, cosmic voids and higher-order statistics, as powerful probes to test cosmological models, both ΛCDM and beyond. To achieve this, we will combine a variety of techniques ranging from semi-analytical methods augmented by machine learning to state-of-the-art galaxy-formation simulations, to make accurate model predictions that can be confronted against observational data from DESI. We aim to test a majority of theoretical models of new physics beyond the standard model that are currently viable, paying particular attention to how improved understanding of galaxy formation could lead to stronger and more reliable constraints.

The ICC is an institutional member of DESI, which means that the student working on this project will automatically become a DESI member, with the possibility of leading certain projects or analyses therein.

Reference 1: Simulating galaxy formation in modified gravity theories
Reference 2: Galaxy clustering from the bottom up
Reference 3: Negative neutrino masses as a mirage of dark energy
Reference 4: Galaxy clustering in modified gravity from state-of-the-art hydrodynamical simulations



Galaxy clustering in redshift space predicted by a high-resolution simulation (left). This has been used as evidence that a popular class of modified gravity models, $f(R)$ gravity (right), can be strongly constrained by data from surveys such as DESI.

Notes:

DARK ENERGY AND GRAVITY: WHEN SCIENCE MEETS SUPERCOMPUTING

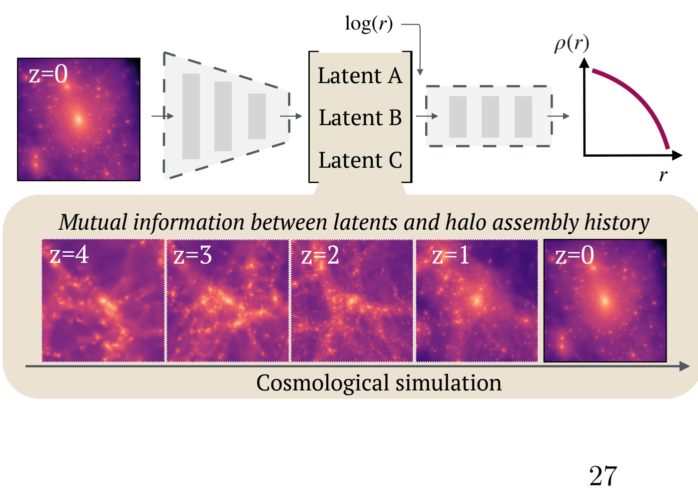
Main Supervisor:	Prof. Baojiu Li	baojiu.li@durham.ac.uk
Office:	Ogden Centre West 218	
2^{nd} Supervisor:	Prof. Andrew Pontzen	andrew.p.pontzen@durham.ac.uk
Funding:	ERC	

Description:

Computing plays a central role in the development of modern cosmology: it is through computer simulations that we can most accurately predict the evolution of the Universe and its large-scale structure, which contains rich information for building and refining our cosmological model. State-of-the-art cosmological simulations are quickly approaching the volume of the observable Universe, while also capturing the detailed interplay between key constituents of the universe such as neutrinos, dark matter and dark energy with the visible stars and gas. Dark matter, dark energy, and neutrinos are all invisible and involve physics that lies beyond current knowledge. By tracing these mysterious components' connection to visible structure in the universe, we can therefore extend our understanding in new directions.

However, large cosmological simulations are highly expensive, making them a privilege available only to a small number of groups around the world, including the ICC. Making most efficient use of computational resources allows for the best possible physics outcomes, while shrinking the environmental and financial costs. There have been growing efforts in developing more efficient methods, often based on artificial intelligence (AI), in recent years. Many of these studies use AI as a black box to increase efficiency. However, to increase simulations' predictive power, reliability and physics insight, there is urgent need to build more transparent, interpretable AI systems that may even be able to aid construct explanations for physical phenomena.

In this open-ended PhD project, the student will explore new ways to improve the efficiency of numerical simulations, enhance their utility in testing cosmological models, and work towards AI as a partner in advancing physics. Possible directions include: (i) applying machine learning (ML) to make predictions of key summary statistics with improved accuracy for models of new physics, and confront against observed data; (ii) going beyond summary statistics to make ML predictions at the field level; (iii) understanding how ML can forge a closer connection between cosmic structure formation—including galaxy formation—and fundamental physics, particularly dark matter, dark energy and gravity; (iv) exploring novel ways to build efficient simulations by augmenting traditional simulation methods with AI and analytical methods.



A neural network is trained to compress information about a simulated dark matter halo into a minimal representation, which can then be interpreted to yield physical insights about the growth of dark matter structures. From Lucie-Smith et al 2024.

Notes:

FINDING HIDDEN ACTIVE GALACTIC NUCLEI USING NOVEL OBSERVATIONAL MODELLING METHODS

Main Supervisor: Dr. Leah Morabito leah.k.morabito@durham.ac.uk
Office: Ogden Centre West 121

Funding: STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)

Description:

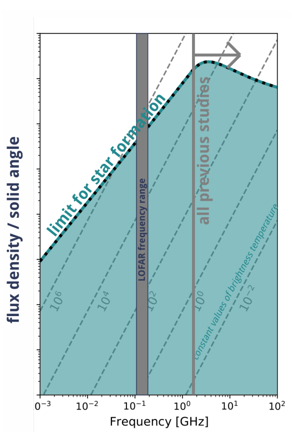
Observational evidence and cosmological simulations both agree that super-massive black holes co-evolve with their host galaxies, but we do not understand the details of this process. It is widely thought that most, if not all, super-massive black holes go through an active phase which can help regulate both their growth and also impact their host galaxy. When in this active phase, super-massive black holes are feeding on their host galaxy, which can provide the fuel to produce powerful outflows such as winds or jets, with observational signatures from X-rays to the radio. When we see these observational signatures, we call this an Active Galactic Nucleus (AGN).

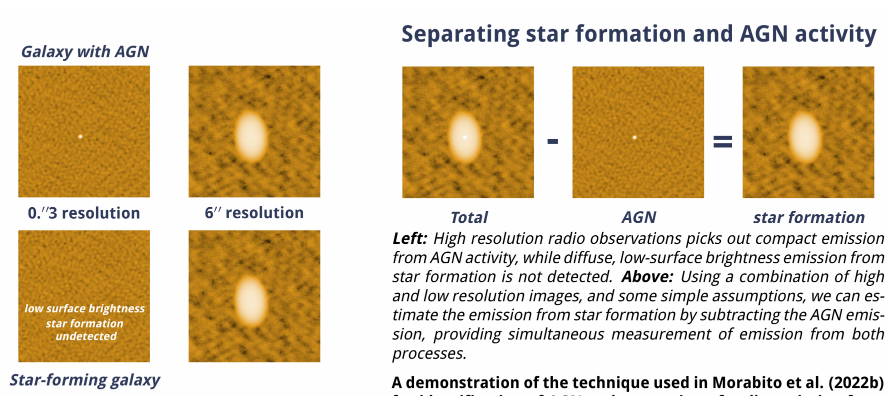
To understand how AGN can impact their host galaxies, we need to track both AGN activity and host galaxy growth. Galaxy growth is traced through star formation. An ideal way to track star formation is via radio observations, since radio waves penetrate dust and provide an orientation-free measurement of the star formation rate. However, AGN activity can also produce radio emission from jets, outflows, or coronal processes. The only way to distinguish between radio emission from AGN activity and radio emission from star formation is through high resolution radio observations. Recent advancements from the LOw Frequency ARray (LOFAR) show that it is possible to do this over a wide field of view (Morabito et al., 2022), but the separation of AGN activity and star formation is quite simple.

You will build a forward-modelling solution to the problem of separating star formation and AGN activity, by starting from first principles to create a model galaxy, using distributions of properties like size and star formation rate, that can be 'observed' with the addition of different levels of AGN luminosities. By comparing a suite of models with observed data, you will be able to place meaningful constraints on the radio emission from star formation and AGN activity. There are several exciting new datasets to work on, including high-resolution images of the Lockman Hole using LOFAR (Sweijen et al. 2022, and shortly the Boőtes and ELAIS-N1 fields. The project will involve both creating simulations of mock galaxies, and working with observational data.

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.

More reading:
Paper 1: https://ui.adsabs.harvard.edu/abs/2022MNRAS.515.5758M/abstract
Paper 2: https://ui.adsabs.harvard.edu/abs/2013A%26A...556A...2V/abstract
Paper 3: https://ui.adsabs.harvard.edu/abs/2022NatAs...6..350S/abstract
Meet the team: https://lmorabit.github.io





Left: *High resolution radio observations picks out compact emission from AGN activity, while diffuse, low-surface brightness emission from star formation is not detected.* ***Above:*** *Using a combination of high and low resolution images, and some simple assumptions, we can estimate the emission from star formation by subtracting the AGN emission, providing simultaneous measurement of emission from both processes.*

A demonstration of the technique used in Morabito et al. (2022b) for identification of AGN and separation of radio emission from AGN and star formation.

Notes:

COMPARING OBSERVED AND SIMULATED DWARF GALAXIES

Joint Supervisors:	Prof Andrew Pontzen	andrew.p.pontzen@durham.ac.uk
	Dr Anna McLeod	anna.mcleod@durham.ac.uk
Office:	Ogden Centre West OCW214 / OCW120	

Funding:	Durham, STFC and other funding schemes (Bell Burnell, DDS, CSC)	

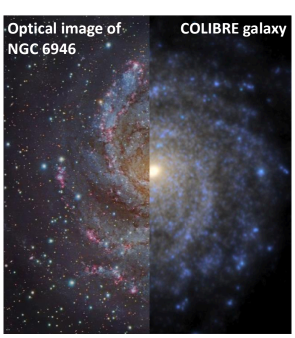
Description:

Dwarf galaxies are, as the name suggests, very small. While our Milky Way contains hundreds of billions of stars, dwarfs may contain only a few million, or even a few thousand. However they are of major importance to our understanding of the universe as a whole. First, because galaxies form 'hierarchically', today's large galaxies have assembled from dwarfs. Second, observations of surviving dwarf galaxies give us vital clues about the physics governing galaxy formation: they are relatively pristine remnants of the early universe, and moreover are sensitive indicators of the physics of dark matter.

This project will bring together breakthroughs in observational and computational studies of dwarf galaxies, to study their physical implications. On the observational side, astronomers have developed the ability to find very diffuse, very faint galaxies and study the individual stars within them. This allows for reconstructing detailed histories of when these tiny objects formed their stars. Integral field unit spectroscopy adds vital information on the movement of ionised gas, while radio observations can pinpoint the location and motion of cool neutral gas.

On the computational side, there has been immense progress in hardware speed coupled to an increasing sophistication of software designed to simulate galaxy formation. This has allowed individual stars, and the effects of energy from their radiation and supernovae, to be resolved within simulations of dwarf galaxies. However as yet comparisons between results from these new observational and computational facilities are only just getting underway. Making such comparisons poses its own challenges, which this project will tackle.

This project will involve analysing data from some of the world's largest telescopes (both ground- and space-based), making comparisons with cutting-edge numerical simulations. Depending on your interests, the work can be sculpted to focus more on the numerical or observational side. Either way, becoming expert in bridging data and numerics will provide you with a valuable astrophysics skill that is also highly transferrable into other sectors. The work will be co-supervised by Andrew Pontzen and Anna McCleod, who are experienced mentors with extensive international networks in the numerical and observational fields respectively.



Comparing simulated and observed galaxies is an essential way to make progress in understanding the universe. Here a comparison is made between spiral galaxies in COLIBRE. This project will have access to state-of-the-art simulations from the EDGE and COLIBRE collaborations, and will focus in on smaller dwarf galaxies.

Relevant computational papers:
EDGE-INFERNO: Simulating every observable star in faint dwarf galaxies and their consequences for resolved-star photometric surveys
EDGE: Predictable Scatter in the Stellar Mass–Halo Mass Relation of Dwarf Galaxies

Relevant observational papers:
Stellar Feedback and Resolved Stellar IFU Spectroscopy in the Nearby Spiral Galaxy NGC 300
Shaken, but not expelled: Gentle baryonic feedback from nearby starburst dwarf galaxies

NON-LINEAR GRAVITATIONAL DYNAMICS OF DARK MATTER

Main Supervisor: Prof Andrew Pontzen andrew.p.pontzen@durham.ac.uk
Office: Ogden Centre West OCW214
Funding: Durham, STFC and other funding schemes (Bell Burnell, DDS, CSC)

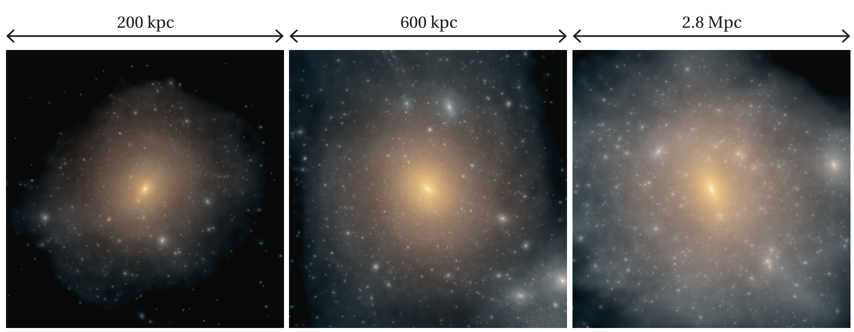
Description:

One of the major goals in cosmology and astrophysics today is to identify the nature of dark matter. In pursuit of this goal, it is essential to understand the dynamics of particles which interact through gravity alone; to a good approximation, dark matter must fall in this category, with any non-gravitational interactions being strongly subdominant. Major unresolved questions in this area include how and why dark matter structures reach an equilibrium bound state, and how these structures can then be altered by the gravitational action of supernovae and other sources of energy. Because gravity is a long-range force, normal thermodynamic arguments about the large-scale behaviour of dark matter fail spectacularly (the 'gravothermal catastrophe').

Sophisticated computer simulations provide considerable insight into how dark matter will behave in reality, but still leave crucial open questions. For example, while it has long been established that dark matter 'halos' that surround galaxies follow a characteristic density profile (specifically the 'Navarro-Frenk-White' profile), the physical reasons for this remain only partially understood. Lacking understanding in this area is both a fundamental shortcoming of current physics and a practical limitation for making robust predictions and comparisons with observations.

This project will involve analysing state-of-the-art simulations and pairing them with new techniques in dynamical analyses including insights from chaos theory. It requires a willingness to learn and develop new computational and mathematical techniques. There is considerable scope to tailor the project to your interests, and ultimately you will be an expert across techniques in computational and theoretical analyses, as well as in the observational properties of dwarf galaxies. There is also the opportunity to work with national and international collaborators (see the GMGalaxies website).

Example paper I: Conserved actions, maximum entropy and dark matter haloes
Example paper II: Milking the spherical cow – on aspherical dynamics in spherical coordinates
Example paper III: From particles to orbits: precise dark matter density profiles using dynamical information



The distribution of dark matter around galaxies is roughly independent of scale, but the exact way that a gravitational equilibrium is established remains only partially understood.

Notes:

ACCELERATING SIMULATION ANALYSIS

Main Supervisor: Prof Andrew Pontzen andrew.p.pontzen@durham.ac.uk
Office: Ogden Centre West OCW214

Funding: Durham, STFC and other funding schemes (Bell Burnell, DDS, CSC)

Description:

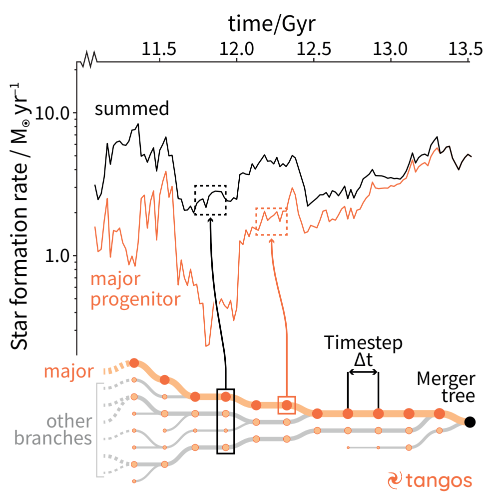
Simulations of the formation of structure in the universe are some of the most challenging computational problems known to humanity. By definition, they push the boundaries of hardware capabilities because the universe is so complex — there is no known limit to the amount of computer power or storage that can be usefully applied. However, astrophysicists often need to focus on science analyses without constantly fretting over technical details of the underlying large datasets.

Enabling this kind of work requires a full understanding of astrophysical questions and challenges, but also an enthusiasm for high-quality code making use of suitable cutting-edge technologies.

This PhD will dive into cutting-edge technologies in the context of simulation analysis, but its particular area of focus can be tailored to your interests. For example, it would be possible to focus on the use of advanced GPU hardware through technologies like WebGPU, the embedding of analysis inside user-friendly browser interfaces via WebAssembly, or the use of emerging database techniques including graph and NoSQL solutions. This project would be ideally suited to a student who would like to focus heavily on technology, while also becoming expert on the relevant aspects of astrophysical simulations to inform solutions that work for a wide variety of users, including the GMGalaxies team led by the supervisor.

Existing relevant software projects include:

topsy – GPU-accelerated visualisation of simulations
pynbody – scientific analysis of simulations
tangos – databases for querying simulations



Even relatively simple astrophysical queries such as 'give me the star formation rate over time from this simulated galaxy' can hide considerable algorithmic complexity, which becomes important for high-quality analyses of large simulation outputs. This illustration (from Pontzen & Tremmel 2018) breaks down some steps involved in retrieving star formation rates when a galaxy has formed from multiple progenitors. Improving reliable reconstructions of a galaxy's history using new database technologies is one possible topic of exploration, amongst many others such as GPU acceleration of scientific analysis.

Notes:

OPTIMISING FREE SPACE OPTICAL COMMUNICATIONS IN STRONG TURBULENCE CONDITIONS WITH MACHINE LEARNING

Main Supervisor:	Dr Andrew P. Reeves	andrew.p.reeves@durham.ac.uk
Office:	Ogden Centre West 022	
Funding:	Durham Space Research Centre	

Description:

Free Space Optical Communication is an exciting and rapidly growing technology with the promise of enabling high bandwidth, secure and license free communications using satellites constellations to anywhere in the world, regardless of terrestrial infrastructure. However, the transmission of laser light from ground to and from space is limited by atmospheric turbulence – refractive index fluctuations cause phase aberrations that quickly change the intensity distribution received on the ground or on the satellite.

Adaptive Optics is a well-known technology, mature in the field of astronomy, that corrects for the effects of atmospheric turbulence on light. A "Wavefront Sensor" detects the phase aberrations and a "Deformable Mirror" corrects them. The requirements for AO systems are different in the field of optical communications as they must operate in the harshest of turbulence conditions, observing at low elevation angles from non-optimal sites such as inner-city locations. This can result in so-called "Strong Turbulence" conditions, where some of the assumptions used in astronomical AO break down, and especially wave-front devices no longer operate in the manner that is expected.

In this studentship, alternative wave-front sensing strategies will be explored by optimise the adaptive optics system for free space optical communications. This first requires understanding the effects of strong turbulence on optical propagation. Machine learning techniques, such as Convolutional Neural Networks, may hold the key to sensing the aberrations in strong turbulence conditions as they can "learn" the potentially non-linear wave-front behaviour. Wavefront sensor machine learning models will be created and tested to sense the wavefront, and simulations of such conditions will be performed to compare it versus existing solutions. Once it is understood, there are facilities ot build the device in the lab and test with emulated turbulence.

The student will join the dynamic environment of the Centre for Advanced Instrumentation (CfAI), within the Physics Department at Durham University. The CfAI is a world leading research centre and is a key node in the recently inaugurated Durham Space Research Centre (SpaRC). The student will be part of the SpaRC, and work with other members of the centre in the Physics and Computer Science departments. In addition, a collaboration with the German Aerospace Centre (DLR) is possible to enable testing of a physical device in real satellite communications links.

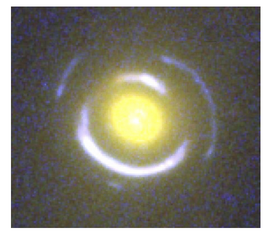
The State-of-the-art DLR Optical Ground Station for Free Space Optical Communications

SCIENCE PROJECT DEVELOPMENT FOR HARMONI ON THE ESO EXTREMELY LARGE TELESCOPE (GRAVITATIONAL LENSING OR STELLAR POPULATIONS)

Main Supervisor:	Dr Russell Smith	russell.smith@durham.ac.uk
Office:	Ogden Centre West 110	
2nd Supervisor:	Dr. Kieran O'Brien	kieran.s.obrien@durham.ac.uk
Funding:	STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)	

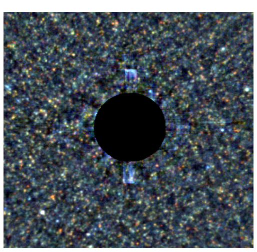
Description:

The advent of 30m-class telescopes will revolutionise optical and infra-red astronomy, with unprecedented light-gathering power at the high angular resolutions afforded by adaptive optics technology. In this project, you will develop and analyse synthetic (i.e. simulated) observations with the HARMONI integral field spectrograph on the 39m ESO Extremely Large Telescope (ELT). Durham is a partner in the international HARMONI consortium, contributing both to the instrument design and construction and to formulating "use cases" which help define the instrument capabilities and operation modes. Your work will help to shape some of the first ELT observations. Depending on your interests, the project will focus on one of the following areas:



The cosmology-sensitive double Einstein ring gravitational lens galaxy J0946+1006.

(1) Strong lensing and dark-matter substructure. Gravitational lensing – the distortion and splitting of a background source image by the presence of a massive galaxy along the line of sight – is a key tool for probing the dark and luminous mass distribution in galaxies, for constraining deviations from general relativity, and for measuring the cosmological structure of the Universe. In this variant of the project, you will develop and analyse synthetic observations of galaxy-scale lenses, optimising strategies for campaigns centred on dark-matter substructure detection (e.g. Nightingale et al. 2022) and cosmological parameter inference (e.g. Collett & Smith 2020). The lensing analysis will be built around the PyAutoLens modelling software developed in Durham (Nightingale et al. 2021).



Partially-resolved star field in galaxy NGC5128 (distance ∼4 Mpc) from MUSE-AO data.

(2) Stellar populations of elliptical galaxies at the resolution frontier. The centres of elliptical galaxies formed stars under conditions not experienced in the Milky Way, and their "total-light" spectra show peculiarities that are hard to reproduce with current stellar population models. At the exquisite angular resolution reached by ELT and HARMONI, the spectrum of each observed "pixel" is subject to discreteness – Poisson variation in the number of giant stars – that can be exploited to probe the stellar content in more detail. With the limitations of current telescopes this method can be applied only to the closest galaxies (see Smith 2022, MNRAS, 509, 5737), but HARMONI promises huge advances. In this version of the project you will generate detailed and realistic simulations to identify optimal observing configurations and analysis methods, to maximize the retrievable information.

Whichever option you choose, you will develop idealised astrophysical "scenes" based on state-of-the-art models, and then use the HARMONI instrument simulation software to create realistic mock datasets, for which the underlying "truth" is known. You will finally apply (and/or build and develop) the tools which will eventually be used to analyse real ELT observations. Science operations with HARMONI are beyond the timeline of the PhD, but there will be opportunities to acquire and analyse pathfinder observations from existing telescopes (e.g. the ESO VLT and the James Webb Space Telescope) to hone your methods.

Notes:

CHARACTERISING AND CORRECTING ATMOSPHERIC TURBULENCE EFFECTS TO ENHANCE GROUND BASED ASTRONOMY

Main Supervisor: Dr Richard Wilson r.w.wilson@durham.ac.uk
Office: Rochester 325
Funding: STFC and other funding schemes (Bell Burnell, DDS, CSC, ...)

Description:

The aim of this studentship is to develop concepts and technology to improve the capabilities of modern astronomical observatories by actively correcting for the detrimental effects of the Earth's atmosphere. The optical effects of atmospheric turbulence, known as 'seeing', are a major limitation for ground–based optical astronomy. Seeing degrades the image resolution that can be achieved with large telescopes and adds noise to photometric measurements.

The student will engage with the development, deployment and exploitation of site testing instrumentation at international observatories, to improve our understanding of the effects of the Earth's atmosphere on astronomical observations. They will explore how these results can be applied to improve the performance of large telescopes, for example through the optimisation of adaptive optics and scintillation correction systems, or the forecasting of optical turbulence conditions at observatory sites. The work will be applicable to the next generation of giant telescopes, such as the 40 metre European Extremely Large Telescope in Chile. It will help them to reach their science goals, including characterising extra-solar planets, understanding the formation of galaxies, and elucidating the nature of dark matter and dark energy.

The student will join the dynamic environment of the Centre for Advanced Instrumentation (CfAI), within the Physics Department at Durham University. The CfAI is a world leading research centre with a large and successful Astronomical Instrumentation group, including Adaptive Optics and Space Science technologies. The Adaptive Optics group has substantial experience in analysing atmospheric turbulence and the use of computer modelling of complex optical systems to design optical instrumentation for some of the world's premier astronomical observatories. The CfAI has also been at the cutting edge of space research for many years, producing key optical components for instruments on the James Webb Space Telescope and Earth observation satellites such as SENTINEL 4 and METimage.

The CfAI 0.5 metre turbulence monitoring telescope at Cerro Paranal, Chile, home of the ESO Very Large Telescope (VLT) and nearby 40 metre European Extremely Large Telescope (ELT). Photo: tim Butterley.

Notes:

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

Supervisor: Prof. David Alexander d.m.alexander@durham.ac.uk
Office: Ogden Centre West 119

Funding (PhD): All non-STFC funding (e.g. DDS, CSC, Bell Burnell, Inlaks...)

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, 2022, 2023; Rosario et al. 2020, 2021; Andonie et al. 2022, 2024). 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.

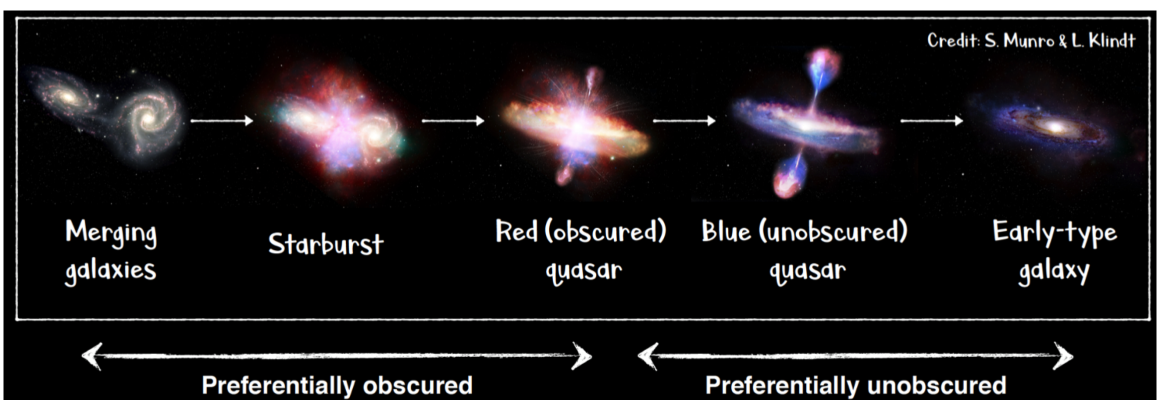


Figure: The leading evolutionary model for quasars. The sequence is triggered by huge amounts of gas inflow (potentially from a merger of two galaxies) which leads to a burst of dust-obscured star formation and a heavily buried (i.e., obscured) quasar. As the quasar ages it drives out energetic winds 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 obscured infrared quasar survey with the 4MOST instrument (Merloni, Alexander et al. 2019), which is due to start its 5-year survey in late 2025, plus our access to the Dark Energy Spectroscopic Instrument (DESI) survey (DESI collaboration et al. 2023; Alexander et al. 2023). Each survey will detect over 1 million quasars, pushing deeper than current surveys and providing an exceptional quasar census. You will undertake systematic analyses using a variety of multi-wavelength datasets to quantify the differences between normal, red, and fully obscured quasars. You will also 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 exploit deep multi-wavelength observations to measure the physical properties of fully obscured quasars to see how they are related to red and normal quasars.

Notes:

FUNDAMENTAL COSMOLOGY WITH LARGE-SCALE STRUCTURE

Main Supervisor: Dr. Sownak Bose sownak.bose@durham.ac.uk
Office: Ogden Centre West 221
Funding (PhD): All non-STFC funding (e.g. DDS, CSC, Bell Burnell, Inlaks...)
Funding (MScR): None defined. Project is adaptable as an MScR project

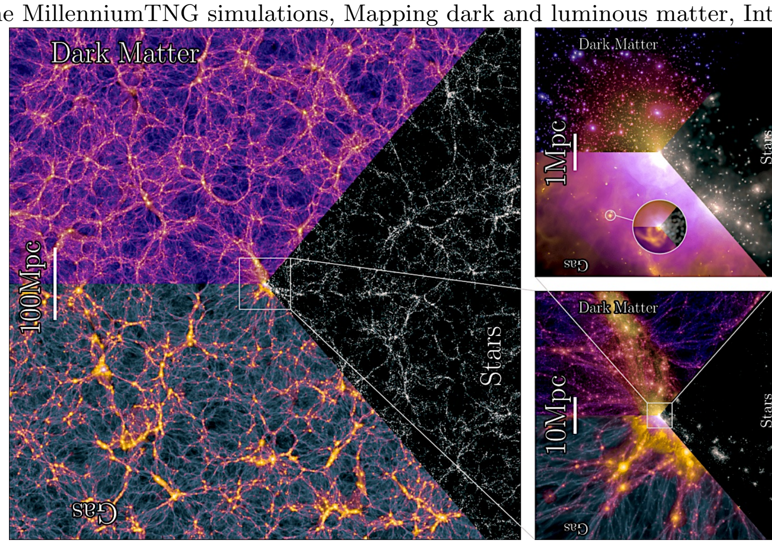
Description:

Cosmology is at the brink of a paradigm-defining decade. Several large-scale surveys of galaxies have been designed for the ultimate goal of answering open questions relating to the makeup and evolution of our cosmos: what is dark matter? Why does the Universe accelerate in its expansion? How do galaxies form? This requires a map of the large-scale structure of the Universe that exceeds far beyond what we have available to us at the moment, both in terms of volume and precision. The astronomy group at Durham is at the forefront of many of these activities, and has key leadership roles in programmes like the Dark Energy Sectroscopic Instrument (DESI) Survey, *Euclid*, the Square Kilometre Array (SKA) etc. To realise the full potential of these surveys, we need equally sophisticated, state-of-the-art cosmological simulations to act as the theoretical counterparts. This latter effort will be the focus of this PhD project. You will have the option of choosing from a number of potential avenues of investigation, including:

- Using state-of-the-art simulations of galaxy formation to understand the mapping between dark and luminous matter on cosmological scales;
- Performing radiation-hydrodynamics simulations to study the onset of the formation of the first stars and galaxies using intensity mapping;
- Development of semi-analytic methods and Machine Learning to create models based on more computationally expensive supercomputer simulations.

You will have the opportunity to work at the cutting edge of one of the most exciting fields of astrophysics and cosmology. This project is predominantly theoretical in nature, but making contact with observations will be a crucial objective. Working with other members of the group, as well as our international collaborators will, therefore, be encouraged. Experience in coding (Python, Julia, C/C++) and interest in programming generally is highly beneficial. You will also receive mentorship in research communication, both in conferences and in scientific publications.

References:
The MillenniumTNG simulations, Mapping dark and luminous matter, Intensity mapping as a probe of cosmology



The large-scale structure of the universe as predicted by the MillenniumTNG simulation. **Left panel***: projections of the dark matter (top), gas (bottom), and stars (right), distributed across more than 700 Mpc on a side. The* **bottom right** *and* **top right** *panels, respectively, show regions zoomed in successively by factors of 10 centred on a massive cluster in the simulation box, displaying the extraordinary dynamic range enabled by these simulations. Figure adapted from Pakmor et al. 2023.*

Notes:

HOW ARE THE NUCLEAR REGIONS OF SPIRAL GALAXIES BUILT UP?

Main Supervisor:	Dr. Francesca Fragkoudi	francesca.fragkoudi@durham.ac.uk
Office:	OCW127	
Funding (PhD):	All non-STFC funding (e.g. DDS, CSC, Bell Burnell, Inlaks...)	
Funding (MScR):	None defined. Project is adaptable as an MScR project	

Description:

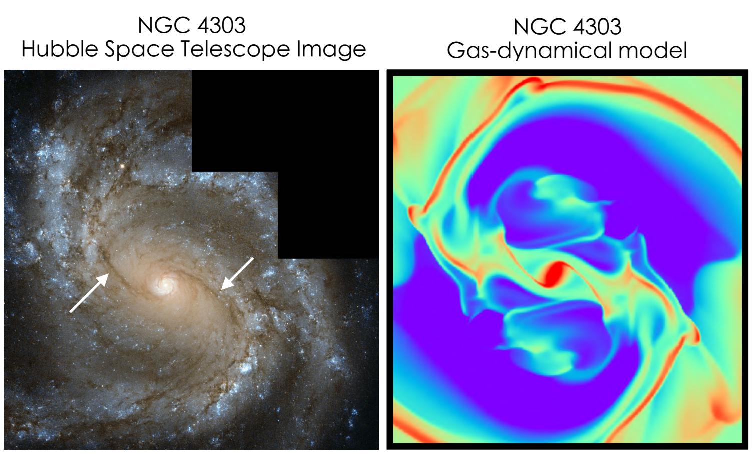
Galaxies build up structures in their central regions through various processes. In this project we will explore one of these processes, in particular how gas funnels through stellar bars towards the central regions of spiral galaxies, and what its ultimate fate is.

Bars in spiral galaxies cause gas to shock, lose angular momentum, and subsequently funnel towards the centre of the galaxy. When gas reaches the central regions it accumulates, becomes very dense and starts forming stars, which give rise to structures called nuclear discs and nuclear rings. Some of the gas which reaches these inner regions is also thought to be able to stream further into the galaxy and reach the supermassive black hole sitting at its centre. How central structures — such as nuclear discs and rings — are built up by the gas flow, how they affect the subsequent gas inflow to the SMBH, and what the properties of stars in these regions are, is being explored with powerful instruments like MUSE on the VLT. To interpret this observational work we will use state-of-the-art numerical models of galaxies to understand the physical processes taking place. Some of the questions we will tackle are:

- How does gas flowing to the central regions of barred galaxies build up nuclear discs and rings?
- What are the properties of these structures and how do they compare to observed structures in galaxies?
- How much of the gas is able to reach deep into the centre of the galaxy to where the Supermassive Black Hole resides? How does feedback from the SMBH affect the gas inflow?

According to the student's interests they would be able to compare these simulations to observational data of spiral galaxies taken with the MUSE instrument on the VLT or work on developing new simulations to model gas accretion and feedback from SMBH.

This project can be either a Masters by Research project (by focusing on one of the above questions) or a PhD project. Meet the team: https://www.francescafragkoudi.com



Left: The barred spiral galaxy NGC4303 as seen by the Hubble Space Telescope. Right: Gas density in a simulation of a barred galaxy like NGC4303. We can see how the gas density responds to the underlying potential and that this leads to higher densities of gas in the inner regions thus building up nuclear structures.

Notes:

ACCURATE MAPPING OF DARK MATTER DISTRIBUTION IN GALAXY CLUSTERS

Main Supervisor: Professor Mathilde Jauzac mathilde.jauzac@durham.ac.uk
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2nd Supervisor: Dr Anna Niemiec anna.niemiec@durham.ac.uk

Funding (PhD): All non-STFC funding (e.g. DDS, CSC, Bell Burnell, Inlaks...)
Funding (MScR): None defined. Project is adaptable as an MScR project

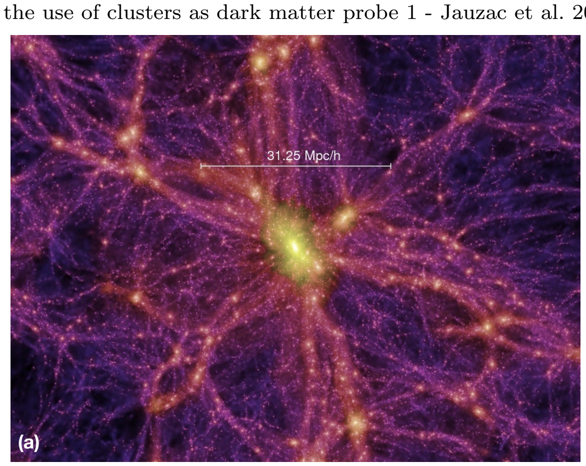
Description:

While easy to detect thanks to their different observational tracers (galaxies, X-ray gas), galaxy clusters are an important probe of the formation history of the Universe. Indeed, as the most massive gravitationally bound objects, they represent the latest stage to date of the hierarchical structure formation, and reside at the nodes of the cosmic web that fuels their growth. Adding to that, clusters are excellent laboratories for probing the physical mechanisms underlying the evolution of the Universe, and they are in particular a privileged location to study the nature of dark matter.

However, in order to use clusters as probes of these different processes, it is first essential to detect the different (sub)structures they are made of, and measure the distribution of matter within them. For the baryonic component of clusters (i.e gas and stars), this is done by combining multi-wavelength observations, from optical imaging tracing galaxy populations, to the hot gas emitting in the X-rays or interacting with the Cosmic Microwave Background (CMB) through the Sunyaev-Zeldovich (SZ) effect. The dark matter component is more elusive, and can for now only be detected indirectly. One way to do so, and a particularly powerful one, is gravitational lensing, that allows to probe a gravitational potential from the bending of passing light rays.

Our team is at the forefront of the study of galaxy clusters using gravitational lensing techniques (Jauzac et al. 2016, 2018). We have developed a new method to model galaxy clusters at all scales, using both strong and weak gravitational lensing constraints, and applied this new technique on very simple simulated clusters (Niemiec et al. 2020). We recently performed a first attempt at using it on real observational data (Niemiec et al. 2023) using very high quality observational data from the *Hubble Space Telescope* (*HST*) BUFFALO programme (Steinhardt et al. 2020). However, it is now important to perform detailed analyses on the different possible systematic errors that could affect these measurements. The goal of the proposed project is to use mock clusters to precisely calibrate our modeling methods. Through this project, the student will have the opportunity to deepen their understanding of the physics of gravitational lensing and galaxy clusters, as well as develop their coding skills. While initially designed for a MSc project, the analysis proposed can easily be broadened for a PhD.

Paper on the analysis of Abell 370 cluster - Niemiec et al. 2023
Paper on the new modeling method - Niemiec et al. 2020
Paper on the HST BUFFALO programme - Steinhardt et al. 2020
Paper on the use of clusters as dark matter probe 2 - Jauzac et al. 2018
Paper on the use of clusters as dark matter probe 1 - Jauzac et al. 2016



(a) *Giant galaxy cluster located at a node of the cosmic web, taken from the Millenium numerical simulation.* ***(b)*** *HST image of the cluster Abell 370. Strong gravitational lensing is visible in the form of giant elongated arcs.*

Notes:

NUMERICAL RELATIVITY IN THE REALM OF NEW PHYSICS

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Funding:	CSC, DDS, Bell Burnell, or other	

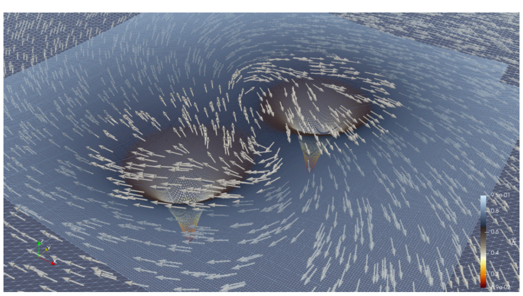
Description:

Numerical Relativity is the holy grail of computational physics. Yet, it took nearly a century after Einstein published General Relativity (GR) that long-term stable simulations of black holes became possible due to the highly nonlinear nature of the gravitational field equations. Since then, there have been huge progresses in this field, and interest has grown much stronger after the first gravitational wave (GW) detection less than a decade ago. Already, such detections have been used to shed light on the mysterious accelerated expansion of our Universe, ruling classes of gravity theories beyond GR.

With the advent of a new generation of GW detectors, in the coming decades GW cosmology will evolve into a mature subject in astronomy. The data collected will allow people to test new theories of fundamental physics with unprecedented exquisiteness. However, even today, simulating the evolution of compact object systems such as black holes and neutron stars in various theories of gravity is still a big challenge.

In this project, the candidate will work on the scientific developments and applications of a new numerical relativity simulation code, ExaGRyPE, developed by a collaboration between the Physics and Computer Science departments at Durham University. There are a range of potential directions this project can lead to, including, but not restricted to, (i) the implementation and test of new physics models in the code (e.g. non-standard gravity), (ii) developing hydrodynamics modules that will enable simulations of complicated coupled multi-physics systems, or (iii) a reformulation of the underlying physical model in a higher-dimensional brane world—a simulation unfeasible with other codes in the field.

Reference: ExaGRyPE code paper



An ExaGRyPE simulation snapshot of two black holes in the process of merging. The colour map and the arrows show respectively two components (potential and shift vector) of the metric tensor, which describe the spacetime. Candidates will have the opportunity to collaborate with a larger group of code developers, and to acquire research software engineering skills. There is also the opportunity to use and learn high-performance computing skills such as GPU programming.

Notes:

FEEDBACK AT LOW METALLICITIES

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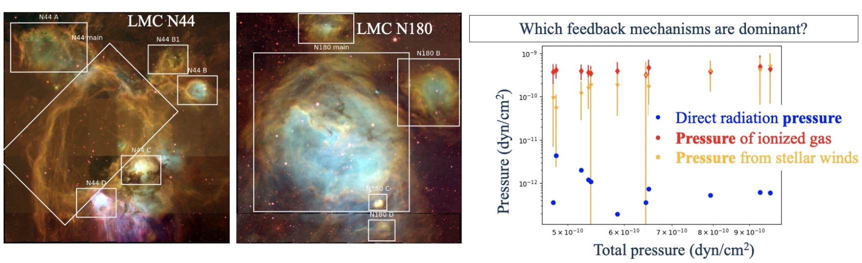
Funding (PhD): All non-STFC funding (e.g. DDS, CSC, Bell Burnell, Inlaks...)

Description:

Throughout their short lives, massive stars (¿ 8 solar masses) have a deep impact on their surroundings via e.g. strong stellar winds, ionizing 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 depend not only on the exact type and number of massive stars 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, and the amount of metals in the interstellar medium. Understanding how the environmental properties influence the effects of feedback from massive stars is crucial to our understanding of star formation and galaxy evolution. In project you will first analyse data of massive star-forming regions in the low-metallicity Magellanic Clouds taken with the highly competitive MUSE instrument on the Very Large Telescope. With this data you will characterize the properties of the stars residing in the regions. Then, using a combination of data sets ranging from the X-rays to the infrared and millimeter regime, you will analyse the gas in these regions to quantify stellar feedback in these low-metallicity environments such as the Magellanic Clouds, directly relating the feedback-driving stars to the feedback-driven gas. In the second part of this project you will extend your studies to other nearby dwarf galaxies. The results from this work will serve as important empirical benchmarks for state-of-the-art numerical simulations of star cluster formation and galaxy evolution. You will get the opportunity to write proposals to obtain new observations, and closely collaborate with leading experts in the field at world-class institutes like the Space Telescope Science Institute in Baltimore.

More about this topic:
Feedback from massive stars at low metallicities: MUSE observations of N44 and N180 in the Large Magellanic Cloud
The Young Massive Star Cluster Westerlund 2 Observed with MUSE. I. Cluster Internal Motion from Stellar Radial Velocities
Magellanic Cloud
The Young Massive Star Cluster Westerlund 2 Observed with MUSE. III. A Cluster in Motion—The Complex Internal Dynamics



Upper left. *The galactic lifecycle: 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, bright pink traces regions in which massive stars have formed (credit: ESO). The white region corresponds to the footprint of the MUSE image.* **Right.** *MUSE integral field mosaic of the central part of NGC 300 tracing regions in which gas is being ionized by star-formation and supernova events. This data is the central focus of this PhD project.*

Notes:

SHOCKS, SHOCKS EVERYWHERE! OR, THE INTERSTELLAR MEDIUM IN 3D

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Funding (PhD): All non-STFC funding (e.g. DDS, CSC, Bell Burnell, Inlaks...)

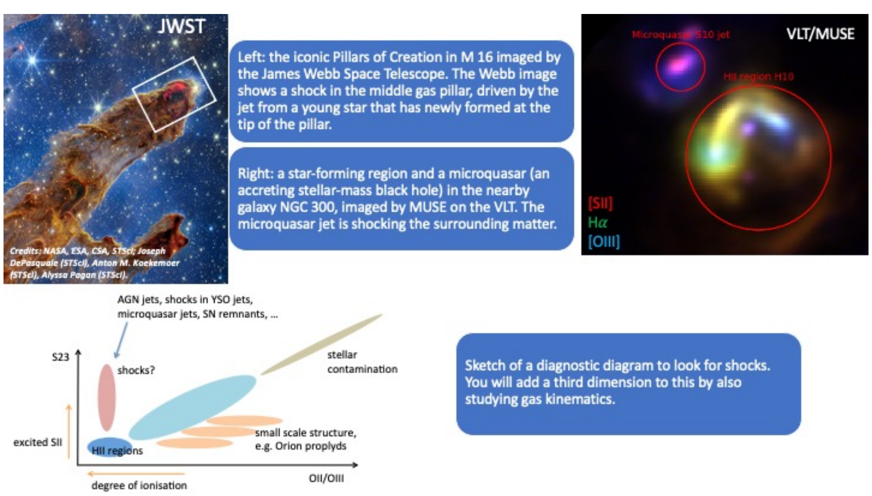
Description:

Shocks are a ubiquitous phenomenon observed in the Universe, occurring whenever gas is overrun and compressed by supersonic motions, such as supernovae shells, jets from accreting objects propagating through the interstellar medium (ISM), or collisions between molecular clouds, to name a few. Tracing shocks yields a crucial indicator of the structure and composition of the interstellar medium, needed to interpret observations and used as inputs for state-of-the-art simulations. In the optical wavelength regime, shocks are observed as low-energy level emission lines of the ionised gas, and pairs of emission line ratios have been used for decades (e.g. with so-called BPT diagrams) to distinguish between regions dominated by star formation and regions dominated by shocks or powerful active galactic nuclei (AGN). However, these kinds of diagnostics cannot distinguish between emission arising from shocks and emission arising from other non-stellar (e.g. AGN) activity. Moreover, the interpretation of BPT diagrams becomes highly non-trivial when applied to spatially-resolved observations, and optical observations alone do not capture the multi-phase nature of the ISM.

This project aims at using integral field spectroscopy data taken with the Very Large Telescope of a variety of different, spatially-resolved, astrophysical objects to develop a novel method to identify shocks. This method is new and unique, as it combines sets of emission line ratios together with emission line widths as a third dimension to trace shocks and distinguish them from photoionisation excitation, perfectly exploiting the spectro-photometric capability of spatially-resolved integral field data. The observations will then be compared to outputs from a series of shock and photoionisation models, therefore providing a valuable tool to interpret the observations as well as test different models.

The developed methodology will then be deployed to novel multi-wavelength observations of the ISM, tracing shocks and photoionisation from the optical to the infrared in the Milky Way out to nearby galaxies using world-class facilities such as the Very Large Telescope, Keck, and James Webb. In this project you will learn to work at the forefront of both observations and modeling, you will write observing proposals to gather new data, and collaborate with an international team of experts in the field.

More about this topic: Interstellar Shock Waves
A new diagnostic to separate line emission from star formation, shocks, and AGNs simultaneously in IFU data
Classification parameters for the emission-line spectra of extragalactic objects
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



Notes: