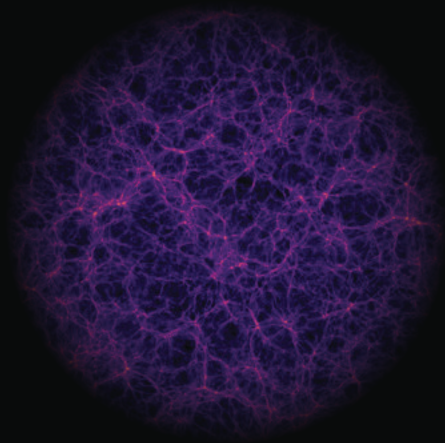
Astronomy PhD & MScR Projects at Durham

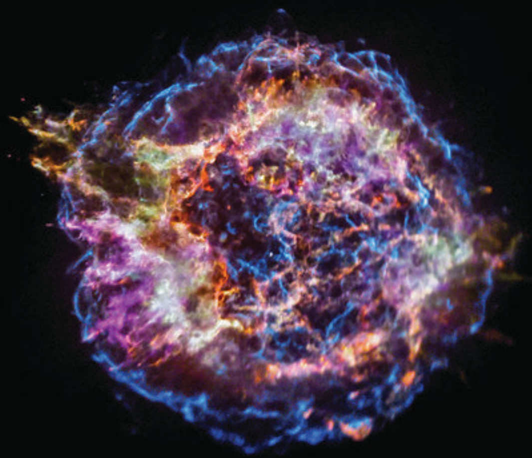
2022

ICC



Durham University

Durham Centre for Extragalactic Astronomy



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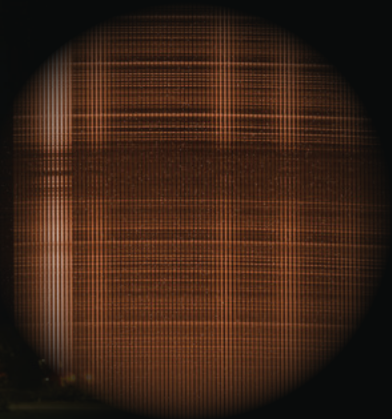


PHD & MSCR PROJECTS IN ASTRONOMY
FOR AUTUMN 2022 START

Introduction

List of STFC/Durham fundable PhD Projects

Bose: Dwarf Galaxies: the ultimate frontier for cosmology in the next decade

Bower: - Simulating the Universe and its Galaxy Population
- Simulating the Universe with GPGPU accelerators

Fattahi: Cosmology in our backyard: what do Milky-Way and dwarf galaxies tell us about DM?

Fragkoudi: Galactic archaeology at the heart of the Milky-Way: digging for ancient merger relics

Gadotti: How to prevent the formation of bars in massive disc galaxies

Lacey: Simulating the effects of AGN feedback on galaxy formation

Li: Cosmological tests of gravity in the era of survey cosmology

Osborne: Exploiting new technology to enhance ground-based astronomy

Swinbank: Galaxy Evolution over the last 10 billion years

Theuns: Searching for neutrinos in the forest

List of additional PhD 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: The extreme universe with CTA and SWGO

Mcleod: - Synthetic observations of star formation and galaxy evolution simulations
- Resolved stellar populations in nearby dwarf starburst galaxies

Scaringi: Exploiting the Gaia/TESS synergy: using machine learning to build a novel discovery tool

List of MScR Projects

Fragkoudi: How well can we disentangle the Dark Matter distribution in spiral galaxies?

Gadotti: Structural decomposition of nearby and distant galaxies

Landt-Wilman: - Machine Learning Algorithms for Time-domain Astronomy
- Infrared Dust Reverberation from Space

Smith: Spectroscopy of stellar populations in the Poisson-fluctuation regime

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 2022.

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 projects 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 up to 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.

Durham funded PhD studentship. This 4-year PhD studentship is open to UK students and/or students with settled status only. We offer 1 Durham funded PhD studentship this year.

Dell funded PhD studentship. This 4-year (TBC) PhD studentship is open to UK students and/or students with settled status only. We offer 1 Dell funded PhD studentship this year, where financial contribution to the studentship comes from Dirac and Durham University as well.

Science and Technology Facilities Council Center for Doctoral Training (STFC CDT) studentships. These 4-year PhD studentships have in general a similar eligibility criteria to standard STFC studentships. Over the past 4 years, we have been able to offer between 3 and 8 STFC CDT studentships per year in astronomy. We hope we will be able to offer such studentships again, subject to a CDT grant award (outcome known in February/March 2022). The CDT studentship includes a 6 months internship with one of the CDT partners of the Durham Data Intensive Science CDT.

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 typically at the end of December / start of January, for an autumn 2022 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 **early/mid December 2021** 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 (date TBD). Hence we recommend applicants interested to be considered for the *Bell Burnell Graduate Scholarship Fund* to submit their application by **early/mid December 2021** 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 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 webpages https://www.gov.uk/postgraduate-loan.

Arthur Browne Bursary 2022. The Bursary awards are based on academic merit and will be selected on a competitive basis, with one award per year expected. The University has directed that the funds (£6,000 for the academic year 2021/22) are to be used towards fees and/or towards other course or living expenses (including research-based travel). Deadline for applications for the 2022 round will be announced in September 2022, with all eligible MScR students in Physics invited to submit a one page application for the Bursary.

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

DWARF GALAXIES: THE ULTIMATE FRONTIER FOR COSMOLOGY IN THE NEXT DECADE

Main Supervisor: Dr. Sownak Bose sownak.bose@durham.ac.uk
Office: Ogden Centre West 221
2nd Supervisor: Dr. Azi Fattahi or Prof. Adrian Jenkins

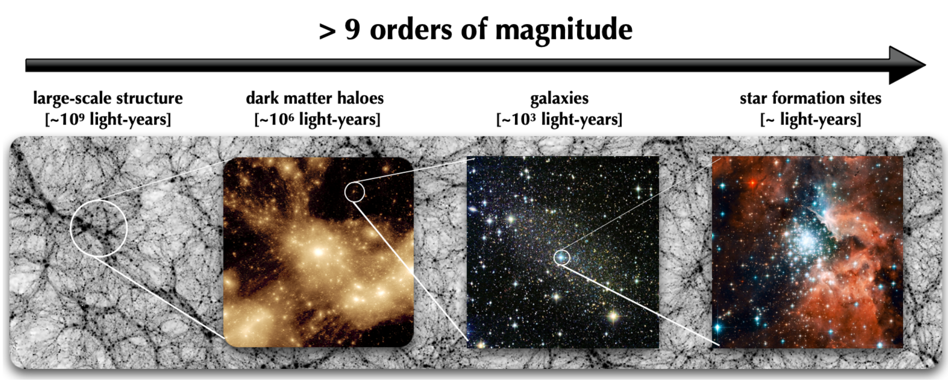
Funding: Durham Funding and other funding schemes (DDS, CSC, ...)

Description:

The faintest galaxies in our Universe–so-called "ultra-faint" dwarf galaxies (UFDs)–are the ghostly relics of early galaxy formation. Despite recent progress in discovering significant numbers of these UFDs, there is still much unknown about their stellar populations, assembly and role in the build-up of the overall galaxy population. A detailed understanding of the UFDs addresses fundamental, outstanding questions in cosmology: their present-day properties encode the details of galaxy formation at the very earliest epochs of the cosmos, the time evolution of ambient radiation fields, and the nature of the dark matter (DM) itself. *In this project, we will develop state-of-the-art models for the formation and evolution of dwarf galaxies* that will enable new predictions for these entities as observed by next generation surveys. To achieve these goals, we will employ a combination of supercomputer simulations of structure formation under different assumptions for the theory of DM, and combine these with semi-analytic and numerical models of galaxy formation. Equipped with these tools, we will be able to answer questions like:

- How do the first billion years of cosmic evolution shape the properties of the galaxy populations we observe today?
- Can we use galactic archaeology to "read-off" the formation history of dwarfs from their stellar populations?
- What do dwarf galaxies in the present-day Universe tell us about the identity of the dark matter?
- And how does the tumultuous history of our own Galaxy influence the ultimate fate of dwarf galaxies once they plunge into the Milky Way's gravitational field?

With this project, you will have the opportunity to work at the cutting edge of one of the most exciting fields of astrophysics and cosmology. You will gain experience in developing and executing codes for analysing data sets on high-performance computing machines. This project is predominantly theoretical in nature, but making contact with observations will be a crucial objective. Collaboration with other members of the ICC and the CEA will be therefore be encouraged. There will also be extensive opportunities for you to steer this project in the research directions that interest you most. While prior coding experience (in e.g. Python) would certainly be beneficial, it is not a requirement. During your studentship, you will also receive mentorship in research communication, both in conferences and in scientific publications.
Some useful reading: A review on UFDs
Modelling the evolution of the Milky Way efficiently
How the early phase of galaxy formation affects the distribution of dwarf galaxies today



The multi-scale arrangement of structure in the universe. Dark matter (shown in greyscale) is spread across several billions of light-years; this distribution has been predicted using supercomputer simulations performed at Durham. Dwarf galaxies are typically formed on scales 10^6 smaller than this. In this project, you will develop methods that allow us to connect the formation of dwarf galaxies with the evolution of the cosmos on much larger scales. Image credit—"galaxies" inset: Ursa Minor, by Giuseppe Donatiello (CC0); "star formation" inset: NGC 3603 by NASA, ESA and the Hubble Heritage (STScI/AURA)-ESA/Hubble.

Notes:

SIMULATING THE UNIVERSE AND ITS GALAXY POPULATION

Main Supervisor: Prof. Richard Bower r.g.bower@durham.ac.uk
Office: Ogden Centre West 214
Funding: STFC and all other funding schemes (DDS, CSC, ...)

Description:

The aim of this project is to some of the worlds largest computers to create a virtual universe. Essentially, we will teach the computer the law of physics, describe how star and black holes form and then track the Universe that emerges from the big-bang to the present day. Such calculations are key to understanding the universe that we observe. Our previous work has shown this approach works: by adopting the 'concordance' Lambda-CDM cosmology, and reasonable laws for star formation and black holes, the EAGLE project was able to broadly recreate the universe that we observe with telescopes. The match is not, however, perfect and the resolution of these earlier simulation significantly limited the physical processes that could be modelled and fidelity of the virtual universe. Advances in computing power, and the algorithms we use to programme them, mean that we can step forward. The step up in simulation capability matches advances in telescope technologies. With this project, you will have the opportunity to develop the next generation of simulations and to address some of the most fundamental questions in cosmology.

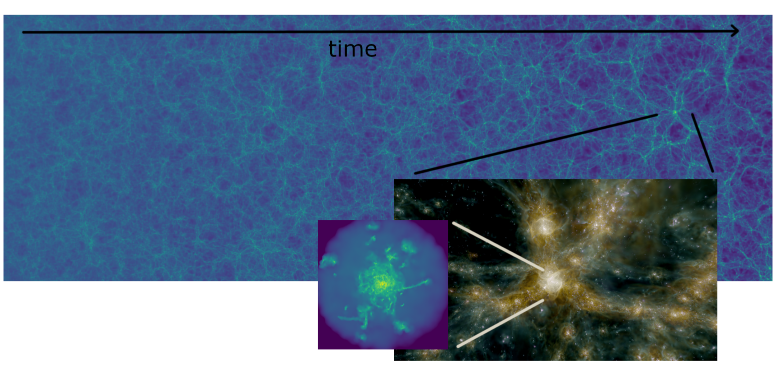
- How do galaxies form and evolve? A particular focus of my research is to better understand the key role played by black holes. It seems that these exotic objects at the centres of galaxies are responsible for the demise of star formation leading to the evolution of galaxies across the Hubble sequence from actively forming spirals to passive ellipticals.

- What will the next generation of astrophysical observatories discover? A key role for the simulations that you will undertake is to predict the properties of galaxies that will be observed with the next generation of telescopes. This includes JWST (the next-generation space telescope observing early galaxies in the infra-red); Euclid (a space based survey of the whole sky mapping the properties of galaxies and their correlations) in unprecedented detail; and the SKA (a radio telescope that will survey the radio emission from galaxies to unprecedented depths).

- How do galaxies trace the structure of the Universe? As well as their own intrinsic interest, galaxies provide our primary means to study the growth of the structure of the universe and thus to test competing models for dark matter and dark energy. But are galaxies completely faithful tracers of this structure? That is a critical question that is open to debate.

During this project you will learn key computing skills, ranging for the development of new code modules to the analysis of complex and large datasets. You will gain hands-on experience of using large high-performance computing systems. Significant flexibility exists within the project, and you will be able to chose between code development and data analysis, or the interpretation of data from real-world telescopes depending on your primary interest.

Schaye et al., 2015: The EAGLE project: Simulating the evolution and assembly of galaxies and their environments Bower et al., 2017: The dark nemesis of galaxy formation: why hot haloes trigger black hole growth and bring star formation to an end Somerville & Dave, 2015: Physical Models of Galaxy Formation in a Cosmological Framework



An example simulation, showing how the web-like structure of the universe emerges from small fluctuations generated in the Big Bang. The background images shows time flowing from left to right as the structure of the universe becomes more complex. The complex hydrodynamic processes leading to the formation of galaxies at the intersections of the web are illustrated in the blow out images. These illustrate the extreme range of scales that must must simulated in this grand-challenge problem, and the level of detail in which the formation of galaxies can be understood.

Notes:

SIMULATING THE UNIVERSE WITH GPGPU ACCELERATORS

Main Supervisor: Prof. Richard Bower r.g.bower@durham.ac.uk
Office: Ogden Centre West 214
2nd Supervisor: Dr Alastair Basden a.g.basden@durham.ac.uk

Funding: Dell, Dirac and Durham University

Description:

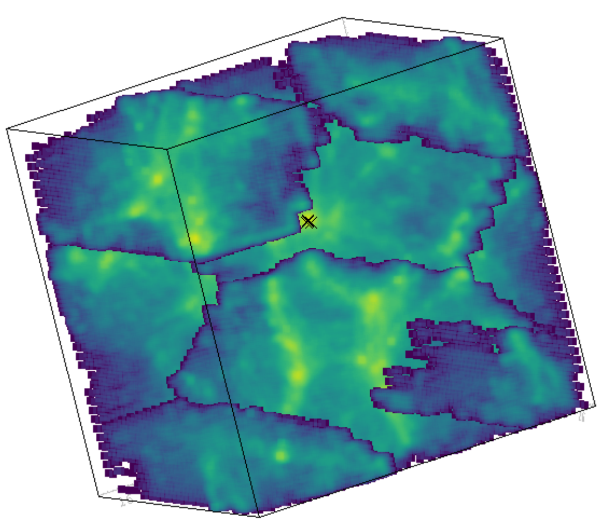
We are recruiting a PhD student for an exciting project to work on applying GPU accelerators to cosmological simulations. applying GPU accelerators to cosmological simulations.

The Institute of Computational Cosmology specialises in simulating the cosmos. Starting from the Big Bang, we use some of the world's largest super computers to evolve the universe using the laws of physics as they are currently understood. Our simulations include the formation of stars and galaxies so the the "virtual universe' that we create can be directly compared to astronomical images seen through the world's most advance telescopes. Over the next few years, our aim is to increase the volume and fidelity of the simulations which will demands large increases in the effectiveness with which we can exploit the latest computing hardware. The focus of this PhD is on GPGPU (General Purpose Graphics Processing Units) in particular.

GPGPU differ from conventional CPU processors in the number of floating point operations that they can simultaneously calculate. The catch, however, is that the GPGPU operates most effectively when all the operations are identical. This is often termed a SIMD (single instruction multiple data) operation. As computers become larger, it has become ever more pressing to be able to efficiently exploit this type of operation in order to minimise the systems energy foot-print. The next generation of super-computers, the Exascale era, will inevitably draw on GPGPUs to provide the bulk of the processing power.

This PhD is part-funded by Dell and will focus on exploiting the next generation Radeon GPU from AMD in order to execute large cosmological simulations. The student will have access to the latest hardware developments and will work with AMD and Dell to achieve the project goals. An exciting aspect of the project is that the candidate will have the opportunity to work with world-leading experts from both cosmology and applied computer science using the latest computing hardware.

Useful references: Schaye et al., 2015: The EAGLE project: Simulating the evolution and assembly of galaxies and their environments Bower et al., 2017: The dark nemesis of galaxy formation: why hot haloes trigger black hole growth and bring star formation to an end Somerville & Dave, 2015: Physical Models of Galaxy Formation in a Cosmological Framework AMD's



An example of how SWIFT's code divides up the cosmosso that it can be evolved simulataneously on a multi-GPU system. The complex shapes of the domains minimise the communication between accelerators, and balance the work load evenly.

Notes:

COSMOLOGY IN OUR BACKYARD: WHAT DO MILKY WAY AND DWARF GALAXIES TELL US ABOUT DARK MATTER?

Main Supervisor:	Dr. Azi Fattahi	azadeh.fattahi-savadjani@durham.ac.uk
Office:	Ogden Centre West 224	
2nd Supervisor:	TBC (potential: Dr. A. Deason, Dr. S. Bose)	
Funding:	STFC and all other funding schemes (DDS, CSC, ...)	

Description:

The over-arching theme of this studentship is understanding the behaviour of dark matter inside and around galaxies, and its connection to galaxy formation and evolution, using cosmological supercomputer simulations. The focus is mainly on the Milky Way halo and/or faint dwarf galaxies around it.

According to the standard model of cosmology (ΛCDM), 80 percent of the gravitating matter in the Universe is in the form of mysterious dark matter, and galaxies are formed in the centre of much larger dark matter halos. We therefor learn about properties of dark matter by studying the interplay between galaxies and their host dark matter halos. Milky Way and dwarf galaxies provide a unique window in these studies for a number of reasons: (i) they are nearby and therefor we can measure their properties in great detail, (ii) the faintest known galaxies are all nearby, around the Milky Way; (iii) dwarf galaxies contain up to 1000 times more dark matter than stars. Therefore they have been on the for-front of dark matter research. Cosmological supercomputer simulations, which follow the evolution of the Universe and the formation of galaxies, are our essential tools in this field. During your PhD you will be involved in developing and analysing state-of-the-art cosmological simulations. The project is flexible and you can choose to focus your studies on one or a combination of the following broad areas:

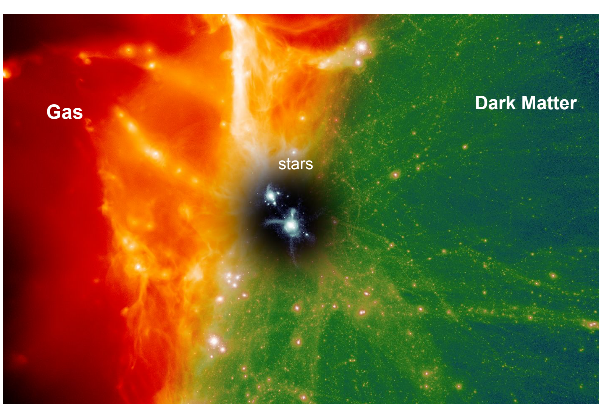
(a) *the relation between dwarf galaxies and dark matter halos, and the threshold for galaxy formation.* In the 'Cold Dark Matter' scenario, the universe is filled with lots of very small dark matter halos (see the figure below) but not all of them are hosting galaxies. You will investigate what determines which dark matter halo is hosting a galaxies, what the relation between dark matter and stellar mass and how the faintest galaxies form.

(b) *Satellite population of dwarf galaxies.* Structure formation in ΛCDM happens hierarchically. This means brighter dwarf galaxies, such as the 'Large Megellanic Cloud', are expected to have very faint dwarf galaxies as their satellites. The high resolution simulations you will use allow resolving this tiny dwarf galaxies and study their properties.

(c) *The formation of Milky Way halo from disruption of dwarf galaxies.* Another consequence of the hierarchical structure formation in ΛCDM is that a large number of dwarf galaxies are expected to have been accreted to the Milky Way and form a diffuse (stellar) halo around it once they are disrupted. We use the simulations to follow the disruption of dwarf galaxies and study the formation of the stellar halos.

This PhD program is primarily based on numerical simulations, being familiar with programming is a plus, but you can also learn and improve along the way. The project is flexible and you may choose to work on more theoretical aspects, or with a closer connection to observations.

Sawala et al. 2016 Fattahi et al. 2020 Pardy et al. 2020



An example of a simulation you may develop or analyse during your PhD. The figures shows the distribution of dark matter (right-hand side), gas (left-hand side) and stars (middle) in a region resembling the Local Group of galaxies. APOSTLE simulation project (Fattahi et al. 2016, Sawala et al. 2016).

Notes:

GALACTIC ARCHAEOLOGY AT THE HEART OF THE MILKY WAY: DIGGING FOR ANCIENT MERGER RELICS

Main Supervisor: Dr. Francesca Fragkoudi francesca.fragkoudi@eso.org
Office: Ogden Centre West (in Durham from April 2022)
Funding: STFC and all other funding schemes (DDS, CSC, ...)

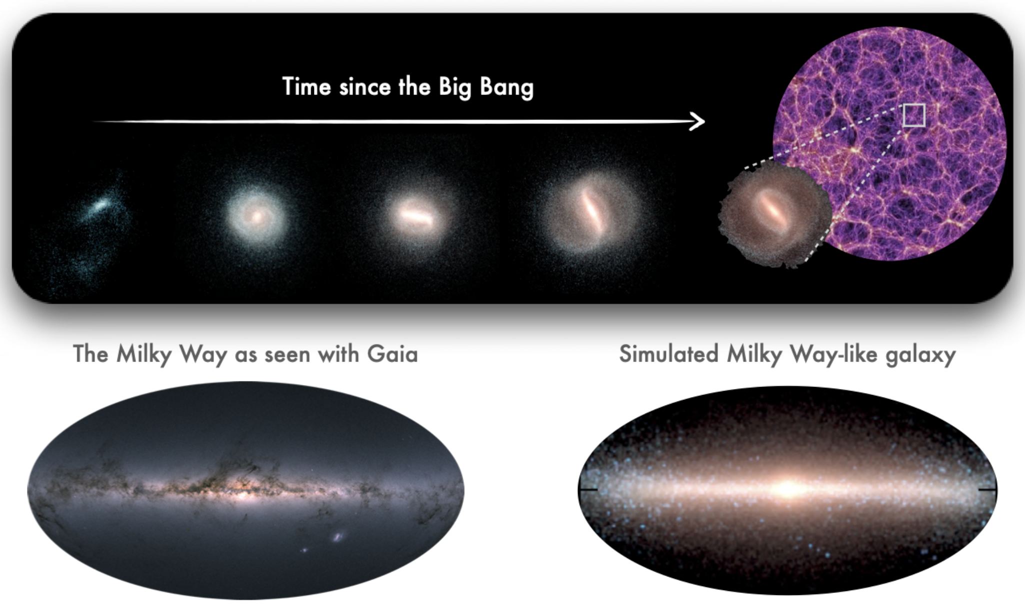
Description:

Our home galaxy, the Milky Way (MW), is a massive spiral galaxy, which we are able to study in unparalleled detail, on a star-by-star basis. This makes it an ideal test-case for our current theories of galaxy formation and evolution. While the MW has had a relatively quiescent merger history over the last 9 billion years or so, many open questions remain about its early assembly. In order to reconstruct the full formation history of the Galaxy, we need to explore its innermost regions – which are the first to assemble – to uncover the relics of its most ancient accretion events. There are a number of ongoing and planned surveys over the next few years (e.g. Gaia, 4MOST, MOONS, SDSS-V MWM) that will provide an unprecedented view of the inner MW. To interpret these data, and in particular, the chemo-dynamical properties of the most metal-poor and ancient stars in the bulge, we need sophisticated models that trace the formation of MW-like galaxies in the full cosmological context. For this we will use the newly developed Auriga Superstars simulations, a suite of high resolution, magneto-hydrodynamical cosmological zoom-in simulations of MW-mass galaxies, to answer questions such as:

- What do the chemo-dynamical properties of the most metal-poor stars reveal about the MW's early assembly history?
- How can we identify substructures, i.e. the building blocks of our Galaxy, in this complex region where dynamical timescales are short and multiple components overlap?
- Can we disentangle different components, such as the disc, bulge and halo, in the innermost regions, and is there a smooth transition between them?

The student involved in this project will be a member of the Auriga Superstars collaboration, will have the opportunity to run their own cosmological simulations, and to compare these models to current and upcoming observational data.

Review on the Milky Way
Chemo-dynamics in cosmological simulations: On the Milky Way's quiescent merger history



Using cosmological simulations we can track the formation and evolution of MW-like galaxies through cosmic history. We can then use these models to interpret the chemo-dynamical properties of stellar populations in the centre of our galaxy.

Notes:

HOW TO PREVENT THE FORMATION OF BARS IN MASSIVE DISC GALAXIES

Main Supervisor: Dr. Dimitri Gadotti dgadotti@eso.org
Office: Ogden Centre West (in Durham from April 2022)
Funding: STFC and all other funding schemes (DDS, CSC, ...)

Description:

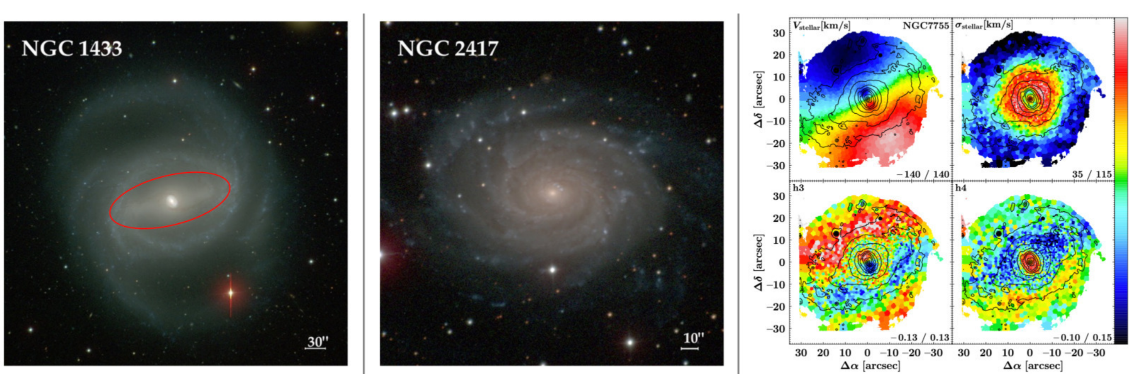
The formation and evolution of disc galaxies is thought to consist essentially of two main phases. After the initial turbulent phase, when violent mergers with other galaxies play a major role, the disc of stars and gas settles in a more uniform configuration. After the disc settling, internal dynamical processes often lead to the formation of a bar in the disc, i.e., a significant number of stars begin to move in more eccentric orbits, forming the elongated bar that is shown in the figure below (left panel). A number of theoretical studies shows that bars can form very easily in a stellar disc, either spontaneously or during interactions with other galaxies. Yet, about 30% of disc galaxies in the local Universe do not host a bar (see figure below, middle panel) and this fraction was larger when the Universe was younger. We still do not fully understand why some disc galaxies remain unbarred and the main goal of this PhD project is to answer this question. Important clues may reside in how stars move in the discs of unbarred galaxies. This therefore calls for a study of the kinematics of stars and the ultimate origin of the gravitational forces that govern their movement.

However, the scientific outcome of this project is not limited to our main question. Since dark matter haloes can also interfere with the formation of bars, the results of this investigation will shed light on the properties of dark matter in the Universe. In addition, we will investigate the properties of stellar populations at the ends of the bar with unprecedented physical spatial resolution, allowing us to study the formation of stellar structures such as spiral arms and galactic rings as never done before.

You will work with archival, state-of-the-art data from the integral-field spectrograph MUSE at the Very Large Telescope in Chile. You will learn how to perform a suite of analyses to explore the kinematics, ages and chemical content of stars in a sample of tens of barred and unbarred galaxies in the local Universe (e.g., Gadotti et al. 2020; Bittner et al. 2020; see figure below, right panel).

Working within an international team of researchers, you will gain experience with large data sets, parallel computing and spectral fitting techniques. Furthermore, you will have the opportunity to participate in (or lead) the writing of proposals for telescope time. If a proposal is successful, you may participate actively in the observations at the telescope in Chile.

Bittner et al. 2020: https://arxiv.org/abs/2009.01856
Gadotti et al. 2020: https://arxiv.org/abs/2009.01852



Examples of a barred and unbarred galaxy in the local Universe (left and middle panels, respectively). The bar is the elongated structure that crosses the centre of the galaxy, and is highlighted by the red ellipse. The right panel shows maps of parameters describing the stellar kinematics of a barred galaxy, derived from thousands of spectra from the MUSE spectrograph (see Gadotti et al. 2020). These maps provide abundant information on the movements of stars, which can helps us answer why some disc galaxies remain unbarred. (The galaxy images are from the Carnegie-Irvine Galaxy Survey.)

Notes:

SIMULATING THE EFFECTS OF AGN FEEDBACK ON GALAXY FORMATION

Main Supervisor:	Prof Cedric Lacey	cedric.lacey@durham.ac.uk
Office:	Ogden Centre West 216	
2nd Supervisor:	Prof Richard Bower	r.g.bower@durham.ac.uk

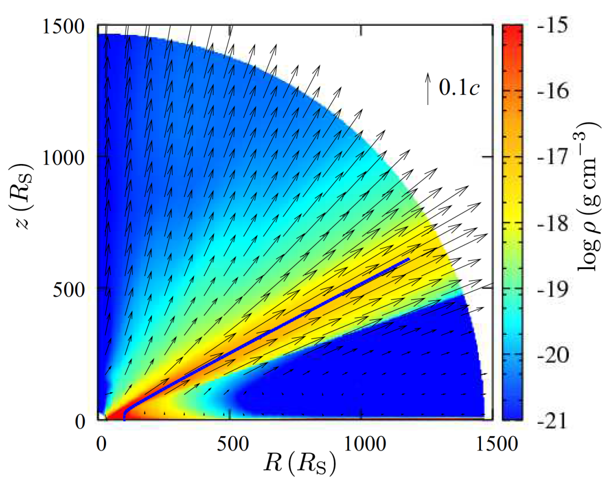
Funding:	STFC and all other funding schemes (DDS, CSC, ...)	

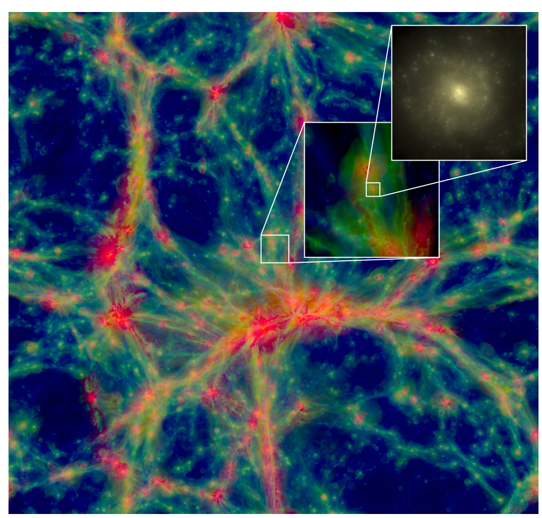
Description:

One of the most important discoveries of recent years is that massive galaxies in the nearby universe nearly all host supermassive black holes at their centres. These black holes grow by accreting gas, and in doing so release enormous amounts of energy, making them visible as active galactic nuclei (AGN). This energy release is thought to play a crucial role in galaxy formation and evolution, limiting the growth of galaxies through AGN feedback. One form of this feedback is from relativistic winds driven off black hole accretion disks by radiation pressure.

Current cosmological simulations of galaxy formation, despite their successes, still treat black hole evolution and AGN feedback in a very simplified way. The aim of this project is to develop improved treatments of these processes in the successors to the EAGLE gasdynamical simulation of galaxy formation. Recent theoretical modelling work at Durham (Quera-Bofarull et al 2021) has greatly advanced our understanding of radiation-driven winds from black hole accretion disks, providing detailed predictions for mass and energy ejection rates, which are very different from what has previously been assumed in cosmological simulations of AGN feedback. In addition, these winds are predicted to be strongly collimated in angle, an effect which is also generally not included in cosmological simulations. The aim of this project is to incorporate these predictions into a new model for black hole evolution and AGN feedback in cosmological simulations of galaxy formation, and investigate the effects on the evolution of galaxies and their black holes.

Schaye, J. et al. 2015, The EAGLE project: simulating the evolution and assembly of galaxies and their environments
Quera-Bofarull, A. et al. 2021, UV line-driven accretion disc wind models for AGN feedback





Left: Numerical simulation of radiatively-driven wind from black hole accretion disk (Nomura et al 2018). Right: EAGLE cosmological simulation. Main panel shows gas density distribution in a 100 Mpc region, coloured from blue (cold) to red (hot). Gas flows into halos along filaments. It is heated by shocks on infall, and also by feedback from supernovae and AGN, which drive outflows. (Schaye et al 2015)

Notes:

COSMOLOGICAL TESTS OF GRAVITY IN THE ERA OF SURVEY COSMOLOGY

Main Supervisor: Prof. Baojiu Li baojiu.li@durham.ac.uk
Office: Ogden Centre West 218
Funding: STFC and all other funding schemes (DDS, CSC, ...)

Description:

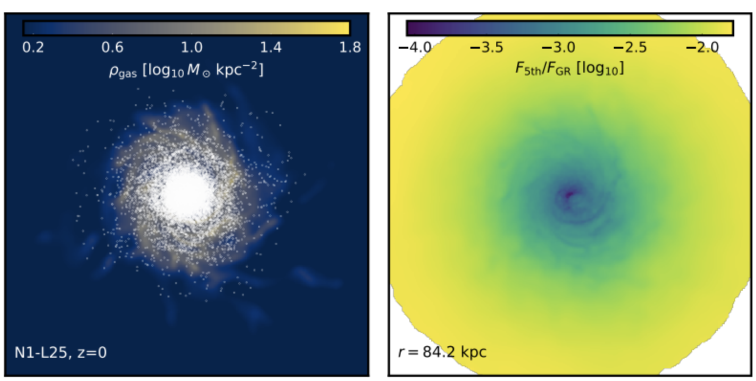
One of the most challenging questions in modern cosmology is the origin of the accelerated Hubble expansion, which implies that something major is missing from our current understanding of particle physics (such as an unknown matter species, called dark energy) or gravity. Alternative theories to Einstein's General Relativity (GR), which often have different behaviours from GR on cosmological scales, have been proposed as an explanation to this mysterious observation. Thanks to the rapid advancement in observations, the coming decade will witness a huge influx of high-precision data of galaxies and galaxy clusters. These will allow us to accurately measure various cosmological parameters and, more interestingly, to test the many candidates of gravity.

Over the years, our group has developed leading expertise in this field, including theoretical predictions based on state-of-the-art cosmological dark matter and galaxy-formation simulations of different gravity models, new statistical probes to exploit information contained in observational data, and pipelines to put the theories into rigorous test against data.

In this project, the student will have the flexibility to choose to work on tests of gravity using one (or some combination) of the three most promising observational probes: (1) weak gravitational lensing, the distortion of background galaxy images by the distribution of intervening matter in the Universe; (2) the spatial distribution and clustering of galaxies, which is sensitive to the underlying theory of gravity or dark energy; (3) the abundance and properties of the largest bound objects in the Universe – clusters of galaxies. Several large galaxy surveys, such as Euclid, DESI, LSST and 4MOST, of which Durham is an institutional member, will enable us to access the best observational data for these probes. In addition to learning theories of cosmology, the student will also have the opportunity to run their own simulations on one of the most powerful supercomputers for astronomy research (COSMA at the ICC), and to constrain gravity models using real observational data.

References:

General framework to test gravity with clusters: self-consistent pipeline for unbiased constraints of $f(R)$ gravity (arXiv:2107.14224)
Constraining cosmology with weak lensing voids (arXiv:2010.11954)
Realistic simulations of galaxy formation in $f(R)$ modified gravity (arXiv:1907.02977)
No evidence for modifications of gravity from galaxy motions on cosmological scales (arXiv:1809.09019)



A simulated spiral galaxy in a popular modified gravity model where gravity is 5-dimensional rather than 4-dimensional. The left panel shows a face-on image of the disc and spiral arms, overplotted with stars (white dots) and gas (colour) in the galaxy. The right panel shows how gravity is modified with respect to GR prediction, with yellow (blue) showing large (small) enhancements.

Notes:

EXPLOITING NEW TECHNOLOGY TO ENHANCE GROUND-BASED ASTRONOMY

Main Supervisor:	Dr James Osborn	james.osborn@durham.ac.uk
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Funding:	STFC and all other funding schemes (DDS, CSC, ...)	

Description:

The aim of this studentship is to develop concepts and technologies to advance the capabilities of modern astronomical observatories by actively correcting for the detrimental effects of the Earth's atmosphere in real-time.

The student will engage with the development, deployment, and exploitation of site-testing instrumentation at observatory sites around the world, to improve our understanding of the effects of the Earth's atmosphere on astronomical observations. They will look to apply these results to improve the performance of adaptive optical or scintillation (the twinkling of the stars) correction systems, or to the forecasting of optical turbulence conditions at observatory sites.

This work will be directly applicable to the next generation of giant telescopes, such as the 40 metre European Extremely Large Telescope in Chile. It will Enable them to reach their science goals including discovering extra-solar planets, reconstructing the formation of galaxies, and even elucidate 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 significant experience in analysing atmospheric turbulence and the use of computer modelling of complex optical systems to design optical instrumentation to 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 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:

GALAXY EVOLUTION OVER THE LAST 10 BILLION YEARS

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

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.

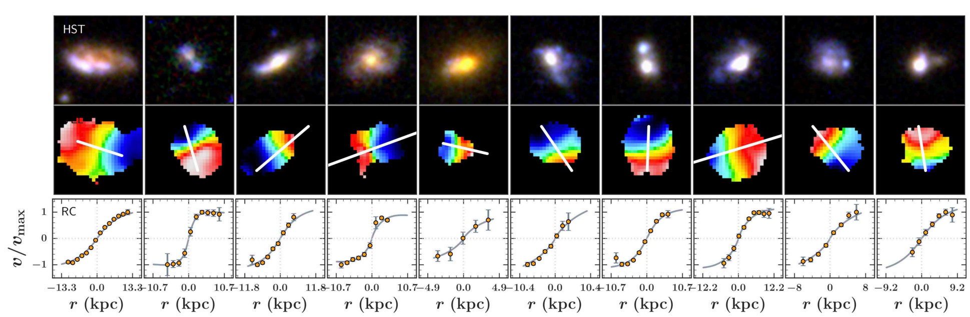

Fig. 1. *Images and dynamical maps of star-forming galaxies at $z \sim 1.5$ from our ongoing KMOS survey. We show the* HST *colour image (top row), velocity field (middle row), and galaxy rotation curve (bottom row). We will exploit maps like these to measure the dynamics, rotation curves, total baryonic 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:

SEARCHING FOR NEUTRINOS IN THE FOREST

Main Supervisor: Prof Tom Theuns tom.theuns@durham.ac.uk
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Funding: STFC and all other funding schemes (DDS, CSC, ...)

Description:

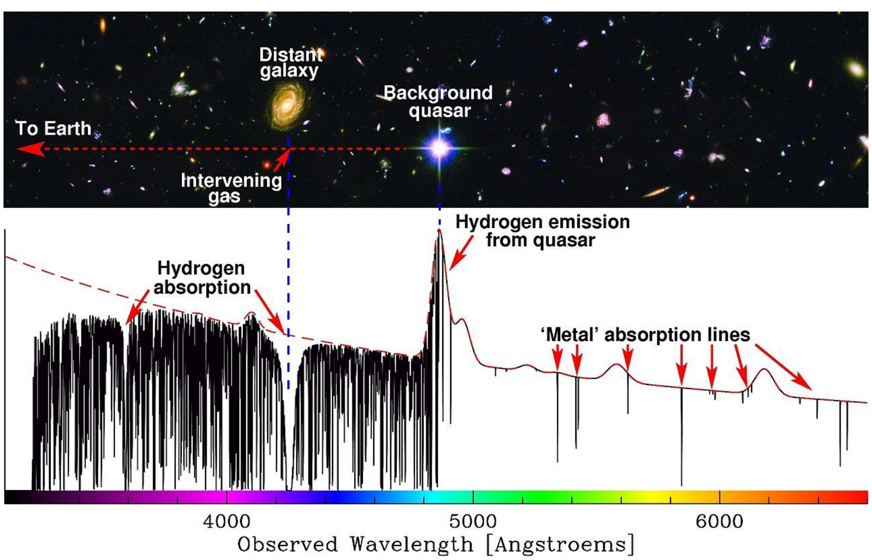
Cosmological measurements are sensitive to $\sum m_\nu$, the combined mass of the three neutrino types. In fact, cosmology provides a more accurate measurement of the neutrino mass than current particle physics experiments. The higher the neutrino mass, the more small-scale power in the cosmological distribution of mass is suppressed compared to a case without neutrinos. The suppression results from the high intrinsic velocities of neutrinos in the early universe.

This project is all about performing numerical simulations of the growth of structure with various values of $\sum m_\nu$, and investigate which value describes the data best. The simulations use a new way for performing such calculations that was developed at the ICC.

We will simulate the Lyman-α forest, which is the region of a quasar spectrum that contains numerous absorption lines caused by quasar photons scattering off neutral hydrogen in intergalactic space; see the cartoon figure below. This intergalactic gas traces the underlying mass distribution very well, and hence provides an exquisite handle of the small-scale mass distribution that is affected by neutrinos. The quasar itself is just a luminous background source, and need not be simulated. We will simulate the three-dimensional distribution of cosmic gas, by performing cosmological hydrodynamical simulations using the SWIFT simulation engine which was developed in Durham and Leiden.

This project is very timely, not just because of our new way of simulating neutrinos, but because we will see a veritable explosion in the quality of the data that can be used to measure $\sum m_\nu$ from upcoming surveys such as WEAVE. We better be prepared to have good models to interpret this data. Providing such models is your task - should you choose to accept it.

This paper by Palanque-Delabrouille is the current state-of-the-art. The WEAVE survey, in which Durham is involved, is described in this paper. The neutrino method is described here. The SWIFT simulation engine is discussed here. We will also interact closely with Prof Simon Morris, who is an expert in data analysis of the Lyman-α forest.



In this cartoon, the upper image illustrates the cosmic distribution of matter between us (to the left) and a distant quasar. The lower image is the corresponding spectrum of the quasar, with the numerous absorption lines (labelled 'Hydrogen absorption') caused by hydrogen atoms along the line of sight. The gas that imprints these lines traces the underlying matter distribution very closely. Neutrinos will smooth this distribution by an amount that depends on their mass. This is the signature of neutrinos that we will search for.

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
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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. 2022), 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. 2022). As shown in the figure below the *NuSTAR* serendipitous survey pushes to higher redshifts than previously possible at these X-ray energies.

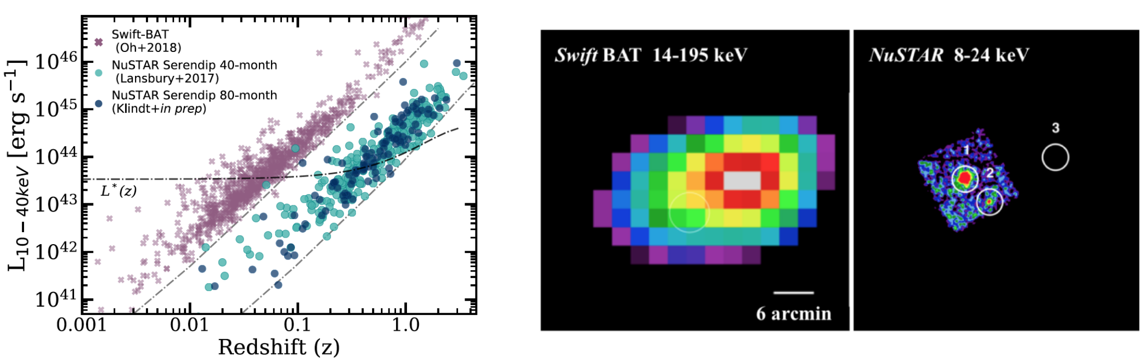

Figure: (left) X-ray luminosity ($L_{10-40\text{keV}}$) versus redshift for the AGNs spectroscopically identified in the 80-month NuSTAR serendipitous survey as compared to the shallower Swift-BAT survey. The evolving knee of the X-ray luminosity function ($L_*(z)$) of AGNs is indicated. Taken from Klindt et al. (2022). (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
Office:	Ogden Centre West 119	
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.

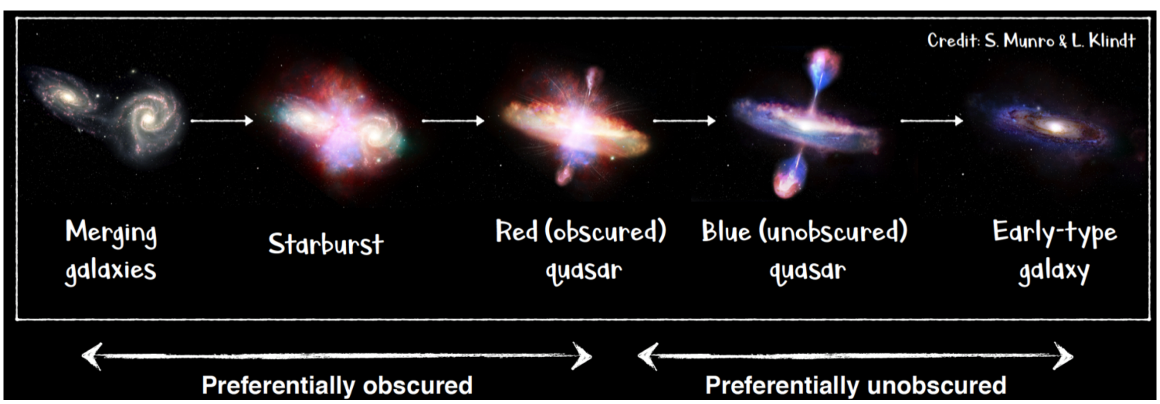

Figure: The leading evolutionary model for quasars. The sequence is triggered by huge amounts of gas inflow (potentially from a merger of two galaxies) which leads to a burst of dust-obscured star formation and a heavily buried (i.e., obscured) quasar. As the quasar ages it drives out energetic winds 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:

THE EXTREME UNIVERSE WITH CTA AND SWGO

Main Supervisor: Prof. Paula Chadwick p.m.chadwick@durham.ac.uk
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Funding: DDS, CSC and other non-STFC funding schemes

Description:

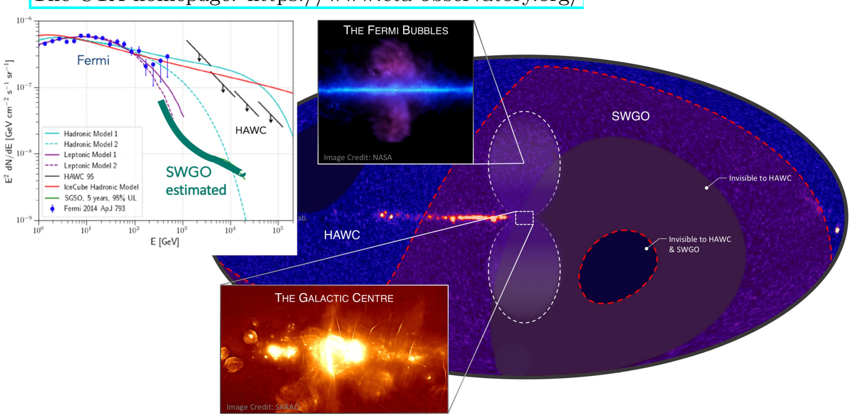
Over the last 10 years, very high energy (VHE) gamma ray astronomy has opened a new window on the extreme universe. The catalogue of known VHE-emitting objects has grown by an order of magnitude and includes many different classes of objects - supernova remnants, pulsars, binary star systems, star formation 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 group at Durham has pioneered this field, and is presently involved in two projects: the Cherenkov Telescope Array (CTA) and the Southern Wide-field Gamma-ray Observatory (SWGO). CTA will consist of two arrays, one in the southern hemisphere and one 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 and construction of the first 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 2023.

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.

As founder members of CTA and SWGO, 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 (particularly for SWGO), SWGO calibration, and the construction of cameras for the small telescopes of CTA. Students can also expect to be involved in work on preliminary data from the first CTA telescopes.

The SWGO homepage: https://www.swgo.org/SWGOWiki/doku.php
The CTA homepage: https://www.cta-observatory.org/



The SWGO will have unprecedented coverage of transients such as gravitational wave events and the ability to image extended objects, including the Galactic centre and the Fermi bubbles.

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: DDS, CSC and other non-STFC funding schemes

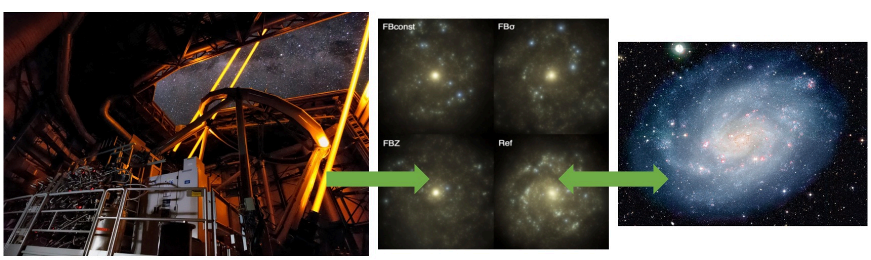
Description:

Throughout their short lives, massive stars (> 8 solar masses) have a deep impact on their surroundings via e.g. strong stellar winds, 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. 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.

Dwarf starburst galaxies represent extreme environments in which the role of stellar feedback remains, from an observational perspective, largely unconstrained. For example, there is need to understand if and how feedback from massive stars can influence the capability of these galaxies to form stars, or how it affects their dark matter content. In this project you will drive progress in understanding stellar feedback by linking observational results to simulations of star-forming dwarf galaxies. Specifically, you will produce synthetic observations of computer simulations, as well as meaningful methods to compare these to real observations.

These 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.

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



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 then quantitatively comparing the mock observations to real ones (e.g. of the nearby galaxy NGC 300 shown in the right panel).

Notes:

RESOLVED STELLAR POPULATIONS IN NEARBY DWARF STARBURST GALAXIES

Main Supervisor: Dr. Anna McLeod anna.mcleod@durham.ac.uk
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Funding: DDS, CSC and other non-STFC funding schemes

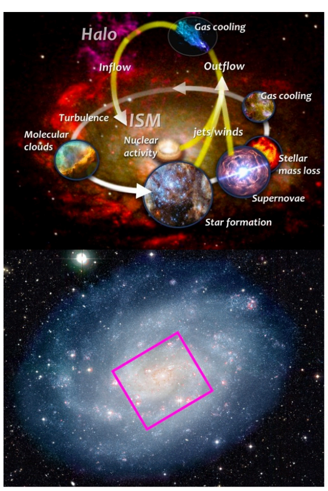
Description:

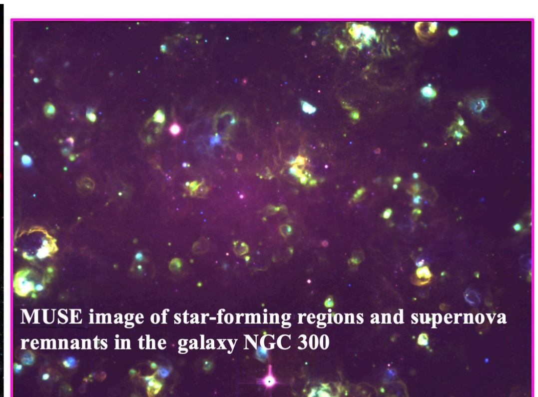
The lifecycle of star-forming galaxies is very complex: cold gas is turned into stars; the formed stellar populations stir, mix, enrich, heat, and expel the gas via stellar winds, radiation, and supernova explosions; the gas can then fall back onto the galaxy, cool, and form new generations of stars. While we qualitatively understand the involved physical processes governing the 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 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.

This project will address a key part in solving this problem by revealing and studying stellar populations in nearby, metal poor, dwarf galaxies. These provide ideal laboratories to study the interplay between stars and gas in extreme environments yet to be studied in detail. The simultaneous study of both the individual stars (or star clusters) and the gas has only recently become possible, thanks to observations from integral field spectrographs and novel analysis methods that allow us to combine these data sets with high-resolution imaging from e.g. the Hubble Space Telescope.

By combining data from the integral field spectrograph MUSE on the Very Large Telescope with data from e.g., the Hubble Space Telescope, the stellar population of the nearest metal-poor dwarf galaxies from DWALIN (DWarf galaxies Archival Local survey for Ism investigatioN, Cresci et al. in prep.) will be studied at unprecedented levels of detail, and directly connected to the star-forming gas reservoir in the galaxies. The results will then be compared to other types of galactic environments, e.g. more massive nearby star-forming galaxies (e.g., NGC 300, McLeod et al. 2020, 2021; the Magellanic Clouds as part of SDSS-V), therefore providing a framework to quantify the environmental dependencies of the interplay between 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





By combining the above MUSE data with data from the Hubble Space Telescope, the stellar and gaseous content of the galaxy can be studied simultaneously at unprecedented high resolution.

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:

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 120

Funding: DDS, CSC and other non-STFC 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

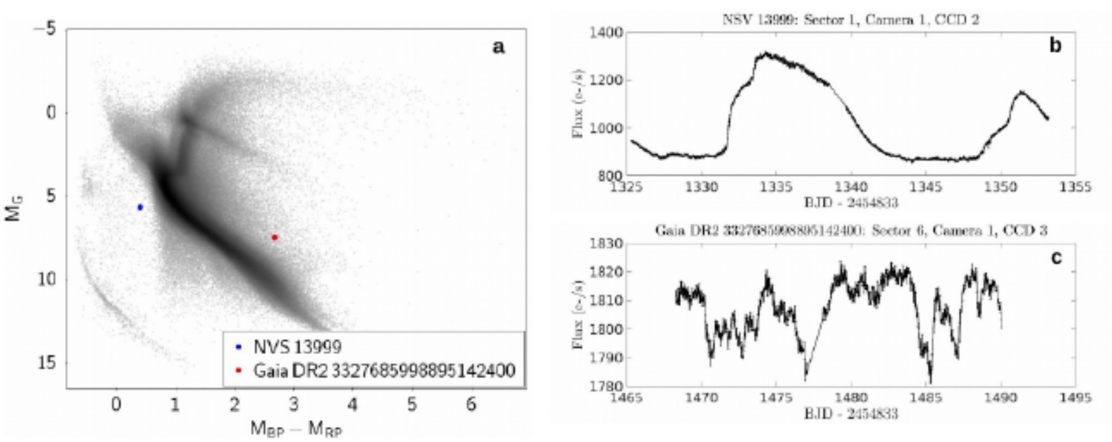


Fig. 1. *Colour-magnitude diagram obtained using Gaia and example lightcurves from TESS. Panel (a) shows the colour-magnitude diagram from Gaia of over 3.6 million targets that reside in the TESS field-of-view for Sectors 1-7. On the right-hand side are two TESS lightcurves of previously unidentified 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:

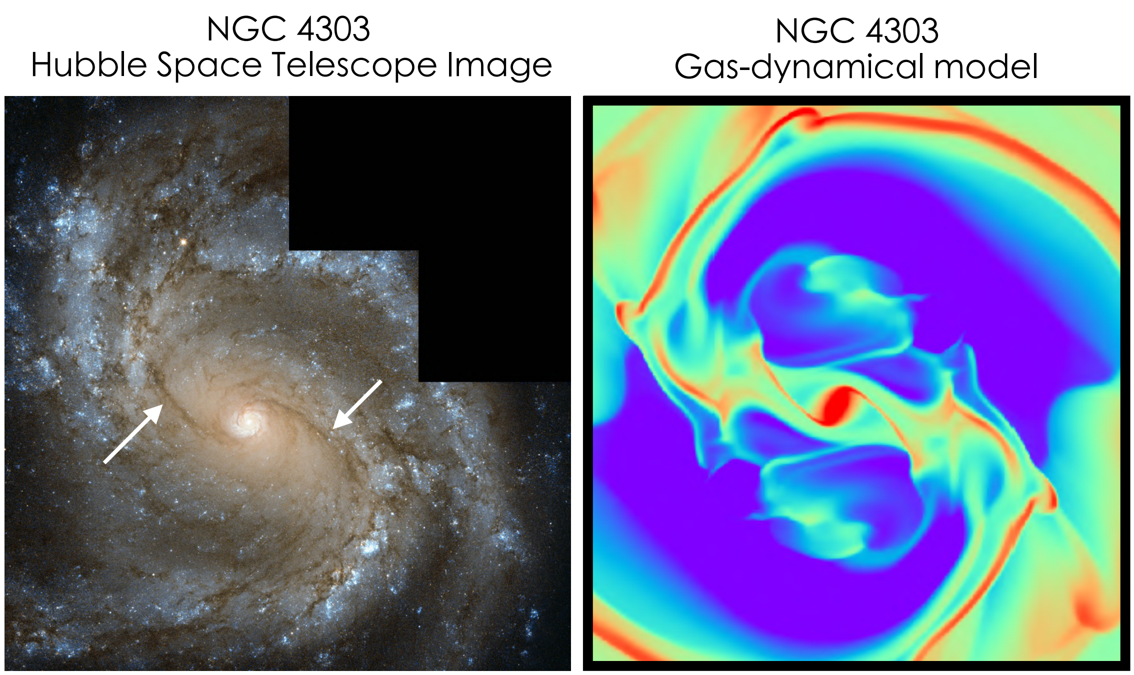
HOW WELL CAN WE DISENTANGLE THE DARK MATTER DISTRIBUTION IN SPIRAL GALAXIES?

Main Supervisor:	Dr. Francesca Fragkoudi	francesca.fragkoudi@eso.org
Office:	Ogden Centre West (in Durham from April 2022)	

Funding:	none defined (MScR project)

Description:

Determining the distribution of dark matter in different types of galaxies is of fundamental importance for understanding more about the nature of the elusive dark matter itself. Various dynamical modelling techniques are used in the literature in order to do this, i.e. to disentangle the contribution of normal (baryonic) matter from the dark matter. Barred spiral galaxies – such as our own Milky Way – are however particularly tricky to model dynamically due to their complex orbital structure. In this project we will test one of the most promising methods for dynamically modelling barred galaxies, which makes use of the morphology and kinematics of gas in these galaxies (see Figure below). The method exploits the effects of non-axisymmetries, such as stellar bars, on the gaseous discs of spiral galaxies. Stellar bars induce shocks in the gas, and the strength and shape of these shocks is highly dependent on the baryon-to-dark matter fraction of the galaxy. To test how well the method works under different assumptions and limiting conditions (e.g. in inclined discs, or with a varying mass-to-light ratio in the disc, etc.) we will use mock observations constructed from state-of-the-art isolated and cosmological simulations, in which the true distribution of dark matter is known. With this project, students will further develop their coding skills, learn about how to disentangle dark matter from normal baryonic matter in spiral galaxies using dynamical modelling techniques, and learn how to analyse state-of-the-art simulations of galaxy formation and evolution.



Example of the 'gas-dynamical modelling technique' used on the galaxy NGC 4303: The left panel shows an HST image of the galaxy NGC 4303 where the dust lanes (created due to shocks in the gas, induced by the bar) are clearly visible. The right panel shows a gas-dynamical model of the same galaxy, where the baryon-to-dark matter fraction is one of the main free parameters obtained through the modelling.

Notes:

STRUCTURAL DECOMPOSITION OF NEARBY AND DISTANT GALAXIES

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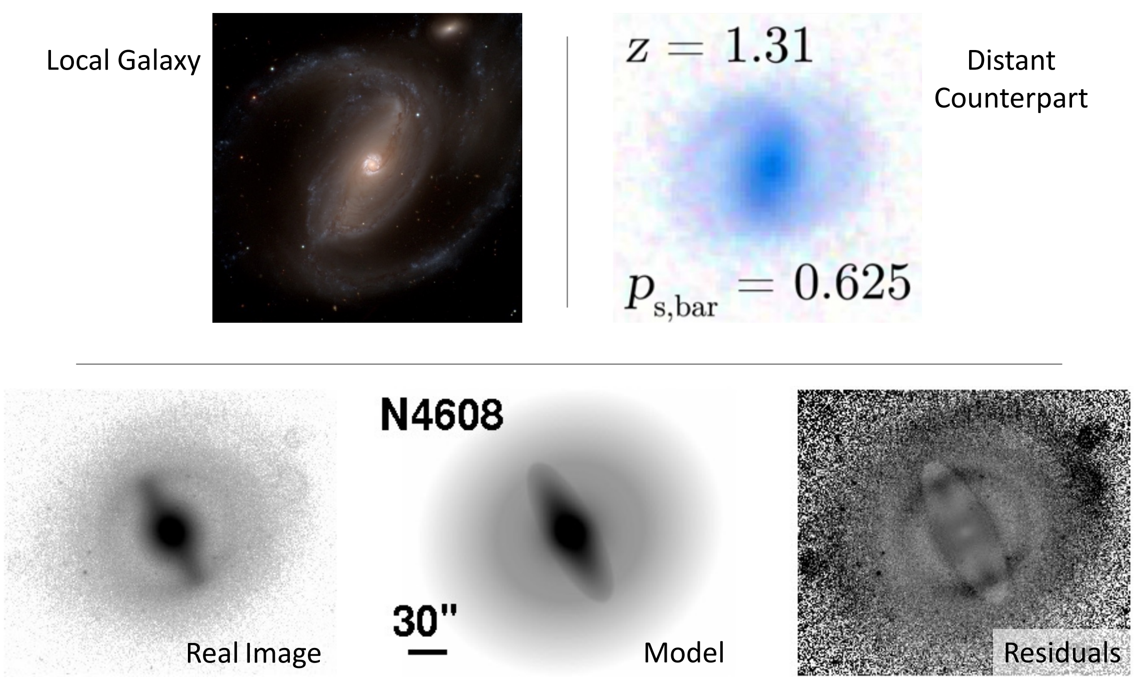
Funding: none defined (MScR project)

Description:

Disc galaxies host a variety of stellar structures. Apart from the disc, often showing spiral arms, structures such as a central spheroid (or bulge), a bar, rings and a nuclear disc are frequently present. These structures hold important clues to understand the evolutionary paths of galaxies. However, they may be difficult to probe in more distant galaxies, due to a decrease in the physical spatial resolution, amongst other effects (see top left and right panels in the figure below). An important tool to quantify the presence and physical properties of these structures is through galaxy image decompositions. In these, a dedicated image analysis software is used to separately model the different stellar structures in the galaxy (see the three bottom panels in the figure). The goal of this project is to understand better how well this technique works for distant galaxies. In the first stage of this project, you will learn how to use a dedicated software and apply this methodology to determine the structural properties of nearby galaxies. Next, we will simulate the effects that affect images of distant galaxies, and rerun the software on these mock images to establish how these effects impact the results obtained from the image decomposition.



Nearby galaxies (top left) often show a variety of stellar structures that hold important clues to understand their formation and evolution. However, even with the best telescopes and instrumental setups, these structures may be difficult to investigate in more distant galaxies, mainly due to the reduced physical spatial resolution (top right). A powerful tool to quantify the properties of such stellar structures is through galaxy image decompositions. The three bottom panels show, respectively, from the left: an image of a nearby barred galaxy, a model obtained by fitting the galaxy image with separate models for the different structural components (bulge, disc and bar), and a residual image, obtained by subtracting the model from the real galaxy image. The residual image shows further, secondary structural components that are not included in the model.

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:

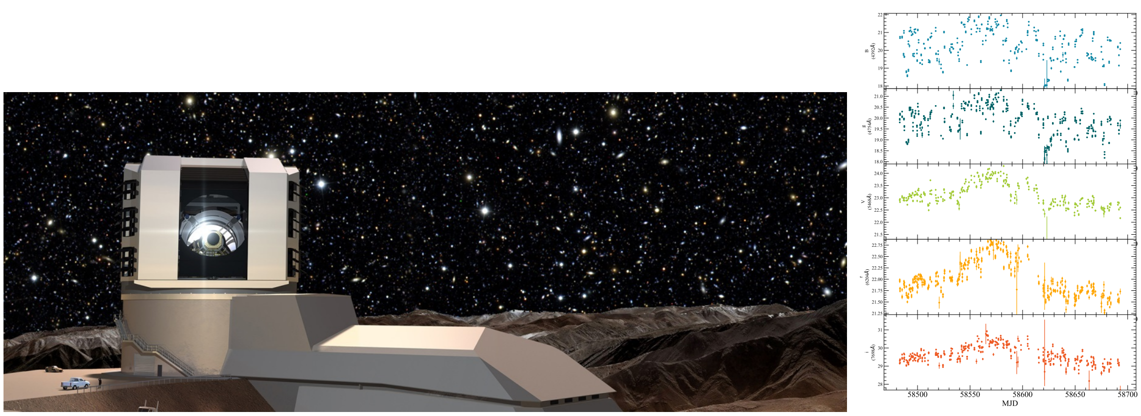
We are now starting the new era of time-domain astronomy. Large sums of money are currently being invested in astronomical facilities that can continuously survey the sky in order to detect and study interesting variable and transient sources. The largest ground-based facility for time-domain astronomy 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 gliff.ai, a company specialised in Image Analysis Solutions.

LSST Science Collaborations et al. 2017
Nancy Grace Roman Space Telescope
gliff.ai



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.*

Notes:

INFRARED DUST REVERBERATION FROM SPACE

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

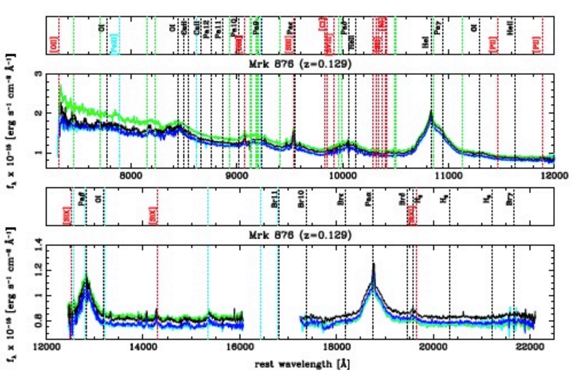
Description:

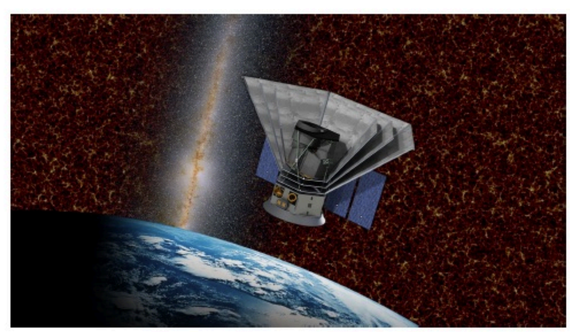
Scales too small to be resolved by direct imaging can be measured out using the time the light takes to travel across them. This is the basic idea behind the method of reverberation mapping. Components around supermassive black holes at the centres of the most massive and luminous galaxies are such small 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 project will extend this program to space. You will prepare for the use of 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 from monitoring data by the Las Cumbres Observatory network of 1 m and 2 m robotic telescopes and also public archives such as, e.g, the Zwicky Transient Facility (ZTF). Candidates in the southern hemisphere will be subsequently targeted by the Legacy Survey of Space and Time (LSST; LSST Science Collaborations et al. 2017) scheduled to operate from 2024 at the Vera C. Rubin Observatory, an 8.4 m telescope currently being built in Chile by a large consortium including the UK. 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:

SPECTROSCOPY OF STELLAR POPULATIONS IN THE POISSON-FLUCTUATION REGIME

Main Supervisor: Dr Russell Smith russell.smith@durham.ac.uk
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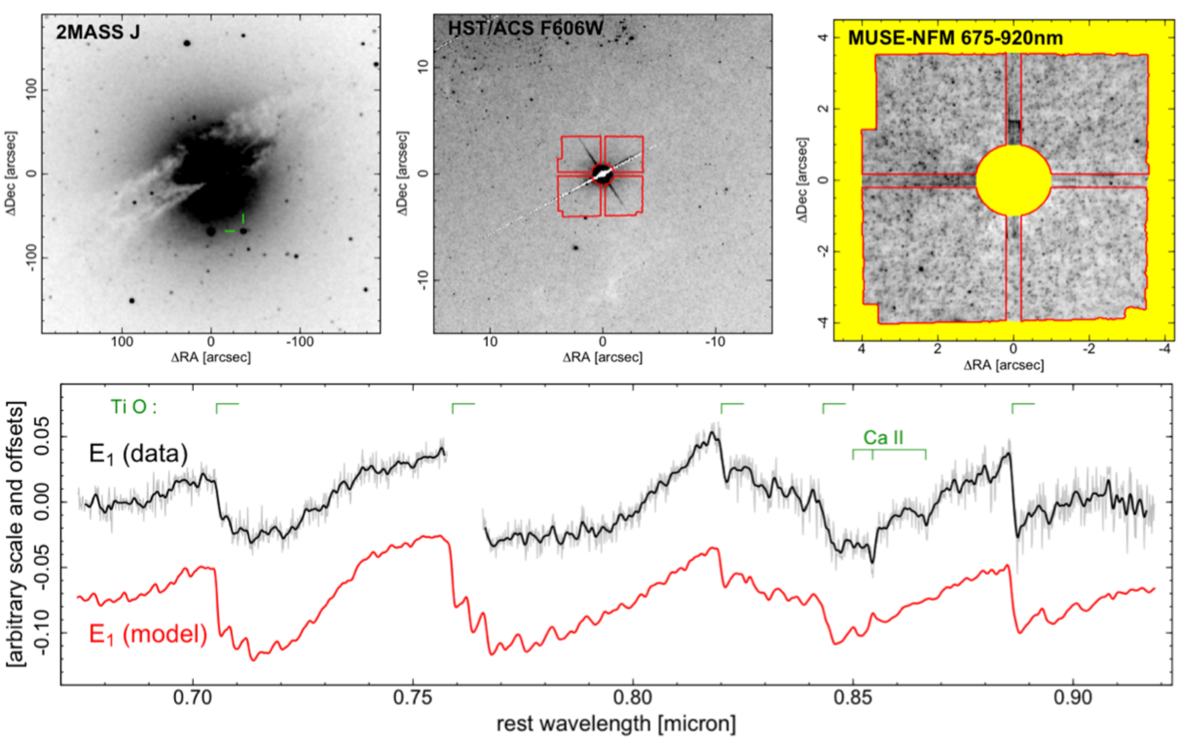
Funding: none defined (MScR project)

Description:

The goal of this project is to develop an innovative method for studying the brightest stars in elliptical galaxies, by analysing the statistical fluctuations in the spectra measured at different locations.

While most stars in external galaxies are individually faint, and present in huge numbers, the most luminous giants are individually bright, but much rarer. The small number of giant stars sampled by each pixel is subject to significant Poisson fluctuations; e.g. while on average we might see 10, some pixels will actually contain 12, or 7 or 15. As a result, the *spectrum* of the galaxy shows variations from pixel-to-pixel which carry the "fingerprints" of the giant stars, which can be extracted using statistical techniques like principal components analysis (PCA). Our recent work has explored this technique using "fake" data generated from an idealised model, and we have also proved that it works in practice, using ESO VLT observations for a particularly nearby galaxy, where the fluctuations are easiest to measure (see figure below).

There are a number of directions this research could be taken by a MScR student, including: (1) investigating how the fluctuation signals depend on the underlying stellar population models (age, metallicity, adopted stellar evolutionary tracks, etc); (2) developing realistic mock datasets for more distant targets, tuned to current and future observational capabilities, to support new science cases for the VLT, JWST, ESO ELT, etc; (3) exploring whether different statistical approaches would outperform PCA, first for idealised data and then in the presence of realistic noise sources.



A field of stars in the nearby peculiar galaxy NGC 5128 (top left), as seen with Hubble Space Telescope (top centre) and MUSE on the VLT in its high-resolution mode (top right). The brightest giant stars are visible in this image but too faint to obtain spectra for individually. A bright foreground star at the centre is used for the adaptive optics correction. The lower panel shows that our Poisson-fluctuation spectroscopy technique can recover the expected spectral features of cool giant stars. In this MScR, you will help develop the method for application to distant elliptical galaxies with the future ESO Extremely Large Telescope.

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