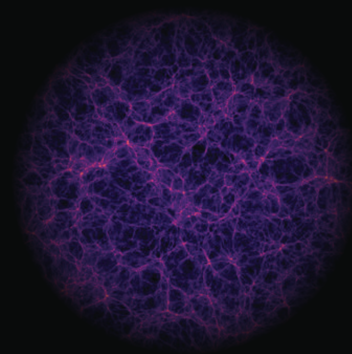
Astronomy PhD Projects at Durham

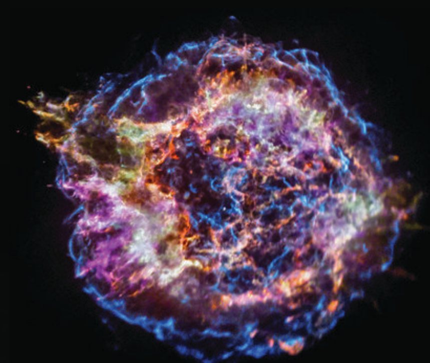
2020

Durham University

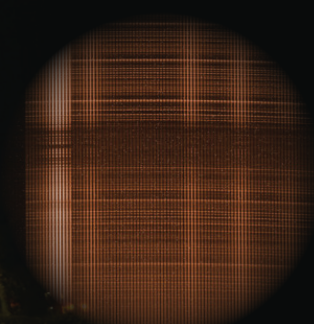
ICC



Durham Centre for Extragalactic Astronomy



CfAI



PHD PROJECTS IN ASTRONOMY
FOR AUTUMN 2020 START

Introduction

List of PhD Projects

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 2020.

Fully Funded PhD Studentship Options

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

Science and Technology Facilities Council (STFC) studentships. These 4-year PhD studentships are only available to EU nationals (i.e. UK + EU-27) domiciled in the UK. The STFC web site[1] provides more specific details regarding STFC studentship eligibility. We expect to offer 6 STFC-funded studentships this year, based on previous years STFC allocations.

EU ITN BiD4BEST studentship. This 3-year EU ITN studentship is available to graduate students from any country. To be eligible for this studentship, the applicant must have spent less than 12 of the last 36 months (prior to the PhD start date) in the UK for either work or study. This PhD position is part of an EU international training network (ITN) called BiD4BEST which links 11 European institutions and provides substantial additional training and travel benefits. We have 1 EU ITN BiD4BEST studentship this year.
BiD4BEST web-site: https://wwwmpa.mpa-garching.mpg.de/∼kdolag/BiD4BEST/index.html

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.

[1] http://www.stfc.ac.uk/ & http://www.stfc.ac.uk/funding/studentships/studentship-terms-conditions-guidance/

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 via remote access if necessary). We expect to interview shortlisted candidates for STFC studentships from mid-February through to mid-March (see our web-pages for up-to-date information regarding possible interview days and effective deadlines to meet).

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 scholarships is Friday January 17th 2020, while the CSC deadline is Sunday January 19th 2020, both for an autumn 2020 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 Friday January 10th 2020 to receive full consideration.

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

MSc by Research Studentship Options

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

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

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

Main Supervisor: Prof. David Alexander d.m.alexander@durham.ac.uk
Office: Ogden Centre West 119
Funding: TBC / Other 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 are leading the *NuSTAR* serendipitious survey (Alexander et al. 2013; Lansbury et al. 2017; Klindt et al. in prep), which is the most powerful component of the overall extragalactic survey program undertaken by *NuSTAR*. Through a combination of deep and shallow wide-area coverage, the *NuSTAR* serendipitious survey fills out the L_X–z plane of AGN and detects *intrinsically rare* AGN populations not otherwise identified; see the figure below. For example, the 40-month catalog contains 497 AGNs over 13 deg^2 with an overall *NuSTAR* exposure of $\approx$ 20 million seconds (Lansbury et al. 2017); these numbers have approximately doubled in the 80-month catalog (Klindt et al. in prep). As shown in the figure below the *NuSTAR* serendipitous survey pushes to higher redshifts than previously possible at these X-ray energies.

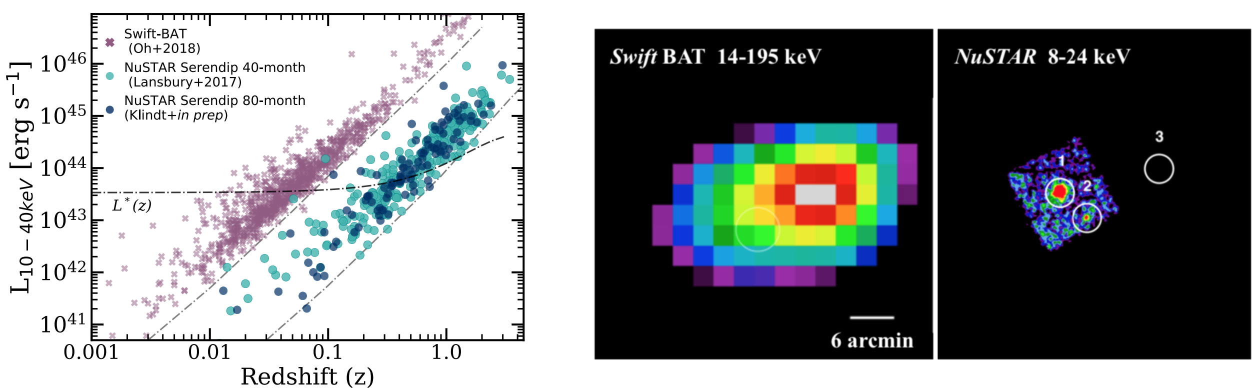


Figure: (left) X-ray luminosity ($L_{10-40\mathrm{keV}}$) versus redshift for the AGNs spectroscopically identified in the NuSTAR serendipitous survey as compared to the shallower Swift-BAT survey. The evolving knee of the X-ray luminosity function ($L_*(z)$) of AGNs is indicated. Taken from Klindt et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

I am looking for a student to take a lead in the *NuSTAR* serendipitious survey to provide the most complete X-ray selection of AGNs to date. During your PhD you will analyse the *NuSTAR* data from this 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). With these data you will construct the most complete census of AGN activity obtained to date and use your *NuSTAR* sample of AGN to measure the cosmic growth of black holes.

Notes:

ARE OBSCURED QUASARS SPECIAL? DISTINGUISHING BETWEEN ORIENTATION AND EVOLUTION MODELS

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

Funding: BiD4BEST (EU ITN)

Description:

Quasars are the most luminous subset of the overall population of Active Galactic Nuclei (AGN) and can be seen out of the edge of the observable Universe. They are powered by mass accretion onto a super-massive black hole 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 obscured and unobscured lower-luminosity AGN appears to be due to the orientation of an optically and geometrically thick structure (often referred to as the "dusty torus"). 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" or the orientation model (see Netzer 2015 for a recent review). However, while being referred to as a "unified model", it is far from clear whether it actually applies to quasars, which require huge mass accretion rates and may be physically distinct from the overall AGN population. A competing model argues that different subsets of the quasar population are related within an evolutionary sequence whereby huge amounts of gas inflow (potentially driven by a merger of two gas rich galaxies) leads to a burst of star formation and a dust-obscured quasar. As the quasar evolves it drives away the obscuring dust, ultimately revealing an unobscured quasar (see Alexander & Hickox 2012 for a review). The huge amount of energy produced during the quasar phase drives jets and winds into the galaxy which shuts down the star formation and forms a "red and dead" early type galaxy. See the figure below for a schematic representation of this evolutionary model.

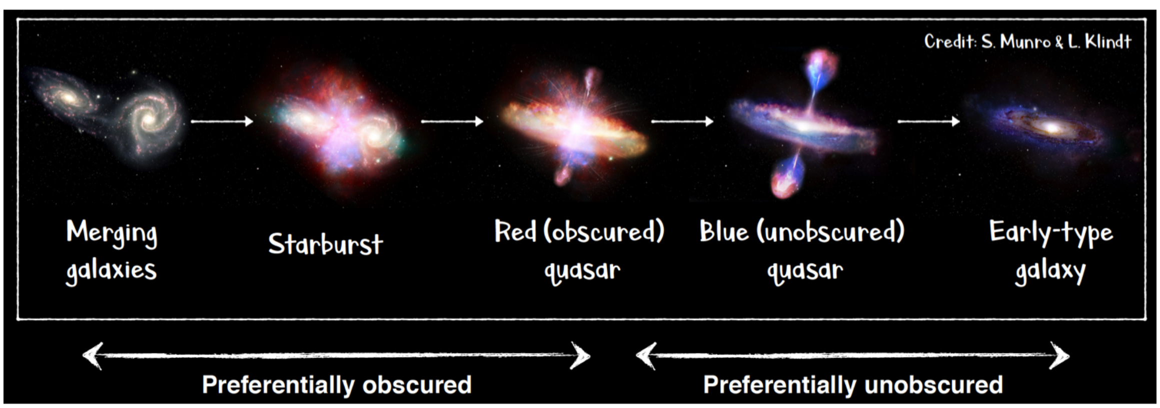


Figure: an evolutionary model for quasars which you will test and develop in your PhD. Based on our recent paper on the discovery of fundamental differences between red and blue quasars from Klindt et al. (2019). Schematic produced by S. Munro and L. Klindt. See https://www.dur.ac.uk/research/news/item/?itemno=39444 for an associated movie.

I am looking for a student to investigate the relationship between obscured and unobscured quasars to test between the evolutionary model and the orientation model (i.e., the "unified model"). This research builds upon a seminal discovery where we found that red quasars (i.e., systems with a modest amount of dust obscuration) have fundamentally different properties to normal blue quasars (Klindt et al. 2019): a larger fraction of red quasars produce radio emission that is compact and yet comparatively weak. Our results comprehensively rule out the orientation model and argue for an evolutionary model. In this PhD project you will use a broad suite of new multi-wavelength observations (from X-rays to radio) to extend this research to the more obscured quasar population to test whether these results apply to the overall quasar population or if it is only red quasars that are special.

This PhD position is part of an international training network called BiD4BEST which links 11 EU institutions and provides substantial training and travel benefits. It is open to **all nationalities**, including EU and overseas students. However, to be eligible you must have spent <12 of the last 36 months (prior to the PhD start) in the UK for either work or study.

Notes:

EXTREME ENVIRONMENT ASTROPHYSICS: GAMMA RAY ASTRONOMY AND THE CHERENKOV TELESCOPE ARRAY

Main Supervisor:	Prof. Paula Chadwick	p.m.chadwick@durham.ac.uk
Office:	Rochester 125c	
2nd Supervisor:	Dr. Anthony M. Brown	anthony.brown@durham.ac.uk
Funding:	TBC / Other funding schemes	

Description:

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

However, we have really opened this new window only a little way, and so some 1450 scientists and engineers from 31 nations are joining together to create a new instrument: the Cherenkov Telescope Array (CTA). Consisting of a 100-telescope array in the southern hemisphere and a 20-telescope array in the north, CTA will have sensitivity around 10 times better than any gamma ray telescope now in operation, will cover 4 orders of magnitude in energy and have better angular resolution than anything we have built before. Prototyping of telescopes and instrumentation has already begun; the first telescope of the northern array is already in place, and construction of the southern array is expected to start in 2020.

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

There is also the opportunity for students to become involved in a newly-founded international project, the Southern Wide-angle Gamma-ray Observatory (SWGO). This will be an all-sky instrument which is designed to complement CTA. It is in its design stages at present, and students would be involved in science simulations and instrumentation for SWGO.

The CTA Project homepage: https://www.cta-observatory.org/
The CTA Science Case: https://arxiv.org/abs/1709.07997
The SWGO homepage: https://www.swgo.org/SWGOWiki/doku.php?id=start

Testing CTA's prototype small telescope in Sicily.

Notes:

THE DESI BRIGHT GALAXY SURVEY

Main Supervisor: Prof Shaun Cole shaun.cole@durham.ac.uk
Office: Ogden Centre West 211
2nd Supervisor: Dr Peder Norberg peder.norberg@durham.ac.uk
Funding: STFC

Description:

The 5000 fibre Dark Energy Spectrosopic Instrument (DESI), which had first light in November 2019, will start collecting millions of galaxy spectra in 2020. It will produce galaxy and quasar redshift catalogues containing tens of millions of objects. These will enable measurements of the large scale clustering of galaxies with unprecedentedly small statistical errors. In turn such measurements can be used to:

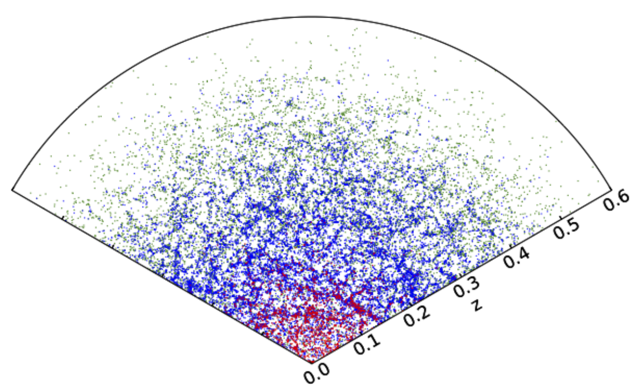
- Probe the nature of Dark Energy – Measuring the position of the Baryon Accoustic Oscillation (BAO) peak over a range of redshifts allows the past expansion history of the Universe to be mapped out and hence the evolution of the Dark Energy density to be inferred.
- Test modifications to Einstein's Gravity – Modified gravity models that explain the expansion history of the Universe without DE predict modifications to the rate at which structure grows. These can be detected via changes to the anisotropic clustering of galaxies in redshift space induced by the peculiar velocities of galaxies in forming structures.
- Test models of galaxy formation – The clustering of galaxies can be used to deduce their relation to DM. We can determine the mass of the DM haloes they inhabit how this depends on the properties of the galaxies (luminosity, colour, size ...) and varies with redshift.

A key component of these surveys is the DESI Bright Galaxy Survey (BGS), whose working group is currently cochaired by Pauline Zarrouk (Durham PDRA) and for the previous four years by Shaun Cole. The BGS aims to measure the redshifts of a magnitude limited ($r < 19.5$) survey of 10 million galaxies across 14,000 $\deg^2$ (roughly ten times the size of the SDSS main galaxy survey).

This project is an opportunity to join this team when the data sample is both substantial and increasing rapidly making the discovery potential its highest.

Possible projects, which all include a mixture of analysing survey and interpreting using cosmological simulations include:

- Quantifying the intrinsic properties of the galaxy population – not just the galaxy luminosity function and its evolution with redshift but the evolution of other properties that have been measured such as galaxy colours and morphology.
- Measuring the 2-point clustering statistics of different galaxy populations to constrain their Halo Occupation Distributions (HODs) and so their relationship with the Dark Matter (DM),
- Quantifying Assembly Bias and other processes that cause the properties of galaxies to be dependent on their environment in the cosmic web of voids, filaments and clusters.



Mock slice of the BGS galaxy distribution. The red points show galaxies that would be probed by the SDSS main galaxy survey, blue those in BGS ($r < 19.5$) and green the BGS faint extension to $r = 20$

DESI homepage: https://www.desi.lbl.gov/

Notes:

THE COSMOLOGICAL LITHIUM PROBLEM

Main Supervisor: Dr. Ryan Cooke ryan.j.cooke@durham.ac.uk
Office: Ogden Centre West 121
2nd Supervisor: Prof. Michele Fumagalli michele.fumagalli@durham.ac.uk
Funding: STFC

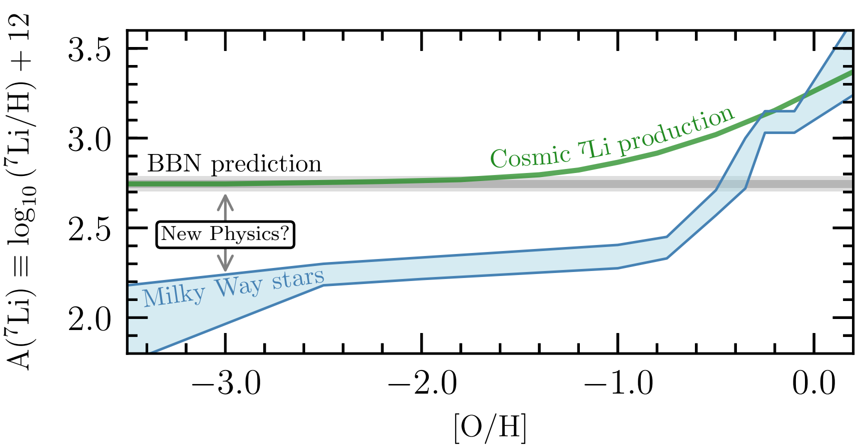
Description:

Our deepest understanding of the Universe and its mechanics is captured by a simple, elegant concept — the Standard Model of particle physics and cosmology. One of the prime goals of this PhD project is to test the foundations of this framework. This will be achieved by studying a period of time (a few minutes after the Big Bang) during which the first chemical elements of the periodic table were made. These are referred to as the 'primordial' elements, and include hydrogen, helium, lithium, and their isotopes. The amount of each primordial element made during this time is sensitive to every known fundamental force: gravity, electromagnetism and the strong and weak nuclear forces. Thus, the relative production of these primordial elements can be used to probe the physics of the Universe just a few minutes after the Big Bang!

To measure the primordial elements, environments must be found that remain as uncontaminated as possible since the Big Bang. For example, the oldest stars in our Galaxy are often used to measure the ratio of primordial lithium to hydrogen (Li/H). At present, such measures disagree significantly with the Standard Model, giving rise to a puzzle known as the 'Cosmological Lithium Problem'. After more than a decade of research, it still remains unclear if the observations need revision, or if this discrepancy requires new (presently unknown) physics beyond the Standard Model.

To solve this impasse, the PhD student assigned to this project will measure the Li/H ratio of gas clouds (instead of stars, as previously done) using data collected with some of the world's largest optical telescopes.

Research group website: http://astro.dur.ac.uk/image/
Relevant paper (https://arxiv.org/abs/1207.3081), Relevant review article (https://arxiv.org/abs/1203.3551).



The amount of lithium created a few minutes after the Big Bang is shown by the grey horizontal band ("BBN prediction"), assuming the Standard Model of physics. The green line shows a model calculation, which predicts how much lithium is produced by other sources (e.g. stars). Measurements of the lithium abundance in near-pristine stars (blue band) deviate from the Standard Model value, which might indicate new physics or a problem with the current measurements. The aim of this project is to develop a novel method of measuring the lithium abundance to test the Standard Model of physics.

Notes:

CLUSTERS OF GALAXIES: THE UNIVERSE'S KALEIDOSCOPES

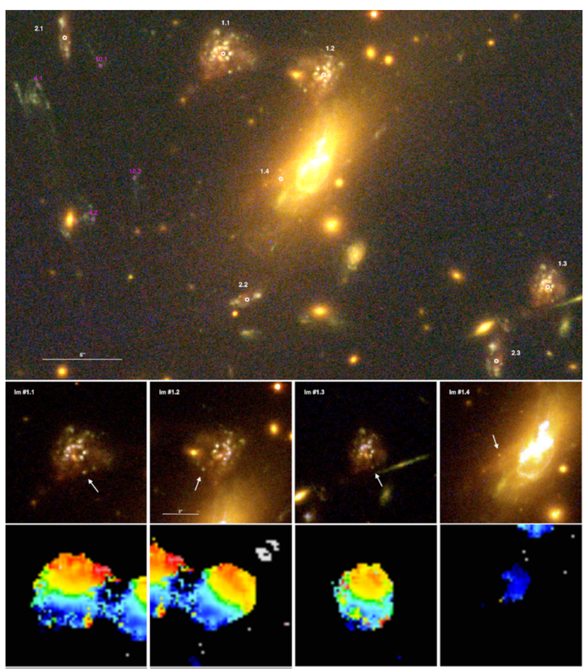
Main Supervisor: Prof Alastair Edge alastair.edge@durham.ac.uk
Office: Ogden Centre West 109
2nd Supervisor: Prof Richard Massey r.j.massey@durham.ac.uk

Funding: TBC / Other funding schemes

Description:

Clusters of galaxies act as the most powerful gravitational lenses in the Universe due to the strong concentration of matter on scales of 100–500 kpc. This is especially true for X-ray selected clusters which are preferentially centrally concentrated. We have catalogued the 128 most X-ray luminous clusters between $0.3 < z < 0.6$ and we have *HST*, *Chandra*, JVLA and *Herschel* data for the large majority. We have an on-going VLT MUSE survey that has observations of over 70 of these clusters to identify the brightest lensed sources as well as spectral information on cluster members. These data can place constraints on the nature of the background, lensed galaxies and thus the Dark Matter distribution in the clusters themselves and provide a rich legacy of targets for follow-up with the VLT, ALMA and *JWST*. In particular, these observations can identify the systems with the brightest lines that are vital for successful AO-assisted follow-up which will sub-divide light into many more spatial elements.

This project would focus on the brightest lensed sources that constrain the gravitational mass of the clusters and also the properties of the lensed galaxy. Through the unprecedented statistics our MUSE survey provides, we can address a wide range of astrophysics questions with both the sample of several hundred lensed sources and the handful of most highly amplified systems that can be followed-up with other telescopes.



(top) HST image of MACSJ0417-11 at z=0.45 showing two prominent triply lensed background galaxies, labelled 1.1/1.2/1.3 and 2.1/2.2/2.3. (next row down) Postage stamps of the images of system 1 showing the symmetry of the images. (bottom rows) MUSE velocity maps of the [OII] line in these galaxies.

Notes:

SIMULATIONS OF PLANETARY IMPACTS

Main Supervisor:	Dr. Vincent Eke	v.r.eke@durham.ac.uk
Office:	Ogden Centre West 215	
2nd Supervisor:	Prof. Richard Massey	r.j.massey@durham.ac.uk
Funding:	STFC	

Description:

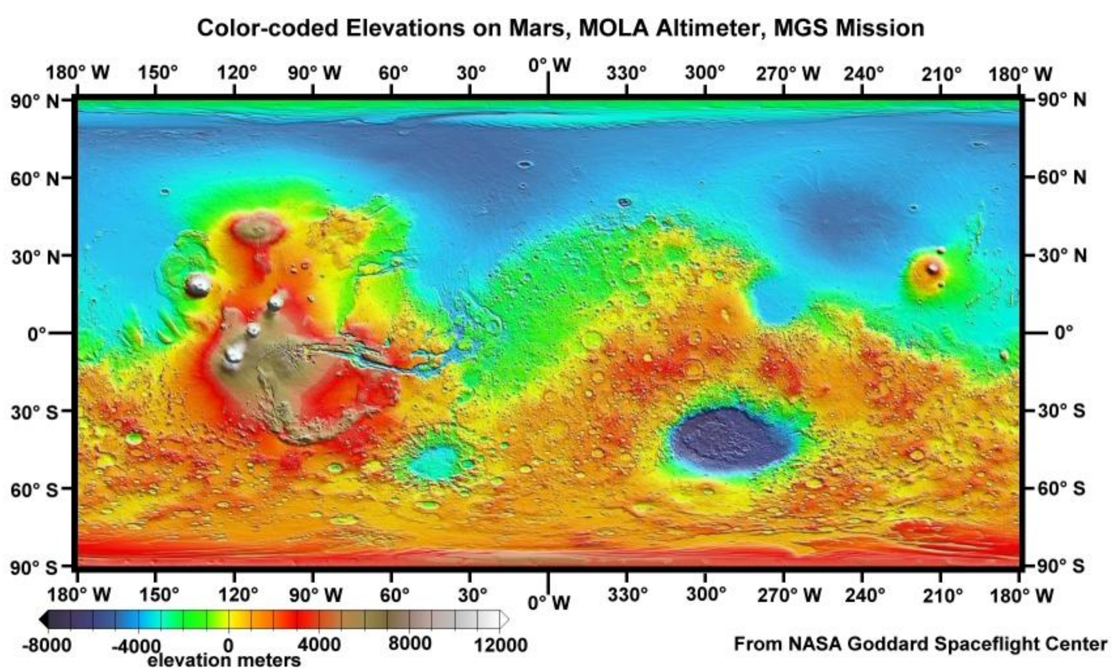
The early Solar System was a violent place where energetic collisions between planetesimals were rife. These impacts represent the most dramatic part of the planet formation process, an understanding of which is required to determine the frequency of exoplanets in habitable zones around other stars.

Observations of the current state of the Solar System provide abundant evidence of past giant impacts: the relatively large core of Mercury, the similar isotope ratios of the Earth and Moon, the diffuse core of Jupiter and the surprising rotation axis of Uranus. With the recent landing of NASA's InSight mission to study the internal structure of Mars, a particularly timely question is what caused the Martian dichotomy, whereby the northern hemisphere is typically much lower than the southern hemisphere?

One of the competing hypotheses to explain the Martian dichotomy is a Moon-sized impactor hitting the northern hemisphere at a low speed and grazing angle, removing some of the crust. An alternative hypothesis involves a south pole strike by a sub-lunar-sized body, causing a hemispherical magma ocean that solidified to form the thicker crust in the south.

The detailed evolution of impacting systems can only be followed using numerical simulations. Durham's astronomy group is involved in running the world's largest numerical simulations in both planetary impacts and extragalactic astrophysics, and the ICC hosts a significant part of the national DiRAC supercomputer facility.

This project, which involves a collaboration with researchers at NASA Ames Research Center, will use the SWIFT state-of-the-art Smoothed Particle Hydrodynamics (SPH) code. While previous Martian impact simulations have used up to a million particles, we will improve the mass resolution by 2-3 orders of magnitude. With these superior numerical capabilities, we will be able to resolve the Martian crust as well as determining the internal structure of the resulting Mars with unprecedented detail. A variety of possible impacts will be investigated and the observable consequences will be inferred, in order to distinguish between competing theories about the formation of the Martian dichotomy.



Notes:

GALAXY CLUSTERS TO REVEAL THE NATURE OF DARK MATTER

Main Supervisor: Dr Mathilde Jauzac mathilde.jauzac@durham.ac.uk
Office: Ogden Centre West 126

Funding: STFC

Description:

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

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

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

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

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

Notes:

SIMULATIONS OF RADIO GALAXIES AND AGN FEEDBACK

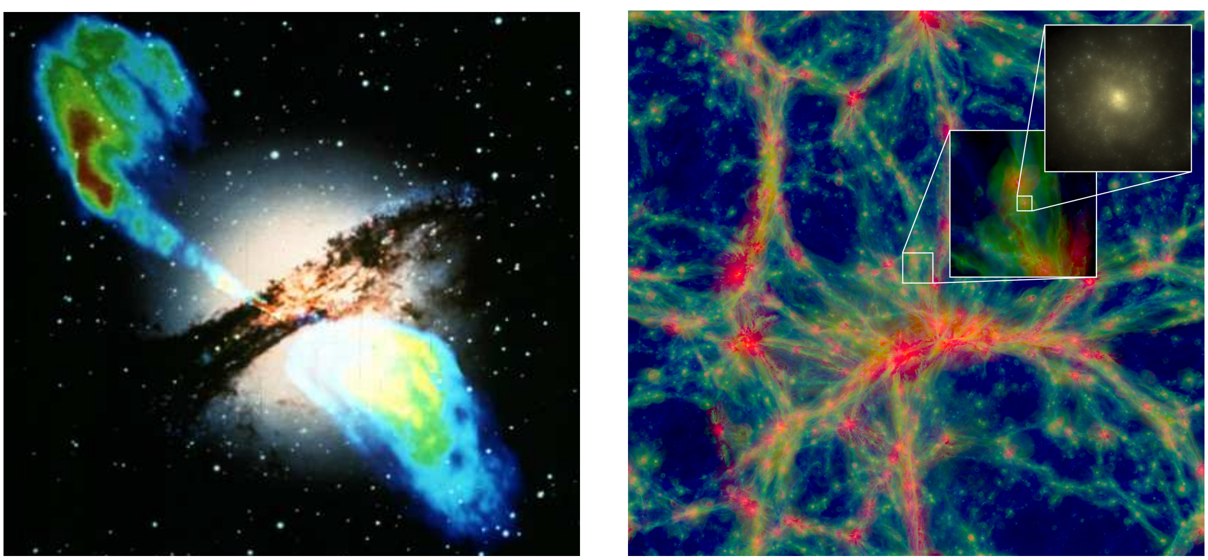
Main Supervisor: Prof. Cedric Lacey cedric.lacey@durham.ac.uk
Office: Ogden Centre West 216
2nd Supervisor: Prof. Richard Bower r.g.bower@durham.ac.uk
Funding: STFC

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 jets emitted by spinning black holes. The jets produce bubbles of relativistic plasma that heat the gaseous halos around galaxies, preventing gas cooling onto galaxies, and are visible as radio galaxies.

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 EAGLE gasdynamical simulation of galaxy formation, focusing on feedback from relativistic jets and the associated radio emission. The first step will be to implement a new model for black hole spin evolution (Griffin et al 2019) into EAGLE, and use this to predict AGN jet powers. These will be used to model radio emission from AGN, and the results compared with the observed properties and evolution of radio galaxies. Finally, the physical mechanism of feedback due to these jets will be studied in more detail.

References:
Schaye, J. et al. 2015, The EAGLE project: simulating the evolution and assembly of galaxies and their environments
Griffin, A.J et al. 2019, The evolution of SMBH spin and AGN luminosities for $z < 6$ within a semi-analytic model of galaxy formation



Left: Combined optical and radio image of the massive elliptical galaxy Centaurus A. The radio emission is due to relativistic jets generated by an accreting massive black hole at the centre of the galaxy. The jets are thought to be heating the gas halo surrounding the galaxy. 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 active galactic nuclei, which drive outflows. (Schaye et al 2015)

Notes:

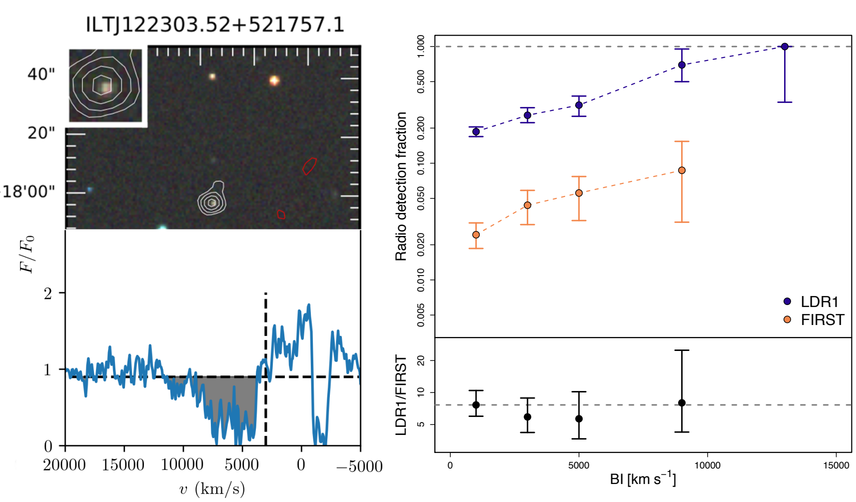
WHAT MAKES BROAD ABSORPTION LINE QUASARS SPECIAL?

Main Supervisor:	Dr. Leah Morabito	leah.k.morabito@durham.ac.uk
Office:	Ogden Centre West 124	
Funding:	STFC	

Description:

Broad absorption line quasars (BALQSOs) are a particular class of quasars which show broad, blue-shifted absorption lines in their optical spectra. This is evidence for strong outflowing winds, which are thought to be driven from an accretion disk around a central super-massive black hole. Not all quasars have broad absorption lines, but it is unclear whether this is because the outflowing winds are a marker for a particular quasar evolution phase, or if all quasars have narrow winds that we only see when they are oriented in our line of sight. Understanding the difference between *evolution* and *geometry* in BALQSOs is therefore key to understanding the quasar population as a whole.

Most broad absorption line quasars are faint when observed at radio frequencies, and we do not know much about their radio emission. New sensitive radio instruments and surveys are changing this, and we can start to make major advances in understanding the radio emission in broad absorption line quasars and the physics of accretion and outflows around black holes. Correlations between properties related to the broad absorption lines (see Figure below) and the radio emission imply a connection – but where does this come from? Is the radio emission generated by the outflows themselves, or merely related to the central quasar driving the entire process?



Left: *An r,g,b image from optical bands with radio emission overlaid as contours. Beneath this image of a BALQSO is the optical spectrum, where you can see the broad absorption line (gray shading) that is blue-shifted from the systemic velocity of the galaxy (dashed line).* ***Right:*** *Using new LOFAR Two-metre Sky Survey (LoTSS) data, we see a correlation between the balnicity index (BI) – which is a measure of how strong is the outflow causing the broad absorption lines – and the radio detection fraction. This implies that there is some connection between the radio emission and the outflows in BALQSOs.*

You will explore these questions using new data from the LOFAR Two-metre Sky Survey (LoTSS) for statistical studies of broad absorption line quasars. Building on published results from data release 1 (Morabito et al. 2019), you will expand this work with data release 2, increasing the sample size by almost an order of magnitude. With such a large sample, you will compare observational trends with toy models to distinguish between *evolutionary* and *geometric* models of quasars. In addition, you will re-process LOFAR data at higher resolution (0.26 arcsec compared to 6 arcsec) to discover the radio morphology of BALQSOs. Finally, you will work with the outputs of hydrodynamical models, comparing them with the observations to determine whether disk winds or jets are creating the radio emission.

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

References

Morabito et al. (2019): https://arxiv.org/abs/1811.07931

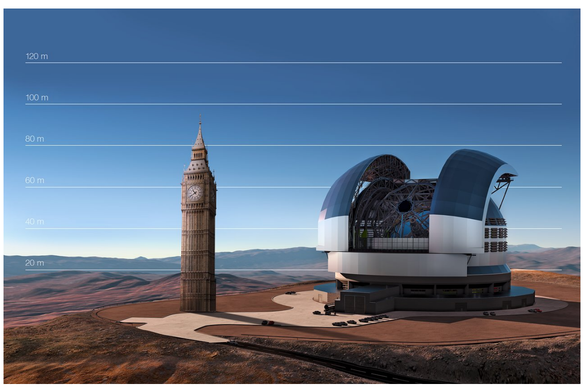
Notes:

ADAPTIVE OPTICS FOR EXOPLANET IMAGING ON THE NEXT GENERATION OF EXTREMELY LARGE TELESCOPES

Main Supervisor:	Dr. Kieran O'Brien	kieran.s.obrien@durham.ac.uk
Office:	Ogden Centre West 029	
2nd Supervisor:	Dr. Tim Morris	t.j.morris@durham.ac.uk
Funding:	STFC (ELT Project)	

Description:

The ESO Extremely Large Telescope (ELT) will be the flagship optical observatory for the coming decades. Its large collecting area and advanced instrumentation fed by a variety of advanced adaptive optics systems will be a driving force for future astronomical discoveries for decades to come. Perhaps the most exciting area of study for the ELT is in the field of exoplanets. The collecting area and angular resolution of the ELT will enable us to probe rocky planets in the habitable zones of nearby stars for the first time. In order to take advantage of these capabilities, ESO intend to fund the ELT Planet Camera and Spectrograph (ELT-PCS). PCS is currently in the early stages of development, with technology studies in a number of different areas, especially in the extreme adaptive optics (XAO) system that is required.



Artists impression of the ESO ELT with Big Ben for scale. Image courtesy of ESO

One of the enabling technologies is a wave-front sensor (WFS) that is capable of achieving the speed and sensitivity required for XAO. We are developing a prototype WFS system that uses Microwave Kinetic Inductance Detectors (MKIDs) coupled to a low-latency wavefront processing system within field-programmable gate arrays (FPGAs) to demonstrate ELT-scale XAO at frame rates far in excess of existing technologies. This brings together several strands of research in the Centre for Advanced Instrumentation, involving the combined developments of the high-speed MKID instrument, its readout electronics and real-time pixel processing at the required frame rates of several kHz. This project includes development of new FPGA code for pulse detection in the data acquisition and the parallel high-speed pixel processing pipeline that comprises the core of the low latency Real Time Computer (RTC), extending the existing FPGA RTC pipeline developed in Durham.

We are looking for a highly motivated student to play an active role in the development of the WFS/AO system within our group. The exact area will depend on the interest of the student, but initial projects could include; designing an optical system to calibrate the MKID arrays; writing software (e.g. Python) to process the output from the MKID array so that they can be interfaced to the RTC; optimising the Adaptive Optics test-bench to demonstrate the closed loop operation of the MKID WFS.

Following from these initial projects, the student's thesis may explore one of several areas with the guidance of experts within CfAI; 1) MKID devices with faster recombination times to enable faster photon rates at the expense of the energy resolution; 2) faster ADC/DAC hardware to enable higher photon fluxes; 3) development of new rolling WFS modes to increase WFS temporal performance; 4) on-sky testing of the MKID WFS; 5) advanced data analysis techniques; 6) another area of hardware or software development.

The student will work with Dr. Kieran O'Brien who is leading the development of MKID instrumentation in Durham University and Dr. Tim Morris who is head of the AO group. The student will have the opportunity to develop skills in areas such as superconducting detectors, cryogenics, adaptive optics, FPGA programming, high-speed data acquisition and processing of 'big data'.

Roadmap for PCS, the Planetary Camera and Spectrograph for the E-ELT, Kaspar et al., AO4ELT3 (2013)

Notes:

CANAPY: AN ADAPTIVE OPTICS TESTBED FOR OPTICAL COMMUNICATIONS AND ASTRONOMY

Main Supervisor: Dr Chris Saunter christopher.saunter@durham.ac.uk
Office: Ogden Centre West 023
2nd Supervisor: Dr James Osborn james.osborn@durham.ac.uk

Funding: STFC

Description:

Canapy is an ambitious and international experiment to develop the concepts and technology for the next generation of optical telescopes. Canapy will bring together researchers from the two overlapping and active fields of astronomical instrumentation and free-space laser communications in order to exploit the knowledge and experience of both. This studentship will develop new concepts and technologies to enhance the capabilities of ground-based astronomy and free-space laser communications, working in association with the Canapy project.

With the Hubble telescope facing imminent retirement and future space telescopes concentrating on longer wavelengths, there is a critical need for ground-based telescopes to deliver high spatial resolution, visible light observations. With sufficiently advanced Adaptive Optics (AO), existing 8m telescopes will deliver visible resolution comparable to the near-IR on the future 39m Extremely Large Telescope. However, observing at shorter wavelengths is difficult due to the turbulent nature of the Earth's atmosphere. Canapy provides an effective on-sky test facility for the required advances in Adaptive Optics (AO), including visible wavelength correction. The extreme challenges of visible light imaging to AO closely relate to the challenges of using AO when communicating with fast moving satellites using light, which is a key development required to deliver higher bandwidth to orbit and beyond.

The Centre for Advanced Instrumentation, Durham University, has significant experience in AO technology, including all aspects of AO system design, operation and performance modelling and verification. Within Canapy, Durham will take a leading role in the performance modelling and verification work with tasks including modelling the AO system, characterising the turbulence in the Earth's atmosphere and understanding the implications for astronomy and free-space optical communications. As such there is significant scope for an active PhD researcher to take the project in one of many directions including theory, computer modelling and simulation, laboratory work and on-sky development depending on their experience and interests.

Canapy is an international enterprise between Durham University, the European Southern Observatory (ESO), the German Aerospace Agency (DLR) and the European Space Agency (ESA).

Photo of the Canapy proof-of-concept experiment (Photo credit: L. Bardou)

Notes:

TRACING MASSIVE GALAXY FORMATION AT HIGH REDSHIFTS USING DUSTY GALAXIES

Supervisors:	Prof. Ian Smail & Prof. Mark Swinbank	ian.smail@durham.ac.uk
Office:	Ogden Centre West 112 / Ogden Centre West 113	
Funding:	TBC / Other funding schemes	

Description:

Our sun collapsed from a cold molecular gas cloud in the disk of the Milky Way around 4.5 billion years ago. However, many of the stars seen in galaxies today were formed at much earlier times, 7–10 billion years ago, corresponding to a redshift, z, of $z \sim 1$–3. Galaxies at these early times were forming stars typically 10–30 × faster than average galaxies today. This period has therefore been herald as the "epoch of galaxy formation" (or "Cosmic Noon"). Star-formation activity in galaxies has declined over the last ∼ 7 billion years (since $z \sim 1$), apparently driven by a corresponding reduction in the amount of cold molecular gas available within galaxies, as this material is converted into stars or heated and expelled from the galaxies.

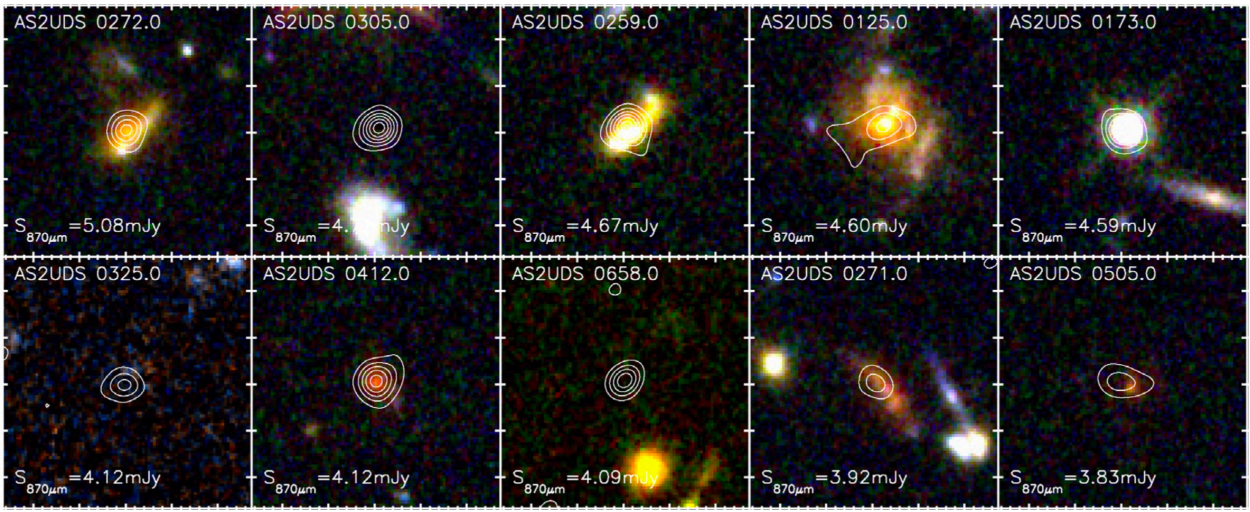
The most actively star forming galaxies at high redshift are converting their gas reservoirs into stars 100–1000 × faster than the Milky Way currently does. Such extreme rates of star formation are seen in less than one per cent of galaxies at the present day, but such active systems appear to be much more common in the early Universe. It has been suggested that up to half of all of the stars seen in local galaxies formed in these intense events at $z \sim 2$–4, making them a crucial phase for understanding galaxy formation.

Despite their high star-formation rates, this population of vigorous star-forming galaxies are in fact some of the hardest to study. This is because a by-product of intense star formation is the creation of large amounts of dust, which forms in the atmospheres of massive stars during the later phases of their evolution and death. This dust absorbs the light from other young stars, making these galaxies very faint in the optical and ultra-violet wavebands that are typically used to survey the distant Universe. However, the dust grains which absorb this optical/ultra-violet light heat-up and subsequently re-emit the radiation in the far-infrared and sub-millimetre wavebands. This emission makes these galaxies some of the most luminous far-infrared sources known, allowing us to pin-point the sites of immense starbursts early in the life of the Universe. The physical processes occuring within these galaxies may be very different to those which operate in the declining phase of "galaxy formation" since $z \sim 1$ and we need to understand and model these processes if we are to build a robust theory of galaxy formation and evolution.

To this end we are undertaking a series of surveys to study this enigmatic population of dusty starburst galaxies. These surveys combine tracers across a broad swathe of the electromagnetic spectrum, from the radio, sub-millimetre and far-infrared, through the mid- and near-infrared, into the optical, ultra-violet and out to X-rays. This multi-wavelength approach allows us to investigate the growth of this population through both their star formation, the growth in their stellar mass and the attendant decline in their gas content, as well as the accretion which occurs onto black holes within these systems. Our goal is to derive an empirical description of the evolution of the population of luminous, dusty starbursts and so to test their part in the formation of the massive, galaxies at the present-day. We also wish to test links between these galaxies and the formation of clusters of galaxies and also the luminous Quasar population, whose activity also peaked at $z \sim 2$–3.

This is an observationally-driven PhD project and the successful student will be expected to 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 bolometric submillimetre surveys, using the JCMT on Hawaii, interferometric data reduction and analysis, based on data from the NOEMA and ALMA millimetre interferometers, as well as the exploitation of integral field spectroscopy (from KMOS on VLT in Chile) and wide-field imaging and spectroscopy. There will also be opportunities to relate the observational results to theoretical models being developed at Durham.

See also: http://www.astro.dur.ac.uk/∼irs and http://www.astro.dur.ac.uk/∼ams.



True–color images constructed from Hubble Space Telescope (HST) imaging in the optical and near-infrared, with Atacama Large Millimetre Array (ALMA) data overlaid as contours, for a selection of high-redshift starburst galaxies. The HST optical/near-infrared imaging traces the light from less dust-obscured stars and the ALMA submillimetre observations indicate the site of the dustiest and most active regions of the galaxies. We see that morphologically complex and potentially disturbed stellar continuum emission, perhaps indicating these galaxies are interacting with neighbours, but with dusty star formation occuring in significantly more compact regions (suggestive of bulge formation). We also see examples of both galaxies which are so dust-obscured (or distant) that they are invisible to HST, while being detectable by ALMA, and also rare examples of accreting supermassive black holes (Quasars) which are also strong submillimntre sources (AS2UDS0173.0). Our on-going studies with ALMA and other observatories seek to understand the cause of this intense activity in young galaxies at high redshifts and to test the link between this population and the formation of both massive galaxies and Quasars. This figure comes from a chapter of Stuart Stach's Durham PhD thesis: http://arxiv.org/abs/1903.02602

Notes:

STRONG LENSING, STELLAR DYNAMICS, AND THE INITIAL MASS FUNCTION IN ELLIPTICAL GALAXIES

Main Supervisor: Dr. Russell Smith russell.smith@durham.ac.uk
Office: Ogden Centre West 127
2nd Supervisor: Dr. John Lucey john.lucey@durham.ac.uk
Funding: STFC

Description:

The stellar initial mass function (IMF) is the distribution of masses formed in a population of stars, i.e. the relative number of high-mass and low-mass stars. Because the crucial properties and evolution of *stars* are controlled to a great degree by their masses, the evolution of *galaxies* depends heavily on the form of the IMF.

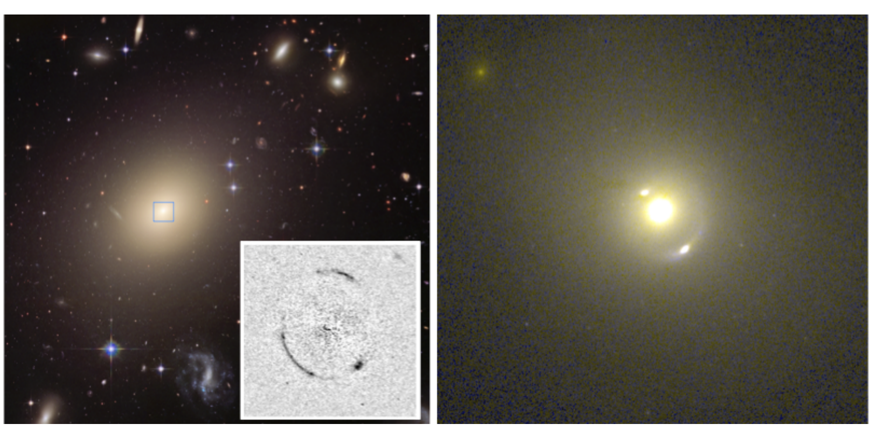
The IMF can only be measured *directly* in the Milky Way and in a few of its satellite dwarf galaxies, where most measurements find a similar mix of initial masses. In the absence of better information, astronomers generally assume that the Milky Way IMF applies equally to *all* other types of galaxy throughout the universe, regardless of galaxy mass, formation redshift, etc. The question of whether the IMF is truly "universal" has been hotly debated in recent years, with a particular focus on massive elliptical galaxies, which formed most of their stars in violent bursts at early cosmic epochs.

For elliptical galaxies, we rely on indirect methods to probe the IMF, either measuring the subtle effects of low-mass stars in the integrated-light spectra of galaxies, or detecting their gravitational influence through stellar dynamics or gravitational lensing. Some observational studies suggest that the largest ellipticals harbour an excess of very low-mass stars, i.e. a so-called "bottom-heavy" IMF, which would have important implications both for interpreting galaxy evolution observations, and understanding how star-formation depends on environmental conditions.

In Durham, we are addressing these questions using rare low-redshift (i.e. nearby) gravitational lens systems, where we can weigh the stellar component of galaxies reliably, with little uncertainty about dark-matter content (which plagues most lensing measurements). Starting with our "SNELLS" project, we developed a novel observing method using integral-field spectrographs to search systematically for such lenses. To date, our systems seem *compatible* with the same IMF as in the Milky Way, in contrast to the studies noted above. With the stellar masses of these galaxies anchored by lensing, follow-up work using stellar dynamics and detailed spectroscopy provide a unique opportunity to understand the apparent discrepancies in previous studies.

As a PhD student joining our group, you will lead a project to develop new lens search programmes (with the ESO VLT and the Subaru Telescope), to enlarge the sample of known low-redshift lenses. In parallel, you will work on the scientific exploitation of the newly discovered systems, using a combination of spectroscopic stellar population analysis, stellar dynamics and lens modelling using Hubble Space Telescope observations. The ultimate goal is to use this uniquely-powerful sample of lensing ellipticals to determine whether and how the IMF depends on galaxy properties, or varies with position within galaxies.

Description of the original SNELLS lensing-galaxy search project: ESO Messenger summary and Smith et al. (2015)
Paper comparing spectroscopic analysis against lensing constraints on the IMF in SNELLS lenses: Newman et al. (2017)
We have also used low-redshift lenses to test the predictions of General Relativity: Collett et al. (2018) and ESO press release.



Hubble Space Telescope images of two nearby gravitational lenses discovered by our group, used in our study of the stellar IMF.

ESO325–G004 (left) was the first such system to be identified; the lensed arcs are only visible after subtracting a model for the foreground elliptical (inset).

J0403-0239 (right) was discovered by a current Durham PhD student, using our integral-field lens-search search method.

Notes:

FROM THE FIRST GALAXIES TO THE MILKY-WAY: GALAXY EVOLUTION OF THE LAST 10 BILLION YEARS

Supervisor: Prof. Mark Swinbank a.m.swinbank@durham.ac.uk
Office: Ogden Centre West 113
Funding: TBC / Other funding schemes

Description:

In the mid 1920's, Edwin Hubble visually classified local galaxies into categories of spirals, ellipticals, lenticulars and peculiar shapes. The Hubble-Sequence remains one of the defining characteristics of galaxies, and provides one of the key constraints that galaxy formation models strive to reproduce.

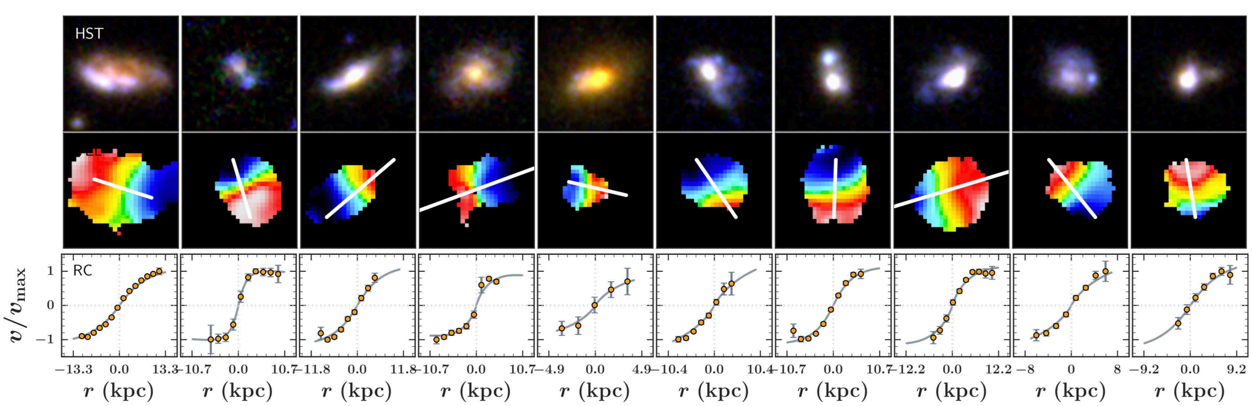
Dynamical studies of local galaxies have shown that the Hubble Sequence of galaxy morphologies follows a sequence of increasing angular momentum at a fixed mass. In the cold dark matter paradigm, galaxies form at the centres of dark matter halos. As the gas collapses within the dark halo, the baryons 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 (e.g. a spiral 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* 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. look-back 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 (e.g. using *Hubble Space Telescope*, KMOS and ALMA). There will also be opportunities to relate the observational results to theoretical models being developed at Durham.
See also: http://www.astro.dur.ac.uk/∼ams/kmos/ and http://www.astro.dur.ac.uk/∼ams



Example images and dynamical maps of star-forming galaxies at $z \sim 1.5$ from our (ongoing) KMOS surveys. For each galaxy, we show the HST *IJH-colour image (top row), the KMOS Hα line-of-sight velocity map (middle row), and the (normalised) 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 of high-redshift galaxies.*

Notes:

GALAXIES IN A MGWDM UNIVERSE

Main Supervisor: Professor Tom Theuns tom.theuns@durham.ac.uk
Office: Ogden Centre West 207
2nd Supervisor: Professor Baojiou Li baojiu.li@durham.ac.uk

Funding: STFC

Description:

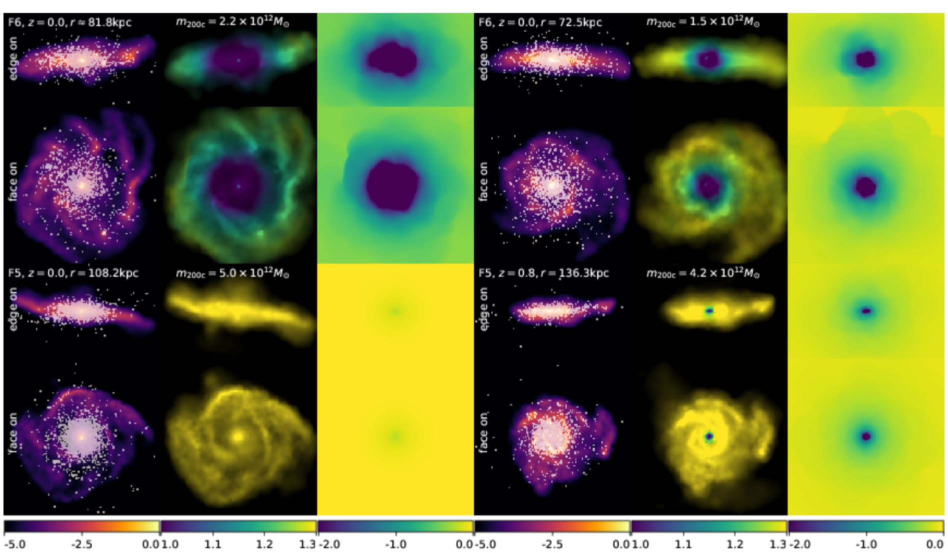
The ΛCDM cold dark matter model is a very successful theory, however the value of the cosmological constant, Λ, is not predicted by particle physics and no cold dark matter particle has yet been discovered in the lab. Developing a physically motivated alternative to ΛCDM is challenging, because ΛCDM describes the observed Universe so well. However, there is such a theory: MGWDM. In this cosmogony, the late-time acceleration results from a modification to Einstein's theory of general relativity, hence Modified Gravity (MG), rather than from a cosmological constant. The dark matter is not cold, but warm: WDM for warm dark matter. A particularly promising WDM candidate is the sterile neutrino, that, unlike standard model neutrinos, does not interact with standard model particles except through gravity. Such sterile neutrinos can also help explaining the matter-anti matter asymmetry.

Even though galaxies in ΛCDM and MGWDM look similar, there are differences. MG results in variations in the effective value of G, the gravitational constant, which might be observable. WDM suppresses the formation of small galaxies due to dark matter free streaming, which might also be observable. In this project, you will use the AREPO hydrodynamical simulation code to contrast ΛCDM galaxies with MGWDM galaxies. In particular, you will look for generic differences, that result from the different gravitational effects due to MG, and the different growth of halos due to warm dark matter particles. You will be the first person to simulate a MGWDM Universe!

You will work with Tom Theuns, who is an expert in simulations of galaxy formation, Baojiu Li, who is an expert in simulations of MG, and post-doc Christian Arnold, who has been studying galaxy formation with AREPO. The simulations use the implementation of galaxy formation of the ILLUSTRIS project.

More reading:

- Arnold, Leo, & Li: arXiv:1907.02977
- hrefhttps://ui.adsabs.harvard.edu/abs/2019arXiv190904641L/abstractLeo, Theuns, Baugh, Li, Pascoli: arXiv:1909.04641
- Illustris project: https://www.illustris-project.org/
- The AREPO code: https://arepo-code.org/.



A selection of four galaxies from an MG simulation. Yellow coloured gas cells experience an enhanced total force due to modified gravity.

Notes: