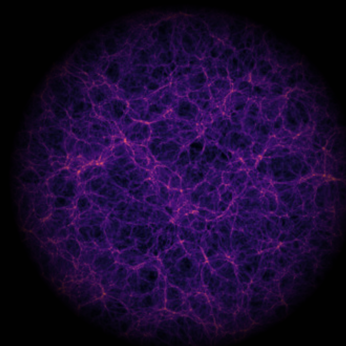
Astronomy PhD Projects at Durham

2019

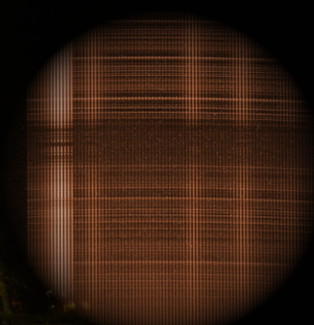
Durham University

ICC



Durham Centre for Extragalactic Astronomy

CfAI



PHD PROJECTS IN ASTRONOMY FOR AUTUMN 2019 START

Fully Funded PhD Projects

Baugh: Machine learning applied to galaxy formation and neutralising security threats

Cooke: The cosmological lithium problem

Deason: Near-field cosmology with destroyed dwarf galaxies

Eke: Simulations of planetary impacts

Frenk: The identity of the dark matter

Frenk: Cosmological constraints on the mass of the neutrino

Fumagalli: Diving deep into the universe

Lucey: Exploiting the new peculiar velocity surveys

Massey: The nature of dark matter and gravity with strong gravitational lensing

Morris: Adapting to the atmosphere at the largest scales

O'Brien: A new era of astronomy with kinetic inductance detectors

Roberts: Black holes and neutron stars in the nearest galaxies

Theuns: The BAO feature in the Lyman-α forest

Wilson: Characterising and correcting atmospheric seeing effects in astronomy

PhD projects with no specific funding confirmed

Alexander: Tracing the cosmic growth of black holes with the NuSTAR X-ray Observatory

Baugh: Using machine learning to uncover the galaxy - dark matter halo connection

Chadwick: Extreme environment astrophysics: γ-ray astronomy and the Cherenkov telescope array

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 31 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 2019.

Fully Funded PhD Studentship Options

This booklet primarily outlines PhD projects for which we can provide full funding (fees plus a stipend) over 4 years typically. 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; see the STFC web site for more specific details regarding STFC studentship eligibility: http://www.stfc.ac.uk. We expect to offer 6 STFC-funded studentships this year.

Science and Technology Facilities Council Center for Doctoral Training (STFC CDT) studentships. These 4-year PhD studentships have in general a broader eligibility criteria than standard STFC studentships. Over the past 2 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. The CDT studentship includes a 6 months internship with one of the CDT partners of the Durham Data Intensive Science CDT.

Science and Technology Facilities Council CASE (STFC CASE) studentship. This PhD studentship has the same eligibility criteria as the standard STFC studentships. We have one STFC CASE studentship this year.

European Research Council (ERC) studentship. These 4-year PhD studentships are available to any graduate student irrespective of domicile. We have up to 2 ERC studentships this year.

Royal Society funded PhD studentship. This 4-year PhD studentship has the same eligibility criteria as the STFC studentships. We offer 1 Royal Society studentship this year.

Durham University Astro Particle Studentship. This 4-year studentship is available to Home/EU students domiciled in the EU. We have 1 studentship this year.

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 studentship from mid-February through to mid-March (see our webpages 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 listed at the end of 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 Wednesday January 16$^{\text{th}}$ 2019, while the CSC deadline is Friday December 14$^{\text{th}}$ 2018, both for an autumn 2019 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.

In the past year 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*, *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 governement 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.

FULLY FUNDED PHD STUDENTSHIPS IN ASTRONOMY FOR AUTUMN 2019 START

Fully Funded Projects

Baugh: Machine learning applied to galaxy formation and neutralising security threats

Cooke: The cosmological lithium problem

Deason: Near-field cosmology with destroyed dwarf galaxies

Eke: Simulations of planetary impacts

Frenk: The identity of the dark matter

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Wilson: Characterising and correcting atmospheric seeing effects in astronomy

MACHINE LEARNING APPLIED TO GALAXY FORMATION AND NEUTRALISING SECURITY THREATS

Main Supervisor: Prof. Carlton Baugh c.m.baugh@durham.ac.uk
Office: Ogden Centre West 122
2nd Supervisor: Dr. Ben Cantwell, Kromek Group PLC

Funding: STFC CASE studentship

Description:

This is a joint project between Durham University and Kromek Group PLC, an SME based at the North East Technology Park (Netpark), which specializes in X-ray imaging and threat detection. An application has been made to STFC for CASE studentship funding and is currently under review. The student would follow the first year of PhD courses at Durham, spending the first 18-24 months mainly at the University, with the second part of the thesis spent applying the research skills developed in academia on industrial research problems at Kromek.

The objective is to develop novel machine learning approaches to solve outstanding problems in the modelling of galaxy formation. The student will apply these techniques to the detection of airport security threats using X-ray imaging of luggage.

Much progress has been made in the simulation of the formation and evolution of galaxies, through hydro simulation and semi-analytical modelling. The models give plausible reproductions of observed galaxies. However, the calibration of the model parameters remains opaque and it is unclear how robust the predictions are for new observations. We will investigate novel techniques to assess the sensitivity of the models to different parameters, using, for example, Sobol indices, and to search multi-dimensional parameter spaces efficiently. The techniques developed and refined in galaxy formation research will then be applied by the student working with the industrial partner, Kromek. Here, the student will work on a new project on the detection of powder-based threats. The work will involve removal of biases in the data and the identification of signatures of security threats.

Industrial partner website: https://www.kromek.com/
http://adsabs.harvard.edu/abs/2017MNRAS.466.2418R - related paper on automatic calibration of model parameters.

An example of a Kromek product for detecting liquid explosives. One objective of this project is to use machine learning to detect powder based security threats.

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

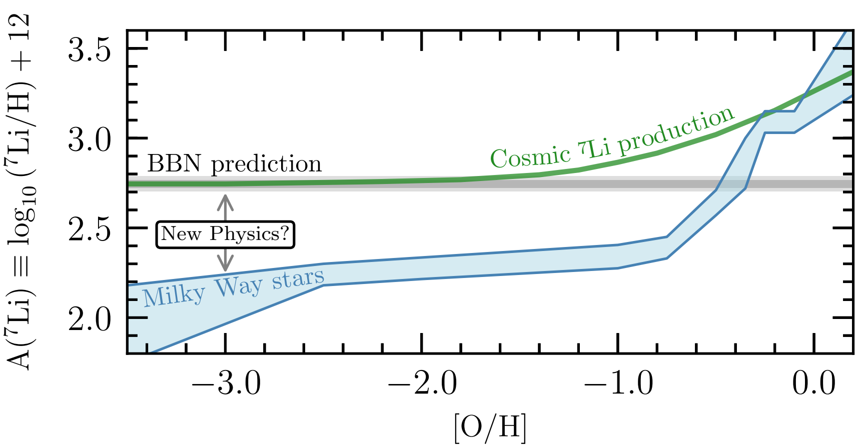
Description:

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:

NEAR-FIELD COSMOLOGY WITH DESTROYED DWARF GALAXIES

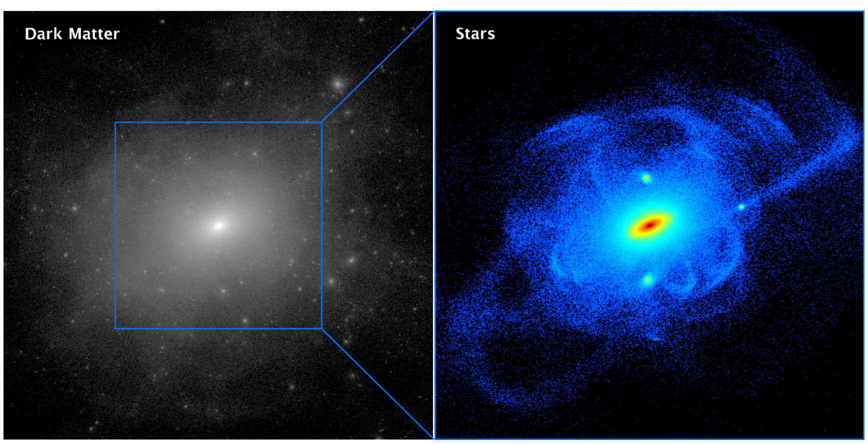
Main Supervisor: Dr. Alis Deason alis.j.deason@durham.ac.uk
Office: Ogden Centre West 219
Funding: Royal Society

Description:

The Milky Way galaxy is a cannibal; throughout its lifetime it devours hundreds of dwarf galaxies. Observable memories of this eating habit are splayed out in a vast stellar halo, which extends out to tens of kpc from the Galactic centre. These halo stars provide a unique insight into the lowest luminosity dwarfs in the Universe, and the dark matter halo of the Milky Way. Dwarf galaxies play a major role in our understanding of dark matter and galaxy formation; while the dwarf satellites continue to challenge our cosmological theories, their destroyed analogues have rarely been used to address the same fundamental questions. Over the next decade, we will witness a surge in the number of observational surveys of the Milky Way halo. Until recently, our view of the halo was limited to 4 dimensions 3 spatial, and 1 velocity component along the line-of-sight. However, we have now entered the era of Galactic halo astrometry, where the *Gaia* mission will measure the transverse motions of millions of halo stars. The combination of wide-field spectroscopy and the *Gaia* astrometry will transform our view of the halo into 6 dimensions.

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

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



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

Notes:

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:

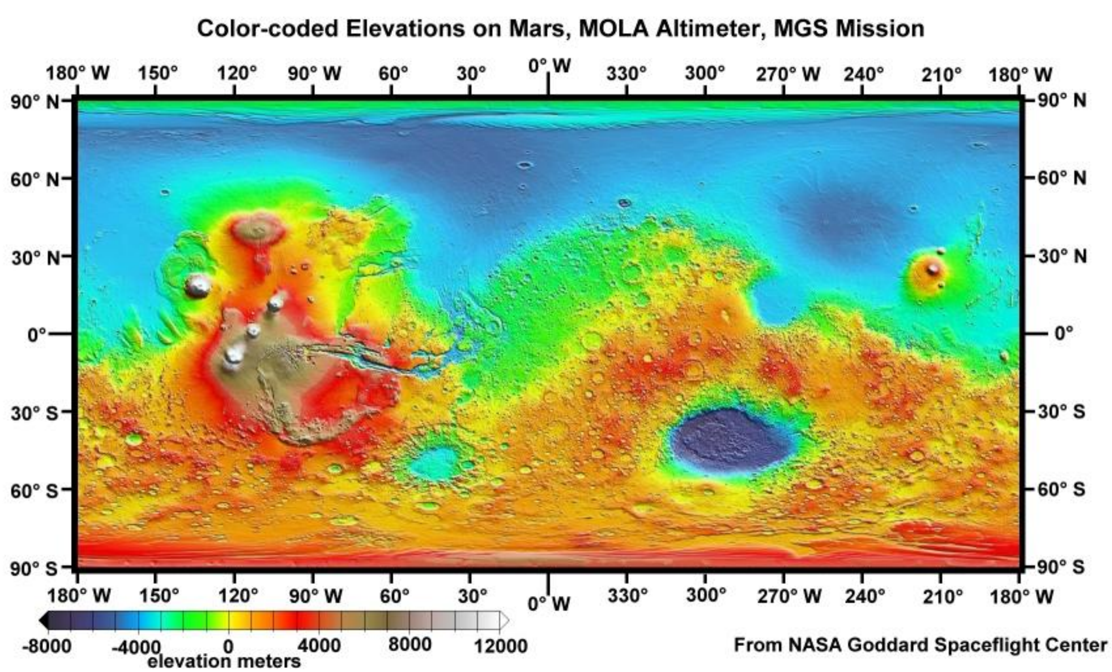
The early Solar System was a violent place where energetic collisions between planetesimals were rife. These impacts represent the most dramatic part of the planet formation process, an understanding of which is required to determine the frequency of exoplanets in habitable zones around other stars.

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, and the surprising rotation axis of Uranus. With the planned November 2018 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:

THE IDENTITY OF THE DARK MATTER

Main Supervisor:	Prof. Carlos Frenk CBE FRS	c.s.frenk@durham.ac.uk
Office:	Ogden Centre West 225	
2nd Supervisor:	Prof. Shaun Cole	shaun.cole@durham.ac.uk
Funding:	ERC	

Description:

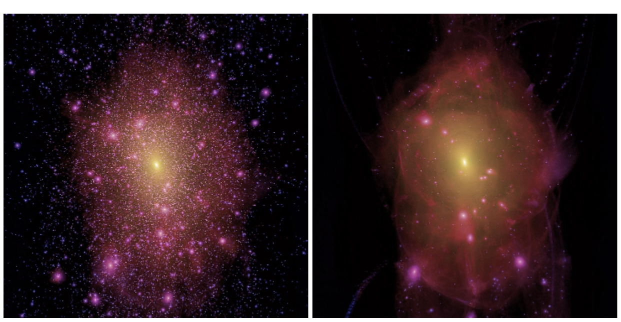
Ever since the idea that the dark matter could consist of non-baryonic particles was put forward in the early 1980s, identifying its nature has been a prime target of physics research. The best studied hypothesis (extensively explored by ICC theorists) is that the dark matter is a cold, collisionless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

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

The goal of this project is to uncover astrophysical observables that might constrain, or perhaps even reveal the identity of the dark matter. It will focus on three key diagnostics: strong gravitational lensing, dwarf galaxies and stellar halos. The project is primarily theoretical but some analysis of real astronomical data may be required. It will rely heavily on cosmological simulations, both using N-body simulations that follow the evolution of the dark matter and gasdynamic simulations that follow, in addition, the evolution of baryonic (or ordinary) material. The simulations are technically challenging but we have a revolutionary new code, SWIFT, developed at Durham, that will enable cosmological simulations an order of magnitude larger than is possible today.

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

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



Images of a cold (left) and a warm (right) dark matter galactic halo at the present day obtained from large N-body simulations carried out at the ICC. The warm case corresponds to a resonantly produced 2keV sterile neutrino. Image intensity indicates the line-of-sight projected density squared, and hue the projected density-weighted velocity dispersion, ranging from blue (low velocity dispersion) to yellow (high velocity dispersion). Each box is 1.5 Mpc on a side. Note the sharp caustics visible at large radii in the WDM image, several of which are also present, although less well defined, in the CDM case.

Notes:

COSMOLOGICAL CONSTRAINTS ON THE MASS OF THE NEUTRINO

Main Supervisor:	Prof. Carlos Frenk CBE FRS	c.s.frenk@durham.ac.uk
Office:	Ogden Centre West 225	
Other supervisors:	Prof. Carlton Baugh	c.m.baugh@durham.ac.uk
	Dr. Baojiu Li	baojiu.li@durham.ac.uk
	Prof. Silvia Pascoli	silvia.pascoli@durham.ac.uk
Funding:	Durham University Astro Particle Scholarship	

Description:

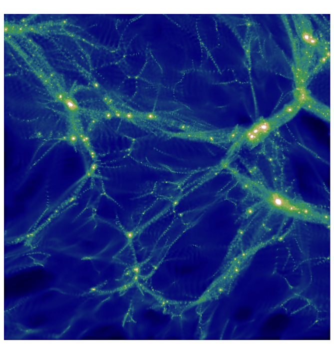
Various experiments have shown that neutrinos have a small mass. (The 2015 Nobel prize in Physics was awarded to Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations, which demonstrate that neutrinos have a mass.) Thus, neutrinos are the only identified form of dark matter particles. As such, they affect the formation of cosmic structures such as galaxies and clusters. Cosmological diagnostics, particularly temperature fluctuations in the cosmic microwave background radiation and the large-scale clustering of galaxies, can be used to set an upper limit on the neutrino mass. The best current upper limit is about 0.3 ev and this implies that neutrinos contribute at most a few percent of the total dark mass in the Universe. The rest is very likely a cold dark matter particle. In the early universe neutrinos behaved like hot dark matter because when they emerged they moved at relativistic speeds. Their main effect is to modify the shape of the primordial spectrum of density perturbations on large scales. This is subsequently reflected in the galaxy distribution.

This project has two main goals. The first is to produce the best predictions to date of the effect of massive neutrinos on the large-scale distribution of galaxies at different cosmic epochs. This will require carrying out and analysing large cosmological supercomputer simulations to follow the evolution of the dark matter and galaxies as a function of cosmic epoch. Although cosmological simulations with neutrinos have been performed before (including by a former ICC PhD student), the problem is far from solved and new techniques will be needed to model the velocities of the neutrinos.

Armed with robust theoretical predictions, the second main goal of the project is to apply the results to real data. The ICC is a partner in DESI, the "dark energy spectroscopic instrument" survey. This is an international venture that will carry out the largest and most detailed survey of galaxies and quasars over a large range of cosmic epochs. The survey will commence in Autmn of 2019 and will deliver exquisite data during the period of this PhD project. Comparing the clustering pattern of galaxies in the DESI survey at different epochs with the simulation results will enable the student to set the best upper limits on the neutrino mass. These can be compared to measurements from laboratory particle physics experiments that will take place on a similar timescale. Comparing the cosmological and laboratory measurements will constrain important properties of the neutrino and may reveal physics beyond the standard model.

Although this project is primarily astrophysical and cosmological, the results will be relevant to particle physics as well. This is why the supervisory team involves colleagues from the ICC and the IPPP (the Institute for Particle Physics Phenomenology). The student will make use of the ICC's large supercomputer (the "Cosmology Machine"), as well as resources provided by the "Virgo consortium", Europe's premier collaboration for cosmological simulations, which is based at the ICC.

Frenk, C. S. & White, S. D. M, 2012, Dark matter and cosmic structure Annalen der Physik, vol. 524, 507
Liu, J. et al. 2017, MassiveNuS: cosmological massive neutrino simulations



The dark matter distribution in slice of 20 Mpc length and 3 Mpc depth taken from an N-body simulation of with massive neutrinos. Courtesy of Matteo Leo, ICC.

Notes:

DIVING DEEP INTO THE UNIVERSE

Main Supervisor: Prof. Michele Fumagalli michele.fumagalli@durham.ac.uk
Office: Ogden Centre West 120
Funding: STFC / ERC

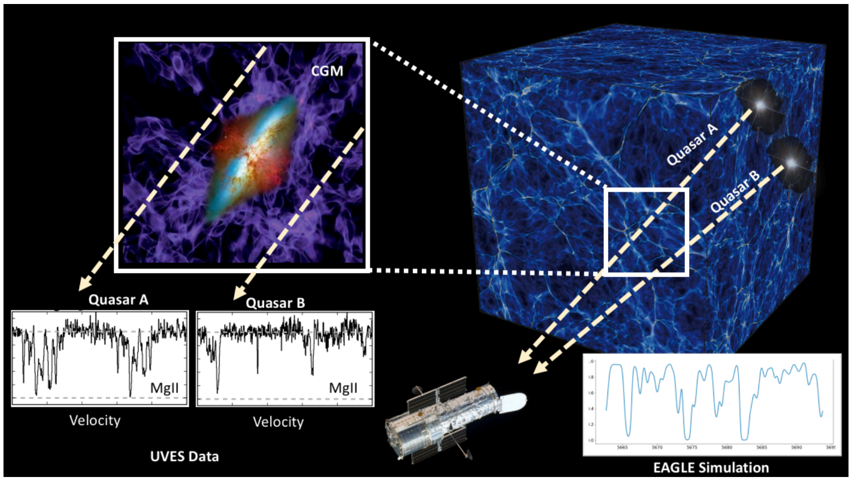
Description:

This project aims to exploit the deepest spectroscopic observations ever collected from the ground and in space of a remarkable region of the sky that hosts several astrophysical structures at different redshifts. By leveraging 150 hours of MUSE integral field spectroscopy at the Very Large Telescope combined with 90 orbits of slitless spectroscopy using the *Hubble Space Telescope*, this project will:

- Redefine our view of the matter distribution at $z \approx 3$ with the exciting prospects of detecting the cosmic web in emission near galaxies and quasars.
- Provide a definite picture of how gas flows inside halos shape the fate of galaxies, complementing observations in absorption against quasars with measurements of the diffuse halo gas in emission (see figure).
- Open a new window into the link between quasars and their environment.
- Allow an unprecedented study of the physical properties of galaxies across 10 billion years of cosmic time, constraining how the Hubble sequence builds up from $z \approx 2.5$ to the present days.
- Pin down the latest stages of reionisation, reshaping our view of faint Lyα emitters up to $z \approx 6$.

This will be a prime spectroscopic survey of faint galaxies for future follow-up with world-class observatories such as ALMA, JWST, E-ELT, and SKA.

Click here to read more about:
The IMAGE group
MUSE@ESO
WFC3@HST



Cartoon representation of one of the experiments enabled by the MUSE+HST Ultra Deep Field. As the light from two quasars travels to Earth, it intersects the IGM (main panel) and CGM of galaxies (inset) along two rays, offering a tomographic view of the spatial distribution of hydrogen and metals next to the galaxies. The unique combination of 90-orbit WFC3 wide-field spectroscopy with 150 hours of MUSE spectroscopy provides a very powerful dataset to probe for the first time the contribution of low-mass galaxies identified via emission lines to the metal enrichment of the CGM and IGM across 5 billion years of cosmic history

Notes:

EXPLOITING THE NEW PECULIAR VELOCITY SURVEYS

Main Supervisor: Dr. John Lucey john.lucey@durham.ac.uk
Office: Ogden Centre West 110

Funding: STFC

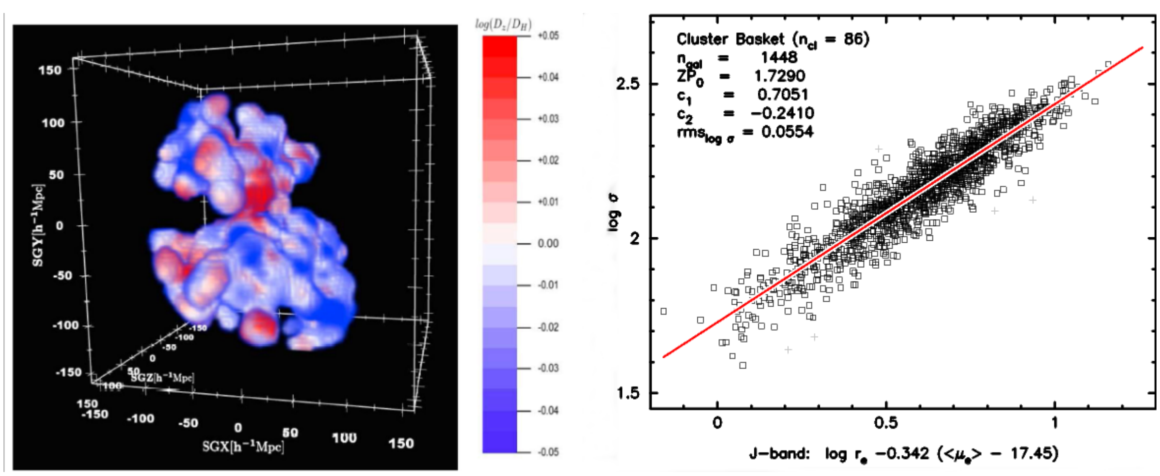
Description:

Peculiar velocities (v_{pec}) arise from inhomogeneities in the large-scale mass distribution and can be determined by accurate distance measurements (D) via $v_{pec} \approx cz - H_0 D$. While much progress has been made in mapping the local peculiar velocity field (see e.g. Springob et al 2014, Carrick et al. 2015), there are several key issues that are still poorly known, e.g. the precise source of the Local Group (LG) motion with respect to the CMB, the bulk flow amplitude at large scales which is a sensitive probe of matter density fluctuations. The quantity and accuracy of existing distance measurements restrict progress to provide robust answers to these fundamental questions.

The Taipan Galaxy Survey (de Cunha et al 2017) is a southern sky, multi-object spectroscopic survey, starting in early-2019, which will obtain redshifts for over a million galaxies and measure Fundamental Plane (FP) distances for ∼50 000 early-type galaxies within $z < 0.07$. The volume surveyed by Taipan will be 4× larger (with denser sampling and improved velocity precision) than the current state-of-the-art provided by 6dFGSv (Springob et al. 2014). The statistical properties of the density and velocity fields, and their mutual consistency, will provide key tests of the cosmological model and independent measures of model parameters that cannot be determined from redshift surveys alone. Taipan, combined with other planned peculiar velocity surveys, will constraint $f\sigma_8$ at low-redshift, allow tests of modified gravity, and measure the local growth rate of large-scale structure (see Howlett et al. 2017).

As a PhD student you will join the Taipan peculiar velocity team and assist in all aspects of this major survey which will include the data reduction and analysis, and exploitation of the results. Initially the work will involve the construction of a new homogeneous all-sky galaxy catalogue. As well as being used to refine the Taipan galaxy selection, this catalogue will be exploited to characterise the local cosmography, i.e. the local cosmic web (clusters, filaments, and voids) including a new assessment of the reality of the "Local Hole". Spectra from the Taipan Galaxy Survey will also discover extremely rare and astrophysically valuable objects, e.g. like the quad-lensed QSOs found in the target preparation work (Lucey et al. 2018).

References: 6dFGSv survey, Springob et al 2014, MNRAS, 45, 2677, Taipan Galaxy Survey "White Paper", da Cunha et al 2017, PASA, 34, 47, "Cosmological forecasts", Howlett et al. 2017, MNRAS, 464, 2517, 2M++ comparison, Carrick et al. 2015, MNRAS, 450, 317, "Two diamonds ...", Lucey et al 2018, MNRAS, 476, 927



Left: *The smoothed 6dFGSv peculiar velocity field in 3D, plotted on a grid in supergalactic cartesian coordinates, with grid-points colour-coded by the value of* $\Delta d = \log(D_z/D_H)$*, from Springob et al 2014.* **Right:** *The FP global fit for an all-sky set of rich clusters from Lucey et al 2019. This has been used to make a new robust determination of the bulk flow.*

Notes:

THE NATURE OF DARK MATTER AND GRAVITY WITH STRONG GRAVITATIONAL LENSING

Main Supervisor: Prof. Richard Massey r.j.massey@durham.ac.uk
Office: Ogden Centre West 115
2^{nd} Supervisor: Dr. James Nightingale james.w.nightingale@durham.ac.uk
Funding: STFC

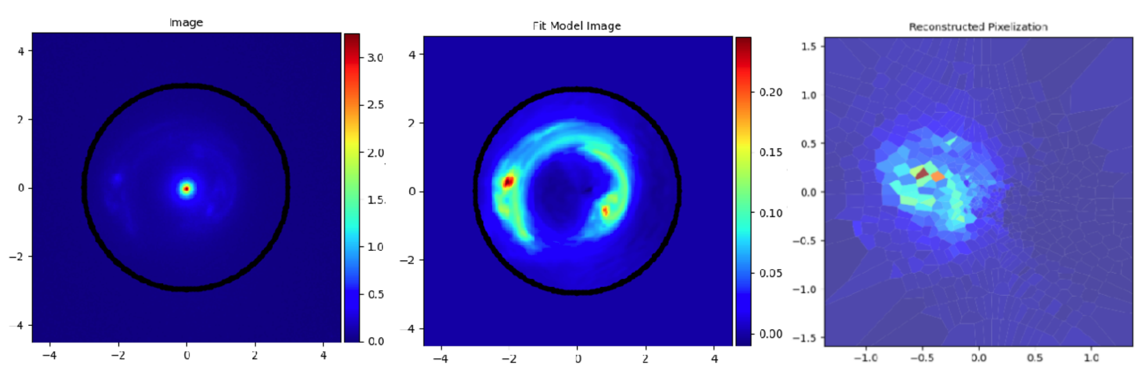
Description:

Einstein's theory of general relativity states that the gravitational field of a massive object curves space-time around it. For massive galaxies, a critical threshold is met where space-time curves back in on itself, such that multiple-light paths become accessible. Thus, when two galaxies align perfectly down our line-of-light, the background source galaxy is observed multiple times, a phenomena termed strong gravitational lensing. In fact, the warping of space-time stretches and distorts the source's light into distinctive arc-like features – as pictured below (left) using imaging from the Hubble Space Telescope.

Because gravitational lensing is dictated purely by gravity, it offers a powerful technique to study dark matter and cosmology. By 'undoing' the gravitational lensing effects, it is possible to determine both the source's intrinsic appearance, and the intervening distribution of (dark and baryonic) matter. An example source-reconstruction is shown below (right), revealing this source is in fact two merging galaxies.

The Hubble Space Telescope has observed about 100 lens systems like this, and space telescopes are about to be launched that will observe $\sim 100,000$ during the next decade. We recently developed open-source software to assist lensing analysis, which includes a fully-automated framework to study the huge influx of data. This project will use the Hubble Space Telescope observations to investigate the nature of dark matter, and as a pilot study for what the future telescopes will also be able to tell us about gravity and cosmology.

PyAutoLens
Press Release
Description of AutoLens
AutoLens paper



One image of a lensing galaxy, taken by the Hubble Space Telescope (left). In this case, the distorted arc around it (centre) is an ordinary but distant galaxy (right) seen along more than one line of sight. The precise bending of light rays tells us about the properties of dark matter and gravity in the foreground lens.

Notes:

ADAPTING TO THE ATMOSPHERE AT THE LARGEST SCALES

Main Supervisor:	Dr. Tim Morris	t.j.morris@durham.ac.uk
Office:	Ogden Centre West 022	
Funding:	STFC	

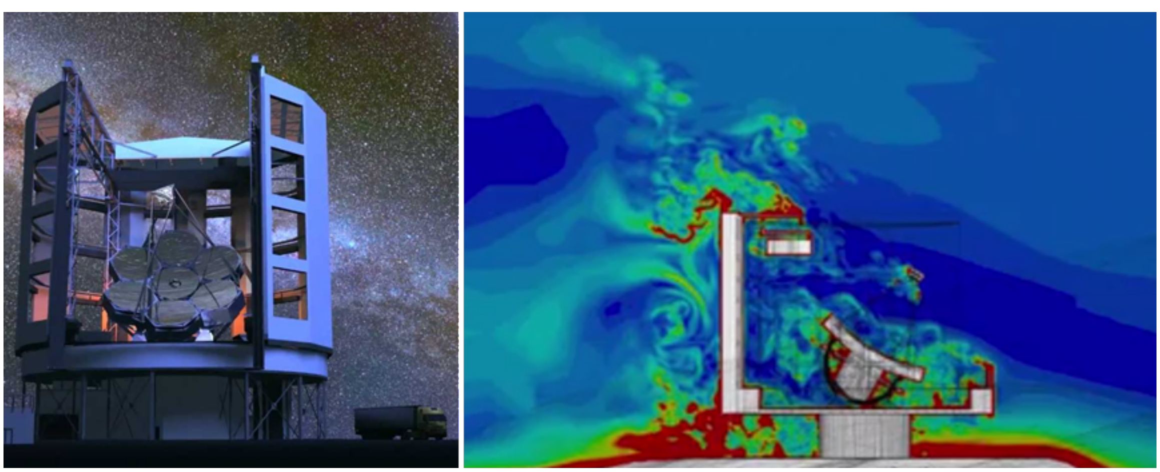
Description:

All major ground-based observatories are equipped with adaptive optics systems to compensate for image distortion caused by atmospheric turbulence. Overcoming the effects of turbulence allows ground-based telescopes to routinely beat the spatial resolving power of their space-based counterparts. For the next generation of 30-40m diameter extremely large telescopes (ELTs) the interaction between the telescope structure, the surface layers of the atmosphere and the adaptive optics system becomes complex. Existing models of atmospheric turbulence describe a characteristic outer scale that constrains the magnitude of refractive index fluctuations across the largest spatial scales. For the ELTs, the impact of a time-varying outer scale on adaptive optics and telescope control can severely degrade image quality and limits the fraction of the sky that can be observed. Characterisation of the outer scale is the biggest unsolved problem in profiling as it cannot be easily disentangled from errors arising from the active control of these giant multiple mirror telescopes.

The aim of this project is to characterise the outer scale in the local environment of the telescope where turbulence is typically strongest and assess the impact of this on the performance of the next generation of adaptive optics instruments currently being designed for the ELTs. The project would investigate the following: a) the distribution of turbulence strength in and around telescope domes as a function of ambient conditions, b) a comparison of the power spectrum of surface layer and internal turbulence with that of turbulence higher in the atmosphere and c) the validity of the Taylor frozen flow approximation, crucially important for predictive adaptive optics control algorithms that are required to compensate for telescope vibrations

This will involve modelling and computer simulation of the effects of atmospheric turbulence, as well as the design and construction of dedicated turbulence profiling instruments that can probe the local telescope environment. The project goals can however be tailored to the successful candidate. The Centre for Advanced Instrumentation (CfAI) has a long-standing collaboration with the European Southern Observatory working on site characterisation at the Very Large Telescope. The CfAI also operates the CANARY tomographic adaptive optics demonstrator at the Isaac Newton Group of telescopes on La Palma. Both of these sites would be ideal locations for experimental work of this nature, and the student can expect to travel to one or both of these sites during the course of their PhD studies.

References: Sarazin M. *et al.*, ESO Messenger 132, 11-17 (2008),, Ziad, A. Proc. SPIE 9909, 99091K (2016),, Guesalaga, A *et al.*, MNRAS 465, 1984-1994 (2016),, Vogiatzis, K. *et al.*, Proc. SPIE 10705, 107050R (2018)



Left: *3D rendering of the Giant Magellan Telescope to be built in Las Campanas, Chile (www.gmto.org);* **Right:** *Single frame from a CFD simulation of optical turbulence under constant windspeed. Turbulence observed by the telescope can be impacted by local environmental conditions including heat sources and telescope structure, and cannot be observed by external turbulence profiling instruments; Vogiatzis et al. (2016)*

Notes:

A NEW ERA OF ASTRONOMY WITH KINETIC INDUCTANCE DETECTORS

Main Supervisor: Dr. Kieran O'Brien kieran.s.obrien@durham.ac.uk
Office: Ogden Centre West 029
Funding: STFC

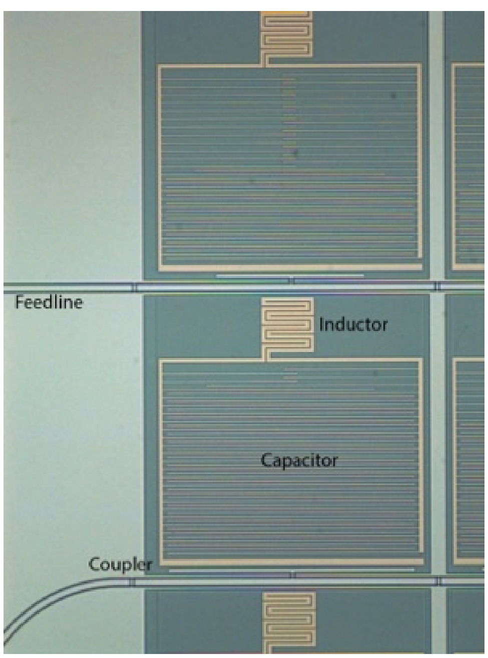
Description:

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

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

This project represents an exciting opportunity to be involved in a novel instrumentation project from an early stage. We are looking for a highly motivated student to work on instrument development in the Centre for Advanced Instrumentation, as well as exploiting observations with current KID cameras. The project would suit students from a wide range of interests, including astronomy, low temperature physics, optics, and superconductivity. The exact focus of development could be chosen to match those interests, but potential areas include computer simulations of KID observations for KIDSpec, cryogenic device testing and digital readout design.

——— Durham KIDs homepage ———— Homepage of Mazin Lab at UCSB ———— KIDspec paper ———



Microscope image of pixels in a KID array, from Mazin Lab website

Notes:

BLACK HOLES AND NEUTRON STARS IN THE NEAREST GALAXIES

Main Supervisor: Prof. Tim Roberts t.p.roberts@durham.ac.uk
Office: Ogden Centre West 123
2nd Supervisor: Prof. Chris Done chris.done@durham.ac.uk

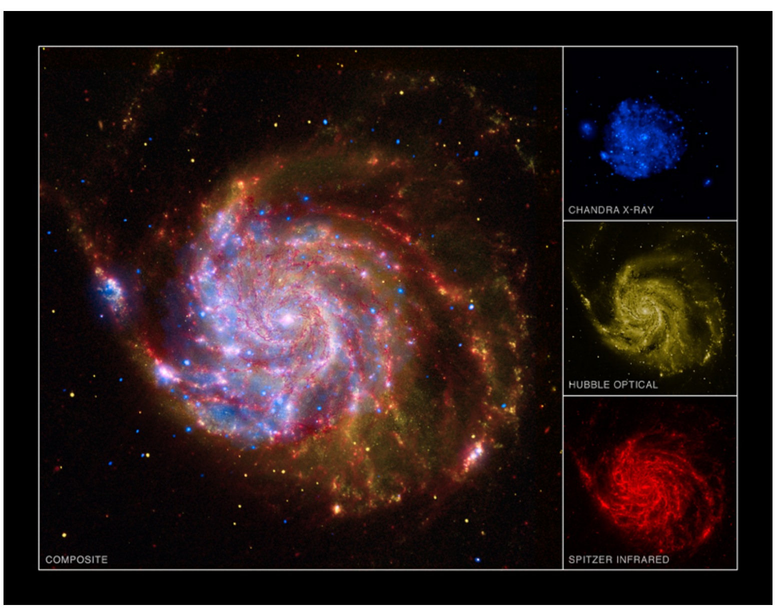
Funding: STFC

Description:

The sky is a spectacular sight when viewed in X-rays; it glows bright from the X-ray emission of super-heated gas close to the event horizons of many billions of black holes, reaching far back into cosmic history. Imprinted on that background our own Galaxy shines bright, lit up by its own populations of feeding black holes, neutron stars and white dwarfs, and the hot debris of stellar explosions. Over the last two decades we have been treated to an unprecedented view of these exotic phenomena, from dedicated X-ray astronomy missions such as NASA's *Chandra* and ESA's *XMM-Newton* observatories and smaller satellites such as *Swift* and *NuSTAR*. These will soon be joined by the German/Russian *eROSITA* detector, and together they will continue to build up a wealth of data on the hot and violent regions of the Universe that shine bright in X-rays.

The PhD projects I am offering will make use of the unparalleled data now available to conduct studies of X-ray phenomena in the nearby universe, focussing in most cases on the accretion of material onto black holes and neutron stars in relatively nearby galaxies. They will use new and archival observations of nearby galaxies, including the opportunity to work on data from *eROSITA*, and will look at both X-rays and complementary multi-wavelength data (see example below), in order to solve some of the most pressing issues in our understanding of accreting objects. In particular we can look at: can we determine whether individual objects contain neutron stars or black holes, and if so what are the proportions of the brightest X-ray sources in nearby galaxies (the ultraluminous X-ray sources, or ULXs) that contain each type of compact object? What are the physical mechanisms that permit neutron stars and black holes to reach the extreme accretion rates we infer for ULXs? How do the populations of objects we see differ between other galaxies and our own? What effects do these X-ray sources have on their immediate environments via radiative and mechanical feedback, and what implications does this have for the evolution of small galaxies throughout cosmic history?

eROSITA project pages at MPE
Recent review paper on ultraluminous X-ray sources



A composite image of the central regions of the nearby, grand design spiral galaxy M101 (NGC 5457), from observations in three wavebands (right hand panels). The X-ray emission is shown in blue, and reveals a population of point-like objects – including known black hole candidates, and a possible active galactic nucleus (AGN) – as well as hot gas in the galaxy disc.

Notes:

THE BAO FEATURE IN THE LYMAN-α FOREST

Main Supervisor: Prof. Tom Theuns tom.theuns@durham.ac.uk
Office: Ogden Centre West 207
2nd Supervisor: Prof. Michele Fumagalli michele.fumagalli@durham.ac.uk
Funding: STFC

Description:

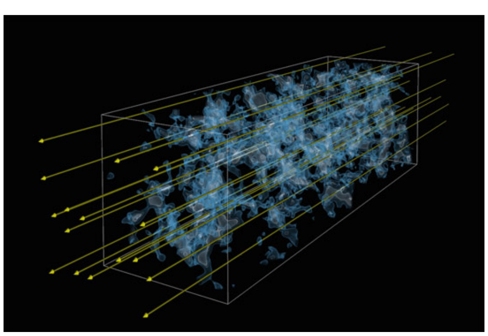
Sound waves traversing the Universe before recombination imprinted a pattern of 'baryon acoustic oscillations' (BAOs) on the distribution of cosmological structures that is still observable today. Determining the location of this BAO feature enables very precise cosmological tests by constraining the evolution of the dark energy contribution to cosmic expansion. The BAO scale was detected first in the clustering of galaxies by Cole et al, and measuring it more accurately and over a larger redshift interval is one of the main science drivers of the planned DESI galaxy survey. However, at higher $z \gtrsim 2$ galaxies are too faint to be detected in large numbers. Fortunately the BAO feature can be detected instead in the Lyα-forest (Slosar 2013), the pattern of intervening absorption lines detected in the spectra of bright quasars. **Performing a numerical simulation to test how well this can be done, given realistic observational limitations of planned surveys, is the aim of this project.**

Cosmological hydrodynamical simulations are able to reproduce observations of the Lyα-forest in great detail, provided they are performed at high enough numerical resolution (particle mass $\sim 10^6 M_\odot$ (Theuns 1998)). This limits the volume they can sample so severely that such simulations cannot currently sample the BAO scale (140 Mpc). **The first step is therefore to perform the very first hydrodynamical simulation that resolves both the small and the large scales in the Lyα-forest.** Two major and recent improvements in simulations technology have made this possible: (*i*) The PANPHASIA method for generating initial conditions with a near unlimited range in scales, and (*ii*) the development of the SWIFT simulation engine that is orders of magnitude faster than its predecessors.

PANPHASIA (Jenkins 2013) is a method for generating the Gaussian initial conditions (ICs) of a simulation by convolving a real-space white-noise density field with the appropriate linear transfer function. Performing this calculation in real space makes it possible to generate the small-scale features in one part of the ICs that are consistent with the large scale modes throughout the simulation volume. The SWIFT code is being developed in Durham in a collaboration with INTEL. It uses task-based parallelism to optimally distribute computation over available compute cores, asynchronous MPI communications to hide network latency, streamed output to optimise I/O, and uses vectorised instructions to fully exploit AVX-instruction sets. Combining these novel techniques to perform the largest hydrodynamical simulation ever performed, in close collaboration with Prof Jenkins and the SWIFT team, will be a major part of this PhD project.

Analysing this large simulation imposing realistic observational limitations to investigate how well the BAO scale can be constrained in planned QSO surveys constitutes the second step of the project. Here you will collaborate with observational groups to test the extent that observational pipelines are able to extract the information from the simulation. This project has a large computational and HPC component, but, forming the core of research at the ICC, there is a large number of other staff, students and postdocs, that work on related aspects and with whom you can interact.

URL references: Slosar A., JCAP, 2013, 26; Theuns T., et al, MNRAS, 1998, 301; Jenkins A., MNRAS, 2013, 434; Swift simulation engine; Link to an overview of the Weave project, with details on the QSO survey



QSO sightlines tracing the intervening neutral hydrogen of the Lyα-forest.

Notes:

CHARACTERISING AND CORRECTING ATMOSPHERIC SEEING EFFECTS IN ASTRONOMY

Main Supervisor:	Dr. Richard Wilson	r.w.wilson@durham.ac.uk
Office:	Rochester 325	
Funding:	STFC	

Description:

The optical effects of atmospheric turbulence, known as ‘seeing’, are a major limitation for ground–based optical astronomy. Seeing reduces the image resolution that can be achieved with large telescopes and adds noise to photometric measurements.

One of the key areas of instrumentation development for astronomy is currently the use of adaptive optical (AO) systems to correct the effects of seeing and improve image resolution in real time. The successful development and application of AO technology is critical to the science programs of modern large telescopes such as the ESO VLT and the planned European ELT. The Centre for Advanced Instrumentation (CfAI) in the Physics department at Durham is centrally involved in the development of complex AO systems for large telescopes.

One of the main methods for study of exoplanets is via measurement of transit light curves, i.e. the dip in brightness observed when a planet transits in front of its parent star as seen from Earth. Transit depths are typically small (less than 1% dip in brightness) so that very high photometric accuracy is essential. The photometric effects of atmospheric seeing (‘scintillation’) are a limiting factor for ground–based observations of exoplanet transits. The optical turbulence group at Durham is developing methods to characterise and reduce the effects of seeing and scintillation for exoplanet transit measurements.

In the frame of these developments in instrumentation to combat the effects of seeing, achieving a good understanding of the properties of atmospheric turbulence at observatory sites is increasingly important. We are leading campaigns to characterise the seeing at the VLT observatory at Paranal in Chile, and at the ORM observatory at La Palma.

The student will engage with the development, deployment and exploitation of site testing instruments at observatory sites, to improve our understanding of seeing and its effects on astronomical observations. They will also look to apply these results to improve the performance of adaptive optical or scintillation correction systems, or to the forecasting of optical turbulence conditions at observatory sites.

URL: Durham Optical Turbulence Group (https://www.dur.ac.uk/cfai/sitecharacterisation/)

The Durham SLODAR optical turbulence profiler instrument at the ESO VLT

Notes:

PHD PROJECTS IN ASTRONOMY WITH NO SPECIFIC FUNDING CONFIRMED FOR AUTUMN 2019 START

Project with no specific funding confirmed

Alexander: Tracing the cosmic growth of black holes with the NuSTAR X-ray Observatory

Baugh: Using machine learning to uncover the galaxy - dark matter halo connection

Chadwick: Extreme environment astrophysics: γ-ray astronomy and the Cherenkov telescope array

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: Other funding schemes (not STFC)

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, hereafter L17), 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 serendipitous survey catalog contains 497 AGNs over 13 deg^2 with an overall *NuSTAR* exposure of $\approx$ 20 million seconds (L17). As shown in the figure below the *NuSTAR* serendipitous survey pushes to higher redshifts than previously possible at these X-ray energies.

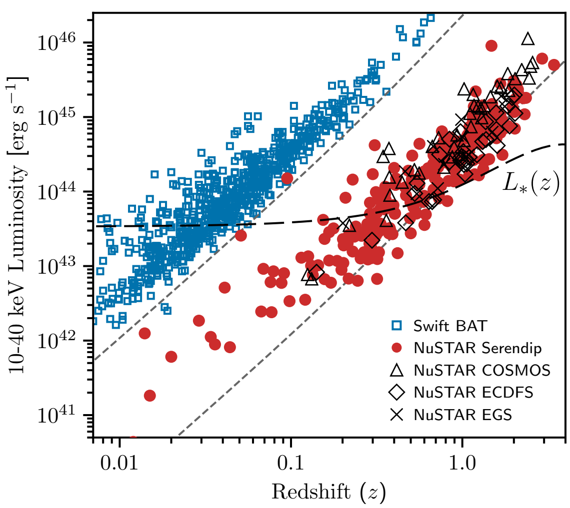


Figure: X-ray luminosity ($L_{10-40\mathrm{keV}}$) versus redshift for the AGNs identified in the 40-month NuSTAR serendipitous survey and the NuSTAR blank-field surveys as compared to the shallower Swift-BAT survey. The evolving knee of the X-ray luminosity function ($L_*(z)$) of AGNs is indicated. Taken from L17.

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 BHs.

Notes:

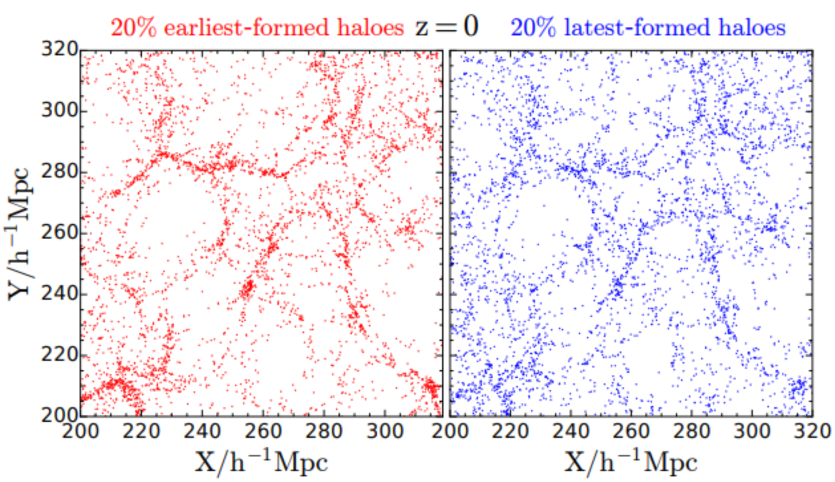
USING MACHINE LEARNING TO UNCOVER THE GALAXY - DARK MATTER HALO CONNECTION

Main Supervisor: Prof. Carlton Baugh c.m.baugh@durham.ac.uk
Office: Ogden Centre West 122
Funding: STFC CDT (TBC)

Description:

The aim here is to understand the connection between dark matter haloes and the properties of the galaxies that they host. Many empirical models have been devised to describe the halo - galaxy connection, such as halo occupation distribution modelling and sub-halo abundance matching. These require assumptions e.g. that the number of galaxies in a halo is a function of halo mass alone in the former, or that there is a tight relation between a galaxy property, such as stellar mass, and the halo mass in the latter. This project will use machine learning to avoid any inaccuracies which may arise due to the prejudices/preconceptions required in the traditional empirical approaches. The machine learning approach will be trained using a physical model to populate haloes with galaxies. Physical models are computationally expensive, so once the behaviour of the model is mimcked by machine learning, very large volume simulations can be populated rapidly with galaxies. The final output of the project will be ensembles of mock catalogues for upcoming surveys like DESI, Euclid and the SKA.

Relevant PhD project url: http://virgoDB.dur.ac.uk/
Xu et al., 2013, ApJ 772, 147: "A first look at creating mock catalogues with machine learning techniques"



The galactic content of dark matter halos depends on other properties besides mass, such as the age of the halo in this example from Contreras et al. (2018).

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
Funding: Other funding schemes (not STFC)

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, 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 a camera designed for an innovative dual-mirror design 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.

The CTA Project homepage: https://www.cta-observatory.org/
The CTA Science Case: https://arxiv.org/abs/1709.07997

The Cherenkov Telescope Array's prototype large-sized telescope, LST1, on La Palma.

Notes: