

Horizon 2020

Call: ERC-2018-COG (Call for proposals for ERC Consolidator Grant)

Topic: ERC-2018-COG

Type of action: ERC-COG
(Consolidator Grant)

Proposal number: 818713

Proposal acronym: Q4D

Deadline Id: ERC-2018-COG

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How to fill in the forms

The administrative forms must be filled in for each proposal using the templates available in the submission system. Some data fields in the administrative forms are pre-filled based on the previous steps in the submission wizard.

Proposal ID 818713

Acronym Q4D

1 - General information

Topic ERC-2018-COG

Call Identifier ERC-2018-COG

Type of Action ERC-COG

Deadline Id ERC-2018-COG

Acronym **Q4D**

Proposal title* **Quasars in the 4th Dimension**

Note that for technical reasons, the following characters are not accepted in the Proposal Title and will be removed: < > " &

Duration in months* **60**

Primary ERC Review Panel* **PE9 - Universe Sciences**

Secondary ERC Review Panel **(if applicable)**

ERC Keyword 1* **Formation and evolution of galaxies**

Please select, if applicable, the ERC keyword(s) that best characterise the subject of your proposal in order of priority.

ERC Keyword 2 **Very large data bases: archiving, handling and analysis**

ERC Keyword 3 **Not applicable**

ERC Keyword 4 **Not applicable**

Free keywords **In addition, please enter free text keywords that you consider best characterise the scope of your research proposal. The choice of keywords should take into account any multi-disciplinary aspects of the proposal.**

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Acronym Q4D

Abstract*

Black holes are intriguing objects. These regions of the Universe where mass is so dense, and gravity so strong, that even light cannot escape, were once thought mere oddities due to their extreme properties. Today, however, black holes are now thought to be vital in the formation and lives of galaxies, including our own Milky Way. Why are there a billion solar mass black holes at the centres of large galaxies? How did they form and how do they grow? Do they have any influence on the galaxy itself? And, are the fate of the galaxy and black hole intertwined? These are the key questions in contemporary astrophysics and the issues this research project will answer.

Data science, is a new interdisciplinary field of scientific methods and computational techniques that extracts knowledge and insights from data in various forms and often large volumes. It employs methods and theories drawn from many fields including mathematics, statistics, and computer science, in particular from the subdomains of machine learning, classification, databases, and visualization. As such, modern observational astrophysics must be considered a ``data science''.

Here we propose to kickstart the new field of Extragalactic Time-Domain Astrophysics by building on the P.I.'s data science experience and by using novel observational techniques to study accreting black holes in the early Universe. We will do this by utilizing and combining the firehose of data from several new large surveys that start to come online from late 2019 onwards. The unique aspect of this proposal is to breakdown the data silos of these new surveys. In doing so, we will learn about one of the two fundamental energy sources available to galaxies (accretion onto the central supermassive black hole) and perform the observational tests to gather the evidence to distinguish between galaxy evolution models and theory. We will also be best positioned to discover totally new extragalactic phenomena.

Remaining characters

26

In order to best review your application, do you agree that the above non-confidential proposal title and abstract can be used, without disclosing your identity, when contacting potential reviewers?

 Yes No

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Declarations

In case of a Synergy grant application 'Principal Investigator' means 'corresponding Principal Investigator on behalf of all Principal Investigators', and 'Host Institution' means 'corresponding Host Institution'.

1) The Principal Investigator declares to have the written consent of all participants on their participation and on the content of this proposal, as well as of any researcher mentioned in the proposal as participating in the project (either as other PI, team member or collaborator).*	<input checked="" type="checkbox"/>
2) The Principal Investigator declares that the information contained in this proposal is correct and complete.	<input checked="" type="checkbox"/>
3) The Principal Investigator declares that all parts of this proposal comply with ethical principles (including the highest standards of research integrity — as set out, for instance, in the European Code of Conduct for Research Integrity — and including, in particular, avoiding fabrication, falsification, plagiarism or other research misconduct).	<input checked="" type="checkbox"/>
4) The Principal Investigator hereby declares that (<i>please select one of the three options below:</i>)	
- in case of multiple participants in the proposal, the Host Institution has carried out the self-check of the financial capacity of the organisation on http://ec.europa.eu/research/participants/portal/desktop/en/organisations/lfv.html or to be covered by a financial viability check in an EU project for the last closed financial year. Where the result was "weak" or "insufficient", the Host Institution confirms being aware of the measures that may be imposed in accordance with the H2020 Grants Manual (Chapter on Financial capacity check) .	<input checked="" type="radio"/>
- in case of multiple participants in the proposal, the Host Institution is exempt from the financial capacity check being a public body including international organisations, higher or secondary education establishment or a legal entity, whose viability is guaranteed by a Member State or associated country, as defined in the H2020 Grants Manual (Chapter on Financial capacity check) .	<input type="radio"/>
- in case of a sole participant in the proposal, the applicant is exempt from the financial capacity check.	<input type="radio"/>
5) The Principal Investigator hereby declares that each applicant has confirmed to have the financial and operational capacity to carry out the proposed action. Where the proposal is to be retained for EU funding, each beneficiary applicant will be required to present a formal declaration in this respect.	<input checked="" type="checkbox"/>
The Principal Investigator is only responsible for the correctness of the information relating to his/her own organisation. Each applicant remains responsible for the correctness of the information related to him and declared above. Where the proposal to be retained for EU funding, the Host Institution and each beneficiary applicant will be required to present a formal declaration in this respect.	

According to Article 131 of the Financial Regulation of 25 October 2012 on the financial rules applicable to the general budget of the Union (Official Journal L 298 of 26.10.2012, p. 1) and Article 145 of its Rules of Application (Official Journal L 362, 31.12.2012, p.1) applicants found guilty of misrepresentation may be subject to administrative and financial penalties under certain conditions.

Personal data protection

The assessment of your grant application will involve the collection and processing of personal data (such as your name, address and CV), which will be performed pursuant to Regulation (EC) No 45/2001 on the protection of individuals with regard to the processing of personal data by the Community institutions and bodies and on the free movement of such data. Unless indicated otherwise, your replies to the questions in this form and any personal data requested are required to assess your grant application in accordance with the specifications of the call for proposals and will be processed solely for that purpose. Details concerning the purposes and means of the processing of your personal data as well as information on how to exercise your rights are available in the [privacy statement](#). Applicants may lodge a complaint about the processing of their personal data with the European Data Protection Supervisor at any time.

Your personal data may be registered in the Early Detection and Exclusion system of the European Commission (EDES), the new system established by the Commission to reinforce the protection of the Union's financial interests and to ensure sound financial management, in accordance with the provisions of articles 105a and 108 of the revised EU Financial Regulation (FR) (Regulation (EU, EURATOM) 2015/1929 of the European Parliament and of the Council of 28 October 2015 amending Regulation (EU, EURATOM) No 966/2012) and articles 143 - 144 of the corresponding Rules of Application (RAP) (COMMISSION DELEGATED REGULATION (EU) 2015/2462 of 30 October 2015 amending Delegated Regulation (EU) No 1268/2012) for more information see the [Privacy statement for the EDES Database](#).



Proposal ID 818713

Acronym Q4D

List of participants

#	Participant Legal Name	Country
1	THE UNIVERSITY OF EDINBURGH	United Kingdom

Proposal ID **818713**Acronym **Q4D**Short name **UEDIN**

2 - Administrative data of participating organisations

Host Institution

PIC	Legal name
999974941	THE UNIVERSITY OF EDINBURGH

Short name: UEDIN

Address of the organisation

Street OLD COLLEGE, SOUTH BRIDGE

Town EDINBURGH

Postcode EH8 9YL

Country United Kingdom

Webpage www.ed.ac.uk

Legal Status of your organisation

Research and Innovation legal statuses

Public body	yes	Legal person	yes
Non-profit	yes		
International organisation	no		
International organisation of European interest	no		
Secondary or Higher education establishment	yes		
Research organisation	yes		

Enterprise Data

SME self-declared status.....2007 - no
SME self-assessment unknown
SME validation sme.....2007 - no

Based on the above details of the Beneficiary Registry the organisation is not an SME (small- and medium-sized enterprise) for the call.

Proposal ID 818713

Acronym Q4D

Short name UEDIN

*Department(s) carrying out the proposed work***Department 1**

Department name	School of Physics and Astronomy	<input type="checkbox"/> not applicable
<input type="checkbox"/> Same as organisation address		
Street	JCMB Peter Guthrie Tait Road	
Town	Edinburgh	
Postcode	EH9 3FD	
Country	United Kingdom	

Proposal ID 818713

Acronym Q4D

Short name UEDIN

Principal Investigator

The following information on the Principal Investigator is used to personalise the communications to applicants. Please make sure that your personal information is accurate and for any ERC specific question please contact the ERC using the following e-mail address:

For Consolidator Grant Applicants: ERC-2018-CoG-applicants@ec.europa.eu

The name and e-mail of contact persons including the Principal Investigator, Host Institution contact are read-only in the administrative form, only additional details can be edited here. To give access rights and contact details of contact persons, please save and close this form, then go back to Step 4 of the submission wizard and save the changes.

ORCID ID

0000-0003-1830-6473

Researcher ID

The maximum length of the identifier is 11 characters (ZZZ-9999-2010) and the minimum length is 9 characters (A-1001-2010).

Other ID

Please enter the type of ID here

Please enter the identifier number here

Last Name* ROSS

Last Name at Birth

Ross

First Name(s)* Nicholas

Gender*

 Male Female

Title

Dr.

Country of residence

United Kingdom

Nationality*

United Kingdom

Country of Birth*

United Kingdom

Date of Birth* (DD/MM/YYYY) 16/07/1980

Place of Birth*

Edinburgh

Contact address

Current organisation name

University of Edinburgh

Current Department/Faculty/Institute/
Laboratory name

Institute for Astronomy

 Same as organisation address

Street

Royal Observatory, Blackford Hill

Postcode/Cedex

EH9 3HJ

Town*

Edinburgh

Phone*

+44 (0)131-668 8351

Country*

United Kingdom

Phone2 / Mobile

07791666145

E-mail*

npross@roe.ac.uk

Proposal ID **818713**

Acronym **Q4D**

Short name **UEDIN**

Contact address of the Host Institution and contact person

The name and e-mail of Host Institution contact persons are read-only in the administrative form, only additional details can be edited here. To give access rights and contact details of Host Institution, please save and close this form, then go back to Step 4 of the submission wizard and save the changes. Please note that the submission is blocked without a contact person and e-mail address for the Host Institution.

Organisation Legal Name **THE UNIVERSITY OF EDINBURGH**

First name* **Alan**

Last name* **Kennedy**

E-Mail* **europ@eri.ed.ac.uk**

Position in org. **European Funding Advisor**

Department **Research Support Office**

Same as organisation

Same as organisation address

Street **1-7 Roxburgh Street**

Town **Edinburgh**

Postcode **EH8 9TA**

Country **United Kingdom**

Phone **+44 (0)131 650 9039**

Phone2/Mobile

+XXX XXXXXXXX

Other contact persons

First Name	Last Name	E-mail	Phone
Katherine	Quinn	katherine.quinn@ed.ac.uk	+441316509032

Proposal ID **818713**

Acronym **Q4D**

3 - Budget

Participant Number in this proposal	Organisation Short Name	Organisation Country	Total eligible costs/€ (including 25% indirect costs)	Requested grant/€
1	UEDIN	UK	2 217 600	2 217 600
Total			2 217 600	2 217 600

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4 - Ethics

		Page
1. HUMAN EMBRYOS/FOETUSES		Page
Does your research involve <u>Human Embryonic Stem Cells (hESCs)</u> ?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Does your research involve the use of human embryos?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Does your research involve the use of human foetal tissues / cells?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
2. HUMANS		Page
Does your research involve human participants?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Does your research involve physical interventions on the study participants?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
3. HUMAN CELLS / TISSUES		Page
Does your research involve human cells or tissues (other than from Human Embryos/ Foetuses, i.e. section 1)?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
4. PERSONAL DATA		Page
Does your research involve personal data collection and/or processing?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
5. ANIMALS		Page
Does your research involve animals?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
6. THIRD COUNTRIES		Page
In case non-EU countries are involved, do the research related activities undertaken in these countries raise potential ethics issues?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Do you plan to use local resources (e.g. animal and/or human tissue samples, genetic material, live animals, human remains, materials of historical value, endangered fauna or flora samples, etc.)?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Do you plan to import any material - including personal data - from non-EU countries into the EU?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Do you plan to export any material - including personal data - from the EU to non-EU countries?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
In case your research involves <u>low and/or lower middle income countries</u> , are any benefits-sharing actions planned?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Could the situation in the country put the individuals taking part in the research at risk?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
7. ENVIRONMENT & HEALTH and SAFETY		Page

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Does your research involve the use of elements that may cause harm to the environment, to animals or plants?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Does your research deal with endangered fauna and/or flora and/or protected areas?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
Does your research involve the use of elements that may cause harm to humans, including research staff?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
8. DUAL USE		Page
Does your research involve dual-use items in the sense of Regulation 428/2009, or other items for which an authorisation is required?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
9. EXCLUSIVE FOCUS ON CIVIL APPLICATIONS		Page
Could your research raise concerns regarding the exclusive focus on civil applications?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
10. MISUSE		Page
Does your research have the potential for misuse of research results?	<input type="radio"/> Yes <input checked="" type="radio"/> No	
11. OTHER ETHICS ISSUES		Page
Are there any other ethics issues that should be taken into consideration? Please specify	<input type="radio"/> Yes <input checked="" type="radio"/> No	

I confirm that I have taken into account all ethics issues described above and that, if any ethics issues apply, I will complete the ethics self-assessment and attach the required documents.

[How to Complete your Ethics Self-Assessment](#)

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5 - Call specific questions

Academic Training

Are you a medical doctor or do you hold a degree in medicine? Please note that if you have also been awarded a PhD, your medical degree may be your first eligible degree.	<input type="radio"/> Yes <input checked="" type="radio"/> No
Date of earliest award (PhD or equivalent)* - DD/MM/YYYY	08/01/2008
With respect to the earliest award (PhD or equivalent), I request an extension of the eligibility window, (indicate number of days) [see the ERC 2018 Work Programme and the Information for Applicants to the Starting and Consolidator Grant 2018 Calls].	<input type="radio"/> Yes <input checked="" type="radio"/> No

Eligibility

Please indicate your percentage of working time in an EU Member State or Associated Country over the period of the grant:	100,00
Please note that you are expected to spend a minimum of 50% of your total working time in an EU Member State or Associated Country.	
I acknowledge that I am aware of the eligibility requirements for applying for this ERC call as specified in the ERC Annual Work Programme, and certify that, to the best of my knowledge my application is in compliance with all these requirements. I understand that my proposal may be declared ineligible at any point during the evaluation or granting process if it is found not to be compliant with these eligibility criteria.*	<input checked="" type="checkbox"/>

Data-Related Questions and Data Protection

(Consent to any question below is entirely voluntary. A positive or negative answer will not affect the evaluation of your project proposal in any form and will not be communicated to the evaluators of your project.)

For communication purposes only, the ERC asks for your permission to publish, in whatever form and medium, your name, the proposal title, the proposal acronym, the panel, and host institution, should your proposal be retained for funding.	<input checked="" type="radio"/> Yes <input type="radio"/> No
Some national and regional public research funding authorities run schemes to fund ERC applicants that score highly in the ERC's evaluation but which can not be funded by the ERC due to its limited budget. In case your proposal could not be selected for funding by the ERC do you consent to allow the ERC to disclose the results of your evaluation (score and ranking range) together with your name, non-confidential proposal title and abstract, proposal acronym, host institution and your contact details to such authorities?	<input checked="" type="radio"/> Yes <input type="radio"/> No
The ERC is sometimes contacted for lists of ERC funded researchers by institutions that are awarding prizes to excellent researchers. Do you consent to allow the ERC to disclose your name, non-confidential proposal title and abstract, proposal acronym, host institution and your contact details to such institutions?	<input checked="" type="radio"/> Yes <input type="radio"/> No
For purposes related to monitoring, study and evaluating implementation of ERC actions, the ERC may need that submitted proposals and their respective evaluation data be processed by external parties. Any processing will be conducted in compliance with the requirements of Regulation 45/2001.	
Have you previously submitted a proposal to the ERC? If known, please specify your most recent ERC application details.	<input checked="" type="radio"/> Yes <input type="radio"/> No



Proposal ID **818713**

Acronym **Q4D**

Proposal number **678679**

Other details **ERC-2015-STG**

Proposal ID 818713

Acronym Q4D

Excluded Reviewers

You can provide up to three names of persons that should not act as an evaluator in the evaluation of the proposal for potential competitive reasons.

First Name	Ezequiel
Last Name	Treister
Institution	Institute of Astrophysics at the Universidad Catolica. Pontificia Universidad Católica de Chile
Town	Santiago
Country	Chile
Webpage	

First Name	Carolin
Last Name	Villforth
Institution	Department of Physics Wessex House University of Bath
Town	Bath
Country	United Kingdom
Webpage	



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Acronym Q4D

Extended Open Research Data Pilot in Horizon 2020

If selected, all applicants will participate in the [Pilot on Open Research Data in Horizon 2020](#)¹, which aims to improve and maximise access to and re-use of research data generated by actions.

However, participation in the Pilot is flexible in the sense that it does not mean that **all** research data needs to be open. After the action has started, participants will formulate a [Data Management Plan \(DMP\)](#), which should address the relevant aspects of making data FAIR - findable, accessible, interoperable and re-usable, including what data the project will generate, whether and how it will be made accessible for verification and re-use, and how it will be curated and preserved. Through this DMP projects can define certain datasets to remain closed according to the principle "as open as possible, as closed as necessary". A Data Management Plan does **not** have to be submitted at the proposal stage.

Furthermore, applicants also have the possibility to opt out of this Pilot completely at any stage (before or after the grant signature), thereby freeing themselves retroactively from the associated obligations.

Please note that participation in this Pilot does not constitute part of the evaluation process. Proposals will not be penalised for opting out.

We wish to opt out of the Pilot on Open Research Data in Horizon 2020.

Yes

No

¹ According to article 43.2 of Regulation (EU) No 1290/2013 of the European Parliament and of the Council, of 11 December 2013, laying down the rules for participation and dissemination in "Horizon 2020 - the Framework Programme for Research and Innovation (2014-2020)" and repealing Regulation (EC) No 1906/2006.

a. Extended Synopsis

Overview and Objectives

Current theories of galaxy formation and evolution strongly suggest that central, supermassive black holes (SMBHs) have a profound effect on the galaxies that they live in (e.g., Kormendy and Ho, 2013). This is not surprising since the potential energy associated with mass accretion onto a supermassive black hole is comparable to that generated via the nuclear fusion in the galaxy's stars (see e.g. Fabian, 2012). Thus when a galaxy goes through a “quasar phase” (where gas is supplied and accreted by the SMBH) there is ample energy to potentially impact the host galaxy and the surrounding intergalactic medium.

However, the critical details of the physical processes involved in how this energy escapes the inner most regions of the galaxy and then interacts with the gas, dust, stars and dark matter, is currently poorly understood. This fact, along with current observational data giving more puzzles than clues is preventing the field from moving forward. Significant further issues arise since startling new observations from my (Nicholas P. Ross; NPR) research team (MacLeod et al., 2016; Ross et al., 2018) show that *quasars vary significantly on timescales of weeks to months*, whereas the accretion disks (that supply ‘fuel’ for the quasar) should take thousands of years to change their optical emission; this has recently been called the “Quasar Viscosity Crisis” (e.g., Lawrence, 2018). Thus, it is unclear if we have an understanding of a physical phenomena prevalent in many astrophysical systems: the accretion disk.

The field of observational extragalactic astrophysics is poised for a fundamental and rapid change. Starting in late 2019, a fleet of new telescopes, instruments and missions will be commissioned, start data taking, and will leap-frog the quality and quantity of data we have available today. These surveys and missions include: the fifth incarnation of the Sloan Digital Sky Survey (SDSS-V¹); the Large Synoptic Survey Telescope (LSST²); the Dark Energy Spectroscopic Instrument (DESI³) survey; the 4-metre Multi-Object Spectroscopic Telescope (4MOST⁴) survey, and the ESA *Euclid* mission⁵. Even more imminent is the launch of the *James Webb Space Telescope* (JWST⁶).

Quasars in the 4th Dimension (Q4D) has two broad and well-posed goals. First, we aim to elucidate in detail **how the energy directly associated with a supermassive black holes impacts the universal galaxy population**. We will gain a deep understanding into the physical mechanisms related to central engine black holes; their accretion disk physics, their dynamics on both human and galactic timescales and the role they might play in forming and regulating the galaxy population. Second, we anticipate **the discovery of brand new extragalactic phenomena**. By tapping into the massive raw discovery space that the new experiments will open up, there is the highly likely outcome of discovering something “brand new” (Ivezic and Tyson, 2008; LSST Science Collaborations et al., 2009), e.g. the EM counterparts to mergers of Binary SMBHs (with their associated gravitational wave chirp and ringdown), objects potentially similar to repeating fast radio bursts Spitler et al. (2016) or more objects akin to the still unexplained ‘SCP 06F6’ (Barbary et al., 2009). Q4D objectives are:

1. Characterize the variable extragalactic universe and quasar population.
2. Establish the energy transport mechanisms associated with the “quasar phase”, and explain the relation between accretion rate, black hole mass build-up with observed light curve and spectral properties.
3. Develop and then link theoretical accretion and galaxy formation models for a fully holistic theory of active galaxies.
4. Discover new extragalactic variable objects.

We will achieve this by leveraging several of the new, large-scale surveys that will all have ‘First Light’ over the lifetime of the project. These critical observations are made by exploiting the large imaging and spectroscopic

¹ www.sdss.org/future/

² lsst.org

³ desi.lbl.gov

⁴ 4most.eu

⁵ sci.esa.int/euclid/

⁶ jwst.stsci.edu

datasets that will be available from the SDSS-V, DESI, 4MOST, LSST and ESA *Euclid*. Crucially, although these projects individually will deliver new state-of-the-art datasets, it is my project that will be the first to break down the associated data silos and combine these data in order to go beyond the state-of-the-art.

1. Current State of the Art.

The current state-of-the-art data samples have either $\approx 10^6$ quasars with one spectral epoch, or only a few objects with repeat photometric data, i.e. light-curve information and the accompanying repeat spectra (see Figure 1). NPR has been involved in the production of both of these two types of samples (MacLeod et al., 2016; Páris et al., 2017). We plan to collate datasets so that the 10^6 sample have *high-fidelity light-curves and ample repeat spectroscopy (necessary of emission/absorption line diagnostics)*, and in doing so will kick start the new field of Variable Extragalactic Astrophysics.

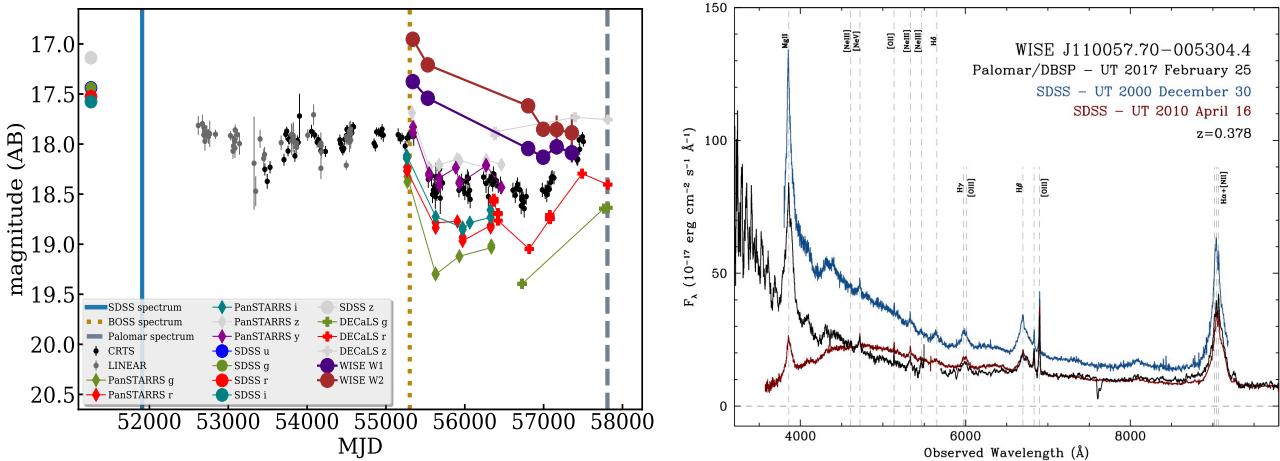


Figure 1: (Left:) The optical and infrared light-curve for the redshift $z = 0.378$ quasar J1100-0053 (Ross et al. 2018). Note the fall in the infrared, whereas there is a decrease, but then recovery in the optical. (Right:) Three epochs of spectra for J1100-0053. The spectacular downturn in the blue for the 2010 spectrum indicates a dramatic change in the accretion disk.

During its initial phases of operation the Sloan Digital Sky Survey (SDSS) obtained spectra of 1 million galaxies in the local Universe. This dataset has become the *de facto* standard for understanding the present day galaxy population, and sets the boundary conditions for all theoretical comparisons. The paradigm changing success of the SDSS was due to having 1,000,000 objects with *very high signal-to-noise photometry and spectra*, enabling multivariate analysis that is required for galaxy astrophysics investigations. *Q4D will generate the same sample size and revolutionary understanding with a new temporal dimension of the quasar population, as the SDSS had with the low-redshift $z \sim 0.1$ galaxy population.* The ground-breaking aspect of Q4D is that it takes quasar astrophysics into the 2020s, going from single objects samples, to surveys and samples of millions of objects, with massive spectroscopic monitoring giving access to the time-domain and leveraging these very large scale next generation missions, telescopes and their datasets.

The timing for this proposal could not be better. The first of the data “firehoses” turns on in late 2019, with the full datastream from our key sources fully online by mid-2022. As such, we have the time to mature our analysis techniques, and then be in the ideal position to take advantage of the initial data releases of all these new projects. Prompt ERC Consolidator level-support is also imperative since final survey design and optimization trade-off studies are being made e.g. for DESI, SDSS-V and LSST over the next $\sim 12\text{-}18$ months. Having the ability to influence and fully optimise these decisions for our science objectives would be very powerful. The ground breaking nature of the Q4D will attract high quality PDRAs, who would be guaranteed “First Light” data and science.

The importance of this branch of astrophysics is already well established in Europe and is a priority for the next two decades.⁷ This is demonstrated by noting that one of the two primary mission goals for the ATHENA

⁷ ESA Cosmic Visions

⁸ L-Class Mission Timeline

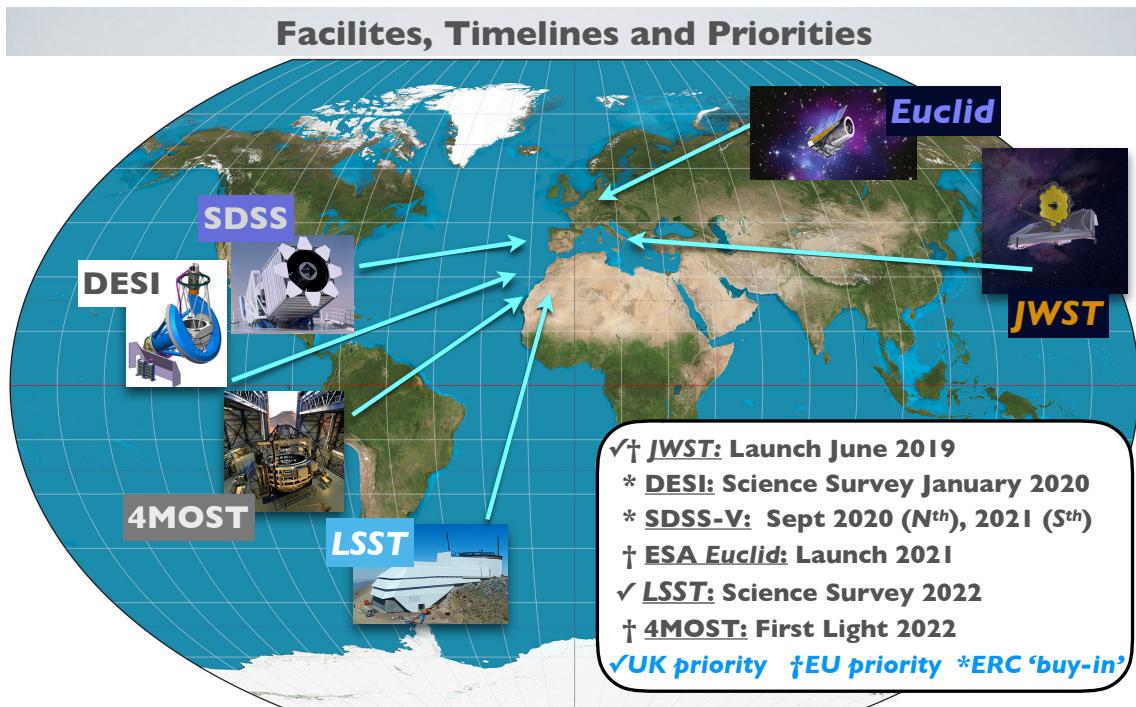


Figure 2: Facilities, Timelines and Priorities. With SDSS-V and DESI in the Northern Hemisphere and 4MOST, LSST in the South, we have full celestial sphere coverage.

mission is answering the question “How do black holes grow and shape the Universe?”. ATHENA is ESA’s second L-class flagship mission, due for launch in 2028.

The scope and remit of an ERC Consolidator grant will allow us to combine these data products in a manner that will not only establish the new state-of-the-art in variable extragalactic astrophysics, but it will also establish and kickstart the new field of variable extragalactic astrophysics itself.

2. Methodology

Our proposal contains six work packages that fall into three broad and complementary categories: observational studies of large numbers (millions) of objects; high-risk, very high-reward observational studies of a small number (10s) of objects; theoretical modeling investigations. Figure 3 summarises our overall WP plan. Risks and mitigation strategies are present for each WP as are Key Deliverables. NPR, three PDRA, “PDRA1”, “PDRA 2”, “PDRA 3”, and one PhD student, “PhD1” are the personnel required to carry out these work packages.

NPR is a world-leader in the field of extragalactic observational astrophysics. NPR’s research focuses on implementing novel data science and machine learning algorithms and techniques in order to discover and study the physical processes in quasars. I have an exceptionally strong track record including being the lead of a science Working Group, with prodigious scientific output (over 400 published, peer-reviewed papers from that particular collaboration). **I was the Co-Founder and Chief Data Scientist of String Security Inc. where I built a predictive threat detection and remediation platform for cyber security teams by applying machine learning and predictive algorithms. Thus the P.I.’s research strengths, ability to quickly develop bleeding-edge software and science output are all ideally matched to this proposal.**

The skill set of PDRA1 would include development of the underlying tools and techniques necessary to extract meaning from large and/or complex data sets. PDRA1 would have a strong physical sciences background, and a PhD in astrophysics or computer science. The skill sets of PDRA2 would include expertise in time series analysis, primarily with optical data but potentially also in other wavebands. PDRA2 would have a PhD in astrophysics or a related field. The skill set of PDRA3 would include experience with fluid mechanics modelling and/or large computer simulations. PDRA3 would have a PhD in astrophysics, mathematics or computer

	Personel	Year 1	Year 2	Year 3	Year 4	Year 5
WP1	PDRA1, NPR	QuasarSieve				
WP2	PDRA1, PDRA2, PhD1, NPR		Quasar Catalog Generation and Demographics Studies			
WP3	PDRA2, PDRA1, PhD1, NPR			Light Curve+Spectral analysis		
WP4	PDRA3, NPR (WKMR, RSD)			Accretion Disk and Cosmological Simulations		
WP5	NPR	James Webb Space Telescope studies				
WP6	PDRA1, PDRA2, PDRA3, PhD1, NPR		New Object Discovery			

Figure 3: An overview of the WPs, with the personnel attached to each WP and a guide to their start and duration. As given by the shadings, WP1, 2 and 3 are observational studies of large numbers of objects; WP4 are theoretical modeling investigations and WP5 and 6 are high-risk, very high-reward observational studies of small numbers of objects.

science. PhD1 would have a Masters or a strong 4-year undergraduate degree in Physics or Mathematics with evidence of research-level project work.

WP1: BUILD QUASARSIEVE: In order to utilize the LSST datastream for our science goals we will build a “Stage 2 filter”, which we name *QuasarSieve*. This will identify the quasars, add context, perform outburst forecasting etc. The heavy-industry computing infrastructure is being supplied by the UK LSST Data Access Center (DAC, based at the University of Edinburgh) and our task will be to build software in a timely and robust manner. This is a novel enterprise and a rate-limiting step in our overall programme, with the associated high-risk. We mitigate this risk with the data science and machine learning experience from PDRA1 and the P.I. (NPR). We thus classify **WP1 as medium-risk, high-reward.** **Key Deliverables:** An open-source, well-documented software package that can interact with and return data from the LSST Data Access Center.

WP2: QUASAR CATALOGUE GENERATION AND DEMOGRAPHIC STUDIES: Building the quasar corpus and cataloguing the observational data will be a vital step for our science goals. Following on from the quasar catalogue generation, a key science output will be the study of the quasar demographics. All these are vital observational tests for galaxy formation models and theory (see WP4 below). The goal of this WP is to construct a quasar catalogue and make key observational tests. Given the P.I.s experience at these specific tasks, plus the effort level of PDRA1, PDRA2 and PhD this WP is deemed medium-risk. **WP2 is medium-risk, high-reward.** **Key Deliverables:** A science-enabling compendium that will be the state-of-the-art quasar dataset for the 2020s. A suite of new, beyond-the-state-of-the-art quasar demographic measurements which are the boundary conditions for theoretical models.

WP3: LIGHT-CURVE AND SPECTRAL ANALYSES: Another major scientific output will be the full and detailed light-curve and spectral analyses of the conglomerate datasets. This WP will have a data science/machine learning aspect. The goal of this WP is to elucidate the physical processes that drive quasar variability and as such is significant high-reward science. This level of investigation is highly novel, though we envisage no major barriers outside of our control to achieving our science goals and PDRA1, PDRA2, as well as the P.I. (NPR) and PhD1 effort will be directed towards this. As such, **WP3 as medium-risk, high-reward.** **Key Deliverables:** Measurements, for the first time of how the light-curves and spectra of quasars depend on key physical quasar properties e.g. M_{SMBH} , luminosity, $\lambda = \log(L/L_{\text{Edd}})$, spin etc. These measurements will allow us to make direct comparisons to accretion disk models.

WP4: ACCRETION DISK AND QUASAR FEEDBACK SIMULATIONS: New accretion models are needed to fully explain the “changing look” quasars and the “Quasar Viscosity Crisis”. New radiation MHD codes begin to explain the observations here, but further development is needed to gain the desired deep understanding. Cosmological-scale simulations with stellar and quasar feedback are now also online. The exceedingly am-

bitious goal of WP5 is to develop new holistic accretion disk-to-cosmological scale simulations that explain our observational results and links them to “quasar feedback”. WP4 is thus high-risk due to its novel nature and algorithmic complexity. We also envisage ramp-up time to get our theoretical simulations to the level that will be required by our beyond-the-state-of-the-art dataset. However, we mitigate this risk first by noting this will be the lead WP and top priority for PDRA3. We further mitigate this risk by invoking collaboration with accretion disk theorist Prof. Ken Rice (WKMR; Chair of Computational Astrophysics at the IfA, University of Edinburgh) and cosmological simulation expert Prof. Romeel Dave (RSD; Chair of Physics at the IfA, University of Edinburgh). Thus PDRA3, NPR, with guidance from WKMR and RSD would collaborate on this WP. We thus classify **WP4 as medium-to-high risk, very high-reward. Key Deliverables:** New accretion disk models and theory that explain the light curve data of our beyond-the-state-of-the-art dataset. New galaxy evolution models, describing the hydrodynamics involved on galactic scales, but related to the quasar central engine.

WP5: OBSERVATIONS OF QUASARS BY THE JAMES WEBB SPACE TELESCOPE: What are the star-formation properties of luminous quasars at the peak of quasar activity? We aim to answer this by looking for the presence of polycyclic aromatic hydrocarbon (PAH) spectral features in infrared bright quasars with the *James Webb Space Telescope* (JWST). **WP5 is high risk, high-reward.** This is an ideal investigation for the JWST, but we classify this as high-risk since we have to apply for the telescope time and are not guaranteed the data. We note this WP does not impact in any direct way the other WPs and would lead to very-high gain science. **Key Deliverables:** State-of-the-art data products from the JWST, with the observational evidence and physical interpretation of how “quasar feedback” regulates galaxy formation in high-redshift quasars.

WP6: NEW OBJECT DISCOVERY: The LSST will scan the sky repeatedly, enabling it, and us, to both discover new, distant transient events and to study variable objects throughout our universe. The most interesting science to come may well be the discovery of new classes of objects. Suffice to say, this would be exceptionally high-reward. **WP6 is high risk, exceptionally high-reward.** We class this as high risk, since it is complex to class a WP with essentially unknown discovery potential as ‘low-risk’. However, we *nota bene* that a lack of any novel discovery here would be a startling null result. **Key Deliverables:** Potential discovery of new classes of astronomical objects.

3. Resources, Survey ‘buy-in’ and Budget

PERSONNEL: We request the resources and support for 100% of the time and effort for the P.I. We request the resources and support for 3 Postdoctoral Research Associates (PDRA), for a total of 10 PDRA year equivalents (3+3+4). We request the resources and support for 1 PhD studentship.

SURVEY BUY-IN: We request support for the “buy-in” to two of the new surveys, SDSS-V and DESI. The costs here are €184,100 for SDSS-V and €200,100 for DESI. We ask this support to come from the “additional funds that can be made available to cover access to large facilities.” We request access to these funds as it gives our project access to telescopes and data in the North and South Hemispheres for complete coverage of the celestial sphere and delivers the crucial early spectroscopy that will be vital to train, test and build our data science and machine learning codes and algorithms. We emphasise that the science return is ‘exponentially’ dependent on the breadth of data available and heralds a brand new regime of “several-survey” or “multi-mission” astronomy. *Buy-in here would place the P.I. and the University of Edinburgh as the only group and institute in the world to be involved in SDSS-V, DESI, 4MOST, LSST and ESA Euclid and JWST.*

COMPUTING REQUIREMENTS: With the availability of the facilities at an institute (e.g. IfA Cullen), university (e.g. [Edinburgh Compute and Data Facility](#)) and at a national ([The Hartree Centre](#)) level, the rate limiting factor will be how quickly and efficiently we can deploy our codes and analysis.

TRAVEL: We request support for travel for all 5 members of the group, including repeat medium-term (i.e., few weeks) travel to the US and ESO Chile to work with key collaborators at critical timings for the First Light of the new telescopes.

References

- K. Barbary et al. Discovery of an Unusual Optical Transient with the Hubble Space Telescope. *ApJ*, 690: 1358–1362, Jan 2009. doi: 10.1088/0004-637X/690/2/1358.
- A. C. Fabian. Observational Evidence of Active Galactic Nuclei Feedback. *ARA&A*, 50:455–489, Sept 2012. doi: 10.1146/annurev-astro-081811-125521.
- Z. Ivezić and J. A. for the LSST Collaboration Tyson. LSST: from Science Drivers to Reference Design and Anticipated Data Products. *ArXiv e-prints*, May 2008.
- J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *ARA&A*, 51:511–653, Aug 2013. doi: 10.1146/annurev-astro-082708-101811.
- A. Lawrence. Quasar viscosity crisis. *Nature Astronomy*, 2:102–103, Jan 2018.
- LSST Science Collaborations, P. A. Abell, J. Allison, S. F. Anderson, J. R. Andrew, J. R. P. Angel, L. Armus, D. Arnett, S. J. Asztalos, T. S. Axelrod, and et al. LSST Science Book, Version 2.0. *ArXiv 0912.0201v1*, Dec 2009.
- C. L. MacLeod, N. P. Ross, et al. A systematic search for changing-look quasars in SDSS. *MNRAS*, 457: 389–404, March 2016. doi: 10.1093/mnras/stv2997.
- I. Pâris, P. Petitjean, N. P. Ross, et al. The Sloan Digital Sky Survey Quasar Catalog: Twelfth data release. *Astron. & Astrophys.*, 597:A79, Jan 2017. doi: 10.1051/0004-6361/201527999.
- N. P. Ross et al. A new physical interpretation of optical and infrared variability in quasars. *Nature Astronomy*, 2018.
- L. G. Spitler et al. A repeating fast radio burst. *Nat*, 531:202–205, March 2016. doi: 10.1038/nature17168.

PERSONAL INFORMATION

ROSS, Nicholas P.

ORCID: 0000-0003-1830-6473

Date of birth: 16th July 1980

Nationality: British

URL for website: <http://www.roe.ac.uk/~npross>**EDUCATION**

- 2003 - 2007 Ph.D., Astrophysics, Dept. of Physics, University of Durham, U.K.,
“The Clustering and Evolution of Massive Galaxies”, Advisor: Prof. Tom Shanks
- 1999 - 2003 M.Sc., (a 4 year combined Bachelors and Masters), Physics & Astronomy,
Dept. of Physics, University of Durham, U.K. First Class Honours,

CURRENT POSITIONS

- 2014 - present STFC Ernest Rutherford Fellow, University of Edinburgh, U.K.

PREVIOUS POSITIONS

- 2016 - 2017 Co-Founder and Chief Data Scientist, String Security, Inc., San Francisco, USA
- 2013 - 2014 Research Assistant Professor, Dept. of Physics, Drexel University, Philadelphia, U.S.A.
- 2009 - 2013 Project Scientist, Physics Division, Lawrence Berkeley National Lab, Berkeley, U.S.A.
- 2007 - 2009 Postdoctoral Scholar, Dept. of Astronomy and Astrophysics,
Pennsylvania State University, State College, U.S.A.

FELLOWSHIPS AND AWARDS

- 2014 – 2019 Science & Technology Facilities Council Ernest Rutherford Fellowship

PUBLICATION RECORD

- | | | |
|------------------------------------|----------------------------|--------------------------------|
| Author on 118 published papers | Total number of citations: | 14,942 (126.6 citations/paper) |
| First author on 6 published papers | Total number of citations: | 640 (106.7 citations/paper) |
| <i>h</i> -index of 59. | | |

GRANTS/FUNDING OBTAINED

- | | |
|--|----------|
| STFC Ernest Rutherford Fellowship (PI.) | €679,569 |
| NASA <i>Spitzer Space Telescope</i> Cycle 9, 820 hours (Lead Co-I) | €359,745 |
| NASA <i>Hubble Space Telescope</i> Cycle 20, 18 orbits (P.I.) | €87,330 |
| NASA <i>Swift</i> XRT and UVOT ToO observations, Cycle 5, 17.8ks (P.I.) | €27,820 |
| <i>Chandra</i> Cycle 12 Co-I Archival proposal “The Dark Matter-AGN-Weak
Lensing connection” (co-I) | €41,912 |

SUPERVISION

- | | |
|-------------|---|
| 2015- | David Homan, University of Edinburgh PhD student |
| 2015 | Thomas Kemp, University of Edinburgh MSc student |
| 2013 - | John Timlin, Drexel University Graduate Student, Philadelphia, USA
(On Ph.D. Dissertation Committee) |
| 2013 - 2014 | Victoria Tielein, Drexel University Senior Thesis (Final Year UG) Student,
Philadelphia PA, USA |
| 2009 - 2012 | Jessica Kirkpatrick, UC Berkeley Graduate Student, Berkeley CA, USA |
| 2009 - 2010 | Rachel Kennedy, UC Berkeley Honors Student, Berkeley CA, USA |
| 2008 - 2009 | Michael Peth, Pennsylvania State University Honors Student, State College PA, USA |

APPOINTMENTS AS EXTERNAL EXAMINER

- 2016 Ben Chehade, PhD, “*The luminosity and redshift dependence of quasar clustering*”,
University of Durham

2016 Behzad Ansarinejad, M.Res, “*An Empirical Analysis of Baryon Acoustic Oscillations in Galaxy and Quasar Clustering*”, University of Durham

TEACHING ACTIVITIES

2015, 2016 Examples Class Supervisor, *Introduction to Astrophysics*, University of Edinburgh
 2009 Lead Instructor, *Astro 010: Introduction to Astronomy*, Penn State University
 2007 Postgraduate Instructor, *Stars and Galaxies* course, Durham University

ORGANISATION OF SCIENTIFIC MEETINGS

2017 Co-Chair SOC *Unveiling the Physics Behind Extreme AGN Variability*
 University of the Virgin Islands, St. Thomas, U.S. Virgin Islands.
 2016 Chair S/LOC *JWST@ROE* University of Edinburgh, International meeting
 2015 Chair S/LOC *Quasar Day* University of Edinburgh, National meeting,
 2014 SOC Member *Multi-wavelength Heritage of Stripe 82 Workshop*, Princeton University
 2011 SOC Chair *SDSS-III BOSS Quasar Working Group* meeting, Princeton University

COMMISSIONS OF TRUST

Referee *Physical Review Letters*
Monthly Notices of the Royal Astronomical Society
The Astrophysical Journal
The Astronomical Journal
Journal of Cosmology and Astroparticle Physics
 Reviewer for the NASA Postdoctoral Fellowship Program
 Session Chair, “Wide-Field Surveys and QSO Physics” Parallel, UK National Astronomy Meeting, 2015.
 Founder “Astronomers for America” and “Scots for Science”

MEMBERSHIPS OF SCIENTIFIC SOCIETIES

Fellow Royal Astronomical Society (since July 2004)
 Full Member American Astronomical Society, (since Nov 2009)
 Founder “Astronomers for America”

PRESS RELEASES

2012 BOSS Lyman- α Forest BAO Detection (incl. image credit)
 2012 Quasar Broad Absorption Line Disappearance
 2009 SDSS-III: BOSS First Light

SELECTED OUTREACH

2015, 2016 ROE Open Day
 2013, 2014 Public Observing Nights, Drexel University
 2012 LBNL Open House
 2008, 2009 Penn State In-Service Workshop in Astronomy
 2008, 2009 Penn State Astronomy and Astrophysics annual “AstroFest”

MAIN COLLABORATORS

John Timlin (PhD student, Drexel University)
 Prof. Gordon Richards (Drexel University)
 Dr. Chelsea MacLeod (former postdoc in UoE research group; now CfA, Harvard)
 Prof. Andy Lawrence (UoE)
 Prof. Fred Hamann (UC Riverside),
 Prof. Nadia Zakamska (Johns Hopkins),
 Prof. David Aspinall (School of Informatics, UoE),
 Dr. Isabelle Pâris (formerly Aix-Marseille Université)

Appendix: All on-going and submitted grants and funding of the PI (Funding ID)
Mandatory information (does not count towards page limits)

On-going Grants

<i>Project Title</i>	<i>Funding source</i>	<i>Amount (Euros)</i>	<i>Period</i>	<i>Role of the PI</i>	<i>Relation to current ERC proposal</i>
STFC Ernest Rutherford Fellowship (ERF)	STFC, U.K.	679,569	01-OCT-2014 to 30-SEP-2019	To perform world leading research, either independently, or with collaborators of the PIs choice.	Current ERF grant has research linked to, but in no way overlapping with ERC proposal. Latest results from current research will be the preliminary data for the novel research proposed here.

Grant applications
n/a

c. Early Achievements Track-record

My (NPR) research focuses on implementing novel algorithms and techniques in order to discover and study the physical processes in quasars. After spending 7 years in the United States (working at Penn State, Lawrence Berkeley National Lab and then as an Assistant Research Professor at Drexel University) I returned to the U.K. with the award of an STFC Ernest Rutherford Fellowship, one of the most senior personal astrophysics fellowships in the UK, which has an application oversubscription of ~20:1 and is over £500,000 (€630,000) on award.

I have established myself as an independent lead investigator and have led the discovery of new types of quasars: the **Extremely Red Quasars**, (NPR et al. 2015, MNRAS) and with my research team leading the discovery of the first sample of the new **Changing Look Quasars** (MacLeod, NPR et al. 2016, MNRAS). My team has also led the production of the largest areal space-based survey using NASA's *Spitzer Space Telescope* (Timlin, NPR et al. 2016, ApJS). This has led to the ground breaking and novel first measurement of infrared quasar clustering at high-redshift (Timlin, NPR et al. 2018, ApJ, accepted).

The PI led the team that was responsible for obtaining the quasar data necessary for the SDSS-III BOSS cosmology experiment, leading to the first measurement of baryon acoustic oscillations at high-redshift. The PI's leadership includes leading science teams such as the **SDSS-III BOSS Quasar Science Working Group** which has resulted in an *extremely high publication output including 118 peer-review journal articles with 15,000 citations and an h-index of 59 (SAO/NASA Astrophysics Data System)*. This is world-leading for any astrophysicist and virtually unparalleled by his contemporaries at a similar career stage.

Dr. Ross has become an expert in a suite of research methodologies in **data science** and machine learning. In particular, at the heart of Dr. Ross's research with the SDSS-BOSS project, was anomaly detection in extremely large datasets. Dr. Ross was a co-founder and Chief Data Scientist of, **String Security Inc.** There he built a predictive threat detection and remediation platform for cyber security teams by applying machine learning and predictive algorithms. The PI is currently in discussion with the School of Informatics at the UoE on potential joint projects and research avenues.

Relevant Selected Journal Publications (N.B. None with PhD supervisor, **citations in red**)

Pâris, Isabelle; Petitjean, Patrick; **Ross, Nicholas P.** et al “*The Sloan Digital Sky Survey Quasar Catalog: Twelfth data release*”, [10.1051/0004-6361/201527999](https://doi.org/10.1051/0004-6361/201527999), [2017A&A...597A..79P](#) (96) Production of the current state-of-the-art quasar catalogue with associated metadata.

Hamann, Fred; Zakamska, Nadia L.; **Ross, Nicholas P.** et al. “*Extremely red quasars in BOSS*”, [10.1093/mnras/stw2387](https://doi.org/10.1093/mnras/stw2387), [2017MNRAS.464.3431H](#), (13) Follow-up analysis to the Ross et al. (2015) discovery paper.

Timlin, John D.; **Ross, Nicholas P.** et al. “*SpIES: The Spitzer IRAC Equatorial Survey*”, [10.3847/0067-0049/225/1/1](https://doi.org/10.3847/0067-0049/225/1/1) [2016ApJS..225....1T](#), (13) Survey paper and catalogue for the largest areal *Spitzer Space Telescope* programme.

MacLeod, Chelsea L.; **Ross, Nicholas P.** et al. “*A systematic search for changing-look quasars in SDSS*”, [10.1093/mnras/stv2997](https://doi.org/10.1093/mnras/stv2997), [2016MNRAS.457..389M](#), (43) Field-leading paper for CLQ studies; first systematic search with detailed theoretical interpretation.

Ross, Nicholas P. et al. “*Extremely red quasars from SDSS, BOSS and WISE: classification of optical spectra*”, [10.1093/mnras/stv1710](https://doi.org/10.1093/mnras/stv1710) [2015MNRAS.453.3932R](#), (25) The discovery paper for the new class of “Extremely Red Quasars”.

Font-Ribera, Andreu; Kirkby, David; Busca, Nicolas; Miralda-Escudé, Jordi; **Ross, Nicholas P.** et al. “*Quasar-Lyman α forest cross-correlation from BOSS DR11: Baryon Acoustic Oscillations*”, [10.1088/1475-7516/2014/05/027](https://doi.org/10.1088/1475-7516/2014/05/027) [2014JCAP..05..027F](#) (166) Ground-breaking first detection of the “Baryon Acoustic Oscillation” phenomena in the quasar population.

Pâris, Isabelle; Petitjean, Patrick; Aubourg, Éric; **Ross, Nicholas P.** et al. “*The Sloan Digital Sky Survey quasar catalog: tenth data release*” [10.1051/0004-6361/201322691](https://doi.org/10.1051/0004-6361/201322691), [2014A&A...563A..54P \(153\)](#)
Key “v2.0” data release of the SDSS-III BOSS quasar data and associated data products.

Ross, Nicholas P. et al. “*The SDSS-III Baryon Oscillation Spectroscopic Survey: The Quasar Luminosity Function from Data Release Nine*”, [10.1088/0004-637X/773/1/14](https://doi.org/10.1088/0004-637X/773/1/14) [2013ApJ...773...14R, \(99\)](#)
Critical demographic “1-point” measurement of the BOSS quasar Sample (was a BOSS “Key Project”).

Ross, Nicholas P et al. “*The SDSS-III Baryon Oscillation Spectroscopic Survey: Quasar Target Selection for Data Release Nine*”, [10.1088/0067-0049/199/1/3](https://doi.org/10.1088/0067-0049/199/1/3), [2012ApJS..199....3R \(179\)](#) Overview of the work my team lead and a opus of using novel machine learning techniques for astrophysics research.

Pâris, I.; Petitjean, P.; Aubourg, É.; Bailey, S.; **Ross, Nicholas P.** et al. “*The Sloan Digital Sky Survey Quasar Catalog: Ninth Data Release*”, [10.1051/0004-6361/201220142](https://doi.org/10.1051/0004-6361/201220142), [2012A&A...548A..66P \(184\)](#) Production of the first catalogue and data release from the SDSS-III BOSS Quasar Survey.

Schneider, Donald P.; Richards, Gordon T.; Hall, Patrick B.; Strauss, Michael A.; Anderson, Scott F.; Boroson, Todd A.; **Ross, Nicholas P.** et al. “*The Sloan Digital Sky Survey Quasar Catalog. V. Seventh Data Release*”, [10.1088/0004-6256/139/6/2360](https://doi.org/10.1088/0004-6256/139/6/2360), [2010AJ...139.2360S \(588\)](#) Production of the previous state-of-the-art quasar catalogue, with associated metadata.

Ross, Nicholas P et al. “*Clustering of Low-redshift ($z \leq 2.2$) Quasars from the Sloan Digital Sky Survey*”, [10.1088/0004-637X/697/2/1634](https://doi.org/10.1088/0004-637X/697/2/1634), [2009ApJ...697.1634R \(158\)](#) Critical demographic ‘2-point’ measurement of the SDSS Quasar Sample (was SDSS Quasar “Key Project”).

PRIZES AND AWARDS

2014 - 2019	STFC Ernest Rutherford Senior Fellowship
2009 - 2016	Architect SDSS-III: Baryon Oscillation Spectroscopic Survey (BOSS)
2003 - 2008	PPARC Student Fellowship, Durham University

SELECTED LEADERSHIP

2018	P.I. Liverpool Telescope program: <i>The Optical Monitoring of IR-variable Quasars</i>
2018 -	P.I. <i>JWST</i> Cycle 1 GO program: <i>Quasar Physics with the MIRI MRS</i> (to be submitted)
2017 -	P.I. WISE W4 Compendium (WW4C)
2016 - 2017	Co-founder and Chief Data Scientist of <i>String Security Inc.</i>
2014 - 2019	P.I., STFC Ernest Rutherford Fellowship
2013 - 2016	Co-P.I., <i>Spitzer Space Telescope</i> program “ <i>SpIES: The Spitzer-IRAC Equatorial Survey</i> ”
2012 - 2014	Co-P.I., <i>Hubble Space Telescope</i> , program “ <i>High-Luminosity Obscured Quasars at $z \sim 2.5$</i> ”
2011	Chapter Editor, <i>BigBOSS</i> NOAO Proposal, arxiv.org/abs/1106.1706v1
2011	P.I., SDSS-IV: BOSS-Plus (accepted Nov 2011; merged into SDSS-IV: eBOSS)
2009 - 2012	Chair, SDSS-III BOSS Quasar Working Group
2008 - 2010	Lead, SDSS-III BOSS Quasar Target Selection Group
2008 - 2010	P.I., NASA <i>Swift</i> Cycle 5 Long-term local AGN monitoring program

SELECTED PRESENTATIONS

2017 Nov	<i>Dealing With Data 2017 Workshop</i> , Selected Oral Contribution
2017 Jul	Unveiling the Physics Behind Extreme AGN Variability, Conference Summary
2017 May	University of Cambridge Galaxies Discussion Group
2017 Apr	University of Glasgow Weekly Seminar
2016 Jun	JWST@ROE conference Contributed talk
2016 May	University of Michigan Astrophysics Seminar
2016 May	Great Lakes Quasar Symposium Oral Contribution
2016 April	Liverpool John Moores University Astrophysics Seminar
2015 Sep	Multiwavelength AGN Conference, Crete, Invited Review
2015 Jun	ICG, Portsmouth Cosmology Colloquium
2015 Apr	Adler Planetarium, Chicago, Astrophysics Seminar
2015 Jan	225th AAS, Seattle Special Session talk

2014 Sep	Princeton University	Invited talk “Heritage of Stripe 82” meeting
2014 May	Harvard University	HEAD talk
2014 Apr	University of Pennsylvania	Astrophysics Seminar
2013 May	Stanford University	KIPAC Talk
2013 Jan	University of Washington	Colloquium
2012 Jan	New York University	Plenary Talk, BOSS Collaboration meeting
2011 Jul	Oxford University	BICAP Cosmology Seminar
2011 May	Yale University	YCAA Seminar

Q4D: Quasars in the 4th Dimension

All massive galaxies are thought to have supermassive black holes at their centres, and to have undergone a “quasar phase” in their past. Along with fusion in stars, accretion onto the central supermassive black hole is the main energy source available to a galaxy. However, we are missing a deep understanding of galaxy formation theory since we still do not understand in key detail how the energy associated with the quasar escapes the central engine to impact the host galaxy and the intergalactic medium. Further issues arise since recent observations of extreme variability in quasars have broken standard viscous accretion disk models.

In this proposal, we propose the ground breaking idea of combining the data from several next-generation state-of-the art surveys (SDSS-V, DESI, LSST, 4MOST, ESA Euclid and JWST) in order to go beyond the state-of-the-art and construct the extragalactic dataset with the crucial time-domain aspect that is necessary to address the current challenges. The experience of the P.I., along with the strategic data nexus aspect of the Royal Observatory at the University of Edinburgh makes my group uniquely placed to address and answer this problem. The goal is to create a holistic theory of accretion disk physics and quasar feedback in galaxy formation theory. We are also extremely well placed to discover brand new extragalactic variable phenomena.

a State-of-the-art and Objectives

The objectives for this proposal are: to access and combine several new state-of-the-art large astronomical datasets; to kick start the new field of variable extragalactic astrophysics; to create a holistic theory of accretion disk physics and quasar feedback in galaxy formation theory, and to discover brand new astronomical phenomena. Details are given in Table 1. We stress that the novel and high-risk/high-gain combination of these new state-of-the-art large datasets will by design *go significantly beyond the state-of-the-art* and will allow substantial advances in the frontiers of understanding astrophysical phenomena as well as discovering new objects.

a.1 Background

Quasars¹ are powered by accretion of material onto supermassive black holes (SMBHs), via accretion disks. In the local Universe, there is a link between the key properties of massive galaxies, such as bulge mass, and their central supermassive black holes (e.g., McLure and Dunlop, 2002; Häring and Rix, 2004; Salviander et al., 2007; Greene et al., 2010; Kormendy and Ho, 2013). This has led to the proposal that the supermassive black hole, when accreting, has an influence on its host galaxy by the means of some regulatory “feedback” mechanism(s) (e.g., Sijacki et al., 2007; Hopkins et al., 2008; Alexander and Hickox, 2012; Fabian, 2012; King and Pounds, 2015). However, the details of the physical processes involved in this ‘AGN/quasar feedback’ are still disputed and, moreover, direct observational evidence for quasar feedback in the early universe is conspicuous by its absence (e.g., Heckman and Best, 2014; Naab and Ostriker, 2017). Hence, a major source of uncertainty in our current understanding of galaxy evolution is how supermassive black holes influence, and potentially regulate, their host galaxies (Vogelsberger et al., 2013, 2014; Schaye et al., 2015; Anglés-Alcázar et al., 2013, 2017).

What is the main quasar triggering mechanism at the height of quasar activity? What direct observational evidence in individual objects links quasar activity to star formation? Can we observe “quasar feedback” in action, *in situ*, for the most luminous sources? Such unknowns about the co-evolution of black holes and their host galaxies remain among the most fundamental unanswered questions in extragalactic astronomy.

Furthermore, the details of the physical processes involved in the quasar activity including how the SMBH directly couples and affects its most local environment, i.e., the accretion disk, broad line region and dusty torus, are still unknown at this point (e.g., Netzer, 2015; Padovani et al., 2017).

¹ Historically, “quasars” and “Active Galactic Nuclei (AGN)” have described different luminosity/classes of objects, but here we use these terms interchangeably (with a preference for quasar) in recognition of the fact that they both describe accreting supermassive black holes (e.g. Haardt et al., 2016).

Although it has long been established that quasars are powered by accretion discs surrounding supermassive black holes, there have also been long-standing issues. For example, the observed spectral energy distributions (SEDs) of typical quasars (e.g., Koratkar and Blaes, 1999; Sirko and Goodman, 2003) differ markedly from classical predictions (Shakura and Sunyaev, 1973; Pringle, 1981) with a typical observed quasar SED flat in λF_λ over several decades in wavelength (Elvis et al., 1994; Richards et al., 2006). Also, real accretion disks seem to be cooler (e.g., Lawrence, 2012) and larger (e.g., Pooley et al., 2007; Morgan et al., 2010, 2012; Mosquera and Kochanek, 2011) than the standard accretion disk model predictions.

However, even more troubling are new observations of *extreme variability* in some objects (see next section) - factors of several over a decade or so, including, crucially, at optical wavelengths, and not just in the extreme UV or in X-rays. This has led to the “Quasar Viscosity Crisis” (Lawrence, 2018).

As such, we are left in the embarrassing current situation of invoking galaxy-wide “quasar feedback” in order to reconcile demographic observations in cosmological-scale simulations, but where we currently do not understand the physics of mechanism that is supposed to initiate this necessary and vital energy transport.

a.1.1 Observational State-of-the-Art

Here we present a concise overview of the observational state-of-the-art in the brand new field of variable extragalactic astrophysics, concentrating on quasar studies.

A MICROSCOPE FOR RAPID CENTRAL ENGINES: “Changing-look” quasars (CLQs; LaMassa et al., 2015; Runnoe et al., 2016; Ruan et al., 2016; Runco et al., 2016; MacLeod et al., 2016; Yang et al., 2017) are defined to be luminous quasars which have a dramatic appearance, or disappearance, of their broad emission-line component on observed-frame month-to-year timescales. CLQs are important since they offer a direct observational probe into the physical processes dictating the structure of the broad-line region (BLR). These timescales can potentially be associated with the viscous timescale (the drift time through the accretion disk), the light crossing timescale (critical for reverberation mapping and disk reprocessing) and the dynamical timescale of the BLR. *CLQs are thus an ideal laboratory for studying accretion physics, as the entire system responds to a large change in ionizing flux on a human timescale.*

In MacLeod et al. (2016) I co-led the first systematic search for CLQs based on photometry from SDSS and Pan-STARRS1, along with repeat spectra from the SDSS/BOSS, and reported the discovery of 10 CLQs. This is a startling result since we now estimate \approx 10-15% of bona fide quasars may exhibit ‘changing look’ behaviour on \sim 10 year (rest-frame) timescales. However, plausible time-scales for variable dust extinction are factors of 2 – 10 too long to explain the dimming and brightening in these sources. Changes in accretion rate are the currently favored explanation for CLQs, but then the question of how the inner accretion disk couples to the BLR immediately arises. Further investigation is thus warranted.

NEW IR INVESTIGATIONS INTO THE CLQ POPULATION: Taking advantage of new optical imaging data from the Dark Energy Camera Legacy Survey (DECaLS) and new IR light-curves from NEOWISE (Meisner et al., 2017b,a), I have made further in-roads into understanding the CLQ population. This includes identifying objects with rapidly changing IR light-curves and also accretion disk changes, e.g. the $z = 0.378$ quasar SDSS J110057-005304.4, see Figure 1. From J1100-0053, my new model (Ross et al., 2018) suggests a dramatic new picture of the physics of the CLQs governed by processes at the innermost stable circular orbit (ISCO) and the structure of the innermost disk. Expanding these new observations in sample and temporal size, in order to properly inform our theoretical models is the next big challenge.

In summary, as of the time of writing, the observational state-of-the-art for extreme variable quasars is 44 objects, 11 of which I have either discovered or co-led the discovery.

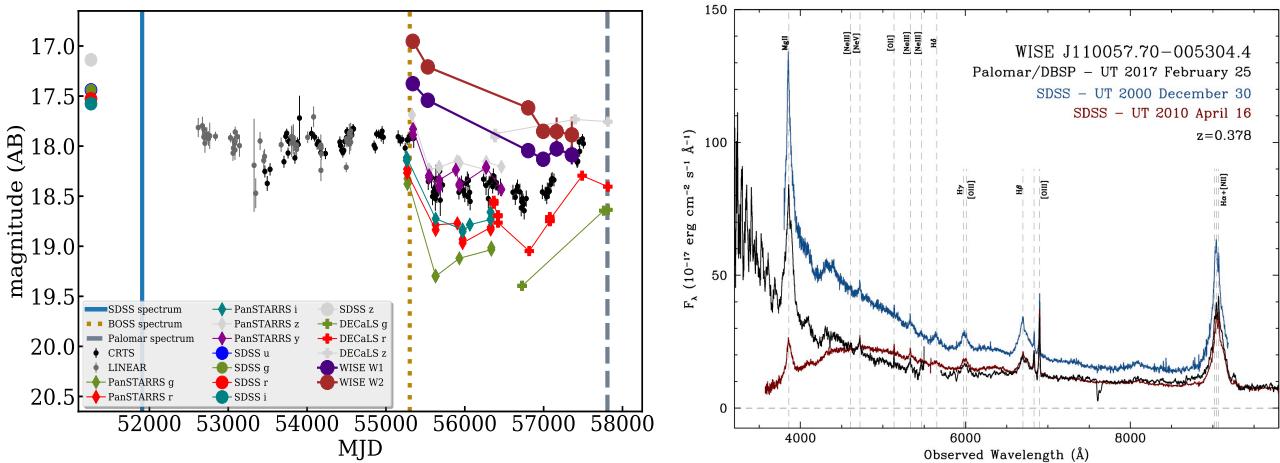


Figure 1: (Left:) The optical and infrared light-curve for J1100-0053; Note the fall in the infrared, whereas there is a decrease, but then recovery in the optical. (Right:) Three epochs of spectra for J1100-0053. The spectacular downturn in the blue for the 2010 spectrum indicates a dramatic change in the accretion disk.

a.1.2 Theoretical State-of-the-Art

Here we present a concise high-level overview of the theoretical state-of-the-art and in particular focus on issues related to our quasar studies.

CONTEMPORARY ACCRETION DISK THEORY: The accretion disk scale is $\lesssim 10^3 - 10^6 r_g$, which is $\approx 5 \times 10^{-3}$ to 5 pc for a $10^8 M_{\text{BH}}$. Yuan and Narayan (2014) review, black hole accretion flows can be divided into two broad classes: cold and hot. Cold accretion flows consist of cool optically thick gas and are found at relatively high mass accretion rates. Hot accretion flows, are virially hot and optically thin, and occur at lower mass accretion rates. How a accretion disk flow transitions between ‘cold’ and ‘hot’, e.g. as the mass flowrate \dot{m} changes, is not well understood, and is an area of current activity.

CONTEMPORARY GALAXY FORMATION THEORY: Contemporary cosmological magnetohydrodynamical galaxy formation simulations take into account a wide range of physical processes, use state-of-the-art numerical codes and take weeks to months to run on the largest supercomputers. They are incredibly sophisticated apparatus and allow us to gain deep insight into the physical processes that drive galaxy formation, including the energy connected to an accreting central SMBH. Naab and Ostriker (2017) present an up to date review of the major challenges for galaxy formation theory.

Current state-of-the-art cosmological simulations, for example, the EAGLE Project (Schaye et al., 2015; Crain et al., 2015) and the IllustrisTNG Project (Pillepich et al., 2018) employ and track 10s of billions resolution elements across 100s of megaparsec-cubed volumes. For EAGLE (e.g. their L100N1504 simulation), the fundamental units of dimensions mass (M), length (L) and time (T, i.e. resolution) are $\sim 2 \times 10^5$ for initial baryonic particle mass, “softening lengths” of 0.35-0.7 pkpc; and time-steps sampling ~ 1000 years ($\sim 10^6$ time-steps across the age of the Universe)². For the new IllustrisTNG “TNG100” model one has 1.4×10^6 for baryonic particle mass, softening lengths $\approx 0.2-1$ pkpc, and $8 \times 10^5 h^{-1} M_{\odot}$ for the seed black hole mass. As such, these are extremely powerful for global galactic properties, but these simulations cannot, and were never designed to, explicitly address inner central engine physics.

Further progress is made with the new high-resolution “zoom-in” galaxy simulations, e.g. Feedback In Realistic Environments (FIRE-2; Wetzel et al., 2016; Hopkins et al., 2017) or MUFASA (Davé et al., 2016). In FIRE-2 for example, Wetzel et al. (2016) run a cosmological scale dark-matter-only simulation to redshift $z = 0$. An isolated DM halo is then selected, the particles are traced back to very high, $z = 100$ redshift and the ‘convex hull’ is regenerated at high resolution (embedded within the full lower-resolution volume). The fiducial baryonic simulation contains dark matter, gas, and stars within the zoom-in region, comprising 140 million

² The times are spaced logarithmically in the expansion factor a such that $\Delta a = 0.005a$.

total particles, with $M_{\text{DM}} = 3.5 \times 10^4 M_{\odot}$ and $M_{\text{gas,initial}} = 7070 M_{\odot}$. The dark matter and stars have fixed gravitational softening lengths of 20pc and 4pc, respectively. In these zoom-ins, the shortest time step achieved is 180 years. As such, these ‘zoom-in’ simulations are impressive, but still not close enough to resolving the scales, masses and cadences needed in order to successful model e.g. the “changing look” quasars.

However, what remains very concerning is that even once the mass, length and timescales are computationally accessible, *we currently do not know what physical prescriptions should be directed for the central black hole and quasar engines to follow.*

For example and as described in detailed in Weinberger et al. (2017), modelling AGNs in cosmological simulations poses several fundamental challenges. The detailed physical mechanisms of both accretion on to SMBHs, and the AGN-gas interaction are poorly understood (Hopkins and Quataert, 2010, 2011; Huarte-Espinosa et al., 2011; Gaibler et al., 2012; Anglés-Alcázar et al., 2013; Gaspari et al., 2013; Cielo et al., 2014; Costa et al., 2014; Anglés-Alcázar et al., 2015; Emsellem et al., 2015; Curtis and Sijacki, 2015, 2016a,b; Rosas-Guevara et al., 2015; Roos et al., 2015; Hopkins et al., 2016; Bieri et al., 2017; Anglés-Alcázar et al., 2017). This makes it at present impossible to formulate a ‘correct’ treatment for simulations. The long-time standard physical mechanism of Bondi-Hoyle-Lyttleton accretion, i.e. that of spherical accretion onto a compact object traveling through the interstellar medium (Hoyle and Lyttleton, 1939; Bondi and Hoyle, 1944; Bondi, 1952) with the accretion rate given by $\dot{M}_{\text{Bondi}} = \pi G^2 M_{\text{BH}}^2 \rho / c_s^3$, is known to be a considerable oversimplification (e.g., Edgar, 2004). We need a new theory. And we need new observations to guide us here.

a.1.3 Upcoming Surveys, Instruments and Missions

(Lawrence, 2016) emphasize that variability studies hold information on otherwise unresolvable regions in quasars. And population studies of large samples likewise have been very productive for our understanding of quasars. These two themes are coming together in the idea of systematic variability studies of large samples and *over the next 5 or so years* the field of observational extragalactic astrophysics is poised for a fundamental and rapid change.

Starting in late 2019, a fleet of new telescopes, instruments and missions are coming online over the next few years that will leap-frog the quality and quantity of data we have available today. Over the course of the next 5-6 years, surveys and missions including the fifth incarnation of the Sloan Digital Sky Survey (SDSS-V³), the Large Synoptic Survey Telescope (LSST⁴), the Dark Energy Spectroscopic Instrument (DESI⁵) survey, the 4-meter Multi-Object Spectroscopic Telescope (4MOST⁶) survey, and the ESA *Euclid* mission⁷, will see first light. Even more imminent is the launch of the *James Webb Space Telescope* (JWST⁸).

Overview of Facilities and Surveys related to this proposal

IMMINENT:

The Sloan Digital Sky Survey (SDSS): An ongoing project, currently in its fourth phase, SDSS-IV. **The P.I. was a leading member of the SDSS-III: Baryon Oscillation Spectroscopic Survey (BOSS; see Track Record and C.V.).** The fifth generation of Sloan Digital Sky Surveys, SDSS-V will be an all-sky, multi-epoch spectroscopic survey, yielding spectra of over 6 million objects during its lifetime. In particular, the SDSS-V Black Hole Mapper (BHM) will focus on long-term, time-domain studies of AGN, including direct measurement of black hole masses and changing-look quasars, and on the optical characterization of eROSITA X-ray sources. Data taking is due to start in 2020. Access would be through a €184,100 ‘buy-in’, which allows access for the P.I. and one PDRA. *Data Products: Repeat spectra in the North and Southern Hemisphere for 500,000 bright QSOs.*

³ www.sdss.org/future/ ⁴ lsst.org ⁵ desi.lbl.gov ⁶ 4most.eu ⁷ sci.esa.int/euclid/ ⁸ jwst.stsci.edu

The **Dark Energy Spectroscopic Instrument (DESI) Survey:** is a 5 year cosmology survey that will be conducted on the Mayall 4-meter telescope at Kitt Peak National Observatory starting in 2019. It uses the 5,000 fiber Dark Energy Spectroscopic Instrument and will obtain optical spectra for ≈ 20 million galaxies and quasars. **The P.I. helped write the original science case and proposal for DESI (Schlegel et al., 2011) but having left the U.S./LBNL, no longer has data access rights.** The DESI Survey starts in late 2019 and data access is through a €200,100 ‘buy-in’, which allows access for the P.I. and two PDRAs. *Data Products: Spectra of 1e6 quasars across 14,000 deg² of the Northern Sky.*

The **Large Synoptic Survey Telescope (LSST)** project will conduct a 10-year survey of the sky, imaging the full Southern Sky every 3 nights. The LSST survey is designed to address four science areas (Understanding the Mysterious Dark Matter and Dark Energy; Hazardous Asteroids and the Remote Solar System; The Transient Optical Sky; The Formation and Structure of the Milky Way) and is an absolutely unique facility as far as areal, temporal and wavelength coverage. The U.K. is a member of LSST. *Data Products: ugrizY broadband optical and near-infrared imaging for 20,000 deg². Images the full Southern Sky every 3 days.*

Euclid is an ESA Medium Class mission to map the geometry of the dark Universe. It aims to understand why the expansion of the Universe is accelerating and what the nature of the source responsible for this acceleration (“dark energy”) is. The mission will investigate the distance-redshift relationship and the evolution of cosmic structures by measuring shapes and redshifts of galaxies and clusters of galaxies out to redshifts ~ 2 , or equivalently to a look-back time of 10 billion years. *Euclid* will also discover a range of near-infrared (NIR) detected quasars, *Euclid* is planned for launch in mid-2021. *Data Products: Very broadband optical and 3 filter near-infrared space-based imaging for 15,000 deg².*

The **4-metre Multi-Object Spectroscopic Telescope (4MOST):** is a fibre-fed spectroscopic survey facility on the VISTA telescope with a large enough field-of-view to survey a large fraction of the southern sky. The facility will be able to simultaneously obtain spectra of 2,400 objects distributed over a field-of-view of 4 square degrees. The initial Galactic and Extragalactic surveys will operate over a five-year period delivering spectra for ≥ 25 million objects over $\gtrsim 15,000$ deg. 4MOST will commence science operations in early 2022. *Data Products: 4MOST will operate continuously for an initial five-year public survey delivering spectra for ≥ 25 million object over 15,000 deg².*

The **James Webb Space Telescope (JWST)** is a space telescope developed in coordination among NASA, the European Space Agency, and the Canadian Space Agency. It is scheduled to be launched in June 2019. The telescope will offer unprecedented resolution and sensitivity from 0.6 to $27\mu\text{m}$. JWST is a partnership between NASA, ESA and the Canadian Space Agency. In particular, ESA’s contributions to JWST include (but are not limited to) the NIRSpec instrument and the Optical Bench Assembly of the MIRI instrument. In return for these contributions, ESA gains full partnership in JWST and secures full access to the JWST observatory for astronomers from ESA Member States on identical terms to those of today on the *Hubble Space Telescope*. *Data Products: Revolutionary optical to mid-infrared deep-field imaging and spectra. Unique access to wavelengths $\lambda > 2\mu\text{m}$, inaccessible from the ground, ideal for high-z quasar studies.*

The **Extended Roentgen Survey with an Imaging Telescope Array (eROSITA)** is the main instrument on the Spektr-RG mission, an international high-energy astrophysics observatory. Set to launch in 2019 with both high sensitivity and a large FOV, eROSITA will discover as many new X-ray sources in its first twelve months as are known today, after more than 50 years of X-ray astronomy. SDSS-V will provide optical spectroscopic measurements including identifications and redshifts, of $\sim 400,000$ eROSITA X-ray sources detected in the first 1.5 years of the all sky survey. In addition, SDSS-V’s BHM

will characterize numerous serendipitous discoveries, extreme and rare objects, transients, and other peculiar variables found in the eROSITA survey (Merloni et al., 2012), and expand an optical+X-ray quasar sample with implications for observational cosmological constraints (e.g. Risaliti and Lusso, 2015).

Notes: 4MOST has full access to the full LSST footprint. LSST will overlap half ($7,500 \text{ deg}^2$) of the *Euclid* footprint. Data access to eROSITA sources is via an MOU with SDSS-V.

ONGOING:

The **Wide-field Infrared Survey Explorer (WISE)** is a NASA infrared-wavelength astronomical space telescope launched in December 2009 and is still operation (as at the time of writing, in its “NEOWISE-R” mission phase). WISE performed an all-sky astronomical survey with images at 3.4, 4.6, 12 and $22\mu\text{m}$ using a 40cm (16 in) diameter infrared telescope in Earth orbit. **The P.I. is a world expert in quasar identification using WISE** (e.g., Ross et al., 2012, 2015; Timlin et al., 2016, 2018) and exploiting mid-infrared light curve data.

The **ESA Gaia** mission is an ongoing mission to chart a three-dimensional map of our Galaxy, the Milky Way, in the process revealing the composition, formation and evolution of the Galaxy. Gaia is providing unprecedented positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about \sim one billion stars in our Galaxy and throughout the Local Group. This amounts to about 1 per cent of the Galactic stellar population.

The timing for this proposal could not be better or more imperative. The first of the data “firehoses” turns on in late 2019, with the full datastream from our key sources fully online around 2022. As such, with two years to use existing datasets as testbeds, we have the time to ramp-up our efforts, while also being able to take advantage of the initial data releases of all these new projects.

a.2 Objectives

The outstanding issues and novel investigations that are pertinent to this proposal are summarised in the Table below.

Our ERC Consolidator grant proposal will radically improve our understanding of one of the two fundamental energy sources available to galaxies; that of accretion onto the compact object in the central engine. We will achieve this by leveraging several of the new, large-scale surveys that are coming online in the next few years. The scope and remit of an ERC Consolidator grant will allow us to combine these data products in a manner that will not only establish the new state-of-the-art in extragalactic variable astrophysics, *it will establish and kick start the new field of extragalactic variable astrophysics itself*. The P.I. is a world-leader in observational quasar astrophysics, both in terms of survey work and individual object study. Our proposal takes astrophysics into the 2020s, going from single objects samples, to surveys and samples of millions of objects leveraging these multi-billion €/£/\$ next generation missions, telescopes and their subsequent datasets.

Outstanding Issues in Variable Extragalactic Astrophysics	
Key Objective	Investigation and Resolution
THE PHYSICS OF ACCRETION	
Investigate “hot” and “cold” mode accretion in the quasar population; determine the rates and timescales, and characterising the Changing Look Quasar (CLQ) population.	Identify and characterize all the CLQs in DESI, SDSS-V, 4MOST and LSST.
Probe and determine the physical state of the inner parsec of the quasar central engine	Rapid analysis and response for LSST quasar light curves. Detailed accretion disk theoretical modeling.
OBSCURED ACCRETION AND GALAXY FORMATION	
Establish the relative importance of major mergers, minor mergers, cold streams and secular evolution have towards the growth of SMBHs across cosmic time.	Deep imaging data from LSST combined with searching for post-starburst signatures in DESI, SDSS-V, 4MOST spectra. Also NIRcam and MIRI imaging from JWST.
Establish the bolometric output and origin of IR emission, and determine presence of extreme outflows in the $z \sim 2 - 3$ quasar population.	NIRSpec and MIRI MRS spectroscopy with JWST.
Establishing the range of SED parameter space the quasars occupy by a multi-wavelength multi-epoch “truth table dataset”	Build “The Quasar SED Rosetta Stone” using X-ray, UV/optical, IR data as well as repeat optical observations from LSST.
Discover the physical conditions under which SMBH grew at the epoch when most of the accretion and star formation in the Universe occurred ($z \sim 1 - 4$)	Perform a complete census of AGN across $z \sim 0 - 7$, focussing on $z = 1 - 4$ using the very wide-field surveys to boost statistics for rare objects and medium-deep multiwavelength datasets to sample the faint-end of the luminosity function.
GALAXY-SCALE FEEDBACK	
Establish the theoretical impact of extreme outflows in the $z \sim 2 - 3$ quasar population	Next-generation Hydro-simulation modelling.
Understand how the accretion disks around black holes launch winds and outflows and determine how much energy these carry. Quantify the amount of “Maintenance/Jet/Kinetic” mode and “Transition/Radiative/Wind” mode feedback.	Connect accretion disk theory and models to cosmological-scale hydro simulations for a holistic theory of “quasar feedback”.

MAXIMISING SCIENCE RETURNS FROM EUROPEAN PRIORITIES: Contemporary astronomy is a multi-national endeavor with many leading facilities being international collaborations. Although a project, with similar but much less ambitious science goals and return could be envisaged at the national level, the full discovery and break-through nature being described herein only comes to the fore when the data from the various international collaborations are combined intelligently. Critically data from leading European Southern Observatory (ESO) and European Space Agency (ESA) facilities will play a pivotal role here.

b Methodology

This ERC Consolidator proposal kick starts the new field of Variable Extragalactic Astrophysics. Due to the Data Science aspect of this proposal, it is, at its heart interdisciplinary. We present a bold research vision that is designed to be addressed by a research group, and the environment, current research areas and telescope access at the Institute for Astronomy at the University of Edinburgh is ideal to carry out these investigations. The

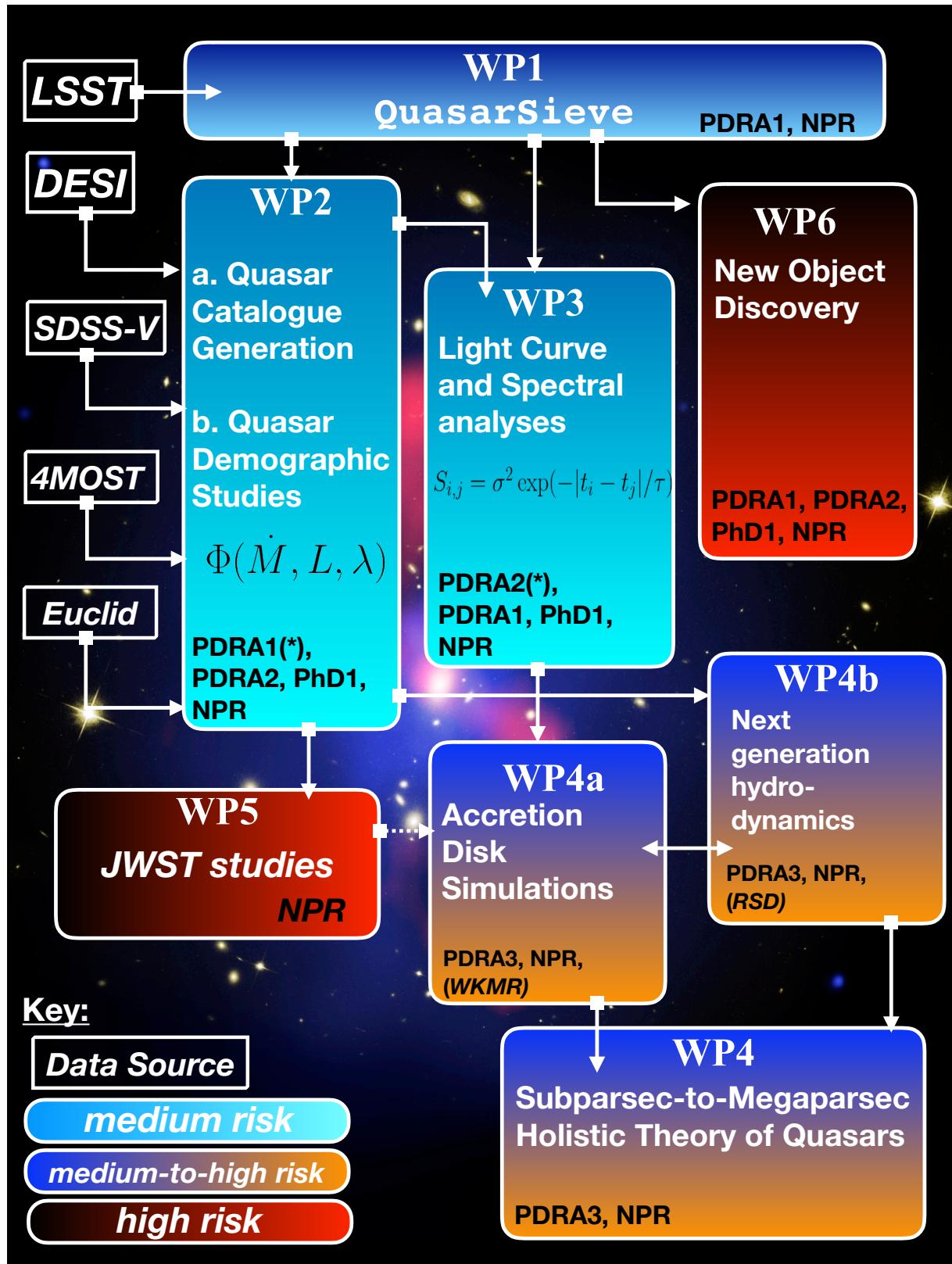


Figure 2: An overview of our WPs. Arrows give general data or workflow, though natural iteration is expect, accounted and not necessarily shown. Asterisks show lead PDRA where necessary. Φ indicative of giving quasar space density, see e.g., Ross et al. (2013). $S_{i,j}$ indicative of a model for the time variability of quasars as a stochastic process described by the exponential covariance matrix (see e.g., MacLeod et al., 2010).

science questions we seek to address are well-posed, yet strike at the heart of major and still open extragalactic astrophysical questions: Do we have a full accounting for the accretion history in the Universe? How does the energy ‘escape’ from the central engine to the host galaxy? Are the modes of AGN “feedback” that regulate a galaxy the same that regulate the AGN itself? What are the star-formation properties of mid-infrared luminous quasars at the peak of quasar activity?

Before laying out our Workplans, we make a note of the ethos involved in this project.

b.1 Project ethos

DATA SCIENCE AND OBSERVATIONAL ASTROPHYSICS: Data science is a new interdisciplinary field of scientific methods to extract knowledge or insights from data in various forms, either structured or unstructured. It employs techniques and theories drawn from many fields within the broad areas of mathematics, statistics, information science, and computer science, in particular from the subdomains of machine learning, classification, cluster analysis, data mining, databases, and visualization. *Modern day observational astrophysicists are in all but name data scientists, and as such, this proposal is inherently interdisciplinary.*

BREAKING DOWN THE DATA SILOS: The bottleneck to using advanced data analysis is not skill base or technology; it is simply access to the data. A data silo is a repository of fixed data that remains under the control of one department/collaboration and is isolated from the rest of the world, much like grain in a farm silo is closed off from outside elements. These silos are isolated islands of data, and they make it prohibitive to extract data and put it to other uses. In research environments, and especially in contemporary observational astrophysics, the data silos are open, but due to the lack of raw person-power, still remain uncombined. *The combination of P.I. and host institute means we are uniquely positioned to break down these astro-data silos for massively significant science gain.*

TARGETING BIG DATA: This ERC will develop and employ leadership-computing systems and infrastructure to explore, prove, and improve a wide range of data science techniques: uncertainty quantification; statistics; machine learning; deep learning; databases; pattern recognition; image processing; graph analytics; data mining; real-time data analysis; and complex and interactive workflows.

ALGORITHMS: Our algorithms and methodology are based on the latest machine-learning and data science techniques. Specifically we will use Python as the CS-glue, NumPy for high-speed numerical processing, pandas for efficient data ingestion and Matplotlib for data visualization. The Astropy Project is a community effort to develop a common core package for Astronomy in Python and foster an ecosystem of interoperable astronomy packages, and one the P.I. and his team fully use and support. scikit-learn is a Python module integrating classic machine learning algorithms in the scientific Python world. It aims to provide simple and efficient solutions to learning problems, accessible to everybody and reusable in various contexts. Resources such as the Python Data Science Handbook have full details. *We nota bene that the P.I. and his research group has a strong track record of building, combining and utilizing new ML algorithms for quasar science e.g., Ross et al. (2012).*

OPEN INNOVATION, OPEN SCIENCE, OPEN TO THE WORLD: The P.I. is an exceptionally strong, long-time and vocal supporter of “Open Access”. All my codes, data⁹, papers and proposals can be found at github.com/d80b2t. Indeed, this proposal itself is now at that location. One of the major research outputs of this ERC will be computer code. As such, we are already working with the The Software Sustainability Institute which was founded to support the UK’s research software community. Our software will be developed using the FAIR ideology (Findable, Accessible, Interoperable, Reusable¹⁰) and will be delivered in a manner which is fully inline with “Open Innovation, Open Science, Open to the World”.

⁹ Where I am not breaking current data access agreements ¹⁰ Wilkinson, MD, Sci Data. 2016 Mar 15;3:160018. doi: 10.1038/sdata.2016.18.

b.2 Work Packages

Our proposal contains six work packages that fall into three broad and complementary categories: observational studies of large numbers (millions) of objects; high-risk, very high-reward observational studies of a small number (10s) of objects; theoretical modeling investigations. Figure 2 summarises our overall WP plan. Risks and mitigation strategies are present for each WP as are Key Deliverables. The P.I. (NPR), three PDRA, “PDRA1”, “PDRA 2”, “PDRA 3”, and one PhD student, “PhD1” are the personnel required to carry out these work packages.

NPR is a world-leader in the field of extragalactic observational astrophysics. NPR’s research focuses on implementing novel data science and machine learning algorithms and techniques in order to discover and study the physical processes in quasars. I have an exceptionally strong track record including being the lead of a science Working Group, with prodigious scientific output (over 400 published, peer-reviewed papers from that particular collaboration).

I was the Co-Founder and Chief Data Scientist of String Security Inc. I built a predictive threat detection and remediation platform for cyber security teams by applying machine learning and predictive algorithms. Thus the P.I.’s research strengths, ability to quickly develop bleeding-edge software and science output are all ideally matched to this proposal.

The skill set of PDRA1 would include development of the underlying tools and techniques necessary to extract meaning from large and/or complex data sets. PDRA1 would have a strong physical sciences background, and a PhD in astrophysics or computer science.

The skill sets of PDRA2 would include expertise in time series analysis, primarily with optical data but potentially also in other wavebands. PDRA2 would have a PhD in astrophysics or a related field.

The skill set of PDRA3 would include experience with fluid mechanics modelling and/or large computer simulations. PDRA3 would have a PhD in astrophysics, mathematics or computer science.

PhD1 would have a Masters or a strong 4-year undergraduate degree in Physics or Mathematics with evidence of research-level project work.

WP1: BUILD QUASARSIEVE:

Raw events come from LSST. The UK LSST Data Access Center (DAC, based here at the University of Edinburgh) ingests this datastream and re-emits a filtered stream. In order to utilize this filtered datastream for our science goals we will build a “Stage 2 filter”, which we name QuasarSieve. This second stage filter will identify the quasars, add context, perform outburst forecasting etc. Our light-curve algorithm will sit on top of QuasarSieve and will trigger other telescopes to get e.g. timely spectrum or infrared data.

We will veto stars using ESA Gaia, the data of which are hosted by the Wide-Field Astronomy Unit (WFAU) here at the Royal Observatory, Edinburgh.

The heavy-industry computing infrastructure is being supplied by the LSST DAC and our task will be to build software in a timely and robust manner. This is a novel enterprise and a rate-limiting step in our overall programme, with the associated high-risk. We mitigate this risk with the data science and machine learning experience from PDRA1 and the P.I. (NPR). We will also mitigate risk by taking advantage of the algorithm resources and LSST DAC staff, here at the Royal Observatory, Edinburgh. We thus classify **WP1 as medium-risk, high-reward**.

Key Deliverables: An open-source, well-documented software package that can interact with and return data from the LSST Data Access Center. **Timeline:** *QuasarSieve* will be the first project to be started and a ‘beta’-version will appear within 3 months. The v1.0 will appear after 6 months. We budget 2 years of time here, but the main effort will be frontloaded, with continually tweaks throughout the full run of the grant.

WP2: QUASAR CATALOGUE GENERATION AND DEMOGRAPHIC STUDIES:

Building the quasar corpus and cataloguing the observational data will be a vital step in beginning to pursue our science goals. This catalogue will be the glue that binds the observational projects together and will have not only the data, but also the metadata to enable the other WPs. Following on from the quasar catalogue generation, a key science output will be the study of the quasar demographics. Luminosity function, clustering and higher-order statistics will be made in order to precisely determine the census of quasars, their environments, their host galaxy preferences and their evolution. All these are vital observational tests for galaxy formation models and theory (see WP4 below). The goal of this WP is to construct a quasar catalogue and make key observational tests. Given the P.I.s experience at these specific tasks, plus the effort level of PDRA1, PDRA2 and PhD this WP is deemed medium-risk. **WP2 is medium-risk, high-reward.**

Key Deliverables: A science-enabling compendium that will be the state-of-the-art quasar dataset for the 2020s. A suite of new, beyond-the-state-of-the-art quasar demographic measurements which are the boundary conditions for theoretical models. **Timeline:**

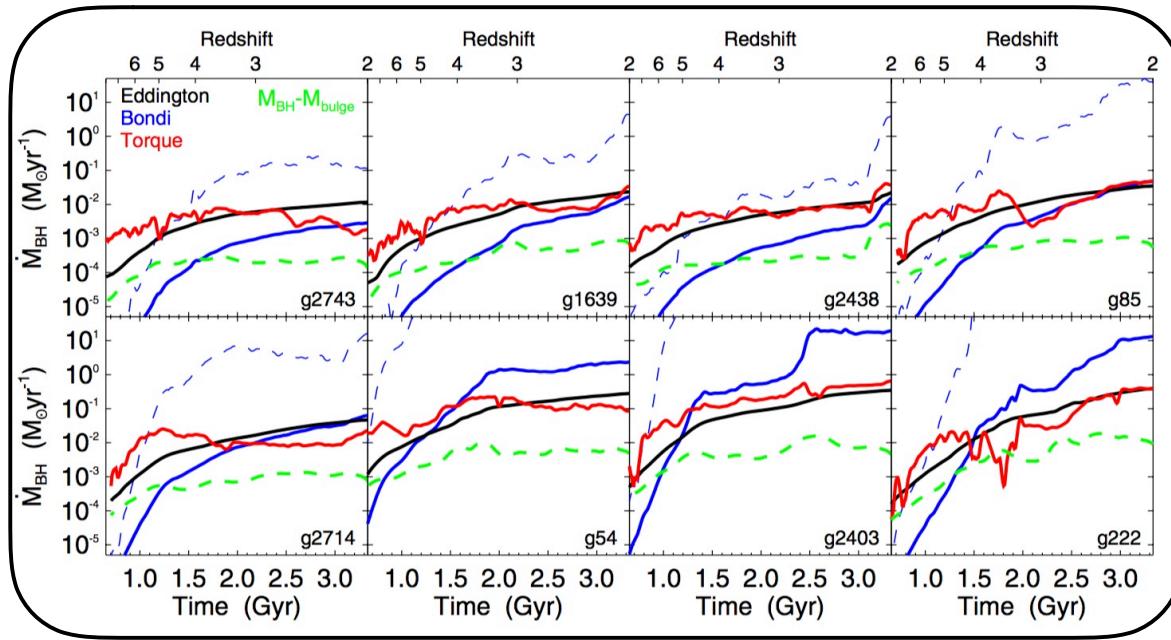


Figure 3: From Anglés-Alcázar et al. (2013): inferred accretion rates as a function of time for a black hole located at the center of each simulated galaxy. Black hole masses are taken from the $M_{\text{BH}} - M_{\text{bulge}}$ relation for the total stellar mass within the effective radius at all times, and accretion rates are calculated based on the properties of the host galaxy over time, according to (1) the Bondi-Hoyle-Lyttleton parameterization with the “boost-factor” $\alpha = 100$ (solid blue line) and for the density-dependent α introduced by Booth and Schaye (2009, dashed blue line)), (2) the gravitational torque model of Hopkins and Quataert (2011, red line), and (3) the Eddington rate (black line). Dashed green lines correspond to the actual accretion rates required for black holes to grow according to the $M_{\text{BH}} - M_{\text{bulge}}$ relation for each galaxy at all times.

WP3: LIGHT-CURVE AND SPECTRAL ANALYSES:

Another major scientific output that will originate from the quasar corpus catalogue generation will be the full and detailed light-curve and spectral analyses of the said catalogue. This will result in the discovery of light-curve trends with quasar type, new methods to measure black hole mass and the key science goal to see which quasars are “changing-look” objects. This WP will have a data science/machine learning aspect. The goal of this WP is to elucidate the physical processes that drive quasar variability. The full Light-Curve and

Spectral Analyses that we envisaged will be a significant amount of work, leading to significant high-reward science.

WP3 is medium-risk, high-reward. This level of investigation is highly novel, though we envisage no major barriers outside of our control to achieving our science goals and PDRA1, PDRA2, as well as the P.I. (NPR) and PhD1 effort will be directed towards this. As such, we deem this medium-risk.

Key Deliverables: Measurements, for the first time of how the light-curves and spectra of quasars depend on key physical quasar properties e.g. M_{SMBH} , luminosity, $\lambda = \log(L/L_{\text{Edd}})$, spin etc. These measurements will allow us to make direct comparisons to accretion disk models. **Timeline:**

WP4: ACCRETION DISK AND QUASAR FEEDBACK SIMULATIONS:

New accretion models are needed to fully explain the observational data of “changing look” quasars that we have examples of today and the “Quasar Viscosity Crisis”. New radiation MHD codes begin to explain the observations here, but further development is needed to gain the desired deep understanding. Cosmological-scale hydrodynamic simulations with stellar and quasar feedback are now also online. The exceedingly ambitious goal of WP5 is to develop new holistic accretion disk-to-cosmological scale simulations that explain our observational results and link them to “quasar feedback”.

WP4 is thus high-risk due to its novel nature and algorithmic complexity. We also envisage ramp-up time to get our theoretical simulations to the level that will be required by our beyond-the-state-of-the-art dataset. However, we mitigate this risk first by noting this will be the lead WP and top priority for PDRA3. We further mitigate this risk by invoking collaboration with accretion disk theorist Prof. Ken Rice (WKMR; Chair of Computational Astrophysics at the IfA, University of Edinburgh) and Prof. Romeel Dave (RSD; Chair of Physics in the IfA, University of Edinburgh). Thus PDRA3, NPR, potentially PDRA2, with guidance where necessary from WKMR and RSD would collaborate on this WP. We thus classify **WP4 as medium-to-high risk, very high-reward.**

Key Deliverables: New accretion disk models and theory that explain the light curve data of our beyond-the-state-of-the-art dataset. New galaxy evolution models, describing the hydrodynamics involved on galactic scales, but related to the quasar central engine. **Timeline:**

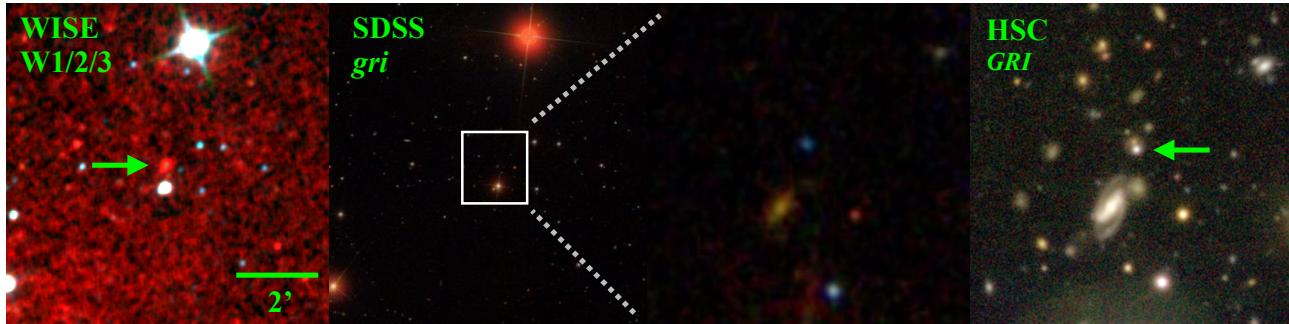


Figure 4: The IR and optical imaging of J2323-0100, an archetype of the “Extremely Red Quasars” (ERQs) at $z \approx 2.5$ and a JWST target. Shown are WISE (left), where the quasar booms out as indicated by the arrow; the SDSS image (middle left) with zoom-in (middle right) on the optically faint source, and new HSC imaging (right), which shows tantalizing evidence for a faint companion galaxy. Optical rest-frame spectra of J2323-0100, revealed very broad ($\text{FWHM} = 2500\text{-}5000 \text{ km s}^{-1}$), strongly blue-shifted (by up to 1500 km s^{-1}) [O III] $\lambda 5007\text{\AA}$ emission lines in the ERQs. This is suggestive of active outflows and potentially evidence for AGN feedback in action at the height of SMBH activity.

WP5: OBSERVATIONS OF QUASARS BY THE JAMES WEBB SPACE TELESCOPE

In Ross et al. (2015) I discovered a new class of object, the “extremely red quasars”, that have optical spectroscopy from SDSS/BOSS, and $r - [22\mu\text{m}] > 14$ colors (i.e., $F_{\nu, \text{MIR}}/F_{\nu, \text{opt}} \gtrsim 1000$) from the Wide-field

Infrared Survey Explorer (WISE; Wright et al., 2010) satellite, see Figure 4. The ERQs are a unique obscured quasar population with extreme physical conditions related to powerful outflows across the line-forming regions. As my team have shown, these sources are the signposts of the most dramatic form of quasar feedback at the peak epoch of galaxy formation, and may represent an active “blow-out” phase of quasar evolution (Zakamska et al., 2016; Hamann et al., 2017). However, due to the current lack of access to mid-infrared spectroscopy, it is still unknown whether the large IR luminosities observed in these quasars is from star formation, which would produce strong polycyclic aromatic hydrocarbon (PAH) spectral features, or, if it is from the hot dust near the central quasar, which should produce much weaker/no PAH emission.

What are the star-formation properties of luminous quasars at the peak of quasar activity? We aim to answer this by looking for the presence of polycyclic aromatic hydrocarbon (PAH) spectral features in infrared bright quasars with the *James Webb Space Telescope* (JWST).

WP5 is high risk, high-reward. This is an ideal investigation for the JWST, but we classify this as high-risk since we have to apply for the telescope time and are not guaranteed the data. We note this will be the single WP NPR would lead and does not impact in any direct way the other WPs. This would lead to very-high gain science.

Key Deliverables: State-of-the-art data products from the JWST, with the observational evidence and physical interpretation of how “quasar feedback” regulates galaxy formation in high-redshift quasars. **Timeline:** The deadline for JWST Cycle 1 GO programmes is 06th April 2018, so I will know if I have been awarded observing time here before the start of the ERC.

WP6: NEW OBJECT DISCOVERY:

The LSST will scan the sky repeatedly, enabling it, and us, to both discover new, distant transient events and to study variable objects throughout our universe. The LSST will extend our view of the changeable universe a thousand times over current surveys. The most interesting science to come may well be the discovery of new classes of objects.

WP6 is medium-risk, exceptionally high-reward. We class this as medium-risk, since it is tricky to class a WP with essentially unknown discovery potential as fully ‘low-risk’. However, we do not classify this as ‘high-risk’ since if there was a paucity of discovery of novel classes of objects, this would be the first time in the history of observational astrophysics that a new facility such as LSST has come online and found nothing new.

Key Deliverables: Potential discovery of new classes of astronomical objects. **Timeline:** Peak Discovery Potential will come during the very early operation of LSST. We have to thus have QuasarSieve, our ML light curve algorithms trained, and be ready to follow-up where necessary these

b.3 Feasibility

By its inherent nature, our programme is high-risk and high-reward, but we *fundamentally* have the personnel and skill sets that are necessary to make this project feasible. The P.I. has a track-record of managing scientific groups in large international and world-leading collaborations. *Critically, he also has a track record of developing key software packages on strict deadlines, e.g. the BOSS Quasar Target Selection software package (that contained a suite of novel ML algorithms).*

c Resources (including project costs)

Here we summarize and justify the budget.

Cost Category		Total in Euro
Direct Costs	Personnel	PI 403,854
	Senior Staff	
	Postdocs	617,145
	Students	84,545
	Other	
	<i>i. Total Direct Costs for Personnel (in Euro)</i>	
	Travel	190,000
	Equipment	53,000
	Other goods and services	Consumables 0 Publications (including Open Access fees), etc. 15,000 Other, incl. SDSS-IV Project buy-in, DESI Project buy-in, Audit, Recruitment, Publication. 413,535
	<i>ii. Total Other Direct Costs (in Euro)</i>	
A – Total Direct Costs (i + ii) (in Euro)		1,762,080
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)		262,457
C1 – Subcontracting Costs (no overheads) (in Euro)		15,000
C2 – Other Direct Costs with no overheads (in Euro)		0
Total Estimated Eligible Costs (A + B + C) (in Euro)		2,217,600
Total Requested EU Contribution (in Euro)⁶		2,217,600

For the above cost table, please indicate the duration of the project in months:	60
For the above cost table, please indicate the % of working time the PI dedicates to the project over the period of the grant:	100%

The P.I. will spend 100% of their time on the project, which will include achieving the science objectives, managing and supervising personal, as well as the associated logistical overhead time commitments.

TEAM COMPOSITION: Our team will consist of the P.I., three postdoctoral research associates (PDRAs), and 1 PhD student. Two postdoctoral appointments will be for three years each and one will be for a four year appointment (a total of 10 FTE over 5 years). The one PhD student will have a four year appointment. The ambitious nature of this project requires a large team of both observational and theoretical postdoctoral scholars and PhD students to complete the proposed research. The P.I. is not a current member of academic staff and therefore has no responsibilities extending beyond research. As such, the P.I. is charged at 100% and, if successful, will focus solely on the aims of the project. Again, this will be necessary to achieve all our goals on the given schedule.

SALARIES: The primary expenditure of our project corresponds to salaries in order support the large team necessary for this project. The P.I. will be fully involved (project management, scientific analysis, student supervision, postdoc mentorship, proposal writing, communication with external collaborations, and paper writing) and is covered at the 100% level over 5 years. Salaries are determined according to the UoE salary scale: €80.7k per FTE for the P.I., €61.3k per FTE for the PDRAs and €21.1k per FTE for PhD students. The total cost of salaries over 5 years is **€1106k**.

TRAVEL: A major expense is in the form of travel. I expect all group members to disseminate our results in international conference but also to participate in external collaboration meeting (at least one per year). Due to the nature and timing of our proposal, it will almost certainly be critical for the PDRAs to have extended (several week long) visits to the US and ESO Chile. I have allocated thus allocated €10k/year for all members of the group for travel. This level of commitment is necessary as has been proved by the P.I.'s recent and continued involvement with the e.g. US-based surveys (and the benefit to his research fellowship). The total travel budget is **€190k**.

PUBLICATIONS: Our work will be published in international journals such as Nature, Nature Astronomy, Science, Monthly Notices of the Royal Astronomical Society and the Astrophysical Journal. I have allocated €3k/year for the cost of publications. In addition, all papers will be on the arXiv preprint server free of charge. The total publications budget is **€15k**.

EQUIPMENT & CONSUMABLES: I have allocated €10k/person for the initial purchase of a desktop and laptop computer. Consumables are limited to €600/year (for the purchase of back-up drives and other equipment). The total equipment and consumables budget is **€53k**.

ACCESS TO LARGE FACILITIES: We ask for additional funds that are available to cover "access to large facilities". We request support for the "buy-in" to two of the new surveys, SDSS-V and DESI. The costs here are €184.1k for SDSS-V and €200.1k for DESI. We specifically request access to these funds as it gives our project access to telescopes and data in the North and Southern Hemispheres (for complete coverage of the celestial sphere) and delivers the crucial early spectroscopy that will be vital to train, test and build our data science and machine learning codes and algorithms. We emphasise that the science return is 'exponential' (rather than 'linearly') dependent on the breadth of data available and heralds a brand new regime of "several-survey" or "multi-mission" astronomy. Buy-in allows the two observational PDRAs along with the PhD student to have data access rights here and *would place the P.I. and the University of Edinburgh as the only group and institute in the world to be involved in SDSS-V, DESI, 4MOST, LSST and ESA Euclid and JWST*. The total budget for the access to large facilities is **€384.2k**.

Total budget before facilities costs: **€this amount**.

Total budget including facilities costs: **€this amount+384.2k**.

References

- D. M. Alexander and R. C. Hickox. What drives the growth of black holes? *New A.R.*, 56:93–121, June 2012. doi: 10.1016/j.newar.2011.11.003.
- D. Anglés-Alcázar, F. Özel, and R. Davé. Black Hole-Galaxy Correlations without Self-regulation. *ApJ*, 770: 5, June 2013. doi: 10.1088/0004-637X/770/1/5.
- D. Anglés-Alcázar, F. Özel, R. Davé, N. Katz, J. A. Kollmeier, and B. D. Oppenheimer. Torque-limited Growth of Massive Black Holes in Galaxies across Cosmic Time. *ApJ*, 800:127, Feb 2015. doi: 10.1088/0004-637X/800/2/127.
- D. Anglés-Alcázar, C.-A. Faucher-Giguère, E. Quataert, P. F. Hopkins, R. Feldmann, P. Torrey, A. Wetzel, and D. Kereš. Black holes on FIRE: stellar feedback limits early feeding of galactic nuclei. *MNRAS*, 472: L109–L114, Nov 2017. doi: 10.1093/mnrasl/slx161.
- R. Bieri, Y. Dubois, J. Rosdahl, A. Wagner, J. Silk, and G. A. Mamon. Outflows driven by quasars in high-redshift galaxies with radiation hydrodynamics. *MNRAS*, 464:1854–1873, Jan 2017. doi: 10.1093/mnras/stw2380.
- H. Bondi. On spherically symmetrical accretion. *MNRAS*, 112:195, 1952. doi: 10.1093/mnras/112.2.195.
- H. Bondi and F. Hoyle. On the mechanism of accretion by stars. *MNRAS*, 104:273, 1944. doi: 10.1093/mnras/104.5.273.
- C. M. Booth and J. Schaye. Cosmological simulations of the growth of supermassive black holes and feedback from active galactic nuclei: method and tests. *MNRAS*, 398:53–74, Sept 2009. doi: 10.1111/j.1365-2966.2009.15043.x.
- S. Cielo, V. Antonuccio-Delogu, A. V. Macciò, A. D. Romeo, and J. Silk. 3D simulations of the early stages of AGN jets: geometry, thermodynamics and backflow. *MNRAS*, 439:2903–2916, Apr 2014. doi: 10.1093/mnras/stu161.
- T. Costa, D. Sijacki, and M. G. Haehnelt. Feedback from active galactic nuclei: energy- versus momentum-driving. *MNRAS*, 444:2355–2376, Nov 2014. doi: 10.1093/mnras/stu1632.
- R. A. Crain et al. The EAGLE simulations of galaxy formation: calibration of subgrid physics and model variations. *MNRAS*, 450:1937–1961, June 2015. doi: 10.1093/mnras/stv725.
- M. Curtis and D. Sijacki. Resolving flows around black holes: numerical technique and applications. *MNRAS*, 454:3445–3463, Dec 2015. doi: 10.1093/mnras/stv2246.
- M. Curtis and D. Sijacki. Powerful quasar outflow in a massive disc galaxy at $z \sim 5$. *MNRAS*, 457:L34–L38, March 2016a. doi: 10.1093/mnrasl/slv199.
- M. Curtis and D. Sijacki. Resolving flows around black holes: the impact of gas angular momentum. *MNRAS*, 463:63–77, Nov 2016b. doi: 10.1093/mnras/stw1944.
- R. Davé, R. Thompson, and P. F. Hopkins. MUFASA: galaxy formation simulations with meshless hydrodynamics. *MNRAS*, 462:3265–3284, Nov 2016. doi: 10.1093/mnras/stw1862.
- R. Edgar. A review of Bondi-Hoyle-Lyttleton accretion. *New A.R.*, 48:843–859, Sept 2004. doi: 10.1016/j.newar.2004.06.001.
- M. Elvis et al. Atlas of quasar energy distributions. *ApJS*, 95:1–68, Nov 1994. doi: 10.1086/192093.
- E. Emsellem, F. Renaud, F. Bournaud, B. Elmegreen, F. Combes, and J. M. Gabor. The interplay between a galactic bar and a supermassive black hole: nuclear fuelling in a subparsec resolution galaxy simulation. *MNRAS*, 446:2468–2482, Jan 2015. doi: 10.1093/mnras/stu2209.
- A. C. Fabian. Observational Evidence of Active Galactic Nuclei Feedback. *ARA&A*, 50:455–489, Sept 2012. doi: 10.1146/annurev-astro-081811-125521.
- V. Gaibler, S. Khochfar, M. Krause, and J. Silk. Jet-induced star formation in gas-rich galaxies. *MNRAS*, 425: 438–449, Sept 2012. doi: 10.1111/j.1365-2966.2012.21479.x.
- M. Gaspari, M. Ruszkowski, and S. P. Oh. Chaotic cold accretion on to black holes. *MNRAS*, 432:3401–3422, July 2013. doi: 10.1093/mnras/stt692.
- J. E. Greene, C. Y. Peng, M. Kim, C.-Y. Kuo, J. A. Braatz, C. M. V. Impellizzeri, J. J. Condon, K. Y. Lo, C. Henkel, and M. J. Reid. Precise Black Hole Masses from Megamaser Disks: Black Hole-Bulge Relations

- at Low Mass. *ApJ*, 721:26–45, Sept 2010. doi: 10.1088/0004-637X/721/1/26.
- F. Haardt, V. Gorini, U. Moschella, A. Treves, and M. Colpi, editors. *Astrophysical Black Holes*, volume 905 of *Lecture Notes in Physics*, Berlin Springer Verlag, 2016. doi: 10.1007/978-3-319-19416-5.
- F. Hamann et al. Extremely red quasars in BOSS. *MNRAS*, 464:3431–3463, Jan 2017. doi: 10.1093/mnras/stw2387.
- N. Häring and H.-W. Rix. On the Black Hole Mass-Bulge Mass Relation. *ApJ Lett.*, 604:L89–L92, Apr 2004. doi: 10.1086/383567.
- T. Heckman and P. Best. The Co-Evolution of Galaxies and Supermassive Black Holes: Insights from Surveys of the Contemporary Universe. *ArXiv:1403.4620v1*, March 2014.
- P. F. Hopkins and E. Quataert. How do massive black holes get their gas? *MNRAS*, 407:1529–1564, Sept 2010. doi: 10.1111/j.1365-2966.2010.17064.x.
- P. F. Hopkins and E. Quataert. An analytic model of angular momentum transport by gravitational torques: from galaxies to massive black holes. *MNRAS*, 415:1027–1050, Aug 2011. doi: 10.1111/j.1365-2966.2011.18542.x.
- P. F. Hopkins, L. Hernquist, T. J. Cox, and D. Kereš. A Cosmological Framework for the Co-Evolution of Quasars, Supermassive Black Holes, and Elliptical Galaxies. I. Galaxy Mergers and Quasar Activity. *ApJS*, 175:356–389, Apr 2008. doi: 10.1086/524362.
- P. F. Hopkins, P. Torrey, C.-A. Faucher-Giguère, E. Quataert, and N. Murray. Stellar and quasar feedback in concert: effects on AGN accretion, obscuration, and outflows. *MNRAS*, 458:816–831, May 2016. doi: 10.1093/mnras/stw289.
- P. F. Hopkins et al. FIRE-2 Simulations: Physics versus Numerics in Galaxy Formation. *ArXiv e-prints*, Feb 2017.
- F. Hoyle and R. A. Lyttleton. The effect of interstellar matter on climatic variation. *Proceedings of the Cambridge Philosophical Society*, 35:405, 1939. doi: 10.1017/S0305004100021150.
- M. Huarte-Espinosa, M. Krause, and P. Alexander. 3D magnetohydrodynamic simulations of the evolution of magnetic fields in Fanaroff-Riley class II radio sources. *MNRAS*, 417:382–399, Oct 2011. doi: 10.1111/j.1365-2966.2011.19271.x.
- A. King and K. Pounds. Powerful Outflows and Feedback from Active Galactic Nuclei. *ARA&A*, 53:115–154, Aug 2015. doi: 10.1146/annurev-astro-082214-122316.
- A. Koratkar and O. Blaes. The Ultraviolet and Optical Continuum Emission in Active Galactic Nuclei: The Status of Accretion Disks. *PASP*, 111:1–30, Jan 1999. doi: 10.1086/316294.
- J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *ARA&A*, 51:511–653, Aug 2013. doi: 10.1146/annurev-astro-082708-101811.
- S. M. LaMassa, S. Cales, E. C. Moran, A. D. Myers, G. T. Richards, M. Eracleous, T. M. Heckman, L. Gallo, and C. M. Urry. The Discovery of the First “Changing Look” Quasar: New Insights Into the Physics and Phenomenology of Active Galactic Nucleus. *ApJ*, 800:144, Feb 2015. doi: 10.1088/0004-637X/800/2/144.
- A. Lawrence. The UV peak in active galactic nuclei: a false continuum from blurred reflection? *MNRAS*, 423: 451–463, June 2012. doi: 10.1111/j.1365-2966.2012.20889.x.
- A. Lawrence. Clues to the Structure of AGN Through Massive Variability Surveys. In A. Mickaelian, A. Lawrence, and T. Magakian, editors, *Astronomical Surveys and Big Data*, volume 505 of *Astronomical Society of the Pacific Conference Series*, page 107, June 2016.
- A. Lawrence. Quasar viscosity crisis. *Nature Astronomy*, 2:102–103, Jan 2018.
- C. L. MacLeod, N. P. Ross, et al. A systematic search for changing-look quasars in SDSS. *MNRAS*, 457: 389–404, March 2016. doi: 10.1093/mnras/stv2997.
- C. L. MacLeod et al. Modeling the Time Variability of SDSS Stripe 82 Quasars as a Damped Random Walk. *ApJ*, 721:1014–1033, Oct 2010. doi: 10.1088/0004-637X/721/2/1014.
- R. J. McLure and J. S. Dunlop. On the black hole-bulge mass relation in active and inactive galaxies. *MNRAS*, 331:795–804, Apr 2002. doi: 10.1046/j.1365-8711.2002.05236.x.
- A. M. Meisner, B. C. Bromley, P. E. Nugent, D. J. Schlegel, S. J. Kenyon, E. F. Schlafly, and K. S. Dawson. Searching for Planet Nine with Coadded WISE and NEOWISE-Reactivation Images. *AJ*, 153:65, Feb 2017a.

- doi: 10.3847/1538-3881/153/2/65.
- A. M. Meisner, D. Lang, and D. J. Schlegel. Deep Full-sky Coadds from Three Years of WISE and NEOWISE Observations. *AJ*, 154:161, Oct 2017b. doi: 10.3847/1538-3881/aa894e.
- A. Merloni, P. Predehl, W. Becker, H. Böhringer, T. Boller, H. Brunner, M. Brusa, K. Dennerl, M. Freyberg, P. Friedrich, A. Georgakakis, F. Haberl, G. Hasinger, N. Meidinger, J. Mohr, K. Nandra, A. Rau, T. H. Reiprich, J. Robrade, M. Salvato, A. Santangelo, M. Sasaki, A. Schwone, J. Wilms, and t. German eROSITA Consortium. eROSITA Science Book: Mapping the Structure of the Energetic Universe. *ArXiv e-prints*, Sept 2012.
- C. W. Morgan, C. S. Kochanek, N. D. Morgan, and E. E. Falco. The Quasar Accretion Disk Size-Black Hole Mass Relation. *ApJ*, 712:1129–1136, Apr 2010. doi: 10.1088/0004-637X/712/2/1129.
- C. W. Morgan et al. Further Evidence that Quasar X-Ray Emitting Regions are Compact: X-Ray and Optical Microlensing in the Lensed Quasar Q J0158-4325. *ApJ*, 756:52, Sept 2012. doi: 10.1088/0004-637X/756/1/52.
- A. M. Mosquera and C. S. Kochanek. The Microlensing Properties of a Sample of 87 Lensed Quasars. *ApJ*, 738:96, Sept 2011. doi: 10.1088/0004-637X/738/1/96.
- T. Naab and J. P. Ostriker. Theoretical Challenges in Galaxy Formation. *ARA&A*, 55:59–109, Aug 2017. doi: 10.1146/annurev-astro-081913-040019.
- H. Netzer. Revisiting the Unified Model of Active Galactic Nuclei. *ARA&A*, 53:365, 2015.
- P. Padovani, D. M. Alexander, R. J. Assef, B. De Marco, P. Giommi, R. C. Hickox, G. T. Richards, V. Smolčić, E. Hatziminaoglou, V. Mainieri, and M. Salvato. Active galactic nuclei: what's in a name? *A&ARv*, 25:2, Aug 2017. doi: 10.1007/s00159-017-0102-9.
- A. Pillepich et al. Simulating galaxy formation with the IllustrisTNG model. *MNRAS*, 473:4077–4106, Jan 2018. doi: 10.1093/mnras/stx2656.
- D. Pooley, J. A. Blackburne, S. Rappaport, and P. L. Schechter. X-Ray and Optical Flux Ratio Anomalies in Quadruply Lensed Quasars. I. Zooming in on Quasar Emission Regions. *ApJ*, 661:19–29, May 2007. doi: 10.1086/512115.
- J. E. Pringle. Accretion discs in astrophysics. *ARA&A*, 19:137–162, 1981. doi: 10.1146/annurev.aa.19.090181.001033.
- G. T. Richards et al. Spectral Energy Distributions and Multiwavelength Selection of Type 1 Quasars. *ApJS*, 166:470–497, Oct 2006. doi: 10.1086/506525.
- G. Risaliti and E. Lusso. A Hubble Diagram for Quasars. *ApJ*, 815:33, Dec 2015. doi: 10.1088/0004-637X/815/1/33.
- O. Roos, S. Juneau, F. Bournaud, and J. M. Gabor. Thermal and Radiative Active Galactic Nucleus Feedback have a Limited Impact on Star Formation in High-redshift Galaxies. *ApJ*, 800:19, Feb 2015. doi: 10.1088/0004-637X/800/1/19.
- Y. M. Rosas-Guevara, R. G. Bower, J. Schaye, M. Furlong, C. S. Frenk, C. M. Booth, R. A. Crain, C. Dalla Vecchia, M. Schaller, and T. Theuns. The impact of angular momentum on black hole accretion rates in simulations of galaxy formation. *MNRAS*, 454:1038–1057, Nov 2015. doi: 10.1093/mnras/stv2056.
- N. P. Ross et al. The SDSS-III Baryon Oscillation Spectroscopic Survey: Quasar Target Selection for Data Release Nine. *ApJS*, 199:3, March 2012. doi: 10.1088/0067-0049/199/1/3.
- N. P. Ross et al. The SDSS-III Baryon Oscillation Spectroscopic Survey: Quasar Luminosity Function from Data Release Nine. *ApJ*, 773:14, Aug 2013. doi: 10.1088/0004-637X/773/1/14.
- N. P. Ross et al. Extremely red quasars from SDSS, BOSS and WISE: classification of optical spectra. *MNRAS*, 453:3932–3952, Nov 2015. doi: 10.1093/mnras/stv1710.
- N. P. Ross et al. A new physical interpretation of optical and infrared variability in quasars. *Nature Astronomy*, 2018.
- J. J. Ruan, S. F. Anderson, S. L. Cales, M. Eracleous, P. J. Green, E. Morganson, J. C. Runnoe, Y. Shen, T. D. Wilkinson, M. R. Blanton, T. Dwelly, A. Georgakakis, J. E. Greene, S. M. LaMassa, A. Merloni, and D. P. Schneider. Toward an Understanding of Changing-look Quasars: An Archival Spectroscopic Search in SDSS. *ApJ*, 826:188, Aug 2016. doi: 10.3847/0004-637X/826/2/188.

- J. N. Runco et al. Broad H β Emission-line Variability in a Sample of 102 Local Active Galaxies. *ApJ*, 821: 33, Apr 2016. doi: 10.3847/0004-637X/821/1/33.
- J. C. Runnoe, S. Cales, J. J. Ruan, M. Eracleous, S. F. Anderson, Y. Shen, P. J. Green, E. Morganson, S. LaMassa, J. E. Greene, T. Dwelly, D. P. Schneider, A. Merloni, A. Georgakakis, and A. Roman-Lopes. Now you see it, now you don't: the disappearing central engine of the quasar J1011+5442. *MNRAS*, 455: 1691–1701, Jan 2016. doi: 10.1093/mnras/stv2385.
- S. Salviander, G. A. Shields, K. Gebhardt, and E. W. Bonning. The Black Hole Mass-Galaxy Bulge Relationship for QSOs in the Sloan Digital Sky Survey Data Release 3. *ApJ*, 662:131–144, June 2007. doi: 10.1086/513086.
- J. Schaye et al. The EAGLE project: simulating the evolution and assembly of galaxies and their environments. *MNRAS*, 446:521–554, Jan 2015. doi: 10.1093/mnras/stu2058.
- D. J. Schlegel et al. SDSS-III: The Baryon Oscillation Spectroscopic Survey (BOSS). *ApJ, in prep.*, 2011.
- N. I. Shakura and R. A. Sunyaev. Black holes in binary systems. Observational appearance. *Astron. & Astrophys.*, 24:337, 1973.
- D. Sijacki, V. Springel, T. Di Matteo, and L. Hernquist. A unified model for AGN feedback in cosmological simulations of structure formation. *MNRAS*, 380:877–900, Sept 2007. doi: 10.1111/j.1365-2966.2007.12153.x.
- E. Sirkko and J. Goodman. Spectral energy distributions of marginally self-gravitating quasi-stellar object discs. *MNRAS*, 341:501–508, May 2003. doi: 10.1046/j.1365-8711.2003.06431.x.
- J. D. Timlin, N. P. Ross, et al. SpIES: The Spitzer IRAC Equatorial Survey. *ApJS*, 225:1, July 2016. doi: 10.3847/0067-0049/225/1/1.
- J. D. Timlin, N. P. Ross, et al. The Clustering of High-Redshift ($2.9 \leq z \leq 5.1$) Quasars in SDSS Stripe 82. *ApJ*, 2018.
- M. Vogelsberger, S. Genel, D. Sijacki, P. Torrey, V. Springel, and L. Hernquist. A model for cosmological simulations of galaxy formation physics. *MNRAS*, 436:3031–3067, Dec 2013. doi: 10.1093/mnras/stt1789.
- M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. Snyder, D. Nelson, and L. Hernquist. Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. *MNRAS*, 444:1518–1547, Oct 2014. doi: 10.1093/mnras/stu1536.
- R. Weinberger et al. Simulating galaxy formation with black hole driven thermal and kinetic feedback. *MNRAS*, 465:3291–3308, March 2017. doi: 10.1093/mnras/stw2944.
- A. R. Wetzel, P. F. Hopkins, J.-h. Kim, C.-A. Faucher-Giguère, D. Kereš, and E. Quataert. Reconciling Dwarf Galaxies with Λ CDM Cosmology: Simulating a Realistic Population of Satellites around a Milky Way-mass Galaxy. *ApJ Lett.*, 827:L23, Aug 2016. doi: 10.3847/2041-8205/827/2/L23.
- E. L. Wright et al. The Wide-field Infrared Survey Explorer (WISE): Mission Description and Initial On-orbit Performance. *AJ*, 140:1868, Dec 2010. doi: 10.1088/0004-6256/140/6/1868.
- Q. Yang et al. Discovery of 21 New Changing-look AGNs in Northern Sky. *ArXiv e-prints*, Nov 2017.
- F. Yuan and R. Narayan. Hot Accretion Flows Around Black Holes. *ARA&A*, 52:529–588, Aug 2014. doi: 10.1146/annurev-astro-082812-141003.
- N. L. Zakamska et al. Discovery of extreme [O III] $\lambda 5007$ Å outflows in high-redshift red quasars. *MNRAS*, 459:3144–3160, July 2016. doi: 10.1093/mnras/stw718.



THE UNIVERSITY of EDINBURGH

12th February 2018

Research Support Office
The University of Edinburgh
5 Roxburgh Street
Edinburgh EH8 9TA
United Kingdom

Switchboard +44(0)131 650 1000
Tel: +44(0)131 650 9024

www.ed.ac.uk

COMMITMENT OF THE HOST INSTITUTION

Commitment of the host institution for ERC Calls 2018

The University of Edinburgh, which is the applicant legal entity, confirms its intention to sign a supplementary agreement with *Nicholas P. Ross* in which the obligations listed below will be addressed should the proposal entitled *Q4D : Quasars in the Fourth Dimension* be retained.

Performance obligations of the *applicant legal entity* that will become the beneficiary of the H2020 ERC Grant Agreement (hereafter referred to as the Agreement), should the proposal be retained and the preparation of the Agreement be successfully concluded:

The *applicant legal entity* commits itself to hosting [*and engaging*] the *principal investigator* for the duration of the grant to:

- a) ensure that the work will be performed under the scientific guidance of the *principal investigator* who is expected to devote:
 - *in the case of a Starting Grant at least 50% of her/his total working time* to the ERC-funded project (action) and spend at least 50% of her/his total working time in an EU Member State or associated country;
 - *in the case of a Consolidator Grant at least 40% of her/his total working time* to the ERC-funded project (action) and spend at least 50% of her/his total working time in an EU Member State or associated country;
 - *in the case of an Advanced Grant at least 30% of her/his total working time* to the ERC-funded project (action) and spend at least 50% of her/his total working time in an EU Member State or associated country.

b) carry out the work to be performed, as it will be identified in Annex 1 of the Agreement, taking into consideration the specific role of the *principal investigator*;

c) enter — before signature of the Agreement — into a '*supplementary agreement*' with the *principal investigator*, that specifies the obligation of the *applicant legal entity* to meet its obligations under the Agreement;

d) provide the *principal investigator* with a copy of the signed Agreement;

e) guarantee the *principal investigator's* scientific independence, in particular for the:

- i) use of the budget to achieve the scientific objectives;

- ii) authority to publish as senior author and invite as co-authors those who have contributed substantially to the work;
 - iii) preparation of scientific reports for the project (action);
 - iv) selection and supervision of the other *team members* (hosted [*and engaged*] by the *applicant legal entity* or other legal entities), in line with the profiles needed to conduct the research and in accordance with the *applicant legal entity's* usual management practices;
 - v) possibility to apply independently for funding;
 - vi) access to appropriate space and facilities for conducting the research;
- f) provide – during the implementation of the project (action) – research support to the *principal investigator* and the team members (regarding infrastructure, equipment, access rights, products and other services necessary for conducting the research);
- g) support the *principal investigator* and provide administrative assistance, in particular for the:
- i) general management of the work and his/her team
 - ii) scientific reporting, especially ensuring that the team members send their scientific results to the *principal investigator*;
 - iii) financial reporting, especially providing timely and clear financial information;
 - iv) application of the *applicant legal entity's* usual management practices;
 - v) general logistics of the project (action);
 - vi) access to the electronic exchange system (see Article 52 of the Agreement);
- h) inform the *principal investigator* immediately (in writing) of any events or circumstances likely to affect the Agreement (see Article 17 of the Agreement);
- i) ensure that the *principal investigator* enjoys adequate:
- i) conditions for annual, sickness and parental leave;
 - ii) occupational health and safety standards;
 - iii) insurance under the general social security scheme, such as pension rights;
- j) allow the transfer of the Agreement to a new beneficiary ('portability'; see Article 56a of the Agreement).
- k) take all measures to implement the principles set out in the Commission Recommendation on the European Charter for Researchers and the Code of Conduct for the Recruitment of Researchers - in particular regarding working conditions, transparent recruitment processes based on merit and career development – and ensure that the *principal investigator*, researchers and third parties involved in the project (action) are aware of them.

For the institution: The University of Edinburgh

Name: Alan Kennedy

Function: European Funding Advisor

Email: Alan.Kennedy@ed.ac.uk

Signature of legal representative:



Stamp of institution:

The University of Edinburgh
Old College, South Bridge
Edinburgh EH8 9YL



UNIVERSITY OF DURHAM



NICHOLAS PATRICK ROSS OF TREVELYAN COLLEGE, HAS BEEN AWARDED

DOCTOR OF PHILOSOPHY

IN THE FACULTY OF SCIENCE

11 JANUARY 2008

Brian Bryson

CHANCELLOR

REGISTRAR AND SECRETARY

Lee Sanders





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