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.

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: *Instrumentation - telescopes, detectors and techniques*

ERC Keyword 4: *High energy and particles astronomy - X-rays, cosmic rays, gamma rays, neutrinos*

Free keywords: *Quasars; black holes; accretion disk physics; machine learning; very wide-field surveys.*

Proposal ID **818713** *Acronym* **Q4D**

Abstract*

Along with nuclear fusion in stars, accretion onto a central supermassive black hole is the main energy source available to a galaxy. All massive galaxies are thought to have supermassive black holes at their centres, and to have undergone a "quasar phase" in their past, which has led to the hypothesis that energy from the quasar feeds back into the galaxy, becoming a regulating mechanism and shutting down star formation. However, while the fusion processes in stars have been on a solid theoretical footing for over 70 years, current theories of galaxy formation and evolution are still missing a deep understanding of how the energy associated with the supermassive black hole escapes the central engine to impact the host galaxy and the intergalactic medium.

Further issues arise since very recent observations of extreme variability in quasars, where some objects show changes in luminosity and activity over the course of weeks to years, have broken standard viscous accretion disk models.

Here we propose to use and combine 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 these current challenges. Our goal is to create and exploit a revolutionary new extragalactic dataset of the variable extragalactic Universe. We will use this as the boundary conditions for a holistic theory of accretion disk physics and quasar feedback in galaxy formation theory. I am also extremely well placed to discover brand new extragalactic variable phenomena. The experience of the PI, along with the strategic data centre aspect of the Royal Observatory at the University of Edinburgh makes my group uniquely positioned to answer this challenge, and provide a fundamental new understanding of quasars and galaxy formation and evolution.

Remaining characters 57

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

Proposal ID 818713 **Acronym** Q4D

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).*	☒
2) The Principal Investigator declares that the information contained in this proposal is correct and complete.	☒
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).	☒

4) The Principal Investigator hereby declares that *(please select one of the three options below)*:

- 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).	◉
- 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).	○
- in case of a sole participant in the proposal, the applicant is exempt from the financial capacity check.	○
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.	☒

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).

List of participants

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

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.

Department(s) carrying out the proposed work

Department 1

Department name	School of Physics and Astronomy	☐ not applicable
	☐ Same as organisation address	
Street	JCMB Peter Guthrie Tait Road	
Town	Edinburgh	
Postcode	EH9 3FD	
Country	United Kingdom	

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			
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

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

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* **europe@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 xxxxxxxxx

Other contact persons

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

3 - Budget

Participant Number in this proposal	Organisation Short Name	Organisation Country	Total eligible costs/€ (including 25% indirect costs)	Requested grant/€
1	UEDIN	UK	2 221 349	2 221 349
Total			2 221 349	2 221 349

Proposal ID **818713** *Acronym* **Q4D**

4 - Ethics

1. HUMAN EMBRYOS/FOETUSES		Page
Does your research involve Human Embryonic Stem Cells (hESCs)?	○Yes ◉No	
Does your research involve the use of human embryos?	○Yes ◉No	
Does your research involve the use of human foetal tissues / cells?	○Yes ◉No	
2. HUMANS		**Page**
Does your research involve human participants?	○Yes ◉No	
Does your research involve physical interventions on the study participants?	○Yes ◉No	
3. HUMAN CELLS / TISSUES		**Page**
Does your research involve human cells or tissues (other than from Human Embryos/ Foetuses, i.e. section 1)?	○Yes ◉No	
4. PERSONAL DATA		**Page**
Does your research involve personal data collection and/or processing?	○Yes ◉No	
5. ANIMALS		**Page**
Does your research involve animals?	○Yes ◉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?	○Yes ◉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.)?	○Yes ◉No	
Do you plan to import any material - including personal data - from non-EU countries into the EU?	○Yes ◉No	
Do you plan to export any material - including personal data - from the EU to non-EU countries?	○Yes ◉No	
In case your research involves low and/or lower middle income countries, are any benefits-sharing actions planned?	○Yes ◉No	
Could the situation in the country put the individuals taking part in the research at risk?	○Yes ◉No	
7. ENVIRONMENT & HEALTH and SAFETY		**Page**

Does your research involve the use of elements that may cause harm to the environment, to animals or plants?	○ Yes ◉ No	
Does your research deal with endangered fauna and/or flora and/or protected areas?	○ Yes ◉ No	
Does your research involve the use of elements that may cause harm to humans, including research staff?	○ Yes ◉ 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?	○ Yes ◉ No	
9. EXCLUSIVE FOCUS ON CIVIL APPLICATIONS		Page
Could your research raise concerns regarding the exclusive focus on civil applications?	○ Yes ◉ No	
10. MISUSE		Page
Does your research have the potential for misuse of research results?	○ Yes ◉ No	
11. OTHER ETHICS ISSUES		Page
Are there any other ethics issues that should be taken into consideration? Please specify	○ Yes ◉ 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

Proposal ID **818713**	*Acronym* **Q4D**

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.	○ Yes ◉ 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].	○ Yes ◉ No
Eligibility	
Please indicate your percentage of working time in an EU Member State or Associated Country over the period of the grant: 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.	100,00
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.*	☒
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.	◉ Yes ○ 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?	◉ Yes ○ 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?	◉ Yes ○ 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.	◉ Yes ○ No

Proposal number	678679
Other details	ERC-2015-STG

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	

Proposal ID **818713** *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.*

ERC Consolidator Grant 2018
Research proposal [Part B1]
(Part B1 is evaluated both in Step 1 and Step 2, Part B2 is evaluated in Step 2 only)

Quasars in the 4th Dimension

Q4D

Principle Investigator: Nicholas P. Ross
Host Institution: University of Edinburgh
Duration: 60 months

Along with nuclear fusion in stars, accretion onto a central supermassive black hole is the main energy source available to a galaxy. All massive galaxies are thought to have supermassive black holes at their centres, and to have undergone a "quasar phase" in their past, which has led to the hypothesis that energy from the quasar feeds back into the galaxy, becoming a regulating mechanism and shutting down star formation. However, while the fusion processes in stars have been on a solid theoretical footing for over 70 years, current theories of galaxy formation and evolution are still missing a deep understanding of how the energy associated with the supermassive black hole escapes the central engine to impact the host galaxy and the intergalactic medium.

Further issues arise since very recent observations of extreme variability in quasars, where some objects show changes in luminosity and activity *over the course of weeks to years,* have broken standard viscous accretion disk models.

Here we propose to use and combine 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 these current challenges. Our goal is to create and exploit a revolutionary new extragalactic dataset of the variable extragalactic Universe. We will use this as the boundary conditions for a holistic theory of accretion disk physics and quasar feedback in galaxy formation theory. I am also extremely well placed to discover brand new extragalactic variable phenomena. The experience of the PI, along with the strategic data centre aspect of the Royal Observatory at the University of Edinburgh makes my group uniquely positioned to answer this challenge, and provide a fundamental new understanding of quasars and galaxy formation and evolution.

Section a. Extended Synopsis of the scientific proposal (max. 5 pages, references do not count towards the page limits)

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-V[1]); the Large Synoptic Survey Telescope (LSST[2]); the Dark Energy Spectroscopic Instrument (DESI[3]) survey; the 4-metre Multi-Object Spectroscopic Telescope (4MOST[4]) survey, and the ESA *Euclid* mission[5]. Even more imminent is the launch of the *James Webb Space Telescope* (JWST[6]).

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). The 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 and 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). I have been intimately involved in the production of both of these two types of samples (MacLeod et al., 2016; Pâris et al., 2017). My group plans to collate datasets so that the 10^6 sample have *high-fidelity light-curves and ample repeat spectroscopy (necessary for emission/absorption line diagnostics)*, and in doing so will kick start the new field of Variable Extragalactic Astrophysics.

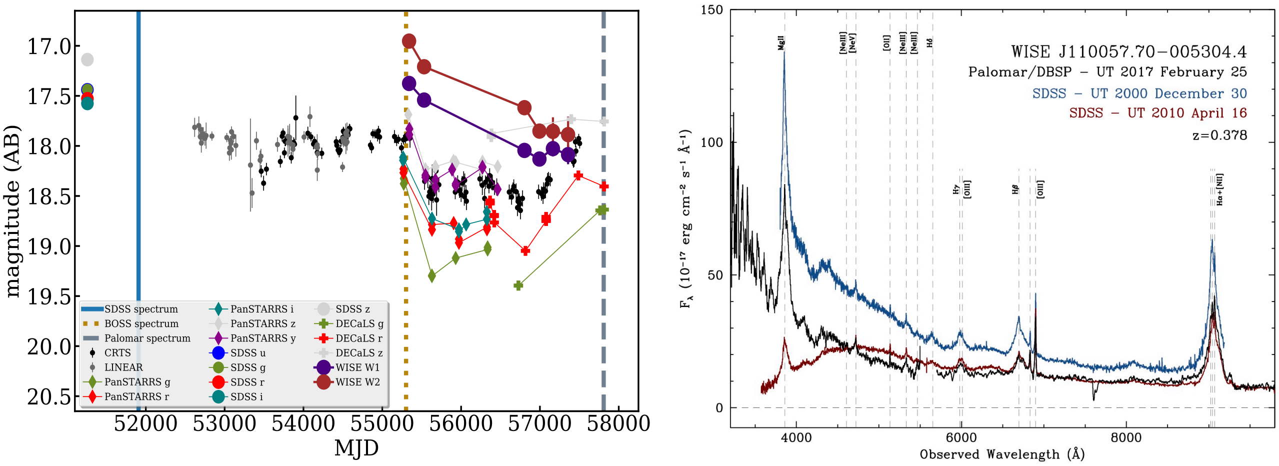

Figure 1: *(Left:)* The optical and infrared light-curve for the redshift $z = 0.378$ quasar J1100-0053 (Ross et al. 2018). Note the fall in the infrared, whereas there is a decrease, but then recovery in the optical. *(Right:)* Three epochs of spectra for J1100-0053. The spectacular downturn in the 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 SDSS-V and LSST over the next ~12-18 months. Having the ability to influence and fully optimise these decisions for our science objectives will 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],[8] 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

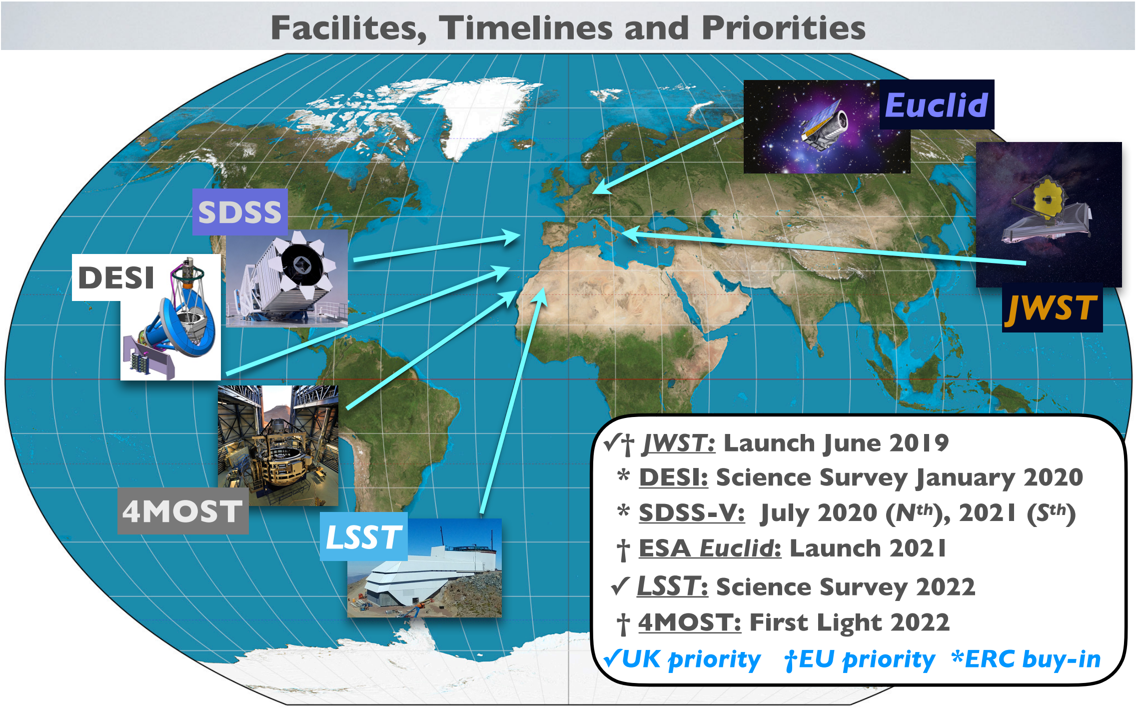

Figure 2: Facilites, Timelines and Priorities. With SDSS-V and DESI in the Northern Hemisphere and 4MOST, LSST in the South, we have full celestial sphere coverage.

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 tudies of a small number of objects; theoretical modeling investigations. Figure 3 summarises our overall WP plan. Risks and mitigation strategies are presented for each WP, as are Key Deliverables. NPR, three PDRAs, "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 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

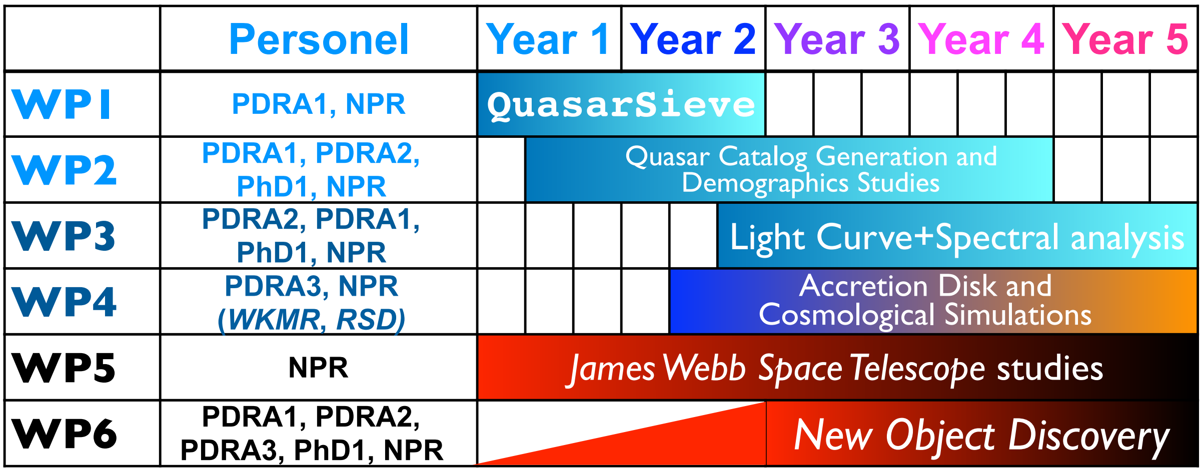

Figure 3: An overview of the WPs, with the personnel attached to each WP and a guide to their start and duration. As given by the shadings, WP1, 2 and 3 are observational studies of large numbers of objects; WP4 are theoretical modeling investigations and WP5 and 6 are high-risk, very high-reward observational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

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 PhD1 **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. $M_{\rm SMBH}$, luminosity, $\lambda = \log(L/L_{\rm Edd})$, 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 ambitious 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 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 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 (PDRAs), for a total of 10 PDRA year equivalents (3+3+4). We request the resources and support for 1 four-year 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 new 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. Ivezic 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.

Section b. Curriculum vitae (max. 2 pages)

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.Sci., (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

h-index of 59

Author on 118 published papers	Total number of citations:	14,942	(126.6 citations/paper)
Binomial author on 9 published papers	Total number of citations:	824	(82.4 citations/paper)

GRANTS/FUNDING OBTAINED

STFC Ernest Rutherford Fellowship (PI.)	€679,569
NASA *Spitzer Space Telescope* Cycle 9, 820 hours (Lead Co-I)	€359,745
NASA *Hubble Space Telescope* Cycle 20, 18 orbits (P.I.)	€87,330
NASA *Swift* XRT and UVOT ToO observations, Cycle 5, 17.8ks (P.I.)	€27,820
Chandra 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 Tielebein, 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)
Prof. Andy Lawrence (UEDIN)
Prof. David Aspinall (School of Informatics, UEDIN)
Prof. Fred Hamann (UC Riverside)
Prof. Nadia Zakamska (Johns Hopkins)
Dr. Chelsea MacLeod (former PDRA in UEDIN research group; now PDRA CfA, Harvard)
Dr. Isabelle Pâris (formerly Aix-Marseille Université)
Prof. Patrick Petitjean (Institue d'Astrophysique de Paris)

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

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*
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

Section c. Early Achievements Track-record (max. 2 pages)

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 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 my contemporaries at a similar career stage.

I am an expert in a suite of research methodologies in **data science** and machine learning. In particular, at the heart of my research with the SDSS-BOSS project, was anomaly detection in extremely large datasets. I was a co-founder and Chief Data Scientist of, **String Security *Inc.*** There I 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, **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, **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 **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, **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 **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 **2014JCAP...05..027F** **(166)** Ground-breaking first detection of the "Baryon Acoustic Oscillation" phenomena in the quasar population.

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 **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, **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, **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, **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 <= 2.2) Quasars from the Sloan Digital Sky Survey,* 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: *The Optical Monitoring of IR-variable Quasar*s
2018 -	P.I. *JWST* Cycle 1 GO program: *Quasar Physics with the MIRI MRS* (to be submitted)
2017 -	P.I. WISE W4 Compendium (WW4C)
2016 - 2017	Co-founder and Chief Data Scientist of *String Security Inc.*
2014 - 2019	P.I., STFC Ernest Rutherford Fellowship
2013 - 2016	Co-P.I., *Spitzer Space Telescope* program "SpIES: The Spitzer-IRAC Equatorial Survey'"
2012 - 2014	Co-P.I., *Hubble Space Telescope,* program "High-Luminosity Obscured Quasars at z~2.5"
2011	Chapter Editor, *BigBOSS* 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 *Swift* Cycle 5 Long-term local AGN monitoring program

SELECTED PRESENTATIONS

2017 Nov	*Dealing With Data 2017 Workshop*	Selected Oral Contribution
2017 Jul	*Unveiling the Physics Behind Extreme AGN Variability*	Conference Summary
2017 May	University of Cambridge	Galaxies Discussion Group
2016 Jun	*JWST@ROE* conference	Contributed talk
2016 May	University of Michigan	Astrophysics Seminar
2016 May	Great Lakes Quasar Symposium	Oral Contribution
2015 Sep	*Multiwavelength AGN*, Crete	Invited Review
2015 Apr	Adler Planetarium, Chicago	Astrophysics Seminar
2015 Jan	225th AAS, Seattle	Special Session talk
2014 Sep	*Heritage of Stripe 82*, Princeton University	Invited talk
2014 May	Harvard University	HEAD talk
2014 Apr	University of Pennsylvania	Astrophysics Seminar
2013 May	Stanford University	KIPAC Talk
2011 Jul	Oxford University	BICAP Cosmology Seminar
2011 May	Yale University	YCAA Seminar

ERC Consolidator Grant 2018
Research proposal [Part B2]
(not evaluated in Step 1)

Part B2: *The scientific proposal* (max. 15 pages, references do not count towards the page limits)

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 where some objects show changes in luminosity and activity over the course of weeks to years, have broken standard viscous accretion disk models.

In Q4D we propose 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. 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.

Q4D has several ambitious goals: (i) to access and combine several new state-of-the-art large astronomical datasets; (ii) to characterize the variable extragalactic universe and quasar population and in doing so kick start the new field of variable extragalactic astrophysics; (iii) to create a holistic theory of accretion disk physics and quasar feedback in galaxy formation theory, and (iv) discover brand new astronomical phenomena. The experience of the PI (Nicholas P. Ross; NPR) along with the strategic data nexus aspect of the Royal Observatory at the University of Edinburgh makes my group uniquely positioned to address this problem and carry out this research.

a State-of-the-art and Objectives

a.1 Background

Quasars[1] 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 hypothesis 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).

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 uncomfortable 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.

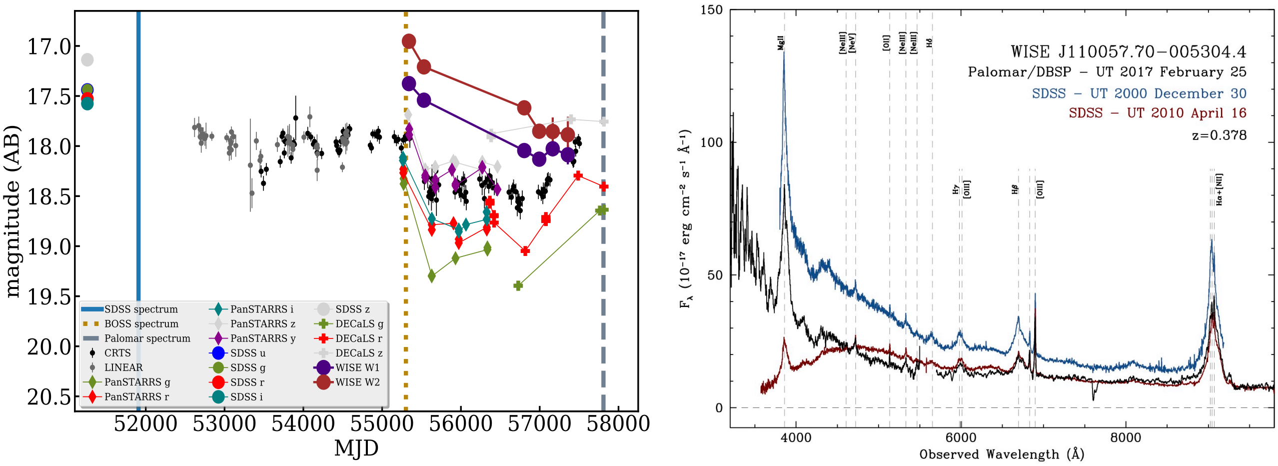

Figure 1: *(Left:)* The optical and infrared light-curve for J1100-0053; Note the fall in the infrared, whereas there is a decrease, but then recovery in the optical. *(Right:)* Three epochs of spectra for J1100-0053. The spectacular downturn in the blue for the 2010 spectrum indicates a dramatic change 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$_g$, (where r_g is the gravitational radius; $r_g = \frac{GM}{c^2}$) which, for a 10^8 M$_{BH}$ is $\approx 5\times10^{-3}$ to 5 pc. 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 flow rate $\dot{m}$ 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 and time-steps sampling $\sim$1000 years ($\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 $8\times10^5 h^{-1}$ 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 $M_{\rm DM} = 3.5 \times 10^4 M_\odot$ and $M_{\rm gas,initial} = 7070 M_\odot$. 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 is 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 $\dot{M}_{\rm Bondi} = \pi G^2 M_{\rm BH}^2 \rho / c_s^3$, *is known to be a considerable oversimplification* (e.g., Edgar, 2004). There is an urgent need for a new theory, and new observations will play a key role in guiding us and achieving this.

***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 data stream 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 science questions we seek to address are well-posed, yet strike at the heart of major and still open extragalactic astrophysical questions:

- What is the main quasar triggering mechanism at the height of quasar activity?
- Do we have a full accounting of the accretion history in the Universe?
- What direct observational evidence links quasar activity to star formation?
- What are the star-formation properties of luminous quasars at the peak of quasar activity?
- How does the energy escape from the central engine and impact the host galaxy?
- Are the modes of AGN "feedback" that regulate the host galaxy the same that regulate the AGN itself?
- Can we observe "quasar feedback" in action, in situ, for the most luminous sources?
- What is the link between the observed properties of quasars, such as light curves and emission/absorption line spectra, and their underlying properties e.g., accretion rate, accretion disk structure and black hole mass and spin?

These questions have been raised for some time and are challenges which need to be addressed now in order to make significant progress.

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 PI 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.

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.

In this section, we first introduce the missions, surveys and novel instrumentation that will be the experimental backbone of this proposal. In Table 1, we state in detail our objectives and tie them to the datasets and novel investigations we plan in our Work Packages (WPs). We then describe our approach to building our core data science infrastructure while breaking down the data silos. We give more details for each WP and conclude this section with a Feasibility report.

b.1 Upcoming Surveys, Instruments and Missions

(Lawrence, 2016) emphasize that variability studies hold information on otherwise unresolvable regions in quasars. Likewise, 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-V[3]), the Large Synoptic Survey Telescope (LSST[4]), the Dark Energy Spectroscopic Instrument (DESI[5]) survey, the 4-meter Multi-Object Spectroscopic Telescope (4MOST[6]) survey, and the ESA *Euclid* mission[7], will see first light. Even more imminent is the launch of the *James Webb Space Telescope* (JWST[8]).

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 PI 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 for SDSS-V is due to start in 2020. *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 $\approx$20 million galaxies and quasars. **The PI contributed in writing the original science case and proposal for DESI (Schlegel et al., 2011) but having left the U.S./LBNL, he no longer has data access rights.** *Data Products: Spectra of 1e6 quasars across 14,000 deg*^{2} *of the Northern Sky.*

The **Large Synoptic Survey Telescope (LSST)** project starts data taking in late 2021, and and will conduct a full survey of the 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 giving me free data access rights, (but to the raw, unfiltered data). *Data Products: ugrizY broadband optical and near-infrared imaging for 20,000 deg*^{2}*. Images the full Southern Sky every 3 days.*

Euclid is an ESA Medium Class mission due for launch in mid-2021 that will 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 $\sim$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 deg*^{2}.

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 $\geq$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 $\geq$25 million object over 15,000 deg^2.

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 27μm. 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* $\lambda > 2\mu m$*, 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).

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 22μm 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 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 ~one billion stars in our Galaxy and throughout the Local Group.

In the table below, we state our science objectives and tie them to these telescopes, missions and datasets.

b.2 Data Science and Data Silos

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. These are the solid foundations on which we intended to build our software packages, including `QuasarSieve`. **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).**

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 **(WP1; WP3; WP4)**.
Probe and determine the physical state of the inner parsec of the quasar central engine.	Rapid analysis and response for LSST quasar light curves **(WP3)**. Detailed accretion disk theoretical modeling **(WP4)**.
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. **(WP1; WP2; WP3)** Also NIRcam and MIRI imaging from JWST **(WP5)**.
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 **(WP5)**.
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 **(WP1; WP2)**
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. **(WP2; WP3; WP5)**
GALAXY-SCALE FEEDBACK	
Establish the theoretical impact of extreme outflows in the $z \sim 2-3$ quasar population	Next-generation Hydro-simulation modelling **(WP4)**.
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 cosmolgocial-scale hydro simulations for a holistic theory of "quasar feedback" **(WP4)**.

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, data[9], 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 well be developed

[9] Where I am not breaking current data access agreements

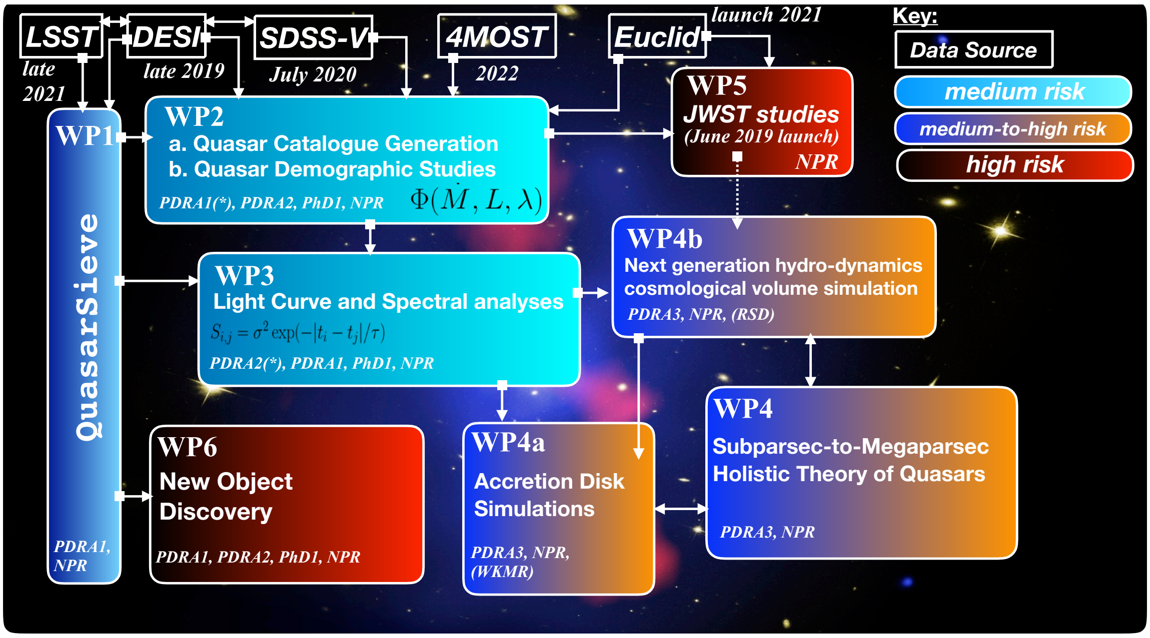

Figure 2: An overview of our WPs. Arrows give general data or workflow, though natural iteration is expect, accounted and not necessarily shown. Asterisks show lead PDRA where necessary. Φ indicative of giving quasar space density, see e.g., Ross et al. (2013). $S_{i,j}$ indicative of a model for the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

using the FAIR ideology (Findable, Accessible, Interoperable, Reusable[10]) and will be delivered in a manner which is fully inline with "Open Innovation, Open Science, Open to the World".

b.3 Work Packages

Our proposal contains six work packages that fall into three broad and complementary categories: observational studies of large numbers (millons) 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 PDRAs, "PDRA1", "PDRA 2", "PDRA 3", and one PhD student, "PhD1" are the personnel required to carry out these work packages. Our team's skill sets are described in detail in Section c.

WP1: Build QuasarSieve:

Raw events come from LSST. The UK LSST Data Access Center (DAC, based here at the University of Edinburgh) ingests this data stream and re-emits a filtered stream. In order to utilize this filtered data stream 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.

One obvious first step for `QuasarSieve` which we can do immediately is to build an effective veto algorithm. This would be to e.g. veto stars using data from *ESA Gaia*, the data of which are hosted by the Wide-Field Astronomy Unit (WFAU) here at the Royal Observatory, Edinburgh. *N.B. The LSST DAC is building up its own simulated training data stream, before LSST First Light, that we will use as initial input to* `QuasarSieve`.

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 overal

[10] Wilkinson, MD, Sci Data. 2016 Mar 15;3:160018. doi: 10.1038/sdata.2016.18.

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 front-loaded, 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:** We will start our cataloguing efforts and production of the quasar corpus in short order after the start of the grant. Experience tells us that initial catalogue production is usually quick, but iterations will invariably be needed once the catalogue starts to get used for science. This WP is scheduled to run until the end of Year 4, but maximal effort will be in Years 1 and 2.

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. $M_{\rm SMBH}$, luminosity, $\lambda = \log(L/L_{\rm Edd})$, spin etc. These measurements will allow us to make direct comparisons to accretion disk models. **Timeline:** WP3 is not scheduled to start until the end of Year 2, but will in practice start as soon as we have a `v1.0` version of `QuasarSieve` working. Our current research outputs provide the very preliminary data to get going here in short order, and this WP will really take-off once SDSS-V and then LSST are in full data-taking mode.

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

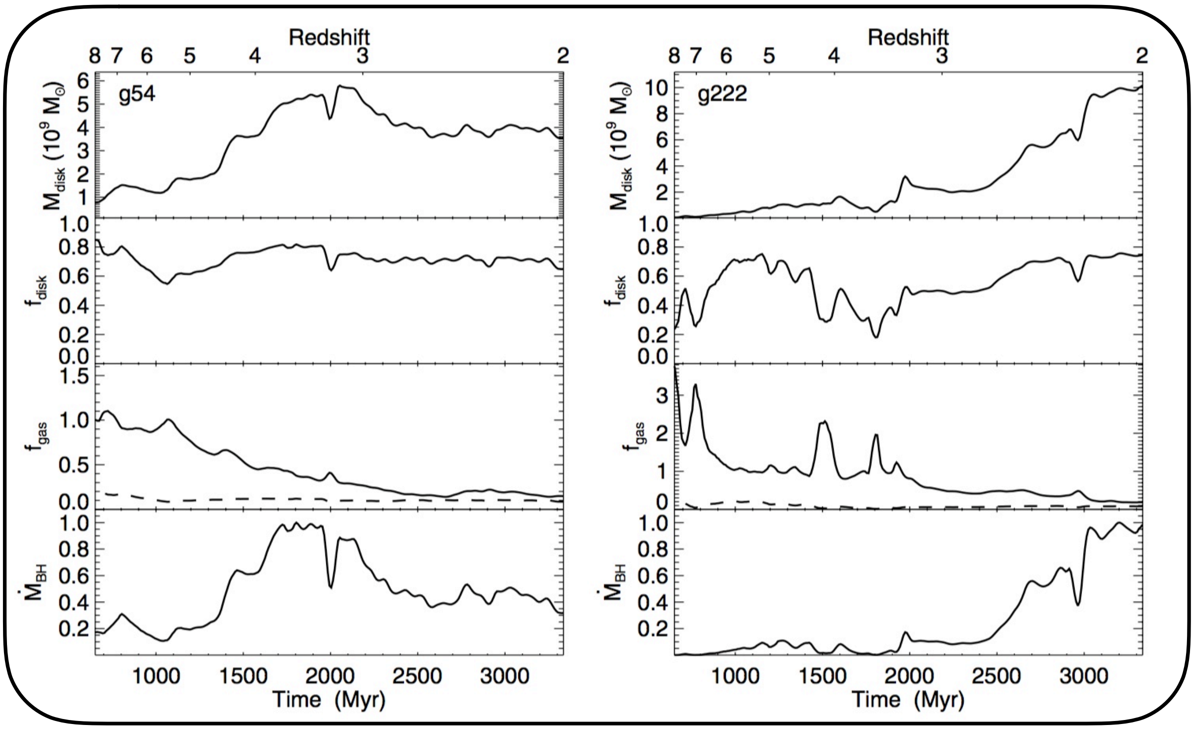

Figure 3: Two theoretical models from Anglés-Alcázar et al. (2013) with different accretion modes. From top to bottom: (1) total (stellar and gas) galaxy disk mass (within $R_0 = 1$ kpc) (2) total disk mass fraction; (3) ratio of gas mass to total (stellar and gas) disk mass at R_0 (solid line), provided that $f_{gas} \geq f_0$ (dashed line) inflow rates are not limited by gas supply, and (4) inferred black hole accretion rates using the analytic model of Hopkins and Quataert (2011). **The key aspect to note here is that two different accretion models make different, testable predictions for the fueling rate of the SMBH, and consequently the light curve properties of quasars. Q4D will be able to differentiate these.**

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:** WP4 will start immediately once PDRA3 is in place. However, low-level preparatory work will be carried out in Year 1/early in Year 2 and the necessary computer hardware, and base software are in place ready for rapid simulation development. WP4 then runs until the end of the project.

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 $r - [22\mu m] > 14$ colors (i.e., $F_{\nu,\mathrm{MIR}}/F_{\nu,\mathrm{opt}} \gtrsim 1000$) from the Wide-field Infrared Survey Explorer (WISE; Wright et al., 2010) satellite, see Figure 4. The ERQs are a unique obscured

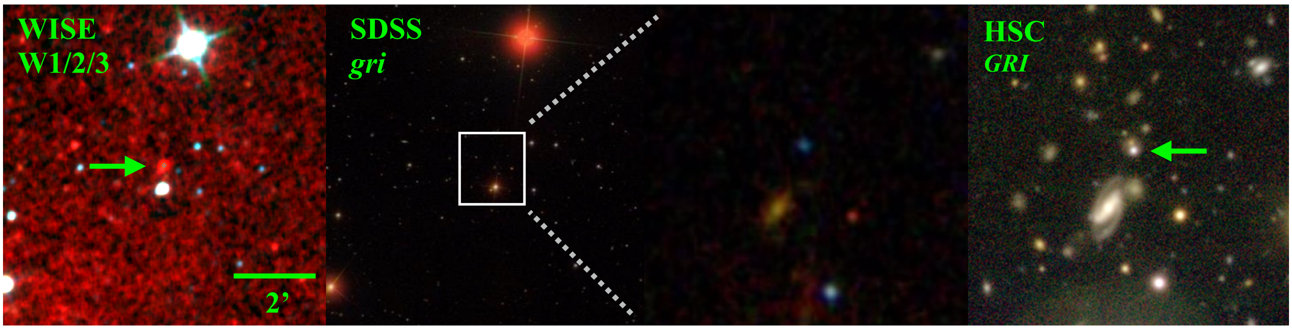

Figure 4: The IR and optical imaging of J2323-0100, an archetype of the "Extremely Red Quasars" (ERQs) at $z \approx 2.5$ and a *JWST* target. Shown are WISE *(left)*, where the quasar booms out as indicated by the arrow; the SDSS image *(middle left)* with zoom-in *(middle right)* on the optically faint 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 (FWHM = 2500-5000 km s^{-1}), strongly blue-shifted (by up to 1500 km s^{-1}) [O III] λ5007Å 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.

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. **Timelime:** 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.

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; Abell et al., 2009). This could include the electromagnetic counterparts to mergers of Binary SMBHs (with their associated gravitational wave chirp and ringdown). After the discovery of GW1708017 (Abbott et al., 2017a) and its EM counterpart, (Abbott et al., 2017c), there has been considerable interest in using merging black holes as standard sirens, (Abbott et al., 2017b). **Q4D does have the ability to detect the EM signatures of the merging SMBHs. Whether they are detected in LIGO as well, will be exceptionally exciting to find out.**

Objects potentially similar to repeating Fast Radio Bursts (Spitler et al., 2016) or more objects akin to 'SCP 06F6' (Barbary et al., 2009) or 'iPTF 16fnm' (Miller et al., 2017) which are suggested to be supernova at the extremes of the luminosity distribution, but are still not convincingly explained.

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 here.

b.4 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.

Team Composition: Our team will consist of the PI, 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 PI is not a current member of academic staff and therefore has no responsibilities extending beyond research. As such, the PI 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.

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 PI'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.

Cost Category			Total in Euro
Direct Costs	**Personnel**	PI	403,854
		Senior Staff	
		Postdocs	617,145
		Students	84,545
		Other	
	i. Total Direct Costs for Personnel (in Euro)		1,105,544
	Travel		190,000
	Equipment		50,000
	Other goods and services	Consumables	3,000
		Publications (including Open Access fees), etc.	15,000
		Other, incl. SDSS-IV Project buy-in, DESI Project buy-in, Audit, Recruitment.	413,535
	ii. Total Other Direct Costs (in Euro)		671,535
A – Total Direct Costs (i + ii) (in Euro)			1,777,079
B – Indirect Costs (overheads) 25% of Direct Costs (in Euro)			444,270
C1 – Subcontracting Costs (no overheads) (in Euro)			0
C2 – Other Direct Costs with no overheads (in Euro)			0
Total Estimated Eligible Costs (A + B + C) (in Euro)			2,221,349
Total Requested EU Contribution (in Euro)[6]			2,221,349

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.

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.

SALARIES: The primary expenditure of our project corresponds to salaries in order support the large team necessary for this project. The PI 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 PI, €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 PI'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. While we will have adequate resources to fully deploy `QuasarSieve` and will run our theory simulations on institute (e.g. IfA Cullen), university (e.g. Edinburgh Compute and Data Facility) or national (The Hartree Centre) facilites, the rate limiting factor of our project and WPs will be how quickly and efficiently we can deploy our new codes and analysis.

We require the budget for mid-to-high end hardware, (with specifications that are not in the typical desktop the university would supply) and also the e.g. large format displays that massively boost productivity. This can include having more than one monitor (e.g. 2 monitors leads to efficient coding, giving one full, often 'portrait' monitor for code, and another for documentation, specifications, StackOverflow help etc.) Laptops are necessary for any extended time away (e.g. "First Light' travel justified above) from the office. 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 and €200.1k, respectively. 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 PI 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: **€1,741,099**.
Total budget including facilities costs: **€2,221,349**.

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THE UNIVERSITY of EDINBURGH

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

12th February 2018

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

Bill Bryson

CHANCELLOR

Lee Sanders

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