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

In Q4D we will address these outstanding issues in order to move the field forward. Q4D has several ambitious goals: (i) to characterize the variable extragalactic universe and quasar population and in doing so kick start the new field of variable extragalactic astrophysics; (ii) to create a holistic theory of accretion disk physics and quasar feedback in galaxy formation theory, and (iii) discover brand new astronomical phenomena.

We will achieve this by 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. This will allow substantial advances in the frontiers of understanding astrophysical phenomena as well as discovering new objects. 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).

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

[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).

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 I present a concise overview of the observational state-of-the-art in the brand new field of variable extra-galactic 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.

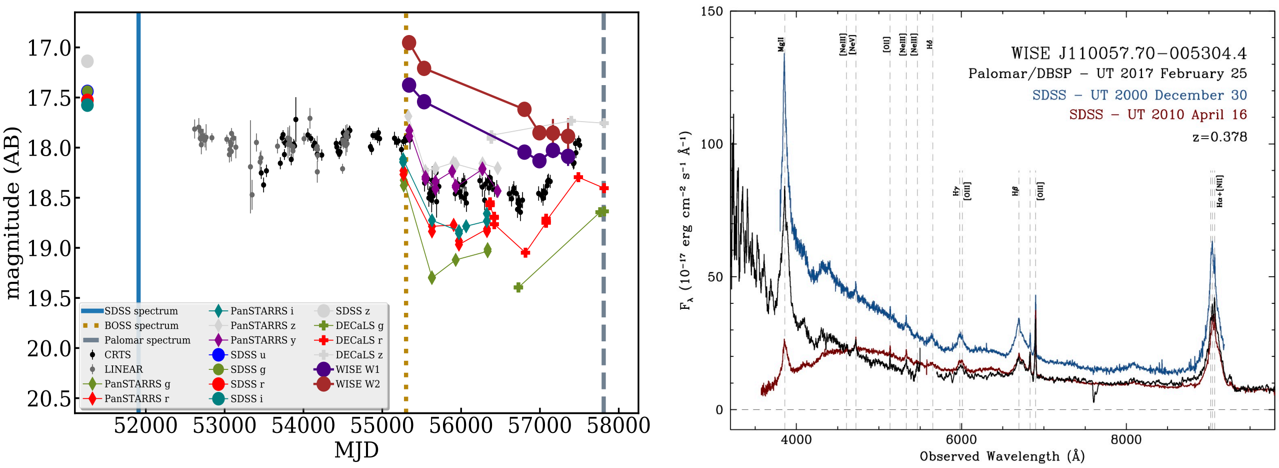

Figure 1: *(Left:)* The optical and infrared light-curve for J1100-0053; Note the fall in the infrared, whereas there is a decrease, but then recovery in the optical. *(Right:)* Three epochs of spectra for J1100-0053. The spectacular downturn in the blue for the 2010 spectrum indicates a dramatic change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

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, 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 size and temporal cadence, 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 of.

a.1.2 Theoretical State-of-the-Art

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

CONTEMPORARY ACCRETION DISK THEORY: The accretion disk scale is $\lesssim 10^3 - 10^6$ r$_g$, (where $r_{\rm g}$ is the gravitational radius; $r_{\rm g} = \frac{GM}{c^2}$) which, for a 10^8 M$_{\rm BH}$ is $\approx 5\times10^{-3}$ to 5 pc. As 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 an 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 investigation.

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 (including 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 $\sim 2\times10^5$ M$_\odot$ for initial baryonic particle mass, "softening lengths" of 0.35-0.7 pkpc; 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 M$_\odot$ for baryonic particle mass, softening lengths $\approx$0.2-1 pkpc, and $8 \times 10^5 h^{-1}$ M$_\odot$ for the seed black hole mass. As such, these are extremely powerful for global galactic properties, but these simulations cannot, and were never designed to, explicitly address inner central engine physics.

Further progress is made with the new high-resolution "zoom-in" galaxy simulations, e.g. Feedback In Realistic Environments (FIRE-2; Wetzel et al., 2016; Hopkins et al., 2017) or MUFASA (Davé et al., 2016). In FIRE-2 for example, Wetzel et al. (2016) run a cosmological scale dark-matter-only simulation to redshift $z = 0$. An isolated DM halo is then selected, the particles are traced back to very high 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 total particles, with $M_{\rm DM} = 3.5 \times 10^4$ M$_\odot$ and M$_{\rm gas} = 7070$ 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 simulations are impressive, but still not close enough to resolving the scales, masses and cadences needed to successfully model e.g. the "changing look" quasars.

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

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

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?
- What are the star-formation properties of luminous quasars at the peak of quasar activity?
- What direct observational evidence links quasar activity to star formation?
- Do we have a full accounting of the accretion history in the Universe?
- 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, black hole mass and black hole spin?

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

My 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 me 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.* I am a world-leader in observational quasar astrophysics, both in terms of survey work and individual object study. My 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 my research group. 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 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 the optical characterization of eROSITA X-ray sources. Data taking for SDSS-V is due to start in 2020. *Data Products: Multiple repeat spectra in the North and Southern Hemisphere for 500,000 quasars.*

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 late 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 will conduct a full survey of the Southern Sky every 3 nights. The LSST survey is designed to address four

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

science areas (Understanding 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 (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, overlapping SDSS-V in the North and LSST in the South.*

The **4-metre Multi-Object Spectroscopic Telescope (4MOST):** is a fibre-fed spectroscopic survey facility on the VISTA telescope with a large field-of-view in order 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 deg^2. 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^2. 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, ESA 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. 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. *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 map the Milky Way in three-dimensions, 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. This amounts to about 1 per cent of the Galactic stellar population.

In the table on the next page, 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 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 PI and host institute means we are uniquely positioned to break down these astro-data silos for massively significant science gain.*

TARGETING BIG DATA: Q4D 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 that the PI and his team fully use and support.

`scikit-learn` is a Python module integrating classic machine learning algorithms in the scientific Python world. It provides efficient solutions ML problems, and is 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 PI 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 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 **(WP1; WP3)**. Detailed accretion disk theoretical modeling **(WP4)**.
OBSCURED ACCRETION AND GALAXY FORMATION	
Establish the relative importance that 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 $z \sim 0-8$, 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 PI 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 Software Sustainability Institute which was founded to support the UK's research software community. Our software will be developed using the FAIR ideology (Findable, Accessible, Interoperable, Reusable[10]) and will be delivered in a manner which is fully inline with "Open Innovation, Open Science, Open to the World".

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

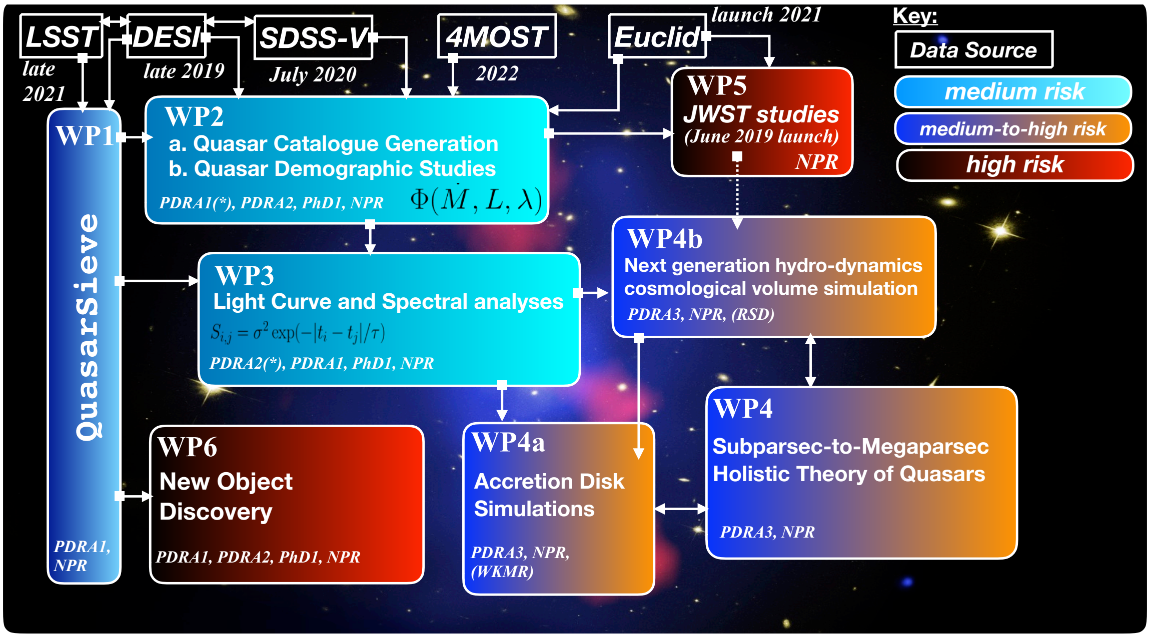

Figure 2: An overview of our WPs. Arrows give general data or workflow, though natural iteration is expected, accounted and not necessarily shown. Asterisks show lead PDRA where necessary. Φ indicative of giving quasar space density, see e.g., Ross et al. (2013). $S_{i,j}$ indicative of a model for the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

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 PI (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 programme, with the associated high-risk. We mitigate this risk with the data science and machine learning experience from PDRA1 and 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 NPR'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.

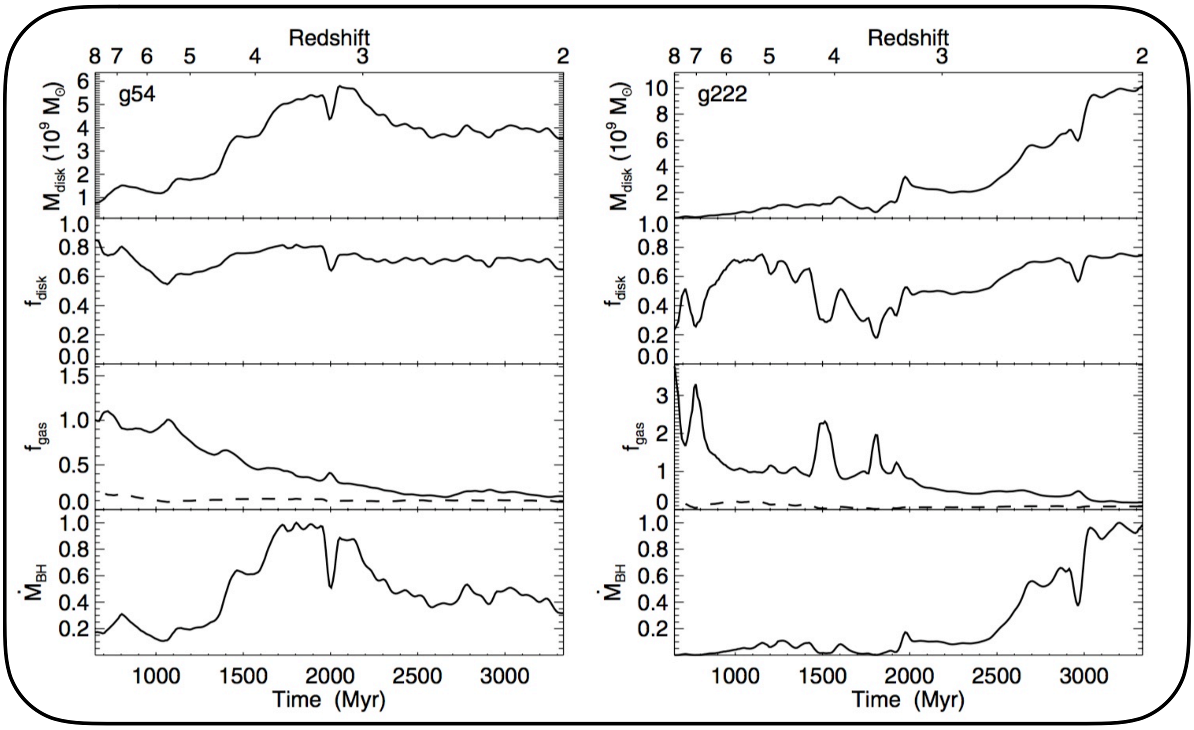

Figure 3: Two theoretical models from Anglés-Alcázar et al. (2013) with different accretion modes. From top to bottom: (1) total (stellar and gas) galaxy disk mass (within $R_0 = 1$ kpc) (2) total disk mass fraction; (3) ratio of gas mass to total (stellar and gas) disk mass at R_0 (solid line), provided that $f_{\rm gas} \geq f_0$ (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.**

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 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 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", see Figure 3.

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 $r - [22\mu{\rm m}] > 14$ colors (i.e., $F_{\nu,{\rm MIR}}/F_{\nu,{\rm opt}} \gtrsim 1000$) from the Wide-field Infrared Survey Explorer (WISE; Wright et al., 2010) satellite, see Figure 4. The ERQs are a unique obscured quasar population with extreme physical conditions related to powerful outflows across the line-forming regions. As my team have shown, these sources are the signposts of the most dramatic form of quasar feedback at the peak epoch of galaxy formation, and may represent an active "blow-out" phase of quasar evolution (Zakamska et al., 2016; Hamann et al., 2017). However, due to the current lack of access to mid-infrared spectroscopy, it is still unknown whether the large IR luminosities observed in these quasars is from star formation,

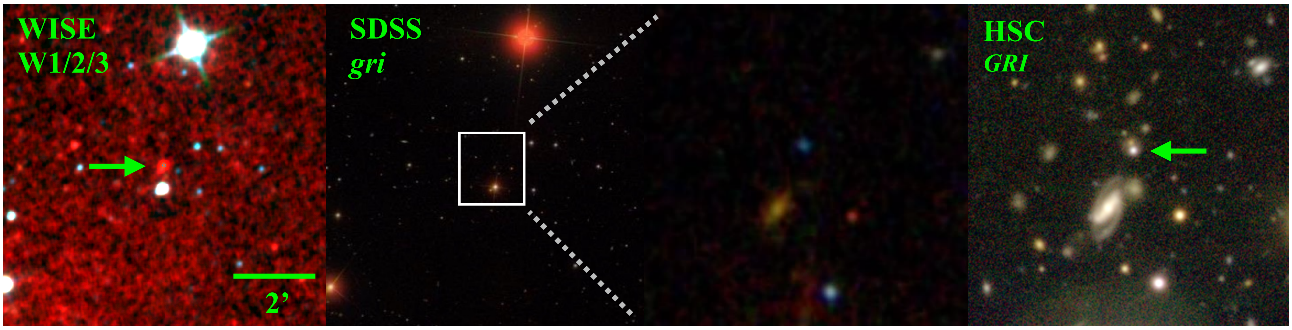

Figure 4: The IR and optical imaging of J2323-0100, an archetype of the "Extremely Red Quasars" (ERQs) at $z \approx 2.5$ and a *JWST* target. Shown are WISE *(left)*, where the quasar booms out as indicated by the arrow; the SDSS image *(middle left)* with zoom-in *(middle right)* on the optically faint 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.

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 will 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. I have 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 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 requests 100% of his salary 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. 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

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.

writing) and is covered at the 100% level over 5 years. Salaries are determined according to the UEDIN 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 AND COMMUNICATION: 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). I am currently tax-payer funded, and a deep believer in letting citizens know how their governments spend public money when investing in scientific projects with potential impact on their lives and on society. Thus broad communication of this research project is a large personal goal. 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**.

References

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, and et al. GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Physical Review Letters*, 119(16):161101, Oct 2017a. doi: 10.1103/PhysRevLett.119.161101.

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, and et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nat*, 551:85–88, Nov 2017b. doi: 10.1038/nature24471.

B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, and et al. Multi-messenger Observations of a Binary Neutron Star Merger. *ApJ Lett.*, 848:L12, Oct 2017c. doi: 10.3847/2041-8213/aa91c9.

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. *The LSST Science Collaboration, 0912.0201v1*, Dec 2009.

D. M. Alexander and R. C. Hickox. What drives the growth of black holes? *New A.R.*, 56:93–121, June 2012. doi: 10.1016/j.newar.2011.11.003.

D. Anglés-Alcázar, F. Özel, and R. Davé. Black Hole-Galaxy Correlations without Self-regulation. *ApJ*, 770: 5, June 2013. doi: 10.1088/0004-637X/770/1/5.

D. Anglés-Alcázar, F. Özel, R. Davé, N. Katz, J. A. Kollmeier, and B. D. Oppenheimer. Torque-limited Growth of Massive Black Holes in Galaxies across Cosmic Time. *ApJ*, 800:127, Feb 2015. doi: 10.1088/0004-637X/800/2/127.

D. Anglés-Alcázar, C.-A. Faucher-Giguère, E. Quataert, P. F. Hopkins, R. Feldmann, P. Torrey, A. Wetzel, and D. Kereš. Black holes on FIRE: stellar feedback limits early feeding of galactic nuclei. *MNRAS*, 472: L109–L114, Nov 2017. doi: 10.1093/mnrasl/slx161.

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.

R. Bieri, Y. Dubois, J. Rosdahl, A. Wagner, J. Silk, and G. A. Mamon. Outflows driven by quasars in high-redshift galaxies with radiation hydrodynamics. *MNRAS*, 464:1854–1873, Jan 2017. doi: 10.1093/mnras/stw2380.

H. Bondi. On spherically symmetrical accretion. *MNRAS*, 112:195, 1952. doi: 10.1093/mnras/112.2.195.

H. Bondi and F. Hoyle. On the mechanism of accretion by stars. *MNRAS*, 104:273, 1944. doi: 10.1093/mnras/104.5.273.

S. Cielo, V. Antonuccio-Delogu, A. V. Macciò, A. D. Romeo, and J. Silk. 3D simulations of the early stages of AGN jets: geometry, thermodynamics and backflow. *MNRAS*, 439:2903–2916, Apr 2014. doi: 10.1093/mnras/stu161.

T. Costa, D. Sijacki, and M. G. Haehnelt. Feedback from active galactic nuclei: energy- versus momentum-driving. *MNRAS*, 444:2355–2376, Nov 2014. doi: 10.1093/mnras/stu1632.

R. A. Crain et al. The EAGLE simulations of galaxy formation: calibration of subgrid physics and model variations. *MNRAS*, 450:1937–1961, June 2015. doi: 10.1093/mnras/stv725.

M. Curtis and D. Sijacki. Resolving flows around black holes: numerical technique and applications. *MNRAS*, 454:3445–3463, Dec 2015. doi: 10.1093/mnras/stv2246.

M. Curtis and D. Sijacki. Powerful quasar outflow in a massive disc galaxy at $z\sim5$. *MNRAS*, 457:L34–L38, March 2016a. doi: 10.1093/mnrasl/slv199.

M. Curtis and D. Sijacki. Resolving flows around black holes: the impact of gas angular momentum. *MNRAS*, 463:63–77, Nov 2016b. doi: 10.1093/mnras/stw1944.

R. Davé, R. Thompson, and P. F. Hopkins. MUFASA: galaxy formation simulations with meshless hydrodynamics. *MNRAS*, 462:3265–3284, Nov 2016. doi: 10.1093/mnras/stw1862.

R. Edgar. A review of Bondi-Hoyle-Lyttleton accretion. *New A.R.*, 48:843–859, Sept 2004. doi: 10.1016/j.newar.2004.06.001.

M. Elvis et al. Atlas of quasar energy distributions. *ApJS*, 95:1–68, Nov 1994. doi: 10.1086/192093.

E. Emsellem, F. Renaud, F. Bournaud, B. Elmegreen, F. Combes, and J. M. Gabor. The interplay between a galactic bar and a supermassive black hole: nuclear fuelling in a subparsec resolution galaxy simulation. *MNRAS*, 446:2468–2482, Jan 2015. doi: 10.1093/mnras/stu2209.

A. C. Fabian. Observational Evidence of Active Galactic Nuclei Feedback. *ARA&A*, 50:455–489, Sept 2012. doi: 10.1146/annurev-astro-081811-125521.

V. Gaibler, S. Khochfar, M. Krause, and J. Silk. Jet-induced star formation in gas-rich galaxies. *MNRAS*, 425: 438–449, Sept 2012. doi: 10.1111/j.1365-2966.2012.21479.x.

M. Gaspari, M. Ruszkowski, and S. P. Oh. Chaotic cold accretion on to black holes. *MNRAS*, 432:3401–3422, July 2013. doi: 10.1093/mnras/stt692.

J. E. Greene, C. Y. Peng, M. Kim, C.-Y. Kuo, J. A. Braatz, C. M. V. Impellizzeri, J. J. Condon, K. Y. Lo, C. Henkel, and M. J. Reid. Precise Black Hole Masses from Megamaser Disks: Black Hole-Bulge Relations at Low Mass. *ApJ*, 721:26–45, Sept 2010. doi: 10.1088/0004-637X/721/1/26.

F. Haardt, V. Gorini, U. Moschella, A. Treves, and M. Colpi, editors. *Astrophysical Black Holes*, volume 905 of *Lecture Notes in Physics, Berlin Springer Verlag*, 2016. doi: 10.1007/978-3-319-19416-5.

F. Hamann et al. Extremely red quasars in BOSS. *MNRAS*, 464:3431–3463, Jan 2017. doi: 10.1093/mnras/stw2387.

N. Häring and H.-W. Rix. On the Black Hole Mass-Bulge Mass Relation. *ApJ Lett.*, 604:L89–L92, Apr 2004. doi: 10.1086/383567.

T. Heckman and P. Best. The Co-Evolution of Galaxies and Supermassive Black Holes: Insights from Surveys of the Contemporary Universe. *ArXiv:1403.4620v1*, March 2014.

P. F. Hopkins and E. Quataert. How do massive black holes get their gas? *MNRAS*, 407:1529–1564, Sept 2010. doi: 10.1111/j.1365-2966.2010.17064.x.

P. F. Hopkins and E. Quataert. An analytic model of angular momentum transport by gravitational torques: from galaxies to massive black holes. *MNRAS*, 415:1027–1050, Aug 2011. doi: 10.1111/j.1365-2966.2011.18542.x.

P. F. Hopkins, L. Hernquist, T. J. Cox, and D. Kereš. A Cosmological Framework for the Co-Evolution of Quasars, Supermassive Black Holes, and Elliptical Galaxies. I. Galaxy Mergers and Quasar Activity. *ApJS*, 175:356–389, Apr 2008. doi: 10.1086/524362.

P. F. Hopkins, P. Torrey, C.-A. Faucher-Giguère, E. Quataert, and N. Murray. Stellar and quasar feedback in concert: effects on AGN accretion, obscuration, and outflows. *MNRAS*, 458:816–831, May 2016. doi: 10.1093/mnras/stw289.

P. F Hopkins et al. FIRE-2 Simulations: Physics versus Numerics in Galaxy Formation. *ArXiv e-prints*, Feb 2017.

F. Hoyle and R. A. Lyttleton. The effect of interstellar matter on climatic variation. *Proceedings of the Cambridge Philosophical Society*, 35:405, 1939. doi: 10.1017/S0305004100021150.

M. Huarte-Espinosa, M. Krause, and P. Alexander. 3D magnetohydrodynamic simulations of the evolution of magnetic fields in Fanaroff-Riley class II radio sources. *MNRAS*, 417:382–399, Oct 2011. doi: 10.1111/j.1365-2966.2011.19271.x.

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.

A. King and K. Pounds. Powerful Outflows and Feedback from Active Galactic Nuclei. *ARA&A*, 53:115–154, Aug 2015. doi: 10.1146/annurev-astro-082214-122316.

A. Koratkar and O. Blaes. The Ultraviolet and Optical Continuum Emission in Active Galactic Nuclei: The Status of Accretion Disks. *PASP*, 111:1–30, Jan 1999. doi: 10.1086/316294.

J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *ARA&A*, 51:511–653, Aug 2013. doi: 10.1146/annurev-astro-082708-101811.

S. M. LaMassa, S. Cales, E. C. Moran, A. D. Myers, G. T. Richards, M. Eracleous, T. M. Heckman, L. Gallo, and C. M. Urry. The Discovery of the First "Changing Look" Quasar: New Insights Into the Physics and Phenomenology of Active Galactic Nucleus. *ApJ*, 800:144, Feb 2015. doi: 10.1088/0004-637X/800/2/144.

A. Lawrence. The UV peak in active galactic nuclei: a false continuum from blurred reflection? *MNRAS*, 423:

451–463, June 2012. doi: 10.1111/j.1365-2966.2012.20889.x.

A. Lawrence. Clues to the Structure of AGN Through Massive Variability Surveys. In A. Mickaelian, A. Lawrence, and T. Magakian, editors, *Astronomical Surveys and Big Data*, volume 505 of *Astronomical Society of the Pacific Conference Series*, page 107, June 2016.

A. Lawrence. Quasar viscosity crisis. *Nature Astronomy*, 2:102âĂŞ103, Jan 2018.

C. L. MacLeod, N. P. Ross, et al. A systematic search for changing-look quasars in SDSS. *MNRAS*, 457: 389–404, March 2016. doi: 10.1093/mnras/stv2997.

C. L. MacLeod et al. Modeling the Time Variability of SDSS Stripe 82 Quasars as a Damped Random Walk. *ApJ*, 721:1014–1033, Oct 2010. doi: 10.1088/0004-637X/721/2/1014.

R. J. McLure and J. S. Dunlop. On the black hole-bulge mass relation in active and inactive galaxies. *MNRAS*, 331:795–804, Apr 2002. doi: 10.1046/j.1365-8711.2002.05236.x.

A. M. Meisner, B. C. Bromley, P. E. Nugent, D. J. Schlegel, S. J. Kenyon, E. F. Schlafly, and K. S. Dawson. Searching for Planet Nine with Coadded WISE and NEOWISE-Reactivation Images. *AJ*, 153:65, Feb 2017a. doi: 10.3847/1538-3881/153/2/65.

A. M. Meisner, D. Lang, and D. J. Schlegel. Deep Full-sky Coadds from Three Years of WISE and NEOWISE Observations. *AJ*, 154:161, Oct 2017b. doi: 10.3847/1538-3881/aa894e.

A. Merloni, P. Predehl, W. Becker, H. Böhringer, T. Boller, H. Brunner, M. Brusa, K. Dennerl, M. Freyberg, P. Friedrich, A. Georgakakis, F. Haberl, G. Hasinger, N. Meidinger, J. Mohr, K. Nandra, A. Rau, T. H. Reiprich, J. Robrade, M. Salvato, A. Santangelo, M. Sasaki, A. Schwope, J. Wilms, and t. German eROSITA Consortium. eROSITA Science Book: Mapping the Structure of the Energetic Universe. *ArXiv e-prints*, Sept 2012.

A. A. Miller et al. Color Me Intrigued: The Discovery of iPTF 16fnm, an SN 2002cx-like Object. *ApJ*, 848: 59, Oct 2017. doi: 10.3847/1538-4357/aa8c7e.

C. W. Morgan, C. S. Kochanek, N. D. Morgan, and E. E. Falco. The Quasar Accretion Disk Size-Black Hole Mass Relation. *ApJ*, 712:1129–1136, Apr 2010. doi: 10.1088/0004-637X/712/2/1129.

C. W. Morgan et al. Further Evidence that Quasar X-Ray Emitting Regions are Compact: X-Ray and Optical Microlensing in the Lensed Quasar Q J0158-4325. *ApJ*, 756:52, Sept 2012. doi: 10.1088/0004-637X/756/1/52.

A. M. Mosquera and C. S. Kochanek. The Microlensing Properties of a Sample of 87 Lensed Quasars. *ApJ*, 738:96, Sept 2011. doi: 10.1088/0004-637X/738/1/96.

T. Naab and J. P. Ostriker. Theoretical Challenges in Galaxy Formation. *ARA&A*, 55:59–109, Aug 2017. doi: 10.1146/annurev-astro-081913-040019.

H. Netzer. Revisiting the Unified Model of Active Galactic Nuclei. *ARA&A*, 53:365, 2015.

P. Padovani, D. M. Alexander, R. J. Assef, B. De Marco, P. Giommi, R. C. Hickox, G. T. Richards, V. Smolčić, E. Hatziminaoglou, V. Mainieri, and M. Salvato. Active galactic nuclei: what's in a name? *A&ARv*, 25:2, Aug 2017. doi: 10.1007/s00159-017-0102-9.

A. Pillepich et al. Simulating galaxy formation with the IllustrisTNG model. *MNRAS*, 473:4077–4106, Jan 2018. doi: 10.1093/mnras/stx2656.

D. Pooley, J. A. Blackburne, S. Rappaport, and P. L. Schechter. X-Ray and Optical Flux Ratio Anomalies in Quadruply Lensed Quasars. I. Zooming in on Quasar Emission Regions. *ApJ*, 661:19–29, May 2007. doi: 10.1086/512115.

J. E. Pringle. Accretion discs in astrophysics. *ARA&A*, 19:137–162, 1981. doi: 10.1146/annurev.aa.19.090181.001033.

G. T. Richards et al. Spectral Energy Distributions and Multiwavelength Selection of Type 1 Quasars. *ApJS*, 166:470–497, Oct 2006. doi: 10.1086/506525.

G. Risaliti and E. Lusso. A Hubble Diagram for Quasars. *ApJ*, 815:33, Dec 2015. doi: 10.1088/0004-637X/815/1/33.

O. Roos, S. Juneau, F. Bournaud, and J. M. Gabor. Thermal and Radiative Active Galactic Nucleus Feedback have a Limited Impact on Star Formation in High-redshift Galaxies. *ApJ*, 800:19, Feb 2015. doi: 10.1088/0004-637X/800/1/19.

Y. M. Rosas-Guevara, R. G. Bower, J. Schaye, M. Furlong, C. S. Frenk, C. M. Booth, R. A. Crain, C. Dalla Vecchia, M. Schaller, and T. Theuns. The impact of angular momentum on black hole accretion rates in simulations of galaxy formation. *MNRAS*, 454:1038–1057, Nov 2015. doi: 10.1093/mnras/stv2056.

N. P. Ross et al. The SDSS-III Baryon Oscillation Spectroscopic Survey: Quasar Target Selection for Data Release Nine. *ApJS*, 199:3, March 2012. doi: 10.1088/0067-0049/199/1/3.

N. P. Ross et al. The SDSS-III Baryon Oscillation Spectroscopic Survey: Quasar Luminosity Function from Data Release Nine. *ApJ*, 773:14, Aug 2013. doi: 10.1088/0004-637X/773/1/14.

N. P. Ross et al. Extremely red quasars from SDSS, BOSS and WISE: classification of optical spectra. *MNRAS*, 453:3932–3952, Nov 2015. doi: 10.1093/mnras/stv1710.

N. P. Ross et al. A new physical interpretation of optical and infrared variability in quasars. *Nature Astronomy*, 2018.

J. J. Ruan, S. F. Anderson, S. L. Cales, M. Eracleous, P. J. Green, E. Morganson, J. C. Runnoe, Y. Shen, T. D. Wilkinson, M. R. Blanton, T. Dwelly, A. Georgakakis, J. E. Greene, S. M. LaMassa, A. Merloni, and D. P. Schneider. Toward an Understanding of Changing-look Quasars: An Archival Spectroscopic Search in SDSS. *ApJ*, 826:188, Aug 2016. doi: 10.3847/0004-637X/826/2/188.

J. N. Runco et al. Broad Hβ Emission-line Variability in a Sample of 102 Local Active Galaxies. *ApJ*, 821: 33, Apr 2016. doi: 10.3847/0004-637X/821/1/33.

J. C. Runnoe, S. Cales, J. J. Ruan, M. Eracleous, S. F. Anderson, Y. Shen, P. J. Green, E. Morganson, S. LaMassa, J. E. Greene, T. Dwelly, D. P. Schneider, A. Merloni, A. Georgakakis, and A. Roman-Lopes. Now you see it, now you don't: the disappearing central engine of the quasar J1011+5442. *MNRAS*, 455: 1691–1701, Jan 2016. doi: 10.1093/mnras/stv2385.

S. Salviander, G. A. Shields, K. Gebhardt, and E. W. Bonning. The Black Hole Mass-Galaxy Bulge Relationship for QSOs in the Sloan Digital Sky Survey Data Release 3. *ApJ*, 662:131–144, June 2007. doi: 10.1086/513086.

J. Schaye et al. The EAGLE project: simulating the evolution and assembly of galaxies and their environments. *MNRAS*, 446:521–554, Jan 2015. doi: 10.1093/mnras/stu2058.

D. J. Schlegel et al. SDSS-III: The Baryon Oscillation Spectroscopic Survey (BOSS). *ApJ, in prep.*, 2011.

N. I. Shakura and R. A. Sunyaev. Black holes in binary systems. Observational appearance. *Astron. & Astrophys.*, 24:337, 1973.

D. Sijacki, V. Springel, T. Di Matteo, and L. Hernquist. A unified model for AGN feedback in cosmological simulations of structure formation. *MNRAS*, 380:877–900, Sept 2007. doi: 10.1111/j.1365-2966.2007.12153.x.

E. Sirko and J. Goodman. Spectral energy distributions of marginally self-gravitating quasi-stellar object discs. *MNRAS*, 341:501–508, May 2003. doi: 10.1046/j.1365-8711.2003.06431.x.

L. G. Spitler et al. A repeating fast radio burst. *Nat*, 531:202–205, March 2016. doi: 10.1038/nature17168.

J. D. Timlin, N. P. Ross, et al. SpIES: The Spitzer IRAC Equatorial Survey. *ApJS*, 225:1, July 2016. doi: 10.3847/0067-0049/225/1/1.

J. D. Timlin, N. P. Ross, et al. The Clustering of High-Redshift ($2.9 \leq z \leq 5.1$) Quasars in SDSS Stripe 82. *ApJ*, 2018.

M. Vogelsberger, S. Genel, D. Sijacki, P. Torrey, V. Springel, and L. Hernquist. A model for cosmological simulations of galaxy formation physics. *MNRAS*, 436:3031–3067, Dec 2013. doi: 10.1093/mnras/stt1789.

M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. Snyder, D. Nelson, and L. Hernquist. Introducing the Illustris Project: simulating the coevolution of dark and visible matter in the Universe. *MNRAS*, 444:1518–1547, Oct 2014. doi: 10.1093/mnras/stu1536.

R. Weinberger et al. Simulating galaxy formation with black hole driven thermal and kinetic feedback. *MNRAS*, 465:3291–3308, March 2017. doi: 10.1093/mnras/stw2944.

A. R. Wetzel, P. F. Hopkins, J.-h. Kim, C.-A. Faucher-Giguère, D. Kereš, and E. Quataert. Reconciling Dwarf Galaxies with ΛCDM Cosmology: Simulating a Realistic Population of Satellites around a Milky Way-mass Galaxy. *ApJ Lett.*, 827:L23, Aug 2016. doi: 10.3847/2041-8205/827/2/L23.

E. L. Wright et al. The Wide-field Infrared Survey Explorer (WISE): Mission Description and Initial On-orbit

Performance. *AJ*, 140:1868, Dec 2010. doi: 10.1088/0004-6256/140/6/1868.

Q. Yang et al. Discovery of 21 New Changing-look AGNs in Northern Sky. *ArXiv e-prints*, Nov 2017.

F. Yuan and R. Narayan. Hot Accretion Flows Around Black Holes. *ARA&A*, 52:529–588, Aug 2014. doi: 10.1146/annurev-astro-082812-141003.

N. L. Zakamska et al. Discovery of extreme [O III] λ5007 Å outflows in high-redshift red quasars. *MNRAS*, 459:3144–3160, July 2016. doi: 10.1093/mnras/stw718.