LSST AGN Science Collaboration Roadmap

Prepared by the LSST AGN Science Collaboration,
with support from the LSST Corporation

Version 3.0
July 26, 2022

Contributing Authors

Ohad Shemmer,[1] Gordon Richards,[2] Niel Brandt,[3] Roberto Assef,[4] Filippo D'Ammando,[5] Yan-Fei Jiang,[6] Aaron Barth,[7] Franz Erik Bauer,[8] Matt Jarvis,[9] Mark Lacy,[10] Andy Lawrence,[11] Paulina Lira,[12] Chelsea MacLeod,[13] Carole Mundell,[14] Jeff Newman,[15] Christina Peters,[16] Matthew Temple,[4] Mara Salvato,[17] Jan-Torge Schindler,[18] Sebastian Hoenig,[19] and Xiaohui Fan[20]

[1]University of North Texas
[2]Drexel University
[3]The Pennsylvania State University
[4]Universidad Diego Portales
[5]INAF - Istituto di Radioastronomia
[6]University of California, Santa Barbara
[7]University of California, Irvine
[8]Pontificia Universidad Católica de Chile
[9]University of Oxford
[10]National Radio Astronomy Observatory
[11]University of Edinburgh
[12]Universidad de Chile
[13]Harvard-Smithsonian Center for Astrophysics
[14]University of Bath
[15]University of Pittsburgh
[16]University of Toronto
[17]Max-Planck Institute for Extraterrestrial Physics
[18]Leiden University
[19]University of Southampton
[20]University of Arizona

Contents

Introduction

Ohad Shemmer

The LSST AGN Science Collaboration (SC) held a meeting on January 3, 2017 in Grapevine, TX. The main goal was to start the development of a comprehensive Roadmap that will guide the SC activities during the pre- and post-commissioning phase of the LSST survey. The Roadmap presented below is intended to serve as an internal AGN SC living document that builds on past and current LSST-related AGN studies, including the AGN chapters in the LSST Science Book (Abell et al. 2009), the LSST Community Observing Strategy Evaluation Paper (Marshall et al. 2017), the LSST Optimization of the Observing Cadence (Bianco et al. 2022), and the various contributions that can be accessed from the LSST AGN SC website.[1] The Roadmap's purpose is to describe and prioritize critical AGN technical goals—needed to achieve science goals, many of which were identified at the meeting, along with tentative timelines to achieving these goals.

Three dedicated Working Groups (WGs), composed of AGN SC members, were formed during the Grapevine meeting to lead specific projects described by the Roadmap. These WGs are focused on: 1) AGN Selection, Classification, and Characterization, 2) AGN Redshift Estimates, and 3) AGN Variability Science. Each WG and its tasks/projects are described in detail in each of the following chapters, which appear in the order that paves the way to AGN investigations during and after LSST operations. The first chapter is devoted to optimizing AGN selection in order to construct the largest possible census. The second is focused on developing methods for improving the crucial redshift information. The third chapter describes precursor AGN variability studies in order to optimize AGN selection and prepare for the arrival of millions of AGN light curves. A fourth chapter, added in version 2 of the Roadmap, describes efforts for follow-up observations of LSST AGN and the ancillary data required for this purpose.

Each chapter begins with a general overview, followed by sections dedicated to a particular topic or topics. The structure of each section includes a short background, followed by a ranked list of major tasks in order of decreasing priority; several sections conclude with a paragraph detailing additional, lower-priority tasks. Each major task can be viewed as an abstract for a particular stand-alone project. Interested SC members are encouraged to pursue one or more of these projects and to seek funding support for these efforts. Additional, more specific questions regarding these projects should be forwarded to the chapters' leading authors. The task lists are not considered to be final, and AGN SC members are encouraged to suggest additional tasks/projects along with their suggested priorities.

[1] https://agn.science.lsst.org/

1 AGN Selection, Classification, and Characterization

Gordon Richards, Niel Brandt, Franz Erik Bauer, Matthew Temple, and Jan-Torge Schindler

1.1 Overview

For all AGN science with LSST, the first goal is seemingly straightforward: identify efficient and complete approaches to pinpoint the location of actively accreting supermassive black holes (SMBHs) on the sky, whether through short-lived transient events or longer-lived fueling. However, optimal search methods are not expected to be generic for all types of AGN, which can be divided into four broad classes: unobscured quasars/AGN, obscured quasars/AGN, low-luminosity AGN (LLAGN), and transient SMBH fueling events. In the following sections of this Chapter, we highlight the challenges LSST will face for each of these classes and identify the most important goals for the AGN SC in coming years for addressing those challenges.

Construction of LSST's AGN census will build upon a considerable volume of past work. Color-selection has been the gold standard for identification of unobscured quasars since their discovery (e.g., Koo & Kron 1982; Warren et al. 1991; Richards et al. 2002). Identification of quasars by their variable nature (e.g., Bonoli et al. 1979; Trevese et al. 1989; Butler & Bloom 2011) and lack of proper motion (e.g., Sandage & Luyten 1967; Kron & Chiu 1981) are also not new. Even the idea of performing a multi-faceted quasar selection (e.g., colors, variability, and proper motion) is not new (e.g., Koo et al. 1986). However, at the same time, the quality, quantity, and type of data that LSST will provide will allow more comprehensive AGN selection and thus these approaches must be considered from a "new again" perspective.

Historically, the selection of AGN, whether via color, variability, or proper motion, has relied on constraints in the observed parameter space. This process works quite well in that it produces samples that are sufficiently efficient that spectroscopic investigation is cost effective. However, such methods are not statistically optimal and only in recent years have we seen the implementation of "machine learning" methods (e.g., Richards et al. 2004; Bovy et al. 2011). The field of "data science" is growing rapidly and LSST science stands to benefit considerably from considering all of the latest research in statistics and computer science (e.g., Feigelson & Babu 2012). Below, we highlight the most pressing tasks required to accomplish the goal of optimal identification of classical type-1 AGN (i.e., those whose luminosity is dominated by their central engines). In a subsequent Section we consider the other three AGN classes.

1.2 Unobscured Quasar/AGN Selection Methods

1.2.1 Colors/Flux Ratios

Color-selection by itself is certainly the most mature of the avenues for identifying AGN (unobscured or otherwise). Any application of modern statistical techniques to color data will be the first step in the process. It is unlikely that any final method(s) adopted for LSST

AGN selection will be completely color based, thus it will be important to extend such efforts to multi-parameter selection methods using the information from the following methods.

1.2.2 Astrometry and (Lack of) Proper Motion

As some AGN and stars have similar colors, the fact that AGN do not have proper motions (while Galactic stars do) has long been used as a discriminant. LSST's use of astrometric data will be no different in that regard. Where LSST *will* be unique is in its ability to take advantage of differential chromatic refraction (DCR) of AGN (Kaczmarczik et al. 2009)[2]. In short, the DCR procedure makes use of the astrometric offset of an emission-line object from that expected (in the astrometric solution) for a power-law source. Here we consider DCR in the context of selection; see Chapter 2 for its use with redshift estimation.

1.2.3 Photometric Variability

As quasars display higher fractional variability in their brightness than the average star and in a much different way than the typical variable star, variability will be a cornerstone of AGN classification for LSST. However, variability by itself is unlikely to be a panacea. Even for luminous quasars, it has been shown that variability combined with colors works better for selection than variability alone (Peters et al. 2015). Moreover, even though lower-luminosity AGN are expected to have the most variable nuclei, increased contamination from the host galaxy will compromise variability-selection methods if insufficient care is taken.

1.2.4 Multiwavelength Data

Another way that AGN can also be identified is by combining LSST observations with multiwavelength data. This approach can be considered more generally as "combination with data from other facilities" (e.g., *Euclid, Gaia*). In some cases we will have to contend with tiered multiwavelength data; e.g., shallow over a large area to deep over a small area. For unobscured AGN, multiwavelength data will enhance our ability to identify high-redshift quasars and can be used to modify the AGN probabilities for objects near the border of the selection criteria; this process will be most useful within the context of a probabilistic redshift distribution (see Chapter 2). Objects detected in the X-ray or infrared (IR) with sufficiently high predicted luminosity will have increased AGN probability. Objects that are bright in the ultraviolet (UV) will have significantly decreased AGN probability (for high photometric redshifts), while objects that are radio bright will have increased probability. Currently, the greatest depth of the full sky is VHS/UHS in the near-infrared (NIR), *WISE* in the mid-infrared (MIR), *eROSITA* in the X-ray, and VLASS in the radio (80% sky coverage with three observing epochs, with EMU/Wodan coming for full sky coverage in the future). Somewhat deeper, but with less coverage, we have UKIDSS and the VISTA surveys in the NIR (soon to be *Euclid*); SpIES, SSDF, SERVS, SDWFS, and SWIRE in the MIR; the *XMM-Newton* Slew Survey and the *Chandra* Source Catalog in the X-ray; and *GALEX* in the UV. The key deep fields will be located within the LSST deep-drilling fields (DDFs),

[2]See also https://dmtn-037.lsst.io/

e.g., X-SERVS which will become important in training general selection in the DDFs (Ni et al. 2021). See Chapter 4 for further details.

1.2.5 Feature Space

LSST will optimize the identification of unobscured AGN using the following relevant parameters:

- color (flux ratio)
- variability
- astrometry (DCR and proper motion)
- brightness
- Galactic coordinates
- morphology
- probability of belonging to another class
- multiwavelength and multi-facility matching

Ideally, all of this information will be used simultaneously. Here we only have considered the inputs to the selection algorithms in generic terms; the LSST "Data Model"[3] will specify the details.

1.2.6 Major AGN SC Tasks Ranked by Decreasing Priority

1. Establish public training/test sets that AGN SC members can use as a benchmark to test different selection algorithms (i.e., a "data challenge" sample). This dataset could include (or be completely based upon) simulated data. It must encompass the color, astrometry, time-domain, morphology, difference imaging, and multiwavelength information needed to test all of the processes described above. See Chapter 4 for further details.

2. Generate realistic catalog-level simulated data (e.g., Rubin Data Preview, HSC-based simulations, or first-principle simulations). Such simulations must cover as much "area" and as many epochs as possible in all six LSST bands in a format that mimics the yearly data releases. As much physics and empirical correlations as possible must be included, e.g., luminosity dependence of emission features, magnitude-color correlations, variability physics, astrometric errors, DCR, proper motion, star-galaxy separation, nuclear versus host galaxy luminosity correlation (and its relationship to morphology), lensing probability, broad absorption lines and dust reddening (intrinsic, host galaxy, and intervening). In other words, the simulations must account for known quasar spectral diversity and its effects on LSST photometry.

[3]https://lse-163.lsst.io/

3. Determine what "color" (and/or flux ratio) means in the LSST context, given lack of simultaneous data in multiple bandpasses; possibly separately for the nucleus itself and for host+nucleus. Alternatively, explore methods that do not compute a single "color" for each object but rather operate on the full multi-band light curves. Nevertheless, it will be important for display purposes to establish what is meant by *the* colors of each object.

4. Explore different machine learning techniques (e.g., Random Forests, Support Vector Machines, Gaussian Mixture Models, Deep Learning, Autoencoders, and Transfer Learning), including both parametric and non-parametric approaches. The algorithms in standard machine learning libraries generally lack the ability to 1) output probabilities, 2) take Bayesian priors (e.g., brightness and Galactic latitude), 3) incorporate errors, and 4) handle missing data. The AGN SC must interact with the Informatics SC to adapt and test different machine learning algorithms in order to determine the optimal approaches.

5. Continue to test the effects of different cadence schemes on AGN selection (and AGN physics; Bianco et al. 2022).

6. Work with (and simulate) asynchronous light curves for variability selection. LSST time domain analysis will be utilizing information more efficiently if data from multiple bands are combined to create a "single" light curve. The AGN SC must determine how best to merge multi-band light curves (e.g., kriging), accounting for (or determining), e.g., colors, brightness-color dependence, time delays, non-simultaneity, and intergalactic absorption. Moreover, traditional variability analysis requires a parametric fit to the data. The possibility of performing non-parametric analysis (i.e., simply using the full, raw light curves) should be investigated; if a parametric fit is needed, determine the best form(s) (e.g., CARMA, DRW, or Slepian wavelet variance; see also Mahabal et al. 2017). Furthermore, given that AGN variability is nuclear, the AGN SC should investigate the possibility of performing such analysis in the context of difference imaging (building on work from other SCs such as those working on supernovae). Many of these issues can be investigated with existing (and ongoing) data sets such as Stripe 82, HSC, DES, Pan-STARRS, Catalina, Kepler, or ZTF (see Chapter 4)

7. Establish "truth tables" in the DDFs for multiwavelength selection. The LSST project must begin to tabulate spectroscopic (and multiwavelength) information in the currently-defined DDFs and establish a mechanism for storing and updating said information. Multiwavelength photometry must be incorporated, using Tractor-based forced photometry at the fiducial optical position (from data most similar to LSST). Alternatively (or in addition), implement true SED-based band merging (e.g., Budavari & Szalay 2008), and establish a 'wish list' for additional spectroscopy in the DDFs prior to the start of survey operations (see Chapter 4).

8. Develop luminosity function and clustering algorithms that work with probabilistic AGN candidates and apply these algorithms to the simulated data. Write papers based on the results that illustrate the size of the uncertainties that LSST data will produce given the model assumptions.

9. Establish a plan for working with intermediate products in the first year of the survey (e.g., reference images and prior classifications).

10. Develop diagnostic methods to identify rare classes of AGNs using colors, variability, and multiwavelength data.

11. Prepare for LSST identification of unidentified sources from multiwavelength data (e.g., *Fermi* and *CTA*).

Additional important tasks that the SC should address on a short timescale include (i) appointment of expert "ambassadors" for each major source of multiwavelength data, (ii) continue ongoing discussions with other LSST SCs and groups (e.g., improve star-galaxy separation techniques in conjunction with the Galaxies SC, work with Data Management (DM) to ensure good AGN-host deblending, folding multiwavelength data back into the LSST Data Model, whether or not to use photo-z's as feedback to produce rest-frame quantities), and (iii) interpretation of LSST Data Model outputs and how they relate to the key parameters mentioned above as well as relevant parameters that were used for the analysis of SDSS data (e.g., proper motion information based on USNO and *Gaia* data, morphology characterization, variability information, and novel DCR parameters that LSST will produce). In particular, collaborate more with SCs that compute photo-z assuming all objects being galaxies.

1.3 Transient, Obscured, and Low-Luminosity AGN Selection

1.3.1 Background

A key goal for the LSST AGN SC is to optimize AGN selection to enable the largest possible robust census. While "traditional" selection/classification/characterization methods are expected to drive the selection of bright AGN in the yearly data releases, there are three motivations for investigating additional "non-traditional" methods. For instance, the nominal angular resolution of LSST should allow separation of galaxy and nuclear components well below the traditional "quasar limit" (i.e., LLAGN) where unresolved host-galaxy contamination had previously been dominant. At the extreme limit of LLAGN are another class, namely obscured AGN, where there is little or no optical continuum emission from the AGN along our line of sight.

The optical data from LSST may not be sufficient to identify obscured AGN and LLAGN as such. Some LLAGN may be identified as having nuclear variability, but for the faintest objects the errors on the variability will be insufficient for robust classification. For these classes of objects we will be dependent upon multiwavelength SED fitting and X-ray or IR and/or radio luminosity and radio morphology to identify as an AGN what LSST data suggest is a galaxy. While we focus here on obscured AGN and LLAGN, many of the tasks listed below will also be related to identifying AGN that are unique in other bandpasses (e.g., blazars). In order to avoid repetition with respect to procedures required for the identification of unobscured AGN (e.g., creating a data challenge set, testing machine learning algorithms, establishing truth tables), these tasks are specifically geared towards identifying/classifying transient, obscured, and low-luminosity AGN.

Finally, to capitalize on the unique time-domain capabilities of LSST, we must assess the potential for "extreme" variability on a nightly basis in order to trigger immediate, rapid follow-up programs of extreme AGN events, for example, tidal disruption events (TDEs). This requirement naturally feeds into the AGN variability WG (see Chapter 3) and collaboration with other LSST Science Collaborations, e.g., Transients and Variable Stars (TVS) and Galaxies.

1.3.2 Major AGN SC Tasks Ranked by Decreasing Priority

1. Liaise with the Galaxies SC to test host and nuclear component fitting/decomposition, which is required for photometric measurements of the nucleus.

2. Determine what special measurements are needed/desired to select LLAGN. The most general constraint should be the point-spread function (PSF) magnitude assessed from the difference image at the location of the galaxy nucleus at each epoch (Δm detection or upper limit).

3. For dwarf and irregular galaxies, where a central nucleus may be ill or undefined, one needs to explore whether the variability of aperture photometry over the entire extent of the source, or whether relying on difference imaging, would allow for a more efficient selection, i.e., one must determine whether it is better to use the position of the variable source within the galaxy to eliminate contaminants or attempt to improve the photometry of the source.

4. Determine the utility of folding into the selection algorithm the host color and morphology, redshift, intrinsic properties, and multiwavelength properties. Test which parameters enhance detection rates and increase AGN probabilities, and investigate the potential for bias.

5. Use existing data and DDFs (e.g., HSC, and X-SERVS) to determine the range of parameter space that can be used to successfully select LLAGN. As no real systematic studies of the optical variability of LLAGN have been made, this effort will be exploring new territory. As such, there is a need to prepare for the unknown and be as open as possible to a large parameter range.

6. Liaise with the TVS SC to identify special measurements required for TDE selection, e.g., a PSF magnitude from a galaxy nucleus to assess variability. Furthermore, we must establish a definition for "strong" or "extreme" variability (e.g., on average, a factor of 5 or 30 increase in amplitude, respectively), and develop a framework for distinguishing between large increases and decreases in flux. Such variability criteria should be determined in a statistical manner based on distributions of variability amplitudes as functions of other properties (e.g., luminosity). In this context, it is important to consider more exotic possibilities such as sources exhibiting "strong"

variability coincident with no observed galaxy or AGN, in consultation with the TVS SC.

7. There is a need to determine the response timescales required for follow-up observations of TDEs, blazars, microlensing events, and changing-look quasars (CLQs) for AGN selection purposes. This topic also requires development of trigger programs and determining how these will be implemented. Additionally, we should determine whether the AGN SC needs a dedicated event broker for this purpose as opposed to collaborating with a general broker for AGN variability science (see Chapter 3).

8. A 'typical' TDE should have no spectroscopic signs of an AGN prior to the outburst. This property is obviously impossible to test after the outburst but one should develop some photometric criterion, e.g., the surface brightness distribution at/near the nucleus before the outburst, that will enable a reliable estimate of the presence of a strong, blue, nuclear point source before the outburst. An alternative way to test that, which is beyond the scope of this Roadmap, would be through late-time spectroscopy (many years in the rest frame after the outburst). These TDEs can be compared to events where a prior AGN is identified in order to establish how such events differ individually and collectively from their typical counterparts.

9. In order to maximize TDE selection, we must explore TDE decay laws that differ from the canonical $t^{-5/3}$ dependence after the initial outburst, as recent suggestions imply that other decay relations (e.g., an exponential decay) may exist.

10. Determine whether there is a need for increased cadence photometry and/or time-dependent color/SED information for TDEs and CLQs.

11. There should be a plan in place for follow-up spectroscopy and multiwavelength imaging of TDEs, CLQs, and other extreme AGN identified by LSST.

12. LSST will undoubtedly find new types of AGN. We should start thinking about what we can expect and how would we select such sources.

13. Investigate the impact of different u-band observing cadences on TDE and CLQ science.

Additional important tasks that the SC should attend to on a short timescale include (i) recruiting "ambassadors" who are experts in galaxy morphology and in transients from the TVS SC, and (ii) identifying critical parameters that are not provided by the DM group.

2 AGN Redshift Estimates

Roberto Assef, Franz Erik Bauer, Niel Brandt, Matt Jarvis, Mark Lacy, Jeff Newman, Christina Peters, Gordon Richards, Mara Salvato, and Matthew Temple

2.1 Overview

Redshift estimates for the vast majority of LSST AGN will have to rely on photometric redshift, or photo-z, techniques. There is a long history of broad-band photometric redshift estimation techniques, although these are most commonly applied to galaxies without nuclear activity. AGN are not only much less common than inactive galaxies, but also their photometric redshift estimates can be much less accurate. It will be important for the AGN SC to optimize and characterize the photo-z method(s) to be used, particularly in terms of their accuracy and biases in light of the specific science goals pursued. In general, photometric redshift techniques can be divided into two broad families: those that rely on SED template fitting, and those that rely on empirical correlations. We briefly discuss each of them in the following, as well as additional improvements that could be implemented. For a recent review on the subject see Salvato et al. (2019).

2.2 Photometric Redshift Methods

2.2.1 SED Template Fitting

SED template fitting is one of the most popular techniques for photometric redshift estimates for galaxies (e.g., Bolzonella et al. 2000; Benitez 2000). In their simplest version, SED template fitting methods operate by taking a number of different, pre-selected SED templates, computing their photometric band colors as a function of redshift, and selecting the template and redshift that best match the observed photometry. For galaxies without AGN activity, broad features identifiable in the color-redshift space, such as the Balmer break and the 1.6 μm peak in the NIR can result in very accurate redshift estimates when considering a filter set such as that of LSST. Unfortunately, this is not the case for QSOs (see, e.g., Rowan-Robinson et al. 2008; Salvato et al. 2009, 2022; Assef et al. 2010; Brescia et al. 2019). The power-law shape that characterizes their continuum emission at rest-frame UV through NIR wavelengths results in a degeneracy of the color-redshift space that becomes very difficult to break when relying solely on optical and NIR broad-band photometry. Emission lines with large equivalent widths, such as the broad Balmer lines, can help break this degeneracy to some extent (see, e.g., Fig. 1 of Temple et al. 2021), although their effect at optical wavelengths can sometimes be subtle when compared to the photometric accuracy. Stronger spectral features such as the Lyα emission line, the IGM Lyα forest absorption, and the Lyman break can have a bigger impact in breaking this degeneracy above $z \sim 2.5$, when they are redshifted into optical wavelengths, highlighting the importance of deep u-band observations for LSST. DCR caused by broad emission lines redshifted into the u- and g-bands will provide further constraints for photometric redshifts.

For obscured AGN or LLAGN, where the host galaxy dominates the optical SED, template methods provide more accurate redshift estimates. Moreover, Assef et al. (2010) note that SED template fitting techniques can provide accurate host galaxy-AGN decompositions, even when suffering from highly inaccurate redshift estimates. Hence, such SED modeling techniques should be considered for science goals requiring SED decomposition, even if the redshift estimates are obtained through a different method.

The DM team of LSST will provide photometric redshifts using a variety of algorithms for extragalactic objects. Estimates for AGNs will come at least from the LePhare template fitting algorithm (Arnouts & Ilbert 2011) relying solely on the LSST photometry, but may also come from other methods yet to be decided on. The SC will need to work closely with DM to characterize the accuracy of these estimates. Information from the DM-led estimates may also be used to inform other algorithms. The MPE in-kind contribution to LSST will provide a well tested and improved version of the LePhare algorithm that should become the default template-fitting algorithm for LSST AGN.

2.2.2 Empirical Methods

These methods rely on a training set with known redshifts from which they construct empirical relations between the inputs, typically (but not limited to) broad-band photometry, and the redshift itself. Because of this approach, these methods can incorporate in a natural manner many other observational properties than simply the observed broad-band fluxes, which is a complicated task for SED template fitting methods. Empirical methods can be based on a number of different approaches, such as neural networks, machine learning algorithms and Bayesian kernel density estimates. Compared to SED template fitting methods, empirical methods typically result in considerably more accurate photometric redshifts (e.g., Weinstein et al. 2004; Brodwin et al. 2006; Richards et al. 2009; Brescia et al. 2019) for type 1 quasars. Hence, as long as a training set that is representative of the LSST AGN sample can be constructed, or at least one that is well characterized, these methods should be much preferable over SED template fitting for luminous quasars. However, building representative training sets have proved to be difficult due to the significant mismatch between the depth of photometric and spectroscopic surveys. This will be particularly true for LSST, where the great majority of objects identified will be too faint for large spectroscopic surveys in the near future. For $i < 21$, spectroscopic samples from DESI, 4MOST, and SDSS-V/SPIDERS will allow for a robust training sample of quasars. Future samples from MOONS and PFS will allow us to extend the training sets to significantly lower brightness. Currently, the best option for low brightness will likely be to base training sets on the spectroscopic redshifts and accurate photometric redshifts in the COSMOS field obtained with a combination of broad-, medium-, and narrow-band photometry (Ilbert et al. 2009, Salvato et al. 2009). The depth, footprint size and large number of photometric bands make COSMOS uniquely well suited to this task.

2.2.3 Major AGN SC Tasks Ranked by Decreasing Priority

1. Determine all the possible sources of information (e.g., colors, fluxes, variability, DCR, and multiwavelength data) that can be used by photometric redshift algorithms.

2. Determine the usage of existing data (e.g., Stripe 82, and DES) to test the scheme of characterizing DCR. Interface with the DM group to determine what DCR parameter will be produced.

3. Identify spectroscopic data set(s) required to create an initial training set. Make this training set public so that it can be used as a benchmark to test different algorithms. One should consider *eROSITA*, *Gaia* and *WISE* AGN samples as a starting point, and one can also add variability selected samples.

4. Construct a training set based on the photometric and spectroscopic redshifts of the COSMOS field. Should consider adding variability selected AGN in the field as well.

5. Use the COSMOS field photometry to simulate Wide Fast Deep (WFD) and DDF depths to characterize algorithms. One may need to incorporate aspects of the LSST pipeline based on the experience of HSC with the proto-LSST pipeline to produce representative photometry.

6. Identify empirical methods that could be used for LSST AGNs.

7. Identify SED fitting methods that could be useful for LLAGN and obscured AGN in addition to the in-kind MPE contribution and the efforts from DM.

8. Consider hybrid classification/regression. As empirical photo-z methods will use the same information that would be used for classification, it should be possible to join both processes and perform the identification and photo-z estimation simultaneously. One needs to explore generation of this information as an LSST Level 2 (rather than Level 3) product.

9. Develop a framework for allowing the inclusion of variability properties. For brighter samples, variability can provide a prior for photo-zs based on luminosity dependence and time dilation. For fainter samples detected only in the stacked imaging, variability can be taken into account by considering redshift dependent systematic uncertainties.

10. Characterize the algorithms to be used based upon data from Data Preview 1 (DP1) and Data Preview 2 (DP2). Note that this effort is already being coordinated to some extent by DM, particularly for the LePhare estimates.

11. Compare the effectiveness of all the photo-z methods and identify the optimal solution(s). Compare the results to sources that have independent galaxy photo-z estimates.

12. Determine the expected photo-z accuracy, considering subsamples of different characteristics (e.g., LLAGN, obscured AGN, and luminous AGN).

13. Develop a MAF that assesses how a given OpSim (e.g., with a rolling cadence and/or high airmass observations) changes the accuracy of the chosen quasar photo-z method(s). Some progress has already been made for the Cadence Notes call.

14. Construct a spectroscopic follow-up plan for the DDFs that would allow the training set to be modified after the first year of the survey (see Chapter 4).

15. Determine what additional data (i.e., data external to LSST) can be added for the photo-z estimations and on which timescales. This can include data from, e.g., *Euclid*, *Roman*, or *eROSITA*. Also, see the multiwavelength discussions in Chapter 1 and Chapter 4.

16. If needed, modify photo-z algorithms to produce probability distribution functions (PDFs) rather than single values. PDFs are already part of the MPE algorithm, and may also be available for the LePhare estimates of DM. One should examine how to store the PDF information in an efficient manner, and develop quasar luminosity function and clustering algorithms that work with PDF photo-z data.

3 AGN Variability Science

Yan-Fei Jiang, Sebastian Hoenig, Carole Mundell, Ohad Shemmer, Chelsea L. MacLeod, Aaron Barth, Paulina Lira, Christina Peters, Andy Lawrence, and Filippo D'Ammando

3.1 Overview

Aside from playing a leading role in the selection of LSST AGN, AGN variability can provide invaluable information about the immediate surroundings of actively accreting SMBHs, including both the accretion disk and broad emission line region (BELR). This information can, ultimately, provide estimates of SMBH mass and accretion power. Different AGN variability timescales, from days, months, to years, in the rest frame, can be directly connected to the dynamical, thermal, and inflow timescales of the accretion disks. Finding statistically robust models to describe the AGN light curves is crucial for these studies. The unprecedented number of multi-band light curves that LSST will provide, covering a wide range of timescales, will enable testing different models of AGN variability that can break the degeneracies between the potential controlling parameters and improve our understanding of the underlying physical processes. AGN variability science is likely to be impacted the most due to changes in the nominal LSST cadence. Therefore, a significant fraction of the AGN SC work should be directed toward assessing the impact of potential LSST observing strategies and identifying potentially harmful cadences.

3.2 Ordinary AGN Variability

Ordinary AGN variability concerns light fluctuations originating in the accretion disk or BELR of an actively accreting SMBH. The characteristic timescales observed in such variations provide a direct link between observations and theoretical models of the accretion disk and BELR. In the simplest case, the shortest observable timescale (light-crossing time) places an upper limit on the size of the variable emission region. Then there are the dynamical and sound-crossing timescales (for a summary, see Lawrence et al. 2016a). In accretion-disk theory, the thermal and viscous timescales correspond to the heat dissipation and radial inflow rates, respectively, and have often been related to the observed timescales in quasar light curves (Lyubarskii 1997; Kelly et al. 2009, 2011; Kasliwal et al. 2017). Microlensing measurements of half-light radii of accretion disks always find that the measured value is larger than the predicted value by a factor of 3–4 (Morgan et al. 2010; Mosquera et al. 2013; Chartas et al. 2016). These results inspired alternative models of accretion disks (Dexter & Agol 2011). Because the effective temperature of accretion disks decreases with increasing distance to the SMBH, emission in different wavelength bands is dominated by different locations on the disk.

Measuring the time lags between the variability of different continuum bands is another way to constrain the properties of accretion disks (Edelson et al. 2015; Jiang et al. 2017). The color variability of AGN has also been shown to exhibit a tight "bluer when brighter" trend (Schmidt et al. 2012). This is another way to distinguish different accretion disk models (Ruan et al. 2014; Zhu et al. 2016). Light curves with daily cadences for a large sample of

AGN covering wide ranges of wavelength bands, that can be provided by LSST, will place a tight constraint on the radial dependence of the effective temperature in the accretion disks. The longer lags, on typical timescales of weeks to months, in the rest frame, between the continuum and the BELR lines will be important for probing the sizes of the BELRs and testing the dependence of the BELR on AGN luminosity. Another type of longer lags, where the variability of longer wavelengths lead those of shorter wavelengths, can also exist in AGN lightcurves (e.g., Hernández Santisteban et al. 2020). These lag signals show opposite perturbation propagation direction as for reverberation signals, and they typically happen on a timescale that is orders of magnitude longer than the light crossing time. This is typically interpreted as fluctuation propagation inside the accretion disks (Lyubarskii 1997). Detection of these lags can be used to probe internal structures of the accretion disks such as disk scale height.

Ordinary AGN variability can be described statistically with various processes ranging from a damped random walk (DRW) to quasi-periodic oscillation (QPO). The analysis of AGN light curves, particularly when the sampling pattern is irregular with few data points, typically relies on a structure function (SF) which is a robust way to estimate variability timescales that can be compared to a DRW model (Kozlowski 2016). The SF can also be modeled by a broken power-law power spectrum distribution (PSD) with multiple break time scales (Kasliwal et al. 2017), or a mixed Ornstein-Uhlenbeck (OU) process (Kelly et al. 2011). Variability on short timescales is sometimes better described by DRW+QPO, or the second-order Continuous time AutoRegressive Moving Average (CARMA) process. The latter is described by second-order stochastic linear differential equations, while DRW is, intrinsically, the first-order CARMA process. It has been shown recently that the second-order CARMA process is a better descriptor for some *Kepler* AGN (Kasliwal et al. 2015) and for $\sim 30\%$ of Optical Gravitational Lensing Experiment (OGLE) AGN (Zinn et al. 2017). Individual sources can have intrinsically varying PSD slopes, showing that the DRW process could not describe optical quasar variability in its entirety (e.g., Graham et al. 2014; Kasliwal et al. 2015; Caplar et al. 2017). For more complicated stochastic models, having larger set of phenomenological parameters, would make it even more difficult to link them to underlying physical processes (Tachibana et al. 2020). Thus, non-parametric (data driven) models of quasar variability based on deep learning have been devised (Tachibana et al. 2020; Sánchez-Sáez et al. 2018, 2021; Čvorović-Hajdinjak et al. 2022).

Circumbinary accretion disks have been theorized to occur around binary SMBHs, and the time-variable mass accretion rate can potentially produce periodic flux variability in the object's light curve (Artymowicz & Lubow 1996). Furthermore, the interaction between the binary SMBH and the gaseous accretion disk can play a major role in the binary orbital evolution and help drive the binary toward its eventual merger (e.g., Rafikov 2013). Since ordinary AGN variability is aperiodic, identifying compelling cases of periodically variable quasars would be an important step toward demonstrating the existence of binary SMBHs and studying their properties. Searches for periodically variable quasars have uncovered an increasing number of candidates using data from the Catalina Real-Time Transient Survey (CRTS) and from Pan-STARRS (Graham et al. 2015a,b; Liu et al. 2015; Zheng et al. 2016). Typical examples from CRTS have candidate periods of $\sim 2-4$ yr, corresponding to estimated binary separations of order $\sim 10^{-2}$ pc (Graham et al. 2015b).

During evolution, the binary orbit may contract, resulting in the broad line regions of both components to contract and being unable to generate broad emission lines during the latter stages of evolution (Kelley et al. 2021). Throughout this phase, periodic photometric variability is the most promising signature (Charisi et al. 2022). Theoretical simulations predict that several hundreds of sub-parsec binary SMBH should be detected over LSST operations (Kelley et al. 2019, 2021; Xin & Haiman 2021). Additionally, the LSST data can be coupled with current time-domain data from northern surveys, resulting in light curves with long baselines and high-quality data, both of which are required for periodicity detection (Charisi et al. 2022).

Some caution is warranted in periodicity searches, however, since DRW or other stochastic behavior can easily produce spurious quasi-periodicities over a short duration, and some false positives are likely to be found when searching large quasar samples. A necessary step is to carry out realistic Monte Carlo simulations to test any possible variability signal against the null hypothesis of aperiodic behavior, in order to assess the probability of a false positive periodicity signal (Vaughan et al. 2016). Generally, the amplitudes of these stochastic effects are greater on longer timescales. Because of this, a range of methodologies may be included in the periodicity-search packages (pipelines) to deal with the problem, since all of them have drawbacks and advantages (VanderPlas 2018; Goyal et al. 2017). Periodicity mining of time-series is one of the highly requested tasks by many science collaborations when LSST starts operations (see talks by Bellm, Richards, and Malanchev during Project and Community Workshop (PCW) 2021.[4]

Typically, periodicity mining algorithms can be categorized into two groups: 1) frequency domain methods relying on periodogram (computationally less expensive, see VanderPlas 2018), 2) time domain methods relying on wavelets (computationally more expensive, e.g., the 2DHybrid method by Kovačević et al. 2018), and autocorrelations. Once a candidate periodic quasar is identified, further monitoring is needed over longer timescales to test whether the past periodicity predicts future behavior. Any confirmed periodic quasars will be important targets for extensive follow-up to determine their physical properties, and could provide potential candidates for gravitational-wave studies. LSST will excel at producing quasar light curves with high signal-to-noise, long duration, and frequent sampling, which will provide the best database for identifying and verifying possible cases of periodic variability.

3.2.1 Major AGN SC Tasks Ranked by Decreasing Priority

1. There is a need to quantify continuum-continuum and line-continuum lags (e.g., Chelouche et al. 2014) in different timescales using both correlation-method and maximum-likelihood method based on fourier analysis (Cackett et al. 2021) for a wide range of black-hole mass and Eddington accretion rates. Particularly, we need to quantify how the cadence will impact the capability to separate more than one lag signal in the lightcurves, and the advantages/disadvantages of the two types of methods.

2. Simulations are needed to construct better lightcurve models for binary AGNs. We

[4]PCW 2021 "Time series variability features" session: `https://project.lsst.org/meetings/rubin2021/content/timeseries-variability-features/`

need better understanding on how the expected periodic signals will be modified by the intrinsic stochastic nature of AGN luminosity, particularly when the period is comparable to the variability timescale of a single AGN. We also want to understand the ability to detect periodic and quasi-periodic signals and a unified means to assess reliability of the detection such as simulations of the data to assess "artificial" periodic signals.

3. Development is needed to test non-parametric (data driven) models for AGN variability based on deep learning (e.g., Tachibana et al. 2020; Čvorović-Hajdinjak et al. 2022). Particularly, it is important to test how these algorithms will scale to millions/billions of lightcurves when they arrive.

4. Simulations are needed to test the possibility of distinguishing different variability processes that will happen in the accretion disks, particularly in the DDFs. This includes reverberation process where fluctuations propagate from the inner region to the outer region, which causes the short wavelength band to vary first. Another type of variability is perturbations in the outer region of the disk which are carried inward with the accretion process itself. This will cause the lag signals to reverse. One should therefore: 1) assess the ability to successfully (in terms of both quantity and quality) recover all these time delays simultaneously given different candidate cadences, especially for potential rolling cadences, and to identify particularly harmful cadences, and 2) plan precursor spectroscopic observations of sources for which photometric reverberation mapping (PRM) will likely yield reliable line-continuum time delays that will lead to SMBH mass estimates given accurate line-width measurements (e.g., Chelouche et al. 2014).

5. Simulations are needed to test how PRM results will be changed if alternative AGN lightcurve models are used instead of DRW or CARMA models. For example, lightcurves generated by radiation MHD simulations of black hole accretion disks can be used for this purpose (Jiang & Blaes 2020).

6. Scripts can be already constructed such that for a given RA and Dec the lightcurves at various wavelength from other instruments can be collected. This way, it will be quicker to exploit LSST data as soon as they are available.

7. Results from pre- and post-commissioning variability science should be fed back into AGN selection in general.

8. Continuous collaboration with other overlapping LSST SCs working on time-domain science, especially with the TVS SC is encouraged. Blazar studies and quasar accretion-disk size measurements are two key intersections between AGN, TVS, and Microlensing collaborations. As an example, Burke et al. (2021) indicate a relationship between the mass of actively feeding black holes and the characteristic timescale of variability, which holds for a large range of black-hole masses (from SMBHs down to white dwarfs).

9. Develop a forced-photomtery pipeline that can be applied to a combination of LSST data and data from previous legacy surveys, such as the Sloan Digital Sky Survey (SDSS).

3.3 Extreme AGN Variability

Aside from regular variability, AGN and their environments can show changes beyond the typical timescales or amplitudes. Examples include rather rapid "bursts" or fading, or long-term consistent trends. The most extreme cases of short time scale/high amplitude changes are usually seen in radio-loud AGN types (blazars/BL Lac objects) and related to jet activity. On the other hand, extreme accretion events can also cause sudden AGN brightening and change the continuum and emission-line characteristics for months to years (e.g. Lawrence et al. 2016b; Graham et al. 2017; Trakhtenbrot et al. 2019).

An increasing number of AGN are found to change their type classification based on the presence or absence of broad emission lines and/or a blue continuum in the UV/optical regime (i.e., "Changing-look" AGN and quasars, or CLQs; e.g. LaMassa et al. 2015; Runnoe et al. 2016). Such changes can occur rather suddenly and due to either a change in obscuration or accretion. Some of the CLQs will revert back to their original type. There are probably several physical mechanisms that lead to CLQ behaviour, which includes reconfiguration of the material along the line of sight, rapid changes in accretion supply, or interaction of inflowing and outflowing material.

Over the long time baseline of Rubin's LSST, we expect that a number of galaxies will turn from non-AGN to AGN and vice versa, constituting the most extreme case of AGN variability. While some relic AGNs have been identified by large off-center ionization regions without a central AGN (e.g., Keel et al. 2017), it is unclear if the switch-on/-off are rather sudden or gradual events. A census of such sources will help us understand the length of AGN duty cycles and gauge models of AGN fuelling and feedback.

Finally, several classes of nuclear transients have been discovered that may or may not be related to accretion onto the SMBHs. Most famously, stars passing close to the SMBH may get disrupted causing sudden low-level, short-lived accretion episodes, known as TDEs. As recently found and contrary to some theories, these TDEs can show recurrent brightening months or years after the original event (e.g., Wang et al. 2022).

The key to understanding the extreme end of AGN variability will be a combination of dedicated and rapid identification of events and multiwavelength follow-up. In this respect, AGN variability has similar logistical requirements as stellar transients, albeit less resource intensive and with slightly less stringent response times. The tasks identified below delineate a path towards optimal exploitation of LSST data and enabling one to test physical theories of AGN activity against unusual events.

3.3.1 Major AGN SC Tasks Ranked by Decreasing Priority

1. Extreme variability lacks any standardized templates. Identification may be relatively simple ("everything behaving outside standard red-noise variability"), but expectations in terms of color evolution and duration is rather unclear. Testing the parameter space that LSST will be able to cover for such events and how to best identify them is of high priority.

2. A reliable (near) real-time alert system for extreme events is required. This is best

linked to one of the data centers and/or brokers already dealing with transients. Ideally, a to-be-selected and updated set of AGN lightcurves is constantly updated and monitored for unusual variability; e.g., calculating the SFs and determining variability outside of $3/4/5\,\sigma$ of any monitored AGN, and simple comparisons to $\sigma_f/\langle f\rangle$. Note that some extreme AGN variability events may be detected in the transient streams, but depending on the filters, after some time, AGN may be flagged and could be ignored by brokers. In addition, slowly evolving changes may be missed and will require stacked data on longer time scales. Resources may be provided through in-kind contributions. Engagement with brokers is also essential to help retain and process AGN data and an AGN SC broker liaison needs to be identified.

3. Organize spectroscopic follow-up of extreme variability triggers. This includes multiwavelength photometric facilities as well as optical spectroscopic observations. The goal is a quick classification of the phenomenon (e.g., absorption, accretion events, jet activity, nuclear transient, or microlensing) and a multiwavelength coverage of the event to secure the ability to monitor continuum and emission-line changes. This follow-up infrastructure is crucially important for providing the observational foundation for physical interpretation.

4. Nuclear events cross the boundary between AGN and transients, most prominently TDEs. Interest in these phenomena span multiple SCs, including TVS SC, Dark Energy SC, and the AGN SC. Some more formal coordination for follow-up and exploitation needs to be established and a nuclear transient liaison need to be identified with the goal of exchanging expertise.

4 AGN Ancillary Data and Follow-up Programs

Franz Erik Bauer and Xiaohui Fan

4.1 Overview

In order to complement the LSST data products and enhance the stated goals in the previous Chapters, we will require complementary ancillary datasets. Our aim here is to identify and consolidate all of the ancillary and follow-up needs from the various WGs (i.e., selection/classification, photo-z, and variability science) in order to forge strong collaborations and build the necessary infrastructure that will lead to successful characterization of AGN, be them LSST-selected or otherwise.

We break down these desired datasets into several potential categories: preparatory multiwavelength and time domain datasets from the pre-LSST era; large spectroscopic training sets; concurrent time-domain imaging and/or spectroscopy; triggered multiwavelength follow-up observations. We elaborate upon these below.

4.2 Multiwavelength Pre-Observations of AGN Fields

As outlined in virtually all of the above Chapters, observations across the electromagnetic spectrum can aid in the identification, classification, and characterization of AGN. However, these datasets are the products of many distinct teams, with different data reduction strategies, photometry methods, and cataloging practices. To the extent that is possible, these datasets need to be homogenized and aggregated into a single common repository.

4.2.1 Wide-Field Datasets

At X-ray wavelengths, the SRG-eROSITA survey will provide the deepest all-sky sample to $F_{0.5-2.0\,\mathrm{keV}} \gtrsim (5-10)\times10^{-15}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. Its PSF and positional accuracy, however, are rather large ($\theta{\approx}26''$ and 4–5$''$, respectively), such that counterparts will need to be assessed in a probabilistic manner (e.g., NWAY; Buchner et al. 2021). At present, a contiguous 140 deg^2 science verification area known as the eROSITA Final Equatorial-Depth Survey (eFEDS) has been made publicly available. In the future, the German hemisphere of eRASS data, which strongly overlaps with LSST's WFD footprint, will be released in three stages (1, 4, and 8 visit depth), each spaced ≈2 yr apart. This can be supplemented by the serendipitous catalogs from *Chandra*, *XMM-Newton* and *Swift* (≈1.3%, 2.9%, and 9.2% of the sky, respectively).

At UV wavelengths, the deepest all-sky sample is provided by GALEX, which has a relatively large PSF ($\theta{\approx}5''$). Blending and artifacts are particularly problematic in the FUV, requiring cleaning and/or pruning.

At optical wavelengths, LSST should ultimately provide the best all-sky sample. Nonetheless, in early years, imaging from the Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) in $grizy$ over 1400 deg^2 could be valuable.

At NIR wavelengths, the VISTA VHS/VIKING and UKIDSS UHS surveys are the de facto surveys in the pre-*Euclid* era.

At MIR wavelengths, the deepest all-sky sample is provided by WISE, which has a relatively large PSF ($\theta \approx 6.1$", ≈ 6.8", ≈ 7.4", ≈ 12" in W1, W2, W3, and W4, respectively). Thus, blending and confusion are major limitations. Moreover, the extended wings of PSFs, which are particularly problematic in W3, need to be accounted for to properly estimate upper limits near bright targets.

At radio wavelengths, ASKAP's Evolutionary Map of the Universe (EMU; PI: Norris) will provide a deep (10 μJy/beam rms) $\approx$1.4 GHz radio continuum survey ($\theta \approx 18$") over the full LSST footprint. Meanwhile, the VLA Sky Survey will provide a moderate depth (69 μJy/beam rms) $\approx$2–4 GHz radio continuum survey ($\theta \approx 2.5$") down to $\delta = -40$ deg.

4.2.2 Deep-Field Datasets

The DDFs generally benefit from long-term legacy campaigns to build out their coverage in a wedding-cake fashion. In particular, *HST*, *Spitzer*, *XMM-Newton* and/or *Chandra*, *Herschel*, and ground-based optical/NIR facilities have all observed at least central portions of four of the five DDFs to unprecedented depths. We briefly list them separately as:

ELAIS-S1: Has $\approx$3.2 deg^2 of deep u to MIR imaging, plus coverage with XMM-Newton, *Herschel*, and radio. See Ni et al. (2021) and Zou et al. (2022) for more details.

WCDF-S: Has $\approx$4.6 deg^2 of deep u to MIR imaging, plus coverage with *XMM-Newton*, *Herschel*, and MeerKAT (MIGHTY). See Ni et al. (2021) and Zou et al. (2022) for more details.

XMM-LSS: Has $\approx$5.3 deg^2 of deep u to MIR imaging, plus coverage with *XMM-Newton*, *Herschel*, and radio. See Chen et al. (2018) and Zou et al. (2022) for more details.

COSMOS: This field has outstanding coverage[5] within the inner 1–2 deg^2, including *HST* imaging in 2 bands and eventually 0.6 deg^2 of *JWST*-NIRCam imaging in 3 bands and 0.2 deg^2 of *JWST*-MIRI.

EDF: This is a relatively new entry as a DDF, nominally spanning $\approx$2 adjacent LSST FOVs at roughly half-depth each. As such, it remains well behind the others, with little currently published data. It has no planned X-ray and UV coverage beyond eROSITA and GALEX, respectively. At optical and MIR wavelengths, the H20 survey aims to provide HSC (*griz*) and Spitzer (ch1/ch2) imaging to AB < 27.5 along with Keck DEIMOS spectroscopy. Assuming *Euclid* launches successfully, it will likely be one of the first fields observed and released to both communities.

4.2.3 Major AGN SC Tasks Ranked by Decreasing Priority

1. A first step should be simply to assemble an indexed set of catalogs of the most useful matched multiwavelength datasets over parts or all of the entire LSST footprint. In discrete areas, this exists (e.g., in S82 via the AGN SC Data Challenge; in three DDFs

[5] https://irsa.ipac.caltech.edu/data/COSMOS/overview.html

via Zou et al. 2022). Developing a strategy for this on a larger scale, including where to host it, remains a fundamental concern to resolve.

2. A more ambitious second step would be to perform joint photometry across some/all multiwavelength datasets, including derivation of upper limits. One possibility is to split out clear detections and then produce residual maps to assess upper limits for non-detections. The UK-LSST group is planning to provide, as an in-kind contribution, matched photometry in regions where VISTA imaging exists.

3. Leveling up coverage of the Euclid Deep Field (Fornax), i.e., the fifth DDF, should be a priority, particularly in X-rays. For COSMOS, outside of the nominal 2 deg^2 footprint, coverage drops rapidly in most bands and desperately needs to be assembled and assessed.

4. Deep public radio (VLA, MeerKAT) and mm (TolTEC; 0.1–1 mJy at 5-σ) datasets over deg^2 regions are lacking.

4.3 Time Domain Pre-Observations of AGN Fields

There are additionally a multitude of past or present time domain surveys which can help to extend baselines for brighter targets, hone selection techniques, and generate pre-LSST AGN samples.

4.3.1 Wide-Field Datasets

SDSS (stripe 82): Has ≈40–80 imaging epochs between *ugriz* over 290 deg^2 (a 2.5 deg strip at δ=0 deg) spanning roughly 2000–2010. Typical 5-σ depth is ≈22 ABmag.

Pan-STARRS: Has ≈100 imaging epochs between *grizy* over 3π spanning 2009–2015 (PS1) above δ=−30 deg. Typical 5-σ depth is ≈21.5 ABmag.

LaSilla-QUEST: Has ∼100–2000 visits over ∼10,000 deg^2 of the Southern Hemisphere to 5-σ depth of 21.5 ABmag.

CRTS, ASASSN, ATLAS: These surveys have been operating for ≈5–27 years, employing 0.5–1.5 m diameter telescopes to perform relatively high cadence (hours to several days) but relatively shallow depth (5-σ depth of 18-20 ABmag in relatively broad, non-standard filters) imaging campaigns of the sky.

ZTF: Has imaging in g and r with a roughly 3-day cadence since 2017 over 3π above δ=−30 deg. Typical 5-σ depth is ≈20.5 ABmag.

Gaia: DR3 covers the full sky minus a large Galactic plane exclusion region, in blue, green, and red filters to $G < 21 ABmag, with 30+ epochs between 2014 - -2017$.

DES + NOAO DECam imaging campaigns: DECam has observed a large fraction of the southern sky with a handful of visits in *grizY* between 2014–2021. Individual frames are available from the archive, but no formal lightcurves have been generated.

HSC-SSP Wide: Hyper-Suprime Camera has covered some portions of the southern sky with excellent depth but very shallow cadence.

4.3.2 Deep-Field Datasets

DES/DECam SN and AGN fields: Thousands of visits between 2012–2021 in *ugrizY* to ∼23–24 ABmag. Largely unpublished.

HSC Deep Drilling Fields: TBD

VISTA (ultraVISTA, VIDEOS, VEILS, Euclid Deep Field): TBD

VST dedicated DDF follow-up (VIDEO+VEILS+Euclid Deep Field): Hundreds of epochs to ∼23 ABmag.

4.3.3 Major AGN SC Tasks Ranked by Decreasing Priority

1. (Re)process DECam images in the DDFs using the LSST pipeline to generate difference images and aperture photometry light curves. This is an immensely important legacy time-domain dataset that can effectively double the baseline of many LSST AGN. These data should be published for broader use.
2. Assemble and publish matched NIR light curves from VISTA in the DDFs.
3. Assemble and publish VST light curves in the DDFs.
4. Gather, publish, and homogenize wide-field survey light curves.

4.4 Large Spectroscopic Training Sets

Large spectroscopically confirmed samples of AGN spanning a wide range of magnitudes will be required as training sets to achieve many of the above science goals. Most of the existing datasets primarily cover the bright end, leaving the samples highly unbalanced and biased. Additional planned spectroscopic surveys of LSST WFD and DDFs, such as SDSS-V, DESI, 4MOST, PFS, MOONS, Euclid, and JWST aim to fill various niches in a wedding cake fashion.

SDSS I–V: $\sim 10^6$ QSOs discovered and characterized down to 21 ABmag and $z \sim$6.5, and several 10^5 AGN down to 19 ABmag and $z \sim$0.5. To date, the bulk are in the Northern Hemisphere, and thus will have little spatial overlap with the LSST footprint. This will change once BHM is installed and operational on the Dupont telescope at Las Campanas. SDSS-V will additionally observe ∼1000 AGN with a cadence of ∼3-30 days for ∼5 yr for RM.

DESI: Currently observing, with significant Southern Hemisphere footprint. Expected to observe $\sim 2.4 \times 10^6$ QSOs with $r < 22.7$ plus $\sim 2.5 \times 10^7$ galaxies to $z \sim$1.6. QSOs will be selected via a random forest algorithm.

4MOST: Likely in operation from late 2023, it will target various samples of AGN to $r\sim$22.5 (IR-selected, X-ray selected, variability selected, SED-selected, radio-selected; upwards of $\sim 2.4\times 10^6$ in total). 4MOST will additionally observe ∼1000 AGN with a cadence of ∼14 days during ∼5 yr for RM.

PFS: Targets selected from HSC-SSP over 1000 $\deg^2$ (28 $\deg^2$) for wide (deep) components, aiming to probe the faint end ($M{\sim}-23$) of the QSO population.

MOONS: Focusing on the DDFs, it will target $\sim 10^4$ AGN selected from every method available to H ∼23.

JWST: Extremely deep imaging and spectroscopy on the order of ∼1 $\deg^2$.

4.4.1 Major AGN SC Tasks Ranked by Decreasing Priority

1. Assemble, homogenize, and clean existing spectroscopic datasets that overlap with the eventual LSST footprint.
2. Ensure that a sufficiently large parameter space is being targeted for useful spectroscopy by ongoing and/or upcoming surveys (to the extent that is feasible).

4.5 Concurrent Time-Domain Observations

At the bright end, there are several currently running broadband surveys (e.g., ZTF, Gaia, Catalina Transient Survey, ASASSN, ATLAS, and Everyscope), as well as some interesting upcoming ones (e.g., BlackGEM, and LS4). There remains substantial room to complement the LSST coverage with other filters and/or augmented time coverage. For example, a dedicated VST, DECam, or similar FOV program could ensure that appropriate contemporaneous SEDs are obtained and/or that time gaps are filled.

4.5.1 Major AGN SC Tasks Ranked by Decreasing Priority

1. Identify any missing coverage windows and investigate possible mechanisms to cover them.

4.6 Multiwavelength and Time-Domain Follow-Up Observations

A subset of AGN and related transients will turn out to be time-critical targets that require rapid optical or spectroscopic confirmation and/or faster/complemented cadences. Work needs to be done to understand what resources are required. On relatively long timescales (weeks to months), CLQs and TDEs will be targeted by 4MOST (WFD) and MOONS (DDFs) on a best-effort basis. On shorter timescales, NTT/SOXS and Gemini/SCORPIO will potentially devote some time to such targets. Another subset may require multiwavelength observations.

4.6.1 Major AGN SC Tasks Ranked by Decreasing Priority

1. Identify need and solidify plans for imaging follow-up (e.g., does it require monitoring? Does it require rapid classification? Does it require multiwavelength follow-up?).

2. Identify need and solidify plans for spectroscopic follow-up (e.g., does it require monitoring? Does it require rapid classification?). Possible outlets for this may be SOXS, SCORPIO, and others.
3. Determine how TDEs will be handled.
4. Investigate potential synergies with brokers in terms of use, development, and enhancement.

References

1. LSST Science Collaboration, Abell, P.A., Allison, J., Anderson, S.F., Andrew, J.R., Angel, J.R.P., Armus, L., Arnett, D., Asztalos, S.J., Axelrod, T.S., Bailey, S., Ballantyne, D.R., Bankert, J.R., Barkhouse, W.A., Barr, J.D., Barrientos, L.F., Barth, A.J., Bartlett, J.G., Becker, A.C., Becla, J., Beers, T.C., Bernstein, J.P., Biswas, R., Blanton, M.R., Bloom, J.S., Bochanski, J.J., Boeshaar, P., Borne, K.D., Bradac, M., Brandt, W.N., Bridge, C.R., Brown, M.E., Brunner, R.J., Bullock, J.S., Burgasser, A.J., Burge, J.H., Burke, D.L., Cargile, P.A., Chandrasekharan, S., Chartas, G., Chesley, S.R., Chu, Y.-H., Cinabro, D., Claire, M.W., Claver, C.F., Clowe, D., Connolly, A.J., Cook, K.H., Cooke, J., Cooray, A., Covey, K.R., Culliton, C.S., de Jong, R., de Vries, W.H., Debattista, V.P., Delgado, F., Dell'Antonio, I.P., Dhital, S., Di Stefano, R., Dickinson, M., Dilday, B., Djorgovski, S.G., Dobler, G., Donalek, C., Dubois-Felsmann, G., Durech, J., Eliasdottir, A., Eracleous, M., Eyer, L., Falco, E.E., Fan, X., Fassnacht, C.D., Ferguson, H.C., Fernandez, Y.R., Fields, B.D., Finkbeiner, D., Figueroa, E.E., Fox, D.B., Francke, H., Frank, J.S., Frieman, J., Fromenteau, S., Furqan, M., Galaz, G., Gal-Yam, A., Garnavich, P., Gawiser, E., Geary, J., Gee, P., Gibson, R.R., Gilmore, K., Grace, E.A., Green, R.F., Gressler, W.J., Grillmair, C.J., Habib, S., Haggerty, J.S., Hamuy, M., Harris, A.W., Hawley, S.L., Heavens, A.F., Hebb, L., Henry, T.J., Hileman, E., Hilton, E.J., Hoadley, K., Holberg, J.B., Holman, M.J., Howell, S.B., Infante, L., Ivezic, Z., Jacoby, S.H., Jain, B., R, Jedicke, Jee, M.J., Garrett Jernigan, J., Jha, S.W., Johnston, K.V., Jones, R.L., Juric, M., Kaasalainen, M., Styliani, Kafka, Kahn, S.M., Kaib, N.A., Kalirai, J., Kantor, J., Kasliwal, M.M., Keeton, C.R., Kessler, R., Knezevic, Z., Kowalski, A., Krabbendam, V.L., Krughoff, K.S., Kulkarni, S., Kuhlman, S., Lacy, M., Lepine, S., Liang, M., Lien, A., Lira, P., Long, K.S., Lorenz, S., Lotz, J.M., Lupton, R.H., Lutz, J., Macri, L.M., Mahabal, A.A., Mandelbaum, R., Marshall, P., May, M., McGehee, P.M., Meadows, B.T., Meert, A., Milani, A., Miller, C.J., Miller, M., Mills, D., Minniti, D., Monet, D., Mukadam, A.S., Nakar, E., Neill, D.R., Newman, J.A., Nikolaev, S., Nordby, M., O'Connor, P., Oguri, M., Oliver, J., Olivier, S.S., Olsen, J.K., Olsen, K., Olszewski, E.W., Oluseyi, H., Padilla, N.D., Parker, A., Pepper, J., Peterson, J.R., Petry, C., Pinto, P.A., Pizagno, J.L., Popescu, B., Prsa, A., Radcka, V., Raddick, M.J., Rasmussen, A., Rau, A., Rho, J., Rhoads, J.E., Richards, G.T., Ridgway, S.T., Robertson, B.E., Roskar, R., Saha, A., Sarajedini, A., Scannapieco, E., Schalk, T., Schindler, R., Schmidt, S., Schmidt, S., Schneider, D.P., Schumacher, G., Scranton, R., Sebag, J., Seppala, L.G., Shemmer, O., Simon, J.D., Sivertz, M., Smith, H.A., Allyn Smith, J., Smith, N., Spitz, A.H., Stanford, A., Stassun, K.G., Strader, J., Strauss, M.A., Stubbs, C.W., Sweeney, D.W., Szalay, A., Szkody, P., Takada, M., Thorman, P., Trilling, D.E., Trimble, V., Tyson, A., Van Berg, R., Vanden Berk, D., VanderPlas, J., Verde, L., Vrsnak, B., Walkowicz, L.M., Wandelt, B.D., Wang, S., Wang, Y., Warner, M., Wechsler, R.H., West, A.A., Wiecha, O., Williams, B.F., Willman, B., Wittman, D., Wolff, S.C., Wood-Vasey, W.M., Wozniak, P., Young, P., Zentner, A., and Zhan, H. 2009, **'LSST Science Book, Version 2.0'**, *ArXiv e-prints*, arXiv:0912.0201

2. Arnouts, S. and Ilbert, O. 2011, **'LePHARE: Photometric Analysis for Redshift Estimate'**, *Astrophysics Source Code Library*, ascl:1108.009

3. Artymowicz, P. and Lubow, S.H. 1996, **'Mass Flow through Gaps in Circumbinary Disks'**, *The Astrophysical Journal*, **467**, L77

4. Assef, R.J., Kochanek, C.S., Brodwin, M., Cool, R., Forman, W., Gonzalez, A.H., Hickox, R.C., Jones, C., Le Floc'h, E., Moustakas, J., Murray, S.S., and Stern, D. 2010, **'Low-Resolution Spectral Templates for Active Galactic Nuclei and Galaxies from 0.03 to 30 μm'**, *The Astrophysical Journal*, **713**, 970-985

5. Benítez, N. 2000, **'Bayesian Photometric Redshift Estimation'**, *The Astrophysical Journal*, **536**, 571-583

6. Bianco, F. B., Ivezić, Ž., Jones, R. L., Graham, M. L., Marshall, P., Saha, A., Strauss, M. A., Yoachim, P., Ribeiro, T., Anguita, T., Bauer, A. E., Bauer, F. E., Bellm, E. C., Blum, R. D., Brandt, W. N., Brough, S., Catelan, M., Clarkson, W. I., Connolly, A. J., Gawiser, E., Gizis, J. E., Hložek, R., Kaviraj, S., Liu, C. T., Lochner, M., Mahabal, A. A., Mandelbaum, R., McGehee, P., Neilsen, E. H., Olsen, K. A. G., Peiris, H. V., Rhodes, J., Richards, G. T., Ridgway, S., Schwamb, M. E., Scolnic, D., Shemmer, O., Slater, C. T., Slosar, A., Smartt, S. J., Strader, J., Street, R., Trilling, D. E., Verma, A., Vivas, A. K., Wechsler, R. H., and Willman, B. 2022, **'Optimization of the Observing Cadence for the Rubin Observatory Legacy Survey of Space and Time: A Pioneering Process of Community-focused Experimental Design'**, *The Astrophysical Journal Supplement Series*, **258**, 1

7. Bolzonella, M., Miralles, J.-M., and Pelló, R. 2000, **'Photometric redshifts based on standard SED fitting procedures'**, *Astronomy and Astrophysics*, **363**, 476-492

8. Bonoli, F., Braccesi, A., Federici, L., Zitelli, V., and Formiggini, L. 1979, **'A study of the optical variability of the quasistellar objects in the $13^{\mathrm{h}} + 36^{\circ}$ field. I - The blue magnitudes'**, *Astronomy and Astrophysics Supplement Series*, **35**, 391-401

9. Bovy, J., Hennawi, J.F., Hogg, D.W., Myers, A.D., Kirkpatrick, J.A., Schlegel, D.J., Ross, N.P., Sheldon, E.S., McGreer, I.D., Schneider, D.P., and Weaver, B.A. 2011, **'Think Outside the Color Box: Probabilistic Target Selection and the SDSS-XDQSO Quasar Targeting Catalog'**, *The Astrophysical Journal*, **729**, 141

10. Brescia, M., Salvato, M., Cavuoti, S., Ananna, T.T., Riccio, G., LaMassa, S.M., Urry, C.M., and Longo, G. 2019, **'Photometric redshifts for X-ray-selected active galactic nuclei in the eROSITA era'**, *Monthly Notices of the Royal Astronomical Society*, **489**, 663-680

11. Brodwin, M., Brown, M.J.I., Ashby, M.L.N., Bian, C., Brand, K., Dey, A., Eisenhardt, P.R., Eisenstein, D.J., Gonzalez, A.H., Huang, J.-S., Jannuzi, B.T., Kochanek, C.S., McKenzie, E., Murray, S.S., Pahre, M.A., Smith, H.A., Soifer, B.T., Stanford, S.A., Stern, D., and Elston, R.J. 2006, **'Photometric Redshifts in the IRAC Shallow Survey'**, *The Astrophysical Journal*, **651**, 791-803

12. Buchner, J., Salvato, M., BudavaÌri, T., and Fotopoulou, S. 2021, **'nway: Bayesian cross-matching of astronomical catalogs'**, *Astrophysics Source Code Library*, ascl:2102.014

13. Budavári, T. and Szalay, A.S. 2008, **'Probabilistic Cross-Identification of Astronomical Sources'**, *The Astrophysical Journal*, **679**, 301-309

14. Burke, C.J., Shen, Y., Blaes, O., Gammie, C.F., Horne, K., Jiang, Y.-F., Liu, X., McHardy, I.M., Morgan, C.W., Scaringi, S., and Yang, Q. 2021, **'A characteristic optical variability time scale in astrophysical accretion disks'**, *Science*, **373**, 789-792

15. Butler, N.R. and Bloom, J.S. 2011, **'Optimal Time-series Selection of Quasars'**, *The Astronomical Journal*, **141**, 93

16. Cackett, E.M., Bentz, M.C., and Kara, E. 2021, **'Reverberation mapping of active galactic nuclei: from X-ray corona to dusty torus'**, *iScience*, **24**, 102557

17. Caplar, N., Lilly, S.J., and Trakhtenbrot, B. 2017, **'Optical Variability of AGNs in the PTF/iPTF Survey'**, *The Astrophysical Journal*, **834**, 111

18. Charisi, M., Taylor, S.R., Runnoe, J., Bogdanovic, T., and Trump, J.R. 2022, **'Multimessenger time-domain signatures of supermassive black hole binaries'**, *Monthly Notices of the Royal Astronomical Society*, **510**, 5929-5944

19. Chartas, G., Rhea, C., Kochanek, C., Dai, X., Morgan, C., Blackburne, J., Chen, B., Mosquera, A., and MacLeod, C. 2016, **'Gravitational lensing size scales for quasars'**, *Astronomische Nachrichten*, **337**, 356

20. Chelouche, D., Shemmer, O., Cotlier, G.I., Barth, A.J., and Rafter, S.E. 2014, **'On the Performance of Quasar Reverberation Mapping in the Era of Time-domain Photometric Surveys'**, *The Astrophysical Journal*, **785**, 140

21. Chen, C.-T.J., Brandt, W.N., Luo, B., Ranalli, P., Yang, G., Alexander, D.M., Bauer, F.E., Kelson, D.D., Lacy, M., Nyland, K., Tozzi, P., Vito, F., Cirasuolo, M., Gilli, R., Jarvis, M.J., Lehmer, B.D., Paolillo, M., Schneider, D.P., Shemmer, O., Smail, I., Sun, M., Tanaka, M., Vaccari, M., Vignali, C., Xue, Y.Q., Banerji, M., Chow, K.E., Häußler, B., Norris, R.P., Silverman, J.D., and Trump, J.R. 2018, **'The XMM-SERVS survey: new XMM-Newton point-source catalogue for the XMM-LSS field'**, *Monthly Notices of the Royal Astronomical Society*, **478**, 2132-2163

22. Čvorović-Hajdinjak, I., Kovačević, A.B., Ilić, D., Popović, L.Č., Dai, X., Jankov, I., Radović, V., Sánchez-Sáez, P., and Nikutta, R. 2022, **'Conditional Neural Process for nonparametric modeling of active galactic nuclei light curves'**, *Astronomische Nachrichten*, **343**, e210103

23. Dexter, J. and Agol, E. 2011, **'Quasar Accretion Disks are Strongly Inhomogeneous'**, *The Astrophysical Journal*, **727**, L24

24. Edelson, R., Gelbord, J.M., Horne, K., McHardy, I.M., Peterson, B.M., Arévalo, P., Breeveld, A.A., De Rosa, G., Evans, P.A., Goad, M.R., Kriss, G.A., Brandt, W.N., Gehrels, N., Grupe, D., Kennea, J.A., Kochanek, C.S., Nousek, J.A., Papadakis, I., Siegel, M., Starkey, D., Uttley, P., Vaughan, S., Young, S., Barth, A.J., Bentz, M.C., Brewer, B.J., Crenshaw, D.M., Dalla Bontà, E., De Lorenzo-Cáceres, A., Denney, K.D., Dietrich, M., Ely, J., Fausnaugh, M.M., Grier, C.J., Hall, P.B., Kaastra, J., Kelly, B.C., Korista, K.T., Lira, P., Mathur, S., Netzer, H., Pancoast, A., Pei, L., Pogge, R.W., Schimoia, J.S., Treu, T., Vestergaard, M., Villforth, C., Yan, H., and Zu, Y. 2015, **'Space Telescope and Optical Reverberation Mapping Project. II. Swift and HST Reverberation Mapping of the Accretion Disk of NGC 5548'**, *The Astrophysical Journal*, **806**, 129

25. Feigelson, E.D. and Babu, G.J. 2012, **'Modern Statistical Methods for Astronomy'**, *Modern Statistical Methods for Astronomy, by Eric D. Feigelson, G. Jogesh Babu, Cambridge, UK: Cambridge University Press, 2012*

26. Goyal, A., Stawarz, Ł., Ostrowski, M., Larionov, V., Gopal-Krishna, Wiita, P.J., Joshi, S., Soida, M., and Agudo, I. 2017, **'Multiwavelength Variability Study of the Classical BL Lac Object PKS 0735+178 on Timescales Ranging from Decades to Minutes'**, *The Astrophysical Journal*, **837**, 127

27. Graham, M.J., Djorgovski, S.G., Drake, A.J., Mahabal, A.A., Chang, M., Stern, D., Donalek, C., and Glikman, E. 2014, **'A novel variability-based method for quasar selection: evidence for a rest-frame ∼54 d characteristic time-scale'**, *Monthly Notices of the Royal Astronomical Society*, **439**, 703-718

28. Graham, M.J., Djorgovski, S.G., Stern, D., Drake, A.J., Mahabal, A.A., Donalek, C., Glikman, E., Larson, S., and Christensen, E. 2015a, **'A systematic search for close supermassive black hole binaries in the Catalina Real-time Transient Survey'**, *Monthly Notices of the Royal Astronomical Society*, **453**, 1562-1576

29. Graham, M.J., Djorgovski, S.G., Stern, D., Glikman, E., Drake, A.J., Mahabal, A.A., Donalek, C., Larson, S., and Christensen, E. 2015b, **'A possible close supermassive black-hole binary in a quasar with optical periodicity'**, *Nature*, **518**, 74-76

30. Graham, M.J., Djorgovski, S.G., Drake, A.J., Stern, D., Mahabal, A.A., Glikman, E., Larson, S., and Christensen, E. 2017, **'Understanding extreme quasar optical variability with CRTS - I. Major AGN flares'**, *Monthly Notices of the Royal Astronomical Society*, **470**, 4112-4132

31. Hernández Santisteban, J.V., Edelson, R., Horne, K., Gelbord, J.M., Barth, A.J., Cackett, E.M., Goad, M.R., Netzer, H., Starkey, D., Uttley, P., Brandt, W.N., Korista, K., Lohfink, A.M., Onken, C.A., Page, K.L., Siegel, M., Vestergaard, M., Bisogni, S., Breeveld, A.A., Cenko, S.B., Dalla Bontà, E., Evans, P.A., Ferland, G., Gonzalez-Buitrago, D.H., Grupe, D., Joner, M.D., Kriss, G., LaPorte, S.J., Mathur, S., Marshall, F., Mehdipour, M., Mudd, D., Peterson, B.M., Schmidt, T., Vaughan, S., and Valenti, S. 2020, **'Intensive disc-reverberation mapping of Fairall 9: first year of Swift**

and LCO monitoring', *Monthly Notices of the Royal Astronomical Society*, **498**, 5399-5416

32. Ilbert, O., Capak, P., Salvato, M., Aussel, H., McCracken, H.J., Sanders, D.B., Scoville, N., Kartaltepe, J., Arnouts, S., Le Floc'h, E., Mobasher, B., Taniguchi, Y., Lamareille, F., Leauthaud, A., Sasaki, S., Thompson, D., Zamojski, M., Zamorani, G., Bardelli, S., Bolzonella, M., Bongiorno, A., Brusa, M., Caputi, K.I., Carollo, C.M., Contini, T., Cook, R., Coppa, G., Cucciati, O., de la Torre, S., de Ravel, L., Franzetti, P., Garilli, B., Hasinger, G., Iovino, A., Kampczyk, P., Kneib, J.-P., Knobel, C., Kovac, K., Le Borgne, J.F., Le Brun, V., Le Fèvre, O., Lilly, S., Looper, D., Maier, C., Mainieri, V., Mellier, Y., Mignoli, M., Murayama, T., Pellò, R., Peng, Y., Pérez-Montero, E., Renzini, A., Ricciardelli, E., Schiminovich, D., Scodeggio, M., Shioya, Y., Silverman, J., Surace, J., Tanaka, M., Tasca, L., Tresse, L., Vergani, D., and Zucca, E. 2009, **'Cosmos Photometric Redshifts with 30-Bands for 2-deg^2'**, *The Astrophysical Journal*, **690**, 1236-1249

33. Jiang, Y.-F., Green, P.J., Greene, J.E., Morganson, E., Shen, Y., Pancoast, A., MacLeod, C.L., Anderson, S.F., Brandt, W.N., Grier, C.J., Rix, H.-W., Ruan, J.J., Protopapas, P., Scott, C., Burgett, W.S., Hodapp, K.W., Huber, M.E., Kaiser, N., Kudritzki, R.P., Magnier, E.A., Metcalfe, N., Tonry, J.T., Wainscoat, R.J., and Waters, C. 2017, **'Detection of Time Lags between Quasar Continuum Emission Bands Based On Pan-STARRS Light Curves'**, *The Astrophysical Journal*, **836**, 186

34. Jiang, Y.-F. and Blaes, O. 2020, **'Opacity-driven Convection and Variability in Accretion Disks around Supermassive Black Holes'**, *The Astrophysical Journal*, **900**, 25

35. Kaczmarczik, M.C., Richards, G.T., Mehta, S.S., and Schlegel, D.J. 2009, **'Astrometric Redshifts for Quasars'**, *The Astronomical Journal*, **138**, 19-27

36. Kasliwal, V.P., Vogeley, M.S., and Richards, G.T. 2015, **'Are the variability properties of the Kepler AGN light curves consistent with a damped random walk?'**, *Monthly Notices of the Royal Astronomical Society*, **451**, 4328-4345

37. Kasliwal, V.P., Vogeley, M.S., and Richards, G.T. 2017, **'Extracting information from AGN variability'**, *Monthly Notices of the Royal Astronomical Society*, **470**, 3027-3048

38. Keel, W.C., Lintott, C.J., Maksym, W.P., Bennert, V.N., Chojnowski, S.D., Moiseev, A., Smirnova, A., Schawinski, K., Sartori, L.F., Urry, C.M., Pancoast, A., Schirmer, M., Scott, B., Showley, C., and Flatland, K. 2017, **'Fading AGN Candidates: AGN Histories and Outflow Signatures'**, *The Astrophysical Journal*, **835**, 256

39. Kelley, L.Z., Haiman, Z., Sesana, A., and Hernquist, L. 2019, **'Massive BH binaries as periodically variable AGN'**, *Monthly Notices of the Royal Astronomical Society*, **485**, 1579-1594

40. Kelley, L.Z., D'Orazio, D.J., and Di Stefano, R. 2021, **'Gravitational self-lensing in populations of massive black hole binaries'**, *Monthly Notices of the Royal Astronomical Society*, **508**, 2524-2536

41. Kelly, B.C., Bechtold, J., and Siemiginowska, A. 2009, **'Are the Variations in Quasar Optical Flux Driven by Thermal Fluctuations?'**, *The Astrophysical Journal*, **698**, 895-910

42. Kelly, B.C., Sobolewska, M., and Siemiginowska, A. 2011, **'A Stochastic Model for the Luminosity Fluctuations of Accreting Black Holes'**, *The Astrophysical Journal*, **730**, 52

43. Koo, D.C. and Kron, R.G. 1982, **'QSO counts - A complete survey of stellar objects to B = 23'**, *Astronomy and Astrophysics*, **105**, 107-119

44. Koo, D.C., Kron, R.G., and Cudworth, K.M. 1986, **'Quasars to B greater than 22.5 in selected area 57 - A catalog of multicolor photometry, variability, and astrometry'**, *Publications of the Astronomical Society of the Pacific*, **98**, 285-306

45. Kovačević, A.B., Pérez-Hernández, E., Popović, L.Č., Shapovalova, A.I., Kollatschny, W., and Ilić, D. 2018, **'Oscillatory patterns in the light curves of five long-term monitored type 1 active galactic nuclei'**, *Monthly Notices of the Royal Astronomical Society*, **475**, 2051-2066

46. Kozłowski, S. 2016, **'Revisiting Stochastic Variability of AGNs with Structure Functions'**, *The Astrophysical Journal*, **826**, 118

47. Kron, R.G. and Chiu, L.-T.G. 1981, **'Stars with zero proper motion and the number of faint QSOs'**, *Publications of the Astronomical Society of the Pacific*, **93**, 397-404

48. LaMassa, S.M., Cales, S., Moran, E.C., Myers, A.D., Richards, G.T., Eracleous, M., Heckman, T.M., Gallo, L., and Urry, C.M. 2015, **'The Discovery of the First "Changing Look" Quasar: New Insights Into the Physics and Phenomenology of Active Galactic Nucleus'**, *The Astrophysical Journal*, **800**, 144

49. Lawrence, A. 2016a, **'Clues to the Structure of AGN Through Massive Variability Surveys'**, *Astronomical Surveys and Big Data*, **505**, 107

50. Lawrence, A., Bruce, A.G., MacLeod, C., Gezari, S., Elvis, M., Ward, M., Smartt, S.J., Smith, K.W., Wright, D., Fraser, M., Marshall, P., Kaiser, N., Burgett, W., Magnier, E., Tonry, J., Chambers, K., Wainscoat, R., Waters, C., Price, P., Metcalfe, N., Valenti, S., Kotak, R., Mead, A., Inserra, C., Chen, T.W., and Soderberg, A. 2016b, **'Slow-blue nuclear hypervariables in PanSTARRS-1'**, *Monthly Notices of the Royal Astronomical Society*, **463**, 296-331

51. Liu, T., Gezari, S., Heinis, S., Magnier, E.A., Burgett, W.S., Chambers, K., Flewelling, H., Huber, M., Hodapp, K.W., Kaiser, N., Kudritzki, R.-P., Tonry, J.L., Wainscoat,

R.J., and Waters, C. 2015, **'A Periodically Varying Luminous Quasar at z = 2 from the Pan-STARRS1 Medium Deep Survey: A Candidate Supermassive Black Hole Binary in the Gravitational Wave-driven Regime'**, *The Astrophysical Journal*, **803**, L16

52. Lyubarskii, Y.E. 1997, **'Flicker noise in accretion discs'**, *Monthly Notices of the Royal Astronomical Society*, **292**, 679

53. Mahabal, A., Sheth, K., Gieseke, F., Pai, A., Djorgovski, S.G., Drake, A., Graham, M., and the CSS/CRTS/PTF Collaboration 2017, **'Deep-Learnt Classification of Light Curves'**, *ArXiv e-prints*, arXiv:1709.06257

54. LSST Science Collaboration, Marshall, P., Anguita, T., Bianco, F.B., Bellm, E.C., Brandt, N., Clarkson, W., Connolly, A., Gawiser, E., Ivezic, Z., Jones, L., Lochner, M., Lund, M.B., Mahabal, A., Nidever, D., Olsen, K., Ridgway, S., Rhodes, J., Shemmer, O., Trilling, D., Vivas, K., Walkowicz, L., Willman, B., Yoachim, P., Anderson, S., Antilogus, P., Angus, R., Arcavi, I., Awan, H., Biswas, R., Bell, K.J., Bennett, D., Britt, C., Buzasi, D., Casetti-Dinescu, D.I., Chomiuk, L., Claver, C., Cook, K., Davenport, J., Debattista, V., Digel, S., Doctor, Z., Firth, R.E., Foley, R., Fong, W.-f., Galbany, L., Giampapa, M., Gizis, J.E., Graham, M.L., Grillmair, C., Gris, P., Haiman, Z., Hartigan, P., Hawley, S., Hlozek, R., Jha, S.W., Johns-Krull, C., Kanbur, S., Kalogera, V., Kashyap, V., Kasliwal, V., Kessler, R., Kim, A., Kurczynski, P., Lahav, O., Liu, M.C., Malz, A., Margutti, R., Matheson, T., McEwen, J.D., McGehee, P., Meibom, S., Meyers, J., Monet, D., Neilsen, E., Newman, J., O'Dowd, M., Peiris, H.V., Penny, M.T., Peters, C., Poleski, R., Ponder, K., Richards, G., Rho, J., Rubin, D., Schmidt, S., Schuhmann, R.L., Shporer, A., Slater, C., Smith, N., Soares-Santos, M., Stassun, K., Strader, J., Strauss, M., Street, R., Stubbs, C., Sullivan, M., Szkody, P., Trimble, V., Tyson, T., de Val-Borro, M., Valenti, S., Wagoner, R., Wood-Vasey, W.M., and Zauderer, B.A. 2017, **'Science-Driven Optimization of the LSST Observing Strategy'**, *ArXiv e-prints*, arXiv:1708.04058

55. Morgan, C.W., Kochanek, C.S., Morgan, N.D., and Falco, E.E. 2010, **'The Quasar Accretion Disk Size-Black Hole Mass Relation'**, *The Astrophysical Journal*, **712**, 1129-1136

56. Mosquera, A.M., Kochanek, C.S., Chen, B., Dai, X., Blackburne, J.A., and Chartas, G. 2013, **'The Structure of the X-Ray and Optical Emitting Regions of the Lensed Quasar Q 2237+0305'**, *The Astrophysical Journal*, **769**, 53

57. Ni, Q., Brandt, W. N., Chen, C.-T., Luo, B., Nyland, K., Yang, G., Zou, F., Aird, J., Alexander, D. M., Bauer, F. E., Lacy, M., Lehmer, B. D., Mallick, L., Salvato, M., Schneider, D. P., Tozzi, P., Traulsen, I., Vaccari, M., Vignali, C., Vito, F., Xue, Y., Banerji, M., Chow, K., Comastri, A., Del Moro, A., Gilli, R., Mullaney, J., Paolillo, M., Schwope, A., Shemmer, O., Sun, M., Timlin, J. D., and Trump, J. R. 2021, **'The XMM-SERVS Survey: XMM-Newton Point-source Catalogs for the W-CDF-S and ELAIS-S1 Fields'**, *The Astrophysical Journal Supplement Series*, **256**, 21

58. Peters, C.M., Richards, G.T., Myers, A.D., Strauss, M.A., Schmidt, K.B., Ivezić, Ž., Ross, N.P., MacLeod, C.L., and Riegel, R. 2015, **'Quasar Classification Using Color and Variability'**, *The Astrophysical Journal*, **811**, 95

59. Rafikov, R.R. 2013, **'Structure and Evolution of Circumbinary Disks around Supermassive Black Hole Binaries'**, *The Astrophysical Journal*, **774**, 144

60. Richards, G.T., Fan, X., Newberg, H.J., Strauss, M.A., Vanden Berk, D.E., Schneider, D.P., Yanny, B., Boucher, A., Burles, S., Frieman, J.A., Gunn, J.E., Hall, P.B., Ivezić, Ž., Kent, S., Loveday, J., Lupton, R.H., Rockosi, C.M., Schlegel, D.J., Stoughton, C., SubbaRao, M., and York, D.G. 2002, **'Spectroscopic Target Selection in the Sloan Digital Sky Survey: The Quasar Sample'**, *The Astronomical Journal*, **123**, 2945-2975

61. Richards, G.T., Nichol, R.C., Gray, A.G., Brunner, R.J., Lupton, R.H., Vanden Berk, D.E., Chong, S.S., Weinstein, M.A., Schneider, D.P., Anderson, S.F., Munn, J.A., Harris, H.C., Strauss, M.A., Fan, X., Gunn, J.E., Ivezić, Ž., York, D.G., Brinkmann, J., and Moore, A.W. 2004, **'Efficient Photometric Selection of Quasars from the Sloan Digital Sky Survey: 100,000 $z < 3$ Quasars from Data Release One'**, *The Astrophysical Journal Supplement Series*, **155**, 257-269

62. Richards, G.T., Myers, A.D., Gray, A.G., Riegel, R.N., Nichol, R.C., Brunner, R.J., Szalay, A.S., Schneider, D.P., and Anderson, S.F. 2009, **'Efficient Photometric Selection of Quasars from the Sloan Digital Sky Survey. II. ~1,000,000 Quasars from Data Release 6'**, *The Astrophysical Journal Supplement Series*, **180**, 67-83

63. Rowan-Robinson, M., Babbedge, T., Oliver, S., Trichas, M., Berta, S., Lonsdale, C., Smith, G., Shupe, D., Surace, J., Arnouts, S., Ilbert, O., Le Févre, O., Afonso-Luis, A., Perez-Fournon, I., Hatziminaoglou, E., Polletta, M., Farrah, D., and Vaccari, M. 2008, **'Photometric redshifts in the SWIRE Survey'**, *Monthly Notices of the Royal Astronomical Society*, **386**, 697-714

64. Ruan, J.J., Anderson, S.F., Dexter, J., and Agol, E. 2014, **'Evidence for Large Temperature Fluctuations in Quasar Accretion Disks from Spectral Variability'**, *The Astrophysical Journal*, **783**, 105

65. Runnoe, J.C., Cales, S., Ruan, J.J., Eracleous, M., Anderson, S.F., Shen, Y., Green, P.J., Morganson, E., LaMassa, S., Greene, J.E., Dwelly, T., Schneider, D.P., Merloni, A., Georgakakis, A., and Roman-Lopes, A. 2016, **'Now you see it, now you don't: the disappearing central engine of the quasar J1011+5442'**, *Monthly Notices of the Royal Astronomical Society*, **455**, 1691-1701

66. Salvato, M., Hasinger, G., Ilbert, O., Zamorani, G., Brusa, M., Scoville, N.Z., Rau, A., Capak, P., Arnouts, S., Aussel, H., Bolzonella, M., Buongiorno, A., Cappelluti, N., Caputi, K., Civano, F., Cook, R., Elvis, M., Gilli, R., Jahnke, K., Kartaltepe, J.S., Impey, C.D., Lamareille, F., Le Floc'h, E., Lilly, S., Mainieri, V., McCarthy, P., McCracken, H., Mignoli, M., Mobasher, B., Murayama, T., Sasaki, S., Sanders,

D.B., Schiminovich, D., Shioya, Y., Shopbell, P., Silverman, J., Smolčić, V., Surace, J., Taniguchi, Y., Thompson, D., Trump, J.R., Urry, M., and Zamojski, M. 2009, **'Photometric Redshift and Classification for the XMM-COSMOS Sources'**, *The Astrophysical Journal*, **690**, 1250-1263

67. Salvato, M., Ilbert, O., and Hoyle, B. 2019, **'The many flavours of photometric redshifts'**, *Nature Astronomy*, **3**, 212-222

68. Salvato, M., Wolf, J., Dwelly, T., et al. 2022, **'The eROSITA Final Equatorial-Depth Survey (eFEDS). Identification and characterization of the counterparts to point-like sources'**, *Astronomy & Astrophysics*, **661**, A3

69. Sánchez-Sáez, P., Lira, P., Mejía-Restrepo, J., Ho, L.C., Arévalo, P., Kim, M., Cartier, R., and Coppi, P. 2018, **'The QUEST-La Silla AGN Variability Survey: Connection between AGN Variability and Black Hole Physical Properties'**, *The Astrophysical Journal*, **864**, 87

70. Sánchez-Sáez, P., Lira, H., Martí, L., Sánchez-Pi, N., Arredondo, J., Bauer, F.E., Bayo, A., Cabrera-Vives, G., Donoso-Oliva, C., Estévez, P.A., Eyheramendy, S., Förster, F., Hernández-García, L., Arancibia, A.M.M., Pérez-Carrasco, M., Sepúlveda, M., and Vergara, J.R. 2021, **'Searching for Changing-state AGNs in Massive Data Sets. I. Applying Deep Learning and Anomaly-detection Techniques to Find AGNs with Anomalous Variability Behaviors'**, *The Astronomical Journal*, **162**, 206

71. Sandage, A. and Luyten, W.J. 1967, **'On the Nature of Faint Blue Objects in High Galactic Latitudes. I. Photometry, Proper Motions, and Spectra in PHL Field 1:36+6° and Richter Field M3, II'**, *The Astrophysical Journal*, **148**, 767

72. Schmidt, K.B., Rix, H.-W., Shields, J.C., Knecht, M., Hogg, D.W., Maoz, D., and Bovy, J. 2012, **'The Color Variability of Quasars'**, *The Astrophysical Journal*, **744**, 147

73. Tachibana, Y., Graham, M.J., Kawai, N., Djorgovski, S.G., Drake, A.J., Mahabal, A.A., and Stern, D. 2020, **'Deep Modeling of Quasar Variability'**, *The Astrophysical Journal*, **903**, 54

74. Temple, M.J., Hewett, P.C., and Banerji, M. 2021, **'Modelling type-1 quasar colours in the era of Rubin and Euclid'**, *Monthly Notices of the Royal Astronomical Society*, **508**, 737-754

75. Trakhtenbrot, B., Arcavi, I., Ricci, C., Tacchella, S., Stern, D., Netzer, H., Jonker, P.G., Horesh, A., Mejía-Restrepo, J.E., Hosseinzadeh, G., Hallefors, V., Howell, D.A., McCully, C., Baloković, M., Heida, M., Kamraj, N., Lansbury, G.B., Wyrzykowski, Ł., Gromadzki, M., Hamanowicz, A., Cenko, S.B., Sand, D.J., Hsiao, E.Y., Phillips, M.M., Diamond, T.R., Kara, E., Gendreau, K.C., Arzoumanian, Z., and Remillard, R.

2019, **'A new class of flares from accreting supermassive black holes'**, *Nature Astronomy*, **3**, 242-250

76. Trevese, D., Pittella, G., Kron, R.G., Koo, D.C., and Bershady, M. 1989, **'A survey for faint variable objects in SA 57'**, *The Astronomical Journal*, **98**, 108-116

77. VanderPlas, J.T. 2018, **'Understanding the Lomb-Scargle Periodogram'**, *The Astrophysical Journal Supplement Series*, **236**, 16

78. Vaughan, S., Uttley, P., Markowitz, A.G., Huppenkothen, D., Middleton, M.J., Alston, W.N., Scargle, J.D., and Farr, W.M. 2016, **'False periodicities in quasar time-domain surveys'**, *Monthly Notices of the Royal Astronomical Society*, **461**, 3145-3152

79. Wang, Y., Jiang, N., Wang, T., Zhu, J., Dou, L., Lin, Z., Sun, L., Liu, H., and Sheng, Z. 2022, **'Discovery of ATLAS17jrp as an Optical-, X-Ray-, and Infrared-bright Tidal Disruption Event in a Star-forming Galaxy'**, *The Astrophysical Journal*, **930**, L4

80. Warren, S.J., Hewett, P.C., Irwin, M.J., and Osmer, P.S. 1991, **'A wide-field multi-color survey for high-redshift quasars, $z > 2.2$. I - Photometric catalog and survey selection function'**, *The Astrophysical Journal Supplement Series*, **76**, 1-22

81. Weinstein, M.A., Richards, G.T., Schneider, D.P., Younger, J.D., Strauss, M.A., Hall, P.B., Budavári, T., Gunn, J.E., York, D.G., and Brinkmann, J. 2004, **'An Empirical Algorithm for Broadband Photometric Redshifts of Quasars from the Sloan Digital Sky Survey'**, *The Astrophysical Journal Supplement Series*, **155**, 243-256

82. Xin, C. and Haiman, Z. 2021, **'Ultra-short-period massive black hole binary candidates in LSST as LISA 'verification binaries''**, *Monthly Notices of the Royal Astronomical Society*, **506**, 2408-2417

83. Zheng, Z.-Y., Butler, N.R., Shen, Y., Jiang, L., Wang, J.-X., Chen, X., and Cuadra, J. 2016, **'SDSS J0159+0105: A Radio-Quiet Quasar with a Centi-Parsec Supermassive Black Hole Binary Candidate'**, *The Astrophysical Journal*, **827**, 56

84. Zhu, F.-F., Wang, J.-X., Cai, Z.-Y., and Sun, Y.-H. 2016, **'The Timescale-dependent Color Variability of Quasars Viewed with /GALEX'**, *The Astrophysical Journal*, **832**, 75

85. Zinn, J.C., Kochanek, C.S., Kozłowski, S., Udalski, A., Szymański, M.K., Soszyński, I., Wyrzykowski, Ł., Ulaczyk, K., Poleski, R., Pietrukowicz, P., Skowron, J., Mróz, P., and Pawlak, M. 2017, **'Variable classification in the LSST era: exploring a model for quasi-periodic light curves'**, *Monthly Notices of the Royal Astronomical Society*, **468**, 2189-2205

86. Zou, F., Brandt, W.N., Chen, C.-T., Leja, J., Ni, Q., Yan, W., Yang, G., Zhu, S., Luo, B., Nyland, K., Vito, F., and Xue, Y. 2022, **'Spectral Energy Distributions in Three Deep-Drilling Fields of the Vera C. Rubin Observatory Legacy Survey of Space and Time: Source Classification and Galaxy Properties'**, *arXiv e-prints*, arXiv:2206.06432