Rationale for DD-ERS Program

We have identified a population of mid-infrared bright quasars at the peak of cosmological quasar activity. Their global star-formation properties are currently unknown, but observations with JWST MIRI, and in particular MRS spectroscopy, will quantify the level of star-formation in these objects. These observations will address the fundamental question of the link between star-formation and AGN activity, at the cosmological epoch for both of these processess; an investigation JWST was specifically built for.

Moreover, we have already begun to design and create science-enabling products (SEPs) to help the community understand JWST's capabilities, Our `MIRI MRS Code Repo` is already active and completely accessible to anyone in the broader community. We will deliver the MIRI MRS SEPs first with mock data before the launch of JWST, and then in rapid fashion once the start of science operations commences in April 2019. Our teams commitment to an open access ideology, not only for data, but for analysis codes, documentation, and scientific manuscripts is already evident and in place (for an example, see `the P.I.'s GitHub`). We aim to engage a broad cross-section of the astronomical community, in particular the extra-galactic community, in familiarizing themselves with JWST data and its scientific capabilities.

Here we initially outline the Scientific and Community Access rationale, and proceed to give details of the Scientific Justification and why our quasars are the ideal ERS targets. Details of our observations are given in the Technical Description. *In brief, we will observe four quasars with MIRI MRS across the full wavelength range. The exposure time for each object is 12,912 seconds, and our entire program (with APT Smart Accounting invoked) is 22.20 hours.* We do not have any special observational requirements, nor any Coordinated Parallel Observations. We give more details of our plan to deliver the SEPs in the Data Processing & Analysis Plan section. This includes a list of analysis code modules we will develop, how the community can rapidly access our findings and technical notes, and the breakdown of who in the Core Analysis Team is going to do what.

Science Rationale

Over 50 years after their formal identification, and over two decades since the calculation of their space density evolution, several fundamental facts remain unknown for high-luminosity AGN, i.e. quasars: What is the main AGN triggering mechanism at the height of quasar activity at redshifts $z = 2-3$? What direct, observational evidence in individual objects links AGN activity to star formation? Can we observe "AGN feedback" in action, in situ, for the most luminous sources at their peak activity? These remain the outstanding observational extragalactic questions of our time. And they will be answered with the launch of the *James Webb Space Telescope*.

The recently identified Extremely Red Quasar (ERQ) objects are a unique obscured quasar population with extreme physical conditions related to powerful outflows across the line-forming regions. These objects are found at the same cosmological epoch as the peak of quasar activity, $z \approx 2.5$, and are the best candidates to date to show outflows on galactic scales in high-luminosity objects at these epochs; we are seeing quasar-level AGN feedback in action, in situ.

With our ERS MIRI observations of these ERQ, so called since they are bright in the WISE W4 23μm band, we will deliver all the tools necessary to the community in order to optimize Cycle 2 proposals of 5-30μm milliJansky bright sources. This is *a fundamental tool* for the exploitation of a key MIRI instrument mode.

The Medium-Resolution Spectrometer: The JWST MIRI medium-resolution spectrometer (MRS; Wells et al. 2015) will observe simultaneous spatial and spectral information between 4.9 and 28.8 μm over a contiguous field of view up to 7.2" 7.9" in size. This is the only JWST configuration offering medium-resolution spectroscopy (with $R \approx$1500-3500) longward of 5.2 μm. MRS observations are carried out using a set of 4 integral field units (IFUs), each of which covers a different portion of the MIRI wavelength range. MRS IFUs split the field of view into spatial slices, each of which produces a separate dispersed "long-slit" spectrum. Post-processing produces a composite 3-dimensional (2 spatial and one spectral dimension) data cube combining the information from each of these spatial slices. *This IFU aspect of the Medium Resolution Spectrometer will allow, for the first time, detailed investigations of the both the central AGN IR emission and potentially extended emission.*

Community Access Rationale

We will satisfy the Goals and Principles of the DD ERS program by: ensuring open access to our datasets in support of the preparation of Cycle 2 proposals, and, engaging a broad cross-section of the astronomical community, in particular the extragalactic community, in familiarizing themselves with JWST data and scientific capabilities.
In particular, we aim to produce several key science products:

- `mrs_analyzer` A Python module for analyzing MRS data;
- `mrsfringe` A Python module for mitigating MRS fringing issues;
- a suite of science results on quasar feedback and evolution.

Critically, we have already begun working closely with the MIRI team (due to the P.I.'s location at Edinburgh) and will continue to develop tools here for the MIRI Imager and MRS. We will produce of SEP analysis code and documentation. However, the 7 month period between the end of commissioning and Cycle 2 proposal deadlines will be too short for dissemination of our findings, novel techniques and potentially even science results in the traditional manner (via journals). Moreover, ongoing updated versions of our analyses are envisaged to happen until right up to the Cycle 2 deadline. To solve these issues, we will fully employ the power of a code version repository system, in our case GitHub, to keep the community informed and updated with or SEPs. GitHu *has code versioning automatically built-in* so proper referencing of e.g. technical notes is straight-forward.

■ Scientific Justification

One lasting scientific legacy of the *Hubble Space Telescope (HST)* will be the discovery of giant black holes at the centers of galaxies, confirming the longstanding theory of the "central engines" of quasars. One of the major surprises from the *Hubble* was the discovery of a correlation between black hole mass and host galaxy properties.[1] This connection, causal or otherwise, may provide crucial clues to how and why these black holes formed and how their host galaxies evolved. *As of the launch of the James Webb Space Telescope (JWST), the question of how black holes affect their host galaxies is one of the outstanding questions in astrophysics.*

Observational and theoretical work now suggests that active galaxies and black holes are potentially linked to both the triggering, and "quenching", of massive star formation. The link between massive galaxies and the central super-massive black holes (SMBHs) that seem ubiquitous in them is now thought to be vital to the understanding of galaxy formation and evolution ([1], [2]), and huge observational and theoretical effort has been invested in trying to measure and understand the physics involved in these enigmatic systems. The two main energy sources available to a galaxy are nuclear fusion in stars and gravitational accretion onto compact objects, and we still do not fully understand the interaction of an active galactic nuclei and the star formation properties of their host galaxies, *especially at the epoch of maximal cosmic SFR and quasar activity, redshifts* $z \sim 1 - 3$.

The "quenching" of galaxy-wide star formation, is supposedly driven by " AGN feedback", where the AGN helps to heat the surrounding gas corona, offsetting cooling losses and disrupting the gas inflow. This feedback manifests itself as high-velocity outflows from the AGN/quasar. However, *direct observational evidence* for AGN feedback is conspicuous by its absence. This is especially true at high-z, e.g. $z = 2 - 3$, at the height of the Quasar Epoch. We have identified the best candidates that suggest we are seeing quasar feedback in action, in situ at high-redshift. These are the "Extremely Red Quasars" identified via their WISE W3/4 colors. As such, these mJy luminous AGN *are ideal targets for JWST MIRI.*

The Extremely Red Quasar Population: By matching the quasar catalogues of the Sloan Digital Sky Survey (SDSS), the Baryon Oscillation Spectroscopic Survey (BOSS) to the Wide-Field Infrared Survey Explorer (WISE), Ross et al. (2015) discovered quasars with extremely red infrared-to-optical colors: $r_{\rm AB} - W4_{\rm Vega} > 14$ mag, i.e., $F_\nu(22\mu{\rm m})/F_\nu(r) \gtrsim 1000$; see Figure 1. These objects have infrared luminosities $\sim 10^{47}$ erg s^{-1}. The original motivation here was to look for PAHs that had redshifted in the WISE W4 band for $z \approx 2.5$ quasars in order to study and link luminous AGN activity and star formation at the "height of the quasar epoch".

[1]Assessment of Options for Extending the Life of the Hubble Space Telescope: Final Report (2005); https://www.nap.edu/read/11169/chapter/5).

Hamann et al. (2017) then fully and properly refined the selection of the ERQs, homing the definition based on further analysis and common properties, and indeed found many more objects in this new scheme. The ERQs have a suite of peculiar emission-line properties including large rest equivalent widths (REWs), unusual "wingless" line profiles, large N V/Lyα, N V/C IV, Si IV/C IV and other flux ratios, and very broad and blueshifted [O III] λ5007 (e.g. spectrum in Figure 1).

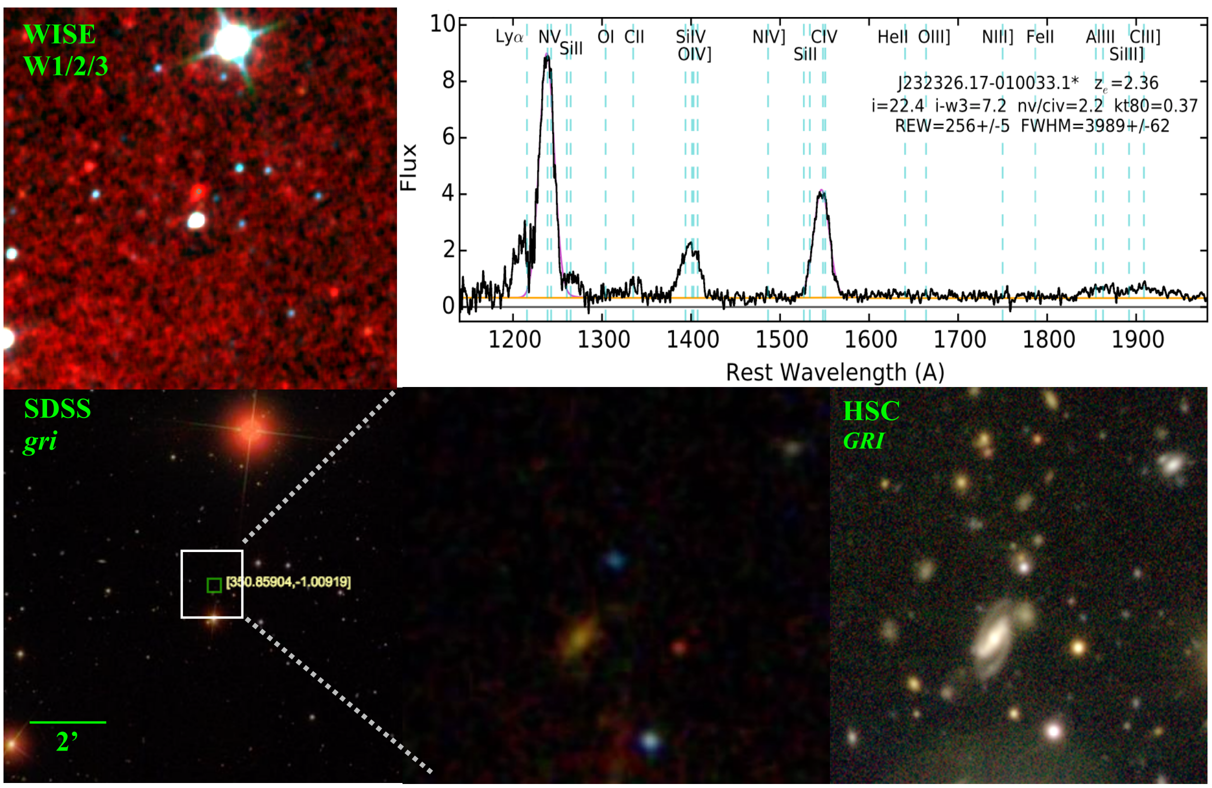

Figure 1. IR and optical imaging of J2323-0100, one of the four Extremely Red Quasar ERS targets. WISE (*top left*), SDSS (*bottom left*) with zoom-in (*bottom center*) and new HSC imaging (*bottom right*). The UV-rest frame spectrum (from Hamann et al. 2017) is given in the top right. Emission lines are labelled at positions marked by dashed blue lines. Note the unusual line flux ratios e.g., N V>Lyα and large N V /C IV. The orange and magenta curves show our fits to the continuum, and the C IV and N V emission lines, respectively. The redshift and other measured properties are also given.

Our team identified a "core" sample of 97 ERQs with nearly uniform peculiar properties selected via i–$W3 \geq 4.6$ (AB) and REW(C IV) $\geq$ 100 Å at redshifts 2.0–3.4. The core ERQs have median luminosity $\langle \log L(\text{ergs/s}) \rangle \sim 47.1$, sky density 0.010 deg^{-2}, surprisingly flat/blue UV spectra given their red UV-to-mid-IR colors, and common outflow signatures including BALs or BAL-like features and large C IV emission-line blueshifts. Their SEDs, see Figure 2, and line properties are inconsistent with normal quasars behind a dust reddening screen. Patchy obscuration by small dusty clouds could produce the observed UV extinctions without substantial UV reddening.

Further observations by our team with VLT-XShooter measured rest-frame optical spectra

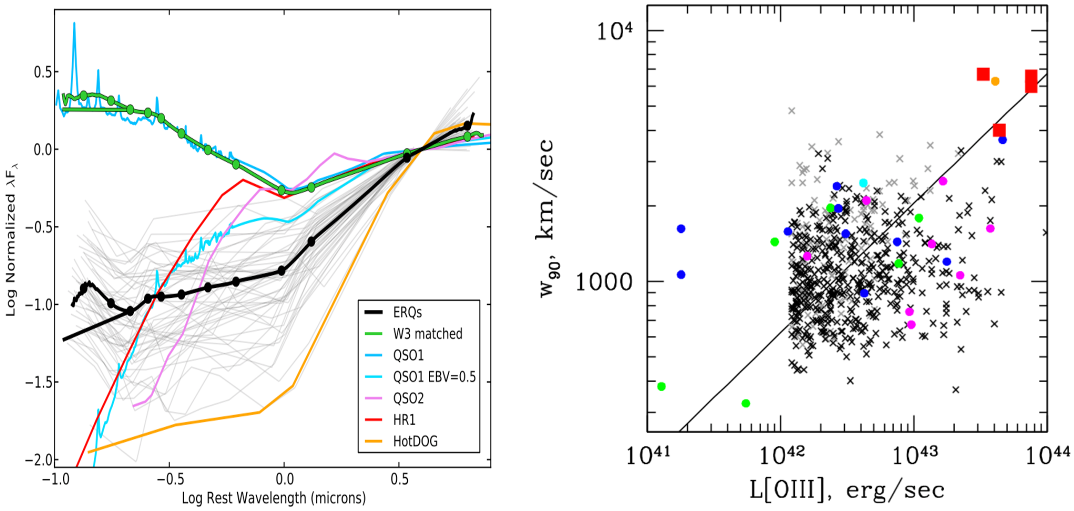

Figure 2: *(Left)* From Hamann et al., 2017, the normalized median SEDs for Type 1 non-BALs in the core ERQ sample (black curve) plus blue quasars matched to the core ERQs in W3 magnitude (green curve). The Type 1 quasar template with and without reddening equal to $E(BV) = 0.5$ (light blue, 'QSO1', from Polletta et al. 2007), a typical Type 2 quasar from Mateos et al. (2013; 'QSO2', purple), a typical heavily reddened Type 1 quasar from Banerji et al. (2013; 'HR1'), and a typical HotDOG from Tsai et al. (2015). The light grey curves are SEDs of individual core ERQs. *(Right)* O III kinematics as a function of luminosities for our four targets, red squares, with other quasar populations are shown by black points and various colored symbols. At these extreme velocities, the gas cannot be confined by any realistic galaxy potential and is thus likely to escape from the galaxy; these objects are likely signposts of the extreme blow-out phase of quasar feedback observed at the peak epoch of galaxy formation.

of four $z \sim 2.5$ extremely red quasars (Zakamska et al. 2016). We discovered very broad (full width at half max= $2600 - 5000$ km s^{-1}), strongly blue-shifted (by up to 1500 km s^{-1}) O III λ5007Å emission lines in these objects. In a large sample of type 2 and red quasars, O III kinematics are positively correlated with infrared luminosity, and the four objects in our sample are on the extreme end both in O III kinematics and infrared luminosity. As such, we estimate that at least 3% of the bolometric luminosity in these objects is being converted into the kinetic power of the observed wind. Photo-ionization estimates suggest that the O IIIemission might be extended on a few kpc scales, which would suggest that the extreme outflow is affecting the entire host galaxy of the quasar.

We now believe that the core ERQs are a unique obscured quasar population with extreme physical conditions related to powerful outflows across the line-forming regions. These sources are the signposts of the most extreme form of quasar feedback at the peak epoch of galaxy formation, and may represent an active "blow-out" phase of quasar evolution.

MIR spectroscopy: How do galaxies form? How do they evolve? How do supermassive black holes fit in this picture of galaxy formation? Which objects are the main contributors to the overall energy budget of the universe? To properly answer these questions, one needs to differentiate objects powered by nuclear fusion in stars (i.e. normal and starburst galaxies) from objects powered by mass accretion onto supermassive black holes (quasars and AGNs). A wide variety of diagnostic tools have been used in the past for this purpose with different degree of success.

IR spectroscopy, previously with the InfraRed Spectrograph (IRS; Houck et al. 2004) on board the Spitzer Space Telescope, provided new insights into the physics and classification of AGN. The unambiguous observations of the silicate feature at 9.7 μm in emission in many known AGN (Hao et al., 2005; Siebenmorgen et al., 2005; Sturm et al., 2005; Buchanan et al., 2006; Shi et al., 2006) came as the long sought confirmation of the unified scheme. At the same time, however, IRS observations indicated that in some cases the source of obscuration resides in the host rather than the torus (e.g. Goulding et al., 2012; Hatziminaoglou et al., 2015). Identification through MIR spectroscopy is very powerful, allowing to detect obscured AGN components even when the MIR is dominated by the host galaxy. Several classification diagrams have been developed to determine the AGN contribution to an observed spectrum based on certain spectral features, such as high ionisation emission lines like Ne V , [Ne II] and O IV, the EW of PAH features and the strength of the silicate feature at 9.7 μm (see, e.g. Spoon et al., 2007; Armus et al., 2007; Veilleux et al., 2009; Hernan-Caballero & Hatziminaoglou, 2011). A number of techniques have also been developed to model the observed MIR spectra and constrain the AGN and starburst contributions (see e.g. Schweitzer et al., 2008; Nardini et al., 2008; Deo et al., 2009; Feltre et al., 2013).

Although MIR spectroscopy has had a great impact on our understanding of AGN, the number of objects studied through these techniques is limited when compared to photometric studies, as spectroscopic observations require significantly longer integration times. Ground-based observations are generally limited to the brightest targets due to the effects of the Earth's atmosphere (e.g. Alonso-Herrero et al., 2016), while medium deep observations were only possible with the IRS during its cryogen-cooled phase. For the most part, such observations were limited to $z \sim 1$ luminous IR galaxies (LIRGs), ultraluminous IR galaxies (ULIRGs), and a hand of Type 1 quasars (Hernan-Caballero & Hatziminaoglou, 2011, and references therein) although a number of higher redshift ULIRGs were also studied by IRS (see e.g. Kirkpatrick et al., 2012).

Polycyclic Aromatic Hydrocarbons: Polycyclic Aromatic Hydrocarbons (PAHs) are abundant, ubiquitous, and a dominant force in the interstellar medium of galaxies (see e.g., Tielens, 2008, ARAA, 46, 289 for a review). Aromatic features are already a significant component of dusty galaxy spectra as early as $z \approx 2$ (Yan et al., 2005, ApJ, 628, 604). and the infrared (IR) emission features at 3.3, 6.2, 7.7, 8.6, and 11.3 μm are generally attributed to IR fluorescence from (mainly) far-ultraviolet (FUV) pumped large polycyclic aromatic hydrocarbon (PAH) molecules. As such, these features trace the FUV stellar flux and are thus a measure of star formation (Peeters et al, 2004, ApJ, 613, 986). Given the redshift of our ERQs and the MIRI wavelength coverage we will coverage $1.36 \leq \lambda_{\rm emitted} \leq 8.6\mu$m.

1 Bibliography

Fabian, 2012, ARAA 50, 455 • Kormendy & Ho, 2013, ARAA, 51, 511 • Yuan & Narayan, 2014, ARAA, 52, 529 • Heckman & Best, 2014, ARAA, 52, 589 •

Technical Description

We propose to use MIRI MRS to observe four quasars across the full MRS wavelength range in order to deliver to the community Science Enabling Products (SEPs) related to the acculmation, reduction and timely analysis of the MIRI Medium Resolution Spectrometer. Details of our four quasar targets, including the current state of our extensive multiwavelength follow-up programs, are given in Table 1.

Overall Experimental Design: Our goals are two-fold for the ERS: ensure open access to representative datasets in support of the preparation of Cycle 2 proposals, and engage a broad cross-section of the astronomical community in familiarizing themselves with JWST data and scientific capabilities. As such, we have honed in on a specific early release science case that will engage a broad cross-section of the astronomical community, and deliver a dataset for MIRI MRS that can be used for e.g. extragalactic galaxy and AGN studies in Cycle 2. fter discussion with the MIRI Team (A. Glasse; priv. comm.), we settled on the ideology of picking out one instrument (MIRI) and one observing mode (MRS) and making sure we deliver the highest quality data analysis and SEPs here for the community. Observations with MIRI MRS will also directly answer the science questions we've posed.

MIRI MRS Observing Overview

We will be utiliSsing the medium-resolution integral field unit (IFU) and spectroscopy mode. For our MRS operations we: shall operate over the full wavelength range; employ the 4-point dithering pattern, optimized for point sources and using the SLOW detector read-out mode. For the observations themselves, a wide range of considerations (sample size, desired very high SNR, time available for ERS programs, level of read noise etc.) we converge on: 15 Groups 3 Integrations and 1 Exposures for a total of 12,912 seconds science exposure per object. *Using Smart Accounting, the total Charged Time is 22.20 hours.*

MIRI Observing Details

Our observational set-up is:

- MIRI MRS.
- Full spectral coverage; thus we will use all three different spectral settings, SHORT (A), MEDIUM (B), and LONG (C).
- Since with the ERQs we are likely to be observing either point sources or compact sources, we choose to use the point source optimized, "4-point ALL" dither pattern (4PTALL dither). According to the pre-flight expected relative performance of MRS dither patterns (Figure 3, https://jwst-docs.stsci.edu/display/JTI/MIRI+MRS+Dithering) this is the only MIRI MRS dither patterns that guarantees "GOOD" (i.e. half-integer)

Object Name (SDSS)	J0834+0159	J1232+0912	J2215-0056	J2323-0100
Object R.A.	08:34:48.48	12:32:41.73	22:15:24.00	23:23:26.17
object declination	+01:59:21.1	+09:12:09.3	−00:56:43.8	−01:00:33.1
r-band AB magnitude	21.20±0.05	21.11± 0.05	22.27±0.12	21.62± 0.08
WISE W4-band Vega magnitude	6.88±0.09	6.78 ±0.09	7.91±0.24	7.76±0.22
WISE W4-band flux, F_ν	>6 mJy	>6 mJy	6 mJy	>6 mJy
$i_{\rm AB} - W3_{\rm AB}$	6.0	6.8	6.2	7.2
Redshift z	2.591	2.381	2.509	2.356
REW C IV	209±6	225±3	153±5	256±5
C IVFWHM km s^{-1}	2863±65	4787±52	4280±112	3989±62
O III FWHM erg s^{-1}	2811	4971	3057	2625
Spectro-polarimertry	×	√	√	×
VLA data	?	?	?	?
ALMA Band 6	tbc	√	tbc	√
HST Cycle 24	ACS/WFC3 **obtained**	ACS/WFC3 *pending*	ACS/WFC3 *pending*	ACS/WFC3 *pending*
JWST target visibility (Start)	2019-04-01	2019-05-08	2019-05-22	2019-06-07
JWST target visibility (End)	2019-05-07	2019-07-01	2019-07-15	2019-07-29

Table 1: Our four Extremely Red Quasar targets. All four quasars were first identifired in Ross et al. (2015). Values of e.g. REWs, FWHMs are from Zakamska et al. (2016) and Hamann et al. (2017).

sampling throughout the common field of view across all four channels. We opt for the 4-point ALL dither pattern, point source optimized. As noted in the preparation pages, this provides robust performance at all wavelengths and adequate point source separation in all channels such that dedicated background observations are not required. It is also the only dither where spatial sampling is "GOOD" (i.e. half-integer sampling) throughout the common field of view across all four channels.

- We are interested in only a single object per point, so no mosaicking is necessary.
- MIRI Detector Readout mode:: SLOW JWST MIRI's "Slow mode" readout pattern offers fewer detector artifacts and slightly lower detector noise than the "fast mode", making it a good choice for faint source medium-resolution spectroscopy where the sky backgrounds are very low. This is exactly what we want for our ERQ observations.
- Subarray is FULL. This is fixed for MRS.

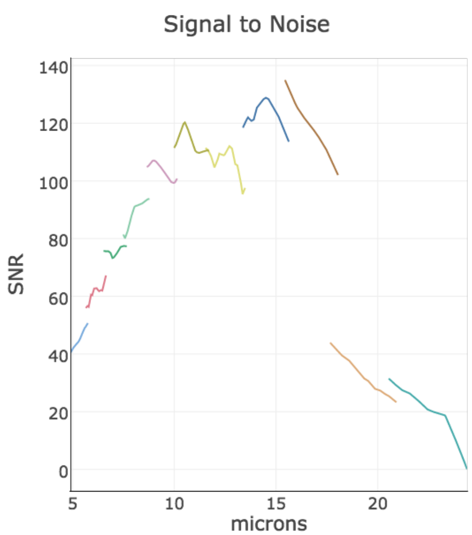

Figure 3: The evolution of linear bias, b, for SDSS Quasars (Ross et al. 2009). We find that quasars tend to inhabit haloes of constant mass, $M_{\rm DM} \sim 2 \times 10^{12} M_{\odot}$ from $z \sim 3$ to the present day.

We take the "core ERQ" SED that is given in Hamann et al. (2017) and is fully representative of the ERQ population at large. The file (found on the GitHub) of `core_ERQ_SED_notLog.dat` is used here. We normalize this SED at a wavelength of 23μm to a source flux density of 5mJy, again very representative of the WISE W3/4-detected ERQ population given in Ross et al and Hamann et al.

At this stage we *do not* include any emission (or absorption) lines since... In the ETC we assume the Shape of the source is Point. Other notes, using the ETC, include having: Medium Backgrounds; 'IFU Nod In Scene'; Aperture location Centered on source; Aperture radius of 0.3"; Nod position in scene of $X = Y = 0.5''$. Our JWST ETC Workbook has `wb ID 7474`.

MIRI MRS Target Acquisition

Observations with the MIRI MRS IFU may often require a target acquisition (TA) procedure, especially at the shortest wavelengths. The required pointing precision for the MIRI MRS is 90 mas (1σ radial), which is approximately the half width of a slice at the shortest wavelength. This required accuracy limits the spacecraft move between the TA region in the imager and the center of the IFU to ¡50" (Sivaramakrishnan et al. 2006). The TA may be achieved with the FND, F560W, F1000W and F1500W on either the target or a suitable offset that is ¡50". The TA centroiding procedure loses accuracy if the pixels are saturated so a brightness limit (Table 1) must be considered for the target.

APT, Overheads and Smart Accounting.

All the above details in are out APT. Visit Planner was loaded and Smart Accounting run. Our full proposal comes in at 20.32 hours of charged time.

Plan for Alternative Targets

We have 15 ERQs that will be observed with ALMA Cycle 5, Band 6, four of which are our primary targets. The remaining 11 objects are given here as alternative targets. As can be seen, redshifts and e.g. WISE W3/W4-band magnitudes and fluxes are essentially the same for the core targets, hence we do not consider changing the observational strategy.

Special Requirements

There are no Special Observational Requirements for our ERS.

Justify Coordinated Parallel Observations

We are not inducing Coordinated Parallels observations.

Justify Duplications

There are no duplicated observations.

■ Data Processing & Analysis Plan

General Outline and Motvations Driving Data Processing & Analysis

We are already ensuring open access to representative data sets, processeing pipelines and analysis tools in support of the preparation of both Cycle 1 and Cycle 2 proposals. The key links are::

`github.com/d80b2t/JWST_ERS`
(the P.I.'s personal and public GitHub repository).

`github.com/miri-mrs`
(a "Organizationl" public GitHub repository for the Community).

`miri-mrs.readthedocs.io`
(With the source code here: `https://github.com/miri-mrs/ERQs/tree/master/docs`).

Our ERQ ERS proposal is the first part of a multi-cycle proposal project and plan. As such, we are *already highly motivated to produce the data processing tools, codes, documentation and identify the critical science-enabling products well in advance of the release of the Cycle 2 Call for Proposals (September 2019).*

Our Science-Enabling Products team consists of four main parts::

- "Core Coders";
- Wedsite and `readthedocs` Writers;
- Observational Follow-up;
- Senior members of staff, able to supply students/ ask for funding;
- Operating akin to a steering committee;

ERS ERQ Science Enabling Products

`mrs_analyzer` is a Python module for analyzing MRS data; `mrsfringe` is a Python module for mitigating MRS fringing issues;

And will integrate with... `https://github.com/STScI-JWST`
see e.g. `https://github.com/STScI-JWST/jwst/blob/master/jwst/mrs_imatch/mrs_imatch_step.py`

Delivery Schedule for Science-Enabling Products.

Here we give the delivery schedule for science-enabling products. Proposals must present a delivery schedule for science-enabling products. A description of STScI pipeline data products, processing and analysis software, and their anticipated availability, will be provided by the May 2017 release of the final version of this Call for Proposals. Proposers may consider multiple deliveries, with more advanced products provided over longer timescales. Proposals may include the collection, processing and analysis of ancillary data as part of an integrated DD ERS proposal.

Co-Investigators and Delivery of Science-Enabling Products.

Co-Investigators, together with the PI (and any Co-PIs) comprise a core team with the responsibility of developing and delivering science-enabling products as described in the proposal, as well as carrying out selected key aspects of the science investigations. A Co-I must have a well-defined, and generally sustained, continuing role in team activities, serve under the direction of the PI, or co-PI(s). Co-investigators may or may not receiving funding, pending eligibility, through the DD ERS program.