1 Scientific Context

Context – The evolution of supermassive black holes (SMBH) at the centers of most galaxies seems connected to how their host galaxies build up their bulges. The quest to understand the physical processes that help establish this connection motivates much of extragalactic astronomy. One of these mechanisms is AGN feedback which can disturb the ISM and so prevent star-formation. Recent SOFIA observations of singly ionized carbon [CII] in nearby low-luminosity AGN suggest that: high ratios of [CII] to FIR may be associated with obscured AGN outflows and that the [CII] is at the interface between warm and cold gas in those outflows. Here we propose to test if and how this effect changes with AGN luminosity and obscuration.

Aims: We will compare star-formation rates (SFR) measured from FIR photometry (Herschel) and MIR spectra (Spitzer) to those from [CII] and will use the [CII]/FIR ratios to estimate how star-formation efficiencies in luminous AGN compare to those in lower luminosity AGN analyzed in previous SOFIA surveys.

Methods: The observations of the [CII] line at 158 microns are uniquely suited to SOFIA's FIFI-LS as FIR measurements from ground are not possible, and the velocity resolution of FIFI-LS is sufficient for our goals. We will use our estimates of [CII] emission fluxes and line-widths to derive star-formation efficiencies and dynamical masses.

Synergies: We will compare dynamical masses measured with the proposed SOFIA [CII] to those from gas (HI or CO), FIR (dust masses), and stellar masses (from NIR). We will also compare SFR measured from FIR photometry and MIR spectra to those estimated from the proposed [CII] observations.

Anticipated results: Recent SOFIA observations of [CII] in nearby low-luminosity AGN suggest that: high ratios of [CII] to FIR may be associated with obscured AGN outflows and that the [CIII] may be at the interface between warm and cold gas in those outflows. The observations we propose here will test whether luminous, obscured AGN have higher [CII]/FIR ratios than luminous, non-obscured AGN.

2 Scientific justification

A central issue in the study of the formation and evolution of galaxies is the connection between the central black hole (BH) and the surrounding bulge stars. Jahnke & Maccio (2011) find that galaxy mergers are able to produce galaxies whose central masses correlate with their bulge masses. However the scatter in this correlation is larger than measurement errors and suggests the need for other mechanisms at play: processes associated with the central accreting black-hole and/or massive star - formation (e.g. supernovae) that shape the evolution of the host galaxy (feedback). Valid tests of these theories are contingent upon a deeper understanding of the processes associated with the formation of the spheroid and those regulating the growth of the BH. Active galactic nuclei (AGN) feedback, in luminous AGN, is considered a key regulator that shapes the stellar mass distribution of the bulge, the ISM content, and the star formation properties of the host galaxy. Models also employ AGN feedback to provide an evolutionary explanation of how Type 1, broad-line (i.e. QSO1s) might have gone through a Type 2, narrow-line (i.e. QSO2) phase.

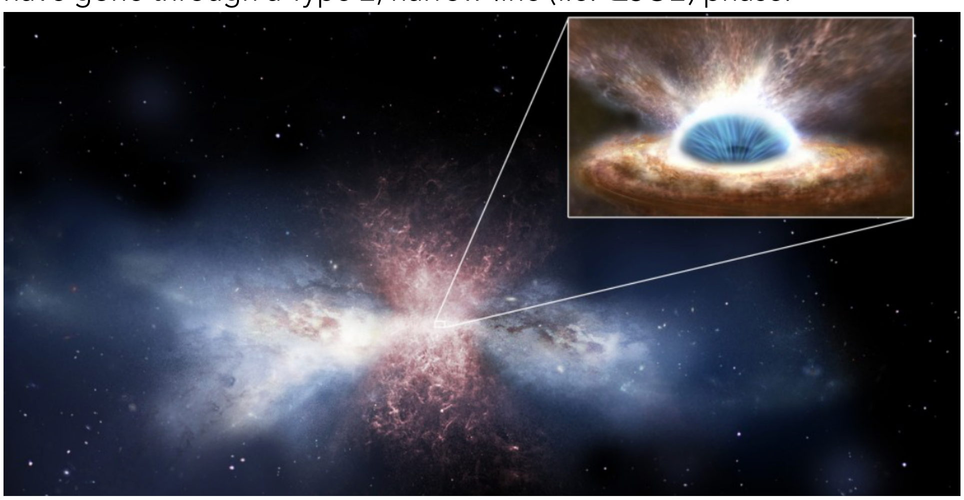

Figure 1: Image from the ESA 2015 press release focused on Tombesi et al. 2015's finding that winds from the accretion disk can drive fast molecular outflows.

Several authors (e.g. Springel et al. 2005; Hopkins et al. 2006) proposed that QSO activity is triggered by gas-rich galaxy mergers. The dense molecular gas is driven to the center of the merger remnant, inducing both significant BH accretion and enhancing star formation. Since this massive quantity of dense gas is associated with dust, the dust obscures much of the accretion and so the AGN appears as a QSO2 source because no emission escapes from the broad-line region. As the BH grows the AGN blows back the gas and dust, the broad-line region thus becomes visible and the source then transforms to a QSO1. This process also truncates star formation and, by pushing away the gas, limits further accretion.

Evidence of how the AGN affects the host gas and lowers the star formation rate is scarce. In low-redshift samples, Greene et al. (2009) find that the star formation and host properties of obscured QSOs are much more diverse than those of unobscured ones. Ho (2005) finds that star formation rates in optically selected QSOs are typically below a few solar masses per year but that those objects have large gas reservoirs. On the other hand, CO studies (e.g. Carilli et al. 2002; Riechers et al. 2011) suggest that luminous high-redshift QSOs are very prolific in making stars. Studies of low-redshift obscured QSOs suggest that the gas in the entire host galaxy is significantly disturbed by the central AGN: the narrow-line region in these sources is almost the size of the entire galaxy. Most recently with SOFIA, Smirnova-Pinchukova et al. (2019) discover that the [CII]/FIR ratios may be used to identify multi-phase AGN outflows that are capable of disrupting the ISM in their host galaxies.

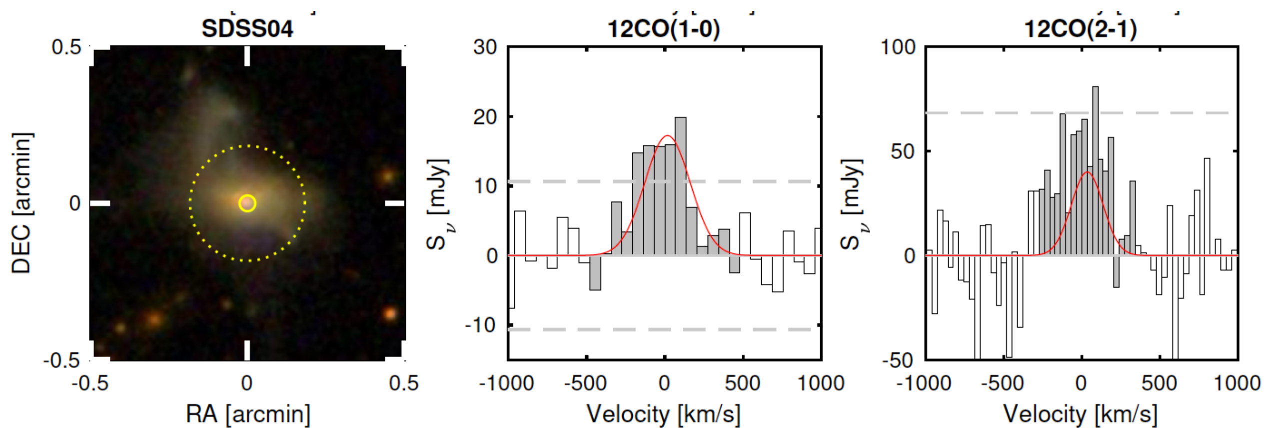

Figure 2: Left: SDSS gri cutout of one of the, the solid and dotted yellow circles show the extend of the 3'' SDSS spectroscopy fiber and the 22'' IRAM30m beam at 3 mm, respectively. Middle: CO(1-0) spectra in units of mJy. Right: CO(2-1) spectra in units of mJy. For both spectra the x-axis indicates the velocity offset of the line corrected to the systemic velocity of the galaxy as determined from the optical spectrum. Spectra are shown at 25 MHz resolution. Figure from (Petric, A, Janssen, R, Flagey, N, Omont, A, Marshall, J., Lacy, M., et al. in prep.)

Here we propose to directly investigate the ISM and star formation efficiencies of QSO2s with SOFIA's and compare them to those of QSO1s selected to have similar redshifts, [OIII] luminosities and CO masses and to the nearby, low-luminosity AGN in the SOFIA observed sample of Husemann et al. (2017). Both the QSO1s and QSO2s in this sample are sources observed by the Herschel mission as part of two large programs to measure the mass and temperature of cold dust in luminous z ≤ 0.5 QSOs (Petric et al. 2015).

Type 2 QSOs represent at least half of the luminous AGN population at all redshifts (Lacy et al. 2007; Reyes et al. 2008), and ALMA is used to study their ISM and cooling properties at higher redshifts. Here we propose to study a unique sample of nearby QSO2s, chosen from the Greene et al. (2011) study and our sample of QSO2s with measurements of Herschel FIR 70-500 microns (Petric et al. 2015, Zakamska et al. 2016) and 12 CO from the IRAM 30m single dish (Fig 2b). When combined with ground-based observations of CO(1-0), the proposed observations will determine the physical conditions of the ISM in the host galaxies. The Herschel PACS and SPIRE photometry gave us the total dust mass, and hence cold gas mass, in these system. BH masses and Eddington ratios will be obtained from the literature and NIR spectroscopy of the CaT from GNIRS (Vitral, AP, et al in prep.) . The proposed spectroscopic data will allow us to determine the fate of the surrounding gas and will provide the long-searched direct coupling between AGN feedback and star formation properties.

The high abundance of Carbon in the universe (fourth most abundant element), its low ionization potential and that it is rarely affected by extinction make the [CII] line an excellent coolant of neutral gas ionized by close-by early-type stars. As such, measuring the properties of the [CII] line is a great method to investigate the physical conditions of the gas mostly associated with star- formation.

The [CII] line is emitted from photon-dominated regions (PDRs) as a result of UV radiation from new stars impacting on molecular clouds. The ratio of [CII] line emission to the CO emission is therefore proportional to the UV radiation per amount of molecular gas. We will estimate the amount of molecular gas from our Herschel data (assuming a gas to dust mass ratio). The diagnostic power of these line is particularly useful when combined with the star formation rates estimated from the FIR and dust masses that can be estimated from the Herschel PACS and SPIRE photometric observations we were awarded as part of Herschel OT2. The [CII] line will provide an invaluable estimate of the star formation efficiency and hence test if and how the star-formation efficiency is different in type 2 and type 1 AGN as predicted by the gas rich merger model of AGN activation.

We will also compare the proposed [CII] observations with the sample of non-QSO Luminous Infrared Galaxies presented in (Diaz-Santos et al. 2013) which were observed in CO (e.g. Sanders et al. 1991, Petric, A, Janssen, R. et al. in prep) as that study provides an excellent benchmark of lower luminosity AGN and non-AGN star-forming galaxies. In addition we will compare to the Herschel observations of AGN by Sargsyan et al. (2012) who derive a calibration of SFR from the [CII] to IR ratios in a sample starbursts and AGN.

The proposed observations compare two uniformly observed QSO2s an QSO1s for which we know the cold and warm ISM component. Those observations cannot be done from the ground or any other current facility. More significantly such observations of nearby bright luminous Type 2s for which we can estimate stellar dispersion properties are necessary to fully investigate the impact of the AGN in sources where we measured the accretion and mass of the BH. This study will also constitute a low-z benchmark for future cooling lines of high-z galaxies with ALMA.

References

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3 Feasibility and Path to Publication

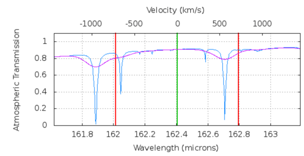
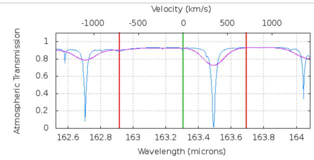
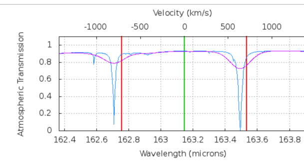
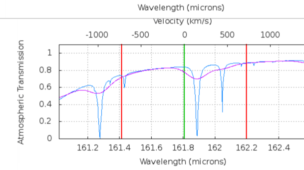
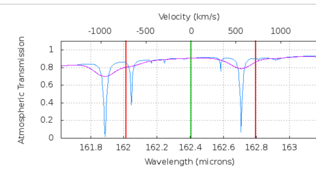
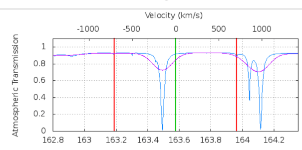
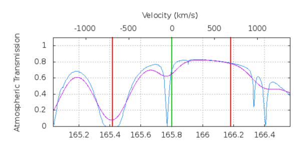
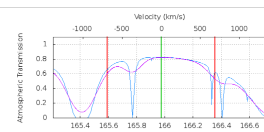
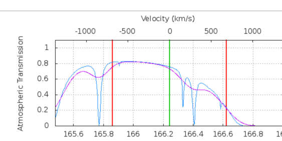
Target Selection

We wish to calibrate the efficiency of using the [CII] line to estimate star-formation rates, star-formation efficiencies, and dynamical masses in the hosts of luminous QSOs. We also want to determine if/how AGN feedback in QSO2s and QSO1 affect the ISM conditions in their hosts galaxies by measuring how the star-formation efficiency changes as a function of BH accretion rates, BH mass and AGN contribution to the IR. We will estimate the AGN/IR contribution using both the MIR continuum slope (e.g. Petric et al. 2011, Veilleux et al. 2009) from WISE and from fitting the SED. We thus will be able to directly test if the impact of the dusty AGN on the ISM can ultimately transform a QSO2 into a QSO1. The proposed sample is ideally suited to this purpose. It includes the nearest (z <0.07) most luminous [OIII] emitters from the SDSS selected sample of Type 2 QSOs of Reyes et a. 2008 and a matched sample of PG QSO1s. For the 10 sources (5 QSO1s and 5 QSO2) we propose to observe here, we have recently acquired NIR spectroscopy from the Gemini GNIRS (PI: Petric, Vitral et al. in prep). We have 12 CO (1-0 and/or 2-1) estimated of the the entire sample of QSO2s from the IRAM 30m telescope (Figure 2, Petric, A., Janssen, R., et al. in prep) and published 12 CO (1-0) measurements of the matching PG QSOs sample (Scoville et al. 2003, Evans, A et al. 2006).

Sensitivity Requirements

We use our Herschel photometry to estimate the FIR luminosities for both samples of QSOs (Petric et al. 2015 and Zakamska et al. 2016). We then the results of Stacey et al. 2010 to estimate a flux of the [CII] line on the order of $1.5{\times}10^{-17}W/m^2$. To estimate the [CII] luminosity we choose the average [CII]/FIR relation from Stacey et al. of 0.5 and we seek to achieve the same sensitivity for all sources. Since upper limits are extremely significant as they represent a limit on the efficiency of producing stars, and hence a possible direct effect of the AGN feedback we seek a 3-5 σ sensitivity of $1{\times}10^{-17}W/m^2$ after smoothing to a velocity resolution of 50-100 km/sec. This will also permit us to probe the full range of L[CII]/[LIR] ratios. We used the FIFI-LS exposure calculator to estimate our integration times, overheads, and the atmospheric transmission at the observed wavelength for the 158 micron [CII] lines from our targets. We thus request a 1 hour of integration time per source for all sources but one PG QSO for which we only need 30min of integration times. Including overheads our total time request is 26 hours.

We also use the results of Busch, Husemann et al. (2018) and Smirnova-Pinchukova et al. (2019) to inform our observing strategy: given the FIR estimated SFR of our sources (~ 3-5 Msun/yr) and the similarity of this project's sources to those of the aforementioned paper, the 1 hr integration time per source is not overly optimistic.

Target	[CII] observed line center	FIR Luminosity [1E10 Lsun]	SITE t_on for an SNR of 5 [minutes]	SITE PLOT
UGC05025	162.405	6.4 +/-2	49	
Mrk 0110	163.306	1.6 +/- 0.6	47	
IISZ010	163.145	1.6 +/- 0.1	46	
MRK0335	161.807	4.6 +/- 0.3	66	
Mrk 0290	162.405	2 +/- 0.2	49	
SDSS01	163.57638	2.4 +/- 0.5	56	
SDSS02	165.800	16.2 +/- 0.2	95	
SDSS03	165.974	5.3 +/- 0.2	60	
SDSS04	166.242	1.7 +/- 0.2	75	
SDSS07	167.91	8.1 +/- 0.2	58