The MOSDEF Survey: The Nature of Mid-infrared Excess Galaxies and a Comparison of IR and UV Star Formation Tracers at $z \sim 2$

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Abstract

We present an analysis using the MOSFIRE Deep Evolution Field (MOSDEF) survey on the nature of “MIR-excess” galaxies, which have star formation rates (SFRs) inferred from mid-infrared (MIR) data that are substantially elevated relative to those estimated from dust-corrected UV data. We use a sample of $\sim 200$ galaxies and active galactic nuclei (AGNs) at $1.40 < z < 2.61$ with $24\mu m$ detections (rest-frame $8\mu m$) from MIPS/Spitzer. We find that the identification of MIR-excess galaxies strongly depends on the methodologies used to estimate IR luminosity ($L_{\text{IR}}$) and to correct the UV light for dust attenuation. We find that extrapolations of the SFR from the observed $24\mu m$ flux, using luminosity-dependent templates based on local galaxies, substantially overestimate $L_{\text{IR}}$ in $z \sim 2$ galaxies. By including Herschel observations and using a stellar-mass-dependent, luminosity-independent $L_{\text{IR}}$, we obtain more reliable estimates of the SFR and a lower fraction of MIR-excess galaxies. Once stellar-mass selection biases are taken into account, we identify $\sim 24\%$ of our galaxies as MIR excess. However, SFR$_{\text{IR}}$, is not elevated in MIR-excess galaxies compared to MIR-normal galaxies, indicating that the intrinsic fraction of MIR excess may be lower. Using X-ray-, IR-, and optically selected AGNs in MOSDEF, we do not find a higher prevalence for AGNs in MIR-excess galaxies relative to MIR-normal galaxies. A stacking analysis of X-ray-undetected galaxies does not reveal a harder spectrum in MIR-excess galaxies relative to MIR-normal galaxies. Our analysis indicates that AGN activity does not contribute substantially to the MIR excess and instead implies that it is likely due to the enhanced polycyclic aromatic hydrocarbon emission.

Key words: galaxies: active – galaxies: high-redshift – galaxies: nuclei – galaxies: star formation – infrared: galaxies – ultraviolet: galaxies

1. Introduction

In the study of galaxies, the star formation rate (SFR) is a fundamental quantity that provides valuable information about the underlying physical processes that drive galaxy evolution. As the energy output from stars is radiated over a wide range of wavelengths from X-ray to radio, the SFR of galaxies can be traced at various wavelengths (see, e.g., Kennicutt 1998; Kennicutt et al. 2009; Hao et al. 2011; Calzetti 2013). Ultraviolet (UV) radiation directly traces the population of young, massive stars in a galaxy and can thus provide a robust tracer of the SFR (e.g., Kennicutt 1998; Calzetti 2001; Magdis et al. 2010; Reddy et al. 2010). However, to reliably estimate the total SFR from the observed UV radiation, one must account for the effects of dust extinction (e.g., Meurer et al. 1999; Bouwens et al. 2009; Reddy et al. 2012, 2015).

H$\alpha$ line emission, originating from ionized nebular gas that reemits the incident stellar luminosity, is another excellent SFR tracer. While less direct than the UV, H$\alpha$ is less affected by dust extinction and thus can provide an accurate and reliable SFR tracer (e.g., Glazebrook et al. 1999; Kewley et al. 2002; Reddy et al. 2010; Shivaei et al. 2015b).

Infrared (IR) radiation traces the thermal emission of dust in a galaxy, which is primarily heated by young stars. The IR emission thus traces the SFR for the dust-obscured stellar populations within a galaxy. With the advent of IR satellites such as the Infrared Astronomical Satellite (IRAS; Neugebauer et al. 1984), the Infrared Space Observatory (ISO; Kessler et al. 1996), and later Spitzer (Werner et al. 2004), the Wide-field Infrared Survey Explorer (Wright et al. 2010), and Herschel (Pilbratt et al. 2010), remarkable progress has been made in our understanding of the stellar content and SFRs of galaxies.

The Multi-band Imaging Photometer on Spitzer (MIPS; Rieke et al. 2004) provides sensitive imaging at mid-IR (MIR) wavelengths. The high sensitivity of the MIPS $24\mu m$ band in particular allows us to directly detect moderately dusty star-forming galaxies out to high redshifts ($z \gtrsim 2$), which may not be detectable at longer wavelengths (e.g., Le Floc’h et al. 2009; Lee et al. 2010).

Many studies have investigated the agreement between IR, UV, and H$\alpha$ SFR tracers (e.g., Kewley et al. 2002; Rosa-González et al. 2002; Daddi et al. 2007a; Magdis et al. 2010; Reddy et al. 2010; Wuyts et al. 2011; Shivaei et al. 2015a, among many others). A number of studies use MIPS $24\mu m$ data in particular to estimate the total IR luminosity of $z \sim 2$ galaxies, providing SFR estimates that correlate well with other star formation tracers such as H$\alpha$ (e.g., Reddy et al. 2006; Shipley et al. 2016).
However, several studies have found that there are $z \sim 2$ galaxies for which the observed 24 $\mu$m flux is substantially elevated relative to what is expected from multiwavelength data (e.g., Daddi et al. 2007a; Papovich et al. 2007), which has resulted in the identification of so-called “MIR-excess” galaxies. Specifically, Daddi et al. (2007a) report the discovery of a large population ($\sim$25%) of $z \sim 2$ BzK-selected galaxies with an MIR excess such that their combined IR and UV SFR exceeds the extinction-corrected UV SFR by a factor of three. However, the fraction of MIR-excess galaxies identified by Daddi et al. (2007b) may depend on the accuracy of both the IR and UV star formation estimates, and there are known uncertainties on each that need to be treated carefully.

It has been shown that the identification of MIR-excess galaxies depends on the template set that is used to estimate the total IR luminosity, $L_{\text{IR}}$. Several studies provide empirically (or semi-empirically) derived IR templates based on local star-forming galaxies (e.g., Chary & Elbaz 2001; Dale & Helou 2002; Rieke et al. 2009). Daddi et al. (2007a) used the luminosity-dependent templates from Chary & Elbaz (2001) to estimate $L_{\text{IR}}$ based on the 24 $\mu$m data for $z \sim 2$ galaxies. Salim et al. (2009), however, used the Dale & Helou (2002) templates to estimate $L_{\text{IR}}$ for galaxies at $z < 1.4$ and identified a much lower fraction of MIR-excess galaxies than Daddi et al. (2007a, 2007b). After the launch of Herschel, which enabled the detection of IR-luminous high-redshift galaxies directly at far-IR (FIR) wavelengths, studies found that the luminosity-dependent templates created based on local galaxies systematically overestimate $L_{\text{IR}}$ in galaxies with $L_{\text{IR}} > 10^{12} L_{\odot}$ at $z > 1.5$ (e.g., Muzzin et al. 2010; Nordon et al. 2010; Elbaz et al. 2011). This is due to high-redshift luminous galaxies having different dust temperatures than their local counterparts (e.g., Symeonidis et al. 2011). To resolve the problem of overestimating $L_{\text{IR}}$, more recent studies propose a single luminosity-independent conversion for $L_{\text{IR}}$ estimation from MIR observations (Wuyts et al. 2008, 2011; Elbaz et al. 2011; Nordon et al. 2012; Reddy et al. 2012). Furthermore, several studies indicate that stellar mass, metallicity, or specific star formation rate (sSFR) can also impact the $L_{\text{IR}}$ estimation from 24 $\mu$m observations (e.g., Smith et al. 2007; Nordon et al. 2012; Utomo et al. 2014; Shivaei et al. 2017; Schreiber et al. 2018).

The identification of MIR-excess galaxies also depends on the method used to correct the unobscured UV SFR for dust. SFR$_{\text{UV}}$ can be corrected for dust absorption using measurements of the UV continuum slope or using an average correction based on different attenuation curves (e.g., Cardelli et al. 1989; Calzetti et al. 2000; Reddy et al. 2015). It has recently become possible using near-IR (NIR) spectroscopic data to directly measure the ratio of Balmer emission lines H$_{\alpha}$/H$\beta$ (the “Balmer decrement”) in statistical samples of individual galaxies at $z \sim 2$ (e.g., Price et al. 2014; Reddy et al. 2015; Nelson et al. 2016). The Balmer decrement is an indicator of reddening of the ionized gas, which can also be used to estimate the reddening of the stellar continuum (e.g., Reddy et al. 2015). However, in dusty galaxies reddening corrections are very uncertain (e.g., Goldader et al. 2002), and $L_{\text{IR}}$/L$_{\text{UV}}$ varies with stellar mass, dust temperature, and evolution of the dust temperature with redshift (e.g., Bouwens et al. 2016). Underestimating the reddening correction will lead to underestimates of the dust-corrected SFR from the UV and thus to the misclassification of galaxies as MIR-excess galaxies.

Some studies have suggested that the elevated MIR flux in MIR-excess galaxies may be due to a contribution from a hidden population of active galactic nuclei (AGNs) that are not identified at other wavelengths (e.g., Daddi et al. 2007b; Alexander et al. 2011; Rangel et al. 2013). Daddi et al. (2007b) find that the spectral energy distribution (SED) of the MIR-excess galaxies peaks at redder wavelengths than the rest-frame 1.6 $\mu$m stellar peak. They also find a redder K–5.8 $\mu$m color in MIR-excess galaxies than in normal galaxies, which they conclude is due to an underlying AGN contribution. By performing an X-ray stacking analysis on MIR-excess galaxies without an X-ray detection, Daddi et al. (2007b) find a much harder X-ray spectrum in MIR-excess galaxies than in normal galaxies, which suggests the presence of Compton-thick AGNs (see also Fiore et al. 2008).

More recently, Rangel et al. (2013) used deeper Chandra observations of BzK-selected galaxies in the Chandra Deep Field North (CDFN) and Chandra Deep Field South (CDFS) fields and found no significant evidence for an elevated X-ray detection rate in MIR-excess galaxies compared to normal galaxies. Stacking analyses in Rangel et al. (2013) show a softer signal than in Daddi et al. (2007b), which they argue is due to a mixture of highly absorbed AGNs, low-luminosity unobscured AGNs, and star-forming galaxies (see also Georgakakis et al. 2010). They conclude that the hard spectrum in the stacking analyses of earlier studies (e.g., Daddi et al. 2007b; Fiore et al. 2008) is due to a few hard X-ray sources that were just below the detection limit of the Chandra data available at the time, which are now directly detected with deeper X-ray observations. Rangel et al. (2013) also find that while there are AGNs among the MIR-excess galaxy population, they are not typically Compton-thick AGNs. They conclude that the bulk of the MIR-excess galaxy population are luminous, dusty, star-forming galaxies where the SFRs are overestimated in the MIR, underestimated in the UV, or both.

The depth and sensitivity of X-ray data clearly play an important role in the rate of AGN identification (e.g., Mendez et al. 2013; Azadi et al. 2017) and thus can affect conclusions regarding the nature of MIR-excess galaxies. AGNs can also be identified at other wavelengths, such as a power-law-like emission in the MIR (e.g., Lacy et al. 2004; Stern et al. 2005; Donley et al. 2012; Mendez et al. 2013) or optical diagnostics such as the “BPT diagram” ([O iii]/H$\beta$ versus [N ii]/H$\alpha$; Baldwin et al. 1981). Using multiwavelength AGN identification techniques can therefore provide a clearer picture of the AGN contribution in MIR-excess galaxies.

We note that the excess 24 $\mu$m emission in $z \sim 2$ galaxies could be due to enhanced emission from polycyclic aromatic hydrocarbon (PAH) molecules rather than obscured AGN activity (e.g., Lutz et al. 2011; Nordon et al. 2012). Emission from PAH molecules is significant at rest-frame wavelengths of 5–12 $\mu$m, but the strength of the emission varies with stellar mass and metallicity (e.g., Engelbracht et al. 2006; Smith et al. 2007; Shivaei et al. 2017) and may contribute up to 20% of the $L_{\text{IR}}$ (e.g., Smith et al. 2007). Therefore, investigations of MIR-excess galaxies should take into account the possible enhancement at MIR-excess wavelengths due to PAH features.

In this paper we study the nature of MIR-excess galaxies at $z \sim 2$ in the MOSFIRE Deep Evolution Field (MOSDEF) survey (Kriek et al. 2015). The MOSDEF survey used the MOSFIRE multiobject NIR spectrograph (McLean et al. 2012) on the Keck I telescope to observe galaxies and AGNs at
Throughout the paper we adopt a cosmology with $z \sim 1.37$–3.80 over the course of 4 yr; for this study we use the data from the first 3 yr of the survey. Our aim is to resolve the outstanding question of whether the identification of MIR-excess sources is due to an overestimation of the IR-based SFR, an underestimation of the UV-based SFR, and/or AGN contamination.

With the MOSDEF survey, unlike previous studies of MIR-excess galaxies, we are not limited to BzK galaxies and benefit from spectroscopic measurements for $z \sim 2$ galaxies. We investigate how the identification of MIR-excess galaxies depends on the choice of templates used for estimating $L_{\text{IR}}$ and the methods used for the reddening correction of $SFR_{\text{UV}}$. The spectroscopic data in MOSDEF allow us to investigate whether other SFR tracers such as H$_\alpha$ are elevated in MIR-excess galaxies compared to the normal galaxies. As discussed above, for identifying the contribution due to AGNs, previous studies had to rely only on X-ray stacking analyses. In this study we additionally use the rest-frame optical spectra obtained in the MOSDEF survey and the BPT diagram (e.g., Baldwin et al. 1981), as well as MIR identification of AGNs, to investigate the contribution of AGNs to the observed MIR excess.

The outline of the paper is as follows: In Section 2 we describe our data set, the procedure used for measuring the optical emission lines, the 24$\mu$m and FIR data, the IR stacking analysis, and the method used for estimating stellar masses. In Section 3 we present our results on the nature of obscured AGNs at $z \sim 2$. In this section we consider various methods for estimating $SFR_{\text{IR}}$ and $SFR_{\text{UV}}$ and extinction correction of $SFR_{\text{UV}}$. We additionally investigate whether AGNs can result in MIR excess and perform X-ray stacking analysis. We discuss our results in Section 4 and conclude in Section 5. Throughout the paper we adopt a flat cosmology with $\Omega_M = 0.7$ and $H_0 = 72$ km s$^{-1}$ Mpc$^{-1}$. We assume a Chabrier (2003) stellar initial mass function (IMF) unless stated otherwise.

2. Data

In this paper we use data from the first 3 yr of the MOSDEF survey to study the nature of MIR-excess galaxies at $z \sim 2$. In this section, we describe our galaxy and AGN sample and the methods used for measuring emission lines and stellar masses. We also describe the 24$\mu$m and FIR data used for our sample, as well as the IR stacking analysis that we perform.

2.1. The MOSDEF Survey

For the MOSDEF survey (Kriek et al. 2015) we obtained spectroscopic data from the MOSFIRE spectrograph (McLean et al. 2012) on the 10 m Keck I telescope. MOSFIRE provides spectroscopic data with wavelength coverage from 0.97 to 2.40$\mu$m at moderate resolution ($R = 3000$–3650). We obtained spectra for sources in five extragalactic fields: AEGIS, COSMOS, GOODS-N, GOODS-S, and UDS. MOSDEF targets were selected from the deep H-band imaging provided by the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011) in areas with overlapping coverage from the 3D-HST grism survey (Brammer et al. 2012; Momcheva et al. 2016). The targets were selected in three redshift intervals ($1.37 < z < 1.70$, $2.09 < z < 2.61$, and $2.95 < z < 3.80$) to ensure coverage of the strong rest-frame optical emission lines (i.e., [O II], H$\beta$, [O III], H$\alpha$, [N II], [S II]) in the Y, J, H, and K bands. AGNs were identified prior to targeting using X-ray imaging from Chandra and/or IR imaging from IRAC on the Spitzer telescope. AGNs were given higher targeting weights, as were brighter sources and sources with more secure prior redshift estimates, either photometric or spectroscopic. For the full details of the MOSDEF survey, see Kriek et al. (2015).

Our full sample using data from the first 3 yr of the MOSDEF survey includes 792 galaxies, 92 of which are identified as AGNs. For this study we limit our sample to sources at $1.4 < z < 2.61$ to ensure that 24$\mu$m observations from MIPS on Spitzer correspond to rest-frame $\sim 8$$\mu$m data. We further restrict our analysis to sources with significant 24$\mu$m and UV detections, which limits our sample in this paper to 194 galaxies, 52 of which are AGNs (see Section 2.3).

2.2. Emission-line Measurements

Using the MOSDEF spectroscopy, we measure the flux of multiple rest-frame optical emission lines and use this to estimate the Balmer decrement (from H$_\alpha$/H$\beta$) and to identify optical AGNs using the [O III]/H$\beta$ versus [N II]/H$\alpha$ BPT diagram. In this section we briefly describe the methods used by Reddy et al. (2015) and Azadi et al. (2017) to measure the flux of these emission lines.

For MOSDEF galaxies the H$\beta$, [O III], H$\alpha$, and [N II] emission line fluxes are estimated by fitting Gaussian functions as described in Reddy et al. (2015). We allow a linear fit to the continuum, a single Gaussian component for H$\beta$ and [O III], and a triple Gaussian function for [N II] $\lambda 6550$, H$\alpha$, and [N II] $\lambda 6585$ fit simultaneously. The spectra of each galaxy were perturbed 1000 times within the error spectra, and the dispersion of the perturbed lines was taken as an estimate of the error in the emission-line flux (Reddy et al. 2015).

To identify optical AGNs, we use the procedure described in Azadi et al. (2017). We use the MPFIT nonlinear least-squares fitting function in IDL (Markwardt 2009) and use the error spectra to determine the errors on the fit. We require the continuum around each emission line to be flat, and we require the same physical components (i.e., narrow line, broad line, outflow) to have the same FWHM and velocity offset, as determined from the line with the highest signal-to-noise ratio (S/N). The spacing between the [O III] $\lambda 4960$ and [O III] $\lambda 5008$ forbidden lines (as well as between the [N II] $\lambda 6550$ and [N II] $\lambda 6585$ lines) is fixed, and their flux ratios are set to be 1:3. We fit [O III] $\lambda 5008$ simultaneously with [O III] $\lambda 4960$, and H$\alpha$ with [N II] $\lambda 6550$ and [N II] $\lambda 6585$, using four different models.

In model 1, all lines are fit with a narrow component with FWHM $< 2000$ km s$^{-1}$. In model 2, in addition to the narrow component, we allow for an underlying broad component for the H$\beta$ and H$\alpha$ lines with FWHM $> 2000$ km s$^{-1}$. In model 3, we fit each line with a narrow component and an additional component with FWHM $< 2000$ km s$^{-1}$ and a velocity offset relative to the narrow component; this represents an outflow component. In model 4, the narrow, outflow, and broad H$\beta$ and H$\alpha$ components are all fit. The fit from model 1, with only single narrow components, is considered to be the best fit for the sources unless the additional components improve the reduced $\chi^2$ at the 99% confidence level. For more details on the AGN line-fitting procedure, see Section 2 in Azadi et al. (2017). We note that the fluxes of the narrow components of the H$\beta$ and H$\alpha$ lines are corrected for the underlying stellar absorption (for more details, see Reddy et al. 2015).
2.3. AGN Sample

In the MOSDEF survey we use three methods to identify AGNs: X-ray imaging from Chandra, IRAC MIR imaging from Spitzer, and the BPT diagram using the MOSDEF spectral line measurements. Details of MOSDEF AGN identification using each method are described in Azadi et al. (2017); relevant details are repeated here.

X-ray AGNs were identified prior to MOSDEF targeting using Chandra observations with a depth of 4 Ms in GOODS-S, 2 Ms in GOODS-N, 800 ks in AEGIS, and 160 ks in the COSMOS field, corresponding to hard-band flux ($f_{2-10\text{keV}}[\text{erg s}^{-1} \text{cm}^{-2}]$) limits of $1.6 \times 10^{-16}$, $2.8 \times 10^{-16}$, and $5.0 \times 10^{-16}$, and $1.8 \times 10^{-15}$, respectively, in each field. X-ray catalogs were generated according to the method described by Laird et al. (2009), Nandra et al. (2015), and Aird et al. (2015). To identify the optical, NIR, and Spitzer IRAC counterparts of the X-ray sources, we use the likelihood criteria listed in Equation (4). IRAC counterparts of the X-ray sources, we use the likelihood

We estimate the rest-frame 2 $\mu$m index of a sample without contamination from non-AGNs, but are held within the 1

... (4) when there is no detection for the hard band.

In the MOSDEF survey we use three methods to identify X-ray AGNs were identified prior to MOSDEF targeting

As noted above, we limit our sample to galaxies and AGNs $\mu$ = 2.61 to ensure that their 24 $\mu$m luminosity $L_{24} \mu m$ falls within the limits of 1.6 to 2.6. In brief, Shivaei et al. (also see Reddy et al. 2010) use higher spatial resolution data from IRAC to determine the location of each object. Around each object a subimage is constructed and a point-spread function (PSF) is fit simultaneously to all sources, including the object of interest, and a covariance matrix is used to determine the robustness of each fit. The background flux is estimated by fitting the PSF to random positions at least 1 FWHM away from the object, and the standard deviation of those fluxes is taken as the noise.

As noted above, we limit our sample to galaxies and AGNs with $1.4 < z < 2.6$ to ensure that their 24 $\mu$m flux densities cover the rest-frame $\sim 8 \mu$m luminosity ($L_{3.6} = n \lambda L_{\lambda}(8 \mu m)$). In our analysis we use various luminosity-dependent template sets (e.g., Chary & Elbaz 2001; Dale & Helou 2002; Rieke et al. 2009) to extrapolate the total IR luminosity ($L_{\text{IR}}$) from the observed 24 $\mu$m band; we describe these templates and the procedure to estimate $L_{\text{IR}}$ fully in Section 3.2.1 below. We estimate the rest-frame 8 $\mu$m luminosity, $L_{8\mu m}$ based on the same template. The values of $L_{8\mu m}$ estimated in this manner do not

sources that require a significant broad component for either of the H$\beta$ or H$\alpha$ lines since broad emission lines can dominate over the host galaxy in the broadband photometry and affect the stellar-mass measurements. As shown in Coil et al. (2015) and Azadi et al. (2017), we consider sources above the Meléndez et al. (2014) line to be optical AGNs in our sample, as this line provides a reliable AGN sample for MOSDEF sources when compared to X-ray and IR AGNs in our sample.

2.4. Stellar-mass Measurements

We estimate stellar masses in MOSDEF using SED fitting of the multiwavelength photometry from 3D-HST and our spectroscopic redshift measurements. We use the FAST stellar population fitting code (Kriek et al. 2009), with a Chabrier (2003) stellar IMF. Conroy et al. (2009) Flexible Stellar Population Synthesis (FSPS) models, the Calzetti et al. (2000) dust reddening curve, and a fixed solar metallicity, with delayed exponentially declining star formation histories (SFHs).

Radiation from AGNs may contribute to the observed SED, particularly at UV and MIR wavelengths, which could impact our derived stellar masses of their host galaxies. We previously tested fitting the potential contribution from AGNs to the SED using additional power-law contributions to the photometry at UV and MIR wavelengths (Azadi et al. 2017). The FAST code can be run with or without the template error function (which accounts for wavelength-dependent mismatch between the observed photometry and the templates; e.g., Kriek et al. 2009), and as shown in Azadi et al. (2017), the stellar masses that we obtain for MOSDEF AGNs by running FAST without the template error function and subtracting power-law components for the AGN light are consistent with those estimated using the template error function (and not subtracting additional AGN components). Therefore, in this study we use results from FAST with the template error function.

2.5. 24 $\mu$m Flux Density and $L_{8\mu m}$ Measurements

In this study we restrict our analysis to galaxies with $3\sigma$ Spitzer/MIPS $24 \mu$m detections. We use $24 \mu m$ data from the Far-Infrared Deep Extragalactic Legacy (FIDEL) Survey (Dickinson & FIDEL Team 2007). We use the measurements of Shivaei et al. (2017) for the $24 \mu$m flux densities. In brief, Shivaei et al. (also see Reddy et al. 2010) use higher spatial resolution data from IRAC to determine the location of each object. Around each object a subimage is constructed and a point-spread function (PSF) is fit simultaneously to all sources, including the object of interest, and a covariance matrix is used to determine the robustness of each fit. The background flux is estimated by fitting the PSF to random positions at least 1 FWHM away from the object, and the standard deviation of those fluxes is taken as the noise.

As noted above, we limit our sample to galaxies and AGNs with $1.4 < z < 2.6$ to ensure that their $24 \mu$m flux densities cover the rest-frame $\sim 8 \mu$m luminosity ($L_{3.6} = n \lambda L_{\lambda}(8 \mu m)$). In our analysis we use various luminosity-dependent template sets (e.g., Chary & Elbaz 2001; Dale & Helou 2002; Rieke et al. 2009) to extrapolate the total IR luminosity ($L_{\text{IR}}$) from the observed $24 \mu$m band; we describe these templates and the procedure to estimate $L_{\text{IR}}$ fully in Section 3.2.1 below. We estimate the rest-frame 8 $\mu$m luminosity, $L_{8\mu m}$ based on the same template. The values of $L_{8\mu m}$ estimated in this manner do not
depend significantly on which template set is used; results using the Chary & Elbaz, Dale & Helou, or Rieke et al. template sets are consistent with each other.

2.6. Herschel/PACS Data and IR Stacking Analysis

As we discuss below in Section 3, including FIR data plays an important role in accurately estimating the bolometric IR luminosity, which allows us to more cleanly select galaxies where the IR emission is substantially elevated relative to the dust-corrected UV. In part of our analysis below (see Section 3.2.3) we include the Herschel/PACS 100 and 160 μm data available in the AEGIS, COSMOS, and GOODS fields (Oliver et al. 2010; Elbaz et al. 2011; Magnelli et al. 2013). The number of MOSDEF galaxies with robust PACS 100 and 160 μm detections is 63 and 58, respectively (40 galaxies have detections at both wavelengths). To measure the 100 and 160 μm flux densities, we use the prescription described above for 24 μm flux densities. We note that the majority of the MOSDEF galaxies do not have a robust detection at 24 μm or FIR wavelengths. While this study is limited to sources with significant 24 μm detection, the \( L_{\text{IR}} \) from Shivaei et al. (2017) used in Section 2.3.2 is estimated using stacks of the MIPS and Herschel images.

3. Analysis and Results

In this section we first define MIR-excess galaxies (Section 3.1) and then describe the various methods used in this study for estimating bolometric infrared luminosities and correcting the UV SFR for dust absorption in Section 3.2. We investigate whether the incidence of MIR excess depends on stellar mass (Section 3.4) and whether detected or obscured AGNs contribute to the identification of MIR-excess galaxies (Sections 3.5 and 3.6). We further consider whether the SFR traced by Hα is elevated in MIR-excess compared to normal galaxies (Section 3.7).

3.1. Definition of MIR-excess Galaxies

Studying a sample of BzK-selected galaxies at \( z \sim 2 \), Daddi et al. (2007a) report the existence of a population of so-called “MIR-excess” galaxies for which the total IR luminosity as estimated from the MIPS 24 μm flux densities shows an excess relative to that expected from other SFR tracers. Specifically, they identify MIR-excess sources as galaxies satisfying the following criterion:

\[
\log \left( \frac{\text{SFR}_{\text{IR}} + \text{SFR}_{\text{UV}}}{\text{SFR}_{\text{UV,corr}}} \right) > 0.5, \tag{8}
\]

where SFR\(_{\text{IR}}\) is the SFR estimated from the MIPS 24 μm flux density, SFR\(_{\text{UV}}\) is the SFR estimated from the UV data, and SFR\(_{\text{UV,corr}}\) is the SFR estimated from the UV data corrected for dust extinction.

The empirical threshold of 0.5 dex is chosen by Daddi et al. (2007a) as the intrinsic scatter in this ratio is symmetric to first order. In their study, Daddi et al. (2007a) use the luminosity-dependent Chary & Elbaz (2001) templates to convert observed 24 μm flux to \( L_{\text{IR}} \). They correct SFR\(_{\text{UV}}\) for dust reddening using the relation between the color excess and \( B - z \) color from Daddi et al. (2004), which is derived using a Calzetti et al. (2000) attenuation law. Daddi et al. (2007a) find that ~25% of their BzK-selected galaxies at \( z \sim 2 \) show such an excess at MIR wavelengths (after removing the X-ray-detected AGNs from their sample) and emphasize that the existence of this population is independent of the templates used for estimating the bolometric IR luminosity.

As noted above, in this paper we aim to investigate how the templates used for estimating \( L_{\text{IR}} \) and the choice of the dust correction methods used for estimating SFR\(_{\text{UV,corr}}\) (which may depend on the adopted SFH as shown below) affect the identification of MIR-excess galaxies.

3.2. Methodology

In this section we describe various methods used in this study for estimating \( L_{\text{IR}} \) and for correcting SFR\(_{\text{UV}}\) for dust extinction. We implement these methods in Section 3.3 in order to identify MIR-excess galaxies in our sample.

3.2.1. Estimating the Total IR Luminosity from Luminosity-dependent Templates

The first sets of templates adopted in our analysis are luminosity-dependent templates from Chary & Elbaz (2001), Dale & Helou (2002), and Rieke et al. (2009) that estimate \( L_{\text{IR}} \) from a single 24 μm band observation. We describe each of these template sets in this section.

Chary & Elbaz (2001) construct their templates using data from ISO, IRAS, and SCUBA for local galaxies to create 105 templates covering 0.1–1000 μm. The \( L_{\text{IR}} \) (8–1000 μm) is determined using the Sanders & Mirabel (1996) relation. These templates span a range of \( L_{\text{IR}} \) of \( 10^{8} \)–\( 10^{13} \) L\(_{\odot}\), from normal galaxies to luminous and ultraluminous IR galaxies (LIRGs: \( 10^{11} \) L\(_{\odot}\) < \( L_{\text{IR}} \) < \( 10^{12} \) L\(_{\odot}\); ULIRGs: \( L_{\text{IR}} \geq 10^{12} \) L\(_{\odot}\)). The templates are luminosity dependent: a single template describes the IR emission is specified for a given luminosity.

To estimate \( L_{\text{IR}} \) using the Chary & Elbaz templates, we first shift the templates to the redshift of each source and then convolve them with the MIPS 24 μm response curve. From the 105 templates, we consider the one that at 24 μm returns the closest value to the observed flux as the best template and adopt the luminosity corresponding to that template from Chary & Elbaz (2001) as the total IR luminosity. We convert \( L_{\text{IR}} \) to SFR\(_{\text{IR}}\) using the relationship given in Kennicutt (1998), converted to a Chabrier (2003) IMF. Thus,

\[
\text{SFR}_{\text{IR}}[M_{\odot} \text{ yr}^{-1}] = 2.8 \times 10^{-44} \times L_{\text{IR}}(8–1000 \text{ μm}) \text{[erg s}^{-1}] . \tag{9}
\]

The semi-empirical templates of Dale & Helou (2002) are constructed using data from ISO, IRAS, and SCUBA for 69 local galaxies with \( L_{\text{IR}}(8–1000 \text{ μm}) < 10^{11} \) L\(_{\odot}\). Dale & Helou (2002) develop a theoretical model with three components for the emission from small and large dust grains, as well as PAH molecules (see also Dale et al. 2001). In their model the mass of each dust grain has a power-law distribution as a function of intensity with a slope of \( \alpha \), and different templates are constructed based on variations of \( \alpha \) from 1 to 2.5. We use Dale & Helou (2002) templates with the empirical calibration of Marcillac et al. (2006) to scale each template (for a given \( \alpha \)) to a specific total \( L_{\text{IR}} \) (see Equation (1) in Marcillac et al. 2006):

\[ \text{SFR}_{\text{IR}}[M_{\odot} \text{ yr}^{-1}] = 2.8 \times 10^{-44} \times L_{\text{IR}}(8–1000 \text{ μm}) \text{[erg s}^{-1}] . \tag{9} \]
see also Papovich et al. 2007; Reddy et al. 2012). We integrate these templates to estimate the total IR LIR and find the template that provides the best match to the observed 24 µm flux in a similar fashion to that described above for the Chary & Elbaz (2001) templates. We convert LIR to SFRIR using Equation (9).

Rieke et al. (2009) consider a sample of 11 local LIRGs and ULIRGs with Spitzer/IRS spectra and additional photometric data from optical to radio wavelengths. Rieke et al. (2009) calculate the IR luminosity for each of their galaxies using the Sanders et al. (2003) calibration and combine the SED of the galaxies with similar luminosities to build a set of average templates with $L_{\text{IR}} (5-1000\mu m)$ between $10^{9.75}$ and $10^{13} L_{\odot}$. We estimate SFRIR directly from the 24 µm flux densities using Equation (14) in Rieke et al. (2009). We note that Rieke et al. (2009) assume a Rieke et al. (1993) IMF, which, according to the author, has a similar behavior to the Chabrier IMF assumed throughout this paper.

3.2.2. Estimating the Total IR Luminosity from Luminosity-independent Conversions

The luminosity-dependent templates described above are created based on local galaxies and may not be applicable at higher redshifts. With the advent of Herschel, direct detection of individual $z \sim 2$ galaxies at FIR wavelengths has become possible. Studies show that extrapolations from observed 24 µm can result in an overestimation of $L_{\text{IR}}$ in luminous galaxies at $z \sim 2$ (e.g., Nordon et al. 2010; Elbaz et al. 2011; Reddy et al. 2012), as these galaxies may have different dust temperatures and different luminosity surface densities than luminous local galaxies (e.g., Symeonidis et al. 2011; Rujopakarn et al. 2013). We also note that at $z \sim 2$ the observed 24 µm band is probing PAH emission regions. The intensity of the PAH emission can vary significantly, and the shape of the SED is thus poorly constrained at these wavelengths.

While in the local universe there is a positive correlation between galaxy luminosity and dust temperature, at $z \sim 2$ there is a large scatter in their relation (e.g., Elbaz et al. 2010; Magdis et al. 2010; Symeonidis et al. 2011; Wuys et al. 2011). Using deep 100-500 µm FIR data from Herschel, Elbaz et al. (2011) show that at $z > 1.5$ an IR excess can occur in individual galaxies with $L_{\text{IR}} > 10^{12} L_{\odot}$, and they argue that while local LIRGs and ULIRGs are typically in a starburst mode, at $z \sim 2$ they are typically on the star-forming main sequence and therefore can be treated asscaled-up versions of local main-sequence galaxies (e.g., Elbaz et al. 2011; Nordon et al. 2012).

To address the problem of overestimation of $L_{\text{IR}}$ for $z \sim 2$ ULIRGs, Elbaz et al. (2011) propose a single luminosity-independent conversion (see also Wuys et al. 2008, 2011; Nordon et al. 2012). They use a normalization derived from the Chary & Elbaz (2001) templates, identify the best template as the one that best fits the Herschel data, and calculate $L_{\text{IR}}$ by integrating over the best-fit SED. Elbaz et al. (2011) find that the bolometric correction factor at 8 µm ($L_{\text{IR}}/L_{\text{S}}$) corresponds to a universal value of 4.9 at $z < 2.5$.

Another commonly used luminosity-independent template is provided by Wuys et al. (2008). Wuys et al. (2008) use the Dale & Helou (2002) models and find $L_{\text{IR},\alpha}$ corresponding to different $\alpha$ values. They then use the average $L_{\text{IR},\alpha}$ as the best luminosity for each galaxy. We note that unlike Elbaz et al. (2011), the Wuys et al. (2008) conversions are not determined using FIR data. In a later paper, Wuys et al. (2011) show that the conversion factors from Wuys et al. (2008) result in IR luminosities that are consistent in the median (although with a large scatter) with Herschel $L_{\text{IR}}$ measurements.

3.2.3. Estimating the Total IR Luminosity from Luminosity-independent, Mass-dependent Conversions

As shown in Elbaz et al. (2011), a luminosity-independent bolometric correction factor, $L_{\text{IR}}/L_{\text{S}}$, calibrated using Herschel FIR data, can provide a robust estimate of $L_{\text{IR}}$ for galaxies. However, it has been shown that due to the variations of PAH intensity with metallicity, the ratio of $L_{\text{IR}}/L_{\text{S}}$ varies with stellar mass, metallicity, and/or sSFR (e.g., Nordon et al. 2012; Shiuva et al. 2017). In this section we test the mass-dependent, luminosity-independent bolometric factor of Shiuva et al. (2017) to estimate $L_{\text{IR}}$.

As noted in Section 2.6, the majority of MOSDEF galaxies are not detected in the Herschel/PACS bands. To derive $L_{\text{IR}}/L_{\text{S}}$ ratios for the MOSDEF galaxies, Shiuva et al. (2011) stack MIPS 24 µm and Herschel/PACS 100 and 160 µm images of MOSDEF sources regardless of their detection and fit the stacks with the luminosity-dependent templates of Chary & Elbaz (2001). They estimate the average infrared luminosity over the 8–1000 µm range, $(L_{\text{IR}})$, using the best-fit template to the stacked data. Shiuva et al. (2017) repeat the same prescription for estimating $(L_{\text{S}})$ and the ratio $(L_{\text{IR}})/L_{\text{S}}$ as a function of stellar mass. The Shiuva et al. (2017) method is based on the assumption that the luminosity scaling of the Chary & Elbaz (2001) templates applies to $z \sim 2$ galaxies and that these templates can accurately estimate $L_{\text{IR}}$ when fitted to only the PACS bands. We note that the calculations in Shiuva et al. (2017) are at 7.7 µm; here we adopt the correction factor of $L_{15.8}/L_{8} = 1.25$ reported in their paper for our analysis. We use this method, along with the other methods discussed above, in Section 3.3 to estimate $L_{\text{IR}}$.

3.2.4. Correcting SFR$_{\text{UV}}$ for Dust Absorption

In this section we describe how the SFR$_{\text{UV}}$ is estimated in our work and describe the four methods used to correct SFR$_{\text{UV}}$ for dust extinction. To estimate SFR$_{\text{UV}}$ (uncorrected for dust extinction), we fit the SEDs of our sources using the 3D-HST photometric catalogs and measure the UV flux (at a rest-frame wavelength of 1600 Å) from the best-fit stellar population model (for more details, see Reddy et al. 2015). We convert the estimated luminosity to SFR$_{\text{UV}}$ using the Kennicutt (1998) relation adjusted to a Chabrier (2003) IMF:

$$\text{SFR}_{\text{UV}} [M_{\odot} \text{yr}^{-1}] = 7.7 \times 10^{-29} \times L_{\nu(1600\text{Å})} [\text{erg s}^{-1} \text{Hz}^{-1}] .$$

(10)

The dust-corrected SFR$_{\text{UV,corr}}$ is given by $\text{SFR}_{\text{UV,corr}} = 10^{0.4\text{A}_{\text{UV}}} \times \text{SFR}_{\text{UV}}$, where $A_{\text{UV}}$ is the UV extinction. To estimate $A_{\text{UV}}$, we either use the color excess, $E(B-V)$, from SED fitting assuming $A_{\lambda} = K(\lambda) E(B-V)$, where $K$ is the attenuation curve, or use the UV continuum slope. We also investigate the effect of changing the assumed dust attenuation law and the assumed SFH in the SED modeling. For the dust attenuation we compare the widely used Calzetti et al. (2000) law with the more recent attenuation curve derived by Reddy et al. (2015) using data from the first 2 yr of the MOSDEF survey. For the SFH, we investigate two models: (i) a delayed exponentially declining SFH, and (ii) a constant SFH. We investigate the effect of the
adopted dust attenuation law and SFH on the UV extinction correction and consequently on our estimates of SFR$_{UV,corr}$, and the fraction of MIR-excess sources that are identified.

In our first method for correcting SFR$_{UV}$, we measure $E(B - V)$ by fitting the SEDs using the FAST code (Kriek et al. 2009) with a Chabrier (2003) IMF, Conroy et al. (2009) FSPS models, a delayed exponentially declining SFH with $\tau$ varying from 100 Myr to 1 Gyr, and the Calzetti et al. (2000) reddening curve and assuming a fixed solar metallicity. In the second method we fit the SEDs with all of the same input parameters, except we use the Reddy et al. (2015) attenuation curve.

In the third method, we use the UV spectral slope, $\beta$, to estimate the dust correction and derive SFR$_{UV,corr}$ for each galaxy in our sample. Rather than measuring the slope directly from the photometry, we measure the slope from the fits to the SEDs (we discuss this choice in Section 4.1). The input parameters in the SED fitting remain the same as in the row above. To measure the UV slopes, we follow the prescription of Calzetti et al. (1994) and use several continuum windows spanning 1250–2600 Å to avoid the stellar absorption features at these wavelengths. We then find the average relation between $A_{UV}$, as recovered from the full SED fits to each of our galaxies, and the observed value of $\beta$:

$$A_{UV} = 1.99 \beta + 4.13.$$  (11)

Finally, we recalculate $A_{UV}$ for each individual galaxy based on the measured $\beta$ and the average relationship given in Equation (11) above.

We note that our derivation of the average relationship between $A_{UV}$ and $\beta$ given in Equation (11) depends on the assumed dust attenuation law and SFH. Our final method for measuring $A_{UV}$ is using the relation between $A_{UV}$ and $\beta$ from Reddy et al. (2015):

$$A_{UV} = 1.84 \beta + 4.48.$$  (12)

Reddy et al. (2015) obtain this relation using the same method described above for Equation (11), but instead of a delayed exponentially declining SFH they assume a constant SFH with a fixed age of 100 Myr when performing the initial SED fitting. Under this assumption, a higher amount of dust is required to turn an intrinsically blue SED into a given observed SED, while with a slowly declining SFR both populations of old and newly formed stars exist. This mix of stellar population can match an observed SED without requiring as much dust (e.g., Schaerer et al. 2013). Additionally, we note that assuming a constant SFH with an age that is allowed to vary over a range similar to the $e$-folding time in our delayed-$\tau$ model (100 Myr–1 Gyr) results in a similar SFR$_{UV,corr}$ to that in our third method.

Another approach for estimating the UV continuum reddening is using the nebular reddening. In general, it has been shown that the visual extinction of nebular lines is greater than the reddening of the UV–optical continuum, as the ionizing radiation originates from regions close to the dusty molecular clouds (e.g., Calzetti et al. 1994; Calzetti et al. 2000). We additionally tested correcting the UV emission for dust absorption and estimating the SFR$_{UV,corr}$ and (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ using the ratio of the Balmer emission lines (H$\alpha$/H$\beta$) and the relation between the nebular and stellar $E(B - V)$ from Reddy et al. (2015, Equations (10) and (13)). While we find that the fraction of MIR-excess galaxies identified with this SFR$_{UV,corr}$ is relatively low, this correction method results in substantial scatter in (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ compared to the other methods discussed above. This scatter is due to both the relatively low S/N in the observed H$\beta$ flux measurements and the large scatter around the average relation between nebular and stellar reddening (Reddy et al. 2015).

3.3. MIR-excess Galaxies in MOSDEF

Figures 1–4 illustrate the (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ as a function of redshift for galaxies in the MOSDEF sample, where the SFR$_{IR}$ in each column is estimated using the templates described in Sections 3.2.1–3.2.3, and SFR$_{UV}$ is corrected for extinction using different methods described in Section 3.2.4. In these figures we present the median (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ and the percentage of galaxies identified as MIR excess in each panel, with errors estimated from bootstrap resampling. A median ratio close to 1 indicates a good agreement between SFR$_{UV,corr}$ and SFR$_{UV}$ for that combination of methods. We note that in some galaxies (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ may legitimately be higher than 1, but we do not expect this ratio to be substantially greater than 1 for the bulk of the population. AGNs are included in Figures 1–4; we discuss the impact of AGNs on the MIR-excess population in Section 3.5.

We note that each of the methods used to calculate the SFR has uncertainties and caveats (e.g., the effect of the adopted SFH on the UV attenuation estimation, or the uncertainty on the UV continuum slope measurements in optically thick galaxies). We discuss these issues further in Section 4. Overall, Figures 1 and 2 indicate that the percentage of 24 μm detected galaxies classified as MIR-excess galaxies can vary widely, from 20% to 78%, depending on the templates used to estimate L$_{IR}$ and the SFR$_{UV,corr}$ estimation. In the first two rows of Figure 1 the percentage of MIR-excess galaxies drops owing to a variation from the Calzetti et al. attenuation curve to that of Reddy et al. As discussed in Reddy et al. (2015), the overall shape of these attenuation curves is similar, but the normalization of Calzetti et al. is higher. The Reddy et al. curve thus results in slightly higher $E(B - V)$ in the red galaxies, which explains the lower percentage of MIR excess and median (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ in the second row of Figure 1. While the numbers do not change significantly from row 2 to row 3 in Figure 1, when we adopt a constant SFH in Figure 2, we find a significantly lower fraction of MIR-excess galaxies. However, the median ratio is closer to 1, indicating that using a constant SFH may result in a larger dust correction when estimating SFR$_{UV,corr}$.

As mentioned above, when the ratio of (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ is close to unity, the SFRs are in better agreement with each other, although each of the SFR tracers has uncertainties (see Section 4, which may result in a scatter around (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr} \sim 1$). The median (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ with the methods shown in Figure 1 varies from 2.8 to 11.0. These high values are due primarily to an overestimation of L$_{IR}$ found when applying local templates at high redshifts, as we discussed in Sections 3.2.2 and 3.2.3.

We note that, using the Chary & Elbaz (2001) templates and the Calzetti et al. (2000) attenuation curve, Daddi et al. (2007b) find that $\sim$20–30% of BzK-selected $z \sim 2$ galaxies are MIR excess, while we find a much higher fraction of MOSDEF galaxies (61%) with the same prescription. In Section 4 we discuss how various effects result in such a substantial difference in the incidence found in these studies.
Figure 1. (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ vs. redshift for MOSDEF galaxies with significant 24 μm detections. The dotted purple line shows (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ ~ 3.2, which is the threshold considered by Daddi et al. (2007a) for MIR-excess galaxy identification. The bolometric IR luminosity is estimated by extrapolating from the 24 μm band using the luminosity-dependent templates of Chary & Elbaz (2001), Dale & Helou (2002), and Rieke et al. (2009) in each column. Each row corresponds to a different method for estimating the extinction correction to SFR$_{UV}$. The methods used, starting at the top row, are as follows: estimating the color excess from the SED fitting with a delayed-τ SFH and assuming the Calzetti et al. (2000) attenuation curve and Reddy et al. (2015) attenuation curve, and using UV spectral slope as measured by fitting power laws at 1200–2600 Å to the best SED fit. The percentage of 24 μm detected galaxies that are also MIR-excess galaxies is shown in purple text, and the black text shows the median (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ in each panel. The fraction of MIR-excess galaxies identified depends on the templates used to estimate L$_{IR}$ and the extinction correction method.

Figure 2. (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ vs. redshift for MOSDEF galaxies with significant 24 μm detections. The bolometric IR luminosity is estimated by extrapolating from the 24 μm band using the luminosity-dependent templates of Figure 1. For estimating the SFR$_{UV}$ extinction correction, we measure the UV spectral slope by fitting power laws at 1200–2600 Å to the best SED fit assuming a constant SFH model with τ = 100 Myr (rather than the delayed τ model considered in Figure 1). The fraction of galaxies identified as MIR excess drops significantly compared to the last panel of Figure 1.
In Figure 3 we use luminosity-independent conversions from Elbaz et al. (2011) and Wuyts et al. (2008) for estimating $L_{IR}$. In the left column we use a universal ratio of $L_{IR}/L_{8} = 4.9$ from Elbaz et al. (2011), and in the right column we use the conversion factors from Wuyts et al. (2008) for MIPS 24 $\mu$m fluxes at the redshift of each of our galaxies. Comparing Figures 3 and 1 indicates that using the Elbaz et al. (2011) method results in a substantial decrease in the median $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$ and the fraction of MIR-excess galaxies compared to the Chary & Elbaz (2001) method. However, given the errors, we do not find any significant differences between the numbers resulting from the Wuyts et al. (2008) and the Dale & Helou (2002) methods. Overall, we find that a luminosity-independent conversion such as the Elbaz et al. (2011) universal ratio leads to better agreement between $SFR_{IR} + SFR_{UV}$ and $SFR_{UV,corr}$ at $z \sim 2$.

In Figure 4 we use $(L_{IR})/(L_{7.7})$ given in bins of stellar mass in Shivaei et al. (2017), combined with $L_{7.7}/L_{8} = 1.25$, to estimate $L_{IR}$ for individual galaxies considered in this study. The median $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$ ratio indicates an improvement compared to the results shown in the left panel of Figure 1, which uses the same template set but where $L_{IR}$ was estimated directly from the 24 $\mu$m data using the luminosity-dependent template from Chary & Elbaz (2001). The percentage of MIR-excess galaxies is substantially lower in Figure 4 as well.

Overall, the results using the stellar-mass-dependent method of Shivaei et al. (2017, see Figure 4) and the luminosity-independent method of Elbaz et al. (2011, see first column of Figure 3) are consistent with each other. These methods, combined with the SFR$_{UV}$ extinction correction based on the relation between $A_{UV}$ and $\beta$ (estimated from the best fit to the SED assuming a delayed exponentially declining SFH model, as shown in the third rows of Figures 3 and 4), lead to $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$ close to unity and identification of 22%–32% of our galaxies as MIR excess, as well as the median $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$. Overall, the fraction of MIR-excess galaxies and the median $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$ drop significantly compared to the values in the left column of Figure 1.
excess. We emphasize again that while the similar UV correction method shown in the fourth rows of Figures 3 and 4 (which is derived assuming a constant SFH) leads to a much lower fraction of MIR-excess galaxies, a larger dust correction for estimating SFR_{UV,corr} may be required.

We further test the methodology of Shivaei et al. (2017) with the Dale & Helou (2002) and Rieke et al. (2009) templates (instead of the Chary & Elbaz 2001 templates) and estimate the average L_{IR} and L_{IR}^\text{cc} values in bins of stellar mass. We show ⟨L_{IR}/L_8⟩ in bins of stellar mass in Figure 5 and list the values in Table 1. The ⟨L_{IR}/L_8⟩ ratios estimated using these various templates are consistent with each other. While the three sets of templates used for estimating ⟨L_{IR}/L_8⟩ in Table 1 are luminosity dependent, we assume that these ratios are luminosity independent and can thus be used to estimate L_{IR} directly for a z ∼ 2 galaxy with a 24 μm detection, whether or not it is detected with Herschel. Figure 5 also illustrates that the stellar-mass-dependent conversions of Shivaei et al. (2017) are consistent with the single, luminosity-independent conversion factor assumed by Elbaz et al. (2011) for high stellar mass sources (log (M_*/M_☉) > 10). Shivaei et al. (2017) find that a larger correction factor is required for lower stellar mass sources, which results in the identification of a larger population of MIR-excess galaxies (32%) with their SFR_{IR} estimation compared to the Elbaz et al. method (22%). We explore the effect of stellar mass in identification of MIR-excess galaxies further in the next section.

3.4. MIR Excess and Stellar Mass

In this section, we examine how the incidence of MIR excess varies with the stellar mass of the galaxies. In the top panels of Figure 6 we plot (SFR_{IR} + SFR_{UV})/SFR_{UV,corr} versus stellar mass for the Daddi et al. (2007b) prescription (left panels) and for our preferred method (right panels), where the stellar masses are derived from SED fitting as discussed in Section 2.4. The correlation coefficients (cc) and their corresponding significance (p) are shown in each panel. We use the r-correlate routine in IDL, which calculates the Spearman’s rank correlation coefficient and the significance of its deviation from zero. In the bottom panels we plot the fraction of MIR-excess galaxies as a function of stellar mass in intervals of Δ log (M_*/M_☉) = 0.5 dex. We calculate the errors assuming a binomial distribution using the Bayesian method of Cameron (2011).

The relation between (SFR_{IR} + SFR_{UV})/SFR_{UV,corr} and stellar mass varies from a statistically significant negative trend in the right panel to a statistically significant positive trend in the left panel. It is possible that neither of these trends reflect an intrinsic, underlying correlation, and instead they may be the result of observational selection biases and inaccurate L_{IR} estimates. Figure 6 shows that there is a selection bias in the lowest-mass bin, where we are unable to detect galaxies with low (SFR_{IR} + SFR_{UV})/SFR_{UV,corr}. This selection bias, combined with an overestimation of L_{IR} in more massive galaxies with Chary & Elbaz (2001) templates, leads to an observed positive correlation in the left panel. In the right panel, for massive galaxies we have a more reliable estimate of L_{IR} and therefore find an overall negative trend due to the selection bias at the low-mass end. If we limit our analysis to the four middle stellar-mass bins where the majority of our sources are, we still find a significant difference between the fraction of MIR-excess galaxies in the two panels.

Investigating the relation between SFR_{IR} and SFR_{UV,corr} with stellar mass in these two methods can help resolve this discrepancy. The method used by Daddi et al. (2007b) overestimates L_{IR} in moderately massive to massive galaxies compared to our preferred method. There is also a large scatter between SFR_{UV,corr} and stellar mass using the Daddi et al. (2007b) prescription with the Calzetti et al. (2000) attenuation curve, compared to our preferred methodology with the Reddy et al. (2015) attenuation curve. A combination of these two trends results in the observed differences in the middle stellar-mass bins in Figure 4.

We note that Daddi et al. (2007b) find that MIR-excess sources are preferentially identified in galaxies with large stellar masses and find that the fraction of MIR-excess galaxies increases with increasing stellar mass. While using the same methodology, we also find a significant positive correlation, and as argued above, this could occur as a result of selection biases and L_{IR} overestimation.

Overall, we find that the relation between (SFR_{IR} + SFR_{UV})/SFR_{UV,corr} and stellar mass, as well as the fraction of MIR-excess galaxies in bins of stellar mass, strongly depends on the templates and reddening corrections used. Observational selection biases, inaccurate L_{IR} estimation, and variations in the reddening correction used can lead to the discrepancies between the trends shown in Figure 6.
3.5. AGNs Identified in MIR-excess Galaxies

Several studies have proposed that the observed MIR-excess occurs in galaxies owing to an underlying AGN contribution (e.g., Daddi et al. 2007b; Alexander et al. 2011). Daddi et al. (2007a), after excluding the X-ray-detected AGNs, find that 20%–30% of the $z \sim 2$ galaxies ($BzK$-selected star-forming galaxies with $K < 20.5$) are MIR excess and argue that the existence of this population reflects the presence of an underlying obscured AGN population. Generally, AGNs can provide a substantial contribution to the observed MIR emission, though the MIR colors (i.e., IRAC colors) are distinguishable from star-forming galaxies (e.g., Alonso-Herrero et al. 2006; Donley et al. 2012). Here we address the question of whether AGNs may substantially contribute to and perhaps even be the main source of the MIR-excess phenomenon.

While the analysis by Daddi et al. (2007b) was limited to X-ray-selected AGNs, in the MOSDEF survey we benefit from having a sample of AGNs identified at different wavelengths. As discussed in Section 2.3, in addition to X-ray- and IR-detected AGNs, we can use optical BPT selection, which can recover AGNs that might be missed by X-ray and IR imaging (Azadi et al. 2017).

In Figures 1–4 we presented 24 different methods for the identification of MIR-excess galaxies, based on different combinations of methods to correct the UV emission for dust and extrapolate from the observed 24 $\mu$m flux to estimate the total IR luminosity. As discussed above, the combination of the dust correction estimated from the UV spectral slope and the Shivaei et al. (2017) method (the luminosity-independent, mass-dependent, $L_{24}$/L$_{6}$ derived using Herschel stacks) results in SFR$_{IR}$ + SFR$_{UV}$ and SFR$_{IR,corr}$ being consistent for the bulk of the galaxies and is therefore the preferred methodology in this paper. The prescription used by Daddi et al. (2007b) corresponds to using the color excess from the SED fits with the Calzetti et al. reddening curve and the Chary & Elbaz (2001) luminosity-dependent IR templates. We compare our preferred methodology and the Daddi et al. (2007b) prescription in Figure 7 and find the fraction of sources that are identified as X-ray, IR, or optical AGNs above and below the MIR-excess threshold. With the Daddi et al. (2007b) prescription in the top panel of Figure 7 we find a higher percentage of X-ray, IR, and/or optical AGNs at $2\sigma$–$3\sigma$ in the MIR-excess region. With our preferred method in the bottom panel, we find that none of the three AGN identification techniques result in AGNs being more prevalent in the MIR-excess region.
However, the median $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$ ratio of 4.9 found with the Daddi et al. (2007b) prescription indicates that the higher incidence of AGNs in MIR-excess galaxies is due to the faulty estimation of the total SFR, and with the more reliable estimates in the bottom panel of this figure we no longer find any evidence for a significantly higher prevalence of AGNs in MIR-excess galaxies.

We note that while in Figure 7 we illustrate only 2 of the 24 methods of SFR estimation discussed in this paper, we perform a similar analysis for all the other methods as well. Of the other 22 combinations of methods investigated for SFR estimation, none result in a significantly higher fraction (at even the 2σ level) of AGNs among MIR-excess galaxies than in MIR-normal galaxies.

### 3.6. X-Ray Stacking Analysis of MIR-excess Galaxies

X-ray detection is a well-known, reliable method for robust AGN identification (e.g., Mendez et al. 2013; Azadi et al. 2017); however, it fails to identify highly absorbed AGNs with hydrogen column densities of $N_H > 1.5 \times 10^{24}$ cm$^{-2}$ (e.g., Della Ceca et al. 2008; Comastri et al. 2011). Studies predict that 10%–50% of AGNs are Compton thick (e.g., Akylas & Georgantopoulos 2009; Alexander et al. 2011; Lanzuisi et al. 2015). The absorbed and reprocessed radiation from these AGNs buried in dust may contribute to the observed MIR radiation in galaxies.

To examine whether the excess observed at MIR wavelengths in our galaxies occurs as a result of obscured AGN activity, we exclude the X-ray-detected AGNs from our sample and then stack the X-ray photons from the remaining sources. In this section we investigate the hardness ratio $(H-S)/(H+S)$, where $H$ and $S$ are the net count rates in the hard (rest-frame 2–10 keV) and soft (rest-frame 0.5–2 keV) X-ray bands, respectively, and are calculated for both the MIR-excess and MIR-normal galaxies. The hardness ratio is a tracer of the X-ray spectrum shape and the amount of obscuration. A positive hardness ratio indicates sources with a hard X-ray spectrum, indicating obscured AGNs, while a negative hardness ratio indicates sources with a softer spectrum, unobscured AGNs or the X-ray emission from star-forming galaxies. To estimate $H$ and $S$, we use the number of counts measured within an aperture with a radius corresponding to 70% of the enclosed energy fraction for the PSF at each galaxy position, while the background is determined from background maps based on smoothing of local counts.

In Figure 8 we present the hardness ratio for the MIR-excess (purple) and MIR-normal (gray) galaxies using the Daddi et al. (2007b) method (left) and our preferred method (right). The errors on the hardness ratios are calculated using bootstrap resampling. We find a relatively harder signal in MIR-normal galaxies compared to the MIR-excess population (at the 2σ...
level with our preferred method). The negative hardness ratios indicate that a soft X-ray signal dominates in MIR-excess galaxies. When we consider all the other combinations of methods as discussed above, in none of them does the hardness ratio of MIR-excess galaxies reflect an underlying hard spectrum that could be due to an AGN. Finding a harder spectrum in MIR-normal galaxies compared to MIR-excess galaxies is at odds with the findings of Daddi et al. (2007b).

We also calculate the average X-ray luminosities for the MIR-normal and MIR-excess galaxies based on our X-ray stacking in the hard X-ray band. When using our preferred method to identify MIR-excess galaxies, we measure an average rest-frame 2–10 keV X-ray luminosity of $\log(L_{2-10\text{ keV}}/\text{erg s}^{-1}) = 42.7 \pm 0.10$ for the MIR-normal galaxies. This luminosity is higher than the expected X-ray emission due to star formation processes: $\log(L_{\text{SF}}/\text{erg s}^{-1}) \approx 42$ for $z \sim 2.1$ star-forming galaxies with stellar masses $\sim 10^{10.5} M_\odot$, typical for our sample (see Lehmer et al. 2016; Aird et al. 2017).

For the MIR-excess galaxies we find a slightly lower average luminosity, $\log(L_{2-10\text{ keV}}/\text{erg s}^{-1}) = 42.5 \pm 0.12$. We note that while the luminosities of both of these populations are consistent with a star formation origin, the slightly higher $L_{2-10\text{ keV}}$ in both MIR-excess and MIR-normal galaxies compared to the main sequence of star formation (for a similar stellar mass and redshift regime) could be due to some contribution from X-ray-detected AGNs in this sample, as might be expected. The slightly lower $L_X$ in MIR-excess galaxies compared to the MIR-normal galaxies may be due to the slightly lower masses of MIR-excess galaxies ($1.7 \times 10^{10} M_\odot$) compared to the MIR-normal galaxies ($2.9 \times 10^{10} M_\odot$).

Using the Daddi et al. (2007b) prescription, we find $\log(L_{2-10\text{ keV}}/\text{erg s}^{-1}) = 42.5 \pm 0.14$ for the MIR-normal galaxies and $\log(L_{2-10\text{ keV}}/\text{erg s}^{-1}) = 42.6 \pm 0.10$ for MIR-excess galaxies. The luminosities and the hardness ratios of the MIR-normal and MIR-excess galaxies identified with the Daddi et al. (2007b) method are both consistent with a star formation origin. The hard spectrum of the MIR-excess galaxy sample originally identified by Daddi et al. (2007b) is probably due to a few undetected X-ray AGNs, which would be detected with deeper X-ray surveys (see also Alexander et al. 2011; Rangel et al. 2013).

We showed in the section above that there is not a higher fraction of detected AGNs above the MIR-excess threshold than below it with our preferred method. Here we find that a stacking analysis of our X-ray-undetected sample does not indicate a harder spectrum in MIR-excess galaxies than in MIR-normal galaxies, which shows that AGNs do not contribute substantially to the MIR radiation in our MIR-excess sample.

### 3.7. SFR_{Hα} of the MIR-excess Galaxies

In MOSDEF we benefit from having spectroscopic measurements for a statistically large sample of galaxies at $z \sim 2$. Therefore, we can also estimate the SFR based on the Hα emission line (hereafter SFR_{Hα}) and investigate whether MIR-excess galaxies have elevated SFR_{Hα} compared to the MIR-normal galaxies.

In Figure 9 we illustrate $\text{SFR}_{\text{IR}} + \text{SFR}_{\text{UV}}/\text{SFR}_{\text{UV,corr}}$ versus SFR_{Hα}/SFR_{UV,corr} for the galaxies and AGNs in our sample. For this analysis we limit our sample to the sources with significant ($>3\sigma$) Hα and Hβ detections, which decreases our sample size to...
114 sources. SFR$_{H\alpha}$ is calculated from the luminosity of the H$\alpha$ line using the relation given by Kennicutt (1998) and is corrected for attenuation using the Balmer decrement ($H\alpha/H\beta$). Similar to the plots shown above, AGNs are included in this analysis and are shown in orange, although the AGNs may contribute to the H$\alpha$ emission. The horizontal dotted line is the threshold of (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ $\sim$ 3.2 defined by Daddi et al. (2007b) for MIR-excess identification. The vertical dotted line shows the equivalent threshold on SFR$_{HI}$/SFR$_{UV,corr}$ $\sim$ 3.2, identifying sources that exhibit an excess in H$\alpha$ emission (relative to the dust-corrected UV continuum emission).

In both the Daddi et al. (2007b) prescription (left) and our preferred methodology (right) we find a positive trend between (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ and SFR$_{HI}$/SFR$_{UV,corr}$. In both panels the majority of the MIR-normal galaxies also have SFR$_{HI}$/SFR$_{UV,corr}$ less than the vertical threshold, and only a very few of the MIR-normal galaxies are beyond this limit. The majority of MIR-excess galaxies identified with our prescription are below the vertical limit in the right panel, while with the Daddi et al. (2007b) prescription in the left panel almost half of them are above the vertical limit. However, as discussed above, such a high (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ using the Daddi et al. (2007b) prescription is due to an overestimation of the total IR luminosity. We also note that almost 40% of the MIR-excess sources that are beyond the vertical limit are AGNs in both panels and are expected to have elevated H$\alpha$ emission.

Overall, Figure 9 shows that MIR-excess galaxies in MOSDEF do not necessarily have high SFR$_{HI}$/SFR$_{UV,corr}$ values. Therefore, while the elevated SFR$_{IR}$ in $\sim$30% of the galaxies in our sample may be due to legitimately higher SFR$_{IR}$ than other SFR tracers, it may also be the result of an overestimation of SFR$_{IR}$.

4. Discussion

In this paper we use data from the MOSDEF survey to investigate the nature of MIR-excess galaxies at $z \sim$ 2. We find that the MIR-excess incidence depends strongly on the templates used for estimating $L_{IR}$ and the reddening correction of SFR$_{UV}$, with the percentage of galaxies identified as MIR-excess varying between $\sim$10% and 80% depending on which of these methods is used. Using the mass-dependent, luminosity-independent templates from Shaviv et al. (2017) for estimating $L_{IR}$ and the UV slope for the SFR$_{UV}$ correction, we identify 32% ± 3% of the MOSDEF galaxies as MIR-excess galaxies. We note that while this combination of SFR$_{IR}$ and SFR$_{UV}$ results in (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ close to unity, there may be some galaxies for which this ratio is legitimately greater than 1, though we do not expect this for the bulk of the population.

In this section we first discuss how the specific method used to determine the UV reddening correction plays an important role in robustly estimating the extinction-corrected SFR$_{UV}$. We then discuss how PAH features may contribute to the observed MIR excess. We then investigate the AGN contribution to MIR-excess galaxies, and finally, we compare the identification of MIR-excess galaxies in this study with Daddi et al. (2007b).

4.1. UV Reddening Correction Estimation

In Section 3 (Figures 1–4), we examine various methods for the reddening correction of the UV photometry: using the color excess estimated directly from SED fitting with the Calzetti et al. (2000) and Reddy et al. (2015) attenuation curves, and using the average relationship between reddening and UV continuum slope assuming either a delayed-$\tau$ or constant SFH model for the underlying stellar population. Our results show that the different methods for estimating the reddening correction result in substantial changes to the fraction of MIR-excess galaxies identified (for a given set of IR templates).

Using the attenuation curve of Reddy et al. (2015) results in a decrease in (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ and the fraction of MIR-excess, compared to using the widely adopted Calzetti et al. (2000) attenuation curve. The magnitude of the decrease depends on the $L_{IR}$ templates used. As discussed in Reddy et al. (2015), the overall shapes of the Calzetti et al. and Reddy et al. attenuation curves are identical at short wavelengths, but the
Reddy et al. curve has a lower normalization. The substantially redder $E(B-V)$ ($\Delta E(B-V) \sim 0.1$) of Reddy et al.\textsuperscript{10} results in a higher UV correction factor compared to Calzetti et al. and hence a lower fraction of MIR-excess galaxies.

We find that using the UV spectral slope for the reddening correction, along with robust estimates of $L_{IR}$, results in a median (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ ratio close to unity, illustrating a consistency between the SFR$_{IR}$ + SFR$_{UV}$ and SFR$_{UV,corr}$ measurements. Using the UV slope also results in the lowest percentage of MIR-excess galaxies (12%–74% depending on the $L_{IR}$ estimation and the adopted SFH).

The UV slope used in this analysis is measured by fitting a power law to the SED fit ($\beta_{SED}$) at 1200–2600 Å assuming a delayed-τ SFH model (see Section 3.2.4). However, it is also common to estimate the UV slope by fitting a power law directly to the photometric data ($\beta_{phot}$) at these wavelengths (e.g., Reddy et al. 2015; Shvai et al. 2015b). We find for the MOSDEF sample that using $\beta_{phot}$ instead of $\beta_{SED}$ increases the fraction of MIR-excess galaxies from 32% ± 3% to 50% ± 3% and the median (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ to 3.2 (using Shvai et al. 2017, $L_{IR}$ estimates). In Figure 10 we plot $\beta_{phot}$ versus $\beta_{SED}$ and find that while the values roughly scatter around the 1:1 line, the best-fit line is $\beta_{SED} = 0.8 \beta_{phot} + 0.1$. This results in a larger extinction correction factor (10$^{0.4\lambda_{UV}}$, assuming Equation (11)) using $\beta_{SED}$, and consequently a smaller fraction of MIR-excess galaxies are identified using $\beta_{SED}$ instead of $\beta_{phot}$.

The error bars in Figure 10 demonstrate the large uncertainty in the $\beta_{phot}$ measurements, due to the relatively large errors on the UV photometric data, particularly in red galaxies that are faint at UV and optical wavelengths. Despite the large errors, $\beta_{phot}$ provides an estimation of the slope independent of any assumption about the stellar population, while $\beta_{SED}$ relies on the models adopted in the SED fitting. However, this can be a disadvantage in galaxies that have redder slopes owing to an older stellar population rather than dust obscuration. We note that while the errors on $\beta_{SED}$ are not calculated here, they are expected to be smaller than the errors on $\beta_{phot}$, as they are estimated using many more photometric data points.

Overall, we find that $\beta_{SED}$ provides a good estimate of SFR$_{UV,corr}$ when comparing SFR$_{UV,corr}$ with SFR$_{UV}$ +SFR$_{IR}$, and the commonly used $\beta_{phot}$ may underestimate the reddening correction factor, as it results in a substantially higher fraction of MIR-excess galaxies and average (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$. Fitting a power law to the SED to estimate the UV spectral slope may be more reliable than fitting to the photometry directly, due to the larger uncertainties in the UV photometric data.

$\Delta E(B-V)$ of the Reddy et al. (2015) attenuation curve compared to that of Calzetti et al. (2000) may also depend on the adopted SFH.

\textsuperscript{10}We note that $\Delta E(B-V)$ of the Reddy et al. (2015) attenuation curve compared to that of Calzetti et al. (2000) may also depend on the adopted SFH.

Figure 10. UV spectral slope estimated from fitting a power law to the full SED fit ($\beta_{SED}$) vs. the slope from fitting a power law to the photometric data at 1200–2600 Å ($\beta_{phot}$). The gray dotted line is the 1:1 line, and the gray solid line is the best-fit line ($\beta_{SED} = 0.8 \beta_{phot} + 0.1$). The large uncertainties on the photometric data lead to the large error bars on $\beta_{phot}$. On average $\beta_{SED}$ is larger than $\beta_{phot}$, which results in a higher reddening correction to SFR$_{UV}$ and consequently a lower (SFR$_{IR}$ + SFR$_{UV}$)/SFR$_{UV,corr}$ and lower fraction of MIR-excess galaxies compared to results using $\beta_{phot}$.

2010; Rodighiero et al. 2010, among others). Using the methods of Elbaz et al. (2011) and Shvai et al. (2017) (along with the UV spectral slope), we identify 22% ± 3% and 32% ± 3% of our galaxies, respectively, as MIR-excess galaxies; these fractions are lower than those obtained using other IR templates. The advantage of Shvai et al. (2017) is that it takes into account the dependence of $<L_{IR}>/L_{8}$ on stellar mass. As illustrated in Figure 5, the ratios using the Shvai et al. (2017) method (with the template sets of Chary & Elbaz 2001; Dale & Helou 2002; or Rieke et al. 2009) are generally consistent with $L_{IR}/L_{8}$ from Elbaz et al. (2011) and are discrepant only in our lowest stellar-mass bin of $M_{*} < 10^{10} M_{\odot}$.

Using a robust $L_{IR}$ estimation and the UV slope for the reddening correction, we find that ~30% of the galaxies in our sample are MIR excess. Our analysis in Sections 3.5 and 3.6 does not provide any evidence for substantial AGN contribution in MIR-excess galaxies compared to the MIR-normal galaxies. Therefore, the excess MIR radiation detected in ~30% of our sources is likely due to other phenomena contributing to MIR radiation. The observed 24 μm band at z ~ 2 also includes line emission from PAH molecules at rest-frame wavelengths of 5–12 μm. Therefore, the incidence of MIR excess may be due to PAH features in normal star-forming galaxies entering the infrared bands (see also Nordon et al. 2010; Lutz et al. 2011; Nordon et al. 2012).

While studies predict that 5%–20% of the bolometric IR radiation is from PAH molecules (e.g., Smith et al. 2007; Shipley et al. 2016), the strength of radiation from PAH molecules varies with galaxy stellar mass, metallicity, and/or star formation activity (e.g., Engelbracht et al. 2006; Smith et al. 2007; Shipley et al. 2016; Shvai et al. 2017). Shvai et al. (2017), after including PAH features in their templates and determining calibrations from Herschel data, find that the PAH radiation at 7.7 μm depends on the age and stellar mass of galaxies and is lower in young galaxies with ages $\leq$500 Myr, as...
well as galaxies with $M_* < 10^{10} M_\odot$. Our analysis in the right panel of Figure 6 indicates that at $M_* \lesssim 10^{10} M_\odot$ we identify many MIR-excess galaxies. This high incidence of MIR excess in low-mass galaxies could be due to a selection effect: given that our sample is selected based on 24 $\mu$m observations, if a galaxy has strong PAH features, it is more likely to be detected at 24 $\mu$m and to be included in our sample. While according to Shivaei et al. (2017) in lower-mass galaxies, for a given $L_{IR}$, PAH emission is suppressed, there could also be an increased scatter in the strength of PAH emission in individual galaxies at lower mass. Such an increased scatter could result in a higher fraction of MIR-excess galaxies at $M_* \lesssim 10^{10} M_\odot$.

Indeed, the scatter in the relative strength of PAH emission to $L_{IR}$ is lower in moderate-mass galaxies with $M_* > 10^{10} M_\odot$ (Shivaei et al. 2017). If we limit our analysis to galaxies with $M_* > 10^{10} M_\odot$, where we likely do not have stellar-mass selection biases in our sample, the fraction of MIR-excess galaxies decreases to 24% ± 2%. However, given that SFR$_{H\alpha}$ is not elevated in the MIR-excess galaxies in our sample, the intrinsic fraction of MIR-excess may be even lower than 24%.

4.3. AGN Contribution

Our multiwavelength AGN and X-ray stacking analysis shows that it is unlikely for either detected or undetected AGNs to contribute substantially to the MIR excess observed in our MIR-excess galaxies. Following a similar prescription to that of Daddi et al. (2007b) for SFR estimations, we find that X-ray AGNs are more prevalent in the MIR-excess region at the 2σ level and that IR and optical AGNs show the same behavior as well (despite the fact that, unlike Daddi et al. (2007b), our sample is not $BzK$ selected). However, when using more robust estimates of SFRs, we do not find a higher incidence of AGNs in the MIR-excess region; therefore, the higher prevalence of detected AGNs in MIR-excess sources using the methodology of Daddi et al. (2007b) primarily occurs as a result of inaccurate SFR estimates.

More recently, using similar methodologies to those of Daddi et al. (2007b), Rangel et al. (2013) find that at $z \sim 2$ the fraction of X-ray-detected AGNs above the MIR-excess threshold is three times higher than below the threshold. However, they argue that this is due to a strong correlation between $(SFR_{IR} + SFR_{UV})/SFR_{UV,corr}$ and $L_{IR}$ and show that the fraction of X-ray-detected AGNs above and below the MIR-excess threshold is very similar if considered in narrow bins of $L_{IR}$.

Our stacking analysis in Figure 8 shows that the hardness ratio of X-ray-undetected MIR-excess and MIR-normal galaxies does not vary depending on the methods used to estimate SFRs. Unlike in Daddi et al. (2007b), in almost all of our combinations of methods we find a harder X-ray spectrum for MIR-normal galaxies than for the MIR-excess population, indicating, if anything, a higher incidence of AGNs in the normal galaxies than the MIR-excess population. With our preferred methodology (right column of Figure 8) we find that the MIR-excess galaxies have a soft X-ray spectrum with a hardness ratio of $-0.16 \pm 0.14$ and an average X-ray luminosity of $\sim 10^{42} \text{erg s}^{-1}$ in both the soft and hard X-ray bands, consistent with a minimal AGN contribution and the bulk of the X-ray emission from the MIR-excess galaxies being associated with star formation.

Using deep X-ray data in the CDFN and CDFS fields, Rangel et al. (2013) stack the X-ray-undetected sources and find hardness ratios of $-0.50 \pm 0.12$ and $-0.45 \pm 0.15$, respectively, above and below the MIR-excess threshold.

Neither of these hardness ratios indicates the presence of underlying obscured AGN activity. By limiting their sample to the same depth (1 Ms) as Daddi et al. (2007b), Rangel et al. (2013) find a harder spectrum with a hardness ratio of $-0.16 \pm 0.16$ for MIR-excess galaxies and argue that the relatively harder spectrum in Daddi et al. (2007b) is due to a few undetected X-ray AGNs in that sample that are detected with the deeper X-ray data. These findings indicate that some of the sources identified as MIR excess in the Daddi et al. (2007b) sample are indeed obscured AGNs, but this does not show that an MIR excess occurs generally owing to a contribution from AGNs.

While the Daddi et al. (2007b) and Rangel et al. (2013) samples utilize the CDFS and CDFN fields (see also Alexander et al. 2011), MOSDEF spans a larger number of fields, which have different X-ray depths. To investigate the effect of X-ray depth, we estimate the hardness ratio of the X-ray-undetected sample in each of our fields above and below the MIR-excess threshold, using our preferred method for SFR estimates. We do not find a harder spectrum in MIR-excess stacks compared to the MIR-normal galaxies in any of these fields. Overall, our stacking analysis does not indicate a hard X-ray spectrum or a strong AGN contribution to MIR-excess galaxies.

4.4. Comparison with Daddi et al. (2007b) Results

In this study using our preferred methodology we identify 32% ± 3% of the MOSDEF sample as MIR-excess galaxies. As discussed in Section 4.2, once the stellar-mass selection biases are taken into account, this fraction decreases to 24% ± 2%. While these fractions are similar to the fraction of MIR-excess galaxies ($\sim 20\%$–$30\%$) identified by Daddi et al. (2007b) in their $BzK$-selected sample at a similar redshift and a similar stellar-mass regime, as discussed extensively above, the overestimation of $L_{IR}$ in the Daddi et al. (2007b) analysis is likely to play an important role in their identification of MIR-excess galaxies. Using a similar approach to Daddi et al. (2007b) (in column 1, row 1 of Figure 1), we identify 61% ± 3% of our sources as MIR-excess galaxies.

We note additional minor differences in our approaches: here we use the color excess estimated from SED fitting with the Calzetti et al. (2000) attenuation curve for the reddening correction in our estimate of SFR$_{UV,corr}$, whereas Daddi et al. (2007b) use the relation between $E(B - V)$ and $B - z$ color from Daddi et al. (2004) assuming the Calzetti et al. (2000) attenuation curve. In addition, the Daddi et al. (2007b) sample is $BzK$ selected, and different galaxy selections could lead to differences in the MIR-excess fraction. With a similar $L_{IR}$ estimation to that of Daddi et al., using our UV spectral slope method instead of the Calzetti et al. attenuation curve results in a significant decrease in the MIR-excess fraction in Figure 1. Therefore, the identification of a large population of MIR-excess galaxies when reproducing the Daddi et al. (2007b) method appears to be due to underestimating the dust-corrected SFR$_{UV,corr}$ combined with an overestimate of SFR$_{IR}$ due to the use of locally calibrated, luminosity-dependent IR templates.

With a more careful estimation of the SFRs, and after correcting for stellar-mass selection biases, in this work we find that 24% of our $z \sim 2$ galaxies are MIR excess. This incidence is primarily due to enhanced PAH emission at $z \sim 2$ in moderate-mass galaxies, rather than obscured AGN activity. PAH emission may also affect the incidence of MIR excess in the Daddi et al. sample, but the inaccurate SFR estimation is likely to play a dominant role in their analysis.
5. Summary

In this paper, we use the data from the first 3 yr of the MOSDEF survey to study the nature of MIR-excess galaxies. We define MIR-excess galaxies as those where the combined SFR$_{IR}$ and SFR$_{UV}$ exceed the extinction-corrected SFR$_{UV}$ by a factor of three or greater. We limit our analysis to galaxies with significant 24 $\mu$m and UV detections, and to ensure that the 24 $\mu$m data trace the rest-frame 8 $\mu$m data, we further restrict our analysis to the 194 galaxies and AGNs at 1.40 < $z$ < 2.61. We investigate templates from various studies for $L_{IR}$ estimation, as well as various reddening correction methods, and identify the preferred combination as the one where the SFR estimates agree such that SFR$_{IR}$ + SFR$_{UV}$ ∼ SFR$_{UV,corr}$. We investigate how different combinations of templates and reddening corrections result in identification of a different fraction of our sample as MIR-excess galaxies. We further investigate the contribution from AGNs in the excess MIR radiation.

Our main conclusions are as follows:

1. The identification of MIR-excess galaxies is strongly dependent on the UV dust reddening correction method used, as well as the total IR luminosity estimation. Our preferred methodology (SFR$_{IR}$ estimation using results from Shivaiei et al. (2017), and UV slope estimation from the best-fit SED assuming a delayed–$\tau$ SFH for SFR$_{UV,corr}$ estimation) results in identification of ∼30% of the MOSDEF sample as MIR-excess galaxies. This fraction decreases to 24% once stellar-mass selection biases are taken into account.

2. The bolometric IR luminosity estimated from locally calibrated, luminosity-dependent templates overestimates $L_{IR}$ and SFR$_{IR}$ in $z$ ∼ 2 galaxies. Our analysis shows that the stellar-mass-dependent, luminosity-independent method of Shivaiei et al. (2017), which is calibrated including PAH emission and using stacks of Herschel FIR data, provides a more robust $L_{IR}$ estimation at higher redshifts and results in the identification of fewer galaxies as MIR-excess sources.

3. The UV spectral slope estimated by fitting a power law to the SED fit at UV wavelengths provides a reliable reddening correction in that it results in consistency between SFR$_{UV,corr}$ and SFR$_{IR}$ + SFR$_{UV}$. The UV spectral slope can also be measured by fitting a power law directly to the photometric data, though this has larger errors and leads to the identification of a higher fraction of galaxies as MIR-excess galaxies.

4. The SFR$_{IR}$ in MIR-excess galaxies is not elevated compared to MIR-normal galaxies in our sample, such that an overestimation of SFR$_{IR}$ may result in identification of some galaxies as MIR excess in our sample. Therefore, the intrinsic fraction of MIR-excess galaxies may be even lower than 24%.

5. Using reliable estimates of SFR$_{IR}$ and dust-corrected SFR$_{UV}$, we do not find a higher fraction of AGNs detected in MIR-excess galaxies compared to MIR-normal galaxies. Additionally, stacking the X-ray-undetected galaxies does not reveal a hard X-ray spectrum in MIR-excess galaxies. Therefore, AGNs are not the dominant cause of galaxies having an MIR excess.

6. The MIR-excess phenomenon in our moderate-mass galaxies ($M_\odot > 10^{10} M_\odot$) is most likely due to the enhanced emission from PAH dust molecules as the 24 $\mu$m band at $z$ ∼ 2 traces PAH features.

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