No Evidence for Feedback: Unexceptional Low-ionization Winds in Host Galaxies of Low Luminosity Active Galactic Nuclei at Redshift $z \sim 1$

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Abstract

We study winds in 12 X-ray AGN host galaxies at $z \sim 1$. We find, using the low-ionization Fe II $\lambda 2586$ absorption in the stacked spectra, that the probability distribution function (PDF) of the centroid-velocity shift in AGNs has 50th (median), 16th, and 84th percentiles of ($-87, -251, +86$) km s$^{-1}$ respectively. The PDF of the velocity dispersion in AGNs has 50th (median), 84th, and 16th percentiles of (139, 253, 52) km s$^{-1}$ respectively. The centroid velocity and the velocity dispersions are obtained from a two-component (ISM+wind) absorption-line model. The equivalent width PDF of the outflow in AGNs has 50th (median), 84th, and 16th percentiles of (0.4, 0.8, 0.1) Å. There is a strong ISM component in Fe II $\lambda 2586$ absorption (with (1.2, 1.5, 0.8) Å, implying the presence of a substantial amount cold gas in the host galaxies. For comparison, star-forming and X-ray undetected galaxies at a similar redshift, matched roughly in stellar mass and galaxy inclination, have a centroid-velocity PDF with percentiles of ($-74, -258, +90$) km s$^{-1}$, and a velocity dispersion PDF with percentiles of (150, 259, 57) km s$^{-1}$. Thus, winds in the AGN are similar to star formation-driven winds, and are too weak to escape and expel substantial cool gas from galaxies. Our sample doubles the previous sample of AGNs studied at $z \sim 0.5$ and extends the analysis to $z \sim 1$. A joint reanalysis of the $z \sim 0.5$ AGN sample and our sample yields consistent results to the measurements above.

Key words: galaxies: active – galaxies: high-redshift – galaxies: star formation – galaxies: nuclei – intergalactic medium – quasars: absorption lines

1. Introduction

Galactic-scale winds are one of the most fundamental, yet least understood, facets of galaxy evolution. They are recognized to be fundamental in shaping the baryonic growth, dark matter density profile, star formation and metallicity of galaxies as well as the enrichment of the intergalactic medium (e.g., Aguirre et al. 2001; Veilleux et al. 2005; Oppenheimer et al. 2010; Davé et al. 2011; Pontzen & Governato 2012). Galaxy formation models that do not include feedback processes form stars too efficiently and fail to reproduce even basic observed galaxy properties.

High-velocity winds are predicted manifestations of the AGN feedback process invoked to reproduce observed properties of massive galaxies (Silk & Rees 1998; Fabian 1999; Granato et al. 2004; Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2008; Debahr et al. 2012). In the AGN feedback process, a tremendous energy output from accretion onto a black hole, if somehow harnessed, removes or heats gas in the host galaxy and shuts down subsequent star formation. The consequence of the black hole’s action in turn limits gas accretion onto the black hole and stunts its growth. AGN feedback is an essential ingredient in current theoretical models of massive galaxy evolution (for recent reviews, see Alexander & Hickox 2012; Fabian 2012; Kormendy & Ho 2013; Heckman & Best 2014). Many semi-analytical models and theoretical simulations require AGN feedback to correctly predict the observed color bi-modality of galaxies and the lack of extremely luminous galaxies (e.g., Benson et al. 2003; Croton et al. 2006; Hopkins et al. 2006; Cattaneo et al. 2007; Somerville et al. 2008; Gabor et al. 2011).

It is predicted that outflows driven by stellar feedback alone are less likely to reach typical velocities higher than 500 km s$^{-1}$ (Thacker et al. 2006; Bower et al. 2012; Hopkins et al. 2013). In their simulations of stellar feedback (without AGN feedback) in major mergers, Hopkins et al. (2013) found that in all cases the winds have a broad velocity distribution extending up to $\sim 1000$ km s$^{-1}$, but most of the wind mass is near the circular velocity ($\sim 100$–200 km s$^{-1}$), with relatively little (<1% of the wind mass) at $v \gtrsim 500$ km s$^{-1}$. Muratov et al. (2015) also found winds with similar properties in their analysis of galaxy-scale outflows from the Feedback in Realistic Environments cosmological simulations. In contrast, considerably higher bulk outflow velocities $v \sim 1000$–3000 km s$^{-1}$ are predicted from AGN feedback (e.g., King et al. 2011; Choi et al. 2012; Debahr et al. 2012; Zubovas & King 2012; Gabor & Bournaud 2014). In observations, particularly in those that indirectly infer the bulk velocity, the high-velocity tail of the star formation-driven wind could be confused for a wind powered by an AGN.

However, other models predict that AGN feedback affects a galaxy very little, despite the large outflow velocities (Gabor & Bournaud 2014; Roos et al. 2015) or it could even enhance star formation (Silk & Nusser 2010; Ishibashi & Fabian 2012; Bourne et al. 2015). Bourne et al. (2015) claim that the mass resolution of a simulation significantly affects the inferred AGN feedback. At resolutions typical of cosmological simulations, they found that simulated AGNs are artificially more efficient in gas removal. However, at a higher resolution, the authors found that simulated AGNs expel only diffuse gas, and a denser gas falls in toward the black hole and forms stars. Thus, it is not clear whether AGNs have negative or positive feedback or if both are happening simultaneously.
Recent observational studies at $z \sim 0.5$–2.5, using the background light of star-forming galaxies in self-absorption, have observed ubiquitous velocity offsets from the the systemic zero velocities of the galaxies, indicative of galactic winds (Weiner et al. 2009; Erb et al. 2012; Law et al. 2012; Martin et al. 2012; Bordoloi et al. 2014; Rubin et al. 2014; Tang et al. 2014; Zhu et al. 2015). Using the background light of galaxies gives a clearer indication of inflow or outflow unlike using bright background QSOs to probe gas associated with the foreground galaxies (e.g., Churchill et al. 2000). Since galaxies are much fainter, the analysis is performed on stacks of hundreds of short exposure galaxy spectra or on very deep spectra of a modest sample of individual galaxies (3–8 hr integration on Keck for instance). The outflows studied in both ways show asymmetric absorption profiles with a typical velocity offset of $\sim 200$ km s$^{-1}$ and a high-velocity tail, which may reach up to $\sim 1000$ km s$^{-1}$ (e.g., Weiner et al. 2009; Martin et al. 2012). Note that this high-velocity tail in star-forming non-AGN galaxies is observed more prominently in Mg II $\lambda 2796$ and it is consistent with the theoretical expectation (e.g., Hopkins et al. 2013; Muratov et al. 2015).

In the latest works that used deep spectroscopic data of individual galaxies, the wind speed is best correlated with star-formation-rate (SFR) surface density but it is not significantly correlated with either galaxy stellar mass or inclination (Kornei et al. 2012; Martin et al. 2012; Rubin et al. 2014). The wind detection rate on the other hand is highly dependent on inclination (Rubin et al. 2014). While the recent works have made important advances in characterizing such outflows and in establishing their relationships to host galaxy properties, many basic properties of these winds and their driving physics remain uncertain. One such uncertainty is the wind velocity of AGN host galaxies.

The evidence for AGN hosts having ubiquitous high mean galaxy-wide velocity outflows with the potential to impact star formation is sparse (see a more detailed discussion in Section 4). Ionized outflows have been studied in emission using large samples both at low-redshift (e.g., Zakamska & Greene 2014) and high-redshift (e.g., Harrison et al. 2016). Even though convincing evidence for ubiquitous, ionized outflows exists, details on the interpretation of the observed wind properties are debatable. Most of the emission-line studies have found high-velocity, extended outflows on a several kiloparsec scale, resulting in very large inferred mass outflow rates and kinetic power, in support of AGN feedback models (e.g., Liu et al. 2013; Harrison et al. 2014; McLelroy et al. 2015). However, recent studies have questioned these results and have argued that the apparently very extended emission is a consequence of seeing smearing (Husemann et al. 2016; Karouzos et al. 2016; Villar-Martín et al. 2016). Accounting for the seeing effect, these later works found much smaller and weaker winds, which may not significantly impact the star formation in their host galaxies.

On the other hand, absorption-line wind studies are hard to undertake in distant galaxies but are relatively easy to interpret. Existing absorption-line studies of winds in AGN host galaxies have small sample sizes of $\sim 10$–30 at $z \sim 0.5$–2.5 (Coil et al. 2011; Hainline et al. 2011; Cimatti et al. 2013) and the aforementioned deep spectroscopic wind absorption studies did not primarily target AGNs. This may be because AGN hosts are rare and are generally fainter than the targeted star-forming galaxies. Coil et al. (2011) studied a sample of 10 low-luminosity, narrow-line AGNs ($L_X \sim 10^{41}$–$10^{42}$ erg s$^{-1}$) at $0.2 < z < 0.6$. Of the 10 X-ray AGN host galaxies, 5 show a wind in Fe II $\lambda 2586$ absorption, with typical mean outflow velocity signatures of only $\sim 200$ to $300$ km s$^{-1}$. The velocity widths are generally unresolved but are $\sim 100$–300 km s$^{-1}$. On the other hand, Hainline et al. (2011) qualitatively studied a stacked spectrum of 33 UV-selected narrow-line AGNs at $z \sim 2.5$ and reported a detection of a highly blueshifted ($v \sim -850$ km s$^{-1}$) and weak Si IV $\lambda 1393$, 1402 absorption line, which is different from the Si IV absorption in the composite spectrum of non-AGN Lyman break galaxies at a similar redshift.

It should be noted that Prochaska et al. (2011) have found that atomic transitions that are only coupled to the ground state (e.g., Si IV, Mg II, Na I) have line emission preferentially at the systemic velocity and their observed absorption profiles are significantly reduced in depth and are significantly offset in velocity from the intrinsic profile. On the one hand, they also found that resonance transitions that are strongly coupled to fine-structure transitions (e.g., Fe II and Si II) dominantly produce florescent emissions at a longer wavelength, which do not affect the absorption profiles. These resonance absorption lines offer the best characterization of the opacity of the wind as well as the opacity of the gas near the systemic velocity. Therefore, the discrepancy between the two previous works on AGN winds may be due to this effect. The AGN sample in Hainline et al. (2011) shows a stronger Si IV $\lambda 1393$, 1402 emission near the systemic and have much weaker absorption than do their non-AGN star-forming counterparts. In a follow up work, the same authors showed that the stellar population properties of their AGN sample are consistent with those of the mass-matched control sample of star-forming galaxies. They inferred that the presence of an AGN is not connected with the cessation of star formation activity in star-forming galaxies at $z \sim 2$–3 (Hainline et al. 2012). In other words, the observed high winds in these AGNs have not yet affected star formation even if the measured mean velocity is reliable.

The work in this paper bridges the gap in redshift between the two major previous studies of AGN winds in absorption and aims to independently confirm the previously reported wind velocities in AGNs. We examine winds in a composite spectrum of 12 X-ray selected AGNs at $z = 0.9$–1.5 or that of a comparison sample of star-forming galaxies using Fe II $\lambda 2586$, a preferred wind diagnostic. Our AGN sample has a comparable X-ray luminosity to that of Coil et al. (2011). Our spectral resolution is two times higher than theirs and we have three times more wavelength sampling. Our sample also has more extensive multi-wavelength deep HST photometry and other ancillary data to better characterize the host galaxy properties. This has enabled a first attempt to have a control sample for star-forming galaxies matched both in stellar mass and galaxy inclination. Furthermore, we use a similar wind model and methods that have been adopted in the most recent wind studies (Martin et al. 2012; Rubin et al. 2014). These methods were not used in the two previous studies of AGNs. Thus, for a fair comparison, we present a reanalysis of the Coil et al. (2011) data using the new approach, which also has better quantified model uncertainties.
The rest of the paper is organized as follows. Section 2 presents the data and sample selection. Section 3 presents the analysis and results on winds in AGNs at $z \sim 1$, AGNs at $z \sim 0.5$, and the comparison sample. Section 4 extensively discusses previous works to put the result of this work in a larger context. A brief summary and conclusion is given in Section 5. $(\Omega_m, \Omega_{\Lambda}, h) = (0.3, 0.7, 0.7)$ cosmology is assumed and AB magnitude is adopted. A wavelength measured in air is given throughout the paper. We use words “wind” and “outflow” interchangeably to mean outward movement of gas without making subtle distinctions in some previous works.

2. Data

2.1. Observation and Data Reduction

The spectroscopic data are taken from our on going deep (8–24 hr) Keck/DEIMOS (Faber et al. 2003) spectroscopic survey in CANDELS fields (Grogin et al. 2011; Koekemoer et al. 2011; Guo et al. 2013) called HALO7D. This multi-semester program will survey faint halo stars with HST-measured proper motions, to measure their line-of-sight velocities and chemical abundances, giving 6D phase-space information and chemical abundances for hundreds of Milky Way halo stars. The deep exposures necessary to reach the faintest stars in the Galaxy halo is an opportunity for a novel synergy of extragalactic and Galactic science. In addition to the primary halo star targets, which only occupy about a quarter of slitlets on a given DEIMOS mask, we are conducting a survey of galactic winds in star-forming galaxies at $z \sim 1$, and stellar populations of quiescent galaxies at redshifts $0.4 < z < 0.8$. A total of about ~1500 deep spectra of galaxies are expected with survey completion in a year.

The HALO7D survey uses the 600 line/mmillimeter grating on DEIMOS centered around 7200 Å with the GG455 order-blocking filter. This setup gives a nominal wavelength coverage of 4600–9500 Å at a resolution (FWHM) of ~3.5 Å for a 1″ slit width and 0.65 Å/pixel dispersion. The slit position angles are set to within ±30° of the parallactic angle to minimize light loss in the blue due to atmospheric dispersion. The exposure times for AGNs studied in this work range between 5 and 12 hr and the observations were taken over the course of two years under variable seeing (0′′8–1′′2) and fair to good transparency conditions. Despite the long integration times, poor seeing has significantly lowered the signal-to-noise for almost half of the AGN sample in the current work. Additional make-up observations of these AGNs are scheduled.

The observations were reduced using the automated DEEP2/DEIMOS spec2d pipeline developed by DEEP2 team (Newman et al. 2013). Calibrations were done using a quartz lamp for flat fielding and both red NeKrArXe lamps and blue CdHgZn lamps for wavelength calibration. The spectroscopic redshifts were measured from the reduced spectra using the spec1d pipeline. All spectra were visually inspected using the interactive zspec tool to access the quality of the redshift estimated by spec1d (for software details, see Newman et al. 2013). Almost all galaxies studied in this work have previous spectroscopic measurements and the new spectroscopic redshifts imply minor changes if any.

Based on the available redshifts, stellar masses and other stellar population properties (age, extinction $A_V$, etc.) were computed with FAST (Kriek et al. 2009) using a combination of the newly obtained CANDELS HST/WFC3 multi-wavelength photometric data with existing ground-based and space-based multi-wavelength data as inputs (e.g., Guo et al. 2013). The modeling is based on a Bruzual & Charlot (2003) stellar population synthesis model and assumes a Chabrier (2003) IMF, exponentially declining star formation histories, solar metallicity, and a Calzetti et al. (2000) dust extinction law. The typical uncertainty in stellar masses is ~0.1 dex. The SFRs are the sum of the SFR$_{UV}$, derived from the rest-frame near-UV luminosity at 2800 Å, and the SFR$_{IR}$, derived from the total infrared luminosity. If a galaxy is not detected in infrared, its dust-corrected UV-based SFR is used (Barro et al. 2011; Wyuits et al. 2011). The SFR estimates are uncertain by a factor of $\lesssim 2$. The axis-ratio measurements were done on HST/WFC3 F160W (H) band imaging using GALFIT (Peng et al. 2002).

For comparison, we also used data of six previously studied low-luminosity AGNs at 0.3 < $z$ < 0.6 with Fe II coverage (Coil et al. 2011). These AGNs were observed using Keck LRS (Oke et al. 1995) for roughly one half hour to one hour. The average apparent brightness for this sample is $B \sim 20.9$ and our AGN sample has about nine times fainter average apparent brightness. Coil et al. (2011) have stellar mass and SFR measurements for four of the six AGNs. We adopted their measurements. In comparison plots that use the stellar mass and SFR measurements, we only show their four AGNs with such measurements, but we reanalyzed the spectra of all six AGNs.

2.2. Sample Selection

For the wind study, we primarily targeted sources that are brighter in the $V$ band ($V < 23.5$) and above $z > 0.7$, such that we would detect near-UV continuum levels in the individual spectra in eight hours at a signal-to-noise ratio per Angstrom (S/N/Å) of five in good observing conditions. We gave higher priority to sources that are brighter and are above $z > 0.9$, which likely have both Fe II and Mg II coverage. Galaxies with $V > 23.5$ were targeted at lower priority as fillers. AGNs make up a small fraction (<10%) of all galaxies in our survey. In some cases, we targeted bright X-ray sources (Alexander et al. 2003; Laird et al. 2009; Xue et al. 2011) and gave them the highest weights in the mask design process. In other cases, the AGNs were selected by chance (i.e., were selected for other reasons). So far, there are about one hundred X-ray sources in the observed sample. Only about a third of them are above $z > 0.9$ and, therefore, have coverages of Fe II λ2586.

Out of the ~100 targeted/serendipitous X-ray sources, we selected all 12 AGN candidates at $z > 0.9$ that have X-ray luminosity $L_X \gtrsim 5 \times 10^{41}$ erg s$^{-1}$, S/N/Å >2.7 around Fe II λ2586, and uncontaminated Fe II λ2586 by skylines. We also require that they have HST WFC3 imaging for axis-ratio measurements and have highly reliable redshift measurements (show clear O III emission and/or Ca II H and K absorption lines).

Figure 1(a) plots SFR against X-ray luminosity. Nine of the selected AGN candidates are 2σ outliers from the relationship

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* The following filters are used in the SED fitting. In EGS: CFHT (u, g, r, i, z), ACS (F606W, F814W), WFC3 (F125W, F140W, F160W), WIRCAM (J, H, K), NEWFIRM (J1, J2, J3, H1, H2, K), IRAC (CH1, CH2, CH3, CH4). In GOODS-N: KPNO_U, LBC_U, ACS (F435W, F606W, F775W, F814W, F850LP), WFC3 (F105W, F125W, F140W, F160W, F275W), MOIRCS_K, CFHT_K, IRAC (CH1,CH2,CH3,CH4). In GOODS-S: CITO_U, VIMOS_U, ACS (F435W, F606W, F775W, F814W, F850LP), WFC3 (F105W, F125W, F140W, F160W), ISAAC_KS, HAWKI_KS, IRAC (CH1,CH2,CH3,CH4).
between X-ray luminosity and SFRs for normal star-forming galaxies (Mineo et al. 2014). Of these, three show broad Mg II emission. When we have previous spectroscopic data, we targeted objects with broad Mg II emission at lower priority. Quasars have hard X-ray luminosities \( L_X \gtrsim 10^{44} \) erg s\(^{-1}\) (e.g., Ku et al. 1980; Piconcelli et al. 2005). Except for the three AGNs with broad Mg II emissions, the AGNs studied in this work have significantly lower X-ray luminosities compared to quasars. We thus refer to them as low-luminosity AGNs to differentiate them from quasars.

Furthermore, 3 of the 12 X-ray sources lie within 2\( \sigma \) of the mean relation between X-ray luminosity and SFR. One of them has strong Ne V \( \lambda 3426 \) emission, a strong signature of AGNs. Therefore, 10 of the AGN samples have robust AGN identifications. Excluding the two X-ray sources that may not be AGN does not change the main results of this work. We have excluded from our sample some AGN candidates that satisfy the S/N cut but their spectra around Fe II are contaminated by a skyline or possible absorption from a foreground galaxy.

The three broad-line AGNs in our sample show no or very weak and narrow Fe II and/or Mg II absorption but have higher X-ray luminosity \( L_X \gtrsim 10^{43} \) erg s\(^{-1}\). Coil et al. (2011) did not target objects with broad Mg II emission in their spectra because strong broad emission may affect one’s ability to detect or interpret blueshifted absorption features because of emission infill or ionization to a higher state. The current estimates of stellar masses and SFRs of broad-line AGNs do not properly account for the presence of the luminous AGNs and thus they may be biased compared to the measurements for the star-forming comparison sample. However, for low-luminosity narrow-line AGNs, the stellar mass and SFR measurements are not significantly affected by presence of AGNs (Ciesla et al. 2015). Thus, we present analyses both with and without the inclusion of the three broad-line AGNs.

To test for the effects of the presence of AGNs on winds in their host galaxies, here we define a comparison galaxy sample that lacks AGNs but has a similar distribution of stellar masses and axis ratios. For each AGN host, we select the X-ray undetected object that has the most similar stellar mass and axis ratios. The masses and axis ratios agree within a factor of two for all AGNs and their comparison galaxies. All galaxies except one have matches with similar SFRs within a factor of two.

Figures 1(b)–(d) show the stellar mass, SFR, and axis ratio of the AGN and the comparison sample of star-forming X-ray undetected galaxies at \( z \sim 1 \). Due to the limited sample size of the parent sample from which the comparison sample of X-ray

Figure 1. Sample properties: in all panels the red dots are the low-luminosity AGNs at \( z \sim 1 \), the diamonds are the X-ray undetected star-forming comparison sample at \( z \sim 1 \), and the blue triangles are AGNs at \( z \sim 0.5 \) from Coil et al. (2011). Panel (a) shows the star formation rates (M\(_{\odot}\) yr\(^{-1}\)) vs. the full X-ray luminosities (erg s\(^{-1}\)) of AGNs and non-AGNs. The blue triangles are shown with arrows to indicate upper and lower limits of their X-ray luminosities. The + sign denotes X-ray detected star-forming galaxies in Chandra Deep Field South (CDFS) from Mineo et al. (2014). The solid line shows the line of best linear fit for the relationship between star formation rate and X-ray luminosity in the star-forming non-AGN galaxies. The dashed lines and the dotted lines indicate the 95% confidence and predictive bands, respectively, for these galaxies. Panel (b) plots the stellar mass (M\(_{\odot}\)) against the star formation rate. The black lines indicate the star formation main sequence of galaxies at \( z = 1 \) and \( z = 0.5 \) (Whitaker et al. 2014). Panel (c) shows the stellar mass vs. the H-band axis ratio. Panel (d) depicts the redshifts and the star formation rates of the samples.
undetected galaxies were drawn (<100 galaxies with z > 0.9 and V < 23.5), our matching is crude. It may be sufficient since winds are expected to depend weakly on galaxy properties (Coil et al. 2011; Martin et al. 2012; Rubin et al. 2014; Balmaverde et al. 2016). We think the comparison galaxies do not host AGNs because they are located in regions of the sky with X-ray coverage by Chandra observations, yet they are not detected in X-ray. However, it has been argued that a substantial fraction of AGNs are missed by the X-ray selection (e.g., Juneau et al. 2013). Future near-IR spectroscopic data for rest-frame optical line-ratio AGN diagnostics are needed to completely rule out the presence of AGNs in the comparison sample.

The galaxy properties of the AGN and the star-forming X-ray undetected galaxies are summarized in Tables 1 and 2. The rest-frame pseudo RGB images of the two samples are shown in Figures 2 and 3. Pseudo-color images are created by simply combining three high-resolution HST ACS/WFC3 band-cut-out images (e.g., Koekemoer et al. 2011) that have central wavelengths closest to R (700 nm), G (546.1 nm), and B (435.8 nm) after correcting for redshift (i.e., λ/(1 + z), z ~ 1). The images are normalized and combined with the ratio of 1/(R):6(G):3(B).

### 3. Analysis and Results

#### 3.1. Coadding Spectra

First, multiple exposures of the same object were averaged with inverse-variance weighting per pixel, which minimizes the variance of the weighted average spectrum. Then to coadd the spectra of AGNs or their comparison sample, each spectrum was shifted to its rest-frame wavelength. The rest-frame spectra were then interpolated on a linear wavelength grid with a Δλ = 0.3 Å bin, which is close to the pixel size of the DEIMOS spectrograph at z ~ 1 for our setup. We co-added the observed photon counts at a given wavelength bin for each rest-frame spectrum with inverse-variance weighting.

The individual near-UV spectra of the redshift z ~ 1 AGN sample are plotted in Figure 4. The Fe II and Mg II absorption lines are observed in most of the spectra. Figure 5 shows the normalized near-UV composite spectra of all AGNs and subsets of the AGN sample separated into narrow and broad-line AGNs. The normalization was determined by a linear fit to the continuum around both sides of the Fe II absorption doublet. We used the wavelength ranges of 2520–2578 Å, 2640–2770 Å, and 2900–2970 Å to fit the continuum level. Figure 6(a) shows the normalized composite spectrum near the

### Table 1

|$z$ ~ 1 AGN Sample

| Field | ID | R.A. (degree) | Decl. (degree) | $z$ | log $L_X$ (erg s$^{-1}$) | log $M$ ($M_{\odot}$) | SFR ($M_{\odot}$ yr$^{-1}$) | b/a | B | V | S/N (per Å) | $t_{\text{obs}}$ (hr) |
|-------|----|---------------|---------------|-----|------------------------|----------------|----------------------|-----|---|---|------------|----------------|
| EGS   | 10518 | 214.877075 | 52.819477 | 1.19500 | 42.4 | 10.8 | 66 | 0.4 | 24.6 | 24.1 | 3 | 6 |
| EGS   | 30572 | 214.671600 | 52.773415 | 1.48599 | 44.2 | 10.5 | 163 | 0.6b | 23.9 | 23.1 | 8 | 9 |
| GDN   | 17041 | 189.282730 | 62.268250 | 0.93573 | 42.2 | 11.1 | 54 | 0.8 | 23.8 | 22.6 | 3 | 9 |
| GDN   | 17389 | 189.282242 | 62.271099 | 0.93971 | 42.2 | 11.1 | 35 | 0.7 | 23.1 | 23.0 | 3 | 9 |
| GDN   | 1878 | 189.194458 | 62.142590 | 0.97115 | 41.9 | 11.0 | 115 | 0.9 | 22.9 | 22.1 | 12 | 9 |
| GDN   | 12523 | 189.193115 | 62.336434 | 0.96023 | 43.9 | 10.9 | 35 | 0.9 | 23.8 | 22.6 | 10 | 11 |
| GDN   | 6274 | 189.077515 | 62.187534 | 1.01933 | 44.1 | 10.7 | 146 | 0.8 | 22.1 | 21.5 | 16 | 10 |
| GDS   | 21627 | 53.045460 | −27.282624 | 0.99829 | 42.8 | 11.0 | 45 | 0.6b | 23.1 | 22.6 | 3 | 9 |
| GDS   | 7837 | 53.107758 | −27.838812 | 1.09525 | 41.7 | 10.4 | 48 | 0.7 | 23.2 | 22.7 | 9 | 12 |
| GDS   | 15870 | 53.065838 | −27.751313 | 1.02060 | 41.9 | 10.2 | 31 | 0.4 | 23.7 | 23.4 | 10 | 9 |
| GDS   | 23803 | 53.150719 | −27.716194 | 0.96708 | 42.2 | 10.1 | 68 | 0.6 | 22.3 | 22.1 | 7 | 5 |
| GDS   | 20168 | 53.150126 | −27.739926 | 1.03670 | 41.8 | 10.0 | 48 | 1.0 | 23.2 | 22.9 | 3 | 5 |

### Notes.

* Has a bad or suspicious GALFIT flag.
b Has a strong Ne V emission.

### Table 2

|$z$ ~ 1 Inactive Star-forming Comparison Sample

| Field | ID | R.A. (degree) | Decl. (degree) | $z$ | log $M$ ($M_{\odot}$) | SFR ($M_{\odot}$ yr$^{-1}$) | b/a |
|-------|----|---------------|---------------|-----|----------------|------------------------|-----|
| EGS   | 9240 | 215.054153 | 52.937103 | 1.03030 | 10.6 | 88 | 1.0 |
| EGS   | 13622 | 214.953293 | 52.890411 | 1.39770 | 10.3 | 100 | 0.7 |
| EGS   | 31460 | 214.708572 | 52.79135 | 0.95830 | 10.6 | 115 | 0.8 |
| EGS   | 25589 | 214.658823 | 52.738495 | 1.39700 | 10.9 | 128 | 0.8 |
| EGS   | 15131 | 215.097374 | 52.999435 | 1.11690 | 10.0 | 45 | 0.8 |
| EGS   | 27292 | 214.931488 | 52.945190 | 0.89330 | 10.3 | 40 | 0.9 |
| EGS   | 12671 | 215.110123 | 52.994293 | 1.24070 | 11.0 | 214 | 1.0 |
| GDN   | 17481 | 189.379868 | 62.272289 | 0.97500 | 11.2 | 102 | 0.7 |
| GDN   | 11799 | 189.219743 | 62.231889 | 1.35896 | 10.2 | 49 | 0.5 |
| GDS   | 25246 | 53.046593 | −27.690841 | 1.05765 | 10.5 | 24 | 0.8 |
| GDS   | 26255 | 53.144206 | −27.700337 | 1.04180 | 9.8 | 24 | 0.6 |
| GDS   | 19443 | 53.086326 | −27.748261 | 0.96900 | 10.8 | 68 | 0.7 |

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Fe II absorption line of the seven narrow-line AGNs at $z \sim 1$ with robust AGN identifications. The composite spectrum of the comparison sample of X-ray undetected, star-forming galaxies is overplotted in the same figure. It is clear from this figure that both AGNs and normal star-forming galaxies have asymmetrically blueshifted Fe II absorption lines. The absorption profiles of AGNs and the comparison sample have very similar width and depth. Therefore, without detailed modeling, one can infer that they have similar wind velocities and strengths. The wind velocities in both samples are on the order of $100–200 \, \text{km s}^{-1}$ and extend to $\sim 500 \, \text{km s}^{-1}$. A variant of this figure for all 12 AGN candidates can be found in the Appendix Figure 9. Figure 6(b) plots the O II emission lines of AGN and the comparison sample. O II is vital in determining the redshift and the systemic zero velocity of the galaxies.

Figures 6(c) and (d) are similar to Figures 6(a) and (b). In the latter figures, the comparison is made between the composite spectrum of our AGN at $z \sim 1$ and that of the six AGNs studied by Coil et al. (2011) at $z < 0.6$. We note that these authors studied winds in their AGNs using individual spectra. Since we coadded the spectra of our AGNs for improved signal-to-noise average spectrum, we also coadded the AGN at $z < 0.6$. We interpolate the individual AGN spectra onto a linear wavelength grid with $\Delta \lambda = 1.3 \, \text{Å}$, which is about the pixel size of the LRIS spectrograph at $z \sim 0.6$ for their setup. We convolve our composite spectrum to the instrumental resolution of LRIS and rebin it to match the resolution and bin size of the composite spectrum of their data. There is a very good agreement between the Fe II absorption profiles of the AGN at $z \sim 1$ and that of the AGN at $z \sim 0.5$. The strength of the O II emission lines of the two AGN samples also agree with each other.

We reanalyze the Coil et al. (2011) data both separately and jointly with our data. For the joint analysis, we linearly interpolate the composite spectrum of their data to a wavelength grid with $\Delta \lambda = 1.2 \, \text{Å} \text{ bin}$, convolve our AGN composite spectrum to the LRIS resolution but here our spectrum is not rebinned (has $\Delta \lambda = 0.3 \, \text{Å}$). The two-component model decomposition may be sensitive to binning and therefore we do not rebin our composite spectrum. To combine the two data sets, we...
average the normalized counts in the bins where the two data sets coincide (i.e., every fourth bin in our spectrum). The averaging uses inverse-variance weighting per pixel. In the bins where the two data sets do not overlap, we use values of our composite spectrum. The joint analysis is done using the composite spectrum of our seven narrow-line AGNs with robust AGN identification, which are more similar to the Coil et al. (2011) sample, as well as with the composite spectrum of all AGNs in our sample.

To give a quantitative gauge of both the dispersion intrinsic to a sample (to account for the effects caused by the outlier galaxies within a sample) and the measurement errors, we use the bootstrapping scheme to estimate the standard errors of the average composite spectrum at different wavelengths. In the bootstrapping scheme, we randomly resample, with replacement, the ID of galaxies of a sample size equal to the size of the original sample size at each iteration. This resampling was done 1000 times. At each iteration, we averaged the spectra of the selected galaxies using inverse-variance weighting at each wavelength pixel. We used the standard deviation of the average counts in a given wavelength bin of all 1000 composite spectra as the error of the original averaged spectrum at that given bin. We add the bootstrap standard deviations of the composite spectra in quadrature when we combine the two AGN samples at $z \sim 1$ and $z \sim 0.5$. An alternative analysis, which may better minimize the effects of poor measurements, provided that the dispersion intrinsic to the sample is small, is to simply use the errors of the inverse-variance weighted average. The results from this alternative analysis are presented in Appendix A.2. Because the errors from this method are significantly smaller than the errors from the bootstrapping scheme, the wind parameters are better constrained in the results presented in the Appendix. In the next section, we quantitatively show that the winds in the two samples are similar using a standard wind model.

### 3.2. The Simple Wind Model

We adopt the partial covering wind model of Rupke et al. (2005b) to model the observed Fe II $\lambda 2585.876$ absorption$^5$

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$^5$ More information and references for this and other atomic transition used in the paper can be found in NIST Atomic Spectra Database at https://www.nist.gov/pml/atomic-spectra-database or in Morton (2003).
profile, similar to recent works that studied galactic winds in star-forming galaxies (Kornei et al. 2012; Martin et al. 2012; Rubin et al. 2014; Tang et al. 2014). Due to signal-to-noise and spectral resolution limitations of observational data to fully constrain the wind model, the following simplifying assumptions were customarily made in the previous works and are also adopted in this work: (1) the covering factor of the wind is independent of velocity. Some studies suggest that this may not be a good assumption (Martin & Bouché 2009); (2) the stellar continuum emission is fully covered by a uniform screen of ISM absorption. If this assumption is not valid, the inferred ISM column density is lower than the actual column density since the covering fraction anti-correlates with column density. In this work, we do not aim to constrain these two values independently. We show in Appendix A.4 that the wind velocities are not significantly affected by this assumption when using a covering fraction of 50% for the ISM; (3) the line profile shape is due entirely to the absorption of the stellar continuum. However, scattered emission infill may also affect the absorption profile. This effect is expected to be less significant for Fe II λ2586 compared to resonant lines without fluorescent emission lines such as Mg II (see Prochaska et al. 2011). Zhu et al. (2015) estimated that the equivalent width of the Fe II λ2586 absorption profile is affected by only 10% due to emission infill; (4) two absorption components, an ISM component centered at zero systemic velocity and a wind component, are sufficient to characterize the observed absorption-line profiles.

Figure 4. Near UV spectra of the AGN sample at $z \sim 1$. The pink shadings are 1σ error bands. The spectra are boxcar smoothed by 7 pixels (2 Å). Absorption lines of Fe II and Mg II are evident in most AGNs. Spectra in the second row are for the three broad-line AGNs. The Fe II absorption are very weak in two of the AGNs with broad Mg II emission. These galaxies have high X-ray luminosities in Figure 1.
Figure 5. Near UV composite spectra of the AGN sample and subsamples at $z \sim 1$. The pink shadings are 1$\sigma$ bootstrap error bands.

This assumption may result in inaccurate column densities and line widths, if the profiles are composed of multi-components from multiple clouds. Higher-resolution galaxy spectra are required to test the effects of this assumption. Studies using high-resolution spectra of background quasars find that the absorption lines are composed of multiple clouds with more complex kinematics (e.g., Churchill et al. 2000); (5) the velocity distribution of absorbing atoms within a component is Maxwellian such that each absorption optical depth is modeled as a Gaussian, $\tau(\lambda) = \tau_c \exp \left(-\frac{(\lambda - \lambda_c)^2}{\sigma^2}\right)$ where $\tau_c$ is a central optical depth at the line center, $\lambda_c$, $c$ is the speed of light, and $b = \sqrt{\frac{2}{3}} \sigma$ is the Doppler parameter. This assumption is likely to be an over-simplification but it is reasonable given that the observed shape of the absorption trough is strongly influenced by the instrumental resolution.

According to this simple model, the normalized continuum can be described as a product of the line intensity of the galaxy component and of the wind component. Each component has the form $1 - C(1 - \exp -\tau(\lambda))$. $C$ is the covering fraction for the galaxy ISM component. We can express $\lambda_c$ in terms of centroid velocity $v = \frac{c(\lambda_c - \lambda_0)}{\lambda_0}$, where $\lambda_0$ is the rest wavelength of the transition. For the galaxy component, $\lambda_c = \lambda_0$ (i.e., no velocity shift). The central optical depth is expressed in terms of the column density, $N$, oscillator strength, $f_0$, and $b$ using the relation $\tau_c = 1.45 \times 10^{15} b f_0 N / b$ for $N$ in units of $\text{cm}^{-2}$, $\lambda$ in $\mu\text{m}$ and $b$ in $\text{km s}^{-1}$.

To summarize, the six free parameters of this two-component model are the covering fraction of the wind, $C_w$, the velocity centroid shifts of the wind, $v_w$, the Doppler broadening parameter of the wind, $b_w$, the Doppler parameter of the ISM in the galaxy, $b_0$, column density of the wind, $N_w$, and the column density of the gas in the galaxy, $N_g$. The model is convolved with the instrumental resolution and rebinned to match the observed data before comparing the two.

The model is fit to the data using a Bayesian method with custom Python code. Only the Fe\ II $\lambda 2585.876$ absorption line is fitted. The entire wavelength ranges $\lambda = (2572, 2578)$ and $\lambda = (2591, 2632)$ are masked out prior to fitting because they are contaminated by Mn\ II $\lambda 2576.877$, 2594.499, 2606.462 absorptions or Fe\ II $\lambda 2599.395$ absorption or the Fe\ II $\lambda 2611.873$, 2625.489, 2631.047 emissions. The posterior probability densities (PDFs) of the model parameters were computed using the affine-invariant ensemble Metropolis–Hastings sampling algorithm (Foreman-Mackey et al. 2013) assuming uniform priors: $v_w = (-450, 450)$, $b_w = (20, 450)$, $b_0 = (20, 450)$, log $N_w = (14, 17.5)$, and log $N_g = (14, 17.5)$. A centroid-velocity shift greater than 500 km s$^{-1}$ is ruled out by the data without the model, so we have restricted the velocity prior to estimate the velocity shift, which is supported by the data. To compute the likelihood of the data given the model parameters, we assumed that each data point is drawn from independent Gaussians centered around the model profile with a dispersion given by the measurement errors. This is equivalent to assuming a $\chi^2$ distribution for the sum of squares of flux differences between the model and the data, with degrees of freedom equal to the number of observed data points.

3.3. The Wind Velocities of X-Ray AGNs at $z \sim 1$ Are Similar to Those of Star-forming X-Ray Undetected Galaxies at Similar Redshifts

Table 3 summarizes the marginalized PDFs of the six model parameters fitted to Fe\ II $\lambda 2586$ absorption lines for both the AGN and the comparison samples. We used the 50th (median), 16th, and 84th percentiles as summary statistics for the marginalized PDFs. For convenience, we express the percentiles as $\pm$ deviations from the median throughout the text. For instance, $X \pm 2\sigma$ denotes that $X$ is the median, $X + Y$ is the 84th percentile and $X - Z$ is the 16th percentile. For a Gaussian PDF, $Y$ and $Z$ are equal to its standard deviation but note that the PDFs of the wind centroid-velocity shift and of the Doppler dispersion parameter are non-Gaussian in almost all cases.

Figure 7 shows, for both AGN and the comparison sample at $z \sim 1$, the observed Fe\ II $\lambda 2586$ absorption profiles and the fitted model profiles. In the top row, we show the fit to the composite spectrum of all 12 AGN candidates (Figure 7(a)) or of only the nine AGNs without broad-line AGNs (Figure 7(b))
or only the seven narrow-line AGNs with robust AGN identifications (Figure 7(c)). In the second row, Figures 7(d)–(f) show the corresponding velocity centroid and Doppler parameter PDFs for the three AGN subsamples. Figures 7(g) and (h) are similar to the Coil et al. (2011) z \sim 0.5 AGN sample analyzed separately or jointly with our data. Figure 7(i) shows observed Fe II λ2586 absorption profiles and the model profiles for the comparison sample of X-ray undetected star-forming galaxies at z \sim 1. In the last row, Figures 7(j)–(l) show the velocity centroid and Doppler parameter PDFs of two reanalyses of the Coil et al. (2011) data and of the comparison sample. In each plot of the Fe II profile, the black points with error bars are the observed data points. The blue curve is the wind component, while the orange curve is the galaxy absorption component. Both the blue and orange curves are shown before the convolution with the instrumental line-spread-function and thus represent the true components. The red curve is the product of the two components after convolution. All three curves are constructed from medians of the six marginalized model parameters. The marginalized median model fits the data well. The randomly drawn 500 model profiles from the PDFs of the model parameters are shown in pink. They also characterize the flux uncertainties very well. Cutting the histograms depicting PDFs of the centroid velocities and Doppler parameters, the dashed vertical lines mark the 16th, 50th (median), and 84th percentiles of the PDFs.

To summarize results presented in Table 3 and Figure 7, the wind centroid velocity for all 12 AGNs in Fe II λ2586 is \nu_w = -87_{-156}^{+161} \text{ km s}^{-1} and its Doppler dispersion parameter is \sigma_w = 197_{-124}^{+160} \text{ km s}^{-1}. For the nine narrow-line AGNs the centroid velocity is \nu_w = -109_{-129}^{+141} \text{ km s}^{-1} and its Doppler parameter is \sigma_w = 160_{-48}^{+142} \text{ km s}^{-1}. These two parameters anticorrelate and their joint PDF is asymmetric. \nu_w may also be degenerate with the covering factor of the wind (see Figure 11). The value of \nu_w quoted above is after integrating over \sigma_w. The maximum, centroid, velocity-shift (\nu_w - 2\sigma_w, where \sigma_w is the dispersion of \nu_w estimated from its PDF) in the narrow-line AGN is likely less than \sim 370 \text{ km s}^{-1}. Similarly, the star-forming comparison sample has a wind centroid velocity of
Table 3
Wind Model Parameter Fits to Fe II λ2586 Profiles

| Model | AGN \( z \approx 1 \) (N = 12) | NL AGN \( z \approx 1 \) (N = 9) | NL AGN \( z \approx 1 \) (N = 7) | SF \( z \approx 1 \) (N = 12) | AGN \( z \approx 0.5 \) (N = 6) | AGN \( z \approx 0.5-1.5 \) (N = 13) | AGN \( z \approx 0.5-1.5 \) (N = 18) |
|-------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| \( v_w \) (km s\(^{-1}\)) | \(-87^{+167}_{-151} \) | \(-109^{+111}_{-89} \) | \(-143^{+109}_{-98} \) | \(-74^{+167}_{-184} \) | \(-93^{+124}_{-209} \) | \(-119^{+144}_{-115} \) | \(-94^{+153}_{-180} \) |
| \( b_w \) (km s\(^{-1}\)) | \(197^{+149}_{-232} \) | \(160^{+72}_{-42} \) | \(134^{+145}_{-84} \) | \(212^{+154}_{-130} \) | \(190^{+166}_{-130} \) | \(131^{+175}_{-84} \) | \(171^{+178}_{-116} \) |
| \( C_v \) | \(0.2^{+0.4}_{-0.2} \) | \(0.3^{+0.4}_{-0.2} \) | \(0.3^{+0.2}_{-0.2} \) | \(0.3^{+0.4}_{-0.2} \) | \(0.4^{+0.2}_{-0.1} \) | \(0.4^{+0.4}_{0.3} \) | \(0.3^{+0.4}_{-0.2} \) |
| \( \log N_w \) (cm\(^{-2}\)) | \(14.7^{+0.5}_{-1.3} \) | \(14.9^{+1.4}_{-0.6} \) | \(14.9^{+0.2}_{-0.6} \) | \(14.9^{+1.3}_{-0.6} \) | \(15.2^{+0.6}_{-0.7} \) | \(15.0^{+0.7}_{-0.6} \) | \(14.9^{+1.4}_{-0.6} \) |
| \( b_v \) (km s\(^{-1}\)) | \(240^{+78}_{-74} \) | \(228^{+61}_{-61} \) | \(238^{+96}_{-83} \) | \(187^{+39}_{-89} \) | \(137^{+99}_{-97} \) | \(162^{+115}_{-115} \) | \(158^{+112}_{-112} \) |
| \( \log N_f \) (cm\(^{-2}\)) | \(14.5^{+0.2}_{-0.2} \) | \(14.6^{+0.2}_{-0.2} \) | \(14.5^{+0.2}_{-0.2} \) | \(14.7^{+0.2}_{-0.3} \) | \(14.7^{+0.3}_{-0.3} \) | \(14.6^{+0.3}_{-0.2} \) | \(14.6^{+0.2}_{-0.2} \) |

Notes.
- The parameters of the two-component wind model are the velocity centroid shift of the wind, \( v_w \), the Doppler broadening parameter of the wind, \( b_w \), the covering fraction of the wind, \( C_v \), column density of the wind, \( N_w \), the Doppler parameter of the ISM in the galaxy, \( b_v \), and the column density of the gas in the galaxy, \( N_f \). The 50th (median), 84th, and 16th percentile deviations of the PDFs of the model parameters are given in the table. In our notation, \( X_{<z} \) denotes that \( X \) is the median, \( X + Y \) is the 84th percentile and \( X - Z \) is the 16th percentile.
- A joint reanalysis of Coil et al. (2011) data.
- A joint reanalysis of Coil et al. (2011) data with all AGNs including three broad-line AGNs and two with less reliable AGN identification.
- \( N \) denotes the number of galaxies in the stacked spectra.

The escape velocity from a galaxy is approximately \( 5-6 \times \) its O II emission-line velocity dispersion (Weiner et al. 2009), which is \( 122 \pm 16 \) km s\(^{-1}\) for the AGN sample and is \( 131 \pm 18 \) km s\(^{-1}\) for the comparison sample (see Appendix A.3 and Figure 12 therein for detailed information on the measurement of the velocity dispersion). Therefore, most of the outflowing gas does not escape from the host galaxies. Incidentally, the galaxy (ISM) velocity dispersion inferred from fitting the Fe II \( \lambda 2586 \) absorption profile is consistent with the O II emission-line, velocity-dispersion in both AGNs and the comparison samples.

The total equivalent width (the combined contribution of the ISM and the wind components) is \( 1.6^{+0.3}_{-0.2} \) Å for all 12 AGNs, \( 1.8^{+0.3}_{-0.2} \) Å for the 9 narrow-line AGN and \( 1.9^{+0.4}_{-0.3} \) Å for the star-forming sample. About a third of the total equivalent width is due to the wind component in both samples (i.e., \( 0.4^{+0.4}_{-0.3} \) Å for all AGNs and \( 0.5^{+0.7}_{-0.3} \) Å for the star-forming sample). The presence of the strong ISM component (\( 1.2^{+0.3}_{-0.4} \) Å) in the AGN implies that substantial amount cold gas is present in the host galaxies and it has not been affected by AGN feedback. The maximum wind velocity \( (v_w - 2b_w/\sqrt{2}) = -234^{+153}_{-193} \) km s\(^{-1}\) for the 12 AGNs while it is \( -228^{+177}_{-127} \) km s\(^{-1}\) for the comparison sample. The equivalent width and maximum velocity measurements for the other samples of AGNs are found in Table 4.

We also find weak winds in AGNs at \( z \approx 0.5 \) upon reanalysis of Coil et al. (2011) data. The wind centroid velocity for this sample is \( -93^{+248}_{-209} \) km s\(^{-1}\) and its Doppler dispersion parameter is \( 190^{+166}_{-130} \) km s\(^{-1}\), Coil et al. (2011) have measured the Fe II \( \lambda 2586 \) centroid velocities and velocity widths for four of their AGNs. Their measurements for both of these two quantities range roughly between 130 and 330 km s\(^{-1}\). Averaging their four measurements with inverse-variance weighting gives a centroid-velocity shift of \( -180 \pm 9 \) km s\(^{-1}\) and a Doppler parameter of \( 274 \pm 13 \) km s\(^{-1}\). The total equivalent width of Fe II in this sample is \( 2.0^{+0.5}_{-0.3} \) Å and the equivalent width due to the wind component is \( 0.6^{+0.4}_{-0.2} \) Å. The average wind equivalent width measured by Coil et al. (2011) is \( 1.2 \) Å.

4. Discussion

A key physical manifestation of AGN feedback is predicted to be powerful galactic winds. However, the relative roles of AGN activity and star formation in driving such winds remain largely unexplored at redshifts \( z \approx 1 \), near the peak of cosmic activity for both. We study winds in 12 X-ray AGN host galaxies at \( z \approx 1 \) in the CANDELS fields using deep Keck rest-frame UV spectroscopy. We find that winds in the AGNs are similar to those found in star formation-driven winds, and are too weak to escape and expel substantial cool gas from their host galaxies.

Despite theoretical appeal, confirming evidence of star-formation quenching by powerful winds in AGNs remains elusive. Here, we discuss some of the evidence reported in the literature, with emphasis on those with larger samples when multiple, similar studies exist. Our aim is to show that most wind studies using cold, warm, or molecular gas are either in agreement or consistent with our finding that low-luminosity AGNs \( (L_X \approx 10^{42} \) erg s\(^{-1}\) have similar winds as those from star-forming galaxies of similar galaxy properties, especially if the comparison is made at similar AGN luminosities as those of our sample.

4.1. Most Previous Cold Gas Absorption Studies Also Found Low Wind Velocities

Neutral gas outflows in low-redshift \( z \approx 0.1 \) AGNs have been extensively studied using Na I (e.g., Rupke et al. 2005a; Krug et al. 2010). The clearest result from these studies is that the wind velocities of narrow-line (type 2) AGNs are similar to the wind velocities of starburst and star-forming galaxies. Krug et al. (2010) studied outflows in 35 infrared-faint (i.e., low star-forming) Seyferts in an effort to disentangle the starburst effects on the winds from the AGN effects. The authors compared the outflow properties of these Seyferts with that of
Figure 7. Fitting the wind model to Fe II λ2586 absorption lines of AGNs and a comparison sample of X-ray undetected galaxies. The black points are data with bootstrap errors. The red curves are convolved wind models constructed from the medians of marginalized posterior PDFs of the model parameters. The pink shadings are regions spanned by 500 randomly drawn wind models from the posterior PDFs of the model parameters. The orange curves are the unconvolved ISM components while blue curves are the unconvolved wind components. The histograms show the posterior PDFs of wind velocities and wind Doppler dispersion parameters. The dashed lines dividing the histograms indicate 16th, 50th (median), and 84th percentile values. AGNs have a wind centroid velocity of ~150 km s\(^{-1}\) which extends only to ~300 km s\(^{-1}\). Similar wind velocities are observed in star-forming X-ray undetected galaxies.
infrared-bright composite Seyferts in which both starbursts and AGNs co-exist. The wind detection rates for the infrared-faint Seyfert 1s (6%) and Seyfert 2s (18%) are lower than previously reported for infrared-luminous Seyfert 1s (50%) and Seyfert 2s (45%). In addition, the outflow velocities of both high and low SFR Seyfert 2s are similar to those of starburst galaxies, while the outflow velocity in only 1 out of 18 Seyfert 1s is significantly higher. The measured average wind velocity for infrared-faint Seyfert 2 galaxies ($v = -137 \pm 8$ km s$^{-1}$, $b = 250 \pm 214$ km s$^{-1}$) and the authors’ conclusion that AGNs do not play a significant role in driving the outflows in most local infrared-faint and infrared-bright Seyfert 2s is consistent with our result. The particular Seyfert 1 with the strong wind has an average wind velocity $-600$ km s$^{-1}$ and very small velocity dispersion ($b = 21 \pm 6$ km s$^{-1}$). It is likely that this object’s high-velocity measurement is affected by emission infill at systemic velocity.

Likewise, Rupke et al. (2005a) studied a sample of 26 Seyfert ULIRGs using NaI. They found no significant differences between the velocities of Seyfert 2s, which are ultra-infrared galaxies (ULIRGs; $v = -456^{+330}_{-206}$ km s$^{-1}$, $b = 232^{+244}_{-119}$ km s$^{-1}$) and starbursts of comparable infrared luminosity ($v = -408^{+224}_{-191}$ km s$^{-1}$, $b = 232^{+244}_{-119}$ km s$^{-1}$). They also found very high velocities ($\sim5000$ km s$^{-1}$) in two Seyfert 1 AGNs and argued that they are likely small-scale ($\sim10$ pc) disk winds. They stressed that large-scale, lower velocity outflows certainly exist in Seyfert 1 ULIRGs, since such winds are common in general infrared bright galaxies, but the wind signatures are likely rendered unobservable by the intense nuclear radiation in Seyfert 1s due to infilling of the absorption profile by scattered emission or due to ionization to higher states of the absorbing atoms.

Recently, Sarzi et al. (2016) studied a sample of 456 nearby galaxies of which 103 exhibit compact radio emission indicating radio AGN activity. They found that only 23 objects (5%) out of their entire sample exhibited outflow signatures in NaI. Not even a single object showed evidence of AGN activity in radio and of cold-gas outflow simultaneously. Radio-AGN activity was found predominantly in early-type galaxies, while cold-gas outflows were mainly observed in late-type galaxies with central star formation or with composite galaxies of star formation and AGN activities. The authors emphasized that their work supports a picture in which the onset of AGN activity appears to lag behind the peak of starburst activity (e.g., Wild et al. 2010; Yesuf et al. 2014), and in which the gas reservoir has been significantly depleted by star formation or stellar feedback before the AGN had a chance to couple to it.

Similarly, Sato et al. (2009) found NaI outflow velocities of $\sim100$ km s$^{-1}$ in fading post-starburst galaxies with low-level nuclear activity at $0.1 < z < 0.5$. Within a similar redshift range, Coil et al. (2011) also found low-velocity winds ($\sim200$ km s$^{-1}$) in 13 post-starburst galaxies by using MgII and FeII absorption lines. This result is in addition to the low-velocity outflows they found in low-luminosity AGNs.

In contrast, Tremonti et al. (2007) observed high-velocity winds (with median $v \sim 1100$ km s$^{-1}$) in massive transitional post-starburst galaxies and concluded that AGNs likely played a major role in the abrupt truncation of star formation in these systems. However, in subsequent works, they argued that these fast outflows are most likely driven by feedback from extremely compact, obscured, star formation rather than AGNs (Diamond-Stanic et al. 2012; Geach et al. 2014; Sell et al. 2014). However, it remains possible that the outflows were driven by AGN activity that has recently been switched off or are driven by extremely obscured AGNs. Sell et al. (2014) found low-luminosity AGNs in half of their post-starburst sample. Nevertheless, it should be noted that the authors concluded that the fast outflows are most likely driven by feedback from star formation rather than AGNs. Generally, AGNs are known to be common among post-starburst galaxies but are not directly linked to quenching starbursts (Yesuf et al. 2014).

To summarize the discussion so far, to our knowledge, all AGN host galactic-wind studies using (near-)UV or optical absorption lines, with the exception of Hainline et al. (2011), mentioned in the Introduction, found moderate wind velocities in AGNs that are similar to those from star-forming galaxies. Attributing emission infill for the difference with Hainline et al.’s (2011) absorption profiles, Coil et al. (2011) concluded that their finding, namely, AGN host galaxies at $z \sim 0.2$–0.5 do not have significantly faster winds than star-forming galaxies at similar redshifts, was not strongly at odds with results from lower and higher redshifts. Our work and those discussed above affirm this conclusion.

4.2. Some Previous Ionized Gas Emission-line Studies Found High Wind Velocities and Some Did Not

Next, we discuss AGN winds detected in emission lines of ionized gas. Emission lines as wind diagnostics are much more difficult to interpret compared to absorption lines. For instance, to infer the mean velocity of the wind from emission lines, detailed understanding of the geometry of the wind, velocity distribution of the gas, and dust extinction in the host galaxy is needed. In a spherically symmetric optically thin outflow, the emission-line profile is symmetric and peaks at the systemic

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**Table 4**

| Derived Quantity | AGN $z \sim 1$ (N = 12) | NLAGN $z \sim 1$ (N = 9) | NLAGN $z \sim 1$ (N = 7) | SF $z \sim 1$ (N = 12) | AGN $z \sim 0.5$ (N = 6) | AGN $z \sim 0.5$–1.5 (N = 13) | AGN $z \sim 0.5$–1.5 (N = 18) |
|------------------|-------------------------|--------------------------|--------------------------|------------------------|--------------------------|-----------------------------|-----------------------------|
| Wind EW (Å)      | 0.4^{+0.4}_{-0.3}       | 0.5^{+0.6}_{-0.3}        | 0.5^{+0.5}_{-0.3}        | 0.5^{+0.7}_{-0.3}      | 0.6^{+0.7}_{-0.4}        | 0.0^{+0.5}_{-0.3}           | 0.5^{+0.3}_{-0.3}           |
| ISM EW (Å)       | 1.2^{+0.4}_{-0.3}       | 1.3^{+0.5}_{-0.2}        | 1.3^{+0.5}_{-0.3}        | 1.4^{+0.5}_{-0.3}      | 1.4^{+0.6}_{-0.3}        | 1.4^{+0.4}_{-0.3}           | 1.4^{+0.4}_{-0.5}           |
| Total EW (Å)     | 1.6^{+0.2}_{-0.3}       | 1.8^{+0.2}_{-0.3}        | 1.8^{+0.2}_{-0.3}        | 1.9^{+0.4}_{-0.3}      | 2.0^{+0.4}_{-0.5}        | 1.7^{+0.3}_{-0.3}           | 1.7^{+0.2}_{-0.3}           |
| Max. Velocity (km s$^{-1}$) | $-234^{+194}_{-107}$ | $-236^{+114}_{-124}$ | $-242^{+108}_{-124}$ | $-228^{+177}_{-127}$ | $-204^{+214}_{-266}$ | $-202^{+112}_{-166}$ | $-203^{+140}_{-243}$ |

Note. The 50th (median), 84th, and 16th percentile deviations of the PDFs of the derived quantities from the wind model are given in the table. In our notation, $X^{+Z}_{-Z}$ denotes that $X$ is the median, $Y + Z$ is the 84th percentile and $X - Z$ is the 16th percentile.
velocity of the galaxy (i.e., zero velocity). In contrast, in absorption lines that are minimally affected by resonant emission, the wind velocity profile is significantly offset from the systemic velocity. Regardless of how the emission-line observations are interpreted, the result that low-luminosity AGNs at redshifts $z \sim 0.2$–1 do not have significantly faster winds (in absorption) than star-forming galaxies is consistent with the wind speeds inferred from emission lines in AGNs of comparable luminosities.

Rupke & Veilleux (2013) have explored the multiphase structure of galactic winds in six local ULIRGs using deep integral-field spectroscopy. Three of the ULIRGs host obscured quasars. Despite its small sample size, this work is unique in that it studies winds in the same objects in both emission and absorption, and it serves as a benchmark for interpreting myriad emission-line-only wind studies. Both the neutral and ionized gas of the six ULIRGs were studied by fitting the Na I absorption line and multiple Gaussian components to strong, nebular, emission lines ([O I], Hα, and [N II]). In all systems, high-velocity, collimated, multiphase kiloparsec-scale outflows were reported and the neutral phase dominates the mass outflow rate. The spatially averaged, mean, wind velocities were found to be similar ($v \sim 200$–400 km s$^{-1}$) in AGNs and non-AGNs, both for cold, neutral, and warm, ionized gas. While the maximum wind velocities reach $\sim 1000$ km s$^{-1}$ in neutral gas for both AGNs and non-AGNs, the highest gas velocities ($2000$–3000 km s$^{-1}$) were only observed in ionized gas in the obscured quasars.

Several spatially resolved, spectroscopic studies at both low and high redshifts have shown that broad, ionized emissions are common in luminous AGNs (Liu et al. 2013, 2014; Förster Schreiber et al. 2014; Genzel et al. 2014; Zakamska & Greene 2014; McElroy et al. 2015; Harrison et al. 2016). For example, Harrison et al. (2016) studied ionized gas kinematics in a representative sample of 89 X-ray AGNs using [O III] at $z = 1.1$–1.7 or Hα emission at $z = 0.6$–1.1. The authors found high-velocity emission-line features in about half of the targets studied using [O III]. The velocity-width containing 80% ($W_{80}$) of the [O III] line flux was found to mildly correlate with X-ray luminosity. For a Gaussian velocity distribution, $W_{80} = 2.56\sigma$, where $\sigma$ is the velocity dispersion. Liu et al. (2013) found $W_{80}$ $\sim 1.3$–1.6 $v_0$ for their wind models, where $v_0$ is the initial velocity of the wind. Liu et al. (2013) modeled the observed extended emission lines of their quasars as ensembles of narrow-line-emitting clouds embedded in the wind. Their model relates the observed projected surface brightness of the [O III] emission line to the unobserved three-dimensional outflow velocity profile assuming power-law luminosity density and velocity distributions, which depend on the three-dimensional radius vector of the outflow. They consider both a spherically symmetric outflow and a biconical outflow with or without the effect of dust extinction from the host galaxy.

Harrison et al. (2016) found that 70% of higher-luminosity AGNs ($L_X > 6 \times 10^{43}$ erg s$^{-1}$) have line widths of $W_{80} > 600$ km s$^{-1}$, while only 30% of the lower-luminosity AGNs have velocity widths above $600$ km s$^{-1}$. If we use the trend in Harrison et al. (2016), the nine low-luminosity AGNs studied in this work would have $W_{80} \sim 300$ km s$^{-1}$ based on their X-ray luminosity. This value is roughly consistent with the velocity estimated using the Fe II absorption line.

AGNs are known to exhibit jet-ISM interactions that accelerate gas to high velocities (Morganti et al. 2005; Nesvadba et al. 2006, 2008; Dasyra et al. 2015). Based on their current sample, Harrison et al. (2016) could not conclusively determine whether the radio luminosity or the X-ray luminosity is more fundamental in driving the highest-velocity outflows. They found marginal evidence that a higher fraction of the radio-luminous AGNs have $W_{80} > 600$ km s$^{-1}$ compared to the non-radio-luminous AGNs. Thus, high-velocity outflows may be due to small-scale, compact radio jets instead of radiation from the quasar (Mullaney et al. 2013; Villar Martí et al. 2014). Spatially resolved studies have observed very-broadened [O III] emission lines that are co-spatial with kiloparsec-scale jets (Holt et al. 2008; Müller-Sánchez et al. 2011; Husemann et al. 2013; Shih et al. 2013). At $z \sim 0.4$, using a large sample from SDSS, Mullaney et al. (2013) have shown that the highest-velocity outflows are better linked to the mechanical radio luminosity of the AGN rather than to the radiative luminosity of the AGN. Alternatively, Zakamska & Greene (2014) have proposed that radio emission in radio-quiet quasars could be due to relativistic particles accelerated in the shocks initiated by the quasar-driven outflow. The authors also found that the velocity width of [O III] is positively correlated with mid-infrared luminosity, suggesting that outflows are linked to the radiative output of the quasar (i.e., are ultimately radiation-driven).

Furthermore, Husemann et al. (2013) performed a detailed analysis of the extended ionized gas around 31 low-redshift QSOs and found only 3 QSOs have outflows with velocities greater than $400$ km s$^{-1}$. In all three cases, they found a radio jet that is most likely driving the outflows, and they argued that jet–cloud interactions are the most likely cause of disturbances in the kinematics of the quasars. Husemann et al. (2016) have argued that disagreements between their work and the aforementioned previous works, that claimed high-velocity outflows in luminous AGNs, are likely due to the effects of beam smearing of unresolved emission lines caused by seeing (see also Karouzos et al. 2016; Villar-Martín et al. 2016). They reanalyzed the unobscured QSO sample of Liu et al. (2014) and found that the widths of [O III] lines on kiloparsec scales are significantly narrower after PSF deblending. The estimated kinetic power of the outflow is reduced by two orders of magnitude ($<0.1\%$ of the quasar bolometric luminosity) after the correction. Thus, the feedback efficiency is smaller than required by some numerical simulations of AGN feedback. As the authors pointed out, the majority of previous works have not carefully taken into account the effects of beam smearing. The incidence and energetics of large-scale AGN-driven outflows still remain an unsolved issue, especially in spatially unresolved observations of ionized gas outflows beyond the local universe.

4.3. Some Previous Molecular Gas Studies Found High Wind Velocities

Molecular outflows have been reported in several AGNs both in absorption and emission (Feruglio et al. 2010; Fischer et al. 2010; Sturm et al. 2011; Spoon et al. 2013; Veilleux et al. 2013; Cicone et al. 2014; García-Burillo et al. 2014; Sun et al. 2014). Veilleux et al. (2013) studied molecular OH 119 $\mu$m outflows in a sample of 43, $z < 0.3$, galaxy mergers, which are mostly ULIRGs and QSOs. The OH 119 $\mu$m feature is observed in emission, absorption, or both depending on the AGN strength. The OH emission is stronger relative to OH absorption in quasar-dominated systems and the feature is seen
in pure emission in the most luminous quasars. The authors found that the median outflow velocities are typically \( \sim 200 \text{ km s}^{-1} \) but the maximum velocities may reach \( \sim 1000 \text{ km s}^{-1} \) in some objects. For even the most AGN-dominated systems with pure OH emissions, the emission-line widths and shifts are \( \sim 200 \text{ km s}^{-1} \). The authors also reported that the absorption-line centroids are distinctly more blueshifted among systems with large AGN fractions and luminosities. It is not clear how much this trend is due to emission infill of the absorption profile.

A recent X-ray observation of a mildly relativistic accretion disk wind in a local Seyfert 1 ULIRG, which also shows high-velocity molecular OH 119 \( \mu \text{m} \) outflow have been hailed as providing direct connections between large-scale molecular outflows and the small-scale, AGN accretion wind in ULIRGs (Tombesi et al. 2015). A review of the powerful and highly ionized accretion winds observed in X-ray spectra of luminous AGNs can be found in King & Pounds (2015).

Cicone et al. (2014) have studied CO emission in 19 local ULIRGs and quasar hosts. They found that starburst-dominated galaxies can have outflow rates that are \( \sim 2-4 \) times their SFRs and the presence of AGNs may enhance the outflow rates by a large factor depending on their luminosity. The maximum velocities reach up to \( \sim 750 \text{ km s}^{-1} \). The authors estimated that the outflow kinetic power for galaxies with the most powerful AGNs is about 5% of the AGN luminosity, as expected from some numerical models of AGN feedback.

In contrast, recent, local studies of molecular gas in recently quenched or quenching post-starbursts surprisingly found that these galaxies have large molecular gas reservoirs comparable to star-forming galaxies (French et al. 2015; Rowlands et al. 2015). Therefore, they did not find evidence that the global gas reservoir is expelled by stellar winds or active galactic nuclei feedback. Similarly, at \( z \sim 2 \), Prochaska et al. (2014) observed that quasar halos have abundant, cool gas, which is sufficient to fuel the observed SFR for at least 1 Gyr. These authors note that the current AGN feedback models remove too much gas from galactic halos and, therefore, underpredict the gas observed within quasar halos at \( z \sim 2 \).

To summarize, most absorption-line studies found that the wind velocities in AGNs are moderate (\( \sim 200-400 \text{ km s}^{-1} \)) and are similar to velocities in star formation-driven winds. Most high-velocity AGN winds reported to date are controversial and can be attributed to observational complications such as emission infill and PSF smearing, or they may not be due to radiation from luminous AGNs, or they may just be spatially unresolved, small-scale wind confined to the vicinity of black holes.

### 4.4. The Feedback Efficiency in the Low-luminosity AGN at \( z \sim 1 \) and in Other AGN Samples

The wind kinetic power can be parametrized in terms of the radiative luminosity of an AGN as \( E = \epsilon_f L_{\text{AGN}} \), where \( \epsilon_f \) is the fraction of the radiative luminosity transferred to the wind. Popular AGN feedback models invoke feedback efficiency, \( \epsilon_f \sim 5\% \), to reproduce the properties of massive galaxies (e.g., Scannapieco & Oh 2004; Di Matteo et al. 2005; Choi et al. 2012; Zubovas & King 2012). Following the thin, partially filled shell wind model of Rupke et al. (2005c), we estimate \( E \) from their equation given below, which includes a contribution from both bulk flow and turbulent energy.

\[
dE/dt = 1.4 \times 10^{41} \text{ erg s}^{-1} \left( \frac{C_{\text{f}}}{0.4} \right) \left( \frac{r}{10 \text{ kpc}} \right) \times \left( \frac{N(\text{H})}{10^{21} \text{ cm}^{-2}} \right) \left( \frac{v_w}{200 \text{ km s}^{-1}} \right) \times \left[ \left( \frac{v_w}{200 \text{ km s}^{-1}} \right)^2 + 1.5 \left( \frac{b}{200 \text{ km s}^{-1}} \right)^2 \right].
\]

In the above estimate, we use the wind measurements in Table 3 and assume a wind radius of \( r = 3 \text{ kpc} \) and global covering factor \( C_{\text{f}} = 0.3 \) (which is reasonable for the average opening angle of winds in star-forming galaxies \( z \sim 1 \) as estimated by Rubin et al. 2014). To convert the iron column density to hydrogen column density (\( \text{N(H)} \), which is a lower limit), we adopt a solar abundance ratio and a dust depletion factor of 0.1 and no ionization correction (Rubin et al. 2014). The sample bolometric luminosity of our AGN is estimated by multiplying the mean X-ray luminosity of our sample with a bolometric correction of 20 (Vasudevan & Fabian 2007). With these assumptions, we find a feedback efficiency lower-limit estimate of \( \epsilon_f \gtrsim 0.02\% \) for our nine narrow-line AGN sample.

Note that the metal abundance ratio, dust depletion factor, and ionization correction are completely unconstrained by the current data. From the mass–metallicity relation at \( z \sim 1 \) (Zahid
The mean oxygen abundance, $12 + \log(O/H)$, of our sample ranges between 8.9 and 9.1 and the typical 1σ scatter of the relation is $\sim 0.15$ dex. Therefore, the gas phase metallicity of our sample is not very inconsistent with the assumed solar value of 8.7. In the local ISM of the Milky Way, the dust depletion factor for iron is 0.005–0.1 (Jenkins 2009). The ionization correction for Fe II is uncertain and there are not many measured values of it. In the Orion Nebula, the ionization correction is $\sim 0.08$, and the column densities of $N(Fe IV) \sim 0.87 \times N(Fe III)$ and $N(Fe II) \sim 0.16 \times N(Fe III)$ (Rodríguez & Rubin 2005). The $N(Fe II)/N(Fe III)$ ratio ranges between 0.04 and 0.35 in eight Galactic H II regions, including the Orion Nebula (García-Rojas & Esteban 2007). Since $N(Fe IV)$ is not measured in most of these H II regions, 0.04–0.35 is a crude range for the ionization correction for Fe II. Since we do not do the ionization correction in our lower-limit estimate of the column density, the true column density may be a factor of 3–10 higher than our limit, other things being equal.

To put the present measurements in larger context, Figure 8 shows AGN bolometric luminosity against the wind kinetic power for our sample and other AGN wind samples in the literature. A very heterogeneous data, covering a wide range in redshift $z \sim 0.1–2$, are used in the figure. Our compilation includes AGNs that are known to show wind signatures in absorption (Rupke et al. 2005a; Krug et al. 2010a; Edmonds et al. 2011; Borguet et al. 2012, 2013; Arav et al. 2013; Rupke & Veilleux 2013; Chamberlain & Arav 2015), in ionized gas emission (Liu et al. 2013; Rupke & Veilleux 2013; Harrison et al. 2014, 2016; Carniani et al. 2015; McClure et al. 2015; Zakamska et al. 2016), and in molecular gas.

All the absorption line and molecular gas based kinetic wind power measurements are taken directly from values published in the literature, while all of the emission lines are based on the wind power measurements, except for those taken from Rupke & Veilleux (2013), which are based on our calculations. Where the wind power measurements for the ionized gas are not available, we estimate them following the standard methods and assumptions (e.g., Nesvadba et al. 2006; Harrison et al. 2014; Zakamska et al. 2016). Using the equation below, the wind power for all ionized gas measurements is estimated from nebular emission lines assuming a wind radius of 3 kpc, an electron density of 100 cm$^{-3}$, and the velocity-width is 1.3 times the initial wind velocity, $W_{80} = 1.3v_0$ (for a spherically symmetric and constant velocity wind).

$$dE/dt \sim 1/2M_{gas}v_0^2/\tau \sim 1/2M_{gas}v_0^3/r$$

$$\sim 6 \times 10^{44} \text{erg s}^{-1} \times \left(\frac{M_{gas}}{2.8 \times 10^9 M_\odot}\right) \times \left(\frac{W_{80}}{1300 \text{ km s}^{-1}}\right)^3 \left(\frac{3 \text{kpc}}{r}\right).$$

where

$$\frac{M_{gas}}{2.8 \times 10^9 M_\odot} = \frac{L_{H\beta}}{10^{43} \text{erg s}^{-1}} \times 100 \text{cm}^{-3}$$

and

$$L_{H\beta} = 0.1 \times L_{O III}^{10} \text{or } L_{H\beta} = 0.35 \times L_{H\alpha} \frac{2.86}{\text{Hz/Hz}}.$$

As discussed in Zakamska et al. (2016), a standard method of estimating the wind power for the ionized gas is to use hydrogen recombination lines to estimate the mass of the emitting hydrogen, but the [O III] emission-line may be a better probe of the extended emission. When they are available, O III velocity width and luminosity are used to estimate wind kinetic power, assuming a [O III]/H$\beta$ ratio of 10. Otherwise, hydrogen lines are used. Due to unaccounted for dust extinction of emission lines and turbulent kinetic energy, the estimated wind kinetic energy for the ionized gas is a lower limit.

The outflow rate in molecular gas is estimated assuming continuously filled spherical wind ($M = 3vM/R$, where $M$ is the mass, $v$ is velocity, and $R$ is the radius of the wind). These estimates are three times lower if shell-like geometry is assumed instead (Cicone et al. 2014). The molecular wind kinetic energy is estimated simply as $1/2Mv^2$. For 90% of the galaxies, the molecular wind mass is estimated from CO luminosity, assuming conversion factors from CO to molecular hydrogen, $X_{CO}$, which is about one-fifth of the Milky Way value (Bolatto et al. 2013). If the true $X_{CO}$ is higher than assumed, the current wind kinetic energy values underestimate the true values.

For the consistency, we adjust the literature wind power measurements for the cool gas to our assumed wind radius of 3 kpc when the wind radius was not previously measured. When the bolometric luminosities are not provided in the
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Table 5
Model Parameter Fits to Fe II λ2586 Profiles Using Errors of Inverse-variance-weighting

| Model | AGN $z \sim 1$ ($N = 12$) | NL AGN $z \sim 1$ ($N = 9$) | NL AGN $z \sim 1$ ($N = 7$) | SF $z \sim 1$ ($N = 12$) | AGN $z \sim 0.5^a$ ($N = 6$) | AGN $z \sim 0.5 - 1.5^b$ ($N = 13$) | AGN $z \sim 0.5 - 1.5^c$ ($N = 18$) |
|-------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| $v_w$ (km s$^{-1}$) | $-137_{-87}^{+76}$ | $-152_{-76}^{+76}$ | $-194_{-41}^{+68}$ | $-135_{-13}^{+75}$ | $-169_{-42}^{+78}$ | $-139_{-47}^{+48}$ | $-132_{-46}^{+51}$ |
| $b_w$ (km s$^{-1}$) | $150_{-79}^{+20}$ | $112_{-60}^{+40}$ | $76_{-20}^{+40}$ | $198_{-102}^{+90}$ | $112_{-54}^{+54}$ | $116_{-53}^{+63}$ | $135_{-72}^{+61}$ |
| $C_w$ | $0.5_{-0.3}^{+0.1}$ | $0.4_{-0.1}^{+0.1}$ | $0.4_{-0.1}^{+0.1}$ | $0.4_{-0.1}^{+0.2}$ | $0.4_{-0.1}^{+0.2}$ | $0.4_{-0.1}^{+0.3}$ | $0.4_{-0.1}^{+0.3}$ |
| $\log N_e$ (cm$^{-3}$) | $14.8_{-0.5}^{+0.5}$ | $15.1_{-0.7}^{+1.3}$ | $15.2_{-0.7}^{+1.2}$ | $14.9_{-0.8}^{+1.1}$ | $15.2_{-0.6}^{+1.3}$ | $15.4_{-0.7}^{+1.3}$ | $15.2_{-0.6}^{+1.3}$ |
| $b_g$ (km s$^{-1}$) | $243_{-34}^{+45}$ | $224_{-34}^{+48}$ | $214_{-34}^{+48}$ | $154_{-52}^{+48}$ | $98_{-33}^{+35}$ | $181_{-46}^{+46}$ | $179_{-49}^{+45}$ |
| $\log N_g$ (cm$^{-3}$) | $14.5_{-0.2}^{+0.2}$ | $14.5_{-0.3}^{+0.3}$ | $14.5_{-0.3}^{+0.3}$ | $14.6_{-0.3}^{+0.2}$ | $14.6_{-0.3}^{+0.2}$ | $14.5_{-0.3}^{+0.1}$ | $14.5_{-0.3}^{+0.1}$ |

Notes. The 50th (median), 84th, and 16th percentile deviations of the PDFs of parameters are given in the table. In our notation, $X_{\pm 25}$: $X$ is the median, $X + Z$ is the 84th percentile, and $X - Z$ is the 16th percentile.

$^a$ Reanalysis of Coil et al. (2011) data.
$^b$ A joint reanalysis of Coil et al. (2011) data with our seven narrow-line AGNs with highly reliable AGN identification.
$^c$ A joint reanalysis of Coil et al. (2011) data with all AGN including three broad-line AGNs and two with less reliable AGN identification.
$^d$ $N$ denotes the number of galaxies in the stacked spectra.

Table 6
Wind Equivalent Width (EW) and Maximum Wind Velocity Derived from Fe II λ2586 Model Profiles

| Derived Quantity | AGN $z \sim 1$ ($N = 12$) | NL AGN $z \sim 1$ ($N = 9$) | NL AGN $z \sim 1$ ($N = 7$) | SF $z \sim 1$ ($N = 12$) | AGN $z \sim 0.5^a$ ($N = 6$) | AGN $z \sim 0.5 - 1.5^b$ ($N = 13$) | AGN $z \sim 0.5 - 1.5^c$ ($N = 18$) |
|------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| Wind EW (Å)      | $0.5_{-0.3}^{+0.2}$ | $0.6_{-0.4}^{+0.5}$ | $0.3_{-0.2}^{+0.4}$ | $0.8_{-0.1}^{+0.5}$ | $0.8_{-0.3}^{+0.5}$ | $1.0_{-0.4}^{+0.5}$ | $0.9_{-0.3}^{+0.5}$ |
| ISM EW (Å)       | $1.2_{-0.4}^{+0.2}$ | $1.5_{-0.6}^{+0.3}$ | $1.5_{-0.4}^{+0.2}$ | $1.3_{-0.3}^{+0.3}$ | $1.2_{-0.4}^{+0.3}$ | $1.1_{-0.3}^{+0.5}$ | $1.1_{-0.3}^{+0.5}$ |
| Total EW (Å)     | $1.6_{-0.1}^{+0.1}$ | $1.8_{-0.1}^{+0.1}$ | $1.7_{-0.1}^{+0.1}$ | $1.9_{-0.1}^{+0.1}$ | $1.9_{-0.1}^{+0.1}$ | $1.9_{-0.1}^{+0.1}$ | $1.9_{-0.1}^{+0.1}$ |
| Max. Velocity (km s$^{-1}$) | $-341_{-104}^{+77}$ | $-318_{-59}^{+75}$ | $-303_{-57}^{+77}$ | $-432_{-116}^{+24}$ | $-263_{-68}^{+24}$ | $-237_{-51}^{+24}$ | $-250_{-54}^{+24}$ |

Note. The 50th (median), 84th, and 16th percentile deviations of the derived quantities from the wind model are given in the table.

previous works, they are estimated from literature X-ray luminosities using a bolometric correction of 20.

In summary, the existing data hint that the wind kinetic energy is correlated with the bolometric luminosity AGN. However, better future data, which can characterize well the geometry of the wind are need to constrain AGN feedback models. We caution that the systematic uncertainties in $\epsilon_f$ are substantial and the values $\epsilon_f$ inferred from Figure 8 should be considered as lower limits. Because of the uncertain assumptions made and the heterogenous data used to estimate wind kinetic power, our aim is rather to qualitatively show that wind kinetic power increases with AGN bolometric luminosity. This trend is mainly driven by the correlation between the wind velocity and the AGN luminosity. We hope Figure 8 shows how our study broadly fits into wind characteristics reported in previous studies of AGNs, and perhaps explains our finding of low velocity winds in low-luminosity AGNs.

5. Summary and Conclusion

We study winds using the Fe II λ2586 absorption line in 12 AGN host galaxies at $z \sim 1$. Nine of these galaxies significantly deviate from the relationship between star-formation and X-ray luminosity and one of them has strong Ne V emission. We find that the probability distribution function (PDF) of the centroid-velocity shift in AGNs has 50th (median), 16th, and 84th percentiles of $-87$ km s$^{-1}$, $-251$ km s$^{-1}$, and $+86$ km s$^{-1}$ respectively. The PDF of the velocity dispersion in AGNs has 50th (median), 84th, and 16th percentiles of $139$ km s$^{-1}$, $253$ km s$^{-1}$, and $52$ km s$^{-1}$ respectively. The centroid velocity and the velocity dispersions are obtained from a two-component (ISM+wind) absorption-line model. The wind velocities in these AGNs are significantly lower than their escape velocities. Thus, the bulk of their gas likely remains bound. The equivalent width PDF of the outflow in AGNs has 50th (median), 84th, and 16th percentiles of 0.4 Å, 0.8 Å, and 0.1 Å respectively. There is a strong ISM component in Fe II λ2586 absorption (has a PDF with 50th (median), 84th, and 16th percentiles of 1.2, 1.5, and 0.8 Å), implying that a substantial amount of cold gas is present in the AGN host galaxies. For comparison, star-forming and X-ray undetected galaxies at a similar redshift, matched roughly in stellar mass and galaxy inclination, have a centroid-velocity PDF with 50th (median), 84th, and 16th percentiles of $-74$, $-258$, and $+90$ km s$^{-1}$, and a velocity-dispersion PDF with 50th (median), 84th, and 16th percentiles of 150 km s$^{-1}$, 259 km s$^{-1}$, and 57 km s$^{-1}$ respectively. The equivalent width PDF of the outflow in the comparison sample has 50th (median), 84th, and 16th percentiles of 0.5, 1.2, and 0.2 Å. We have reanalyzed the sample of six low-luminosity AGNs at $z \sim 0.5$ from Coil et al. (2011). Our result is consistent with the wind velocities previously reported in these and other lower-redshift low-luminosity AGNs. We conclude that the wind-mode AGN feedback is insignificant in low-luminosity AGN hosts. Future, large-sample-size and high-signal-to-noise studies of winds in AGNs and in a well-matched control sample of non-AGNs are needed to significantly advance our knowledge from existing small sample absorption-line studies and to enable a detailed modeling of winds that will potentially uncover subtle differences between the winds in AGNs and in their control sample.

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Figure 10. Similar to Figure 7 but the errors of the composite spectra are estimated using errors of inverse-variance-weighting as described in Appendix A.2. In panel (g), the error bars are invisible because they were too small.

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Appendix

In this section, we give ancillary information to support the results presented in the main sections of the paper.
Figure 12. Result of fitting two-Gaussian with an equal width to the O II doublet. The velocity dispersions of the fits are shown in the figures. Comparing the observed wind velocity to the O II width, we conclude that the winds, both in AGN and the comparison sample, are too weak to escape the gravitational potentials of their galaxies.

Table 7

Model Parameter Fits to Fe II λ2586 Profiles after Adopting a Covering Fraction of 50% for the ISM Component of the Wind Model

| Wind Model Parameters | All AGN at z ≈ 1 (N = 12) | NL AGN at z ≈ 1 (N = 9) | NL AGN at z ≈ 1 (N = 7) | SF at z ≈ 1 (N = 12) | AGN at z ≈ 0.5 (N = 6) |
|----------------------|-----------------------------|--------------------------|--------------------------|-----------------------|------------------------|
| $v_0$ (km s$^{-1}$)   | $-77^{+108}_{-109}$         | $-99^{+120}_{-121}$      | $-127^{+113}_{-112}$     | $-123^{+130}_{-203}$  | $-93^{+204}_{-205}$    |
| $\sigma_v$ (km s$^{-1}$) | 206^{+144}_{-129}          | 174^{+142}_{-96}        | 152^{+145}_{-30}         | 227^{+148}_{-137}     | 190^{+126}_{-167}      |
| $C_{i}$               | 0.2^{+0.4}_{-0.2}           | 0.3^{+0.2}_{-0.3}       | 0.4^{+0.4}_{-0.2}        | 0.2^{+0.4}_{-0.2}     | 0.3^{+0.2}_{-0.2}      |
| log $N_e$ (cm$^{-2}$) | 14.9^{+1.8}_{-1.6}          | 14.8^{+1.5}_{-1.5}      | 15.0^{+1.4}_{-0.6}       | 14.9^{+1.5}_{-0.6}    | 15.0^{+1.5}_{-0.3}     |
| $\delta_s$ (km s$^{-1}$) | 218^{+88}_{-76}            | 200^{+65}_{-65}        | 210^{+116}_{-106}        | 101^{+73}_{-36}       | 128^{+117}_{-143}      |
| log $N_i$ (cm$^{-2}$) | 14.9^{+0.2}_{-0.5}          | 15.0^{+0.2}_{-0.4}      | 15.0^{+0.2}_{-0.4}       | 15.5^{+0.4}_{-0.4}    | 15.3^{+1.2}_{-0.6}     |

Note. The errors of the composite spectra are estimated by the bootstrap scheme. The 50th (median), 84th, and 16th percentile deviations of the PDFs of parameters from the median are given in the table.

A.1. NUV Composite Spectra of AGNs and the Comparison Sample

Similar to Figure 6, Figure 9 shows the near-UV composite spectra around Fe II λ2586 for AGN subsamples (N = 12 or N = 9) and the comparison sample of X-ray undetected galaxies at z ≈ 1.

A.2. Reanalysis with Simple Errors of Inverse-variance-weighting (No Bootstrapping)

The errors of each individual spectrum are outputs by DEEP2 spec1d pipeline. If $\sigma_{ij}$ is the error of the photon count, $C_i(\lambda_j)$, at the wavelength pixel $\lambda_j$ of a galaxy $i$, averaging over all $N$ galaxies, the inverse-variance-weighted mean count at pixel $\lambda_j$ is $\hat{C}(\lambda_j) = \frac{\sum_{i=1}^{N} C_i(\lambda_j) / \sigma_{ij}^2}{\sum_{i=1}^{N} 1 / \sigma_{ij}^2}$. The standard error of the mean count at pixel $\lambda_j$ is $\hat{\delta}_j = \frac{1}{\sqrt{\sum_{i=1}^{N} 1 / \sigma_{ij}^2}}$. The inverse-variance weighting analysis gives lower weights to galaxies having low signal-to-noise spectra in the sample and may not capture well the dispersion intrinsic to the sample. On the other hand, it has the advantage of down-weighting poorly measured data. In the case where the intrinsic sample dispersion is negligible, it may be preferred over the bootstrapping scheme. In the latter case, poor data may be resampled instead of good data, thereby increasing the inferred dispersion. This section presents results of the reanalysis using $\hat{\delta}_j$ errors of the inverse-variance-weighting as shown in Tables 5 and 6, and Figures 10 and 11. In the latter figure, we plot the posterior PDFs of all six wind model parameters for the AGNs and the comparison samples. Note that some of the parameters strongly correlate with each other and their PDFs are very asymmetric (non-Gaussian). For example, the covering fraction and the column density of the wind are degenerate with each other. Thus, the column density estimates are uncertain by more than a factor of 10.

A.3. Fitting O II Profile to Estimate the Escape Velocity

Figure 12(a) shows the result of fitting two Gaussians + a linear continuum model to the O II λ3726.03, λ3728.82 doublet to the mean AGN spectra using Levenberg–Marquardt least square minimization. In the model, the two Gaussians have the same width, and the centroid shifts and the amplitudes of the doublet are also free parameters of the fit. The two-Gaussian model is convolved to match the DEIMOS instrumental resolution and rebinned to match the observed data. Figure 12(b) shows the corresponding fit for the star-forming comparison sample. The velocity dispersions of the fits are $131 \pm 18$ km s$^{-1}$ for SF galaxies and $122 \pm 4$ km s$^{-1}$ for AGNs. The errors of the velocity dispersions are estimated by repeating the least square fitting procedure for all 1000 bootstrap spectra around O II (similar to what is shown in Figure 6) and then taking the standard deviation of the 1000 velocity dispersions. The centroid shifts of the doublet are...
consistent with no shift from the rest wavelengths of the doublur.

### A.4. The Effect of the ISM Covering Fraction

In the fiducial wind model in the main text of the paper, we assumed that the ISM fully covers the stellar continuum emission. Tables 7 and 8 show that the results of the analyses using a covering fraction of 50%. Our main conclusion does not depend on the assumption of the covering fraction.

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### Table 8

| Wind Model | All AGN at $z \sim 1$ (N = 12) | NL AGN at $z \sim 1$ (N = 9) | NL AGN at $z \sim 1$ (N = 7) | SF at $z \sim 1$ (N = 12) | AGN at $z \sim 0.5$ (N = 6) |
|------------|-------------------------------|-----------------------------|----------------------------|-----------------------------|-----------------------------|
| $v_w$ (km s$^{-1}$) | $-121_{-102}^{+74}$ | $-148_{-86}^{+46}$ | $-190_{-103}^{+80}$ | $-110_{-51}^{+185}$ | $-169_{-74}^{+76}$ |
| $b_w$ (km s$^{-1}$) | $153_{-94}^{+84}$ | $114_{-63}^{+74}$ | $79_{-62}^{+67}$ | $197_{-137}^{+13}$ | $120_{-56}^{+52}$ |
| $C_m$ | $0.3_{-0.0}^{+0.0}$ | $0.3_{-0.1}^{+0.0}$ | $0.4_{-0.0}^{+0.0}$ | $0.3_{-0.2}^{+0.0}$ | $0.4_{-0.1}^{+0.0}$ |
| log $N_C$ (cm$^{-2}$) | $14.5_{-0.5}^{+1.2}$ | $15.2_{-0.8}^{+1.3}$ | $15.2_{-0.8}^{+1.4}$ | $15.0_{-0.6}^{+0.7}$ | $15.2_{-0.7}^{+1.8}$ |
| $b_k$ (km s$^{-1}$) | $231_{-49}^{+66}$ | $204_{-42}^{+42}$ | $204_{-42}^{+40}$ | $165_{-0.1}^{+1.3}$ | $78_{-0.5}^{+0.8}$ |
| log $N_h$ (cm$^{-2}$) | $14.9_{-0.3}^{+0.1}$ | $15.0_{-0.3}^{+0.1}$ | $14.9_{-0.3}^{+0.1}$ | $14.6_{-0.3}^{+0.2}$ | $15.7_{-0.8}^{+1.8}$ |

Note. The 50th (median), 84th, and 16th percentile deviations of the PDFs of parameters from the median are given in the table.
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