

Correlations of ALMA CO(2-1) with JWST mid-infrared fluxes down to scale of $\lesssim 100$ parsec in nearby star-forming galaxies from PHANGS

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ABSTRACT

We investigate the correlations of CO (2-1) emission (I_{CO}) with PAH ($I_{\text{F770W,PAH}}$ and I_{F1130W}) and dust (I_{F2100W}) emission down to scales of $\lesssim 100$ pc, by applying **raddest**, a novel regression technique recently developed by T. Jing & C. Li (2025) that effectively handles uncertainties and outliers in datasets, to 19 nearby star-forming galaxies in the PHANGS sample. We find that for the majority of the data points in all galaxies, the scaling of I_{CO} with $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} can be well described by log-linear relations, though with substantial dependence on ionization conditions (i.e., H II-like, composite-like, and AGN-like). Under given ionization conditions, significant galaxy-to-galaxy variations are identified, and are primarily attributed to variations of intercept b , which exhibits clear bimodality. This bimodality is related to the overall host galaxy star formation strength. The differences in slope k and intrinsic scatter σ across different MIR bands ($I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W}) are minor compared to their galaxy-to-galaxy variations. All parameters (k , b , and σ) depend on the spatial scale of measurement, suggesting that the coupling among CO, PAH, and dust is regulated by different mechanisms at varying scales. We identify non-log-linear behaviors in the brightest regions, where deviations are primarily characterized by flattening of slope. No significant (3σ) correlations are found between global properties and the best-fit parameters. We discuss the comparison to previous studies and plausible physics behind the statistical results obtained in this work.

1. INTRODUCTION

A central pursuit in modern galaxy evolution studies is to understand the coevolution of the multiphase interstellar medium (ISM), which is an ecosystem of molecular gas, polycyclic aromatic hydrocarbons (PAHs) and dust, in addition to the ubiquitous warm/hot gas ionized by various mechanisms. Molecular gas traces the dense ISM and directly fuels star formation. PAHs are regarded as the carriers of absorption features, such as the ultraviolet (UV) bump around 2175 Å (e.g. A. Li & B. T. Draine 2001; M. Declerck et al. 2019; D. Massa et al. 2022; I. Shivaee et al. 2022; Q. Lin et al. 2023; K. D. Gordon et al. 2024; A. Battisti et al. 2025), and diffuse interstellar bands (e.g. A. Leger & L. D’Hendecourt 1985; M. K. Crawford et al. 1985; G. P. van der Zwet & L. J. Allamandola 1985; F. Salama et al. 1996, 2011; F. Salama & P. Ehrenfreund 2014). PAH emission originates from the immediate re-radiation of absorbed UV photons and is destroyed in hot and ionized environments. As a result, PAH emission serves as a tracer for photodissociation regions. Dust influences the shielding

and chemistry of the ISM through its absorption, scattering, and chemical catalytic properties.

The evolution of molecular gas, PAH and dust is interconnected. Stars formed within molecular clouds are the primary source of dust. Dust, in turn, facilitates the shielding of UV photons, thereby promoting the formation of molecular clouds. Furthermore, the transition from H I to H II is significantly accelerated on dust surfaces. The aromatization of small dust grains produces PAHs. In addition, the behavior of these components is regulated by ionization conditions, such as radiation from stars, radiation from active galactic nuclei (AGN), and shocks. Therefore, the relationships among these components encode essential information about the physical state of the ISM, physical and chemical processes that affect ISM, and the regulation of star formation across different environments and scales.

Due to its importance, the correlation of molecular gas with both PAH and dust emission has been extensively studied in recent years, on scales from galaxy sizes down to $\sim \text{kpc}$. For instance, X.-J. Jiang et al. (2015) and Y. Gao et al. (2019) identify log-linear scaling rela-

tions of molecular gas (traced by CO(1-0) or CO(2-1)²) with PAH (traced by the WISE W3 band; [E. L. Wright et al. 2010](#)) and dust (traced by the WISE W4 band) at galactic scales. They find that the CO(1-0)–WISE W3 band correlation exhibits less scatter compared to the CO(1-0)–WISE W4 correlation. The correlation between CO(1-0) emission and 6.2 μm PAH features are also reported in [I. Cortzen et al. \(2019\)](#). [R. Chown et al. \(2021\)](#) extend the correlation between CO(1-0) and the WISE W3 band to kpc scales and find a slope consistent with that observed at galactic scales. [A. K. Leroy et al. \(2023a\)](#) further validate these results by studying the correlation between CO(1-0) and CO(2-1) with 8 μm (Spitzer; [M. W. Werner et al. 2004](#)), 12 μm (WISE W3), 22 μm (WISE W4), and 24 μm (Spitzer) bands across kpc to galactic scales. Comparing different bands, they report steeper CO vs. mid-infrared slopes for the 8 μm and 12 μm bands than for the 22 μm and 24 μm bands. Additionally, they identify an anti-correlation between the intercept of these scaling relations and the host galaxies’ specific star formation rate (sSFR). [Y. Gao et al. \(2022\)](#) find that the W3 band correlates more tightly with ^{12}CO than with ^{13}CO , C^{18}O , or other dense gas tracers (e.g., $\text{HCN}(4-3)$, $\text{HCO}^+(4-3)$). More recently, [Y. Gao et al. \(2025\)](#) report that the CO(1-0)–WISE W3 and CO(2-1)–WISE W3 scaling relations exhibit steeper slopes in early-type galaxies compared to star-forming galaxies.

The launch of JWST ([J. P. Gardner et al. 2006](#)) has recently enabled both PAH and dust emission to be measured at sub-arcsecond spatial resolution. By combining PHANGS-JWST ([J. C. Lee et al. 2023](#); [T. G. Williams et al. 2024](#)) and PHANGS-ALMA ([A. K. Leroy et al. 2021a,b](#)) data, [A. K. Leroy et al. \(2023b\)](#) and [R. Chown et al. \(2025\)](#) are the first to explore the correlations of CO with PAH and dust at cloud scales (~ 100 pc). However, as noted by [T. Jing & C. Li \(2025, hereafter JL25\)](#), the use of suboptimal regression techniques in these studies may bias the results and obscure the analysis of the intrinsic scatter in the scaling relations. For instance, as demonstrated in [JL25](#), the previously reported sublinear slope of the CO–F2100W scaling relation primarily arises from the limited signal-to-noise ratio (S/N) of F2100W and the presence of outliers. Moreover, the effect of ionization conditions on these scaling relations remains unexplored. The ionization condition dependence encodes critical information about the influence of stellar or AGN feedback on the coupling of CO, PAH, and dust in the ISM.

In this work, we analyze 19 galaxies in the PHANGS sample, which are included in the PHANGS-JWST, PHANGS-ALMA, and PHANGS-MUSE ([E. Emsellem et al. 2022](#)) samples. The optical emission line measurements provided by PHANGS-MUSE enable us to divide the regions into H II-like, composite-like, and AGN-like ionization subgroups, facilitating the study of the dependence on ionization conditions. For the regression analysis, we adopt the recently developed method **raddest** ([JL25](#)). As demonstrated by [JL25](#), **raddest** achieves the highest accuracy among all existing widely used techniques, particularly for datasets with limited S/N ratios and outliers. This is validated using both mock datasets and observations of four galaxies included in the PHANGS-JWST and PHANGS-ALMA samples. Consequently, the results obtained with this method minimize the influence of limited S/N and outliers, providing unbiased measurements of scaling relationships, including intrinsic scatter. By utilizing the ability of **raddest** to model any scaling relation formula, we further investigate potential non-log-linear behaviors that may arise.

This paper is organized as follows. In [section 2](#), we describe the data preparation approach and briefly introduce the regression technique. Statistical results are presented in [section 3](#). [section 4](#) compares our findings to previous studies and explores the plausible physical mechanisms underlying the scaling relations. Finally, we summarize our key findings in [section 5](#).

2. DATA AND METHODOLOGY

2.1. The PHANGS galaxy sample

We consider 19 galaxies from the Physics at High Angular Resolution in Nearby Galaxies Survey (PHANGS). For each galaxy, PHANGS-ALMA ([A. K. Leroy et al. 2021a,b](#)) provides the CO(2-1) intensity (I_{CO}) map, while PHANGS-JWST ([J. C. Lee et al. 2023](#); [T. G. Williams et al. 2024](#)) provides maps of PAH emission in the F770W (I_{F770W}) and F1130W (I_{F1130W}) bands, as well as dust emission in the F2100W band (I_{F2100W}). Following [R. Chown et al. \(2025\)](#), we estimate the stellar continuum contamination in the F770W band to be 12% of the F200W band intensity (I_{F200W}). The continuum-subtracted F770W intensity is therefore given by $I_{\text{F770W,PAH}} = I_{\text{F770W}} - 0.12I_{\text{F200W}}$. Additionally, PHANGS-MUSE ([E. Emsellem et al. 2022](#)) provides optical emission line fluxes, including $\text{H}\alpha$ $\lambda 6563$, $\text{H}\beta$ $\lambda 4861$, $[\text{S II}]$ $\lambda\lambda 6717, 6731$, $[\text{N II}]$ $\lambda 6583$, and $[\text{O III}]$ $\lambda 5007$, which we use to diagnose the ionization source in each spaxel. Specifically, we classify spaxels as H II-like, composite-like, or AGN-

² Unless otherwise specified, CO in this paper refers to ^{12}CO

Table 1. Global properties and highest available resolution after PSF matching for the galaxies analyzed in this work

ID ^a	Name	$\log M_*$ [$M_\odot$]	$\log \text{SFR}$ [$M_\odot \text{ yr}^{-1}$]	$\log L_{\text{CO}}$ [$\text{K km s}^{-1} \text{ pc}^2$]	$\log M_{\text{HI}}$ [$M_\odot$]	D [Mpc]	i ^b [deg]	$\text{FWHM}_{\text{ang.}}$ ^c [arcsec]	$\text{FWHM}_{\text{phy.}}$ ^d [pc]	high- b
1	NGC5068	9.41	-0.56	7.26	8.82	5.20	35.70	1.04	26.22	No
2	IC5332	9.68	-0.39	7.09	9.30	9.01	26.90	0.87	38.00	Yes
3	NGC1087	9.94	0.11	8.32	9.10	15.85	42.90	1.60	123.15	No
4	NGC1385	9.98	0.32	8.37	9.19	17.22	44.00	1.27	105.86	No
5	NGC2835	10.00	0.10	7.71	9.48	12.22	41.30	1.15	68.13	No
6	NGC7496	10.00	0.35	8.33	9.07	18.72	35.90	1.68	152.02	No
7	NGC0628	10.34	0.24	8.41	9.70	9.84	8.90	1.12	53.49	Yes
8	NGC3351	10.37	0.12	8.13	8.93	9.96	45.10	1.46	70.66	Yes
9	NGC4254	10.42	0.49	8.93	9.48	13.10	34.40	1.78	113.13	No
10	NGC4303	10.51	0.73	9.00	9.67	16.99	23.50	1.81	149.34	No
11	NGC4535	10.54	0.34	8.61	9.56	15.77	44.70	1.56	119.14	Yes
12	NGC1300	10.62	0.07	8.50	9.38	18.99	31.80	1.23	113.11	Yes
13	NGC1512	10.72	0.11	8.26	9.88	18.83	42.50	1.25	114.11	Yes
14	NGC1672	10.73	0.88	9.05	10.21	19.40	42.60	1.93	181.75	No
15	NGC4321	10.75	0.55	9.02	9.43	15.21	38.50	1.67	122.89	Yes
16	NGC1566	10.79	0.66	8.89	9.80	17.69	29.50	1.25	107.57	No
17	NGC3627	10.84	0.59	8.98	9.09	11.32	57.30	1.63	89.25	No
18	NGC1433	10.87	0.05	8.47	9.40	18.63	28.60	1.10	99.14	Yes
19	NGC1365	11.00	1.24	9.49	9.94	19.57	55.40	1.38	130.81	Yes

^aGalaxies are ordered by increasing stellar mass M_* .

^bInclination angle of the galaxy.

^cAngular FWHM after PSF matching.

^dPhysical FWHM after PSF matching.

like using the $P1 - P2$ diagnostic diagram proposed by X. Ji & R. Yan (2020).

For each galaxy, we perform Gaussian convolution to match the Point Spread Functions (PSFs) of the intensity and flux maps across all bands. The corresponding uncertainty maps are generated through error propagation, which accounts for correlations between nearby pixels as described by R. Klein (2021). All maps are re-sampled to a unified World Coordinate System (WCS) with a pixel size set to half the PSF's Full Width at Half Maximum (FWHM), using the `reproject` package (T. Robitaille et al. 2024). Projection corrections are applied to I_{CO} , $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} to account for the inclination of the galaxy. Unless otherwise specified (e.g., in subsection 3.4, where we investigate the effects of spatial scale), all analyses are performed on this PSF-matched dataset.

Table 1 lists the global properties of the galaxies taken from A. K. Leroy et al. (2021b), along with the FWHM of the matched PSF and the corresponding

physical resolution. All 19 galaxies are located on the star-forming main sequence, with specific star formation rates ($\text{sSFR} \equiv \text{SFR}/M_*$) well above $10^{-11} M_\odot \text{ yr}^{-1}$, and have stellar masses in the range of $\sim 3 \times 10^9 - 10^{11} M_\odot$.

2.2. raddest

We model the correlation between I_{CO} and $I_{\text{F770W,PAH}}$, I_{F1130W} , or I_{F2100W} using a log-linear relation that incorporates Gaussian intrinsic scatter in logarithmic space. The relation is expressed as:

$$\log I_{\text{CO}} = k \log I_X + b + \epsilon, \quad \epsilon \sim \text{N}(0, \sigma^2), \quad (1)$$

where I_X denotes $I_{\text{F770W,PAH}}$, I_{F1130W} , or I_{F2100W} . The parameters to be estimated are the slope k , the intercept b , and the intrinsic scatter σ . These parameters are determined by applying `raddest`, a novel regression code developed by T. Jing & C. Li (2025), to the PHANGS galaxy dataset described in the previous subsection.

As a regression method, `raddest` infers the posterior distribution of the model parameters (i.e., $\theta = \{k, b, \sigma\}$

in this case) given the observed data. In our case, the data $D = \{D_i\}$ (where $i = 1, 2, \dots, m$) consist of a set of spaxels within a galaxy. Each data point D_i includes a dependent variable $y_{\text{obs},i}$ (i.e., I_{CO} from Equation 1), an independent variable $\mathbf{x}_{\text{obs},i}$ (i.e., I_X from Equation 1), and their corresponding uncertainties, $y_{\text{err},i}$ and $\mathbf{x}_{\text{err},i}$. Assuming the data points are independent, the likelihood of the entire dataset $P(D|\theta)$ is the product of the individual likelihoods, $P(D_i|\theta)$. The likelihood for a single data point is derived as follows:

$$\begin{aligned} P(D_i|\theta) &= P(y_{\text{obs},i}, y_{\text{err},i}, \mathbf{x}_{\text{obs},i}, \mathbf{x}_{\text{err},i}|\theta) \\ &= \int P(y|\mathbf{x}, \theta) P(y_{\text{obs},i}, \mathbf{x}_{\text{obs},i} | y_{\text{err},i}, \mathbf{x}_{\text{err},i}, y, \mathbf{x}) \\ &\quad \times P(y_{\text{err},i}|y) P(\mathbf{x}_{\text{err},i}|\mathbf{x}) P(\mathbf{x}) dy d\mathbf{x}, \end{aligned} \quad (2)$$

where $P(y|\mathbf{x}, \theta)$ is the underlying model describing the correlation between $\mathbf{x}$ and y (Equation 1); $P(y_{\text{obs},i}, \mathbf{x}_{\text{obs},i} | y_{\text{err},i}, \mathbf{x}_{\text{err},i}, y, \mathbf{x})$ is the noise model, which we assume to be Gaussian; $P(y_{\text{err},i}|y)$ and $P(\mathbf{x}_{\text{err},i}|\mathbf{x})$ describe how the uncertainties $y_{\text{err},i}$ and $\mathbf{x}_{\text{err},i}$ relate to the intrinsic values y and $\mathbf{x}$, respectively; $P(\mathbf{x})$ represents the intrinsic distribution of the independent variable $\mathbf{x}$. The integral on the right-hand side of the equation is evaluated using Gauss-Hermite quadrature.

The distributions $P(\mathbf{x}_{\text{err},i}|\mathbf{x})$ and $P(\mathbf{x})$ are generally not known from the observed data. To address this, **raddest** employs normalizing flows (NFs; L. Dinh et al. (2014); D. Jimenez Rezende & S. Mohamed (2015)) to model them. In practice, these distributions are estimated by maximizing the observable joint distribution $P(\{\mathbf{x}_{\text{obs},i}\}, \{\mathbf{x}_{\text{err},i}\}) = \prod_i \int P(\mathbf{x}_{\text{obs},i}|\mathbf{x}, \mathbf{x}_{\text{err},i}) P(\mathbf{x}_{\text{err},i}|\mathbf{x}) P(\mathbf{x}) d\mathbf{x}$. The goodness-of-fit for the NF is evaluated using a two-dimensional Kolmogorov-Smirnov (2D KS) test (J. A. Peacock 1983; G. Fasano & A. Franceschini 1987; W. H. Press et al. 2002)³, which compares the generated pairs $(\mathbf{x}_{\text{obs,gen}}, \mathbf{x}_{\text{err,gen}})$ with the observed pairs $(\mathbf{x}_{\text{obs}}, \mathbf{x}_{\text{err}})$. The NF hyperparameters are tuned to achieve a p -value greater than 0.01. The distributions $P(y_{\text{err},i}|y)$ and $P(y)$ are estimated analogously. The estimated $P(\mathbf{x}_{\text{err},i}|\mathbf{x})$, $P(y_{\text{err},i}|y)$, and $P(\mathbf{x})$ are then substituted into Equation 2 to calculate the likelihood for individual data points $P(D_i|\theta)$ and, consequently, the total likelihood $P(D|\theta)$.

The likelihood $P(D|\theta)$ is used for parameter estimation and posterior sampling (under a uniform prior in this work) via two distinct methods. The first method, referred to hereafter as ML based method, involves

standard maximum a posteriori (MAP) or maximum likelihood (ML) estimation. A gradient descent algorithm finds the MAP/ML solution, and then a standard MCMC or HMC algorithm samples the posterior distribution. The second method, termed KS-test based method, leverages the generative capability of NFs. Here, parameters are estimated by minimizing the distribution distance, quantified by the p -value from the 2D KS test between generated $(\mathbf{x}_{\text{obs,gen}}, y_{\text{obs,gen}})$ and observed $(\mathbf{x}_{\text{obs}}, y_{\text{obs}})$ data pairs. However, obtaining a rigorous posterior sample with this approach is infeasible. Instead, an approximate posterior sample is constructed by generating data points from the prior distribution and using the p -value from the 2D KS test as a weight for each point.

As demonstrated by T. Jing & C. Li (2025), tests on both mock data and real PHANGS-ALMA and PHANGS-JWST data show that for large samples (> 1000 spaxels), both the KS-test based method and ML based method significantly outperform existing widely-used methods, particularly in low S/N regimes. Among them, the KS-test based method achieves the highest accuracy and robustness, provided the sample size is sufficiently large (≥ 1000 spaxels, a condition met in most of our analyses). For intermediate sample sizes (300–1000 spaxels), the ML based method delivers optimal performance, while in the low-data regime (below 300 spaxels), it remains competitive with other state-of-the-art methods. A GPU-compatible Python implementation of **raddest** is publicly available⁴. Based on these findings, we employ the KS-test based method for the majority of our analysis, resorting to the ML based method only for specific purposes (e.g., to model the behavior of outliers; see the next subsection).

2.3. Application of **raddest** to PHANGS galaxies

As previously noted, we employ the KS-test based method within **raddest** due to its strong performance with large sample sizes. To ensure statistical robustness, we exclude datasets containing fewer than approximately 100 data points. Such low-data regimes typically occur in regions with AGN-like ionization conditions or in resolution-downgraded samples (see subsection 3.4 for details). We confirm that applying a more stringent sample size threshold (e.g., ≥ 1000 data points) does not alter the key results of this study. The parameters k , b , and σ derived from the KS-test based method are hereafter denoted as k_{KS} , b_{KS} , and σ_{KS} , respectively.

In the **raddest** framework, normalizing flows (NFs) are used to model the distributions $P(\mathbf{x}_{\text{err},i}|\mathbf{x})$, $P(\mathbf{x})$,

³ Implemented in <https://github.com/astro-jingtao/ndtest>

⁴ **raddest** package: <https://github.com/astro-jingtao/raddest>

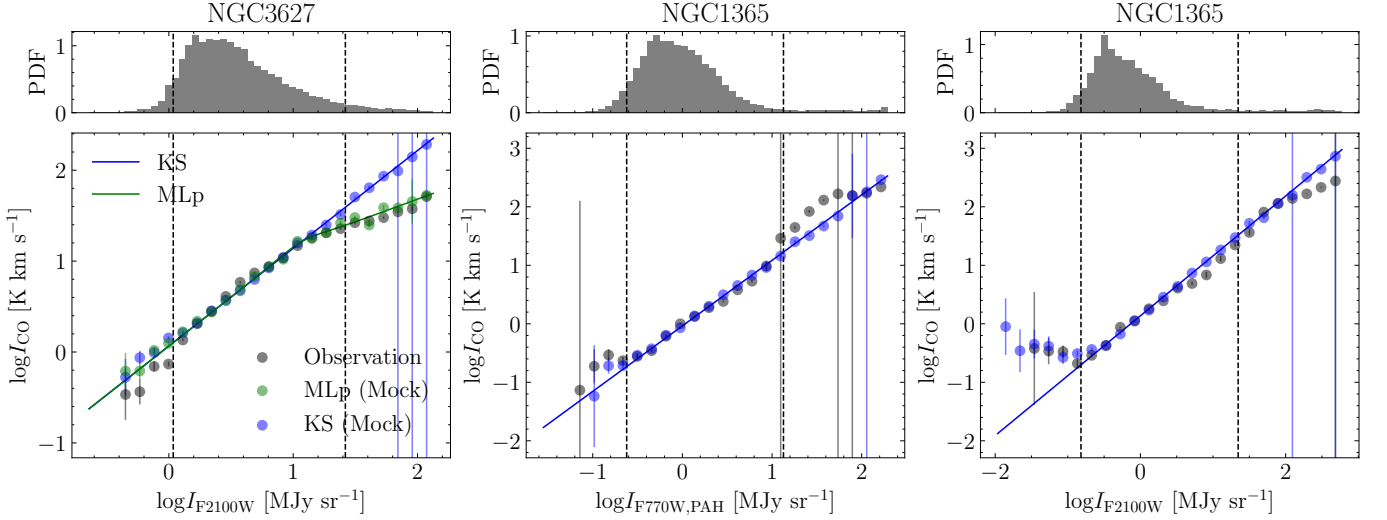


Figure 1. Examples of the three different cases of non-log-linear behavior (case (a), (b), and (c), from left to right). In each panel, the lower sub-panel displays the logarithm of the median observed CO(2-1) flux in each observed F2100W or F770W_{PAH} flux bin as black circles (real data), blue circles (mock data generated by single log-linear fitting), and green circles (mock data generated by piecewise log-linear fitting, available only in the left panel). Error bars represent the 1σ uncertainty of the median. The best-fit relations for the single and piecewise log-linear fits are shown as blue and green lines, respectively. The two vertical dotted lines mark the 5% and 95% percentiles of the observed F2100W or F770W_{PAH} flux distribution. These lines are also shown in the top sub-panel, where the histogram illustrates the marginalized distribution of the observed MIR bands. Note that data points with negative MIR bands measurements are excluded when plotting the marginalized distribution in logarithmic space but are included when calculating the 5% and 95% percentiles and applying regression analysis.

and $P(y_{\text{err},i}|y)$ required for regression analysis. While the fitted NFs perform well for most of our dataset, they fail to generate mock data that pass the 2D KS test in approximately 10% of cases, even after extensive hyperparameter tuning. This failure primarily stems from overestimated uncertainties in the dataset. Specifically, we observe that within given uncertainty bins ($\mathbf{x}_{\text{err}}$ or y_{err} , where $\mathbf{x}$ corresponds to $I_{\text{F770W,PAH}}$, I_{F1130W} , or I_{F2100W} , and y corresponds to I_{CO}), the standard deviation ($\sigma_{\mathbf{x},\text{obs}}$ or $\sigma_{y,\text{obs}}$) of the observed values ($\mathbf{x}_{\text{obs}}$ or y_{obs}) is systematically smaller than the reported uncertainty values ($\sigma_{\mathbf{x},\text{obs}} < \mathbf{x}_{\text{err}}$; $\sigma_{y,\text{obs}} < y_{\text{err}}$). This discrepancy likely originates from the initial data reduction process or error propagation methodology. Since reprocessing the raw data or implementing more sophisticated error propagation falls outside the scope of this work, we adopt a heuristic approach for these problematic cases: we scale $\mathbf{x}_{\text{err}}$ or y_{err} to satisfy $\sigma_{\mathbf{x},\text{obs}} = \mathbf{x}_{\text{err}}$ or $\sigma_{y,\text{obs}} = y_{\text{err}}$. This adjustment enables the NFs to pass the 2D KS test in most instances. The few cases that still fail after scaling are excluded from subsequent analysis. We confirm that all key results presented in this study remain consistent regardless of whether we restrict analysis to non-problematic data or include all data without implementing this correction.

The application of **raddest** for regression analysis confirms that the log-linear relation in Equation 1 provides a good description for the majority of data points

($\geq 80\%$ in most cases) across all galaxies in our sample and under all ionization conditions. Nevertheless, deviations from this relationship are detectable in most cases. We categorize these deviations visually into three types:

- (a) A deviation in the brightest regions that is well-described by a second log-linear relation with a different slope. The “no-deviation” scenario is a special case of this, where the slope for the brightest regions is identical to that of the main trend.
- (b) A deviation in the brightest regions that cannot be adequately fit by another log-linear relation.
- (c) A complex deviation that is more intricate than cases (a) and (b) and cannot be captured by simple functional forms.

Examples of these three cases are presented in Figure 1. We note that, in addition to the three cases of deviation, the faint end usually presents deviations to varying degrees as well. This is due to the limited S/N in the faintest regions: the binning of data points is driven mainly by noise rather than by their true values, so the correlations are smeared out. This behavior is well reproduced by our generative model when uncertainties in both the x- and y-axes are taken into account. For instance, as shown in Figure 1, the median of mock data, represented as blue circles, aligns closely with that of real data, depicted as gray circles, in faint end bins.

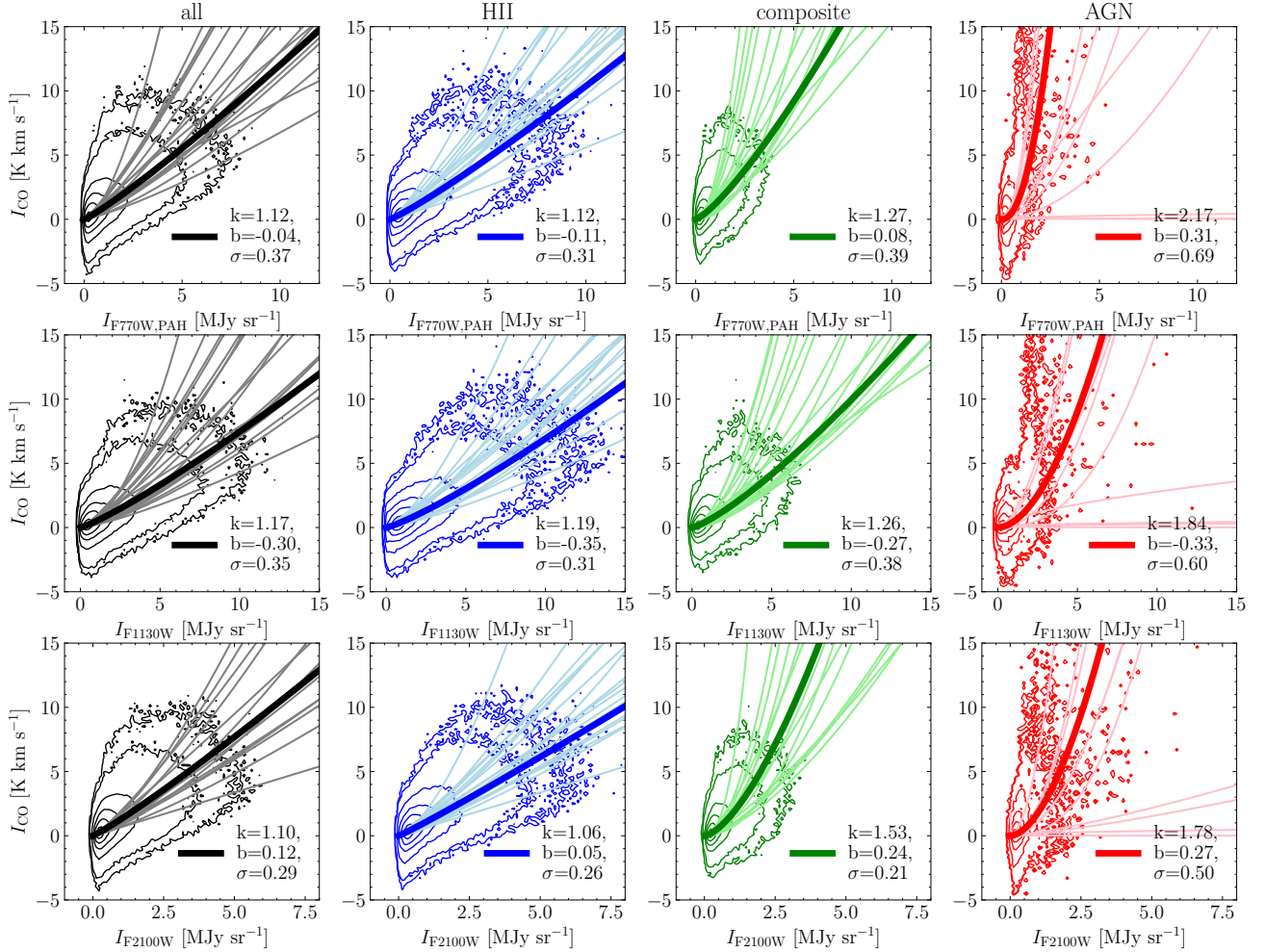


Figure 2. Scaling relation between I_{CO} and $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} (top to bottom) in different ionization conditions (all regions, H II-like regions, composite-like regions, and AGN-like regions from left to right). In each panel, the contour showcase the distribution of spaxels from all galaxies, and the bold line is corresponding best-fit result. The thin lines are best-fit results for each galaxy.

In cases (a) and (b), a turning point x_0 , defined as the MIR bands value above which the deviation occurs, can be identified. For case (a), this turning point is determined using a piecewise log-linear formula:

$$\log I_{\text{CO}} = \begin{cases} k_0 \log I_{\text{JWST}} + b_0 + \epsilon, & \text{if } I_{\text{JWST}} \leq x_0 \\ k_1 \log I_{\text{JWST}} + b_1 + \epsilon, & \text{if } I_{\text{JWST}} > x_0 \end{cases} \quad (3)$$

$$\epsilon \sim N(0, \sigma^2)$$

where k_0 , b_0 , and σ are fixed as k_{KS} , b_{KS} , and σ_{KS} , respectively. To fit k_1 , b_1 , and x_0 , we apply the ML based method in `raddest`, as this method demonstrates performance comparable to KS-test based method while being significantly more sensitive to minority data points that follow a distinct distribution compared to the majority. For case (b), the turning point is identified visually.

The strength of the deviation in cases (a) and (b) is quantified by calculating the difference of the median observed I_{CO} between the real data points and the mock data points above the turning point, x_0 . The mock data points are generated using the best-fit single log-linear relationship. This difference is denoted as $\Delta_{\text{KS}} = \text{MEDIAN}(y_{\text{obs}} | x_{\text{obs}} > x_0) - \text{MEDIAN}(y_{\text{obs,gen}} | x_{\text{obs,gen}} > x_0)$. For case (a), relative difference of the slope above and below the turning point ($R_{\Delta k} = (k_1 - k_{\text{KS}})/k_{\text{KS}}$) is additionally available.

3. RESULT

We first analyze the single log-linear fits characterized by k_{KS} , b_{KS} , and σ_{KS} , examining their dependence on ionization condition in [subsection 3.1](#) and their variation from galaxy to galaxy in [subsection 3.2](#). We then examine the deviation from the log-linear relation in [subsec-](#)

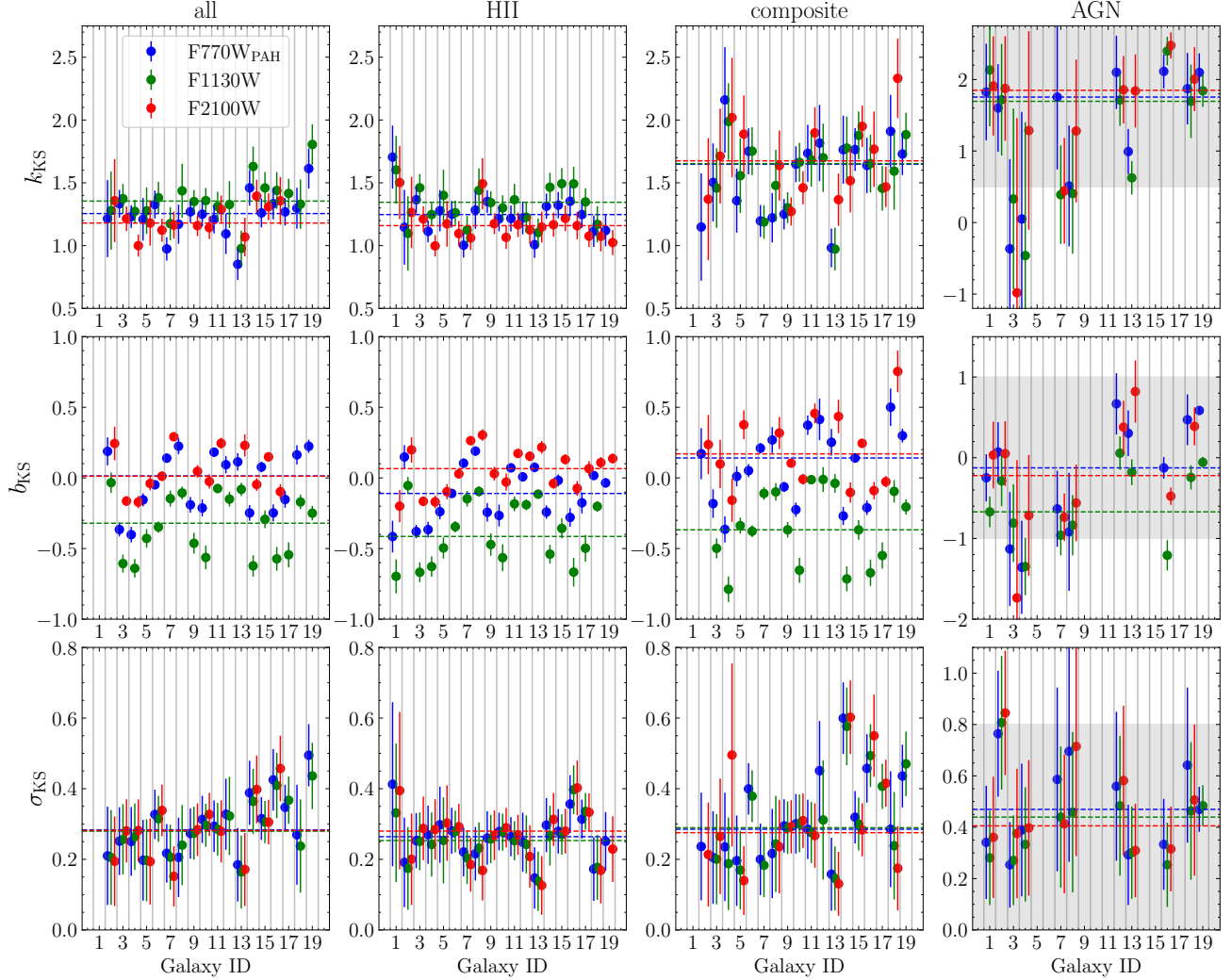


Figure 3. Best-fit slope k_{KS} , intercept b_{KS} , and intrinsic scatter σ_{KS} based on KS-test based method for each galaxy, of different MIR bands (blue for $I_{\text{F770W,PAH}}$, green for I_{F1130W} , and red for I_{F2100W}), and under different ionization conditions (all regions, H II-like regions, composite-like regions, and AGN-like regions from left to right). In each panel, the galaxies are sorted on the x-axis by total stellar mass (and also by galaxy ID, as shown in Table 1). The horizontal dashed lines with different colors show the median value of the best-fit parameters across different MIR bands. Error bars represent 1σ uncertainties. In each row, panels in the first three columns share the same y-axis range, which is indicated as a shaded region in the last column panel.

tion 3.3. Finally, in subsection 3.4, we investigate the spatial scale dependence of the log-linear relationship.

3.1. Dependence on Ionization Condition

We present the correlations of I_{CO} with $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} obtained with all spaxels from all the 19 galaxies as black contours in the first column of Figure 2. The best-fit log-linear scaling relations are shown as black thick lines, and the corresponding model parameters (k_{KS} , b_{KS} , σ_{KS}) are indicated in each panel. Although we use a log-linear formula, we display the correlations in linear space to avoid the clipping of data points with negative values caused by noise. Such clipping could create a misleading impression. The fitting techniques we employ properly handle these neg-

ative values in the log-linear regression, thus ensuring unbiased estimations. As shown in these three panels, I_{CO} remains correlated with $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} on ~ 100 pc scales. For the majority of data points, the correlations are well described by log-linear formulas with similar slopes.

In the second to fourth columns of Figure 2, we show the correlations and corresponding best-fit log-linear relationships for spaxels classified as H II-like, composite-like, and AGN-like regions. The correlations of I_{CO} with $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} differ significantly across different ionization conditions. H II-like regions exhibit relatively flatter slopes k_{KS} , and resemble the correlations obtained when all ionization conditions

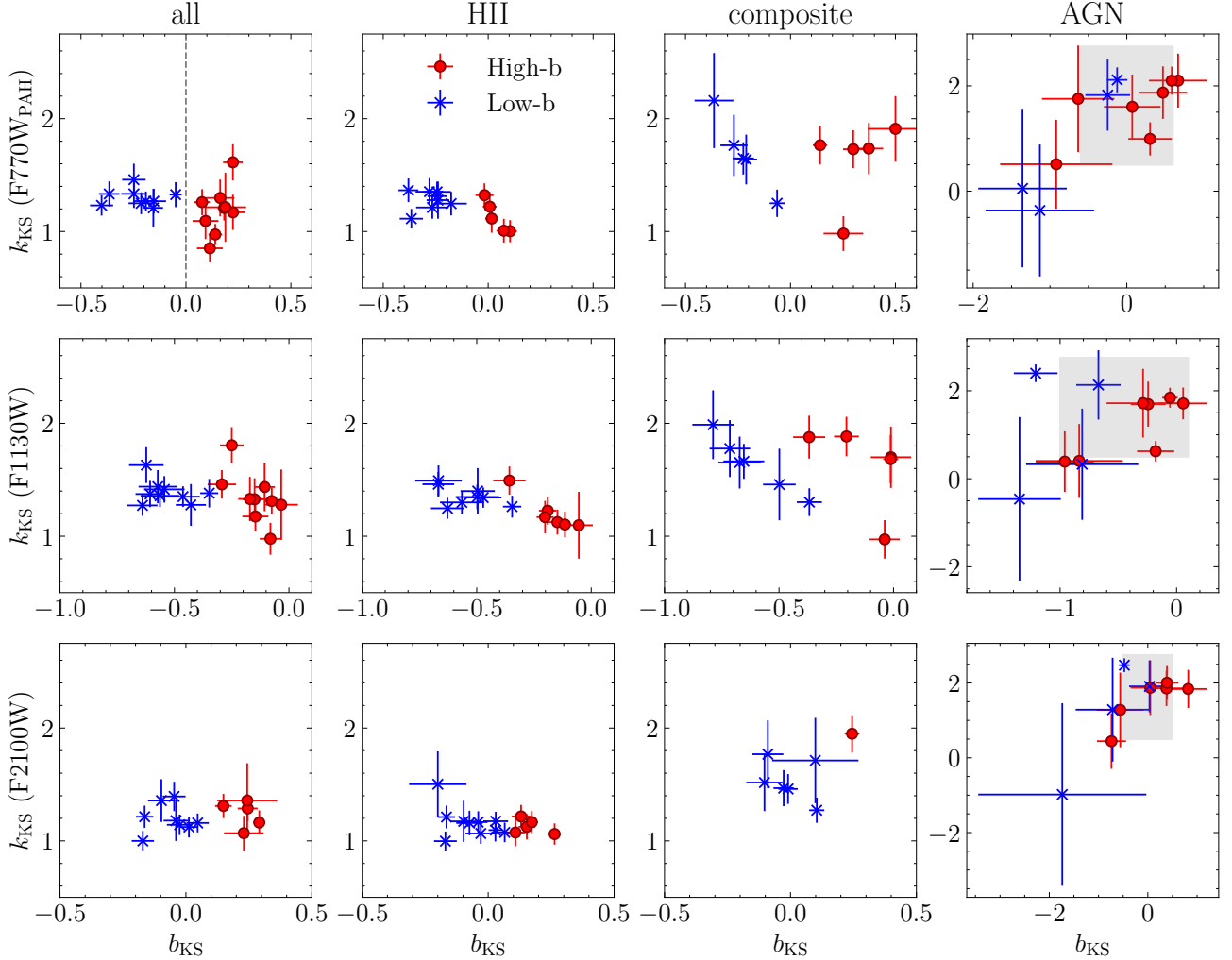


Figure 4. The correlation between the slope k_{KS} and the intercept b_{KS} is shown for each MIR band (top to bottom) and each ionization condition (left to right). The vertical dashed line in the top-left panel indicates $b_{\text{KS}} = 0$, the criterion used to classify galaxies into high- b and low- b subgroups. The high- b galaxies are represented by red dots, while the low- b galaxies are shown as blue crosses. In each row, the first three panels share identical x-axis and y-axis ranges; these ranges are highlighted as gray shaded regions in the last panel of each row.

are combined. This is consistent with the fact that all galaxies in our sample are main-sequence star-forming galaxies, where young stellar populations dominate the ionization. In composite-like regions, both I_{CO} and the intensities of MIR bands show relatively narrower dynamical ranges, and the slopes k_{KS} are steeper. In AGN-like regions, the dynamical range of I_{CO} is broader, while that of the MIR bands is narrower, resulting in the steepest slopes k_{KS} among the three ionization conditions. This may be related to the destruction of PAH and dust in AGN-like regions (see discussion in [subsubsection 4.2.1](#)).

The scaling relations under different ionization conditions also exhibit varying b_{KS} values. Overall, H II-like regions have smaller b_{KS} than composite-like and AGN-like regions. The comparison between composite-

like and AGN-like regions depends on the MIR band: AGN-like regions have larger b_{KS} than composite-like regions for $\text{F770W}_{\text{PAH}}$, while the values are comparable for F1130W and F2100W .

Regarding the intrinsic scatter σ_{KS} , we find the highest values in AGN-like regions. In the two PAH bands ($\text{F770W}_{\text{PAH}}$ and F1130W), composite-like regions exhibit larger intrinsic scatter σ_{KS} than H II-like regions. In the dust band (F2100W), however, H II-like regions show larger intrinsic scatter σ_{KS} than composite-like regions.

All the results reported above are based on the scaling relations of spaxels from all 19 galaxies. We will revisit the ionization dependence after analyzing galaxy-to-galaxy variations in the following subsection ([subsubsection 3.2.2](#)).

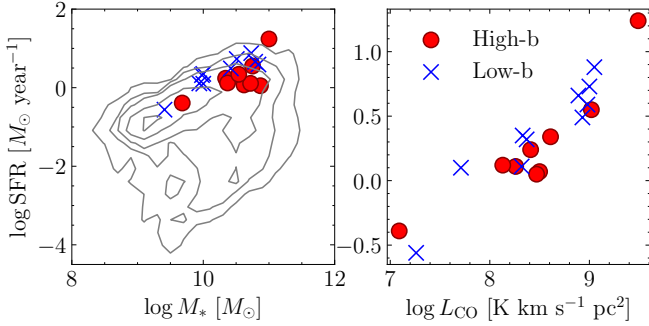


Figure 5. *Left:* Distribution of low- b (blue crosses) and high- b (red circles) galaxies on $\log \text{SFR}$ vs. $\log M_*$ diagram. The gray contour represents the distribution of a volume-limited sample of nearby galaxies, constructed from the MaNGA (K. Bundy et al. 2015; M. R. Blanton et al. 2017; D. A. Wake et al. 2017) sample with galaxy weight corrections. *Right:* Same as the left panel, but the x-axis is $\log L_{\text{CO}}$.

3.2. Galaxy-to-Galaxy Variation

The best-fit relations of individual galaxies are plotted as thin gray lines in Figure 2. Even at a fixed ionization condition, galaxy-to-galaxy variations persist, suggesting that this variation is driven by mechanisms beyond differences in ionization conditions. To provide more details on galaxy-to-galaxy variations, Figure 3 displays the best-fit k_{KS} , b_{KS} , and σ_{KS} (from top to bottom) for different MIR bands (blue for $I_{\text{F770W,PAH}}$, green for I_{F1130W} , and red for I_{F2100W}) across regions with different ionization conditions (from left to right) for each galaxy. The corresponding data is provided in Appendix A. The galaxies are sorted by their total stellar mass, from low to high, as indicated by their IDs on the x-axis. As can be seen from the figure, while k_{KS} (first row) and σ_{KS} (third row) vary across galaxies, their deviations from the median values are within the $1\text{--}2\sigma$ range. In contrast, b_{KS} exhibits deviations exceeding 3σ , suggesting that galaxy-to-galaxy variation is primarily driven by variations in b_{KS} .

This is more clearly illustrated in Figure 4, where we show the k_{KS} vs. b_{KS} diagram for each ionization condition (columns) and each MIR bands (rows). Compared to their estimation uncertainties, b_{KS} has a larger dynamical range than k_{KS} . The most striking feature of b_{KS} is its bimodality, with two distinct subgroups of galaxies exhibiting higher and lower b_{KS} values. Accordingly, we classify galaxies into high- b and low- b subgroups based on the b_{KS} value of the $I_{\text{CO}}\text{--}I_{\text{F770W,PAH}}$ scaling relation for spaxels under all ionization conditions (first panel of Figure 4). Galaxies with $b_{\text{KS}} > 0$ are categorized as high- b , while those with $b_{\text{KS}} < 0$ are categorized as low- b . These subgroups are marked in red (high- b) and blue (low- b) in all panels of Figure 4.

This classification clearly shows that the high- b (low- b) galaxies consistently exhibit overall larger (smaller) b_{KS} values across all MIR bands and ionization conditions, while their k_{KS} values remain similar.

This finding indicates that the physics driving the b_{KS} bimodality regulates the correlation between CO, PAH, and dust in entire galaxies. To explore the origin of this bimodality, we examine the global properties of low- b and high- b galaxies, including star formation rate (SFR), stellar mass (M_*), and CO luminosity (L_{CO}). As shown in Figure 5, although all galaxies lie on the star-forming main sequence, low- b galaxies tend to have higher SFR at a given M_* or L_{CO} . This may be related to enhanced PAH and dust emission caused by stronger overall UV background in galaxies with stronger star formation activity (see subsection 4.2.2 for discussion).

3.2.1. Dependence on Galaxy Properties

Next, we investigate whether the galaxy-to-galaxy variation can be explained by differences in their global properties. For this analysis we focus on H II-like regions due to their well-defined physical origins and the availability of a sufficient number of data points. In contrast, composite-like regions exhibit complex physical origins, while AGN-like regions are limited by insufficient data, leading to noisier results. We calculate the correlation coefficients and corresponding p -values between the best-fit parameters (k_{KS} , b_{KS} , and σ_{KS}) and various global properties ($\log \text{SFR}$, $\log M_*$, $\log \text{sSFR}$, $\log L_{\text{CO}}$, and $\log M_{\text{HI}}$) for different bands (F770W_{PAH}, F1130W, and F2100W). The results are presented in Figure 6.

For k_{KS} , anti-correlations at the 2σ level are observed in F2100W with $\log \text{SFR}$, $\log M_*$, $\log L_{\text{CO}}$, and $\log M_{\text{HI}}$. This suggests a possible role for these global properties in modulating the correlation between I_{CO} and I_{F2100W} . However, due to the low statistical significance, these correlations cannot be confirmed with the current dataset. Future analyses using larger samples are required to either confirm or refine these results.

For b_{KS} and σ_{KS} , 2σ correlations with $\log \text{sSFR}$ are evident across all bands, consistent with the relationship between $\log \text{sSFR}$ and b_{KS} in F770W_{PAH} reported by A. K. Leroy et al. (2023a) and R. Chown et al. (2025). As shown in Figure 7, however, these correlations primarily arise from the bimodality of intercept b_{KS} : high- b galaxies generally exhibit lower $\log \text{sSFR}$ and σ_{KS} , while low- b galaxies tend to have higher $\log \text{sSFR}$ and σ_{KS} . Within each subgroup (high- b or low- b), these dependences weaken significantly. This suggests that the underlying physics that drive the intercept bimodality play a more fundamental role than apparent sSFR.

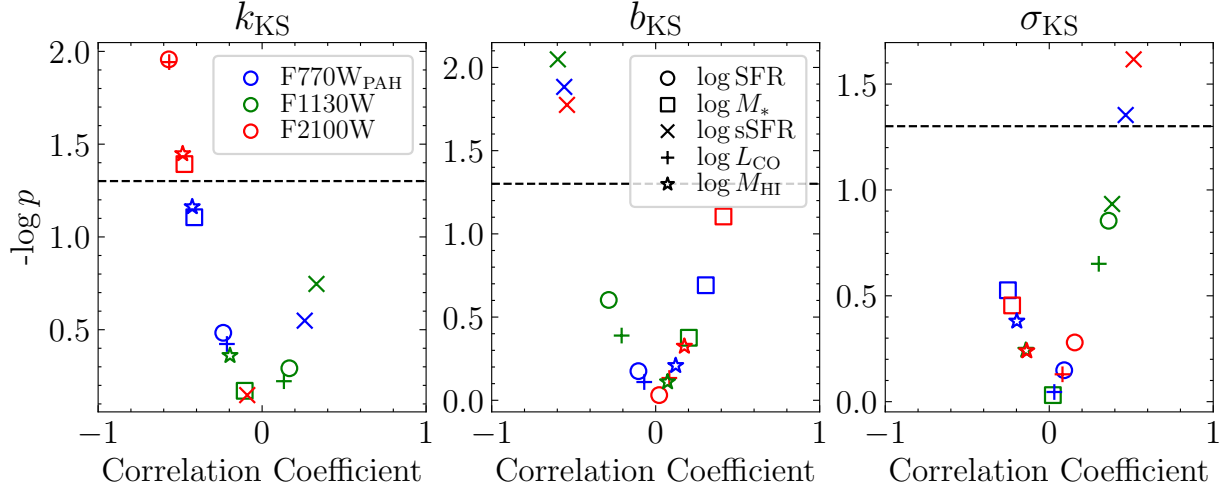


Figure 6. Correlation coefficient and corresponding $-\log p$ between the best-fit parameters (k_{KS} , b_{KS} , and σ_{KS} , from left to right) and various global properties ($\log \text{SFR}$, $\log M_*$, $\log \text{sSFR}$, $\log L_{\text{CO}}$, and $\log M_{\text{HI}}$, represented by different symbols) for different bands (F770W_{PAH}, F1130W, and F2100W, shown in blue, green, and red, respectively). Horizontal dashed line in each panel represents $-\log p \approx 1.3$ (2σ).

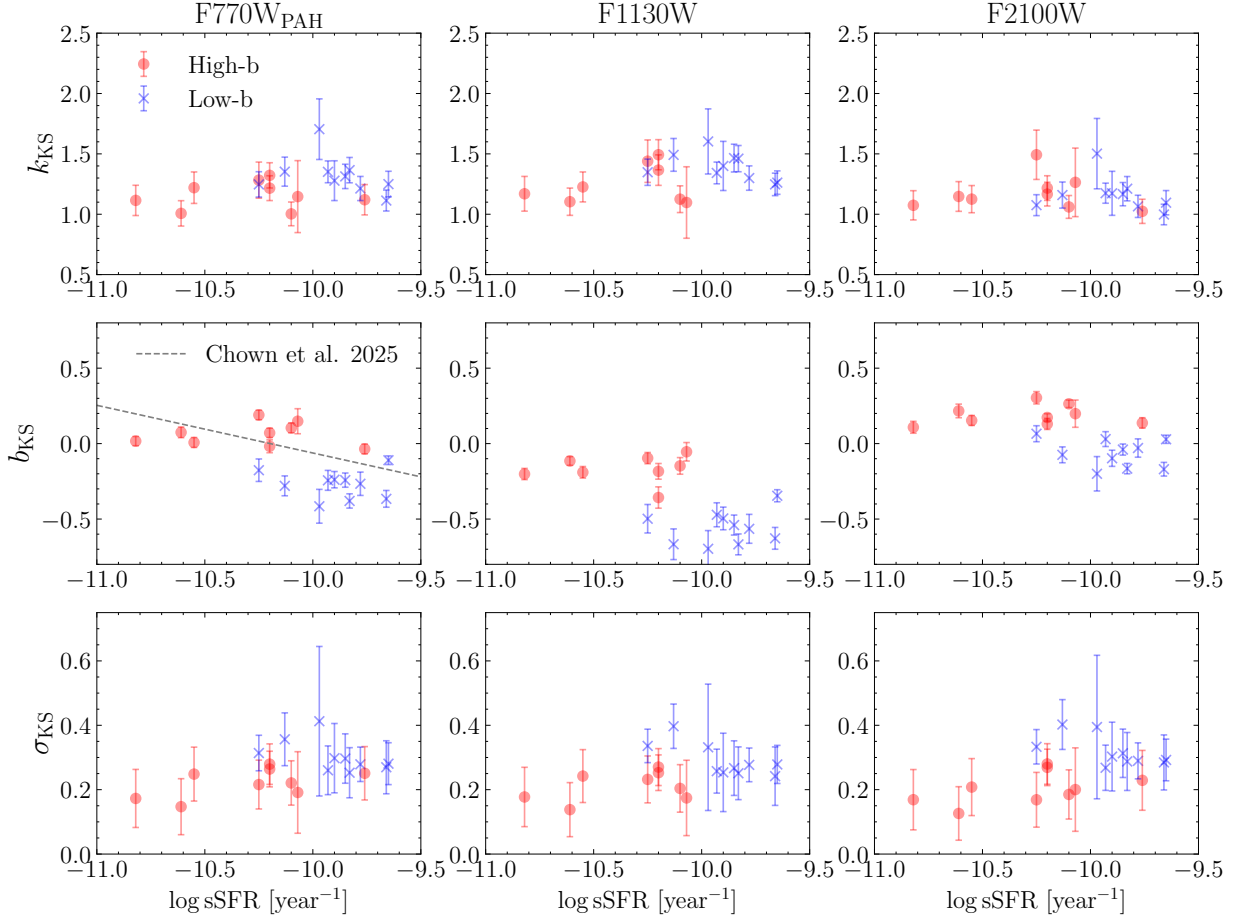


Figure 7. Correlation between the best-fit parameters and galactic $\log \text{sSFR}$ for different MIR bands (F770W_{PAH}, F1130W, and F2100W from left to right). High- b (low- b) galaxies are shown as red circles (blue crosses), with error bars representing 1σ uncertainties. The correlation between b and $\log \text{sSFR}$ reported by R. Chown et al. (2025) is displayed as a gray dashed line in the corresponding panel (left panel in the second row).

3.2.2. Dependence on Ionization Condition

Keeping the galaxy-to-galaxy variation in mind, we revisit the ionization condition dependence of the scal-

ing relations. The parameter k_{KS} still follows the same

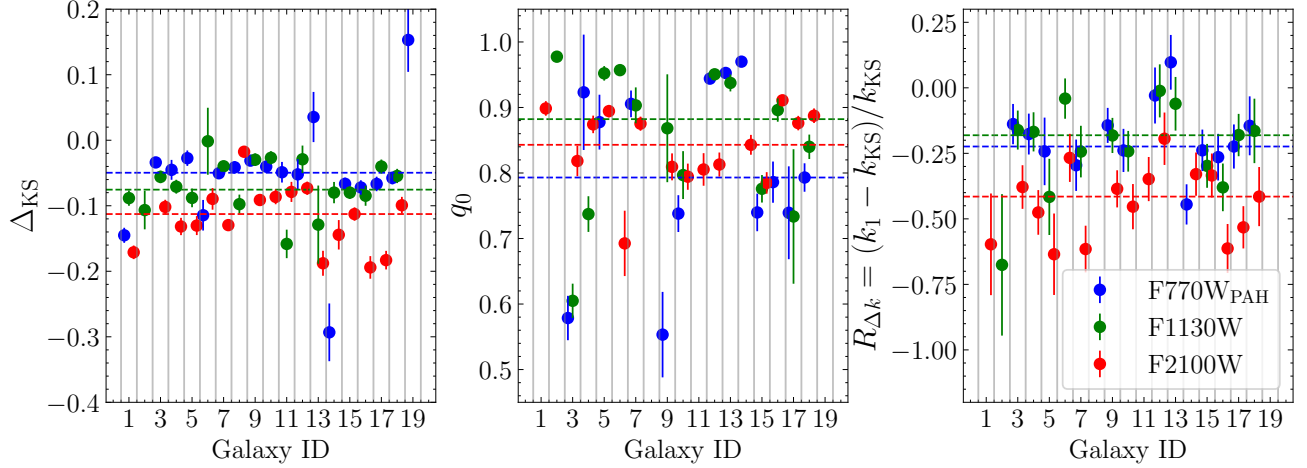


Figure 8. Same as Figure 3, but showing the difference of the median observed I_{CO} between the real data points and the mock data points above the turning point (Δ_{KS}), the quantile of the turning point (q_0), and the relative difference between the slope above and below the turning point ($(k_1 - k_{\text{KS}})/k_{\text{KS}}$), in H II-like regions of each galaxy. Δ_{KS} and q_0 are available for both cases (a) and (b), while $(k_1 - k_{\text{KS}})/k_{\text{KS}}$ is only available for case (a).

ascending order among H II-like, composite-like, and AGN-like regions when comparing their median values, even after accounting for galaxy-to-galaxy variation. This is consistent with the conclusion that the galaxy-to-galaxy variation is not primarily driven by differences in k_{KS} . For b_{KS} , while differences are observed across different ionization conditions, these differences are significantly smaller than the galaxy-to-galaxy variation in b_{KS} . The median value of σ_{KS} is comparable between H II-like and composite-like regions, whereas AGN-like regions exhibit a consistently larger σ_{KS} . This suggests that the difference in σ_{KS} between H II-like and composite-like ionization conditions, as derived from spaxels across all 19 galaxies, is primarily due to the varying levels of galaxy-to-galaxy variation under different ionization conditions. However, AGN-like regions retain a larger σ_{KS} , even after removing the contribution from galaxy-to-galaxy variation.

3.2.3. Comparison across Different MIR Bands

It is also valuable to compare the scaling relations across different MIR bands in the context of galaxy-to-galaxy variation. For k_{KS} , we find a slight difference in the median values within H II-like regions, following an ascending order across F2100W, F770W_{PAH}, and F1130W. This order is consistently observed in individual galaxies. However, the magnitude of this difference is small compared to the galaxy-to-galaxy variation within each MIR band. In composite-like and AGN-like regions, the slope variation across different MIR bands is even less significant. Clear differences in b_{KS} are observed across the three MIR bands in H II-like regions, reflecting distinct overall $I_{\text{CO}}/I_{\text{F770W,PAH}}$, $I_{\text{CO}}/I_{\text{F1130W}}$, and $I_{\text{CO}}/I_{\text{F2100W}}$ ratios. In composite-

like and AGN-like regions, the b_{KS} values for F770W_{PAH} and F2100W are more similar, while F1130W shows a smaller b_{KS} . For σ_{KS} , there are no significant differences across the MIR bands within any given ionization condition. This suggests that the coupling between CO, PAH, and dust remains similarly tight at ~ 100 pc scales (see subsection 4.2.3 for detailed discussions).

3.3. Deviations from the Log-linear Relation

In this subsection, we analyze the non-log-linear behavior observed in the brightest regions. Again, we focus on H II-like regions due to their clear physical origins and the availability of a sufficient number of data points. For H II-like regions, the fractions of cases (a), (b), and (c) are 75%, 20%, and 5%, respectively (refer to subsection 2.2 for classification and description of these cases). We concentrate on cases (a) and (b) since they are the dominant cases, and their non-log-linear behavior can be characterized using well-defined statistical methods. As described in subsection 2.3, we quantify the strength of the deviation by two parameters: Δ_{KS} (the difference of the median observed I_{CO} between the real data points and the mock data points above the turning point) and $R_{\Delta k}$ (the relative difference of the slope above and below the turning point). In addition, we consider a third parameter: the quantile of the turning point q_0 , which is defined as the fraction of data points with the considered MIR intensity below the turning point.

Figure 8 displays (from left to right) Δ_{KS} , q_0 and $R_{\Delta k}$ as function of galaxy ID, for the three MIR bands as indicated. As shown, in all three bands, all galaxies exhibit negative Δ_{KS} values or values that are statistically consistent with zero. This indicates that, where deviations exist, the observed values are systematically

smaller than the single log-linear predictions in the brightest regions. The only exception is the $F770W_{\text{PAH}}$ of NGC1365, as shown in the middle panel of Figure 1. This discrepancy is likely related to the presence of bar-induced inflows, a central starburst, and a powerful AGN in that galaxy. However, the exact causes require further analysis. When comparing the three MIR bands, we see more negative values of Δ_{KS} in the dust band ($F2100W$) than in the PAH bands ($F770W_{\text{PAH}}$ and $F1130W$), indicating that the strongest deviation occurs in $F2100W$.

The quantile of turning points, q_0 , shows a wide distribution between 0.5 and 1.0 (center panel of Figure 8). This result shows that the majority of data points (at least $> 50\%$, $> 80\%$ in most case) can be well described by a single log-linear relation in all galaxies. On the other hand, however, the wide range of q_0 indicates that although deviations consistently occur in brighter regions, there is no characteristic value of q_0 . Similarly, an examination of the absolute turning point value, x_0 , also reveals no characteristic value. These findings suggest that PAH or dust intensity is not the primary driver of the deviation from the log-linear relation. It is noticeable that, the dust band exhibits a narrower distribution of q_0 than two PAH bands.

As shown in the right panel of Figure 8, the relative difference in the slope, $R_{\Delta k}$, is smaller than zero in all bands, with the overall largest slope differences observed in the dust band. This result indicates that, when deviations occur, the slope above the turning point is consistently flatter. This result aligns with the negative values of Δ_{KS} and suggests that the physical mechanism driving the deviation likely suppresses CO(2-1) emission and/or enhances PAH and dust emission.

The combination of q_0 and $R_{\Delta k}$, expressed as $R_{\Delta k}(1 - q_0)$, provides a more comprehensive description of the deviation. Specifically, $1 - q_0$ represents the fraction of data points above the turning point, i.e. those that cannot be described by the single log-linear relation, while $R_{\Delta k}$ quantifies the degree of deviation for these data points. Figure 9 displays our galaxies on the plane of $R_{\Delta k}$ versus $1 - q_0$, with points of different colors for the three MIR bands. The black lines represent constant values of $R_{\Delta k}(1 - q_0)$ as indicated. As can be seen, the two PAH bands ($F770W_{\text{PAH}}$ and $F1130W$) exhibit similar distributions on this diagram, with larger dynamical ranges in both $1 - q_0$ and $R_{\Delta k}$, along with lower absolute values of $R_{\Delta k}(1 - q_0)$, when compared to the dust band ($F2100W$). In contrast, the dust band shows a more concentrated distribution of $1 - q_0$ and $R_{\Delta k}$, as well as higher absolute values of $R_{\Delta k}(1 - q_0)$, thus clearly separated from the PAH bands in this diagram. This result

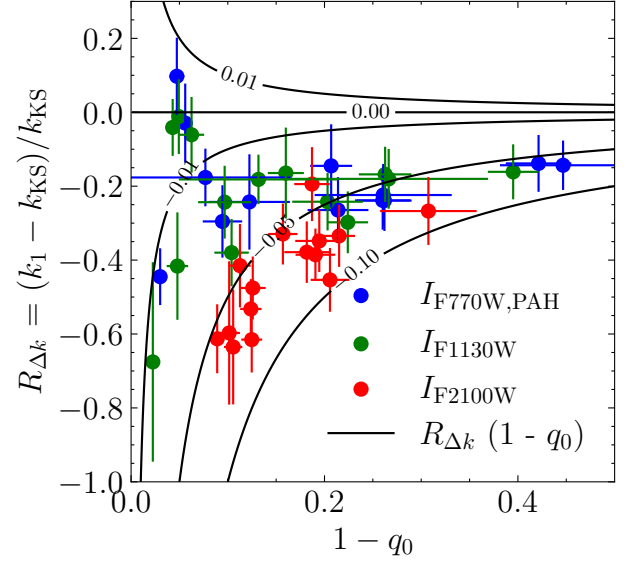


Figure 9. Diagram of $R_{\Delta k} = (k_1 - k_{\text{KS}})/k_{\text{KS}}$ vs. $1 - q_0$. Results using $I_{F770W, \text{PAH}}$, I_{F1130W} , and I_{F2100W} as MIR bands are shown in blue, green, and red, respectively, with corresponding 1σ uncertainties as error bars. The solid black lines represent different levels of $R_{\Delta k}(1 - q_0)$.

highlights the stronger deviation and flattening in the dust band than in the PAH bands as noticed from the previous figure. This result implies that the physical origin of the deviation likely works differently between the PAH and dust components (see subsection 4.2.4 for discussion on plausible mechanisms behind this result).

In Figure 10, we examine the correlation between global galaxy properties and the parameters that describe non-log-linear behavior, as quantified by both p -values and correlation coefficients. We identify only two 2σ anti-correlations: one between $(k_1 - k_{\text{KS}})/k_{\text{KS}}$ and $\log \text{SFR}$, and another between $R_{\Delta k}(1 - q_0)$ and $\log \text{sSFR}$. These findings suggest that the global properties explored here are unlikely to be the primary drivers of the deviation from the log-linear scaling relation.

3.4. Scaling Relations at Different Spatial Scale

To investigating the variation of the scaling relation across different spatial scales, we reduce the spatial resolution of the data to 50, 100, 200, 400, and 800 pc through Gaussian convolution. Additionally, we resample the pixel size to half of the PSF size to minimize correlations between data points. For a given galaxy, the spatial resolution can only be downgraded to a value comparable or poorer than its original resolution after preprocessing. Consequently, not all of the listed resolutions are available for all galaxies. Furthermore, resolution downgrading and subsequent resampling reduce the number of data points. Samples with fewer than ~ 100

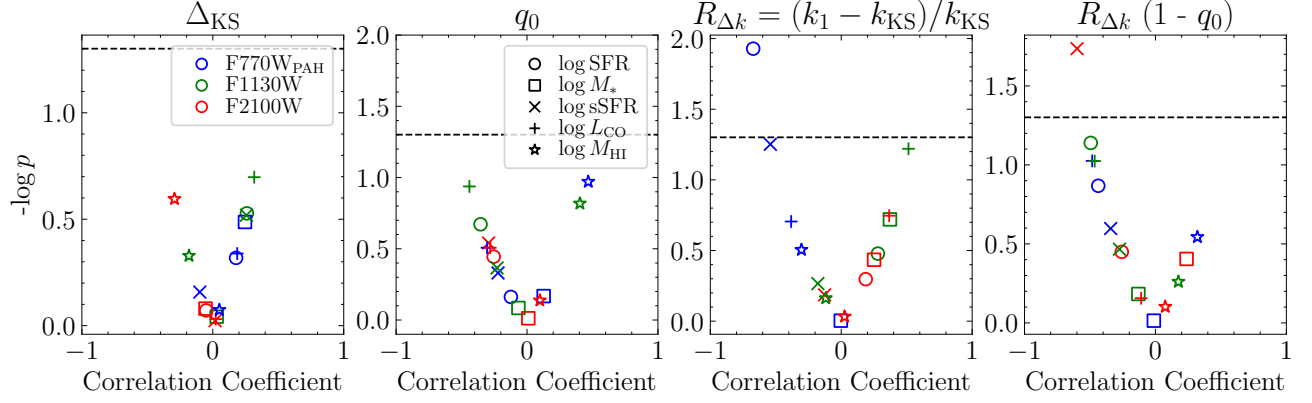


Figure 10. Same as Figure 6, but for Δ_{KS} , q_0 , $R_{\Delta k}$, and $R_{\Delta k}(1 - q_0)$.

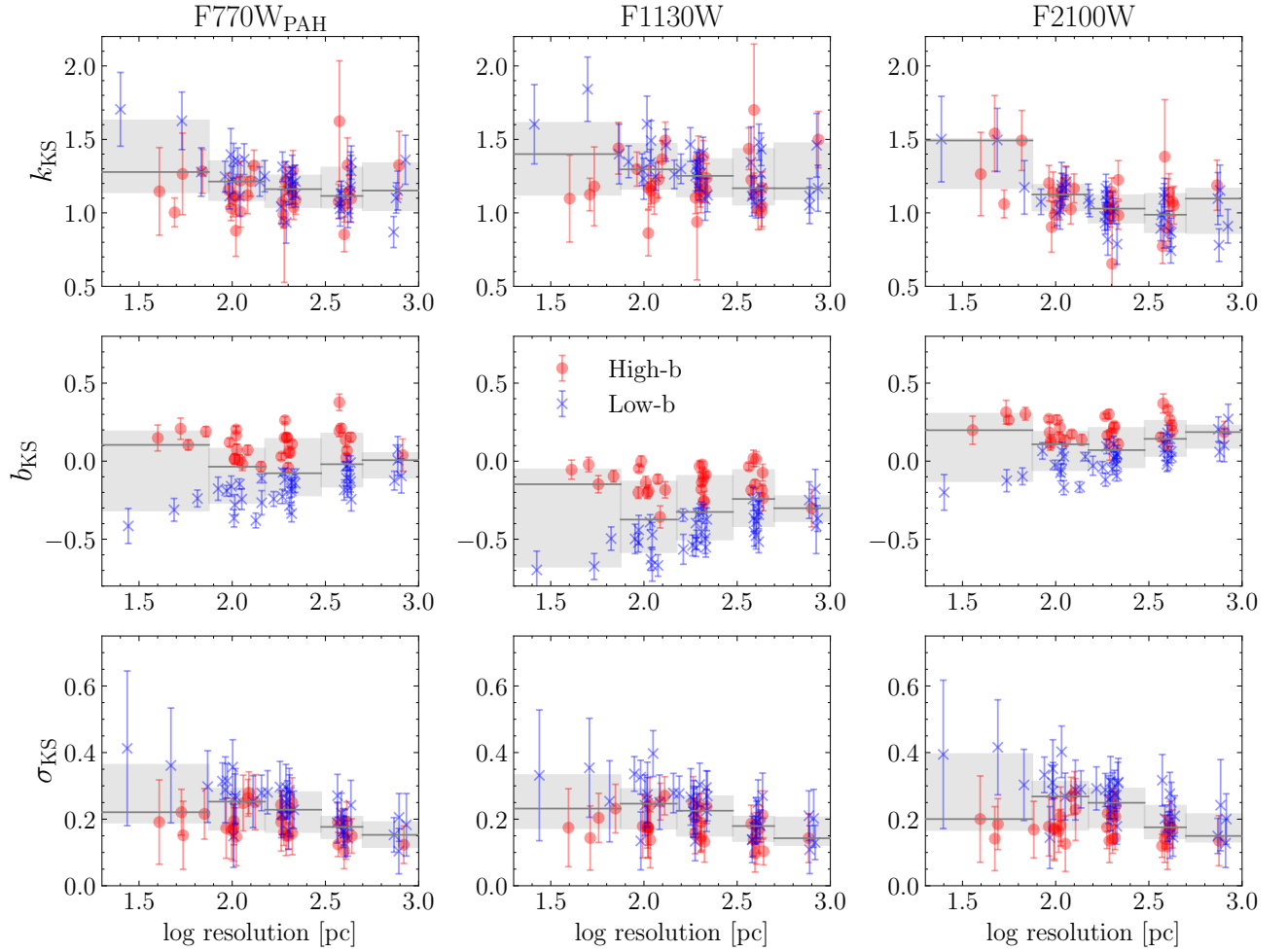


Figure 11. Best-fit slope k_{KS} , intercept b_{KS} , and intrinsic scatter σ_{KS} in H II-like regions at different spatial scales (resolutions) for different MIR bands (F770W_{PAH}, F1130W, and F2100W from left to right). The low(high)- b galaxies are represented as blue crosses(red circles), with error bars indicating 1σ uncertainties. The gray horizontal lines and corresponding gray shaded regions represent the median value and 16% to 84% intervals in each resolution bin.

data points are excluded, as described in subsection 2.1. Since our galaxies are dominated by H II-like regions and these regions exhibit the highest completeness (i.e.,

they are less likely to be excluded due to limited sample sizes after resolution downgrading) across different resolutions, we focus on H II-like regions in this analysis.

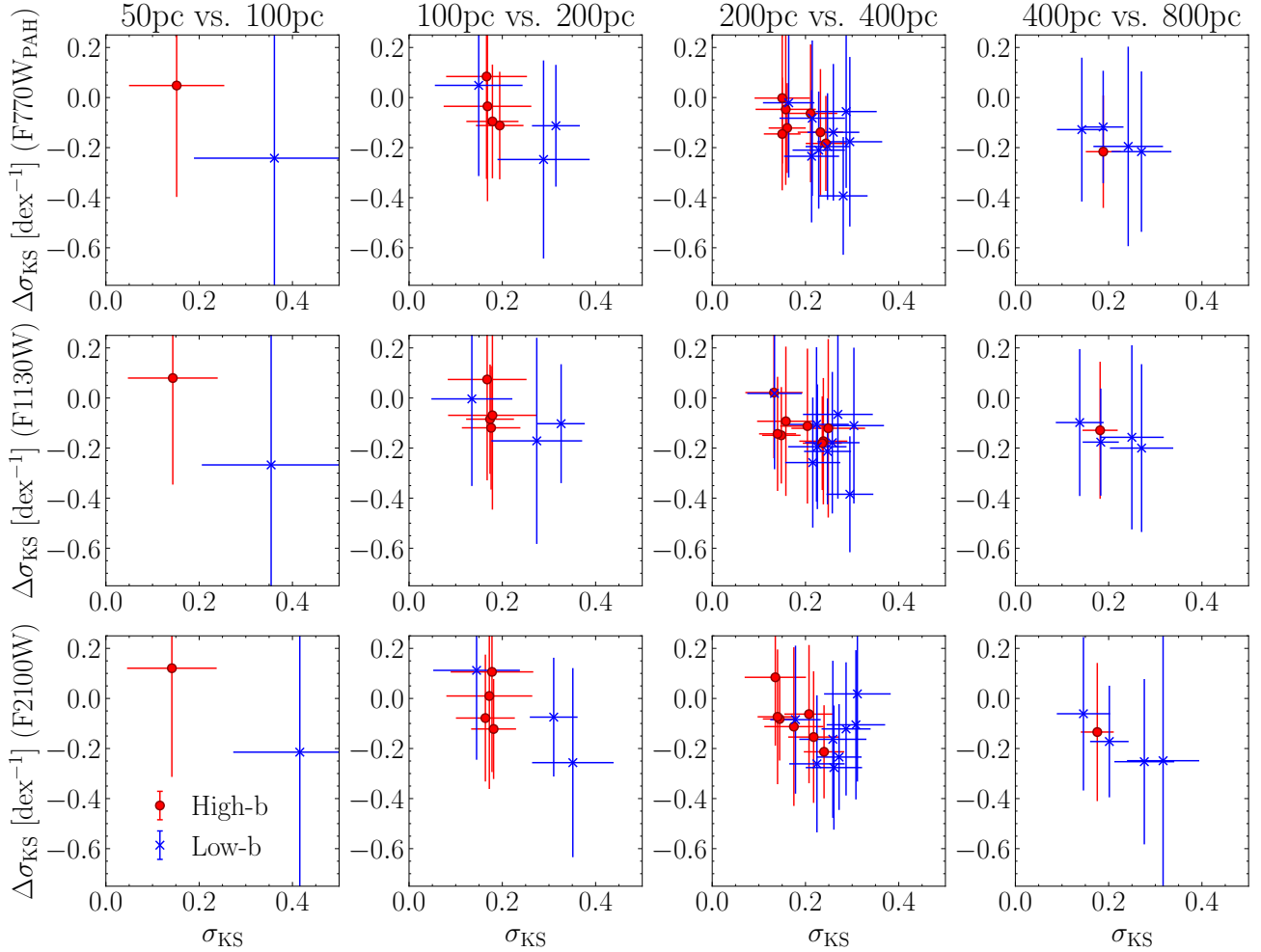


Figure 12. Difference in σ_{KS} estimated in H II-like regions between relatively larger spatial scale (lower-resolution) and smaller spatial scale (higher-resolution) data (calculated as the former minus the latter), plotted as a function of σ_{KS} of relatively smaller scales. The low(high)- b galaxies are represented as blue crosses(red circles), with error bars indicating 1σ uncertainties.

Figure 11 shows the best-fit model parameters (k_{KS} , b_{KS} , σ_{KS}) as function of physical scale, with red and blue symbols for H II regions in high- b and low- b galaxies. As can be seen, overall, k_{KS} appears to weakly depend on spatial scale at scales larger than ~ 100 pc in all bands, but it increases as once goes to smaller scales. The increase is most pronounced for I_{F2100W} . The variation of k_{KS} on small scales implies that the coupling between CO, PAH, and dust primarily occurs in their compact components rather than in the diffuse ones.

For b_{KS} , we observe different effects of spatial scale on low- b and high- b galaxies. Specifically, b_{KS} for high- b galaxies remains nearly constant across different spatial scales, whereas b_{KS} for low- b galaxies increases with increasing scale. This trend makes the bimodality unrecognizable in low-resolution data.

Overall, σ_{KS} decreases with increasing spatial scale (decreasing resolution). This trend qualitatively aligns with the expectation that random scatter cancel out as

the PSF covers larger regions. However, this random scatter cancellation is not the complete explanation. On the one hand, σ_{KS} is defined in logarithmic space, while flux accumulation within the PSF occurs in linear space. On the other hand, neighboring regions are likely physically correlated. Therefore, the cancellation mechanism only applies to scatter caused by physical processes operating on scales smaller than the PSF of the higher resolution data. Notable differences in spatial scale dependence of σ_{KS} are also apparent between low- b and high- b galaxies. This distinction can be attributed to the fact that high- b galaxies tend to have lower σ_{KS} , and the reduction in σ_{KS} during resolution downgrading is suppressed if σ_{KS} is already small. This effect does not imply an intrinsic difference between low- b and high- b galaxies. Evidence for this is provided in Figure 12, where we plot the difference of σ_{KS} between different spatial scales ($\Delta\sigma_{\text{KS}}$) as a function of σ_{KS} at relatively small spatial scales for each galaxy. Anti-correlations

between $\Delta\sigma_{\text{KS}}$ and σ_{KS} are observed in all panels and across all bands. Moreover, at a given σ_{KS} , both low- b (blue crosses) and high- b (red circles) galaxies exhibit similar $\Delta\sigma_{\text{KS}}$.

It is important to note that the results obtained at larger spatial scales (lower resolution) are not solely due to observational effects. They also provide insights into the mechanisms regulating scaling relations across different spatial scales, which are discussed in [subsubsection 4.2.5](#).

4. DISCUSSION

4.1. Comparison to Previous Work

4.1.1. MIR fluxes from WISE

The WISE W3 band, centered at $\sim 12\ \mu\text{m}$, is broadly comparable to the JWST F1130W filter. The correlation between CO(1-0) emission and W3-band surface brightness was investigated in the EDGE-CALIFA sample by [R. Chown et al. \(2021\)](#), who found a mean slope of ~ 1 at kpc scales. This is slightly flatter than the mean slope we find for F1130W at 800 pc scale, $\langle k_{\text{KS}} \rangle \sim 1.2$ (top central panel of [Figure 11](#)). The discrepancy likely stems from the different CO transitions used. Indeed, a slightly steeper correlation for CO(2-1) with W3 than for CO(1-0) with W3 has been reported in other studies ([Y. Gao et al. 2019](#); [A. K. Leroy et al. 2023a](#)), where CO(1-0) versus W3 relations yield slopes consistent with [R. Chown et al. \(2021\)](#) ([Y. Gao et al. 2019, 2022](#); [A. K. Leroy et al. 2023a](#)).

Furthermore, [R. Chown et al. \(2021\)](#) investigated the spatial scale dependence of the CO–W3 relation by comparing contiguous regions of increasing size. They found that while the slopes were consistent from kpc scales up to entire galaxies, the scatter in the relation decreased as the region size approached that of a whole galaxy (their [Figure 8](#)). This led the authors to suggest that the global correlation observed at galaxy scales emerges from the local correlation operating at kpc scales. Comparing our results at the 800 pc scale with those reported for galactic scales in the literature confirms the consistency of slopes from kpc to galaxy-wide scales. However, by extending the analysis to sub-kpc resolution, we uncover a key new insight: significant variation in k_{KS} that depends on local physical conditions (e.g., ionization condition dependences and the non-log-linearity in the brightest regions). This indicates that the local correlation is intrinsically different from the global one, even though the latter is an aggregate of the former. In other words, the correlation is modulated by physical processes operating on scales between 100 pc and ~ 1 kpc, such as feedback from massive stars or AGN activity. This interpretation is supported by

multiple lines of evidence. We find that composite-like and AGN-like regions exhibit different slopes compared to H II-like regions. This aligns with the steeper relation reported by [Y. Gao et al. \(2025\)](#) in early-type galaxies—systems predominantly characterized by such ionization conditions—compared to star-forming galaxies. Furthermore, the scale-dependent variation is significantly weaker when the analysis is restricted to the high- b subsample, reinforcing the connection to local ionization physics. Collectively, our findings provide a more granular understanding of how local physical conditions shape the integrated scaling relations observed in galaxies.

In addition to W3, the WISE W4 band, centered at $\sim 22\ \mu\text{m}$ and thus comparable to JWST F2100W, has also been previously used to trace dust emission in galaxies. One notable result is the smaller intrinsic scatter in the scaling relation between CO(2-1) and the W3 band compared to that between CO(2-1) and the W4 band reported in [Y. Gao et al. \(2019\)](#) and [C. M. Whitcomb et al. \(2023\)](#). However, our work finds that all three MIR bands exhibit similar intrinsic scatter in their correlations with I_{CO} . Our tests show that this conclusion is robust regardless of whether the tightness of the correlation is assessed using intrinsic scatter or correlation coefficient, and it is unaffected by the specific methods used for regression and correlation coefficient analysis. In fact, similar correlation coefficients across different MIR bands are also reported for four PHANGS galaxies in [A. K. Leroy et al. \(2023b\)](#). As shown in [Figure 11](#) (bottom panels), although σ_{KS} varies with resolution, no significant differences are detected between the three bands across all resolutions investigated. The remaining plausible explanations for the differences between our results and those previously obtained using W3 and W4 involve variations in instruments and/or sample selection. Resolving this issue requires a direct comparison of WISE and JWST data on the same sample, which should be a focus of future work.

4.1.2. MIR fluxes from JWST

By applying median orthogonal distance regression (`mODR`) on four PHANGS galaxies (IC5332, NGC0628, NGC1365, NGC7496), [A. K. Leroy et al. \(2023b\)](#) analyze the correlation of CO(2-1) with four MIR bands from JWST: F770W_{PAH}, F1000W, F1130W, and F2100W. They report that, in all four galaxies, F2100W exhibits a sublinear slope (< 1), which is significantly flatter than those of the other three bands. This result disagrees with our findings, where the differences in slopes between F770W_{PAH}, F1130W, and F2100W are slight, and all three bands show superlinear slopes

(> 1), as presented in Figure 3. As demonstrated in JL25, this discrepancy arises from the suboptimal mODR technique, which tends to produce flatter slopes when the MIR bands have limited S/N and is sensitive to the presence of outliers (e.g., deviations from log-linear correlations in the brightest regions, as discussed in subsection 3.3). These issues affect all bands analyzed. Consequently, the slopes reported in A. K. Leroy et al. (2023b) are systematically flatter than our results and those in JL25. The significant flattening of the F2100W slope compared to other bands is due to its lower S/N and stronger deviations from log-linear correlations in the brightest regions. This highlights the importance of carefully selecting an appropriate regression technique when analyzing datasets with limited S/N and outliers.

More recently, R. Chown et al. (2025) investigate the correlations of I_{CO} with $I_{\text{F770W,PAH}}$ and I_{F1130W} using a much larger sample of 66 galaxies from PHANGS (including the 19 galaxies analyzed in this work). They apply the LINMIX regression method (B. C. Kelly 2007) on binned data, here referred to as “mLINMIX”. Although they do not apply line ratio-based classifications, their fitting results for spaxels outside galaxy centers are broadly comparable to those for spaxels with H II-like ionization conditions in most of our galaxies. In the left column of Figure 13, we compare our best-fit slope k_{KS} and intercept b_{KS} with the values (k_{C25} , b_{C25}) reported by R. Chown et al. (2025). The best-fit parameters are consistent within $1-2\sigma$, and no distinct behavior emerges between high- b and low- b galaxies. However, a systematic underestimation of slope and overestimation of intercept by R. Chown et al. (2025) is evident. The differences in k and b are anti-correlated, consistent with the well-known k - b degeneracy.

In addition to the different regression methods, differences in sample selection may also contribute to the discrepancies between our results and those in R. Chown et al. (2025). The sample differences can be attributed to two key factors: (1) To subtract the continuum in I_{F770W} and calculate the uncertainties of $I_{\text{F770W,PAH}}$, we restrict our analysis to spaxels with I_{F200W} coverage. Furthermore, the classification of ionization conditions requires the additional coverage provided by PHANGS-MUSE data. In contrast, R. Chown et al. (2025) do not utilize PHANGS-MUSE data and estimate the continuum contribution for spaxels without I_{F200W} coverage by using the median ratio of $0.12I_{\text{F200W}}/I_{\text{F770W}}$ ⁵ in spaxels with I_{F200W} coverage, enabling larger spatial

coverage. (2) We select spaxels with H II-like ionization conditions using optical line ratios, whereas R. Chown et al. (2025) include all spaxels outside galaxy centers. To evaluate the impact of sample differences, we apply mLINMIX to our sample and compare the results with those reported by R. Chown et al. (2025), as shown in the center column of Figure 13. No systematic differences are found for F770W_{PAH}; however, for F1130W, the k (b) values reported by R. Chown et al. (2025) are systematically smaller (larger) than those obtained with mLINMIX on our sample. This discrepancy may be related to the radial dependence of the I_{CO} - I_{F1130W} correlation, which warrants further investigation in future work.

The right column of Figure 13 directly compares the results obtained using mLINMIX and the KS-test based method on our sample. As shown, mLINMIX tends to yield a flatter slope compared to the KS-test based method in both F770W and F1130W. This agrees with the expectation that binning a noisy x-axis variable (as done by mLINMIX) biases the slope toward zero (e.g., W. A. Fuller 2009; JL25). Additionally, outliers in the brightest regions, which exhibit lower I_{CO} than the overall correlation predicts (as discussed in subsection 3.3), also leads to underestimated slope. Due to the k - b degeneracy, mLINMIX also produces larger b values. In summary, while sample differences account for part of the discrepancy between our results and those of R. Chown et al. (2025), the primary source of the differences lies in the suboptimal treatment of x-axis uncertainties and outliers in mLINMIX.

R. Chown et al. (2025) also report variations in the scaling relationships when spaxels are divided into central and disk regions or into morphologically selected H II regions and diffuse regions. This finding aligns with the ionization condition dependencies identified in our work. However, the specific differences and connections between these dependencies require further investigation in future studies.

Finally, R. Chown et al. (2025) detect galaxy-to-galaxy variations and identify the intercept b (their C) as the dominant contributor to these variations. As discussed in subsection 3.2, we confirm these results, and further reveal that the correlation between intercept b and global sSFR likely originates from the observed bimodality in intercept b values.

4.2. Plausible Physics Implied by the Scaling Relations

We attempt to understand the underlying physics behind the scaling relations obtained in this work. For this purpose, we express I_{CO} , I_{F2100W} , I_{F1130W} and

⁵ This formula is applied to the 19 galaxies used in our work (Cycle 1). For Cycle 2 galaxies, R. Chown et al. (2025) estimate the continuum contribution as $0.22I_{\text{F300W}}$.

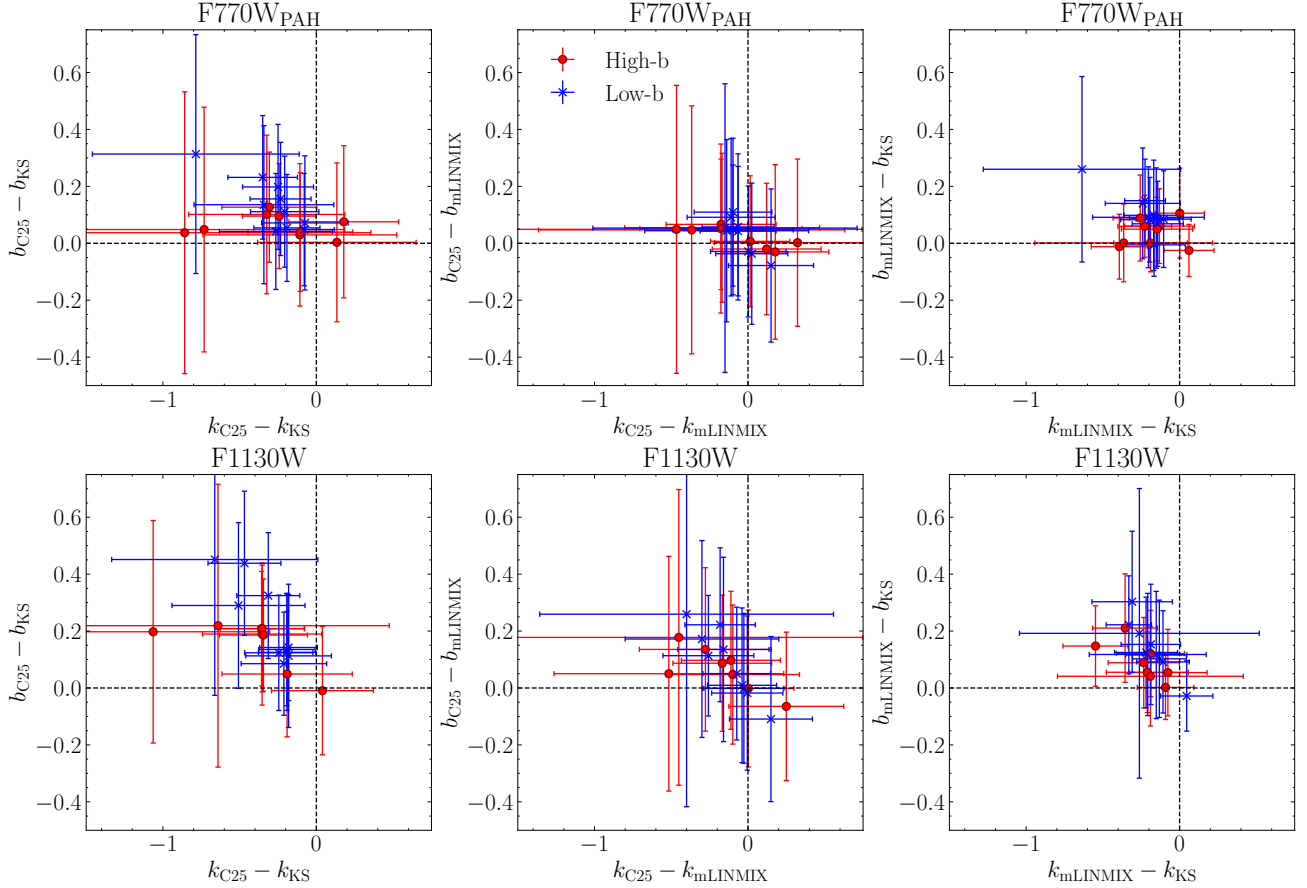


Figure 13. Comparison of the slope (k) and intercept (b) reported by R. Chown et al. (2025) (k_{C24} , b_{C24}) with those derived in this work using KS-test based method (k_{KS} , b_{KS}) and mLINMIX ($k_{mLINMIX}$, $b_{mLINMIX}$). From left to right, the columns compare R. Chown et al. (2025) with KS-test based method, R. Chown et al. (2025) with mLINMIX, and KS-test based method with mLINMIX, respectively. The top row shows results for F770W_{PAH}, while the bottom row corresponds to F1130W. In each panel, the x-axis represents the differences in k , and the y-axis represents the differences in b . Galaxies classified as high- b are marked as red dots, and those classified as low- b are shown as blue crosses.

$I_{F770W,PAH}$, in terms of more physical quantities:

$$I_{CO} = \beta_{CO} n_{\text{gas,cold}},$$

$$I_{F2100W} = \beta_{F2100W} \frac{n_{\text{dust}}}{n_{\text{gas,cold}}} n_{\text{gas,cold}},$$

$$I_{F1130W} = \beta_{F1130W} \frac{n_{\text{PAH}}}{n_{\text{dust}}} \frac{n_{\text{dust}}}{n_{\text{gas,cold}}} n_{\text{gas,cold}},$$

$$I_{F770W,PAH} = \beta_{F770W,PAH} \frac{n_{\text{PAH}}}{n_{\text{dust}}} \frac{n_{\text{dust}}}{n_{\text{gas,cold}}} n_{\text{gas,cold}},$$

where β_{CO} , β_{F2100W} , β_{F1130W} and $\beta_{F770W,PAH}$ are the emissivities (intensity per unit volume density) of I_{CO} , I_{F2100W} , I_{F1130W} and $I_{F770W,PAH}$, and terms $n_{\text{gas,cold}}$, n_{dust} , and n_{PAH} represent the density of cold gas, dust, and PAH. To the first order, the correlations of I_{CO} with $I_{F770W,PAH}$, I_{F1130W} , and I_{F2100W} arise from their common dependence on $n_{\text{gas,cold}}$. However, the specific values of the slope, intercept, and intrinsic scatter are determined by variations in emissivities, the dust-to-gas density ratio, and the PAH-to-dust density ratio. Based

on this framework, we now discuss the plausible physical mechanisms that may be implied from the key results obtained in this work.

4.2.1. Implications of Ionization Condition Dependence

Ionization condition dependencies reflect the influence of the ionization source on the emissivities, the dust-to-gas ratio, and the PAH-to-dust ratio. The scaling relations observed in H II-like regions capture these physical properties in typical star-forming environments. The steeper slope k_{KS} in AGN-like regions likely results from the destruction of PAHs and dust under strong, hard ionizing radiation fields (e.g., S. Zhou et al. 2023; R. Guo et al. 2025; A. Battisti et al. 2025; Z. Liu et al. 2025; T. C. Fischer et al. 2025; R. Katayama et al. 2025). In composite regions, in addition to PAH and dust destruction, variations in β_{CO} may also play a significant role. Evidence for β_{CO} variation comes from the observed changes in α_{CO} and the $I_{CO(2-1)}/I_{CO(1-0)}$ ratio across different galaxies and within various sub-

structures of individual galaxies (e.g., F. Maeda et al. 2022; C. S. Luo et al. 2025; R. P. Keenan et al. 2025; S. Komugi et al. 2025; J. Koda et al. 2025; J. Sun et al. 2025).

4.2.2. Implications of the b_{KS} Bimodality

As we showcase in subsection 3.2, the galaxy-galaxy variation of the scaling relation is primarily led by b_{KS} and secondly contributed by k_{KS} and σ_{KS} . The most obvious feature of b_{KS} is bimodality, which is related to overall host galaxy star formation strength: the low- b (high- b) galaxies tend to have higher (lower) sSFR and star formation efficiency (SFE). The intenser star formation in low- b galaxies would enhance UV radiation field, which would heat dust to a warmer temperature and thus enhance β_{F2100W} . The main emission mechanism of PAH is the immediate reradiation of absorbed UV photons. The stronger UV field can enhance $\beta_{\text{F770W}_{\text{PAH}}}$ and β_{F1130W} naturally. It is important not to confuse the “stronger UV radiation field” discussed here with the “strong, hard ionizing radiation field” associated with AGN-like regions. The former refers to a relatively stronger field that enhances PAH and dust emission without significantly destroying them. In contrast, the latter describes an extremely intense radiation field with a hard spectrum, capable of effectively destroying both dust and PAHs. This distinction highlights the complex effects of radiation fields on CO, PAH, dust, and their coupling. These enhancements are manifested primarily in b_{KS} and secondly in k_{KS} . The higher σ_{KS} in low- b galaxies is plausibly related to more bustling star formation in galaxies with stronger star formation.

In terms of details, this mechanism can be divided into two scenarios. The first one is that in the galaxies with stronger star formation, there are more H II regions and consequently more leaky photons from them. Therefore, these galaxies have stronger background UV field, which enhance dust and PAH emission in the whole galaxy. Another scenario is that the H II regions in the galaxies with stronger star formation have higher star formation efficiency. The dust and PAH emission are mainly enhanced in these regions. In reality, these two scenarios could coexist, while the comparison between scaling relations obtained in different scales suggest the stronger background UV field case is more dominated (see subsection 3.4 for details).

We would like to emphasize that these are reasonable inferences based on the current results, but they have not been confirmed by conclusive evidence. Moreover, it is also rather difficult to explain why it is a b_{KS} bimodality rather than a continuum. Therefore, more works should be done in future to explore the exact ori-

gin of scaling relation galaxy-galaxy variation and b_{KS} bimodality.

4.2.3. Implications of Band-to-Band Variation

After addressing the limited S/N, particularly in I_{F2100W} , and mitigating the impact of outliers, we find that although the differences in slopes k_{KS} of PAH bands ($\text{F770W}_{\text{PAH}}$ and F1130W) and dust band (F2100W) are detectable, they are minor compared to the galaxy-to-galaxy variation. This suggests that within a given galaxy and under a specific ionization condition, the variation in $\frac{n_{\text{PAH}}}{n_{\text{dust}}}$ exists but is not significant across regions of varying brightness. The different intercepts b_{KS} reflect the overall difference in the $I_{\text{CO}}/I_{\text{F770W}_{\text{PAH}}}$, $I_{\text{CO}}/I_{\text{F1130W}}$, and $I_{\text{CO}}/I_{\text{F2100W}}$ ratios. The similar σ_{KS} values across different MIR bands found in this study indicate that the coupling strength between CO and PAHs, as well as that between CO and dust (at least the hot dust traced by I_{F2100W}), is comparable in our sample.

4.2.4. Implications of the Non-log-linear Behavior

As we show in subsection 3.3, although a log-linear formula effectively describes the overall correlation of CO with PAH and dust, significant deviations from this relation are evident in the brightest regions. The different non-log-linear behaviors between the PAH bands ($\text{F770W}_{\text{PAH}}$ and F1130W) and the dust band (F2100W) suggest that these deviations primarily originate from variations associated with PAH and dust properties. For the PAH bands, a plausible explanation is the multi-photon effect, which enhances the PAH emissivity normalized by the radiation field intensity ($\beta_{\text{F770W}_{\text{PAH}}}/U$ and β_{F1130W}/U , where U is the radiation field intensity) under stronger radiation fields (e.g., B. T. Draine et al. 2021; H. M. Richie & B. S. Hensley 2025). Similarly, for F2100W , higher dust temperatures in stronger radiation fields likely contribute to the enhancement of β_{F2100W} . Future detailed studies are necessary to confirm or refine these proposed mechanisms.

4.2.5. Implications of Spatial Scale Dependence

As we point out in subsection 3.4, the scaling relation measured at different resolutions should not be regarded solely as a mimicry of observational effects. The scaling relation observed on larger scales (lower resolution) is a combined result of multiple aspects: the underlying scaling relation on smaller scales (higher resolution), dependence of the underlying scaling relation on ionization conditions, and the physical relationships among regions within the considered scale. Therefore, comparing scaling relations obtained at different scales provides

insights into the physical scales of the mechanisms that regulate the coupling between CO, PAH, and dust.

The overall decrease in k_{KS} at scales larger than ~ 100 pc as particularly seen in low- b galaxies, suggests that CO, PAH, and dust primarily couple within compact components rather than diffuse ones. At smaller scales, the measured scaling relation directly reflects that in dense clumps. At larger scales, in contrast, the measured scaling relation is dominated by the number of clumps within the corresponding area, approaching a linear correlation (equivalent to a unit slope in the log-linear formula) gradually. The stronger tendency observed for I_{F2100W} further supports this, as I_{F2100W} is more concentrated on smaller scales compared to $I_{\text{F770W,PAH}}$ and I_{F1130W} , as revealed by power spectrum analysis of the PHANGS sample (C. Lind-Thomsen et al. 2025).

The absence of b_{KS} bimodality on scales larger than 100 pc suggests that the corresponding physical mechanism operates on cloud or sub-cloud scales (≤ 100 pc). This supports the “stronger background UV field” scenario as the origin of b_{KS} bimodality, rather than the “H II regions with higher star formation efficiency” scenario (see [subsubsection 4.2.2](#) above for an introduction of these two scenarios). While the background UV field exists throughout a galaxy, it is negligible in the brightest areas of H II regions (typically at their centers). Instead, it significantly enhances dust and PAH emissions in relatively faint areas of H II regions (usually at their outskirts). On scales smaller than 100 pc, the scaling relations resolve both the bright and faint regions, making the b_{KS} bimodality clearly visible. On larger scales, the measured emissions for each resolution element are dominated by the brightest regions, rendering the b_{KS} bimodality undetectable. If the “higher star formation efficiency H II regions” scenario were the dominant mechanism, the b_{KS} bimodality would remain detectable across different scales.

Beyond the cancellation of random scatter, the intrinsic scatter σ_{KS} measured at different scales also encodes the physical correlation between nearby regions. However, reliably decoding this information requires careful removal of the effects of random scatter cancellation, which is beyond the scope of this work. We leave this analysis to future studies.

4.2.6. Prospects for Future Studies

As discussed above, the statistical results obtained in this work qualitatively relate to a wide range of physical processes. However, directly deriving emissivities, the dust-to-gas ratio, and the PAH-to-dust ratio remains challenging due to degeneracies among these properties.

To fully realize their potential, we propose comparing the statistical results with simulations that incorporate detailed molecular gas, dust, and PAH physics (e.g., D. Narayanan et al. 2023) to constrain the underlying physical processes. The statistical results presented in this work, with careful treatment of noise and outliers, also facilitate a more direct and fair comparison with such simulations.

5. SUMMARY

By applying the recently developed regression technique, **raddest**, which effectively handles both uncertainties and outliers in observational data while achieving accurate parameter estimation, we analyze the correlations of CO (I_{CO}) with PAH ($I_{\text{F770W,PAH}}$ and I_{F1130W}) and dust (I_{F2100W}) emissions in 19 PHANGS galaxies at spatial scales down to $\lesssim 100$ pc. We adopt a log-linear formula to model these scaling relations, and examine the dependence of the best-fit model parameters (slope, intercept and intrinsic scatter) on ionization conditions, host galaxy properties, and spatial scales. Our key findings are summarized as follows:

- We confirm that log-linear scaling relations of I_{CO} with $I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W} persist at the 100 pc scale ([Figure 1](#), left column of [Figure 2](#)). However, deviations from log-linearity are observed in regions with the brightest dust or PAH emissions ([Figure 1](#)).
- The scaling relations exhibit a strong dependence on the ionization conditions (H II-like, composite-like, and AGN-like; see the second-to-last columns of [Figure 2](#)). This highlights the critical role of ionization conditions in regulating the interplay between CO, PAH, and dust in the ISM (refer to [subsubsection 4.2.1](#) for discussion).
- Even within the same ionization conditions, significant galaxy-to-galaxy variations in the scaling relations persist ([Figure 3](#)). These variations are primarily driven by differences in the intercept b , which exhibits a bimodal distribution ([Figure 4](#)). This bimodality correlates with the overall star formation strength of the host galaxy ([Figure 5](#)). A plausible explanation is that galaxies with stronger star formation activity have enhanced UV radiation background field, which increase PAH and dust emissivity (see [subsubsection 4.2.2](#) for further discussion).
- No significant (3σ) correlations are detected between global galaxy properties ($\log \text{SFR}$, $\log M_*$, $\log \text{sSFR}$, $\log L_{\text{CO}}$, and $\log M_{\text{HI}}$) and k_{KS} , b_{KS} , or

σ_{KS} (Figure 6). This lack of correlation could result from the limited sample size but also suggests that global galaxy properties are not the dominant drivers of the observed galaxy-to-galaxy variations. Although previously reported anti-correlations between b_{KS} and $\log \text{sSFR}$ are confirmed in 2σ sense, our results indicate that this trend likely arises from the bimodality of b_{KS} rather than a continuous correlation (Figure 7).

- When comparing across different MIR bands ($I_{\text{F770W,PAH}}$, I_{F1130W} , and I_{F2100W}), the variations in median k_{KS} and σ_{KS} are detectable but minor relative to the galaxy-to-galaxy differences (Figure 3). In contrast, b_{KS} exhibits significant differences across bands. The potential underlying physical mechanisms are discussed in subsection 4.2.3.
- For H II-like regions, deviations from log-linearity are well characterized by a flattening of the slope in the brightest regions in 75% of cases. The non-log-linear behavior of $\text{F770W}_{\text{PAH}}$ and F1130W is similar, whereas F2100W exhibits stronger deviations (Figure 8, Figure 9). No significant (3σ) correlations are found between non-log-linearity and global galaxy properties (Figure 10). The slope flattening in the brightest regions may result from enhanced PAH and dust emissivities normalized by the radiation field intensity in regions with stronger radiation fields (see subsection 4.2.4 for discussion).
- The parameters k_{KS} , b_{KS} , and σ_{KS} all depend on the spatial scale of measurement, indicating that the coupling between CO, PAH, and dust are regulated by different mechanisms at varying spatial scales (Figure 11, see subsection 4.2.5 for discussion).

The comparison to previous literature is discussed in subsection 4.1. Leveraging the high-quality dataset provided by the PHANGS project and the improved handling of noise and outliers through the **raddest** method, this work provides a detailed statistical description of the correlations of CO with PAH and dust. However, several unresolved issues require further investigation: the exact origin of galaxy-to-galaxy variations, particularly the intercept bimodality; the cause of the non-log-linear behavior; and the cause of the inconsistent results regarding the comparison of the $I_{\text{CO}}-I_{\text{F1130W}}$ (or WISE W3 band) and $I_{\text{CO}}-I_{\text{F2100W}}$ (or WISE W4 band) scaling relations tightness.

This analysis is based on a relatively small sample of 19 main sequence galaxies and should be regarded as a description of the behavior within these and similar galaxies. Future studies that extend this analysis to a larger and more representative sample would provide more robust and comprehensive results. As discussed in subsection 4.2.6, the full potential of these findings can be realized by comparing them with simulations that incorporate detailed molecular gas, dust, and PAH models. Such comparisons would offer valuable constraints and lead to a deeper understanding of the underlying physics driving galaxy evolution. The regression technique **raddest**, which demonstrates clear advantages in handling datasets with limited S/N and outliers in this work and JL25, can also be applied to other astrophysical analyses to provide more accurate and unbiased statistical foundations.

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AUTHOR CONTRIBUTIONS

TJ performed all the data analysis, made all the figures and carried out the first version of the manuscript. CL supervised the whole project, and thoroughly edited the manuscript.

Facilities: JWST(MIRI, NIRCам), VLT(MUSE), ALMA

Software: Python3(G. Van Rossum & F. L. Drake 2009), NumPy(C. R. Harris et al. 2020), Matplotlib(J. D. Hunter 2007), Astropy(Astropy Collaboration et al. 2013, 2018, 2022), SciPy(P. Virtanen et al. 2020), reproject(T. Robitaille et al. 2024), raddest(T. Jing & C. Li 2025), LINMIX(B. C. Kelly 2007)

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APPENDIX

A. RESULTS OF SINGLE LOG-LINEAR REGRESSION ANALYSIS

Best-fit results based on KS-test based method for different MIR bands in regions with varying ionization conditions across different galaxies are listed in [Table 2](#).

Table 2. Best-fit results based on KS-test based method for different MIR bands in regions with varying ionization conditions across different galaxies

ID	^a Name	Ionization Condition	F770W _{PAH}			F1130W			F2100W		
			k_{KS}	b_{KS}	σ_{KS}	k_{KS}	b_{KS}	σ_{KS}	k_{KS}	b_{KS}	σ_{KS}
1	NGC5068	all	—	—	—	—	—	—	—	—	—
		HII-like	1.70 ± 0.25	-0.42 ± 0.11	0.41 ± 0.23	1.60 ± 0.27	-0.70 ± 0.12	0.33 ± 0.20	1.50 ± 0.29	-0.20 ± 0.11	0.39 ± 0.22
		composite-like	—	—	—	—	—	—	—	—	—
		AGN-like	1.82 ± 0.68	-0.25 ± 0.29	0.34 ± 0.22	2.13 ± 0.79	-0.67 ± 0.19	0.28 ± 0.18	1.91 ± 0.69	0.03 ± 0.41	0.36 ± 0.24
2	IC5332	all	1.21 ± 0.31	0.19 ± 0.10	0.21 ± 0.14	1.28 ± 0.31	-0.03 ± 0.07	0.21 ± 0.13	1.36 ± 0.33	0.24 ± 0.12	0.19 ± 0.13
		HII-like	1.15 ± 0.30	0.15 ± 0.08	0.19 ± 0.13	1.10 ± 0.30	-0.05 ± 0.06	0.17 ± 0.12	1.26 ± 0.28	0.20 ± 0.09	0.20 ± 0.13
		composite-like	1.15 ± 0.43	0.17 ± 0.18	0.24 ± 0.15	—	—	—	1.37 ± 0.49	0.24 ± 0.21	0.21 ± 0.15
		AGN-like	1.60 ± 0.61	0.07 ± 0.37	0.76 ± 0.25	1.72 ± 0.78	-0.29 ± 0.31	0.81 ± 0.26	1.87 ± 0.73	0.05 ± 0.40	0.84 ± 0.24
3	NGC1087	all	1.33 ± 0.11	-0.37 ± 0.05	0.25 ± 0.10	1.37 ± 0.12	-0.61 ± 0.06	0.26 ± 0.10	1.21 ± 0.10	-0.16 ± 0.03	0.28 ± 0.09
		HII-like	1.37 ± 0.10	-0.38 ± 0.05	0.25 ± 0.08	1.46 ± 0.11	-0.67 ± 0.07	0.25 ± 0.08	1.21 ± 0.10	-0.17 ± 0.03	0.29 ± 0.09
		composite-like	1.50 ± 0.31	-0.18 ± 0.10	0.20 ± 0.13	1.46 ± 0.32	-0.50 ± 0.07	0.20 ± 0.13	1.71 ± 0.38	0.10 ± 0.17	0.27 ± 0.16
		AGN-like	-0.37 ± 1.25	-1.13 ± 0.71	0.25 ± 0.17	0.33 ± 1.26	-0.81 ± 0.48	0.27 ± 0.17	-0.98 ± 2.44	-1.74 ± 1.71	0.38 ± 0.25
4	NGC1385	all	1.23 ± 0.09	-0.40 ± 0.06	0.25 ± 0.10	1.27 ± 0.09	-0.64 ± 0.07	0.26 ± 0.09	1.00 ± 0.09	-0.17 ± 0.04	0.28 ± 0.09
		HII-like	1.11 ± 0.09	-0.37 ± 0.06	0.27 ± 0.08	1.25 ± 0.09	-0.63 ± 0.07	0.24 ± 0.09	1.00 ± 0.09	-0.17 ± 0.05	0.28 ± 0.09
		composite-like	2.16 ± 0.42	-0.36 ± 0.09	0.24 ± 0.15	1.99 ± 0.30	-0.79 ± 0.09	0.19 ± 0.13	2.02 ± 0.48	-0.16 ± 0.15	0.50 ± 0.26
		AGN-like	0.05 ± 1.50	-1.36 ± 0.58	0.39 ± 0.26	-0.46 ± 1.86	-1.35 ± 0.35	0.33 ± 0.22	1.29 ± 1.39	-0.72 ± 0.75	0.40 ± 0.26
5	NGC2835	all	1.21 ± 0.17	-0.16 ± 0.05	0.20 ± 0.11	1.28 ± 0.18	-0.43 ± 0.07	0.20 ± 0.12	1.18 ± 0.18	-0.04 ± 0.05	0.19 ± 0.12
		HII-like	1.28 ± 0.16	-0.24 ± 0.05	0.30 ± 0.11	1.40 ± 0.20	-0.50 ± 0.08	0.25 ± 0.12	1.17 ± 0.18	-0.10 ± 0.05	0.30 ± 0.11
		composite-like	1.36 ± 0.25	0.01 ± 0.07	0.20 ± 0.13	1.56 ± 0.30	-0.34 ± 0.06	0.17 ± 0.11	1.89 ± 0.31	0.38 ± 0.10	0.14 ± 0.10
		AGN-like	—	—	—	—	—	—	—	—	—
6	NGC7496	all	1.33 ± 0.11	-0.05 ± 0.03	0.33 ± 0.07	1.38 ± 0.13	-0.35 ± 0.04	0.31 ± 0.07	1.12 ± 0.09	0.01 ± 0.03	0.34 ± 0.07
		HII-like	1.25 ± 0.11	-0.11 ± 0.03	0.28 ± 0.07	1.26 ± 0.10	-0.35 ± 0.04	0.28 ± 0.06	1.10 ± 0.10	0.03 ± 0.03	0.29 ± 0.06
		composite-like	1.75 ± 0.18	0.05 ± 0.05	0.40 ± 0.07	1.75 ± 0.19	-0.38 ± 0.04	0.38 ± 0.07	—	—	—
		AGN-like	—	—	—	—	—	—	—	—	—
7	NGC0628	all	0.97 ± 0.09	0.14 ± 0.03	0.22 ± 0.08	1.17 ± 0.13	-0.15 ± 0.06	0.21 ± 0.09	1.16 ± 0.11	0.29 ± 0.02	0.15 ± 0.09
		HII-like	1.00 ± 0.10	0.10 ± 0.03	0.22 ± 0.07	1.12 ± 0.11	-0.15 ± 0.06	0.20 ± 0.07	1.06 ± 0.09	0.26 ± 0.02	0.19 ± 0.08
		composite-like	1.20 ± 0.13	0.21 ± 0.04	0.20 ± 0.10	1.19 ± 0.13	-0.11 ± 0.05	0.18 ± 0.09	—	—	—
		AGN-like	—	—	—	—	—	—	—	—	—

Table 2 continued

Table 2 (continued)

ID ^a	Name	Ionization Condition	F770W _{PAH}			F1130W			F2100W		
			k_{KS}	b_{KS}	σ_{KS}	k_{KS}	b_{KS}	σ_{KS}	k_{KS}	b_{KS}	σ_{KS}
8	NGC3351	AGN-like	1.75 ± 1.01	-0.63 ± 0.47	0.59 ± 0.36	0.39 ± 0.69	-0.96 ± 0.25	0.44 ± 0.27	0.44 ± 0.74	-0.74 ± 0.29	0.41 ± 0.27
		all	1.17 ± 0.16	0.22 ± 0.06	0.21 ± 0.11	1.44 ± 0.21	-0.11 ± 0.05	0.24 ± 0.11	–	–	–
		Hrr-like	1.28 ± 0.15	0.19 ± 0.03	0.22 ± 0.08	1.44 ± 0.18	-0.10 ± 0.04	0.23 ± 0.07	1.49 ± 0.20	0.30 ± 0.04	0.17 ± 0.09
		composite-like	1.22 ± 0.20	0.27 ± 0.09	0.22 ± 0.13	1.48 ± 0.28	-0.10 ± 0.06	0.24 ± 0.14	1.64 ± 0.28	0.32 ± 0.11	0.24 ± 0.13
9	NGC4254	AGN-like	0.51 ± 0.84	-0.92 ± 0.73	0.70 ± 0.43	0.41 ± 0.84	-0.84 ± 0.37	0.46 ± 0.31	1.28 ± 1.00	-0.56 ± 0.48	0.71 ± 0.43
		all	1.27 ± 0.09	-0.19 ± 0.06	0.27 ± 0.07	1.35 ± 0.09	-0.46 ± 0.07	0.27 ± 0.07	1.16 ± 0.08	0.05 ± 0.04	0.28 ± 0.07
		Hrr-like	1.35 ± 0.09	-0.24 ± 0.07	0.26 ± 0.08	1.34 ± 0.09	-0.47 ± 0.08	0.26 ± 0.07	1.17 ± 0.08	0.03 ± 0.05	0.27 ± 0.07
		composite-like	1.25 ± 0.12	-0.06 ± 0.04	0.29 ± 0.08	1.30 ± 0.12	-0.37 ± 0.05	0.29 ± 0.07	1.27 ± 0.11	0.10 ± 0.03	0.29 ± 0.08
10	NGC4303	AGN-like	–	–	–	–	–	–	–	–	–
		all	1.25 ± 0.10	-0.21 ± 0.06	0.31 ± 0.07	1.36 ± 0.10	-0.56 ± 0.08	0.30 ± 0.06	1.14 ± 0.09	-0.03 ± 0.05	0.33 ± 0.06
		Hrr-like	1.21 ± 0.10	-0.27 ± 0.08	0.28 ± 0.05	1.30 ± 0.10	-0.56 ± 0.10	0.28 ± 0.05	1.07 ± 0.09	-0.03 ± 0.06	0.29 ± 0.06
		composite-like	1.65 ± 0.14	-0.22 ± 0.05	0.30 ± 0.08	1.66 ± 0.15	-0.65 ± 0.09	0.30 ± 0.08	1.46 ± 0.13	-0.01 ± 0.04	0.31 ± 0.08
11	NGC4535	AGN-like	–	–	–	–	–	–	–	–	–
		all	1.21 ± 0.11	0.18 ± 0.03	0.29 ± 0.07	1.31 ± 0.12	-0.08 ± 0.03	0.29 ± 0.07	1.29 ± 0.11	0.25 ± 0.04	0.28 ± 0.09
		Hrr-like	1.22 ± 0.10	0.07 ± 0.03	0.26 ± 0.06	1.37 ± 0.13	-0.18 ± 0.05	0.25 ± 0.06	1.17 ± 0.10	0.17 ± 0.03	0.27 ± 0.06
		composite-like	1.73 ± 0.23	0.37 ± 0.07	0.28 ± 0.08	1.68 ± 0.21	-0.01 ± 0.03	0.28 ± 0.09	1.90 ± 0.20	0.46 ± 0.07	0.27 ± 0.09
12	NGC1300	AGN-like	–	–	–	–	–	–	–	–	–
		all	1.09 ± 0.16	0.09 ± 0.06	0.33 ± 0.10	1.33 ± 0.19	-0.15 ± 0.05	0.32 ± 0.11	–	–	–
		Hrr-like	1.22 ± 0.13	0.01 ± 0.03	0.25 ± 0.08	1.23 ± 0.12	-0.19 ± 0.04	0.24 ± 0.08	1.13 ± 0.11	0.15 ± 0.03	0.21 ± 0.09
		composite-like	1.82 ± 0.30	0.41 ± 0.15	0.45 ± 0.14	1.70 ± 0.27	-0.01 ± 0.09	0.31 ± 0.17	–	–	–
13	NGC1512	AGN-like	2.10 ± 0.51	0.67 ± 0.38	0.56 ± 0.29	1.71 ± 0.36	0.06 ± 0.21	0.48 ± 0.27	1.86 ± 0.47	0.38 ± 0.33	0.58 ± 0.29
		all	0.85 ± 0.12	0.11 ± 0.06	0.18 ± 0.10	0.98 ± 0.14	-0.08 ± 0.05	0.16 ± 0.10	1.07 ± 0.15	0.23 ± 0.08	0.17 ± 0.10
		Hrr-like	1.01 ± 0.11	0.07 ± 0.04	0.15 ± 0.09	1.10 ± 0.11	-0.11 ± 0.03	0.14 ± 0.08	1.15 ± 0.12	0.22 ± 0.05	0.13 ± 0.08
		composite-like	0.98 ± 0.15	0.25 ± 0.09	0.16 ± 0.10	0.97 ± 0.17	-0.04 ± 0.07	0.15 ± 0.09	1.37 ± 0.21	0.43 ± 0.12	0.13 ± 0.09
14	NGC1672	AGN-like	0.99 ± 0.32	0.30 ± 0.28	0.29 ± 0.20	0.63 ± 0.23	-0.18 ± 0.16	0.30 ± 0.18	1.84 ± 0.51	0.82 ± 0.39	0.31 ± 0.18
		all	1.46 ± 0.14	-0.25 ± 0.06	0.39 ± 0.09	1.63 ± 0.16	-0.62 ± 0.08	0.36 ± 0.09	1.39 ± 0.13	-0.05 ± 0.05	0.40 ± 0.10
		Hrr-like	1.31 ± 0.10	-0.24 ± 0.05	0.30 ± 0.08	1.46 ± 0.12	-0.54 ± 0.07	0.27 ± 0.08	1.17 ± 0.10	-0.04 ± 0.04	0.31 ± 0.08
		composite-like	1.76 ± 0.27	-0.27 ± 0.06	0.60 ± 0.10	1.78 ± 0.25	-0.71 ± 0.09	0.58 ± 0.11	1.52 ± 0.25	-0.10 ± 0.07	0.60 ± 0.10
		AGN-like	–	–	–	–	–	–	–	–	–

Table 2 continued

Table 2 (continued)

ID ^a	Name	Ionization Condition	F770W _{PAH}			F1130W			F2100W		
			k_{KS}	b_{KS}	σ_{KS}	k_{KS}	b_{KS}	σ_{KS}	k_{KS}	b_{KS}	σ_{KS}
15	NGC4321	all	1.26 ± 0.11	0.08 ± 0.04	0.32 ± 0.06	1.46 ± 0.13	-0.29 ± 0.06	0.31 ± 0.06	1.31 ± 0.11	0.15 ± 0.03	0.31 ± 0.06
		HII-like	1.32 ± 0.10	-0.02 ± 0.04	0.28 ± 0.06	1.49 ± 0.12	-0.36 ± 0.07	0.27 ± 0.06	1.22 ± 0.10	0.13 ± 0.04	0.28 ± 0.06
		composite-like	1.76 ± 0.17	0.14 ± 0.03	0.32 ± 0.07	1.88 ± 0.19	-0.37 ± 0.07	0.30 ± 0.07	1.95 ± 0.16	0.24 ± 0.03	0.28 ± 0.08
		AGN-like	-	-	-	-	-	-	-	-	-
16	NGC1566	all	1.33 ± 0.12	-0.25 ± 0.06	0.43 ± 0.09	1.44 ± 0.15	-0.57 ± 0.08	0.41 ± 0.09	1.36 ± 0.19	-0.10 ± 0.05	0.46 ± 0.09
		HII-like	1.35 ± 0.12	-0.28 ± 0.07	0.36 ± 0.08	1.49 ± 0.14	-0.67 ± 0.10	0.40 ± 0.07	1.16 ± 0.11	-0.07 ± 0.05	0.40 ± 0.08
		composite-like	1.64 ± 0.22	-0.21 ± 0.05	0.46 ± 0.10	1.65 ± 0.23	-0.67 ± 0.09	0.49 ± 0.09	1.77 ± 0.30	-0.09 ± 0.06	0.55 ± 0.12
		AGN-like	2.11 ± 0.24	-0.13 ± 0.13	0.33 ± 0.18	2.40 ± 0.20	-1.21 ± 0.19	0.25 ± 0.16	2.48 ± 0.18	-0.48 ± 0.11	0.32 ± 0.17
17	NGC3627	all	1.27 ± 0.11	-0.15 ± 0.06	0.35 ± 0.06	1.42 ± 0.12	-0.54 ± 0.09	0.37 ± 0.07	-	-	-
		HII-like	1.25 ± 0.10	-0.18 ± 0.07	0.31 ± 0.06	1.35 ± 0.11	-0.50 ± 0.09	0.34 ± 0.05	1.08 ± 0.09	0.07 ± 0.05	0.33 ± 0.05
		composite-like	-	-	-	1.46 ± 0.18	-0.55 ± 0.09	0.41 ± 0.06	1.47 ± 0.16	-0.03 ± 0.04	0.42 ± 0.07
		AGN-like	-	-	-	-	-	-	-	-	-
18	NGC1433	all	1.30 ± 0.16	0.16 ± 0.07	0.27 ± 0.14	1.33 ± 0.20	-0.17 ± 0.05	0.24 ± 0.13	-	-	-
		HII-like	1.11 ± 0.13	0.02 ± 0.03	0.17 ± 0.09	1.17 ± 0.14	-0.20 ± 0.04	0.18 ± 0.09	1.07 ± 0.12	0.11 ± 0.04	0.17 ± 0.09
		composite-like	1.91 ± 0.29	0.50 ± 0.13	0.29 ± 0.16	1.59 ± 0.31	-0.10 ± 0.08	0.24 ± 0.15	2.33 ± 0.32	0.75 ± 0.15	0.17 ± 0.12
		AGN-like	1.87 ± 0.50	0.47 ± 0.31	0.64 ± 0.30	1.69 ± 0.51	-0.24 ± 0.15	0.46 ± 0.27	2.01 ± 0.45	0.39 ± 0.23	0.51 ± 0.29
19	NGC1365	all	1.61 ± 0.16	0.22 ± 0.05	0.49 ± 0.09	1.81 ± 0.16	-0.25 ± 0.05	0.44 ± 0.09	-	-	-
		HII-like	1.12 ± 0.13	-0.04 ± 0.03	0.25 ± 0.08	-	-	-	1.02 ± 0.10	0.14 ± 0.03	0.23 ± 0.09
		composite-like	1.73 ± 0.17	0.30 ± 0.05	0.44 ± 0.09	1.88 ± 0.17	-0.21 ± 0.05	0.47 ± 0.09	-	-	-
		AGN-like	2.10 ± 0.27	0.59 ± 0.04	0.47 ± 0.09	1.84 ± 0.23	-0.06 ± 0.07	0.48 ± 0.08	-	-	-

^aAs defined in Table 1, ordered by galactic stellar mass M_* .

NOTE—We discard results based on datasets with fewer than 100 data points or those that fail the goodness-of-fit test for NF, as outlined in subsection 2.2. Such results are indicated as “-” in the table.