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### ABSTRACT

We present GBT-EDGE, a new CO (1–0) survey using the Green Bank Telescope to map 62 nearby (10–140 Mpc) galaxies spanning the star-forming main sequence (SFMS), green valley, and red sequence. The galaxy sample is selected from the CALIFA survey with integral field spectroscopy (IFS), which provides a representative census of local galactic environments. Combining the CO dataset with CALIFA’s optical IFS measurements, we derive molecular gas masses, star formation rates (SFR), metallicities, and stellar mass densities to measure star formation efficiency (SFE) and investigate the physical drivers of galaxy quenching. We obtain a median molecular gas depletion time of  $2.10^{+2.35}_{-1.31}$ ,  $6.90^{+17.00}_{-3.67}$ , and  $127.7^{+201.6}_{-113.4}$  Gyr for our sample of main sequence, green valley, and red galaxies, respectively, assuming a Galactic CO-to-H<sub>2</sub> conversion factor. By applying various conversion factor prescriptions, we also confirm a systematic decrease of SFE with galaxy’s offset below the SFMS, regardless of the adopted prescription. This suggests that the low SFR in some quenched galaxies is primarily driven by suppressed SFE rather than an absence of molecular gas. Our results provide evidence that galaxies below the main sequence can retain substantial molecular gas reservoirs comparable to star-forming galaxies, but they exhibit longer depletion times and form stars inefficiently, possibly due to the combined effects of low gas density and morphological quenching mechanisms.

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## 1. INTRODUCTION

Galaxy evolution is driven by variations in the level of star formation activities within galaxies. Observational studies on nearby galaxies over the past two decades have confirmed a strong correlation between a galaxy’s star formation rate (SFR) and its stellar mass ( $M_{\text{star}}$ ), namely, the star formation main sequence (SFMS; J. Brinchmann et al. 2004; S. Salim et al. 2007; M. Cano-Díaz et al. 2016; A. Saintonge et al. 2016). This relation has also been found to hold for spatially resolved observations down to kpc scales, and thus the relation is sometimes expressed in terms of surface densities ( $\Sigma_{\text{SFR}}$  and  $\Sigma_{\text{star}}$ ; e.g., L. Lin et al. 2019a; S. F. Sánchez et al. 2021). The established SFMS relation has further led to a common galaxy classification based on the offset from the SFMS relation: main sequence (MS) galaxies are those aligned with the SFMS, red galaxies (RGs) are those falling on the “red cloud sequence” which is substantially below the SFMS (e.g., T. K. Wyder et al. 2007), and green valley (GV) galaxies are those in between, which implies a transitioning stage where star formation begins to shut down (S. Salim et al. 2007). As a result, the offset from the SFMS (or many studies also use “specific SFR”, which is defined as  $\text{sSFR} \equiv \text{SFR}/M_{\text{star}}$ ) has been widely adopted to indicate a galaxy’s evolutionary stage in terms of its star formation level (e.g., A. Saintonge et al. 2017; D. Colombo et al. 2020; S. Salim et al. 2023).

To probe the reasons for the rise and fall of star formation in galaxies, it is critical to study the cold molecular interstellar medium, which is the birthplace of stars and thus determines the capacity for star formation in a galaxy. Specifically, star formation is governed by the amount of molecular gas as well as how efficiently molecular gas is converted into stars (R. C. Kennicutt & N. J. Evans 2012; A. Saintonge & B. Catinella 2022). Previous studies have revealed a roughly constant star formation efficiency (SFE  $\equiv \text{SFR}/M_{\text{mol}}$ , where  $M_{\text{mol}}$  represents the molecular gas mass) in nearby MS galaxy disks, where the molecular gas depletion time ( $t_{\text{dep}} \equiv \text{SFE}^{-1}$ ) is around 2 Gyr, despite variations found between galaxy centers (e.g., F. Bigiel et al. 2008; A. Saintonge et al. 2011; A. K. Leroy et al. 2013; D. Utomo et al. 2017; K. Muraoka et al. 2019; J. Sun et al. 2023; Y.-H. Teng et al. 2024). The SFE in star-forming galaxy centers is sometimes found to be higher than the value in their disks, which would enhance star formation and support central starbursts (e.g., D. Utomo et al. 2017; S. L. Ellison

et al. 2020a). SFE in centers may also be lower than in the disks, which can indicate galaxy quenching due to feedback from active galactic nuclei (AGN; M. J. Page et al. 2012) or morphological quenching driven by bars or bulges (M. Martig et al. 2009; A. Saintonge et al. 2012; D. Colombo et al. 2018; F. Maeda et al. 2023). While these SFE estimations are known to be sensitive to the choices of SFR indicator and CO-to- $\text{H}_2$  conversion factor ( $\alpha_{\text{CO}}$ ; A. D. Bolatto et al. 2013), measurements and/or prescriptions for SFR and  $\alpha_{\text{CO}}$  are relatively well-developed for MS galaxies (e.g., Y.-H. Teng et al. 2023, 2024; I.-D. Chiang et al. 2024; E. Schinnerer & A. K. Leroy 2024; J. Sun et al. 2025), and thus recent SFE studies are able to account for such systematic variations (e.g., J. Sun et al. 2023; M. Querejeta et al. 2024; Y.-H. Teng et al. 2024; D. Colombo et al. 2025a).

On the other hand, SFE across quenched galaxies, including GV galaxies, and especially RGs, remains under-explored. This is because obtaining high-quality molecular gas observations (usually via CO rotational line emission) in such environments requires significant integration time, given the sensitivity of current millimeter-wave telescopes. Therefore, current molecular gas studies are limited to a small sample of GV galaxies and tend to focus only on the transition from MS to GV rather than extending to a comparable sample of RGs. The sensitivity limitation also makes measuring accurate gas mass and  $\alpha_{\text{CO}}$  even more challenging in the GV and RGs, and thus most studies on these systems still rely on assuming a constant Galactic-like  $\alpha_{\text{CO}}$  value to determine molecular gas-related properties (e.g., K. Alatalo et al. 2013; T. A. Davis et al. 2014; L. Lin et al. 2022; V. Villanueva et al. 2024). Furthermore, while both molecular gas fraction and SFE are known to play a role in galaxy quenching, there is not yet a consensus about whether one of these factors dominates, and how they might change across different galaxy evolutionary stages (A. Saintonge et al. 2017; D. Colombo et al. 2020; S. Brownson et al. 2020; S. L. Ellison et al. 2020b; G. G. Kacprzak et al. 2021; L. Lin et al. 2022; H.-A. Pan et al. 2024; V. Villanueva et al. 2024).

The physical cause of a reduced molecular gas fraction or SFE in quenched galaxies is also under debate. Previous studies have found that galaxies below the MS tend to be associated with early-type morphologies (e.g., bigger bulges; M. Cano-Díaz et al. 2019) and they are more likely to host AGN (e.g., J. Aird et al. 2019; E. A. D. Lacerda et al. 2020). Such structural differences can

affect the local star formation processes but also complicate explanations of different quenching mechanisms. For instance, the existence of AGN could either indicate increased gas availability due to black hole accretion and its co-evolution with the galaxy (T. M. Heckman & P. N. Best 2014; S. R. Ward et al. 2022), or it may lead to a strong depletion of gas via AGN feedback processes (A. Saintonge et al. 2017; S. L. Ellison et al. 2021). Similarly, bar-driven inflows are known to bring in more gas and boost star formation (K. Sakamoto et al. 1999; K. Sheth et al. 2005; N. Kuno et al. 2007; R. Chown et al. 2019; R. G. Tress et al. 2020; S.-Y. Yu et al. 2022), whereas the gas stabilization from bulge potential or bar-induced shear can support the presence of substantial quiescent gas reservoirs (M. Martig et al. 2009; T. A. Davis et al. 2014; J. Gensior et al. 2020; F. Maeda et al. 2023).

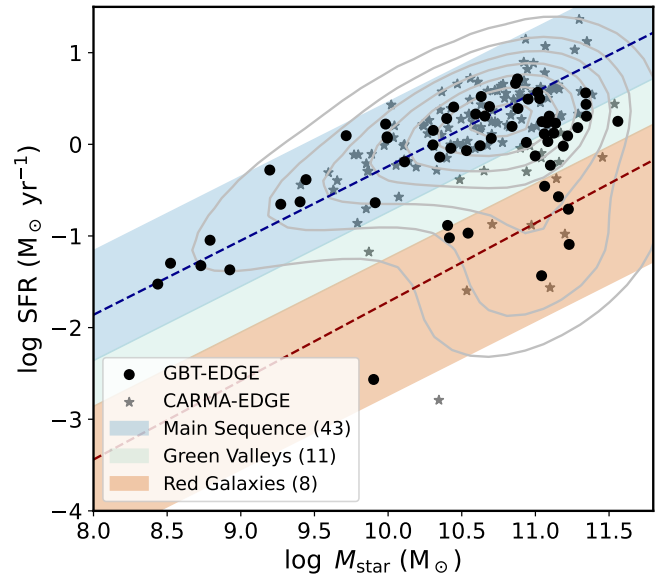
In this paper, we present new CO  $J=1-0$  observations with the Robert C. Byrd Green Bank Telescope (GBT) toward 62 nearby galaxies with  $M_{\text{star}}$  between  $3 \times 10^8$  to  $3 \times 10^{11} M_{\odot}$ . Our targets include GV and RGs in a similar sample size ( $\sim 10$  galaxies each), along with a sizable sample of MS galaxies to be compared with. With optical integral field unit (IFU) data available from the Calar Alto Legacy Integral Field Area (CALIFA) survey (S. F. Sánchez et al. 2012, 2016a), this sample allows a comprehensive study of SFE variations across galaxy populations with varying locations in the SFMS relation. We estimate  $M_{\text{mol}}$  and SFE with multiple  $\alpha_{\text{CO}}$  treatments and investigate their roles in the quenching of star formation throughout different galaxy evolutionary stages.

The paper is structured as follows. Section 2 describes our sample, observations, data processing, and ancillary data. Section 3 presents our analyses and results, including the derivation of data products and various galaxy-integrated properties. In Section 4, we discuss implications from our results on galaxy quenching mechanisms and compare them to those from the literature. The conclusions are summarized in Section 5. In this work, we assume a flat  $\Lambda$ CDM cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.27$ , and  $\Omega_{\Lambda} = 0.73$ .

## 2. OBSERVATIONS AND DATA

### 2.1. The GBT-EDGE Sample

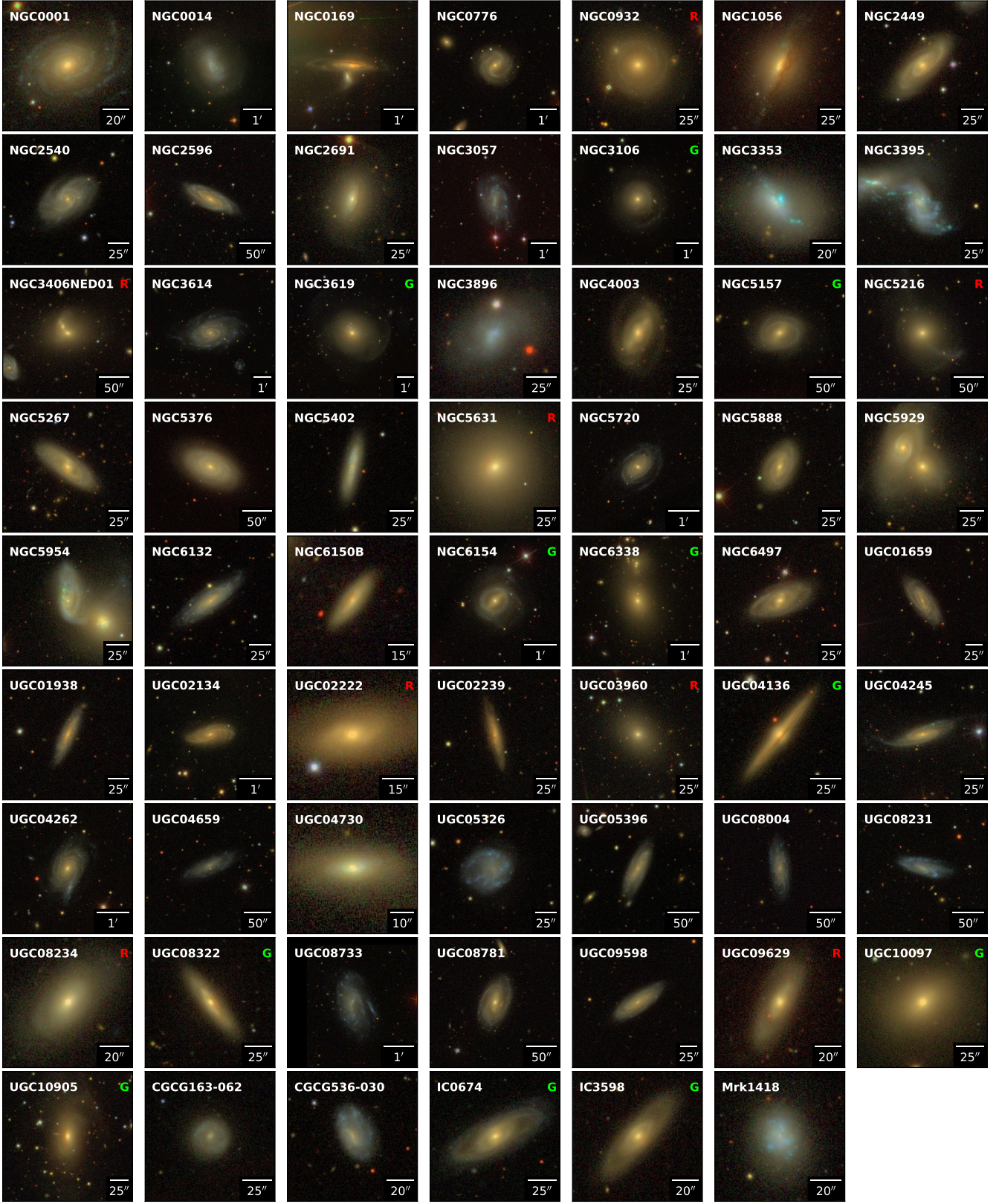
We use the GBT to observe CO (1–0) across 62 galaxies selected from the CALIFA survey (S. F. Sánchez et al. 2012), aiming to complement previous Extragalactic Database for Galaxy Evolution (EDGE) surveys (A. D. Bolatto et al. 2017; D. Colombo et al. 2020; V. Villanueva et al. 2024; T. Wong et al. 2024). The selection criteria of our parent sample, the CALIFA galaxies, include redshift ( $0.03 > z > 0.005$ ), Galactic latitude



**Figure 1.** The relation between global star formation rate (SFR) and stellar mass ( $M_{\text{star}}$ ) for our GBT sample (black points; 62 galaxies), the CARMA sample (gray stars; A. D. Bolatto et al. 2017), and the full CALIFA sample (contours; S. F. Sánchez et al. 2016a). The blue (upper) and red (lower) dashed lines indicate best linear fits from M. Cano-Díaz et al. (2016) for the main sequence and red galaxies, respectively. The GBT-EDGE sample is representative of the  $z = 0$  galaxy population with  $M_{\text{star}} = 10^{8.5-11.5} M_{\odot}$ .

( $|b| > 20^\circ$ ), declination ( $> 7^\circ$ ), and cuts in the angular isophotal diameter ( $45'' - 79.2''$ ) and flux ( $< 20$  in Petrosian magnitudes) in the SDSS  $r$ -band images (C. J. Walcher et al. 2014; S. F. Sánchez et al. 2016a). We note that the cut on low redshift effectively excluded objects with distance  $\lesssim 20$  Mpc, which avoided the sample to be overwhelmed by dwarf galaxies and/or compact objects in the local Universe. In addition, the imposed flux limit excluded many low surface brightness objects. These selection criteria also indicate that the largest and most massive galaxies in the sample are more distant than the smallest and least massive galaxies. To select our GBT-EDGE sample from CALIFA, we further impose a declination cut of  $\delta > 10^\circ$  and avoid any overlap with the published CARMA-EDGE sample (A. D. Bolatto et al. 2017). This results in our proposed sample of 150 galaxies for GBT observations. However, 79 of the galaxies were not observed and 9 of the observed galaxies were further removed due to severe artifacts, leaving us with the final sample of 62 galaxies (see Section 2.2 for more details).

Figure 1 shows the SFR– $M_{\text{star}}$  (or SFMS) relation of the 62 observed galaxies, with comparison to the full CALIFA sample and a previously published sub-sample using the Combined Array for Research in Millimeter-



**Figure 2.** SDSS  $g$  (blue channel),  $r$  (green channel), and  $i$  (red channel) composite images for all 62 galaxies in our GBT-EDGE sample. Green valley (GV) and red galaxies (RGs) are labeled by a letter ‘G’ and ‘R’, respectively, in the top-right corners of their panels. These galaxies cover a variety of morphologies and galaxy environments, which constitute a representative sample of the local Universe (Figure 1) and enable comprehensive studies on the galaxy quenching process.

wave Astronomy (CARMA; [A. D. Bolatto et al. 2017](#)). Our sample of galaxies is representative of the galaxy population with  $M_{\text{star}} = 10^{8.5-11.5} M_{\odot}$  in the local Universe, spanning distances from 10–140 Mpc (see Table 1). Figure 2 presents the optical composite images of these galaxies from the Sloan Digital Sky Survey (SDSS), which show diverse morphological and environmental conditions. The basic properties of the entire galaxy sample are listed in Table 1.

Our GBT sample selection does not overlap with that of the CARMA observations and extends to lower  $M_{\text{star}}$ , covering 43 galaxies on the main sequence, 11 galaxies in the green valley, and 8 galaxies on the red cloud. In this

work, we define main sequence (MS) galaxies as those with SFRs between -0.5 and 0.7 dex from the best-fit relation in [M. Cano-Díaz et al. \(2016\)](#):

$$\log(\text{SFR})_{\text{MS}} = 0.81 \log(M_{\text{star}}) - 8.34, \quad (1)$$

where  $M_{\text{star}}$  and SFR are in units of  $M_{\odot}$  and  $M_{\odot} \text{ yr}^{-1}$ , respectively. We also define GV as galaxies with SFRs between -0.5 and -1 dex from Equation 1. Similarly, RGs are defined as those having  $\text{SFR} < -1$  dex from Equation 1. These boundary definitions are consistent with previous studies showing similar ranges for these galaxy populations ([M. Cano-Díaz et al. 2016](#); [S. F. Sánchez et al. 2018](#); [D. Colombo et al. 2020](#); [L. Lin et al. 2020](#); [V. Villanueva et al. 2024](#)).

**Table 1.** Basic Properties of the GBT-EDGE Sample

Galaxy	R.A.	Decl.	Dist.	$\log(d_{25})$	P.A.	Incl.	vmaxg	$\log(\text{SFR})$	$\log(M_{\text{star}})$	Type
(1)	[deg]	[deg]	[Mpc]	[0.1 arcmin]	[deg]	[deg]	[km s <sup>-1</sup> ]	[M <sub>⊙</sub> yr <sup>-1</sup> ]	[M <sub>⊙</sub> ]	(11)
NGC0001	1.816000	27.708250	64.1	1.2	110.5	48.8	146	0.71	10.88	MS
NGC0014	2.192375	15.815750	12.0	1.18	23.1	55.7	35.2	-1.32	8.73	MS
NGC0169	9.215500	23.990361	65.3	1.18	92.5	69.8	278	0.56	11.34	MS
NGC0776	29.977083	23.644389	69.4	1.13	50.0	18.3	60	0.57	11.02	MS
NGC0932	36.977833	20.332500	57.7	1.3	40.0	24.4	90	-0.46	11.06	RG
NGC1056	40.701625	28.574111	21.9	1.27	162.5	46.7	124.2	0.15	10.31	MS
NGC2449	116.834542	26.930306	69.6	1.16	135.5	73.7	101	0.02	10.94	MS
NGC2540	123.193500	26.361833	89.4	1.094	123.3	60.4	153	0.52	10.63	MS
NGC2596	126.860250	17.283972	84.5	1.14	63.9	74.2	203.2	0.67	10.87	MS
NGC2691	133.693083	39.538778	56.1	1.1	166.0	47.9	182	0.33	10.59	MS
NGC3057	151.416583	80.284972	21.2	1.16	8.0	58.3	100	-0.65	9.27	MS
NGC3106	151.021833	31.185472	88.8	0.95	150.0	26.0	102	0.09	11.22	GV
NGC3353	161.343042	55.960306	13.6	1.13	75.7	45.5	41.4	-0.28	9.20	MS
NGC3395	162.458792	32.982889	22.3	1.2	40.5	57.8	86.1	0.09	9.72	MS
NGC3406NED01	162.932542	51.023083	107.0	1.16	84.4	62.3	150	-0.71	11.22	RG
NGC3614	169.588833	45.747972	32.7	1.4	87.7	47.0	131.5	-0.19	10.11	MS
NGC3619	169.839792	57.758111	21.8	1.59	25.0	42.4	165.1	-0.89	10.40	GV
NGC3896	177.234792	48.674639	12.7	1.15	128.4	55.4	110.6	-1.53	8.44	MS
NGC4003	179.495958	23.124917	93.5	1.02	159.7	65.2	150	0.26	11.08	MS
NGC5157	201.820208	32.030778	105.0	1.12	115.5	35.4	241	-0.23	11.10	GV
NGC5216	203.028625	62.700694	41.3	1.23	54.0	83.9	150.1	-1.02	10.42	RG
NGC5267	205.166417	38.794194	84.8	1.19	53.3	75.1	69.8	0.23	11.08	MS
NGC5376	208.816875	59.506611	29.5	1.17	66.3	54.8	135	-0.14	10.35	MS
NGC5402	209.569000	59.815000	42.8	1.05	166.0	81.2	122.2	0.07	9.99	MS
NGC5631	216.638542	56.582528	27.4	1.29	150.0	0.0	165.4	-0.97	10.54	RG
NGC5720	219.638625	50.815222	111.0	1.28	132.0	52.0	194.8	0.31	11.09	MS
NGC5888	228.280500	41.264694	125.0	1.12	156.7	54.6	150	0.44	11.34	MS
NGC5929	231.526625	41.671667	35.3	0.96	38.2	24.4	111.8	0.06	10.70	MS
NGC5954	233.645500	15.200167	27.0	1.01	19.2	63.6	111.4	0.22	9.98	MS

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Galaxy	R.A.	Decl.	Dist.	$\log(d_{25})$	P.A.	Incl.	vmaxg	$\log(\text{SFR})$	$\log(M_{\text{star}})$	Type
(1)	[deg]	[deg]	[Mpc]	[0.1 arcmin]	[deg]	[deg]	[km s <sup>-1</sup> ]	[M <sub>⊙</sub> yr <sup>-1</sup> ]	[M <sub>⊙</sub> ]	(11)
NGC6132	245.911708	11.787194	71.0	1.11	126.5	79.9	154.6	0.28	10.40	MS
NGC6150B	246.435167	40.475667	137.0	0.96	142.9	78.8	150	0.50	11.03	MS
NGC6154	246.377000	49.840306	85.2	1.15	149.6	47.9	59.3	0.11	11.06	GV
NGC6338	258.845708	57.411361	118.0	1.24	16.0	66.0	150	0.25	11.56	GV
NGC6497	267.824792	59.471000	86.2	1.16	110.3	67.1	150	0.25	11.05	MS
UGC01659	32.487042	16.032500	118.0	1.14	38.0	69.4	196	0.49	10.95	MS
UGC01938	37.092167	23.214639	90.0	1.07	155.0	81.9	186.1	0.41	10.69	MS
UGC02134	39.715833	27.847500	64.9	1.21	106.0	71.8	150	0.39	10.88	MS
UGC02222	41.291750	32.988417	70.1	1.12	103.0	67.6	150	-1.43	11.04	RG
UGC02239	41.648500	32.449556	68.0	1.12	14.0	86.2	150	-0.04	10.43	MS
UGC03960	115.094708	23.275000	31.4	1.1	46.7	72.4	150	-2.57	9.90	RG
UGC04136	119.976833	47.413306	95.3	1.2	141.5	89.9	296	0.12	11.12	GV
UGC04245	122.190750	18.194167	73.6	1.15	107.7	78.5	163	0.31	10.66	MS
UGC04262	124.764292	83.266417	81.1	1.3	151.7	40.6	188	0.20	10.84	MS
UGC04659	133.668333	47.105139	24.2	1.15	108.5	80.0	79	-1.37	8.93	MS
UGC04730	135.493292	60.151750	46.6	0.99	89.3	67.5	100	0.41	10.45	MS
UGC05326	148.852000	33.262889	18.5	0.97	146.1	16.9	60	-1.05	8.79	MS
UGC05396	150.418708	10.756389	76.7	1.17	155.9	69.9	152.6	-0.07	10.53	MS
UGC08004	192.908208	31.352944	88.3	1.04	5.6	68.7	133.9	-0.01	10.30	MS
UGC08231	197.156250	54.074611	34.8	1.17	74.9	74.4	96.8	-0.39	9.44	MS
UGC08234	197.193792	62.271694	117.0	1.21	142.1	80.2	150	-1.09	11.23	RG
UGC08322	198.753875	12.725278	109.0	1.05	36.1	73.0	238.1	-0.02	11.19	GV
UGC08733	207.162458	43.412444	32.8	1.29	6.3	62.2	80.9	-0.63	9.40	MS
UGC08781	208.094708	21.539444	108.0	1.2	161.8	57.1	238.6	0.23	11.14	MS
UGC09598	223.787833	43.818639	79.9	1.21	122.1	71.2	177	-0.02	10.62	MS
UGC09629	224.296875	52.346167	112.0	1.18	153.5	76.6	100	-0.57	11.16	RG
UGC10097	238.930250	47.867306	85.2	1.15	123.9	48.2	150	0.18	11.29	GV
UGC10905	263.526625	25.344028	111.0	1.18	171.7	68.4	150	0.31	11.35	GV
CGCG163-062	217.298625	30.077361	61.3	0.83	132.0	12.0	13.9	-0.64	9.91	MS
CGCG536-030	20.288542	40.470722	85.1	0.87	30.5	51.3	200	0.08	9.99	MS
IC0674	167.776542	43.633056	108.0	1.14	121.0	85.3	241.9	0.03	11.08	GV
IC3598	189.337792	28.208222	110.0	1.15	139.1	76.0	225.8	-0.13	11.00	GV
Mrk1418	145.112500	48.337528	9.5	0.82	15.8	35.6	47.1	-1.30	8.52	MS

**Note.** (1) Galaxy name; (2, 3) central position of the galaxy in J2000 coordinates; (4) luminosity distance (S. F. Sánchez et al. 2016b); (5–8) log of apparent diameter in 0.1 arcmin, position angle, inclination, and apparent maximum rotation velocity of gas, all from HyperLeda<sup>31</sup> (D. Makarov et al. 2014); (9, 10) log of star formation rate and stellar mass (S. F. Sánchez et al. 2016a; T. Wong et al. 2024); (11) galaxy classification as main sequence (MS), green valley (GV), or red galaxy (RG), as defined in Figure 1 via Equation 1.

## 2.2. GBT CO (1–0) Observations

For each galaxy in the selected sample, we mapped CO (1–0) at a rest frequency of 115.27 GHz across a field of view of  $2.5' \times 2.5'$  centered on the galaxy. We used the Argus array receiver (M. Sieth et al. 2014) on the GBT with an on-the-fly mapping technique (J. G. Mangum et al. 2007). The Argus receiver consists of 16 single-

polarization beams, which form a  $4 \times 4$  square array with a side length of  $1.52'$  and a spacing of  $30.4''$  between beams. This square array also aligns with the elevation and cross-elevation axes of the GBT. The 16 beams on Argus are connected to the 16 banks provided by the VEGAS backend (J. Chennamangalam et al. 2014). Each bank is configured to provide an effective bandwidth of 1.25 GHz with 1024 channels and a spectral res-

olution of 1.465 MHz, which corresponds to  $3.8 \text{ km s}^{-1}$  at the frequency of CO (1–0). The angular resolution of our final maps is  $8.3''$  (see Section 2.3 for further details).

The observations were carried out from November 2021 to March 2025 (project code: GBT21B-024; PI: Bolatto), with a total observing time of 344 hours where 71 galaxies were observed. However, nine of these galaxies<sup>21</sup> were dropped due to poor data quality with severe artifacts<sup>22</sup>, leaving us with a sample of 62. We note that the originally proposed sample includes a total of 150 galaxies, but our observing strategy was to follow up on galaxies that showed hints of detection in order to obtain good maps. Therefore, our final sample of 62 galaxies are possibly biased toward successful detections.

For each observing session, we started with out-of-focus (OOF) holography scans of a bright source, using either the Ka-band, Q-band, or Argus receiver. The OOF procedure re-aligns the surface panels of the GBT to correct for any residual thermal misalignment, and it typically takes 30–40 minutes. The OOF source was also chosen to be an ALMA flux calibrator<sup>23</sup>, so we also used it to take flux calibration scans at our observing frequency after pointing and focusing. Finally, we pointed and focused on a pointing calibration source near our science target to remove residual errors from the telescope pointing model. We then carried out our target observations by alternating mapping scans in the Right Ascension (R.A.) and Declination (Decl.) directions.

To ensure a consistent pointing and focus throughout our observations, we pointed and focused every 30–40 minutes between each R.A. or Decl. mapping scans. For calibration, we employ a vane observation, which uses an ambient temperature load for calibration of the antenna temperature. In Section 2.3, we describe our calibration and imaging processes in detail.

### 2.3. GBT CO (1–0) Data Reduction

The data calibration and gridding are done using an adapted version of `gbtpipe`<sup>24</sup>, a Python-based pipeline for processing spectral line data and making maps from Argus observations. Our data reduction pipeline code is available in a public GitHub repository, GBT-

EDGE<sup>25</sup>, where the method and procedure for running the pipeline are also documented. We summarize our data reduction process below and refer readers to D. T. Frayer et al. (2019) and the GitHub pages for more details.

First, we retrieve the observed ON, OFF, and vane calibration scans for each galaxy and compute the beam brightness temperature ( $T_A^*$ ) following recommendations in D. T. Frayer et al. (2019):

$$T_A^* = \frac{T_{\text{cal}}}{C_{\text{vane}}/C_{\text{OFF}}(t) - 1} \times \frac{C_{\text{ON}}(\nu) - C_{\text{OFF}}(\nu)}{C_{\text{OFF}}(\nu)}, \quad (2)$$

where  $C_{\text{ON}}$ ,  $C_{\text{OFF}}$ , and  $C_{\text{vane}}$  are instrumental counts from the ON, OFF, and vane calibration (which measures the ambient temperature) scans. The left factor represents the time-dependent effective system temperature, which was computed as a scalar for each scan leg, and in the right factor are vector quantities as a function of frequency, computed in this way to improve baseline performance.

The calibration temperature  $T_{\text{cal}}$  is given by

$$T_{\text{cal}} = (T_{\text{atm}} - T_{\text{bg}}) + (T_{\text{amb}} - T_{\text{atm}}) \exp(\tau_0 \cdot A), \quad (3)$$

where  $T_{\text{atm}}$  is the atmospheric temperature,  $T_{\text{bg}}$  is the temperature of the cosmic microwave background (2.73 K),  $T_{\text{amb}}$  is the ambient temperature measured from the vane observation,  $\tau_0$  is the atmospheric opacity at zenith, and  $A$  is the air mass determined from elevation information. Both the  $T_{\text{atm}}$  and  $\tau_0$  are derived from the online GBT weather models<sup>26</sup>. The uncertainty on  $T_{\text{cal}}$  is negligible in comparison to other observational uncertainties, and  $T_{\text{cal}} \approx T_{\text{amb}}$  within 2% for the observations.

In observing near  $\sim 115$  GHz, the Argus instrument shows variations in bandpass power that change significantly over the course of a pass of the receiver over the target galaxy. Using off-galaxy lines of sight to measure the OFF would require making large maps or dedicating a substantial fraction of the observing time to OFF measurements. Moreover, with the instability of the bandpass, such observations may not apply to the actual ON component of the spectrum. We thus develop an empirical model for the OFF that can account for time variation over the course of a scan.

We first define a rectangular region on the sky matching the CALIFA field of view<sup>27</sup> that should contain all

<sup>21</sup> NGC 0495, NGC 5987, UGC 04054, UGC 04258, UGC 04425, UGC 09777, UGC 8909, UGC 9663, and UGC 9837

<sup>22</sup> For data taken in the first year, we identified pointing issues caused by unaccounted movements of GBT’s secondary mirror. While this problem was fixed in later observations and we have excluded some of the early sessions, nine of the galaxies are still badly affected and thus are not presented in this paper.

<sup>23</sup> <https://almascience.nrao.edu/sc/>

<sup>24</sup> <https://github.com/GBTspectroscopy/gbtpipe>

<sup>25</sup> <https://github.com/teuben/GBT-EDGE>

<sup>26</sup> <https://www.gb.nrao.edu/~rmaddale/Weather/index.html>

<sup>27</sup> The CALIFA field of view is a hexagon, and the matched rectangular region is the smallest rectangle that covers that hexagon.

galactic emission. For each Argus receiver, we retrieve all position samples in a scan set outside this rectangular zone of exclusion to build an OFF model. We then apply Principal Component Analysis (PCA) to this set of spectra to find a set of eigenspectra that represent the bandpass variations. The model retains only those components such that  $\sigma_i^2/\sigma_{i+1}^2 > 1.2$  where  $\sigma_i^2$  is the variance explained by the  $i$ th component. We set the 1.2 threshold empirically to exclude noise-dominated components. We typically include 3 to 5 components to represent the OFF. We then fit all the spectra with these eigenspectra, both inside and outside the zone of exclusion, to generate a model of the OFF and apply Equation 3. Finally, we fit each spectrum with a ninth-order Legendre polynomial baseline to remove residual variations in the spectrum, excluding the velocity range where CO emission is expected. Figure 3 demonstrates our PCA-based OFF reconstruction, comparing between the best-fit OFF models (black) and our background OFF data (gray) measured in the start/end of our observing scans. We note that this method allows us to track and remove a time-variable spectral response better than traditional OFF techniques, while the resulting maps are still affected by artifacts likely due to baseline instability at the faint levels (see Section 3.1 for more details).

After calibration, we produce a spectral line data cube by gridding the data. We first reject bad spectra. For each spectrum, we determine an empirical noise measurement as  $\sigma_T = \langle T_A^*(i) - T_A^*(i+2) \rangle / \sqrt{2}$  where  $i$  represents the  $i$ th channel of the data. Using a two-channel lag avoids the channel-to-channel correlation in the spectrometer. We reject those calibrated spectra that 1) show empirical noise values that are a factor of 1.3 times larger than that expected from the radiometer formula at the measured system temperature, 2) have large-scale baseline ripples with a magnitude 1.3 times larger than the noise, and 3) show any single-channel spikes larger than 5 times the empirical noise. These thresholds typically reject  $\sim 1\%$  of the data. The retained scans are then gridded into a data cube using the Bessel function gridding kernel given in J. G. Mangum et al. (2007). Finally, we subtract a seventh-order baseline from each position in the resulting cube, excluding the velocity channels within  $400 \text{ km s}^{-1}$  of the galaxy’s central velocity. We note that a seventh-order baseline fit is necessary for GBT spectra, as the fitting is done across the entire velocity range of  $\sim 3000 \text{ km s}^{-1}$  which is much wider than the galaxy emission scale of  $\sim 300 \text{ km s}^{-1}$ .

To achieve a higher signal-to-noise ratio (S/N) without losing the resolution needed to resolve gas distributions, we apply a factor-of-1.3 smoothing in the spatial dimensions as well as a factor-of-4 smoothing in the

spectral axis using a Hanning window function. Lastly, the final data cube is converted from the  $T_A^*$  scale to the main-beam antenna temperature  $T_{\text{mb}} \simeq T_A^*/\eta_{\text{mb}}$ , where  $\eta_{\text{mb}} = 23\% \pm 3\%$  is the main-beam efficiency. We derive  $\eta_{\text{mb}}$  based on measurements of the calibrators 3C84, 3C279, and 3C454.3 during our observing sessions. First, the aperture efficiency of the GBT is estimated via  $\eta_{\text{a}} = 0.35 T_A^*/S_\nu$ , where  $T_A^*$  is measured from the amplitude of peak scans and  $S_\nu$  is the flux density of the calibrator source, which we obtain from the ALMA Calibration Catalog. We derive a mean  $\eta_{\text{a}}$  of  $12.5\% \pm 2.2\%$ , which corresponds to a surface rms error of  $280 \mu\text{m}$  based on the Ruze equation (J. Ruze 1966). Then, with  $\eta_{\text{a}}$  and assuming a Gaussian beam,  $\eta_{\text{mb}}$  can be derived as

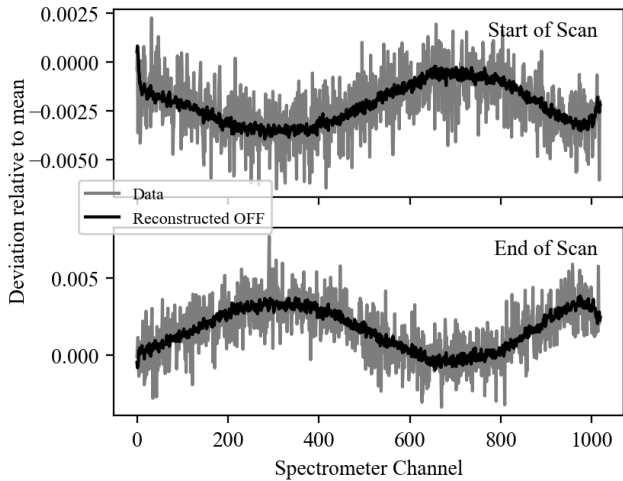
$$\eta_{\text{mb}} = 0.89 \eta_{\text{a}} \left( \theta_{\text{FWHM}} \frac{D}{\lambda} \right)^2, \quad (4)$$

where  $\theta_{\text{FWHM}}$  is the beam size in radians measured from the FWHM of peak scans, the GBT dish size  $D$  is 100 m, and the wavelength  $\lambda$  is 2.6 mm for the CO(1–0) line. More details on these equations and derivations can be found in D. T. Frayer et al. (2019).

Our final data cubes have a spectral resolution of  $15.2 \text{ km s}^{-1}$  and a spatial resolution of  $8.3''$ , which corresponds to  $\sim 2 \text{ kpc}$  for a typical distance of 60–70 Mpc across our sample. The  $8.3''$  beam size can be derived via  $1.18 \times 1.3 \times \lambda/D$ , where 1.18 comes from the GBT optics, and 1.3 is the post-gridding smoothing. We note that due to the uneven integration coverage inherent to the Argus beam layout, the outer regions of our mapping area naturally receive less integration time and therefore have higher noise. Thus, in Section 3, our map products are produced with S/N-based masking, and our results only focus on inner mapping areas around the galaxies.

Figure 4 shows a compilation of all the peak S/N maps derived from the final data cubes. In these maps, we smooth the channel widths to be 6 times wider ( $\sim 90 \text{ km s}^{-1}$ ) so that they better reflect molecular gas features with line widths on a similar scale. The cross section of each galaxy’s projected  $R_{25}$  radius (derived from  $d_{25}$ , inclination, and P.A. in Table 1) and the CALIFA field of view is overlaid as cyan contours, which define the areas for our analysis on galaxy-integrated quantities (e.g., star formation rates, molecular gas masses, and depletion times) in Section 3.

As a check on our data reduction procedure, we compare the galaxy-integrated CO line fluxes from the GBT to those from V. Villanueva et al. (2024), where nine of their galaxies overlapped with our sample and were observed in CO(2–1) with the ALMA ACA array at  $12''$  resolution. These nine galaxies



**Figure 3.** An example of our background measurements (gray) and empirical OFF model construction (black), represented by the start (top panel) and end (bottom panel) of selected observing scans. These OFF models are used to remove variations in the background signals (Equation 3). This figure exemplifies the changes occurring in the spectral baseline during a leg of the on-the-fly map, caused by a combination of atmospheric and instrument instabilities.

are NGC 0001, NGC 0169, NGC 1056, NGC 2540, NGC 2596, UGC 04245, UGC 05396, UGC 08322, and UGC 08781, all of which are MS galaxies except for UGC 08322 (see Table 1). For a consistent comparison, we also convolve the GBT data of these galaxies to  $12''$ . As shown in Figure 5, the CO (2–1)/(1–0) line ratios ( $R_{21}$ ) of these galaxies generally fall between 0.5–1.0, having a median and standard deviation of 0.70 and 0.27, respectively. This is consistent with the  $R_{21}$  values observed across nearby MS galaxies (J. S. den Brok et al. 2021; Y. Yajima et al. 2021; A. K. Leroy et al. 2022).

#### 2.4. Optical IFU Data from CALIFA

Our analyses also make use of various properties measured by the CALIFA survey (S. F. Sánchez et al. 2016a, 2023), which obtained optical IFU spectroscopy with the Potsdam Multi Aperture Spectrograph/PPak instrument mounted on the 3.5-m telescope at the Calar Alto Observatory. These optical IFU data have an effective spatial resolution of  $\sim 1.5''$ , a field of view of  $74'' \times 64''$ , and uncertainties of  $\sim 9\%$  in the absolute photometric calibration and  $\sim 4\%$  in the blue-to-red spectro-photometric precision (S. F. Sánchez et al. 2023).

We use the data products generated by Pipe3D (S. F. Sánchez et al. 2016b,c), which is a widely used pipeline for analyzing the spectroscopic properties of stellar populations and ionized gas measured from optical IFU surveys. For our galaxy sample, we adopt the latest Pipe3D

data products from the extended data release (eDR; S. F. Sánchez et al. 2023). However, an exception is NGC 2596, which is excluded in eDR due to technical issues in its image reconstruction. Therefore, we use an earlier data product release from DR3 (S. F. Sánchez et al. 2016a) only for this galaxy.

From these Pipe3D data products we obtain multiple emission line-related properties used in this work, including their fluxes, velocities, equivalent widths, and associated errors. We also obtain resolved dust-corrected stellar masses ( $M_{\text{star}}$ ) and star formation histories (SFH), which provide luminosity fractions across various bins of age and metallicity from the stellar population. We refer readers to Section 3.2 and S. F. Sánchez et al. (2016b) for more details on these quantities.

### 3. RESULTS

In this section, we present the procedure and results of our map products and scientific analyses. We publish all the reduced GBT data cubes and maps online<sup>28</sup>. We also release all of our calculations and analysis code in a public GitHub repository<sup>29</sup>.

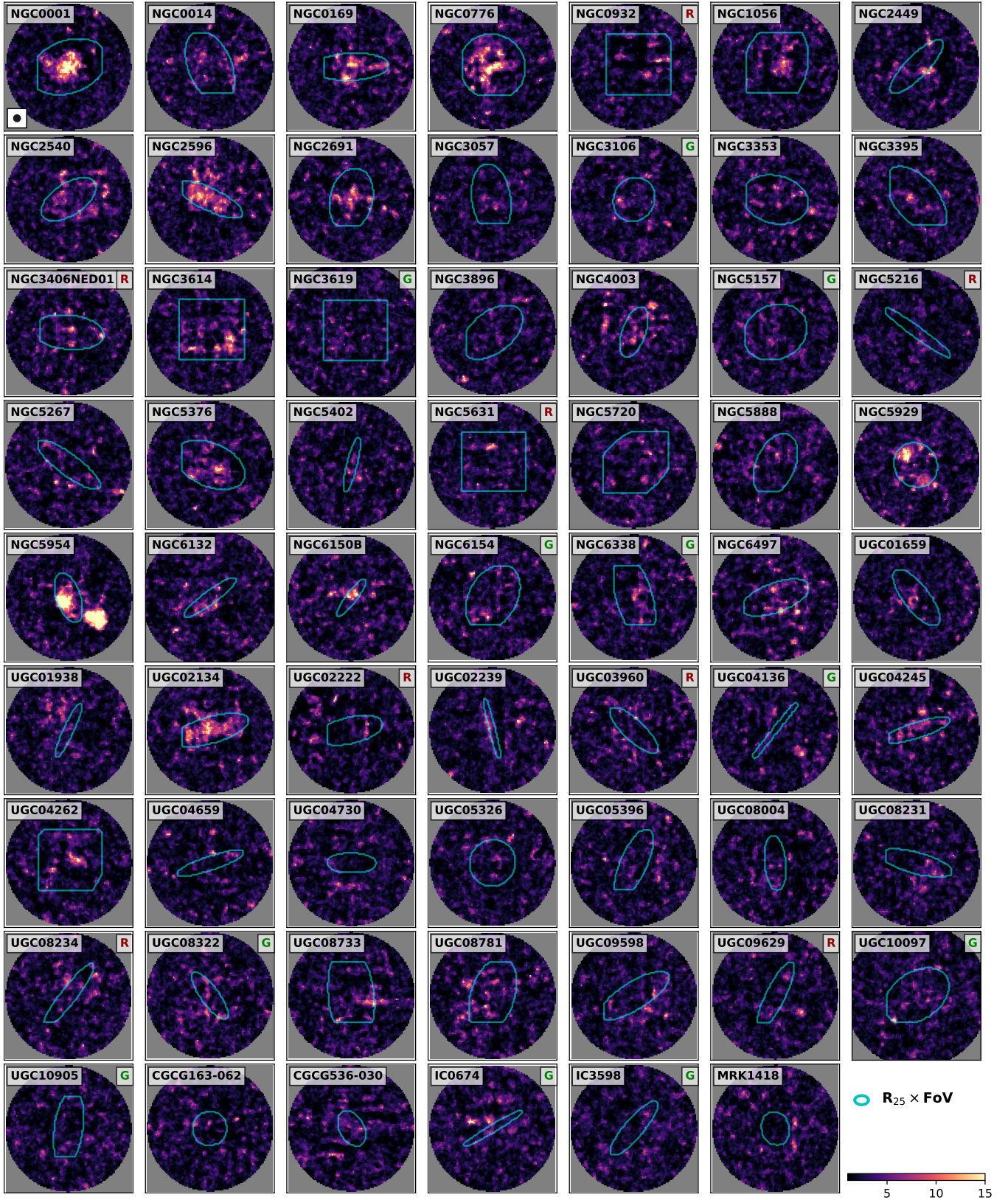
#### 3.1. CO Moment Maps and Error Estimation

From the GBT CO (1–0) data cubes, we derive moment maps for all 62 observed galaxies. These maps include the integrated intensity (moment-0), intensity-weighted velocity (moment-1), and the velocity dispersion (moment-2). For almost all of our sample (except for Mrk1418), we use two different methods to create signal masks. These signal masks are used to select the pixels and channels within the data cubes for moment map productions. We then include pixels and channels covered by either or both (i.e., the logical “inclusive OR”) of these signal masks for creating the final moment maps.

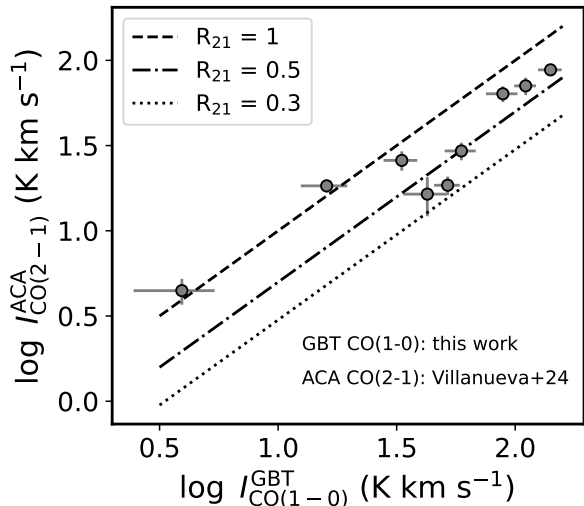
First, we create the ‘H $\alpha$  masks’. Assuming that CO and H $\alpha$  have similar kinematics (R. C. Levy et al. 2018; Y.-C. Su et al. 2022), we construct a signal mask based on the H $\alpha$  velocity field obtained from the extended CALIFA data release (S. F. Sánchez et al. 2023). Based on the CALIFA Pipe3D data, we select regions with well-detected central H $\alpha$  velocity ( $v_0$ ) and include a spectral range of  $v_0 \pm \text{FWHM}$ , where FWHM follows a radial-dependent relation found across a sub-sample of CALIFA galaxies based on CO (1–0) data from CARMA (V. Villanueva et al. 2021). Finally, we re-project the mask onto the GBT data grid, using nearest-neighbor matching implemented in the Astropy-affiliated `reproject`

<sup>28</sup> <https://doi.org/10.5281/zenodo.20707368>

<sup>29</sup> <https://github.com/ElthaTeng/gbt-edge-analysis> and Zenodo: <https://doi.org/10.5281/zenodo.20707910>



**Figure 4.** The peak signal to noise (S/N) maps of all 62 galaxies, integrating over a channel width of  $90 \text{ km s}^{-1}$  to highlight gas structures with line widths at that scale. GV and RGs are labeled by ‘G’ and ‘R’, respectively, on the top-right corner. The color scale (bottom-right panel) ranges from  $S/N = 1$ –15. Each panel shows the entire GBT field of view of  $2.5' \times 2.5'$ , and the common beam size of  $8.3''$  ( $\sim 2$  kpc for our sample) is shown on the top-left panel. The overlaid cyan contours indicate the intersection between each galaxy’s  $R_{25}$  radius and CALIFA’s field of view, which defines the area for computing galaxy-integrated quantities (Section 3).



**Figure 5.** Comparison of the GBT CO (1–0) integrated line fluxes with those from the ALMA ACA CO (2–1) data (V. Villanueva et al. 2024) for the nine galaxies that overlap between both samples. They show a CO (2–1)/(1–0) line ratio ( $R_{21}$ ) of  $0.70 \pm 0.27$ . Galaxies with the highest and lowest  $R_{21}$  tend to have higher uncertainties in the GBT data.

package. This masking approach is similar to the  $H\alpha$  mask adopted in V. Villanueva et al. (2024), and it has the advantage of providing a robust kinematic guidance.

Next, we create the ‘CO-dilated masks’. Based on the reduced CO data cubes, we initially include all position-position-velocity (ppv) spaces with emission above  $2.5\sigma$ <sup>30</sup>. Then, we expand the mask coverage by twice the beam size in the spatial directions and  $\pm 30 \text{ km s}^{-1}$  in the spectral direction (i.e., two adjacent channels). We also exclude spectral regions outside  $\pm 2 \times \text{vmaxg}$ <sup>31</sup>, which ensures covering only the spectral range within the observed maximum rotation velocity of atomic gas. For 12 of the galaxies in our sample without a measured  $\text{vmaxg}$ , we assume a conservative  $\text{vmaxg}$  value of  $150 \text{ km s}^{-1}$  that is slightly larger than the MW value where  $2 \times \text{vmaxg} \sim 250 \text{ km s}^{-1}$  (J. Bland-Hawthorn & O. Gerhard 2016; M. J. Reid & T. M. Dame 2016). This CO-dilated masking procedure is very similar to that adopted in A. D. Bolatto et al. (2017, see also E. Rosolowsky & A. Leroy 2006; T. Wong et al. 2024).

By adopting both the  $H\alpha$  and CO-dilated masks for moment map creation, our selections of pixels and channels avoid biases from only the  $H\alpha$  or CO data. For Mrk 1418, however, we use an alternative signal mask (i.e., the ‘block mask’) due to poor S/N in its  $H\alpha$  and

CO data. To obtain the block mask, we simply select all pixels within the  $R_{25}$  radius and include all channels within  $\pm 2 \times \text{vmaxg}$ . While the block mask is model-independent, it results in high noise because of its broad coverage.

We apply all the above-mentioned signal masks and create corresponding moment 0, 1, and 2 maps using the `spectral-cube` package. Figure 6 presents the moment maps for NGC 0001 and NGC 0014 as a demonstration of the overall data quality. While we have obtained high-quality data with reliably detected signals in some galaxies (e.g., NGC 0001), we also note that a few galaxies show somewhat dubious emission outside the galaxy’s  $R_{25}$  (e.g., NGC 0014)<sup>32</sup>. Inspection of the spectra in those regions shows that most of the emission outside  $R_{25}$  is spurious, likely due to remaining baseline variations across the data cubes that falsely boost S/Ns at certain ppv locations. We do not include those regions in the analysis, and we account for similarly spurious emission within  $R_{25}$  (i.e., our regions of interest) in our uncertainty estimates, as described in the following paragraphs. The galaxies with spurious emission tend to have higher flux uncertainties, which can make estimated total fluxes become upper limits (e.g., see NGC 0014 in Table 2).

The moment maps for all GBT-EDGE galaxies are presented in Appendix B as a figure set. Overall, the moment-0 maps reveal extended molecular gas structures across all galaxies, strengthening many gas features seen in Figure 4. In addition, these moment-0 maps show that CO emission concentrates not only toward galaxy centers, but a significant amount of gas is also found throughout the outer disks. The moment-1 maps reveal clear signatures of rotation across many of the spiral or disk galaxies. The moment-2 maps show CO velocity dispersion up to  $100\text{--}150 \text{ km s}^{-1}$  across the sample, which is expected for molecular gas observations at  $> \text{kpc}$  scales (e.g., A. D. Bolatto et al. 2017; L. Lin et al. 2020).

For all the maps, we also produce their respective uncertainty maps. First, we estimate the rms noise ( $\sigma_{\text{rms}}$ ) for each pixel by calculating the standard deviation of all the signal-free channels. Here we approximate signal-free channels as those with nothing above three times the rms value across the entire spectrum. Then, the integrated uncertainty  $\sigma_{\text{int}}$  per pixel is calculated via Gaussian error propagation:  $\sigma_{\text{int}} = \sigma_{\text{rms}} \cdot \Delta v \cdot \sqrt{N}$ , where  $\Delta v$  is the channel width ( $\sim 15 \text{ km s}^{-1}$ ) and  $N$  is the number of channels integrated with different masking

<sup>30</sup> The CO-dilated mask starting with  $2.5\sigma$  is found to result in most consistent fluxes between the GBT and ALMA ACA data, as shown in Section 2.3

<sup>31</sup> reported in HyperLeda: <http://leda.univ-lyon1.fr/>

<sup>32</sup> excluding the cases of NGC 0169, 5929, and 5954 since they are interacting galaxies

schemes. Summing  $\sigma_{\text{int}}$  over the  $R_{25}$  of each galaxy, the integrated flux uncertainty ( $\sigma_{\text{flux}}$ ) is typically  $\sim 20\%$  of the total flux, with a 16<sup>th</sup>–84<sup>th</sup> percentile range of 16–29% across our sample. This  $\sigma_{\text{flux}}$  is an estimate of the formal error, but it does not include the effect of baseline and mask production systematics.

In addition to  $\sigma_{\text{flux}}$ , we also evaluate the uncertainties induced by our masking procedure as well as baseline variations across our data cubes,  $\sigma_{\text{add}}$ . We assess  $\sigma_{\text{add}}$  by comparing measured fluxes after a ‘fake source’ is added to a series of random locations in our data cubes. For each galaxy, we start by selecting a random ppv position within the defined ‘block’ mask. At that position, we insert a simulated Gaussian emission structure with a peak intensity of 1 K, a size of the beam size, and a typical line FWHM of 60 km s<sup>-1</sup>. We adopt this set of characteristics for the fake source because it is representative of the spurious emission seen outside  $R_{25}$ . Next, we run our H $\alpha$  + CO-dilated masking routine and measure the total flux including both the original and artificial sources. Then, we subtract the originally measured flux (without the inserted source) from the measured total flux. The above procedure is repeated for 100 times per galaxy. Finally, we compare the average measured flux to the known flux of the inserted source to estimate  $\sigma_{\text{add}}$  in terms of percentage for each galaxy. We obtain a median  $\sigma_{\text{add}}$  of 51% across all 62 galaxies, while the 16<sup>th</sup>–84<sup>th</sup> percentile values span from 16–144% depending on the data quality of individual galaxy.

To obtain our final error estimation, we add the additional uncertainty  $\sigma_{\text{add}}$  quadratically to the previously derived  $\sigma_{\text{flux}}$ , namely,  $\sigma_{\text{final}} = \sqrt{\sigma_{\text{flux}}^2 + \sigma_{\text{add}}^2}$ . For 15 of the galaxies in our sample, their final uncertainties exceed 100% of the measured fluxes, and thus their inferred CO luminosities are presented as upper limits (see Table 2). We note that  $\sigma_{\text{add}}$  and  $\sigma_{\text{flux}}$  are not independent, as our  $\sigma_{\text{add}}$  estimates likely contain contributions from  $\sigma_{\text{flux}}$ . This means that our final uncertainty  $\sigma_{\text{final}}$  could be overestimated and be overly conservative.

### 3.2. Derivation of Fundamental Quantities

To study the molecular gas depletion time ( $t_{\text{dep}} \equiv M_{\text{mol}} / \text{SFR}$ ) or star formation efficiency (SFE =  $1/t_{\text{dep}}$ ) across our galaxy sample, we derive the star formation rates (SFR) and molecular gas masses ( $M_{\text{mol}}$ ) for all galaxies. In this subsection, we describe the methods and prescriptions adopted to estimate these quantities. We then compare the resulting  $t_{\text{dep}}$  and discuss their implications in Section 3.3.

#### 3.2.1. Star Formation Rates

Based on the Balmer decrement and assuming the extinction curve from J. A. Cardelli et al. (1989), the ex-

tingtion of H $\alpha$  can be estimated via

$$A_{\text{H}\alpha} = 5.86 \log \left( \frac{F_{\text{H}\alpha}}{2.86 F_{\text{H}\beta}} \right), \quad (5)$$

where  $F_{\text{H}\alpha}$  and  $F_{\text{H}\beta}$  are the corresponding Balmer line fluxes, and 2.86 represents their nominal flux ratio for case-B recombination. The extinction-corrected SFRs in units of  $M_{\odot} \text{ yr}^{-1}$  can then be computed by

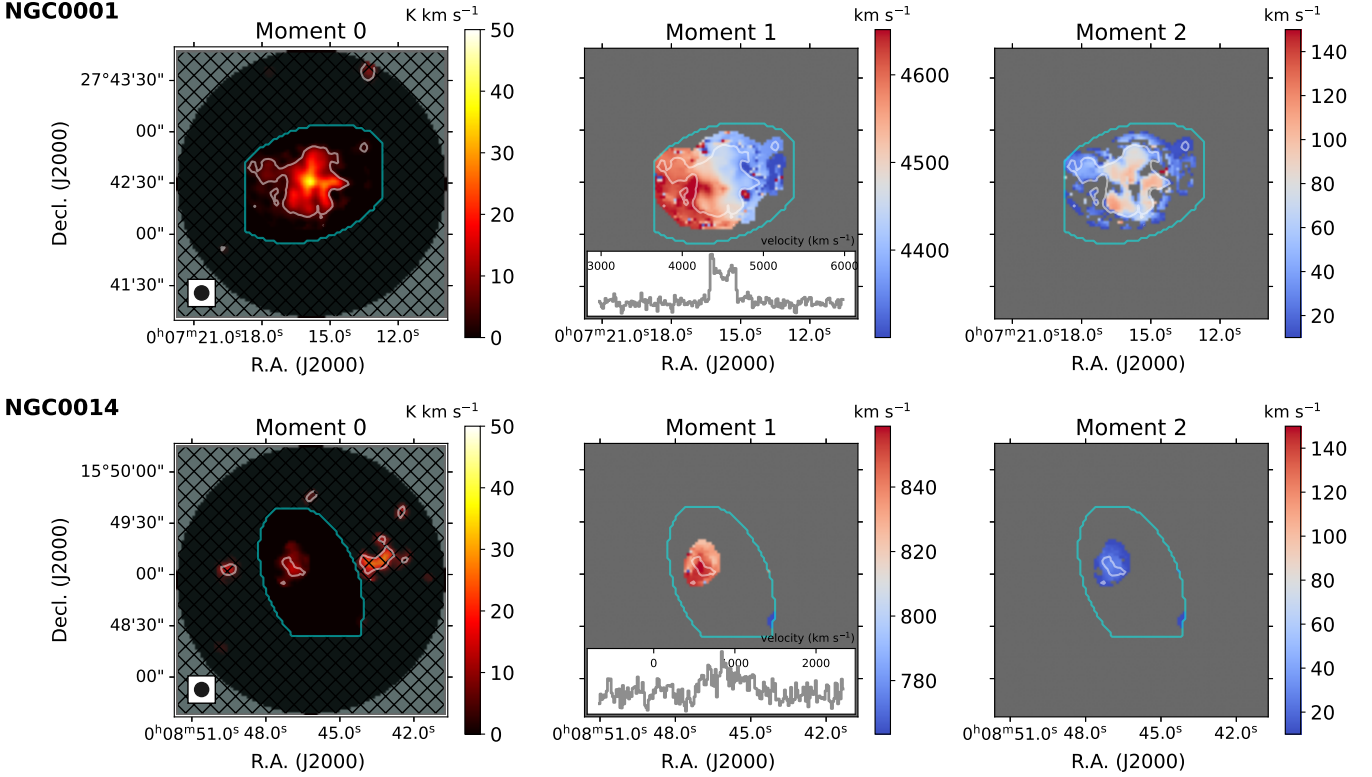
$$\text{SFR} = 7.9 \times 10^{-42} \cdot F_{\text{H}\alpha} \cdot 10^{A_{\text{H}\alpha}/2.5}, \quad (6)$$

where a E. E. Salpeter (1955) initial mass function (IMF) is assumed (D. Rosa-González et al. 2002, and following e.g., D. Colombo et al. 2020; S. F. Sánchez et al. 2023).

With Equations 5 and 6, we use the measured Balmer line properties from the CALIFA Pipe3D products and derive resolved H $\alpha$ -based SFR maps for our galaxies. We exclude non-star-forming pixels where the H $\alpha$  equivalent width is less than 6 Å (e.g., E. A. D. Lacerda et al. 2020; S. F. Sánchez et al. 2021). To avoid unrealistic SFR values from low S/N measurements, we also set  $A_{\text{H}\alpha} = 3$  mag for all pixels with derived  $A_{\text{H}\alpha} > 3$  mag (e.g., A. D. Bolatto et al. 2017). Finally, to obtain an integrated SFR value for each galaxy, we co-add the resolved SFRs over all pixels within the  $R_{25}$  radius. We also error propagate the uncertainties and obtain a  $< 0.1$  dex error for these global SFR values. Such level of error is also consistent with the CALIFA global table in T. Wong et al. (2024).

Since our galaxy sample includes a significant fraction of quenched galaxies with low levels of star formation, the H $\alpha$ -inferred SFRs in these systems could be overestimated due to possible ionization from old stars, AGNs, or shocks (e.g., review by R. C. Kennicutt & N. J. Evans 2012). Therefore, in addition to H $\alpha$ , we also use a simple stellar population (SSP) analysis to derive SFRs based on the young stellar population. In Appendix A, we show that SFRs estimated from both methods agree well for MS and GV galaxies. For RGs, however, we find that H $\alpha$ -based SFRs provide significantly better constraints (i.e., stricter upper limits in SFRs) than using the SSP analysis.

In summary, while we find that SSP does not provide improved constraints on SFRs across our RG sample, the consistency seen across the MS and GV sample suggests that H $\alpha$  as a SFR indicator can be extended to GV galaxies and may still be useful for RGs compared to using SSP. Thus, we adopt H $\alpha$ -based SFRs in all our following analyses and results. We caveat that the H $\alpha$ -based SFRs are likely still overestimated for quenched galaxies, and we will discuss in Section 4.1 how such uncertainties may impact our results and interpretations.



**Figure 6.** Examples of the moment 0 (left), 1 (middle), and 2 (right) maps, based on  $H\alpha$  + CO-dilated masking (see Section 3.1). The white contours show  $S/N > 5$  based on the moment-0 maps. The common beam size and cyan contours are the same as in Figure 4. Some galaxies show high-quality detection in moment 0 and clear velocity gradients indicative of galaxy rotation (e.g., top row, NGC 0001), while some galaxies show spurious emission outside their  $R_{25}$  radii due to baseline variations, leading to high flux uncertainties (e.g., bottom row, NGC 0014). Our analysis only includes regions within the  $R_{25}$  radii, as enclosed by the cyan contours. The integrated spectra of  $S/N > 5$  regions within the cyan contours are inserted into the middle panel.

### 3.2.2. Molecular Gas Masses

The common approach to measure molecular gas in galaxies is to convert observed CO (1–0) line fluxes to the total  $H_2$  mass via assuming a CO-to- $H_2$  conversion factor ( $\alpha_{CO}$ ). The value of  $\alpha_{CO}$  in the Milky Way (MW) disk has been found to be  $\approx 4.35 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$  (see review by A. D. Bolatto et al. 2013), and thus many past studies simply adopt this constant value to obtain the amount of molecular gas in galaxies. However,  $\alpha_{CO}$  does vary within and between galaxies (K. M. Sandstrom et al. 2013; Y.-H. Teng et al. 2022, 2023; J. S. den Brok et al. 2023; J. den Brok et al. 2025; A. Yasuda et al. 2023; I.-D. Chiang et al. 2024), and its value depends heavily on local gas conditions such as metallicity, temperature, density, and dynamical properties (D. Narayanan et al. 2012; P. P. Papadopoulos et al. 2012; A. D. Bolatto et al. 2013; F. Renaud et al. 2019; M. Gong et al. 2020; Y.-H. Teng et al. 2023).

To account for the variations in  $\alpha_{CO}$ , recent studies have proposed various  $\alpha_{CO}$  prescriptions which include the environmental dependence of  $\alpha_{CO}$  and can predict  $\alpha_{CO}$  based on observable quantities such as metallicity,

stellar mass surface density, and CO-line related properties (A. D. Bolatto et al. 2013; G. Accurso et al. 2017; M. Gong et al. 2020; E. Schinnerer & A. K. Leroy 2024; Y.-H. Teng et al. 2024). These prescriptions can be applied to large galaxy samples, which have revealed systematic effects on SFE or other star formation-related quantities across galaxies that were previously unknown due to adopting a constant  $\alpha_{CO}$  (S. L. Ellison et al. 2020a; M. Querejeta et al. 2023; J. Sun et al. 2023; Y.-H. Teng et al. 2024).

In this work, we derive molecular gas masses ( $M_{\text{mol}}$ ) using four different  $\alpha_{CO}$  treatments, aiming to reduce possible biases caused by  $\alpha_{CO}$  variations in our molecular gas measurements. In other words, we will obtain four estimates of  $M_{\text{mol}}$  using four versions of  $\alpha_{CO}$  based on the following equation:

$$M_{\text{mol}} = \alpha_{CO} \cdot L'_{CO(1-0)} = \alpha_{CO} \cdot I_{CO(1-0)} \cdot A_{\text{pc}^2}, \quad (7)$$

where  $L'_{CO(1-0)}$  is the line luminosity of CO  $J=1-0$  (in units of  $\text{K km s}^{-1} \text{pc}^2$ ) and can be determined by integrating our moment-0 maps ( $I_{CO(1-0)}$ ) over a surface area in  $\text{pc}^2$  ( $A_{\text{pc}^2}$ , which depends on the target's dis-

tance, see Table 1 and Equation 3 in A. D. Bolatto et al. 2013). The derived  $L'_{\text{CO}(1-0)}$  and  $\alpha_{\text{CO}}$  values are listed in Table 2, which together provide our  $M_{\text{mol}}$  estimates via Equation 7. The associated uncertainty for

each galaxy is error propagated from the final flux uncertainty ( $\sigma_{\text{final}}$ ) as described in Section 3.1. The statistics of  $\alpha_{\text{CO}}$  and  $M_{\text{mol}}$  among MS, GV, and RG groups are presented in Table 3. We present the details for our  $\alpha_{\text{CO}}$  implementations in Section 3.2.3.

**Table 2.** Derived Global Properties of the GBT-EDGE Galaxies

Name	$a$	$b$	$\log L'_{\text{CO}(1-0)}$ [K km s <sup>-1</sup> pc <sup>2</sup> ]	$\alpha_{\text{CO}} \left[ \frac{M_{\odot}}{\text{K km s}^{-1} \text{ pc}^2} \right]$			$t_{\text{dep}}$ [Gyr]			
				B13	SL24	T24*	MW	B13	SL24	T24*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NGC0001	-0.00397	0.101	9.26 ± 0.17	3.77	3.64	1.95	2.10 ± 0.28	1.82 ± 0.25	1.76 ± 0.25	0.94 ± 0.15
NGC0014	0.0017	-0.146	< 6.88	4.85	6.37	5.94	0.95 ± 0.25	1.05 ± 0.28	1.39 ± 0.37	1.29 ± 0.36
NGC0169	-0.00286	0.0711	9.59 ± 0.14	3.65	5.10	1.61	8.82 ± 1.04	7.39 ± 0.96	10.30 ± 1.29	3.25 ± 0.43
NGC0776	-0.00254	0.0831	9.24 ± 0.09	3.85	3.77	2.26	2.56 ± 0.46	2.27 ± 0.40	2.22 ± 0.39	1.33 ± 0.27
NGC0932	-0.000521	-0.0331	8.84 ± 0.28	4.00	4.56	1.88	7.05 ± 1.31	6.48 ± 1.19	7.38 ± 1.35	3.04 ± 0.64
NGC1056	-0.00219	-0.00685	< 8.18	4.01	4.79	2.06	0.61 ± 0.10	0.56 ± 0.10	0.67 ± 0.12	0.29 ± 0.05
NGC2449	-0.0036	0.0732	9.01 ± 0.09	4.17	4.17	1.94	6.56 ± 1.09	6.28 ± 1.03	6.30 ± 1.04	2.92 ± 0.57
NGC2540	-0.00429	0.0726	9.20 ± 0.13	4.31	4.58	1.89	2.45 ± 0.47	2.43 ± 0.46	2.58 ± 0.49	1.07 ± 0.25
NGC2596	-0.00778	0.185	< 9.19	3.04	3.52	4.02	1.17 ± 0.19	0.82 ± 0.13	0.95 ± 0.16	1.08 ± 0.16
NGC2691	-0.00297	0.0504	8.93 ± 0.21	4.06	4.18	1.40	2.46 ± 0.39	2.29 ± 0.37	2.36 ± 0.38	0.79 ± 0.14
NGC3057	0.000182	-0.165	< 7.66	5.17	7.58	3.43	1.35 ± 0.32	1.60 ± 0.39	2.34 ± 0.56	1.06 ± 0.31
NGC3106	-0.000901	-0.017	8.84 ± 0.26	4.29	4.83	2.54	4.41 ± 1.20	4.36 ± 1.19	4.89 ± 1.33	2.57 ± 0.73
NGC3353	0.00469	-0.307	< 7.03	5.36	9.23	4.97	0.10 ± 0.03	0.12 ± 0.03	0.21 ± 0.06	0.11 ± 0.03
NGC3395	-0.000502	-0.0821	< 7.98	4.58	5.84	2.38	0.63 ± 0.12	0.66 ± 0.13	0.84 ± 0.16	0.34 ± 0.08
NGC3406NED01	-0.00144	0.00597	< 9.10	3.95	4.29	3.17	84.30 ± 16.80	76.40 ± 15.30	82.90 ± 16.70	61.20 ± 14.20
NGC3614	-0.00161	-0.000114	< 8.74	3.76	4.36	1.48	4.32 ± 0.67	3.74 ± 0.55	4.32 ± 0.63	1.47 ± 0.31
NGC3619	0.0000423	-0.0353	< 7.38	2.95	3.26	3.91	1.91 ± 0.50	1.30 ± 0.32	1.43 ± 0.35	1.72 ± 0.48
NGC3896	-0.000233	-0.0891	< 6.68	4.70	6.03	5.82	1.13 ± 0.31	1.22 ± 0.33	1.57 ± 0.43	1.52 ± 0.44
NGC4003	-0.00155	-0.00594	9.09 ± 0.19	4.15	4.68	1.59	6.06 ± 1.13	5.79 ± 1.09	6.52 ± 1.23	2.22 ± 0.45
NGC5157	-0.00149	0.0212	8.82 ± 0.16	4.08	4.44	2.76	5.00 ± 1.79	4.68 ± 1.69	5.10 ± 1.83	3.17 ± 1.02
NGC5216	0.000111	-0.0629	7.76 ± 0.09	4.55	5.34	5.13	171.0 ± 34.4	180.0 ± 35.9	210.0 ± 42.1	202.0 ± 52.4
NGC5267	-0.00158	0.0522	8.81 ± 0.15	4.07	4.00	4.35	3.52 ± 1.02	3.29 ± 0.97	3.23 ± 0.95	3.52 ± 1.00
NGC5376	-0.00287	0.103	8.56 ± 0.23	3.71	3.52	2.03	2.40 ± 0.39	2.05 ± 0.34	1.94 ± 0.32	1.12 ± 0.21
NGC5402	-0.00212	-0.00142	8.02 ± 0.19	4.08	4.58	3.56	0.41 ± 0.10	0.38 ± 0.10	0.43 ± 0.11	0.33 ± 0.08
NGC5631	-0.00529	0.128	< 7.90	4.07	4.41	2.33	1150 ± 218	1080 ± 193	1160 ± 213	615 ± 154
NGC5720	-0.00195	0.00651	9.22 ± 0.11	4.29	4.90	2.28	2.86 ± 0.79	2.83 ± 0.78	3.23 ± 0.89	1.50 ± 0.40
NGC5888	-0.00332	0.0981	8.98 ± 0.12	4.04	3.78	3.87	1.92 ± 0.59	1.78 ± 0.55	1.67 ± 0.52	1.71 ± 0.56
NGC5929	0.000127	-0.058	8.83 ± 0.29	4.22	5.01	0.92	1.22 ± 0.13	1.18 ± 0.13	1.40 ± 0.15	0.26 ± 0.03
NGC5954	-0.0026	0.0669	8.44 ± 0.27	3.83	3.79	2.70	0.85 ± 0.08	0.74 ± 0.08	0.73 ± 0.08	0.52 ± 0.06
NGC6132	-0.0071	0.0551	8.91 ± 0.22	3.66	4.32	3.35	0.93 ± 0.22	0.78 ± 0.17	0.93 ± 0.20	0.72 ± 0.16
NGC6150B	-0.00555	0.0667	9.40 ± 0.26	3.67	3.78	2.02	2.88 ± 0.35	2.42 ± 0.31	2.49 ± 0.33	1.33 ± 0.17
NGC6154	-0.00313	0.0795	8.81 ± 0.12	3.95	4.07	3.71	2.50 ± 0.72	2.28 ± 0.67	2.35 ± 0.69	2.14 ± 0.57
NGC6338	-0.001	-0.0277	9.16 ± 0.09	3.97	4.76	3.29	18.10 ± 3.85	16.50 ± 3.46	19.70 ± 4.18	13.70 ± 2.90
NGC6497	-0.00368	0.0991	9.14 ± 0.18	3.99	3.92	2.05	4.79 ± 0.99	4.40 ± 0.92	4.33 ± 0.90	2.27 ± 0.50
UGC01659	-0.00234	0.00211	9.09 ± 0.13	4.37	4.84	2.45	1.74 ± 0.36	1.75 ± 0.37	1.94 ± 0.41	0.98 ± 0.25
UGC01938	-0.0021	-0.032	8.90 ± 0.20	4.33	5.26	3.59	1.21 ± 0.35	1.21 ± 0.35	1.46 ± 0.43	1.00 ± 0.28
UGC02134	-0.00259	0.0409	9.31 ± 0.05	3.95	4.25	1.91	4.06 ± 0.51	3.69 ± 0.46	3.96 ± 0.49	1.78 ± 0.23
UGC02222	-0.0000146	-0.0554	8.44 ± 0.21	4.57	5.25	2.63	330.0 ± 60.4	346.0 ± 62.4	399.0 ± 72.3	199.0 ± 43.8

Continued on next page

Name	$a$	$b$	$\log L'_{\text{CO}(1-0)}$ $\alpha_{\text{CO}}$ [ $\frac{M_{\odot}}{\text{K km s}^{-1} \text{pc}^2}$ ]				$t_{\text{dep}}$ [Gyr]			
			[K km s <sup>-1</sup> pc <sup>2</sup> ]	B13	SL24	T24*	MW	B13	SL24	T24*
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
UGC02239	-0.00112	-0.0195	8.80 ± 0.07	4.07	4.76	4.97	3.14 ± 0.41	2.94 ± 0.40	3.43 ± 0.46	3.59 ± 0.57
UGC03960	-0.000335	-0.0486	< 7.20	4.20	4.89	9.25	34.60 ± 10.20	33.50 ± 9.34	39.00 ± 10.90	73.90 ± 21.40
UGC04136	-0.000849	-0.0188	8.48 ± 0.30	4.04	4.64	10.70	12.90 ± 2.68	12.00 ± 2.49	13.70 ± 2.84	31.50 ± 6.19
UGC04245	-0.00392	0.0508	8.93 ± 0.17	4.10	4.38	2.55	2.08 ± 0.38	1.96 ± 0.34	2.10 ± 0.37	1.22 ± 0.22
UGC04262	-0.002	0.0145	9.39 ± 0.24	4.22	4.63	1.59	7.61 ± 1.56	7.38 ± 1.49	8.12 ± 1.66	2.77 ± 0.63
UGC04659	-0.00119	-0.104	7.05 ± 0.19	4.63	6.49	5.33	2.59 ± 0.52	2.77 ± 0.52	3.89 ± 0.73	3.19 ± 0.93
UGC04730	-0.000281	-0.0814	7.55 ± 0.26	4.05	5.38	5.53	0.04 ± 0.02	0.03 ± 0.01	0.05 ± 0.02	0.05 ± 0.02
UGC05326	0.00105	-0.212	< 6.68	5.43	8.54	4.45	0.35 ± 0.09	0.44 ± 0.12	0.69 ± 0.18	0.36 ± 0.10
UGC05396	-0.00102	-0.035	8.18 ± 0.17	4.56	5.26	3.58	0.96 ± 0.39	1.01 ± 0.41	1.16 ± 0.47	0.79 ± 0.26
UGC08004	-0.00271	-0.0222	8.59 ± 0.16	4.70	5.86	2.70	2.21 ± 0.69	2.40 ± 0.74	2.98 ± 0.92	1.38 ± 0.39
UGC08231	0.00226	-0.262	7.90 ± 0.23	5.48	8.86	3.50	1.32 ± 0.24	1.67 ± 0.30	2.70 ± 0.48	1.07 ± 0.24
UGC08234	-0.00092	-0.0075	8.73 ± 0.11	3.97	4.32	6.99	324.0 ± 83.1	295.0 ± 74.3	321.0 ± 81.3	520.0 ± 135.0
UGC08322	-0.00178	0.0165	8.89 ± 0.17	4.11	4.61	3.31	9.90 ± 2.62	9.36 ± 2.47	10.50 ± 2.74	7.52 ± 1.75
UGC08733	-0.00101	-0.0859	< 8.05	4.61	6.12	2.30	3.08 ± 0.51	3.27 ± 0.54	4.33 ± 0.71	1.63 ± 0.32
UGC08781	-0.000444	-0.0299	9.32 ± 0.10	4.27	4.79	2.24	6.48 ± 1.56	6.36 ± 1.51	7.14 ± 1.69	3.34 ± 0.82
UGC09598	-0.00398	0.0602	8.80 ± 0.16	4.24	4.59	3.00	3.01 ± 0.87	2.93 ± 0.86	3.17 ± 0.92	2.08 ± 0.53
UGC09629	-0.000801	-0.0171	8.47 ± 0.13	4.19	4.70	6.08	11.50 ± 2.54	11.00 ± 2.43	12.40 ± 2.75	16.00 ± 4.02
UGC10097	0.00022	-0.0642	< 8.63	2.97	3.75	3.49	6.90 ± 1.77	4.71 ± 1.25	5.94 ± 1.59	5.52 ± 1.54
UGC10905	-0.000319	-0.0306	8.58 ± 0.12	3.95	4.56	3.53	32.60 ± 8.58	29.60 ± 7.53	34.30 ± 8.83	26.50 ± 7.12
CGCG163-062	-0.000584	-0.0603	7.90 ± 0.20	4.63	5.49	3.55	1.33 ± 0.44	1.41 ± 0.47	1.67 ± 0.56	1.08 ± 0.32
CGCG536-030	-0.0014	-0.0512	9.75 ± 0.26	4.65	5.63	0.71	11.20 ± 1.10	11.90 ± 1.18	14.50 ± 1.43	1.83 ± 0.21
IC0674	-0.00283	0.0177	9.17 ± 0.16	4.22	4.73	5.12	34.00 ± 7.54	33.00 ± 7.34	37.00 ± 8.27	40.10 ± 9.28
IC3598	-0.000973	-0.0178	8.14 ± 0.16	3.65	3.99	5.45	3.71 ± 1.53	3.11 ± 1.34	3.41 ± 1.47	4.65 ± 1.54
Mrk1418	0.00509	-0.276	6.18 ± 0.19	5.37	8.43	2.21	0.19 ± 0.11	0.23 ± 0.13	0.37 ± 0.20	0.10 ± 0.04

**Note.** (1) Galaxy name; (2, 3) best-fit coefficients for metallicity gradient (Equation 11); (4) integrated CO luminosities with errors propagated from  $\sigma_{\text{final}}$  as described in Section 3.1; all the upper limits have  $> 0.3$  dex uncertainty; (5–7) integrated  $\alpha_{\text{CO}}$  values using B13, SL24, and T24\* prescriptions (Equations 8–10), with expected  $\alpha_{\text{CO}}$  uncertainties of 0.2–0.3 dex; (8–11) global gas depletion time based on  $\alpha_{\text{CO}}$  assumptions of MW ( $\alpha_{\text{CO}} = 4.35 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ ), B13, SL24, and T24\*, respectively. The errors in  $t_{\text{dep}}$  are propagated from the flux error ( $\sigma_{\text{flux}}$ ) in Section 3.1.

### 3.2.3. Variable CO-to-H<sub>2</sub> Conversion Factors

In addition to a constant MW  $\alpha_{\text{CO}}$  assumption as used in most previous studies, we also adopt three other  $\alpha_{\text{CO}}$  prescriptions in recent literature. The first two prescriptions are both functions of the normalized metallicity to the solar value ( $Z'$ ) as well as the stellar mass surface density ( $\Sigma_{\text{star}}$ ). One of these prescriptions originates from A. D. Bolatto et al. (2013, hereafter B13):

$$\alpha_{\text{CO}} = 2.9 \exp\left(\frac{0.4}{Z'}\right) \left(\frac{\Sigma_{\text{star}}}{100 M_{\odot} \text{pc}^{-2}}\right)^{-\gamma}, \quad (8)$$

where  $\gamma = 0.5$  if  $\Sigma_{\text{star}} > 100 M_{\odot} \text{pc}^{-2}$  and  $\gamma = 0$  otherwise. Here we simplify the  $\Sigma_{\text{total}} \equiv \Sigma_{\text{star}} + \Sigma_{\text{gas}}$  term in B13 into  $\Sigma_{\text{star}}$  alone, as  $\Sigma_{\text{star}}$  is generally found to be an order of magnitude higher than  $\Sigma_{\text{gas}}$  in the EDGE-CALIFA sample (D. Colombo et al. 2025b). The

other similar prescription is suggested by E. Schinnerer & A. K. Leroy (2024, hereafter SL24):

$$\alpha_{\text{CO}} = 4.35 (Z')^{-1.5} \left(\frac{\Sigma_{\text{star}}}{100 M_{\odot} \text{pc}^{-2}}\right)^{-\gamma}, \quad (9)$$

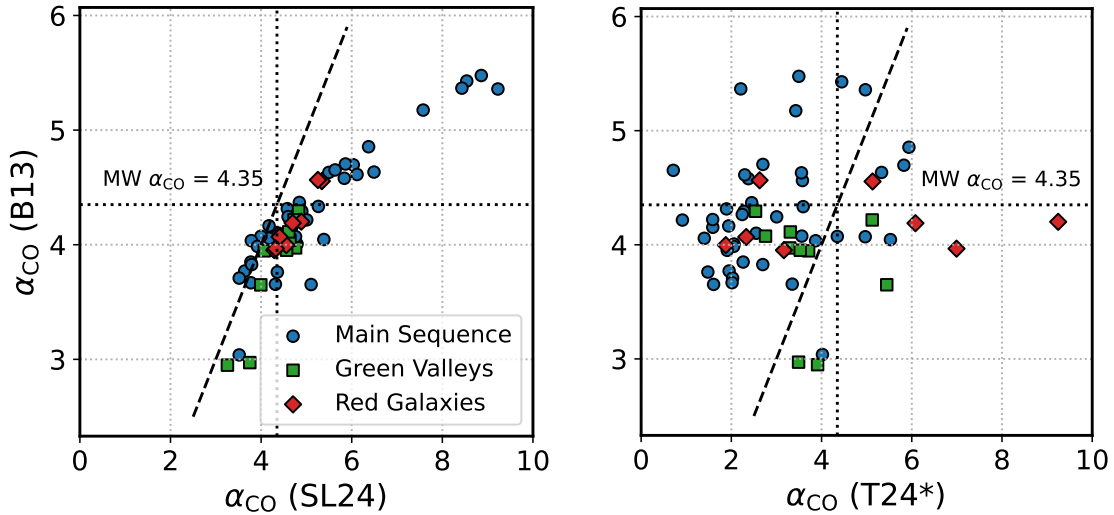
where  $\gamma = 0.25$  if  $\Sigma_{\text{star}} > 100 M_{\odot} \text{pc}^{-2}$  and  $\gamma = 0$  otherwise (I.-D. Chiang et al. 2024). Both the B13 and SL24 prescriptions suggest at least a  $\pm 0.3$  dex uncertainty, based on the  $\alpha_{\text{CO}}$  measurements adopted in their calibrations.

To distinguish from Equations 8 and 9 which rely on indirect (or non-CO) tracers, we also implement a new  $\alpha_{\text{CO}}$  prescription based on inclination-corrected CO velocity dispersion (Y.-H. Teng et al. 2024, and in preparation, hereafter T24\*):

$$\log \alpha_{\text{CO}} = -0.96 \log(\Delta v)_{2\text{kpc}} + 1.77, \quad (10)$$

**Table 3.** Statistics for  $\alpha_{\text{CO}}$ ,  $\log(M_{\text{mol}})$ , and  $t_{\text{dep}}$ 

Statistics	Mean $\pm$ Std			16 <sup>th</sup> /50 <sup>th</sup> /84 <sup>th</sup> Percentile Values		
	MS	GV	RG	MS	GV	RG
$\alpha_{\text{CO}}(\text{B13}) \left[ \frac{M_{\odot}}{\text{K km s}^{-1} \text{ pc}^2} \right]$	$4.29 \pm 0.52$	$3.83 \pm 0.44$	$4.19 \pm 0.23$	3.81/4.22/4.70	3.38/3.97/4.15	3.97/4.13/4.51
$\alpha_{\text{CO}}(\text{SL24}) \left[ \frac{M_{\odot}}{\text{K km s}^{-1} \text{ pc}^2} \right]$	$5.19 \pm 1.44$	$4.33 \pm 0.48$	$4.72 \pm 0.38$	3.88/4.79/6.19	3.89/4.56/4.74	4.33/4.63/5.21
$\alpha_{\text{CO}}(\text{T24}^*) \left[ \frac{M_{\odot}}{\text{K km s}^{-1} \text{ pc}^2} \right]$	$2.93 \pm 1.33$	$4.35 \pm 2.18$	$4.68 \pm 2.46$	1.81/2.45/4.38	3.08/3.53/5.25	2.37/4.15/6.88
$\log(M_{\text{mol},\text{MW}} [M_{\odot}])$	$9.13 \pm 0.88$	$9.27 \pm 0.49$	$8.94 \pm 0.60$	8.27/9.45/9.88	8.98/9.45/9.64	8.41/9.09/9.47
$\log(M_{\text{mol},\text{B13}} [M_{\odot}])$	$9.13 \pm 0.84$	$9.21 \pm 0.53$	$8.93 \pm 0.58$	8.31/9.43/9.84	8.93/9.40/9.61	8.43/9.10/9.43
$\log(M_{\text{mol},\text{SL24}} [M_{\odot}])$	$9.20 \pm 0.80$	$9.26 \pm 0.53$	$8.98 \pm 0.58$	8.47/9.47/9.88	8.98/9.42/9.67	8.49/9.15/9.49
$\log(M_{\text{mol},\text{T24}^*} [M_{\odot}])$	$8.92 \pm 0.77$	$9.23 \pm 0.48$	$8.91 \pm 0.53$	8.26/9.28/9.59	9.02/9.26/9.58	8.29/8.99/9.53
$t_{\text{dep}}(\text{MW}) [\text{Gyr}]$	$2.69 \pm 2.43$	$11.99 \pm 11.05$	$264.1 \pm 356.4$	0.79/2.10/4.45	3.23/6.90/23.90	14.27/127.65/329.28
$t_{\text{dep}}(\text{B13}) [\text{Gyr}]$	$2.59 \pm 2.36$	$10.99 \pm 10.53$	$253.5 \pm 335.1$	0.72/1.96/3.92	2.78/4.71/21.74	13.70/128.20/339.88
$t_{\text{dep}}(\text{SL24}) [\text{Gyr}]$	$2.99 \pm 2.82$	$12.57 \pm 12.05$	$279.0 \pm 360.2$	0.81/2.22/4.33	2.99/5.94/25.54	15.59/146.45/389.64
$t_{\text{dep}}(\text{T24}^*) [\text{Gyr}]$	$1.42 \pm 0.97$	$12.64 \pm 13.02$	$211.3 \pm 218.4$	0.35/1.22/2.41	2.40/5.52/28.50	21.42/136.45/481.84



**Figure 7.** Comparison of  $\alpha_{\text{CO}}$  values estimated via different prescriptions (B13, SL24, and T24\*, which represent Equations 8–10). The dashed lines indicate a one-to-one relation, and the thick dotted lines label the Galactic  $\alpha_{\text{CO}}$  value of  $4.35 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ . While the predicted  $\alpha_{\text{CO}}$  values do not agree well and show no systematic trend among different populations, the overall  $\alpha_{\text{CO}}$  variations are limited to a factor of two within and among prescriptions. The fractional  $\alpha_{\text{CO}}$  uncertainty in these prescriptions is within  $\pm 0.2$  dex for T24\* and  $\pm 0.3$  dex for B13 and SL24.

where  $(\Delta v)_{2\text{kpc}}$  is measured at 2-kpc scales, in units of  $\text{km s}^{-1}$ , and corrected for galaxy inclination by applying a  $\sqrt{\cos i}$  factor (see Appendix in J. Sun et al. 2022). This prescription (Equation 10) is a modified version with slightly different coefficients from Equation 2 in Y.-H. Teng et al. (2024), where they use  $(\Delta v)_{150\text{pc}}$  instead of  $(\Delta v)_{2\text{kpc}}$ . In a follow-up work (Y.-H. Teng et al. 2026, in preparation), it is found that the anti-correlation between  $\alpha_{\text{CO}}$  and  $\Delta v$  can be extended up to 2-kpc scales with a  $< 0.2$  dex scatter, because the value of  $(\Delta v)_{2\text{kpc}}$  is still dominated by  $(\Delta v)_{150\text{pc}}$ , thereby leading to strong correlations among cross-scale  $\Delta v$  across

the same galaxy sample as in Y.-H. Teng et al. (2024). Therefore, here we apply the modified  $(\Delta v)_{2\text{kpc}}$ -based prescription to match our GBT resolutions of  $\sim 2$  kpc.

To obtain  $Z'$  required by Equations 8 and 9, we assume  $12 + \log(\text{O}/\text{H})_{\odot} = 8.69$  (M. Asplund et al. 2009) and employ the O3N2 metallicity calibration from M. Curti et al. (2017). We note that the choice of metallicity calibration can vary the derived metallicity values by a factor of 2–3 (P. De Vis et al. 2019; Y.-H. Teng et al. 2024), and both the B13 and SL24  $\alpha_{\text{CO}}$  prescriptions are sensitive to the choice of calibration. In B13, the metallicity-dependent term in exponential form

is motivated by theoretical derivations (M. G. Wolfire et al. 2010), while the power-law metallicity dependence in SL24 is based on observational measurements using various metallicity calibrators, including M. Pettini & B. E. J. Pagel (2004) and the L. S. Pilyugin & E. K. Grebel (2016) S-calibration. However, we find that using those calibrations result in sub-solar metallicity values for the majority of our sample, which would predict unrealistically high  $\alpha_{\text{CO}}$  values based on B13 and SL24. On the other hand, the M. Curti et al. (2017) calibration is widely tested and accounts for corrections from previous calibration methods (see review by R. Maiolino & F. Mannucci 2019), and it results in near-solar metallicity for most galaxies in our sample.

Therefore, based on M. Curti et al. (2017), we derive  $Z'$  on a pixel-by-pixel basis, using [OIII], [NII],  $\text{H}\alpha$ , and  $\text{H}\beta$  line maps in the Pipe3D data products. We compute  $\log(\text{O}/\text{H})$  values only for pixels that fulfill the criteria of being compatible with star formation ionization (i.e.,  $\text{H}\alpha$  equivalent width  $> 6\text{\AA}$  and  $\text{S}/\text{N} > 1$  for all emission lines involved in the classical O3-N2-BPT diagram, below the L. J. Kewley et al. 2001 curve). As the resulting  $Z'$  measurements can be sparse in many regions of galaxies, we fit a  $Z'$  radial gradient for each galaxy to infer a  $Z'$  value for every pixel:

$$\log Z' = a \cdot \log R_{\text{gal}} + b, \quad (11)$$

where  $Z'$  is in units of  $Z_{\odot}$  and  $R_{\text{gal}}$  is the de-projected galactocentric radius in arcseconds. The best-fit  $a$  and  $b$  values for each galaxy are listed in Table 2. The resolved  $Z'$  map together with the  $\Sigma_{\text{star}}$  map from CALIFA then allows us to obtain a resolved  $\alpha_{\text{CO}}$  map for each galaxy. As for implementing Equation 10, we simply use the derived CO velocity dispersion maps and multiply them with a  $\sqrt{\cos i}$  factor to correct for galaxy inclination (J. Sun et al. 2022; Y.-H. Teng et al. 2024).

To obtain a spatially-weighted global  $\alpha_{\text{CO}}$  value for each galaxy, our procedure is as follows. First, we compute  $\alpha_{\text{CO}}$  values pixel by pixel based on the GBT maps using Equations 8–10, respectively. Next, we multiply these derived  $\alpha_{\text{CO}}$  maps by the moment-0 maps (see Figure 6 and Appendix B) to obtain resolved  $M_{\text{mol}}$  maps. Then, we compute the integrated  $M_{\text{mol}}$  and CO intensity by summing both the moment-0 maps and the derived  $M_{\text{mol}}$  maps over regions within the  $R_{25}$  radius. Lastly, we obtain a global  $\alpha_{\text{CO}}$  value for each galaxy by dividing the total  $M_{\text{mol}}$  by the integrated CO intensity. The derived  $\alpha_{\text{CO}}$  values and their statistics under different prescriptions are listed in Tables 2 and 3.

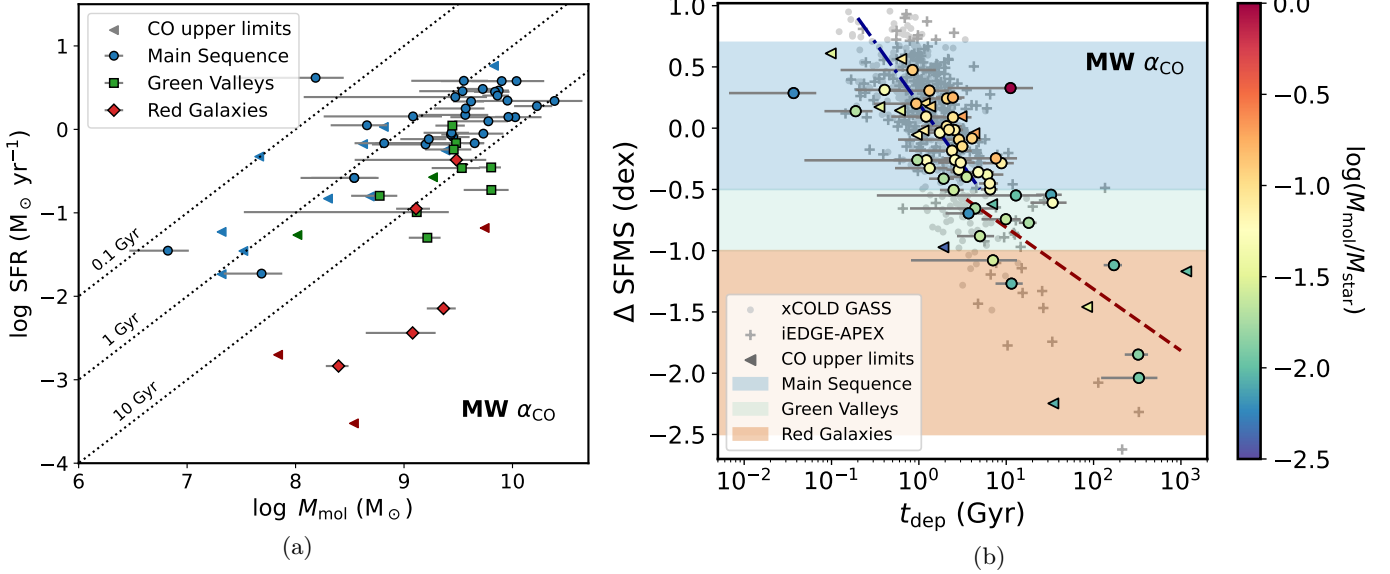
Figure 7 presents comparisons between our derived  $\alpha_{\text{CO}}$  values for all galaxies using Equations 8 (B13), 9 (SL24), and 10 (T24\*), respectively. Comparing be-

tween B13 and SL24 that are both metallicity dependent, we find consistent predictions only for MS galaxies with near-solar metallicities, which show  $\alpha_{\text{CO}}$  values slightly lower than the Galactic value of 4.35 (i.e., the blue points that align well with the 1-to-1 relation in the left panel of Figure 7). For galaxies with sub-solar metallicities, the power-law term in SL24 can easily lead to higher  $\alpha_{\text{CO}}$  values than the exponential term in B13, which explains the deviation from the 1-to-1 relation beyond the Galactic  $\alpha_{\text{CO}}$ . On the other hand, the  $\Sigma_{\text{star}}$  term in B13 has a steeper slope than that in SL24, explaining why  $\alpha_{\text{CO}}$ (B13) is lower for many non-MS galaxies that typically have higher stellar masses and densities. Finally, as shown in the right panel of Figure 7, T24\* depends purely on the CO velocity dispersion and predicts  $\sim 2$  times lower-than-Galactic  $\alpha_{\text{CO}}$  for most MS galaxies. For GV and RG, T24\* gives similar  $\alpha_{\text{CO}}$  predictions to B13 and SL24, all showing a mean  $\alpha_{\text{CO}} \sim 4$  (see Table 3). We note that UGC 04136 is excluded in the figure, as its edge-on inclination ( $i \sim 90^\circ$ ) would lead to unrealistically high  $\alpha_{\text{CO}}$  estimates due to the  $\sqrt{\cos i}$  correction of  $(\Delta v)_{2\text{kpc}}$  in Equation 10.

Overall, the tested  $\alpha_{\text{CO}}$  prescriptions predict diverse  $\alpha_{\text{CO}}$  distributions across our galaxy sample, and no systematic  $\alpha_{\text{CO}}$  dependence is found for different galaxy types. These  $\alpha_{\text{CO}}$  variations are typically within a factor of 2–3 among different prescriptions (see also Table 3). For MS galaxies, the two  $Z'$ -dependent prescriptions (B13 and SL24) tend to give higher  $\alpha_{\text{CO}}$  than the CO-based prescription (T24\*). This is partially because of significant  $Z'$  variations across galaxies which do not affect T24\*, but it also suggests that CO velocity dispersion as a “starburst emissivity term” (e.g., E. Schinnerer & A. K. Leroy 2024; J. Sun et al. 2025) in  $\alpha_{\text{CO}}$  predictions tends to give lower values than using  $\Sigma_{\text{star}}$  in B13 and SL24. Compared to MS galaxies,  $\alpha_{\text{CO}}$  predictions for GV and RG are more consistent among the three prescriptions. We caveat that these  $\alpha_{\text{CO}}$  prescriptions were developed based on MS galaxies, and thus they might not be appropriate for quenched systems below the MS. However, applying these prescriptions is the best approach currently available. To obtain reliable  $\alpha_{\text{CO}}$  predictions for GV and/or RGs, systematic and spatially resolved  $\alpha_{\text{CO}}$  measurements in such environments are needed.

### 3.3. Gas Depletion and Star Formation Efficiency

Based on the derived star formation rates (SFR) and molecular gas masses ( $M_{\text{mol}}$ ) in Section 3.2, we investigate the SFR– $M_{\text{mol}}$  relation (J. S. Young et al. 1996) and study the molecular gas depletion time ( $t_{\text{dep}}$ ; or star



**Figure 8.** (a) The SFR– $M_{\text{mol}}$  relation across all 62 galaxies, using H $\alpha$ -based SFR estimates and  $M_{\text{mol}}$  derived via a Galactic  $\alpha_{\text{CO}}$ . The dotted lines show constant molecular gas depletion times ( $t_{\text{dep}}$ ) of 0.1, 1, and 10 Gyr. (b) The derived  $t_{\text{dep}}$  increases systematically as galaxies go from MS to GV and to RG, suggesting that low SFRs in quenched galaxies are mostly caused by suppressed star formation efficiency (SFE) rather than the lack of molecular gas. The light gray points and pluses are from the xCOLD GASS survey (A. Saintonge et al. 2017) and the iEDGE APEX data (D. Colombo et al. 2025b), respectively, which align with an expected slope of -1 (blue, dashed-dotted line). Our GV and RG sample reveals an increased  $t_{\text{dep}}$  with a best-fit slope of -0.5 (red, dashed line). The color-coded molecular-to-stellar mass ratio shows higher values in MS but remains similarly low across GV and RGs, implying a dominant SFE-driven quenching from the GV to RG populations.

formation efficiency  $\text{SFE} = t_{\text{dep}}^{-1}$ ) across our galaxy sample.

Figure 8a shows the SFR– $M_{\text{mol}}$  relation across all 62 galaxies, assuming a constant MW  $\alpha_{\text{CO}}$ . The MS galaxies span a wide range of  $M_{\text{mol}}$  from  $10^7 - 10^{10} M_{\odot}$ , and their typical  $t_{\text{dep}}$  value is around 2 Gyr. On the other hand, all GV and RGs are found to have  $M_{\text{mol}} \gtrsim 10^8 M_{\odot}$ , which suggests even larger molecular gas reservoirs than some MS galaxies. Thus, combined with the low SFRs for GV and RGs, such a good amount of molecular gas in those galaxies leads to significantly longer  $t_{\text{dep}}$  than most of the MS galaxies. It is also clear from Figure 8a that most RGs have substantially longer  $t_{\text{dep}}$  beyond a few tens of Gyr, causing a clear gap from all other galaxies.

To verify whether  $t_{\text{dep}}$  changes systematically across MS, GV, and RG populations, we examine the relation of  $t_{\text{dep}}$  with the galaxy’s offset from SFMS, defining that  $\Delta \text{SFMS} = \log(\text{SFR}/\text{SFR}_{\text{MS}})$ , where  $\text{SFR}_{\text{MS}}$  is specified in Equation 1. As shown in Figure 8b, we find a steady increase of  $t_{\text{dep}}$  as  $\Delta \text{SFMS}$  decreases, which clearly deviates from the scenario of a constant gas depletion and indicates more amount of molecular gas than expected in quenched galaxies. We note that while  $\Delta \text{SFMS}$  and  $t_{\text{dep}}$  are both functions of SFR, their intrinsic anti-correlation can only cause a linear change between  $\Delta \text{SFMS}$  and  $\log(t_{\text{dep}})$ , which is not sufficient to explain the 4 dex

increase of  $t_{\text{dep}}$  over just 2.5 dex of SFR range in Figure 8b, and thus SFE must play a significant role in this systematic change with  $\Delta \text{SFMS}$ .

By comparison, the detections in the xCOLD GASS survey (i.e., gray points in the background of Figure 8b; A. Saintonge et al. 2017), shows a roughly linear trend that could be caused by the intrinsic correlation between  $\Delta \text{SFMS}$  and  $t_{\text{dep}}$  (see the blue dashed-dotted line in Figure 8b which has a slope of -1). These data points are based on aperture-corrected measurements reported in A. Saintonge et al. (2017, Table 3), using a MW  $\alpha_{\text{CO}}$  to ensure a consistent comparison with our data. Our MS sample aligns well with that of xCOLD GASS, which suggests a consistent SFE among MS galaxies. While xCOLD GASS also includes a small number of detected GV and RGs, the iEDGE survey using the Atacama Pathfinder Experiment telescope (APEX) detected a larger sample of GV and RGs at  $\text{S/N} > 5$  (gray pluses in Figure 8b; D. Colombo et al. 2020, 2025b), and they found a generally longer  $t_{\text{dep}}$  in those galaxies. To compare with our galaxy-integrated measurements, here we extract the aperture corrected global quantities (SFR,  $M_{\text{star}}$ ,  $M_{\text{mol}}$ , and SNR) provided in D. Colombo et al. (2025b) and apply a cut at  $\text{S/N} = 5$ .

Overall, we find our GV and RG sample agrees well the iEDGE APEX survey, and three of our RGs (NGC 5216, UGC 02222, and UGC 08234) show an

even further increase in  $t_{\text{dep}}$  beyond 100 Gyr. We have checked that such long  $t_{\text{dep}}$  in these three galaxies is unlikely to be caused by underestimated uncertainties, as we have done an additional ‘fake source’ test (as described in Section 3.1) customized to the detected CO features in those galaxies and obtained similar uncertainties within 40%. The best-fit relation for our detected GV/RG sample is  $\Delta\text{SFMS} = -0.5 \log(t_{\text{dep}}) - 0.3$  (i.e., red dashed line in Figure 8b), indicating a substantial drop in SFE compared to the MS sample with a slope of -1. In summary, our finding of a significant  $t_{\text{dep}}$  increase across GV and RGs suggests that the star formation quenching process in the galaxies detected in CO is primarily driven by a decline in SFE rather than molecular gas exhaustion (see Section 4 for further discussions).

In Figure 8b, the color coding shows that there is a clear drop in the molecular-to-stellar mass ratio ( $M_{\text{mol}}/M_{\text{star}}$ ) from MS galaxies (where the median  $\log[M_{\text{mol}}/M_{\text{star}}] \sim -1$ ) to those below MS (where  $\log[M_{\text{mol}}/M_{\text{star}}] \sim -2$ ). This suggests that in addition to SFE effects, the reduction in molecular gas plays an important role for the transition from MS to GV. On the other hand, the transition from GV to RG shows no accompanying drop in  $M_{\text{mol}}/M_{\text{star}}$ , which suggests that this evolution is dominated by a decrease in SFE. Furthermore, for MS galaxies we observe a systematic change in  $M_{\text{mol}}/M_{\text{star}}$  across (orthogonal to) the  $\Delta\text{SFMS}-t_{\text{dep}}$  relation, with higher  $M_{\text{mol}}/M_{\text{star}}$  values (red-orange) on the right side and lower (yellow-green) on the left side of the main relation. This change is due to the intrinsic correlation of the  $M_{\text{mol}}/M_{\text{star}}$  ratio with  $\Delta\text{SFMS}$  ( $\sim \text{SFR}/M_{\text{star}}$ ) and  $t_{\text{dep}}$ , indicating that the SFE ( $\text{SFR}/M_{\text{mol}}$ ) shows little variation across the population of MS galaxies — because large variations would cancel the correlation (A. Saintonge et al. 2016, 2017; D. Colombo et al. 2020, 2025a,b). However, this same correlation disappears for the detected galaxies below the MS, which means that SFE must vary substantially across our detected GV and RG sample. In Appendix C, we show that  $\alpha_{\text{CO}}$  choices have no impact on the qualitative results in Figure 8.

Figure 9 compares the derived  $t_{\text{dep}}$  distributions and values using different  $\alpha_{\text{CO}}$  prescriptions. We find that all four prescriptions reveal a gradual increase in the  $t_{\text{dep}}$  range from the MS to GV and an even more substantial increase toward RGs. In Table 3, we report the mean, standard deviation, median, and the 16th and 84th percentile values of  $t_{\text{dep}}$  for each galaxy type. With the MW  $\alpha_{\text{CO}}$ , the median  $t_{\text{dep}}$  derived for MS, GV, and RGs are  $2.10^{+2.35}_{-1.31}$ ,  $6.90^{+17.00}_{-3.67}$ , and  $127.7^{+201.6}_{-113.4}$  Gyr, respectively. Other prescriptions also follow a similar trend. For all

galaxy types, the differences in  $t_{\text{dep}}$  among these prescriptions are generally within a factor of 2, while there is a tendency for SL24 to predict longer  $t_{\text{dep}}$  and T24\* to predict shorter  $t_{\text{dep}}$  for MS galaxies due to the nature of those prescriptions (see Section 3.2.3).

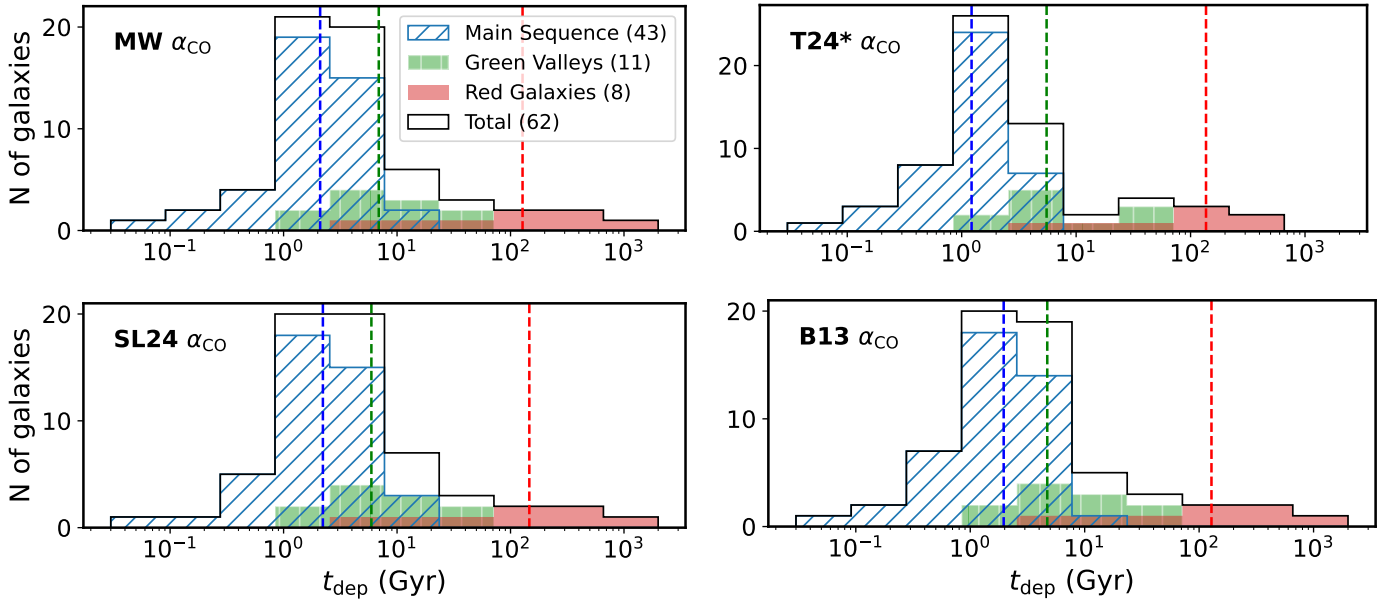
#### 4. DISCUSSION

Our new CO (1–0) nearby galaxy survey, GBT-EDGE, has revealed a comparable amount of molecular gas across a sample of galaxies at different evolutionary stages, with galaxy-integrated molecular gas masses spanning from  $10^8$ – $10^{10} M_{\odot}$  for either main sequence (MS), green valley (GV), or red galaxies (RGs). The CO datasets, combined with existing optical IFU measurements, further uncover a smooth and significant increase in molecular gas depletion time ( $t_{\text{dep}}$ ) as galaxies evolve from MS toward quenched stages. These results suggest that the decline of star formation in quenched galaxies is mainly due to reduced star formation efficiency (SFE) of their molecular gas, rather than a lack of molecular gas reservoir in those galaxies.

##### 4.1. SFR and $\alpha_{\text{CO}}$ Uncertainties

The scenario of suppressed SFE in quenched galaxies strengthens when we account for possible biases or uncertainties in the estimation of SFR and molecular gas mass. Inferring SFRs in quenched galaxies, either using H $\alpha$  or stellar synthesis analyses only provides an upper limit of SFR, as H $\alpha$  emission can be contributed by ionization sources unassociated with star formation (S. Salim et al. 2007; R. C. Kennicutt & N. J. Evans 2012; C. Catalán-Torrecilla et al. 2015; E. A. D. Lacerda et al. 2020). With our SFR estimates being upper limits, all the derived  $t_{\text{dep}}$  are therefore lower limits, indicating that the long  $t_{\text{dep}}$  we found in quenched galaxies may be even longer, which remains supportive of the reduced SFE scenario.

The major uncertainty in molecular gas mass estimation arises from the variation of the CO-to-H $_2$  conversion factor,  $\alpha_{\text{CO}}$ . While there is a lack of systematic  $\alpha_{\text{CO}}$  measurements for quenched galaxies, recent studies using MS-calibrated  $\alpha_{\text{CO}}$  prescriptions have suggested lower  $\alpha_{\text{CO}}$  values for galaxies below the MS (G. Accurso et al. 2017; E. Schinnerer & A. K. Leroy 2024; J. Sun et al. 2025). By implementing four  $\alpha_{\text{CO}}$  prescriptions from current literature (Equations 8–10 and MW  $\alpha_{\text{CO}}$ ), we find that galaxy-integrated  $\alpha_{\text{CO}}$  variations are overall limited to a factor of 2 across our sample (Figure 7 and Table 2), which is incapable of explaining the  $> 2$  dex change in  $t_{\text{dep}}$  spanned by our GV and RG sample (Figures 8 and 9). We note that our RG sample showing  $M_{\text{mol}} \gtrsim 10^8 M_{\odot}$  is also consistent with previous studies



**Figure 9.** Histograms of the derived gas depletion times under four different  $\alpha_{\text{CO}}$  treatments: constant MW value, a CO velocity dispersion-based prescription (T24\*; Equation 10), and two metallicity + stellar mass density-based prescriptions (B13 and SL24; Equation 8 and 9). The vertical dashed lines represent the median  $t_{\text{dep}}$  values for each galaxy population. All four prescriptions reveal distinct  $t_{\text{dep}}$  distributions for MS, GV, and RG groups, showing longer  $t_{\text{dep}}$  in more quenched galaxies.

of CO-rich early-type galaxies at similar distances (e.g., L. M. Young et al. 2011; K. Alatalo et al. 2013).

In addition, we do not observe a significant difference in the global  $\alpha_{\text{CO}}$  values among MS, GV, and RG groups using any of the prescriptions (Table 3 and Figure 7). This is contrary to the result in J. Sun et al. (2025), where they apply the SL24 prescription to local massive galaxies and find systematically lower global  $\alpha_{\text{CO}}$  values for galaxies below the MS. As discussed in J. Sun et al. (2025), this discrepancy may be due to their weighting being biased toward the central regions in those galaxies. To further confirm if  $\alpha_{\text{CO}}$  varies systematically with galaxy’s offset from the SFMS, future molecular gas and  $\alpha_{\text{CO}}$  measurements on a larger sample of quenched galaxies will be crucial.

#### 4.2. The Drivers of Reduced SFE

Our finding of a systematic  $t_{\text{dep}}$  (or SFE) variation with the offset from SFMS (i.e.,  $\Delta\text{SFMS}$ , or “specific SFRs” as used in some studies) is consistent with previous galaxy-integrated molecular gas surveys in the low-redshift Universe (R. Genzel et al. 2015; A. Saintonge et al. 2017; D. Colombo et al. 2020; L. Lin et al. 2020; J. K. Barrera-Ballesteros et al. 2025). In particular, D. Colombo et al. (2020) also suggests that low SFE (instead of low molecular gas fraction) dominates the quenching from GV to RG, which is in line with our result in Figure 8b. Moreover, previous studies on the SFR– $M_{\text{mol}}$  relation of quenched galaxies, including

early-type, GV, and RGs, have reported a significantly lower intercept than that of star-forming galaxies (T. A. Davis et al. 2014; L. Lin et al. 2022; D. Colombo et al. 2025a), showing lower SFE than MS galaxies as indicated in Figure 8a.

Recent spatially-resolved studies have further shown similar trends to those in Figure 8, particularly in the inner regions of galaxies where SFE is found to be suppressed (Y. Garay-Solis et al. 2023; H.-A. Pan et al. 2024; V. Villanueva et al. 2024; D. Colombo et al. 2025b). While these studies tend to classify SFE-driven or gas-driven quenching within different regions of galaxies, it has been shown that the resolved and global classifications on quenching modes are generally in good agreement, and that a low global SFE value can be a strong indicator of SFE-dominated quenching (L. Lin et al. 2026).

Given various supporting evidence for reduced SFE in quenched galaxies, some questions remain: What prevents the molecular gas from forming stars? How do different physical processes control SFE and drive the quenching of active disk galaxies? While it is known that galaxy interactions such as ram pressure stripping or frequent high-speed encounters can cease star formation by removing gas from galaxies (i.e., environmental quenching; B. Moore et al. 1996; M. G. Abadi et al. 1999; Y.-j. Peng et al. 2010; V. Villanueva et al. 2022; Y. Garay-Solis et al. 2023), our results suggest that reduced SFE can play a more dominant role than gas removal in

driving the low SFR of quenched galaxies (Figure 8b). Additionally, the only three galaxies in close interacting pairs (NGC 0169, 5929, and 5954) in our sample also span a wide range of  $t_{\text{dep}}$  (see Table 2), while their  $M_{\text{mol}}/M_{\text{star}} \sim 0.1$  are similar to the average of our MS sample.

Alternatively, feedback processes from AGNs may also disrupt surrounding gas via radiative or shock-induced heating, thereby preventing the gas from gravitational collapse (E. L. Lambrides et al. 2019; E. A. D. Lacerda et al. 2020; A. F. L. Bluck et al. 2023). In our sample, however, only two galaxies are reliably identified to host a weak or strong AGN (NGC 5216 and 5929; V. Kalinova et al. 2021). For NGC 5216 (classified as an RG), only a low amount of CO is located on its galaxy disk (Figure 11), and thus AGN feedback is unlikely to have a significant impact on that gas. A recent study on the EDGE-CALIFA sample has also reported limited effects of AGN feedback on quenched galaxies (Z. Bazzi et al. 2025).

Morphological quenching is another possibility to prevent star formation, which can happen even with substantial amount of gas being present (M. Martig et al. 2009). Such process includes the development of bars, bulges, or spheroids to stabilize galaxies' gas disks (A. Saintonge et al. 2012), and thus morphological quenching is found to be critical in galaxy centers and provides evidence for an inside-out galaxy quenching scenario (L. Lin et al. 2019b; V. Kalinova et al. 2021; A. Lu et al. 2022; F. Maeda et al. 2023; H.-A. Pan et al. 2024; J. K. Barrera-Ballesteros et al. 2025). It is also possible that CO (1–0) is tracing gas that is not dense enough to form stars, since its critical density is only  $\sim 10^3 \text{ cm}^{-3}$  (Y. L. Shirley 2015; Y.-H. Teng et al. 2022). If our CO detections mostly come from low-density gas, it could explain why the gas does not form stars efficiently, and why the derived SFE based on CO is low.

Given that we observe CO emission near  $R_{25}$  in many galaxies (Figure 11), morphological quenching likely has limited influence in those regions. As that gas lies in the outer disks, it could be relatively diffuse, compared to typical star-forming galaxies with molecular gas concentration toward the centers of galaxies. To further examine if our observed CO indeed traces low-density gas and leads to underestimated SFE in quenched galaxies, future observations with dense gas tracers can be helpful (e.g., HCN; L. Lin et al. 2024; L. Neumann et al. 2025). Resolved studies with constraints from multiple CO isotopologue lines (e.g., Y.-H. Teng et al. 2023) in GV and RGs will also be critical to discern what specific gas conditions regulate SFE and how they affect galaxy quenching at various evolutionary stages.

## 5. CONCLUSIONS

We present GBT-EDGE, a new CO (1–0) survey across 62 nearby massive galaxies, covering a sample of 43 main sequence (MS), 11 green valley (GV), and 8 red galaxies (RGs) in the local Universe with stellar masses above  $3 \times 10^8 M_{\odot}$ . By combining the CO observations with optical IFU data from the CALIFA survey, we estimate star formation efficiencies (SFE) across the sample and study possible mechanisms for galaxy quenching. Our main results are summarized as follows:

1. We produce moment maps for all galaxies, using signal masks based on CO data dilation and constraints from  $H\alpha$  velocity field. The moment-0 images reveal diverse and extended molecular gas structures across entire galaxies, including some galaxies with significant emission in their outer radii. The moment-1 images generally show clear rotation features for well-detected disk galaxies.
2. We determine global SFRs via two approaches: 1) extinction-corrected  $H\alpha$  line fluxes and 2) star formation history within an age of 33 Myr. We find that both methods give consistent results for MS and GV galaxies (Figure 7a). For RGs where both are likely overestimates, using star formation history leads to substantially overestimated SFRs (even higher than using  $H\alpha$ ), likely due to large uncertainties in the luminosity fractions assigned to different age bins.
3. We derive and compare galaxy-integrated molecular gas masses ( $M_{\text{mol}}$ ) using different assumptions for the CO-to- $H_2$  conversion (Table 2), including prescriptions from A. D. Bolatto et al. (2013), E. Schinnerer & A. K. Leroy (2024), and Y.-H. Teng et al. (2024). In addition, we employ metallicity calibration from M. Curti et al. (2017) and compute a best-fit metallicity gradient for each galaxy. Overall, the global  $\alpha_{\text{CO}}$  values and thus  $M_{\text{mol}}$  are found to vary by a factor of 2 within and among prescriptions (Figure 7 and Table 3). We obtain comparable  $M_{\text{mol}}$  spanning  $10^8\text{--}10^{10} M_{\odot}$  across our sample, regardless of galaxy types (MS, GV, or RG).
4. The SFR– $M_{\text{mol}}$  relation reveals a distinct gap between detected RGs and other galaxies, indicating a substantially longer gas depletion time ( $t_{\text{dep}}$ ) in such retired environments (Figure 8a). Assuming a Galactic  $\alpha_{\text{CO}}$ , the median  $t_{\text{dep}}$  for MS/GV/RG is  $2.10^{+2.35}_{-1.31} / 6.90^{+17.00}_{-3.67} / 127.7^{+201.6}_{-113.4}$  Gyr, respectively. The gradual increase of  $t_{\text{dep}}$  from MS to GV

and to RG is consistently shown across all  $\alpha_{\text{CO}}$  choices (Figure 9).

5. We find that  $t_{\text{dep}}$  increases systematically with the distance from the MS ( $\Delta\text{SFMS}$ ) across our entire sample (Figure 8b). Both the molecular-to-stellar mass ratio ( $M_{\text{mol}}/M_{\text{star}}$ ) and SFE drop as galaxies transit from MS to GV. However, for GV and RGs, neither does  $M_{\text{mol}}$  nor  $M_{\text{mol}}/M_{\text{star}}$  show correlation with  $\Delta\text{SFMS}$ . These results show that for CO-detected objects, galaxy quenching from GV to RG is primarily driven by low SFE rather than a deficit in molecular gas.
6. As CO is detected near the  $R_{25}$  radius in many quenched galaxies, we do not expect morphological quenching or AGN feedback to be the dominant quenching mechanisms for our sample. We suspect that low gas density can be a major reason for reduced SFE, but additional observations of dense gas tracers such as HCN or CO isotopologues will be needed to clarify the situation.

Our results show that galaxies that are more quenched tend to have longer molecular gas depletion times, suggesting that galaxy quenching is not only driven by exhaustion of gas supply but also a decline in star formation efficiency. In particular, our results are consistent with low SFE being the dominant driver for the stages from green valley to red galaxies, while the transition from main sequence to green valley is caused by a decrease of both molecular gas fraction and SFE. Therefore, it is likely that gas depletion is important in the initial stages of galaxy quenching, whereas a strong suppression of star formation efficiency then takes over to drive a deeper quenching into red galaxies.

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## *Facilities:* GBT

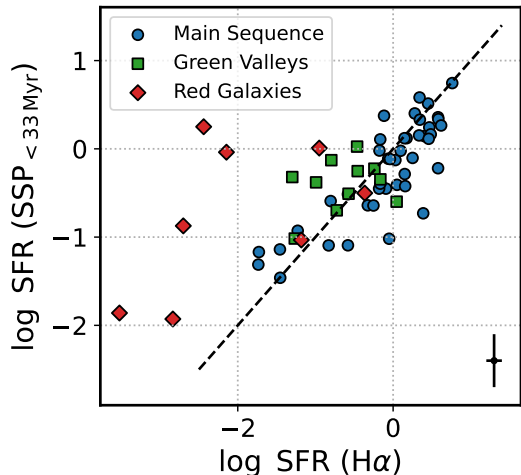
*Software:* `spectral-cube` (A. Ginsburg et al. 2019), `matplotlib` (J. D. Hunter 2007), `numpy` (C. R. Harris et al. 2020), `scipy` (P. Virtanen et al. 2020), `astropy` (Astropy Collaboration et al. 2022), `ipython` (F. Pérez & B. E. Granger 2007), `Pipe3D` (S. F. Sánchez et al. 2016b,c), `reproject` (T. Robitaille et al. 2020), `edge-pydb` (T. Wong et al. 2024), `gbtpipe` (<https://github.com/GBTSpectroscopy/gbtpipe>), `degas` (<https://github.com/GBTSpectroscopy/degas>), `GBT-EDGE` (<https://github.com/teuben/GBT-EDGE>), `gbt-edge-analysis` (<https://github.com/ElthaTeng/gbt-edge-analysis>; doi:10.5281/zenodo.20707910)

## APPENDIX

### A. SFR ESTIMATES FROM SIMPLE STELLAR POPULATION ANALYSIS

By leveraging the simple stellar population (SSP) and star formation history (SFH) tables in the CALIFA

`Pipe3D` products, we compute the mass fraction of stars



**Figure 10.** Comparison between SFRs estimated via  $H\alpha$  (Section 3.2.1) and the simple stellar population (SSP) analysis. The dashed line indicates a one-to-one relation. For the MS and GV populations, SFRs inferred from  $H\alpha$  are consistent with those inferred from the SSP analysis with  $t < 33$  Myr. For RGs, however,  $H\alpha$ -based SFR generally provides better upper limits than using SSP. A typical error bar of  $\sigma_x = \pm 0.1$  dex for  $SFR(H\alpha)$  and  $\sigma_y = \pm 0.3$  dex for  $SFR(SSP)$  is shown in the lower right corner.

younger than 33 Myr ( $f_{M_{\text{young}}}$ )<sup>33</sup> within each galaxy and derive an integrated SFR via

$$SFR [M_{\odot} \text{ yr}^{-1}] = M_{\text{star,tot}} \cdot f_{M_{\text{young}}} / 33 \text{ Myr}, \quad (\text{A1})$$

where  $M_{\text{star,tot}}$  is the total stellar mass of a galaxy, and we define young stars as those younger than 33 Myr, following previous optical IFU surveys (R. M. González Delgado et al. 2016; J. K. Barrera-Ballesteros et al. 2021; S. F. Sánchez et al. 2022). These studies find that SSP-inferred SFRs using  $t \lesssim 30$  Myr aligns best with the gold-standard SFRs obtained from the dust-corrected  $H\alpha$  luminosity, while using a shorter timescale would lead to a systematic deviation. Indeed, we have checked on our sample that using e.g.  $t < 12$  Myr for the SSP analysis generally increases the resulting SFRs by  $\sim 0.2$  dex, which is consistent with the finding in S. F. Sánchez et al. (2022). As our goal here is to cross-compare SFR estimates from different tracers, we present only the SSP results using 33 Myr which align best with the  $H\alpha$ -based SFR estimates.

In detail, we derive the young mass fraction following these steps: 1) convert the luminosity fractions to mass fractions for each age-metallicity bin via SSP-computed mass-to-light ratios and the V-band image, 2) correct

the pixel-by-pixel mass fractions for stellar dust attenuation via  $10^{A_V/2.5}$  using the  $A_V$  map, 3) sum up all the masses contributed from age  $< 33$  Myr over all pixels within the  $R_{25}$  radius, and 4) divide that mass contribution by the (also  $A_V$ -corrected) integrated mass over all age-metallicity bins and within the  $R_{25}$  radius.

Figure 10 shows the comparison between the SSP- and  $H\alpha$ -derived SFRs for all galaxies in our sample. For MS and GV galaxies, we find consistent SFR estimates with both methods, which is in good agreement with previous studies (S. F. Sánchez et al. 2022, 2023). For RGs, however, it is clear that SSP-based SFRs are much higher than those using  $H\alpha$ , indicating even weaker upper limits than  $H\alpha$ -based SFRs. We consider the recombination line based SFRs more reliable and interpret this disagreement to indicate that the SSP analysis results in overestimates of SFRs in these galaxies.

Neither the SSP- nor the  $H\alpha$ -inferred SFRs are model independent, even though this fact is frequently overlooked. Both methods try to estimate the amount of stars, quantified by  $M_{\text{star}}$ , that are formed in a recent time period, i.e.,  $\Delta M_{\text{star}}$  in a certain  $\Delta t$ , as described before. In the case of the SSP-method this estimation is based on the derivation of the fraction of light corresponding to a population younger than a certain timescale. Underlying this method it is assumed (i) a certain set of isochrones that traces the stellar evolution, (ii) an initial mass-function and the corresponding evolving mass-function, (iii) an adopted stellar library to generate the SSP spectra and (iv) a dust-attenuation law and scenario (screen-model in our particular case). Modifying any of these assumptions would alter the derived  $SFR_{\text{SSP}}$ .

In many cases most of the weight in the discrepancy between both methods is placed on these assumptions, minimizing those required to derive the SFR based on  $H\alpha$ . Following the seminal exploration by R. C. Kennicutt (1998), the  $SFR_{H\alpha}$  requires, in addition to the very same assumptions needed to evaluate  $SFR_{\text{SSP}}$ , to assume (i) a particular shape for the recent star-formation history, (ii) the amount of ionizing photons produced by short-lived OB-stars ( $t < 10$  Myr), that requires to assume a certain shape for their spectra in the highly uncertain far ultraviolet wavelength range, and (iii) a photonization model that links the number of these stars of a particular chemical composition with a certain  $H\alpha$  luminosity. The number of physical parameters and assumptions regarding the ionized nebula behind the third assumption is indeed large and again broadly overlooked.

As a result, any attempt to match both measurements in the literature has consistently provided with signifi-

<sup>33</sup> Limited by the discrete age bins in the star formation history measurements from CALIFA, 33 Myr is used as the best approximation to a 30-Myr time scale.

cantly strong, linear and almost slope-one correlations, both integrated galaxy-wide or spatially resolved down to  $\sim 1$  kpc for star-forming galaxies or regions (S. F. Sánchez 2020). It has been also shown that in general there is a scaling factor between both quantities (an offset in logarithm scales). This indicates that (i) both methods are indeed somehow tracing the same physical quantity, i.e., the SFR, and (ii) all differences in the considered assumptions are translated somehow into a scaling factor that can be understood as time-scale renormalization: from  $t \sim 10$  Myr, in the case of  $H\alpha$ - to  $t \sim 33$  Myr, in the case of SSP-based SFR. However, it is important to remind that indeed we do not know the weight of each of these assumptions into this scaling factor or time-scale readjustment.

For this reason, the described offset between  $SFR_{SSP}$  and  $SFR_{H\alpha}$  and the highly overestimated SSP-based SFRs in RGs are likely due to a combination of reasons, and not a single one. First, previous results have reported the existence of a minimum threshold in the ability to recover a certain young stellar fraction when using similar stellar synthesis codes (e.g.,  $\sim 3\%$  R. M. González Delgado et al. 2014). If this is the case, there would be a corresponding minimum SFR based on the SSP of  $0.03 \times M_{\text{star,tot}}/33$ , that may affect the SFR derived for RGs (i.e., those with the lower values of  $f_{M_{\text{young}}}$ ). Even if this limit is somehow overcome due to the most reliable recovery of low fractions of young stellar populations by Pipe3D (E. A. D. Lacerda et al. 2022), there is still an expected mismatch with the values derived based on the  $H\alpha$  luminosity: on one hand, a severe mask was applied to the spaxel-wise  $H\alpha$  intensity ( $S/N > 3$ ), which for RGs may have removed a significant fraction of the spaxels in which the  $H\alpha$  has a  $S/N$  of 1–2 (e.g., J. M. Gomes et al. 2016); on the other hand, this mask was not applied to the SSP-based SFR estimates, and thus the integrated regions are also slightly different. Therefore, the reported SFR differences are expected based on the differences between the analyses, which affects more the RGs, i.e., those with low  $H\alpha$  intensities and  $f_{M_{\text{young}}}$ .

### B. ADDITIONAL MOMENT MAPS

While the analysis of this work is focused on global galaxy quantities, we present in Figure 11 the spatially resolved moment maps for all 62 galaxies in our GBT-EDGE sample. The color scale of the moment-0 maps represents a linear variation from 0 to 50 K km s $^{-1}$

for most galaxies, but to 100/200 K km s $^{-1}$  for NGC0169/CGCG536-030. For the moment-1 maps, the color scale ranges from the 5<sup>th</sup> to 95<sup>th</sup> percentile velocity values of each galaxy. The color scale of moment-2 maps ranges from 0 to 150 km s $^{-1}$  for all galaxies. Regions outside the galaxy  $R_{25}$  are excluded in the moment 1 and 2 maps to highlight velocity fields within the galaxies. A general description of these moment maps and the methods for map creation can be found in Section 3.1.

We caveat that regions outside the  $R_{25}$  radii (cyan contours) may include spurious artifacts in the moment-0 maps. In our public data release, the masked moment maps that exclude regions outside  $R_{25}$  are provided along with the reduced data cubes. The GBT-EDGE dataset is available on Zenodo under an open-source Creative Commons Attribution license: [doi:10.5281/zenodo.20707368](https://doi.org/10.5281/zenodo.20707368), and our analysis code is also available on GitHub and Zenodo: [doi:10.5281/zenodo.20707910](https://doi.org/10.5281/zenodo.20707910).

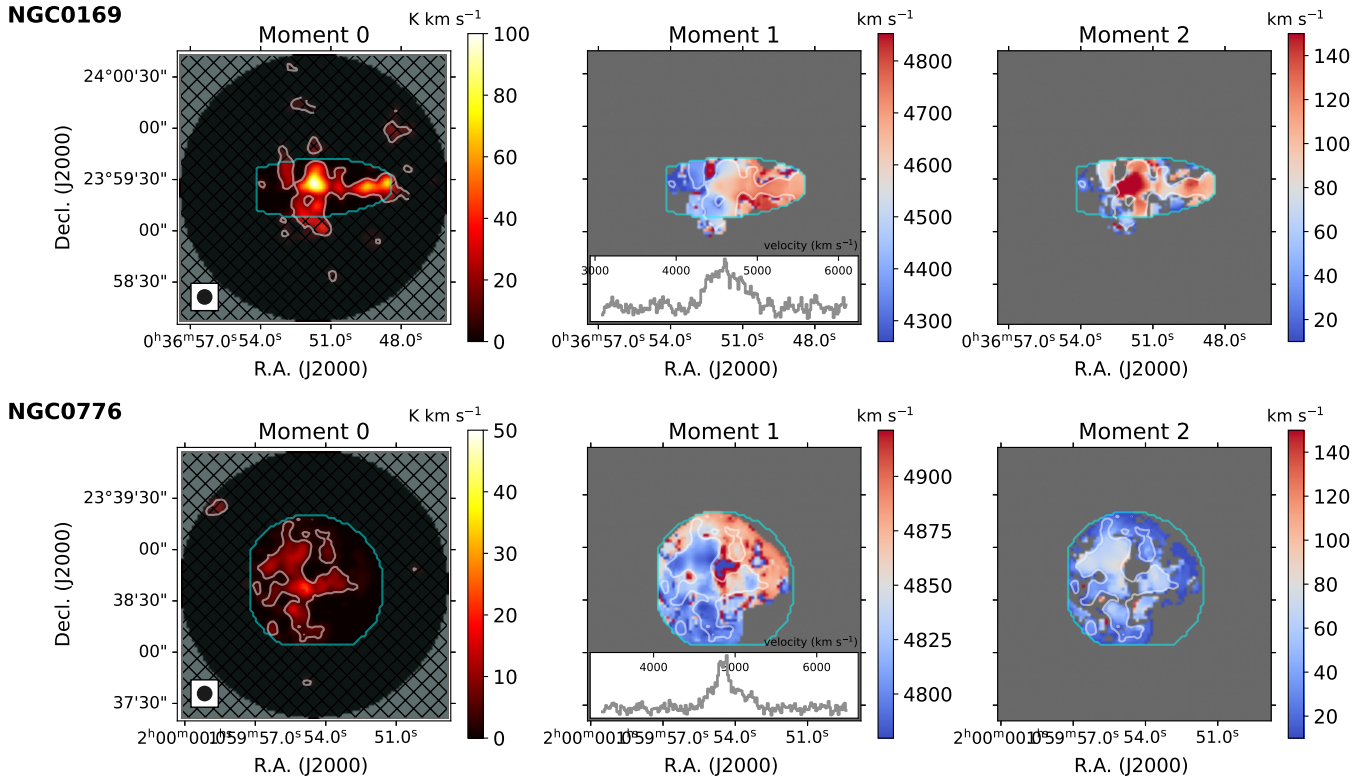
### C. ADDITIONAL SFE RESULTS WITH VARYING $\alpha_{CO}$ PRESCRIPTIONS

The SFR– $M_{\text{mol}}$  relation and the relationship between  $\Delta SFMS$  and molecular gas depletion time ( $t_{\text{dep}}$ ) presented in Figure 8 are based on a constant  $\alpha_{CO}$  assumption. Here we provide the same set of figures that use different  $\alpha_{CO}$  prescriptions, including B13 (A. D. Bolatto et al. 2013), SL24 (E. Schinnerer & A. K. Leroy 2024), and T24\* (Y.-H. Teng et al. 2024, and in preparation) which are implemented and discussed in Section 3. The derived  $M_{\text{mol}}$ ,  $t_{\text{dep}}$ , and their associated uncertainties based on these  $\alpha_{CO}$  prescriptions are all provided in our GitHub repository<sup>29</sup> (see Section 3.1).

As shown by Figure 12, the systematic increase of  $t_{\text{dep}}$  from MS to GV and to RGs remain consistent regardless of the  $\alpha_{CO}$  choice. In particular, T24\* even strengthens the anti-correlation across MS galaxies, showing the least scatter and exacerbating the  $t_{\text{dep}}$  deviation of GV and RGs from MS galaxies. The choice of  $\alpha_{CO}$  does not alter the  $\Delta SFMS$ – $t_{\text{dep}}$  trend, since the  $\alpha_{CO}$  variations among these prescriptions are generally within a factor of two (see Table 3 and Figure 7), which is almost negligible compared to the 2–3 dex range of  $M_{\text{mol}}$  and  $t_{\text{dep}}$  spanned by our galaxy sample. Therefore, we conclude that  $\alpha_{CO}$  variations are unlikely to have much impact on our results, while future  $\alpha_{CO}$  measurements across quenched galaxies will be needed for a solid verification.

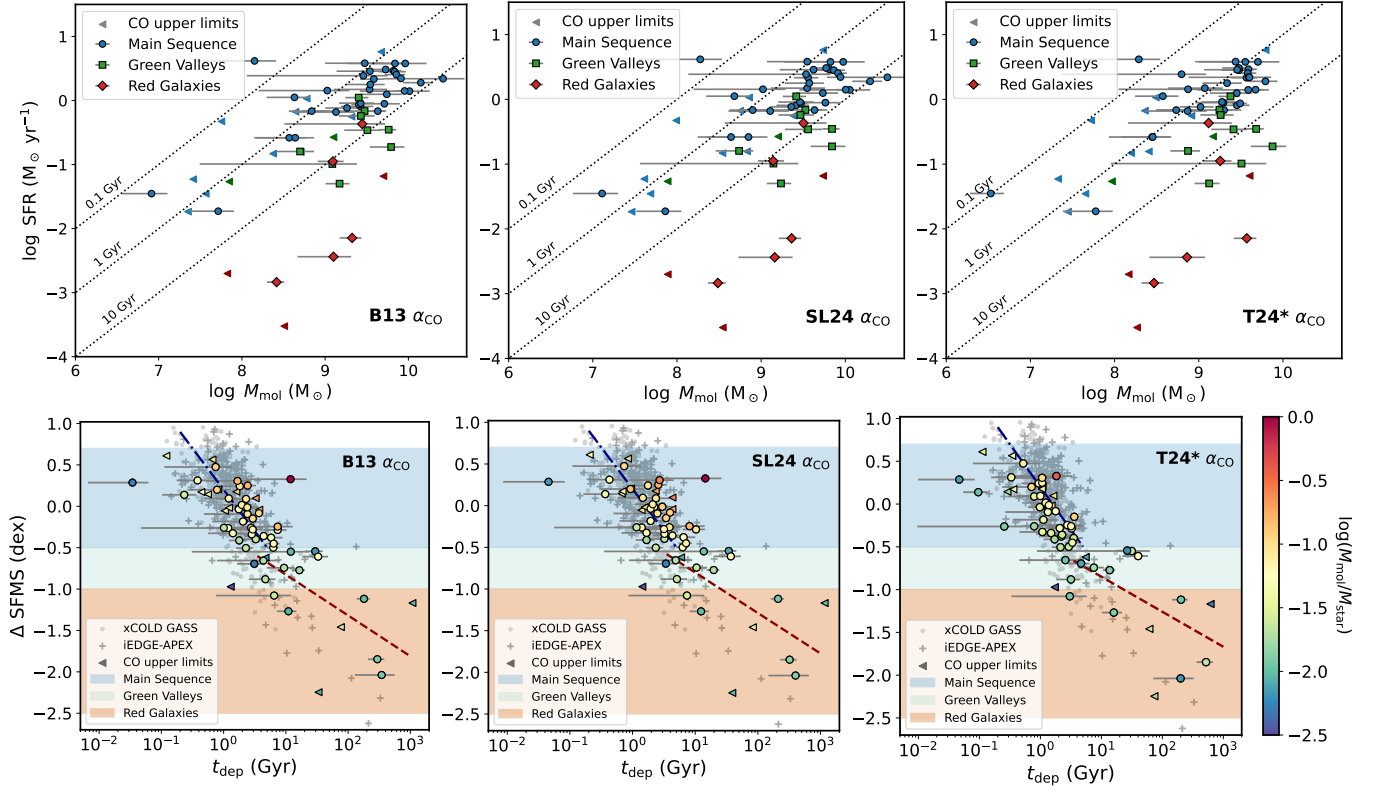
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**Figure 11.** Same as Figure 6 but for all other galaxies in this work. The complete figure set (60 images) is available in the online journal.

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**Figure 12.** Same as Figure 8 but using  $M_{\text{mol}}$  and  $t_{\text{dep}}$  derived via the B13 (left), SL24 (middle), and T24\* (right)  $\alpha_{\text{CO}}$  prescriptions. The best-fit slopes for quenched galaxies (red dashed lines) are -0.49, -0.48, and -0.41 for B13, SL24, and T24\*, respectively. The qualitative results remain the same as using a constant  $\alpha_{\text{CO}}$ , as the  $\alpha_{\text{CO}}$  variation within and among prescriptions is small compared to the orders-of-magnitude span in  $t_{\text{dep}}$ , and there is no systematic  $\alpha_{\text{CO}}$  dependence on  $\Delta \text{SFMS}$ .

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