Compact dust emission in a gravitationally lensed massive quiescent galaxy at $z = 2.15$ revealed in $\sim 130$ pc-resolution observations by ALMA

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ABSTRACT

We present new observations of MRG-M2129, a quiescent galaxy at $z = 2.15$ with the Atacama Large Millimeter/submillimeter Array (ALMA). With the combination of the gravitational lensing effect by the foreground galaxy cluster and the angular resolution provided by ALMA, our data reveal 1.2 mm continuum emission at $\sim 130$ pc angular resolution. Compact dust continuum is detected at 7.9 $\sigma$ in the target but displaced from its stellar peak position by $62 \pm 38$ mas, or $\sim 169 \pm 105$ pc in the source plane. We find considerably high dust-to-stellar mass ratio, $4 \times 10^{-4}$. From non-detection of the [C $i$] $^3P_2 \rightarrow ^3P_1$ line, we derive 3 $\sigma$ upper limits on the molecular gas-to-dust mass ratio $\delta_{\text{GDR}} < 60$ and the molecular gas-to-stellar mass ratio $f_{\text{H}_2} < 2.3\%$. The derived $\delta_{\text{GDR}}$ is $\gtrsim 2 \times$ smaller than the typical value assumed for quiescent galaxies in the literature. Our study supports that there exists a broad range of $\delta_{\text{GDR}}$ and urges submillimeter follow-up observations of quenching/recently quenched galaxies at similar redshifts. Based on the inferred low $\delta_{\text{GDR}}$ and other observed properties, we argue that the central black hole is still active and regulates star formation in the system. Our study exhibits a rare case of a gravitationally lensed type 2 QSO harbored by a quiescent galaxy.

1. INTRODUCTION

Quenching, or shutdown of star formation activity, is one of the key evolutionary phenomena of galaxies toward the local massive populations such as giant elliptical galaxies. Synergies of wide-field surveys and subsequent spectroscopic followups with large telescopes have allowed us to see the emergence of a massive ($\log M_*/M_\odot \gtrsim 11$, where $M_*$ represents stellar mass), quiescent galaxy population as early as redshift $z \sim 4$, when the universe is only a few billion years old (Marsan et al. 2015; Glazebrook et al. 2017; Schreiber et al. 2018a; Tanaka et al. 2019; Valentino et al. 2020a). For such massive galaxies to exist at such an early time, they not only need to form a significant amount of stars, but also stop their star formation activity very rapidly. Extremely intense star formation is observed in sub-millimeter (submm) galaxies and quasars in earlier epochs (e.g., Casey et al. 2019; Spilker et al. 2020), some of which are presumably the progenitors of massive quiescent galaxies seen at lower redshifts (Toft et al. 2014; Straatman et al. 2014). However, it is still an open question how galaxies stopped such extreme star formation, especially in the peak epoch of cosmic star formation (Madau & Dickinson 2014). Understanding the corresponding physical mechanism(s) is critical for theoretical studies, as the predicted number densities of quiescent galaxies at those redshifts span an order of magnitude among studies (e.g., Valentino et al. 2020a).

To advance our understanding of galaxy quenching, one powerful key probe is inter-stellar medium (ISM), such as molecular gas and dust. Observations revealed...
only a small amount of molecular gas in nearby early-type galaxies — < a few percent of the total stellar mass (Leroy et al. 2008; Saintonge et al. 2011), which is an order of ~ 2 magnitude lower than typical star-forming galaxies (Boselli et al. 2014; Davis et al. 2014), suggesting that their low star-formation activity is largely due to the lack of cold gas.

However, investigation of ISM in high-z quiescent galaxies remains challenging due to, by definition, their inactive nature, except for a few cases (e.g., Schreiber et al. 2018b; Williams et al. 2021). Still, recent deep submm observations have made significant progress via the detection of far-infrared emission from thermal dust, as an indirect inference of gas abundance from its tightly correlated origin (e.g., Rémy-Ruyer et al. 2014). Stacking analysis of FIR emission revealed a significant amount of gas (~ 5-10% of the stellar mass) in quiescent galaxies up to z ~ 2 (Gobat et al. 2018; Magdis et al. 2021). Some attempts have revealed gas reservoirs in individual galaxies (Whitaker et al. 2021a), if not all of them (e.g., Spilker et al. 2018; Bezanson et al. 2019; Morishita et al. 2021; Bezanson et al. 2022). These observations suggest that gas depletion may not be the only cause for quenching at high redshifts, which is in line with early studies of lower-z galaxies (e.g., Davis et al. 2014; Alatalo et al. 2015; Suess et al. 2017).

Further investigation of the spatial distribution of dust in those quiescent galaxies is likely the next key step to our understanding of how they ceased star formation and remain quiescent. To reach the characteristic scale of star formation and active galactic nucleus (AGN) activities, gravitational magnification is the only chance for us, even with the exquisite sensitivity and angular resolution provided by current facilities.

In this paper, we present our new observations with the Atacama Large Millimeter/submillimeter Array (ALMA) of a massive quiescent galaxy, MRG-M2129 at z = 2.15. MRG-M2129 is located in the sightline of a massive galaxy cluster, MACS2129-0741, at z = 0.57 (Ebeling et al. 2007). For its strong lens magnification by the foreground galaxy cluster, MRG-M2129 is an ideal target to study its stellar and ISM properties in detail. Geier et al. (2013) conducted near-IR spectroscopic observations and found that MRG-M2129 consists of old (~ 1.7 Gyr) stellar populations. In addition, MRG-M2129 is known for several other interesting properties; Toft et al. (2017) revisited the spectroscopic data of Geier et al. (2013) and found ordered rotation in its stellar disk; Newman et al. (2018a) conducted follow-up spectroscopic observations and reported that its core is classified as Seyfert via emission-line diagnostics (but see Sec. 4.2 where we find it likely being a type 2 quasar); Whitaker et al. (2021a) revealed a significant amount of dust from their ALMA Band 6 observations; Akhshik et al. (2022) analyzed HST’s NIR grism data and inferred relatively fast timescale of quenching in its core (~ 0.3 Gyr) among their 8 quiescent galaxies at z ~ 2. By taking advantage of the rich data sets collected by those early pioneering studies, we aim to advance our understanding of quenching in MRG-M2129. With the spatial resolution provided by ALMA and strong lens magnification by the foreground cluster, our observations aim to reveal the distribution of ISM in MRG-M2129 at an unprecedented angular scale, ~ 130 pc, for a quiescent galaxy at this redshift.

Throughout this paper, we adopt the AB magnitude system (Oke & Gunn 1983; Fukugita et al. 1996), cosmological parameters of Ω_m = 0.3, Ω_Λ = 0.7, H_0 = 70 km s^{-1} Mpc^{-1}, and the Chabrier (2003) initial mass function.

2. DATA

2.1. ALMA Cycle 8 observations

Our interferometric observations with Band 6 were executed during ALMA Cycle 8 (2021.1.00847.S, PI T. Morishita) over three separate blocks (October 11, 14, and 15 2021), with the antenna configuration of C43-8. The pointing of our observations is shown in Fig. 1. The choice of Band 6 was made based on two considerations — 1. robust dust estimate by detecting continuum flux at ~ 1.2 mm and 2. spectral coverage of the [C i] 3P_2 → 3P_1 line (rest-frame wavelength 370.42 μm; hereafter [C i]). The observed frequency range is an efficient window for ALMA, without being severely affected by atmospheric absorption, and thus provides a sweet spot for thermal dust emission originating from extra-galactic sources at z ≥ 1. [C i] is a fine structure line and known as an excellent tracer of cold gas in extra-galactic systems, especially at redshifts where the commonly used CO(J=1-0) is not available (Weiß et al. 2003; Walter et al. 2011). In addition, since [C i] is optically thin, it is suited for a wide range of star-forming properties and redshifts (Papadopoulos et al. 2004; Walter et al. 2011; Alaghband-Zadeh et al. 2013).

Each of the four spectral windows was configured with a bandwidth of 0.938 GHz and 1920 frequency channels. We placed one of the spectral windows at 257.1 GHz, targeting the redshifted [C i] line. We centered another spectral window at 256.5 GHz, to cover the CO(7-6) line. The other two spectral windows were placed at 243 GHz and 246 GHz so that we can robustly estimate the continuum level without being contaminated by any bright emission line. The astrometric calibration was done with two quasars (J2258-2758, J2130-0927), and the flux cali-
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Figure 1. (Left:) HST’s RGB composite image of MACS 2129-0741, a cluster of galaxies at $z = 0.57$. The target of our ALMA observations, MRG-M2129, is located in the center of the white square box. Right: Zoom-in image of MRG-M2129 ($50'' \times 50''$). The FoV of our ALMA Band 6 observations is shown by the central square box of $3'' \times 3''$ (also see Figure 2). The FoV of one of the previous Band 6 programs (2018.1.00276.S) is shown with a gray circle ($r \sim 24''$) for comparison.

The observations were completed without raising severe flags, resulting in the astrometric uncertainty of $\sim 5.5\%$ of the beam size. The on-source exposure time was 139 minutes.

The data are reduced by using the public version of CASA (v.6.4.4). To inspect emission lines, we first subtract the continuum in the uv-space by using the uvcontsub task of CASA after manually flagging visibility data. For robust continuum estimate, we exclude the spectral window that covers the [C i] line but still use the one for the CO line, because the contribution from the line turned out to be negligible (see below). The estimated continuum flux is extrapolated to the spectral window of [C i] and subtracted from it. We examined the results with two continuum models with a different polynomial order, 0 (constant) and 1, and found that the latter presents smaller residual fluxes in the two spectral windows located at line-free frequency ranges. We then run the tclean task of CASA on the continuum subtracted visibility map, with a velocity resolution element $\sim 50\text{ km / s}$. While various sets of parameters are examined, we do not confidently detect the [C i] nor CO(7-6) lines in any case (Appendix A).

For continuum imaging, we run the tclean task of CASA with two different setups. One opts for high-resolution imaging, with briggs weighting, the robust parameter set to 0.5, and the final pixel scale to 0''.01. The final beam size is 0''.077 $\times$ 0''.060 with beam angle of $-70\degr$. The image is used to infer flux distribution but not for absolute flux measure. For flux measurement, we create a continuum image with a low-resolution setup, with natural weighting, where the robust parameter is set to 2.0, and the pixel scale to 0''.1, and taper size of 0''.3, where the beam size is 0''.145 $\times$ 0''.136. Since no confident lines are identified over the frequency range, we use the whole visibility data to make a continuum image to accommodate higher signal-to-noise ratios (but see Section 3.3).

To supplement our spectral energy distribution analyses in Sec. 3.3, we retrieve archival data taken by ALMA with Band 3 (2016.1.01591.S, PI J. Zabl) and Band 6 (2018.1.00035.L, PI K. Kohno; 2018.1.00276.S, PI K. Whitaker). The continuum images of each program were retrieved through the ALMA Science Archive. One of the Band 6 observations shows a clear but unresolved detection of a source (Whitaker et al. 2021a). We do not detect continuum emission in the other two data sets and thus use those to infer flux upper limits.

2.2. Supplemental HST and Spitzer images

We collect the optical to near-infrared images taken in a series of past campaigns, including HST’s CLASH (Postman et al. 2012), GLASS (Schmidt et al. 2014; Treu et al. 2015), REQUIEM, (Akhshik et al. 2021) and Spitzer SURFSUP survey (Bradač et al. 2014; Huang et al. 2016).

For HST images, the raw data are acquired through the MAST archive and processed by an imaging reduc-
Figure 2. Top: Multi-band images of MRG-M2129 in a $3'' \times 3''$ cutout (same size as the white square in Fig. 1) — ALMA 1.2 mm continuum created with the high-resolution setup (Sec. 2.1), HST F160W, F105W, F775W, and pseudo RGB images, from left to right. The continuum flux of ALMA is overlaid in each of the HST images, where the contour represents 3, 4, 5, 6, and 7 $\sigma$. The beam size is shown at the bottom left of the ALMA image. Bottom: zoomed-in version of the images in the top row in a box of $1'' \times 1''$, corresponding to the white square box in the top panel. The flux centroid position measured in the F160W image (Sec. 3.1) is shown in the 1.2 mm image (cross symbol).

3. RESULTS

Table 1. Flux centroids of MRG-M2129.

| Images         | R.A.          | Decl.         |
|----------------|---------------|---------------|
| HST F160W      | 21:29:22.3446 | -07:41:30.966 |
| ALMA 1.2 mm    | 21:29:22.3433 | -07:41:30.907 |

Note— The associated systematic uncertainties are $\sim 37.5$ mas and 5.5 mas for the HST F160W and ALMA 1.2 mm images, respectively (Sec. 3.1).
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3.1. Morphology in the 1.2 mm continuum

In Fig. 2, we show the high-resolution 1.2 mm continuum image of MRG-M2129, which traces thermal emission from dust. With the spatial resolving power of ALMA combined with lens magnification by the foreground cluster (by a factor of µ ∼ 4.5), the image reveals the morphology of the source at the resolution of ∼ 60 pc in radius, an unprecedented resolution for a quiescent galaxy at z > 0.1. The continuum flux is detected at 7.9σ at the flux peak position. The apparent size of the emission is measured by the Two-D Fitting Tool provided by CASA, to be ∼ 0.″22 ± 0.03 and ∼ 0.″10 ± 0.02 along the major and minor axis, respectively, which is sufficiently resolved by our primary beam size. While the continuum morphology is elongated almost along the vertical axis (i.e. South-East to North-West), this is mostly due to the lens magnification effect along the same direction (see below).

The HST images of the same region are shown in Fig. 2. From the comparison of these images, we notice that the flux peak position in the 1.2 mm image is located slightly off from the flux peak of the F160W image, which approximately traces the stellar mass distribution. We measure the flux centroid in each image by using centroid_quadric of astropy (Table 1). The offset is measured as 62 mas.

It is noted that the two images have been independently aligned to the world coordinate system (WCS). The typical uncertainty of astrometry in ALMA, which was calibrated by using a quasar, is calculated by \( \theta_{beam}/SN/0.9 \), where \( \theta_{beam} \) is the Full-Width Half Maximum synthesized beam size in arcseconds and SN is the source signal-to-noise ratio. This provides the pointing accuracy of our observations, ∼ 10.6 mas. There is no flag raised regarding the calibration. The HST images have been aligned to the GAIA DR2 by using a package tweakreg. For the alignment, we identified seven stars in the field by cross-matching with the GAIA DR2 catalog. The final standard deviation of the residual shifts is 37.5 mas. After taking those systematic uncertainties into account (Δ = 39.0 mas), the measured offset is ∼ 1.6σ significant and thus we consider this as tentative.

To infer the physical distance of the observed offset, we correct lens magnification in both images. We use the lens magnification model adopted in Newman et al. (2018b), which was originally presented in Monna et al. (2017). The source plane images are shown in Fig. 3. The physical distance between the two centroids is measured in the source image and inferred to be ∼ 169 ± 105 pc.

We fit a two-dimensional Gaussian to the source plane image and measure the physical size of the 1.2 mm emission to be ∼ 0.44 kpc and 0.22 kpc along the major and minor axes, respectively, characterizing its compact morphology.

In Fig. 2, we also show the HST/ACS F775W image, which traces young stellar populations (at rest-frame ∼ 0.25 μm). We find that the F775W flux distribution does not overlap with the ALMA continuum. This suggests that short-wavelength emission is attenuated at the position of the dust continuum peak, which also assures that the detected dust continuum is likely associated with the system, not a chance superposition.

With the low-resolution image, we measure the total 1.2 mm flux of 0.19 ± 0.03 mJy by using a circular aperture of r = 0.″14. The flux uncertainty is estimated by the RMS of fluxes in a set of r = 0.″14 apertures randomly placed around (but not on) the emission within 0.″26 from the peak position. The measured flux is slightly larger than the previous Band 6 measurement in Whitaker et al. (2021a), 0.16 ± 0.02 mJy (K. Whitaker, priv. comm.), but this reflects the fact that they were taken at different frequencies (1.2 and 1.3 mm). The measured fluxes are in reasonable agreement given the spectral curve of dust emission (see Sec. 3.2).

It is worth noting that the FoV of our observations is much smaller than the one in Whitaker et al. (2021a), where the maximum recoverable scale is ∼ 9.5″ with the beam size of ∼ 1″ (Fig. 1). The agreement in the measured fluxes of the two observations implies that the dust emission seen in the previous study mostly originates in the compact region revealed here.

3.2. Dust mass estimates

In the previous section, we presented a new flux measurement of MRG-M2129 at 1.2 mm. To validate the consistency with the previous measurement at 1.3 mm...
Figure 4. (Top) Spectral energy distribution (SED) of integrated fluxes of MRG-M2129. The best-fit model template is shown in a solid black line. Each component of the fitting template is shown with a different color scheme as in the label. Data points are shown with 2σ errors (blue symbols). 2σ upper limits are shown for non-detection. Normalized residual, (data – model)/data, is shown in the bottom panel with the same symbols as in the top panel. (Bottom) Posterior distributions of the parameters used in our SED fitting analysis.

(Whitaker et al. 2021a), we here estimate dust mass by fitting a modified blackbody template to our 1.2 mm flux data point. By following Bianchi (2013), dust mass is derived by:

$$M_d = \frac{f_\nu D_L^2}{\kappa_{abs} B_\nu(T_d)}$$

(1)

for the observed flux, $f_\nu$, where $D_L$ is the luminosity distance to the source, $B_\nu(T_d)$ the Planck function at the temperature of $T_d$, $\kappa_{abs}$ is the grain absorption cross-section per unit mass, or called emissivity. We use the following formula from Scoville et al. (2014):

$$\kappa_{abs} = \kappa_{abs}(\nu_0) \times \left( \frac{\nu}{345} \right)^\beta.$$

(2)

where $\kappa_{abs} = 0.0484$ m kg$^{-2}$ and $\nu_0$ is rest-frame frequency. We use $T_d = 20$ K and $\beta = 1.8$, the same values used in Whitaker et al. (2021a). With those parameters, we obtain $M_d \sim 2 \times 10^6 M_\odot$ (uncorrected for magnification), which is in excellent agreement with one by Whitaker et al. (2021a, 2 $\times 10^6 M_\odot$). This agreement indicates that the flux probed in our observations represents the whole flux revealed in the previous Band 6 observations that cover the entire stellar extent of MRG-M2129 (Fig. 1).

To characterize the FIR properties of MRG-M2129 in further detail, we attempt to include multiple FIR

Table 2. Best-fit parameters of SED modeling of MRG-M2129

| Parameter | Best-fit value |
|-----------|----------------|
| log($M_*$[$M_\odot$] $\times \mu$) | 11.78 $\pm$ 0.10 |
| log($M_d$[$M_\odot$] $\times \mu$) | 8.36 $\pm$ 0.10 |
| log(SFR[$M_\odot$yr$^{-1}$] $\times \mu$) | 0.64 $\pm$ 0.31 |
| log(sSFR[yr$^{-1}$]) | $-11.20 \pm 0.36$ |
| log(age[Myr]) | 0.20 $\pm$ 0.17 |
| log($Z/Z_\odot$) | $-0.68 \pm 0.37$ |
| $T_d$[K] | 26.77 $\pm$ 1.12 |
| log($L_{IR}$[$L_\odot$] $\times \mu$) | 11.51 $\pm$ 0.17 |
| log($U_{min}$) | 0.98 $\pm$ 0.26 |
| log($\gamma_e$) | $-2.36 \pm 0.46$ |
| log($Q_{PAH}$) | $-0.15 \pm 0.43$ |
| log($f_{AGN, bol}$) | $-3.87 \pm 1.00$ |
| log($\tau_{AGN}$) | 1.35 $\pm$ 0.34 |
| $\hat{\tau}_1$ | 1.86 $\pm$ 0.70 |
| $\hat{\tau}_2$ | 0.25 $\pm$ 0.10 |

Note—$\mu$: Magnification factor. $\hat{\tau}_1$: Dust optical depth of the birth cloud. $\hat{\tau}_2$: Dust optical depth of the diffuse ISM. $T_d$: Dust temperature. $U_{min}$: Minimum starlight intensity that illuminates the dust. $\gamma_e$: Relative fraction of dust heated at a radiation field strength of $U_{min}$ and dust heated at $U_{min} < U \leq U_{max}$. $Q_{PAH}$: Percentage fraction of total dust mass that is in the polycyclic aromatic hydrocarbons (PAHs). $L_{IR}$: Infrared bolometric luminosity summed over 8–1000 μm. $f_{AGN, bol}$: Fraction of the bolometric luminosity that is contributed by the AGN dusty torus emission. $\tau_{AGN}$: Optical depth of the AGN dusty torus.
data points collected from the literature. This supplement dataset spans from MIPS 24 μm to ALMA Band 3 (2.9 mm), as well as rest-frame UV-to-IR data (Sec. 2.1). While most FIR data points from literature are non-detection, flux upper limits of those data points still add constraints on FIR modeling. Three UV-filter images (F225W, F275W, F336W) show positive fluxes but at $S/N \lesssim 2$. We visually inspected the images and only found slight fluctuation in background value around the position of MRG-M2129 but no confident detection. We thus exclude those three data points from our SED fitting analyses.

For FIR modeling, it is critical to cover a wide range of wavelengths and take into account of energy balance between UV–optical and infrared. For this reason, we have used a SED modeling code, pixEdif (Abdurro’uf et al. 2022). pixEdif adopts Flexible Stellar Population Synthesis (FSPS; Conroy et al. 2009), assuming the Chabrier (2003) initial mass function, double power-law star formation history model, two-component dust attenuation law of Charlot & Fall (2000), Nenkova et al. (2008) AGN dusty torus emission model, and dust emission model of Draine & Li (2007). We mainly adopt the same priors as those assumed in Abdurro’uf et al. (2022), except for the following parameters: the power-law index of the dust attenuation model $n=[-1.5, 0.4]$, stellar age $\log(\text{age}[\text{Gyr}])=[-2.0, 0.48]$, and the exponential time scale of star formation $\log(\tau[\text{Gyr}])=[-1.0, 1.5]$. Similarly to Abdurro’uf et al. (2022), we assume uniform priors within those ranges. The interested reader is referred to Abdurro’uf et al. (2022) for the full description of the parameters. For the fitting method, we apply the Markov Chain Monte Carlo (MCMC) and use the number of walkers and step per walker of 100 and 1000, respectively.

In Fig. 4, we show the best-fit model along with the parameter distribution. In Table 2, we summarize the best-fit parameters. The best-fit result provides a slightly larger dust mass $\left(2.3 \pm 0.5 \times 10^8 \, M_\odot\right)$ and dust temperature $\left(26.8 \pm 1.6 \, \text{K}\right)$ than those derived or assumed in the analysis above. The derived temperature is in fact larger than the median value (≈ 21–23 K) of quiescent galaxies at $1 < z < 2.5$ (Gobat et al. 2018; Magdis et al. 2021), which implies that MRG-M2129 is a young, recently quiescent galaxy compared to the average population used in those studies (see also Sec. 4.2). Despite the inclusion of FIR data and different reduction of HST images, the derived stellar mass $\left(\log M_*/M_\odot \times \mu = 11.78^{+0.13}_{-0.10}\right)$ is broadly consistent with two previous measurements — $11.62 \pm 0.05$ (Newman et al. 2018a; Whitaker et al. 2021a) and $11.8 \pm 0.20$ (Toft et al. 2017). In what follows, we use the dust and stellar masses derived with pixEdif.

We obtain dust-to-stellar mass ratio of $3.8^{+1.0}_{-0.7} \times 10^{-4}$. This is considerably high among those of local early-type galaxies ($\lesssim 10^{-5}$; e.g., Smith et al. 2012) but similar to the median values of quiescent galaxies at $z \gtrsim 1$ (Magdis et al. 2021, which adopt the Draine & Li 2007 model for dust mass estimate). Despite the current star formation status of MRG-M2129 ($\text{SFR} \lesssim 10^{-11} \, \text{yr}^{-1}$), the observed high abundance of dust indicates that MRG-M2129 experienced quenching in a relatively short time scale, possibly short enough before dust destruction processes become effective. This conclusion is consistent with the star formation history inferred by Akhshik et al. (2022), where they estimate the declining time scale of star formation to be $\sim 0.3 \, \text{Gyr}$ in the central region. We discuss this in Sec. 4.

It is noted that our use of integrated photometry for SED fitting implicitly assumes that the energy balance between UV-optical and FIR is conserved in the entire system. However, the assumption is not obviously validated for the case of MRG-M2129, where dust distribution is not co-spatial as the stellar emission. To investigate this, we repeat SED fitting process for the central region, by using only resolved images (i.e. HST and our Band 6 ALMA continuum). We extract fluxes across those images in a common region, defined by an $r < 0\arcsec 5$ circular aperture centered on the dust continuum peak. The resulting dust and stellar masses in the central region are $3.0^{+1.2}_{-2.0} \times 10^8 \, M_\odot$ and $3.1^{+2.4}_{-1.1} \times 10^{11} \, M_\odot$, respectively. By adding the remaining stellar mass at the outer region ($\sim 4 \times 10^{11} \, M_\odot$; derived only with the HST images), we obtain dust-to-stellar mass ratio of $\sim 4.2 \times 10^{-4}$, which is consistent with our original estimate above within the uncertainty. The increase in the uncertainties of dust and stellar mass estimates here is attributed to the reduced number of data points.

### 3.3. Inference on molecular gas mass

In this subsection, we aim to place an upper limit on the molecular hydrogen mass in MRG-M2129. We follow a similar procedure presented in Morishita et al. (2021). We first estimate the RMS of each low-resolution cube layer (i.e. two-dimensional image at each frequency) by using the instat task of CASA. We then integrate the derived RMS values over the line width, $\Delta v = 2\sigma_v$, around the systemic redshift of MRG-M2129. We set $\sigma_v = 261 \, \text{km/s}$, which is the stellar velocity dispersion measured in Newman et al. (2018a). Since the dust emission is spatially resolved, we also scale the RMS values by integrating over the area of the dust detection, defined by an ellipse of $\sim 0\arcsec 47 \times 0\arcsec 26$, corresponding to
5σ size obtained in two-dimensional gaussian fit. With these, we obtain a 3σ upper limit of the [C\textsc{ii}] velocity integrated flux $I_{\text{C\textsc{ii}}}/ < 16.3 \text{ mJy km/s}$. We also repeated the same process in the negative cube and found a consistent flux limit.

We then use the recipe described in Man et al. (2019); Jiao et al. (2019), to convert the velocity integrated flux into molecular carbon mass $M_{[\text{C}\textsc{ii}]}$ by

$$L'_{[\text{C}\textsc{ii}]/(2-1)} \doteq 3.25 \times 10^3 \left[ \frac{D_L^2}{(1+z)} \right] \left( \frac{L_{\text{C\textsc{ii}}}/(2-1), \text{rest}}{100 \text{ GHz}} \right)^{-2} I_{\text{C\textsc{ii}}}/,$$  

$$M_{[\text{C}\textsc{ii}]} \doteq 4.566 \times 10^{-4} Q(T_{\text{ex}}) \frac{1}{5} e^{62.5/T_{\text{ex}}} L'_{[\text{C}\textsc{ii}]/(2-1)}$$  

under optically thin and local thermodynamically equilibrium assumptions. We set the [C\textsc{ii}] excitation temperature $T_{\text{ex}}$ to 19.7 K, the median value of those of local star-forming galaxies in Jiao et al. (2019). $Q_{\text{ex}} = 1 + 3e^{-T_1/T_{\text{ex}}} + 6e^{-T_2/T_{\text{ex}}}$ is the C\textsc{ii} partition function, with $T_1 = 23.6$ K and $T_2 = 62.5$ K.

Lastly, we convert the derived atomic carbon mass into molecular hydrogen mass by using a conversion factor, $X[\text{C}\textsc{ii}]/X[\text{H}_2]$. This factor is known to have a wide range, from $\sim 3 \times 10^{-5}$ (Weiß et al. 2003; Papadopoulos et al. 2004) to $8.4 \times 10^{-5}$ (Walter et al. 2011, derived for SMGs and quasars), which may depend on redshifts, stellar populations, and/or star-forming phase (Jiao et al. 2019). Here, for the consistency of the $T_{\text{ex}}$ value used above, we adopt the median value of the sample in Jiao et al. (2019), $2.5 \times 10^{-5}$, which leads to molecular hydrogen mass $M_{\text{H}_2} \lesssim 1.4 \times 10^{10} M_\odot$ ($3\sigma$; uncorrected for magnification). By taking the face value, this gives a molecular gas-to-dust mass ratio $\delta_{\text{CDDR}} \lesssim 60$, which is smaller than quiescent galaxy populations at $z \sim 2$ ($\gg 100$; see the following section). Adopting a higher value for the conversion factor would lower the hydrogen mass estimate.

The derived limit then gives molecular gas-to-stellar mass ratio, $f_{\text{H}_2} = M_{\text{H}_2}/M_\star < 2.3\%$ ($3\sigma$). It is noted, however, that our upper limit of $L_{[\text{C}\textsc{ii}]}$ locates at the upper bound of the main sequence galaxies presented in Valentino et al. (2020b). Therefore, the non-detection of [C\textsc{ii}] in our data cube is still reasonable for its $L_{\text{IR}}$ at the depth of our observations.

In Fig. 5, we show the derived upper limit on the gas-to-stellar mass ratio of MRG-M2129, along with those of quiescent galaxies in the literature (Gobat et al. 2018; Bezanson et al. 2019; Magdis et al. 2021; Caliendo et al. 2021; Whitaker et al. 2021a). The diagram illustrates the current pace of gas consumption in galaxies, i.e. gas depletion time, defined by $t_{\text{depl}} = M_{\text{H}_2}/SFR$. Interestingly, our upper limit on the gas mass fraction of MRG-M2129 is $\sim 2\times$ lower than the previous measurement by Whitaker et al. (2021a), making its gas depletion time decrease by the same factor. The tension is primarily attributed to the assumption on gas-to-dust ratio, where a constant gas-to-dust ratio ($= 100$) was adopted in Whitaker et al. (2021a). A similar value for the ratio was adopted in Gobat et al. (2018); Magdis et al. (2021); Caliendo et al. (2021), whereas Bezanson et al. (2019) derived the upper limit from non-detection of CO(2-1).

### Table 3. Integrated photometric fluxes of MRG-M2129, in units of $\mu$Jy.

| Filter          | Wavelength | Flux  |
|-----------------|------------|-------|
| HST ACS WFC F435W | 0.43       | $< 0.519$ |
| HST ACS WFC F475W | 0.48       | $0.627 \pm 0.309$ |
| HST ACS WFC F555W | 0.54       | $0.756 \pm 0.236$ |
| HST ACS WFC F606W | 0.59       | $0.749 \pm 0.249$ |
| HST ACS WFC F625W | 0.63       | $0.895 \pm 0.382$ |
| HST ACS WFC F775W | 0.77       | $1.804 \pm 0.500$ |
| HST ACS WFC F814W | 0.80       | $2.169 \pm 0.185$ |
| HST ACS WFC F850LP | 0.89      | $4.080 \pm 0.571$ |
| HST WFC3 IR F105W | 1.05       | $6.507 \pm 0.230$ |
| HST WFC3 IR F110W | 1.15       | $13.027 \pm 0.180$ |
| HST WFC3 IR F125W | 1.25       | $18.420 \pm 0.300$ |
| HST WFC3 IR F140W | 1.40       | $28.015 \pm 0.174$ |
| HST WFC3 IR F160W | 1.54       | $35.207 \pm 0.240$ |
| HST WFC3 UVIS F225W | 0.24      | $< 1.171$ |
| HST WFC3 UVIS F275W | 0.27      | $< 1.183$ |
| HST WFC3 UVIS F336W | 0.34      | $< 0.654$ |
| HST WFC3 UVIS F390W | 0.39      | $< 0.352$ |
| SPITZER IRAC CH1 | 3.55       | $87.000 \pm 16.062$ |
| SPITZER IRAC CH2 | 4.51       | $99.900 \pm 18.434$ |
| SPITZER IRAC CH4 | 7.89       | $< 39.680$ |
| SPITZER MIPS CH1 | 23.44      | $< 68.200$ |
| ALMA Band6 (2018.1.00035.L) | 1140.45 | $< 248.000$ |
| ALMA Band6 (This study) | 1199.76 | $191.000 \pm 55.000$ |
| ALMA Band6 (2018.1.00276.S) | 1288.52 | $156.000 \pm 33.000$ |
| ALMA Band3 (2016.1.01591.S) | 2948.53 | $< 16.860$ |

Note—2σ flux errors are quoted for those detected with S/N $> 2$. 2σ upper limits are quoted for the rest. Magnification is not corrected.

### 4. DISCUSSION

#### 4.1. What causes the observed low gas-to-dust ratio?

We start our discussion on the absence of [C\textsc{ii}] emission in our data. Based on our new ALMA observations and multi-band analyses, we found a significant amount of dust in MRG-M2129. The derived $3\sigma$ upper limit on the gas-to-dust mass ratio, $\delta_{\text{CDDR}} \lesssim 60$, which is, at face value, low for quiescent populations. For example,
Whitaker et al. (2021b) show a wide range of to two different methods of deriving gas mass (Sec. 3.3). The difference is attributed to two different methods of deriving gas mass (Sec. 3.3). It is noted that two measurements for MRG-M2129 derived in this study (red star; Table 2) and Whitaker et al. (2021a, orange star) are shown separately. The difference is attributed to two different methods of deriving gas mass (Sec. 3.3).

Whitaker et al. (2021b) show a wide range of $\delta_{\text{GDR}} \sim 10$ to $>10000$ of galaxies taken from the SIMBA simulation (Davé et al. 2019). However, there is a decreasing trend of $\delta_{\text{GDR}}$ with sSFR, such that more quiescence leads to a higher value. With that taken into account, the value found in MRG-M2129 is considered to be relatively low among quiescent galaxies.

Given the observed quiescence of MRG-M2129, it is unlikely to expect that dust is decoupled from gas. By following the argument in McKinnon et al. (2018), we obtain the decoupling time $\sim 3 \times 10^5$ yr, which is considered to be much smaller than the time scale of its last star formation (Akhshik et al. 2021, also Sec. 4.2), and thus we consider that gas should be coupled with dust. Therefore, the absence of [C II] implies that star formation in MRG-M2129 is somehow suppressed while there still exists a gas reservoir.

One possible explanation for the observed low $\delta_{\text{GDR}}$ value is that the gas content is present but in a warm phase, probably at a much higher temperature than the excitation temperature of [C II] ($\sim 20-45$ K; Walter et al. 2011; Jiao et al. 2019). The presence of an active nucleus in its center (Newman et al. 2018a, also Sec. 4.2) as a heating source supports this interpretation. It is also noted that the gas mass limit here is derived under the assumption that [C II] is co-spatial with dust. For example, Gullberg et al. (2018) found that [C II] is $\sim 1.6 \times$ more extended than dust distribution in SMGs.

The observed dust temperature ($\sim 27$ K; Table 2) can be used as an indicator of the dust-heating radiation. Hirashita & Chiang (2022, submitted) provide the expected dust temperature under given $\Sigma_{\text{SFR}}$ (star formation rate surface density) and $\Sigma_{\text{dust}}$ (surface density) with an assumption that the radiation from stars formed in the current episode of star formation is the dominant dust-heating source. Using the (global) SFR and the total dust mass (Table 2) divided by the surface area, we obtain $\Sigma_{\text{SFR}} \sim 3.4 \times 10^{-1}$ $M_\odot$ yr$^{-1}$ kpc$^{-2}$ and $\Sigma_{\text{dust}} \sim 1-3 \times 10^8 M_\odot$ kpc$^{-2}$ after correcting for the lensing effect. By using those values, we derive the expected dust temperature of 20 K. Note that the local $\Sigma_{\text{SFR}}$ at the position of the dust cloud is expected to be much lower given the observed color distribution of MRG-M2129. This means that the observed dust temperature is considered to be the upper limit expected from the stellar heating. Therefore, we conclude that the stellar heating alone cannot explain the observed dust temperature in this object. This is consistent with the argument above that an AGN is significantly heating the surrounding materials including the dust cloud.

It is noted that the observed dust temperature is, despite the presence of an AGN, rather comparable to those in star-forming galaxies. However, this is not unexpected. For example, Chen et al. (2021) found no significant difference in dust temperature of AGN host and non-host galaxies at $1 < z < 3$ (also Sinha et al. 2022). The similarity in dust temperature of the two populations might be explained by a rapid dust destruction process in the vicinity of an AGN, where the observed dust temperature reflects the one that is not significantly affected (and thus remained) from the radiation.

4.2. The presence of an active central black hole and its impact on regulating star formation

The unprecedented resolution provided by the combination of ALMA and lens magnification enabled us to identify compact dust emission in the center of MRG-M2129. The revealed nature of the dust component is of particular interest in the context of massive galaxy quenching at this redshift.

In Sec. 4.1 we concluded that MRG-M2129 is likely to harbour an AGN, as was originally suggested by Newman et al. (2018a, in their Section 7.2). To further in-

\[ \text{Figure 5. Distribution of quiescent galaxies at } z \sim 2 \text{ in the molecular gas-to-stellar ratio (} M_{\text{H}_2}/M_\star \text{)}-\text{specific star formation rate (SFR}/M_\star \text{)} \text{ plane. For those undetected, } 3 \sigma \text{ upper limits of the gas-to-stellar mass ratio are shown. It is noted that two measurements for MRG-M2129 derived in this study (red star; Table 2) and Whitaker et al. (2021a, orange star) are shown separately. The difference is attributed to two different methods of deriving gas mass (Sec. 3.3).} \]
vestigate the nature of the active central engine, we estimate the bolometric thermal luminosity of the accretion flow toward an AGN. We start with the [O III] line luminosity measured in Newman et al. (2018a). Dust attenuation is corrected by applying the measured Balmer decrement in the same study (Hα/Hβ = 3.2), by following the recipe presented in Lamastra et al. (2009). We then convert the [O III] luminosity by using an empirical relation presented in Punsly & Zhang (2011) and obtain bolometric luminosity $L_{\text{bol}} \sim 3.2 \times 10^{45}$ erg / s (lens magnification corrected), which is much more powerful than typical Seyfert and in the regime of (type 2) quasars (e.g., Hopkins et al. 2007; Shen et al. 2020). More recently, Man et al. (2021) revealed a tentative feature of outflows in its Mg I and Mg II lines, supporting our interpretation here.

The presence of an active nucleus is the key to our understanding of possible quenching mechanisms in MRG-M2129. Strong outflows from the central AGN seem to be able to explain the observed properties presented here — spatial offset of dust emission from the stellar center, high dust temperature, and absence of [C i]. Since dust grains are easily heated beyond their sublimation temperature and destroyed in the vicinity of a central black hole (e.g., Barvainis 1987; Ishibashi & Fabian 2014), the observed offset of dust may be an apparent effect; it may instead reflect the absence of dust in the very center of MRG-M2129. Saito et al. (2022) also revealed similar features as here in their high-resolution imaging of NGC 1068, a nearby Seyfert galaxy—centrally concentrated dust emission and [C i] cavity. Through the comparison with several models, they concluded that the observed features are likely due to the interaction of the jet and ionized gas outflow with the galaxy disk originaiting from negative AGN feedback. While the lack of [C i] detection in our study prevents us from reaching the same conclusion, the observed properties of MRG-M2129 are suggestive of the presence of strong outflows from the central black hole.

The conclusion here is reached independently from the one in Sec. 4.1, which is based on the observed $\delta_{\text{GDR}}$ and dust temperature. Those two independent conclusions lead us to the exceptionally unique nature of MRG-M2129, that is, the central black hole is still active whereas the overall system is characterized as quiescent. A picture emerges that we may be witnessing the last breath of its central engine in a recently quenched system.

It is also noted that only a handful of gravitationally lensed type 2 QSOs are known in the literature (e.g., Leung & Riechers 2016). With its strong magnification, MRG-M2129 makes one of the excellent targets that enable in-depth investigation of e.g., co-evolution of supermassive black holes and host galaxies.

5. SUMMARY

In this study, we presented new ALMA observations of MRG-M2129, a massive quiescent galaxy at $z = 2.15$ behind the cluster of galaxies MACS 2129-0741. With the combination of the angular resolution power of ALMA and the gravitational lensing effect, we revealed the spatial distribution of dust in MRG-M2129 at an unprecedented physical scale, $\sim 130$ pc.

Our data revealed significant detection of very compact continuum emission at $1.2$ mm, while [C i], as a tracer of molecular hydrogen, was not detected. From this, we placed a $3\sigma$ upper limit on the gas-to-dust mass ratio, $\delta_{\text{GDR}} < 60$, which is $2 \times$ smaller than the typical value ($\sim 100$) often assumed for quiescent galaxies at $z \sim 2$ in the literature. Our finding supports the idea of there being a wide range of $\delta_{\text{GDR}}$ in galaxies at this redshift as seen in numerical simulations. This is an important implication, as in the literature often a uniform value is adopted to predict the amount of molecular gas content from dust mass measurements. Follow-up observations of recently quenched galaxies will help us understand if the observed low gas-to-dust ratio is common among those galaxies in the early universe.

Our data revealed its compact dust distribution in a quiescent galaxy at unprecedented angular resolution. Based on the observed properties, supplemented by previous spectroscopic observations, we discussed possible quenching mechanisms that occurred in MRG-M2129. The observed properties suggest that outflows from the central active galactic nucleus have played a key role in regulating star formation in MRG-M2129. All features characterize MRG-M2129 as an exceptionally unique object, which will allow us in-depth investigation of galaxy quenching and co-evolution of supermassive black holes and host galaxies.

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APPENDIX A

In Fig. 6, we show the velocity map of MRG-M2129, around the expected velocity position of [C i]. The data cube is generated by running the tclean task of CASA on the continuum subtracted visibility data in the way described in Sec. 2.1, with natural weight, robust parameter of 0.5, and no tapering. While there are positive fluxes identified in some velocity elements (e.g., at \( v = 246 \) km/s), none of these are detected confidently over more than one velocity element.

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Figure 6. Velocity maps of [C i] in MRG-M2129. The velocity maps are shown at an interval of $\Delta v = 50$ km/s with respect to the [C i] line at the redshift of MRG-M2129. Each stamp has size of $1.5'' \times 1.5''$. The contour levels in black solid lines represent positive fluxes at $3\sigma$ and $4\sigma$, in white dashes lines negative fluxes. No confident detection of the [C i] line is identified.

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