

# The kiloparsec-scale gas kinematics in two star-forming galaxies at $z \sim 1.47$ seen with ALMA and VLT-SINFONI

J. Molina,<sup>1\*</sup> Edo Ibar,<sup>2</sup> I. Smail,<sup>3</sup> A. M. Swinbank,<sup>3</sup> E. Villard,<sup>4</sup> A. Escala,<sup>1</sup> D. Sobral,<sup>5</sup>  
T. M. Hughes<sup>2,6,7,8</sup>

<sup>1</sup>*Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile*

<sup>2</sup>*Instituto de Física y Astronomía, Universidad de Valparaíso, Avda. Gran Bretaña 1111, Valparaíso, Chile*

<sup>3</sup>*Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK*

<sup>4</sup>*Joint ALMA Observatory/ESO, Avenida Alonso de Córdova 3107, Vitacura, Santiago, Chile*

<sup>5</sup>*Department of Physics, Lancaster University, Lancaster, LA1 4YB, UK*

<sup>6</sup>*CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, China*

<sup>7</sup>*School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, China*

<sup>8</sup>*Chinese Academy of Sciences South America Center for Astronomy, China-Chile Joint Center for Astronomy, Camino El Observatorio #1515, Las Condes, Santiago, Chile*

Accepted XXX. Received YYY; in original form ZZZ

## ABSTRACT

We present Atacama Large Millimeter/submillimeter Array (ALMA) CO( $J = 2 - 1$ ) observations of two main-sequence star-forming galaxies at  $z \sim 1.47$  taken from the High-Z Emission Line Survey (HiZELS). These two systems have been previously reported to be molecular gas rich  $f_{\text{H}_2} \equiv M_{\text{H}_2}/(M_{\text{H}_2} + M_{\star}) \sim 0.8$ . We carried out a follow-up study to resolve, at  $\sim$ kpc-scales, the CO emission. These new observations are combined with our earlier ALMA observations (sensitive to diffuse CO emission) and compared with our previous  $\text{H}\alpha$ -based study at matched spatial resolution. One target is marginally resolved in CO(2-1), showing complex dynamics with respect to the ionised gas traced by  $\text{H}\alpha$ . While the other source is spatially resolved, enabling a detailed exploration of its internal dynamical properties. In this system, both gaseous phases show similar spatial extension, rotation velocities and velocity dispersions ( $V_{\text{rot}} \sim \sigma_v \sim 100 \text{ km s}^{-1}$ ) suggesting a rotational velocity to velocity dispersion ratio consistent with unity. By comparing the ionized and molecular gas tracers through the use of a two-dimensional kinematic model, we estimate a median depletion time  $\tau_{\text{dep}} = 2.3 \pm 1.2 \text{ Gyr}$  for the galaxy as a whole. This value is in agreement with the average  $\tau_{\text{dep}}$  value observed in local star-forming galaxies at similar spatial scales. Using a thick-disk dynamical modelling, we derive a dynamical mass  $M_{\text{dyn}} = (1.59 \pm 0.19) \times 10^{11} M_{\odot}$  within  $\approx 6 \text{ kpc}$ . This suggests a dark matter fraction ( $f_{\text{DM}} \equiv M_{\text{DM}}/M_{\text{dyn}}$ ) of  $0.59 \pm 0.10$ , in agreement with the average  $f_{\text{DM}}$  value derived from stacked rotation curve analysis of galaxies at similar redshift range.

**Key words:** galaxies: ISM – galaxies: high-redshift – galaxies: kinematics and dynamics – galaxies: star formation – galaxies: evolution

## 1 INTRODUCTION

Understanding how galaxies form and evolve over cosmic time is a major goal in modern astrophysics. Surveys have shown that there is a decline in the overall cosmic star-formation rate density since  $z \sim 2$  (e.g. Madau et al. 1996; Sobral et al. 2013a; Khostovan et al. 2015) which coincides with the decrease of the average fraction of molecular gas mass in galaxies (e.g. Tacconi et al. 2010; Geach et al. 2012; Carilli & Walter 2013). This behaviour is thought to match the cosmic evolution of the mass in stars, and the molecular gas content ( $M_{\text{H}_2}$ ) of the Universe, hence it provides a logical interpretation

for the interplay between, perhaps, the main actors controlling the growth of galaxies (e.g. Madau & Dickinson 2014).

At the peak epoch of the cosmic star formation activity ( $z \sim 2 - 3$ ), spatially-resolved observations of galaxies have mostly come from large *Hubble Space Telescope* (HST) and Integral Field Unit (IFU) surveys (e.g. Koekemoer et al. 2011; Brammer et al. 2012; Law et al. 2012b). The latter trace the ionized gas content in seeing limited conditions ( $\sim 0''.6$  in  $K$ -band, e.g. Sobral et al. 2013b; Wisnioski et al. 2015; Stott et al. 2016; Turner et al. 2017; Johnson et al. 2018). Although adaptive optics (AO)-aided IFU observations have delivered  $\sim 0''.15$  ( $\sim$ kpc-scale) spatial resolution data on smaller galaxy samples (e.g. Förster Schreiber et al. 2009; Swinbank et al. 2012a; Molina et al. 2017; Förster Schreiber et al.

\* E-mail: jumolina@das.uchile.cl

TABLE 1: ALMA OBSERVATIONAL SETUP

**Table 1.** ALMA Cycle-5 observations. These data have been concatenated with the data shown in Hughes et al. (in prep.). ‘PWV’ is the average precipitable water vapour estimate for the observations

Source	Project ID	Observation Date	Flux Calibrator	Bandpass Calibrator	Phase Calibrator	PWV (mm)	Number of antennas	Time on Target (min)
SHiZELS-8	2017.1.01674.S	14 November 2017	J0238+1636	J0238+1636	J0217-0820	3.17	43	47.05
		15 November 2017	J0238+1636	J0238+1636	J0217-0820	2.05	43	45.78
		16 November 2017	J0006-0623	J0006-0623	J0217-0820	1.44	43	45.82
COS-30 / SHiZELS-19	2017.1.01674.S	14 November 2017	J1058+0133	J1058+0133	J0948+0022	3.56	43	43.67
		14 November 2017	J1058+0133	J1058+0133	J0948+0022	3.92	43	44.12
		16 November 2017	J1058+0133	J1058+0133	J0948+0022	0.89	43	44.23
		18 November 2017	J1058+0133	J1058+0133	J0948+0022	0.60	43	44.50
		20 November 2017	J1058+0133	J1058+0133	J0948+0022	0.48	50	44.02

2018; Gillman et al. 2019). Deep observations have focused mainly in sampling the ‘main-sequence’ of star-forming galaxies, i.e., those galaxies that are part of the bulk of the galaxy population in terms of stellar mass ( $M_\star$ ) and star formation rate (SFR; e.g. Noeske et al. 2007; Whitaker et al. 2012).

High redshift ( $z \sim 1-3$ ) IFU surveys targeting the  $H\alpha$  emission have revealed that most of the main-sequence star-forming galaxies (hereafter, ‘typical’ star-forming galaxies), present: (1) highly turbulent galactic disks with high surface brightness, indicating that the interstellar medium (ISM) is highly pressurized with  $P_{\text{tot}} \sim 10^{3-4}$  times higher than the typical ISM pressure in the Milky Way (Swinbank et al. 2015; Molina et al. 2017); (2) the star-formation activity is partly triggered by gravitational fragmentation of dynamically unstable gas potentially leading to the formation of massive clumps which could be up to  $\sim 1000\times$  more massive ( $\sim 10^9 M_\odot$ ) than star-forming complexes seen in local galaxies (e.g. Genzel et al. 2011; Swinbank et al. 2012b).

Although the physical conditions that produce these extreme ISM properties remain poorly understood, one possible explanation may be related to the high molecular gas densities that may arise from the high molecular gas fractions ( $f_{\text{H}_2}$ ; e.g. Escala & Larson 2008). In the local Universe galaxies have typical  $f_{\text{H}_2}$  values of  $\sim 0.1$ , while on the other hand galaxies at  $z \sim 1-3$  have reported molecular gas fractions up to  $\sim 0.8$  (e.g. Tacconi et al. 2010; Daddi et al. 2010; Hughes et al. in prep.). The molecular gas content seems to dominate the baryonic mass budget in the central parts of these high redshift ‘typical’ star-forming systems, but we have little or almost no information about their spatial distribution and kinematics.

Traditionally the workhorse tracer to estimate the molecular gas content are the low- $J$  rotational transitions of the carbon monoxide ( $^{12}\text{C}^{16}\text{O}$ ) molecule (e.g.  $J = 1-0$  or  $J = 2-1$ ; hereafter CO(1-0) and CO(2-1), respectively; Solomon & Vanden Bout 2005; Bolatto et al. 2013). Through the assumption of a CO-to- $\text{H}_2$  conversion factor ( $\alpha_{\text{CO}}$ ), the molecular gas to CO(1-0) luminosity ( $L'_{\text{CO}(1-0)}$ ) relation can be expressed as  $M_{\text{H}_2} = \alpha_{\text{CO}} L'_{\text{CO}(1-0)}$  (e.g. Bolatto et al. 2013). In the Milky Way and other ‘normal’ star-forming local galaxies, the CO emission mainly arises from individual virialized Giant Molecular Clouds (GMCs). On the other hand, the CO emission coming from more extreme star-forming and dynamically disrupted systems, such as Ultra Luminous Infra-red Galaxies (ULIRGs; Downes & Solomon 1998) is likely to be contained in much denser rotating disks or rings (Solomon & Vanden Bout 2005).

Spatially resolved morpho-kinematic studies of the molecular gas content in galaxies are critical to understand the physical

processes that control the star formation activity. Nevertheless, observations of high redshift galaxies with direct spatially resolved molecular gas detections have remained a challenge. Beyond the local Universe, resolved CO detections are limited to the most massive/luminous yet rare galaxies or highly magnified gravitationally lensed sources (e.g. Saintonge et al. 2013; Swinbank et al. 2015; Chen et al. 2017; Calistro Rivera et al. 2018; Motta et al. 2018). With ALMA, we are now able to study the physical conditions of the cold molecular gas in ‘typical’ star-forming galaxies at  $z > 1$  and test if the actual cosmological models successfully explain the characteristics of the high redshift ISM.

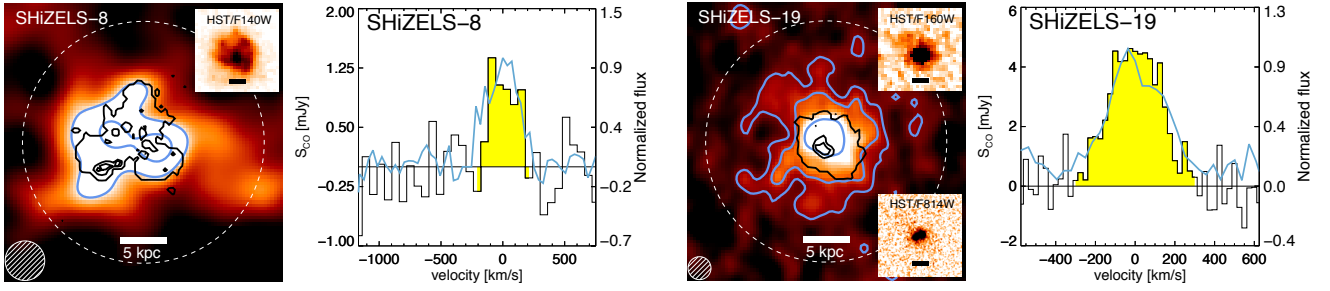
In this paper, we use high angular resolution ALMA observations to characterize the CO(2-1) emission and kinematics of two ‘typical’ galaxies (following the so-called ‘main-sequence’) at  $z \sim 1.47$  drawn from the SHiZELS survey (Swinbank et al. 2012a; Molina et al. 2017; Gillman et al. 2019). Combining ALMA with the available AO-aided  $H\alpha$  data observed by the Spectrograph for INtegral Field Observations in the Near Infrared (SINFONI) on the Very Large Telescope (VLT), we study how the spatially-resolved properties of the ionized and cold molecular gas are related on  $\sim\text{kpc}$ -scales. Throughout the paper, we adopt a  $\Lambda\text{CDM}$  cosmology with  $\Omega_\Lambda=0.73$ ,  $\Omega_m=0.27$ , and  $H_0=70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ , implying a spatial resolution of  $\approx 0''.15$  that corresponds to a physical scale of  $\sim 1 \text{ kpc}$ . We assume a Chabrier (2003) Initial Mass Function (IMF) and a Solar Oxygen abundance of  $8.69 \pm 0.05$  in the  $12+\log_{10}(\text{O}/\text{H})$  metallicity scale (Asplund et al. 2009).

## 2 OBSERVATIONS & DATA REDUCTION

### 2.1 The SHiZELS Survey

In this work, we take advantage of galaxies with previous  $H\alpha$  VLT-SINFONI IFU AO-aided imaging taken from the SHiZELS survey (Swinbank et al. 2012a; Molina et al. 2017; Gillman et al. 2019). This is based on a sub-sample of sources taken from the HiZELS near-infrared narrow-band imaging project (Sobral et al. 2012, 2013a, 2015) and is one of the largest IFU-AO survey observing the  $H\alpha$  emission in ‘typical’ star-forming galaxies on  $\sim\text{kpc}$ -scales in three narrow redshift slices  $z = 0.86, 1.47 \& 2.23$  ( $M_\star \sim 3-30 \times 10^{10} M_\odot$ ;  $\text{SFR} \sim 2-30 M_\odot \text{ yr}^{-1}$ ). All galaxies have a deep multi-wavelength coverage as they line within the UDS, COSMOS and SA22 fields.

From SHiZELS, we select two galaxies, COS-30 and SHiZELS-8, which have been previously detected in CO( $J = 2-1$ ) with ALMA at  $\sim 1''.6 - 2''.5$  resolution (Hughes et al. in prep.).



**Figure 1.** *1st and 3rd columns:* Spectrally integrated 2000 k $\lambda$  data-cubes encompassing the CO(2-1) emission line for each galaxy in a 3''56 ( $\approx$  30 kpc) squared sky region. The synthesized beam size ( $\theta_{\text{BMAJ}} = 0''.50, 0''.29$  for SHiZELS-8 and SHiZELS-19, respectively) is shown in the bottom-left corner in each map. The blue contours represent the 3-, 5- and 10- $\sigma$  levels the image noise. The black contours show the H $\alpha$  emission detected in the SINFONI-AO observations. For SHiZELS-8, we just align its intensity maps by eye in order to improve visualization. The dashed line represents the sky-aperture defined as 2 $\times$ FWHM of the best-fitted two-dimensional Gaussian in each map. If available, we also show the *HST* broad-band images over the same sky region in the right side of the map. In each *HST* cut-out, the black bar represents the 5 kpc scale. *2nd and 4th columns:* Spatially-collapsed spectra extracted within the sky-aperture for each galaxy showing the CO(2-1) emission line. The yellow colour indicates the 2 $\times$ FWHM region for the CO emission line. The blue line shows the H $\alpha$  emission line flux density normalized to the CO emission line peak and extracted from the SINFONI-AO IFU observations using the same sky aperture (Swinbank et al. 2012a; Molina et al. 2017; Gillman et al. 2019). We find good agreement between the CO and H $\alpha$  line widths.

The global stellar masses and SFRs are taken from Gillman et al. (2019). Briefly, the stellar masses were computed by using the Bayesian SED fitting code, MAGPHYS (da Cunha et al. 2008) to the rest-frame UV, optical and near-infrared data available (*FUV*, *NUV*, *U*, *B*, *g*, *V*, *R*, *i*, *I*, *z*, *Y*, *J*, *H*, *K*, 3.6, 4.5, 5.8 and 8.0  $\mu$ m collated in Sobral et al. 2014, and references therein), assuming a Chabrier (2003) IMF and a Calzetti et al. (2000) extinction law.

The SFRs are calculated from the  $M_{\star}$ -based extinction-corrected H $\alpha$  emission line fluxes (Garn & Best 2010; Sobral et al. 2012; Ibar et al. 2013) and adopting the Kennicutt (1998a) calibration  $\text{SFR}_{\text{H}\alpha} (M_{\odot} \text{ yr}^{-1}) = 4.6 \times 10^{-42} L_{\text{H}\alpha} (\text{erg s}^{-1})$  with a Chabrier (2003) IMF. The total H $\alpha$  emission line fluxes are taken from the HiZELS narrow-band survey and are corrected for [NII] flux contamination by considering the [NII]/H $\alpha$  ratio measured from the SINFONI observations. We note that the extinction corrected SFR values presented in this work are consistent with the values reported in Gillman et al. (2019), i.e. with the intrinsic SFR values estimated by MAGPHYS. We note that the COS-30 galaxy is referred to as ‘SHiZELS-19’ in Gillman et al. (2019). Hereafter we use this name to refer to this galaxy.

We adopt the Whitaker et al. (2012)’s definition of the ‘main-sequence’ of star-forming galaxies, and by using the redshift,  $M_{\star}$  and the specific star formation rate ( $\text{sSFR} \equiv \text{SFR}/M_{\star}$ ) estimates for each source, we calculate the ‘distance’ to the main-sequence ( $\Delta \text{MS} \equiv \text{sSFR}/\text{sSFR}_{\text{MS}}(z, M_{\star})$ ). We present the  $\log_{10}(\Delta \text{MS})$  values in Table 2. These values are lower than the 0.6 dex upper limit usually adopted to define the main-sequence (Genzel et al. 2015).

## 2.2 ALMA observations & data reduction

We made use of Cycle-5 ALMA Band-3 observations (2017.1.01674.S; P.I. Molina J.; see Table 1) to detect and resolve the redshifted CO(2-1) emission line ( $\nu_{\text{rest}} = 230.538$  GHz) for SHiZELS-8 (Swinbank et al. 2012a) and SHiZELS-19 (presented as COS-30 in Molina et al. 2017). Those observations were carried during November 2017, reaching a root-mean-squared (r.m.s.) noise of 120–150  $\mu$ Jy beam $^{-1}$  at 0''.15 angular resolution using a channel width of 60 km s $^{-1}$ .

The Cycle-5 observations were taken in an extended configuration (synthesized beam FWHM of  $\approx$  0''.15), thus being more

sensitive to more compact emission. We combine them with previous 2'' resolution Cycle-1 and -3 ALMA data (see Hughes et al. in prep. for more details) to obtain sensitive and high-fidelity imaging of the CO(2-1) emission.

Data were reduced using COMMON ASTRONOMY SOFTWARE APPLICATIONS<sup>1</sup> (CASA) considering a standard ALMA pipeline up to calibrated *u-v* products. We used the task `TCLEAN` to deconvolve the data to produce datacubes for both galaxies. In each datacube we clean the regions where emission is identified down to 3- $\sigma$  using the `TCLEAN` CASA task, allowing multi-scale cleaning (`MULTISCALE=[0.5,5,15,45]`), where image pixel size is fixed at 0''.04). The high-resolution datacubes are produced by using Briggs weighting with robust parameter at 0.5, obtaining synthesized beam FWHMs of  $\approx$  0''.15 ( $\sim$  kpc-scale at  $z \sim 1.47$ ). We also take advantage of the Cycle-1 and -3 data by producing datacubes with different spatial scales by tapering at 2000 k $\lambda$  and reducing the spatial resolution using a circular restoring synthesized beam (0''.29  $\approx$  2.5 kpc at  $z \sim 1.47$ ). These combined tapered datacubes are produced with the aim of recovering as much as the low surface brightness CO(2-1) emission as possible from the outskirts of each galaxy (Fig. 1).

In the case of SHiZELS-8 we are unable to detect the CO emission in the high-resolution datacube or the  $\approx$  2.5 kpc resolution map. Therefore, for this galaxy, we reduce the spectral and spatial resolutions in order to boost the CO emission signal-to-noise (S/N). The spectral channel width is set to 60 km s $^{-1}$  and the spatial resolution is degraded to 0''.50 by performing an additional smoothing step.

In the case for SHiZELS-19, we are able to easily detect the source in the high-resolution datacube. Thus, for this galaxy, we set the spectral channel width to 25 km s $^{-1}$  aiming to minimize spectral resolution effects in the derivation of the kinematic parameters.

We show the spatially integrated spectrum for each galaxy in Fig. 1. Those were extracted by considering a sky-aperture defined in diameter as 2 $\times$ FWHM of the best-fitted two-dimensional Gaussian in each map ( $\sim$  1''.3 – 1''.2 for SHiZELS-8 and SHiZELS-19).

In summary, for SHiZELS-19 we combine Cycle-1, -3 and -5 data to generate a high resolution ( $\approx$  0''.15  $\sim$  kpc-scale) and a ‘low resolution’ ( $\approx$  0''.29  $\sim$  2.5 kpc) datacubes, while for SHiZELS-8 we use a  $\approx$  0''.5 resolution map ( $\sim$  4.3 kpc), optimizing the flux

<sup>1</sup> <http://casa.nrao.edu/index.shtml>

TABLE 2: SPATIALLY-INTEGRATED GALAXY PROPERTIES

**Table 2.** The integrated  $H\alpha$  flux densities ( $f_{H\alpha}$ ) are taken from narrow-band photometry and corrected for [NII] contamination. The  $SFR_{H\alpha}$  values are corrected for  $H\alpha$  extinction ( $A_{H\alpha}$ ) following the  $M_{\star} - A_{H\alpha}$  parametrization presented by [Garn & Best \(2010\)](#).  $\Delta MS$  is the offset of each galaxy with respect to the ‘main-sequence’ of star-forming galaxies.  $\alpha_{CO,A+17}$  and  $\alpha_{CO,N+12}$  are the CO-to- $H_2$  conversion values calculated by following the [Accurso et al. \(2017\)](#) and [Narayanan et al. \(2012\)](#) parametrizations. The  $M_{H_2}$  and  $f_{H_2}$  quantities are computed by using  $\alpha_{CO,N+12}$  (see § 3.4).

ID	SHiZELS-8	SHiZELS-19
RA (J2000)	02:18:21.0	09:59:11.5
Dec (J2000)	-05:19:07.8	+02:23:24.3
$z_{spec}$	1.4608	1.4861
$f_{H\alpha}/10^{-17}$ (erg s $^{-1}$ cm $^{-2}$ )	10.9 $\pm$ 1	7.6 $\pm$ 1
$A_{H\alpha}$	1.1 $\pm$ 0.2	1.1 $\pm$ 0.2
[NII]/ $H\alpha$	<0.1	0.43 $\pm$ 0.03
$SFR_{H\alpha}$ ( $M_{\odot}$ yr $^{-1}$ )	16 $\pm$ 2	13 $\pm$ 2
$\log_{10} M_{\star}$ ( $M_{\odot}$ )	10.3 $\pm$ 0.2	10.3 $\pm$ 0.2
$\log_{10} \Delta MS$ (dex)	0.53	0.41
$S_{CO(2-1)}\Delta v$ (Jy km s $^{-1}$ )	0.38 $\pm$ 0.08	0.64 $\pm$ 0.03
$\log_{10} L'_{CO(2-1)}$ (K km s $^{-1}$ pc $^2$ )	10.04 $\pm$ 0.04	10.27 $\pm$ 0.04
$\alpha_{CO,A+17}$ ( $M_{\odot}$ (K km s $^{-1}$ pc $^2$ ) $^{-1}$ )	21 $\pm$ 8	3.9 $\pm$ 1.5
$\alpha_{CO,N+12}$ ( $M_{\odot}$ (K km s $^{-1}$ pc $^2$ ) $^{-1}$ )	5.0 $\pm$ 1.0	1.5 $\pm$ 0.2
$\log_{10} M_{H_2}$ ( $M_{\odot}$ )	10.81 $\pm$ 0.10	10.51 $\pm$ 0.07
$f_{H_2}$	0.76 $\pm$ 0.24	0.62 $\pm$ 0.16

sensitivity to the compact and diffuse emission in each source, respectively.

### 3 ANALYSIS, RESULTS & DISCUSSION

#### 3.1 CO emission & CO-to- $H_2$ conversion factor

The global CO(2-1) velocity-integrated flux densities ( $S_{CO(2-1)}\Delta v$ ) are taken from [Hughes et al. \(in prep.\)](#) and presented in Table 2. Those are estimated by fitting a 2D Gaussian profile to the spectrally-integrated datacube (moment 0). The CO(2-1) luminosities ( $L'_{CO(2-1)}$ ) are calculated by following [Solomon & Vanden Bout \(2005\)](#);

$$L'_{CO(2-1)} = 3.25 \times 10^7 S_{CO(2-1)}\Delta v v_{obs}^{-2} D_L^2 (1+z)^{-3} [\text{K km s}^{-1} \text{ pc}^2], \quad (1)$$

where  $S_{CO(2-1)}\Delta v$  is in Jy km s $^{-1}$ ,  $v_{obs}$  is the observed frequency of the emission line in GHz,  $D_L$  is the luminosity distance in Mpc, and  $z$  is the redshift. We then estimate the CO(1-0) luminosity for each galaxy by assuming a  $L'_{CO(2-1)}/L'_{CO(1-0)} = 0.85$  ratio (e.g. [Danielson et al. 2011](#)).

To derive molecular gas masses we need to assume a CO-to- $H_2$  conversion factor. By considering a dynamical model we constrain the  $\alpha_{CO}$  value in our galaxies (see § 3.4). However, we also use different prescriptions in the literature to calculate tentative CO-to- $H_2$  conversion factor values. Unfortunately, as we lack of dust masses for SHiZELS-8 and SHiZELS-19 (see [Cheng et al. in prep.](#)), we are unable to use a dust-to-gas ratio motivated  $\alpha_{CO}$  value (e.g. [Leroy et al. 2013](#)). Thus, from the literature we use the [Accurso et al. \(2017\)](#) and [Narayanan et al. \(2012\)](#)  $\alpha_{CO}$  prescriptions as we have direct estimates of the input observables and these parametrizations do not require a minimum observational spatial resolution (e.g. [Feldmann et al. 2012](#)).

Briefly, [Accurso et al. \(2017\)](#)’s prescription considers the effect of the ISM metallicity and the strength of the UV radiation field in the estimation of the CO-to- $H_2$  conversion factor. We note that in this parametrization, the strength of the UV field is traced by the offset of the galaxy with respect to the ‘main-sequence’ of star-forming galaxies ( $\Delta MS$ ; see [Accurso et al. 2017](#), for more details). However, this prescription does not consider deviations of the  $\alpha_{CO}$  value due to high gas surface density ( $\Sigma_{gas}$ ) values (e.g. [Bolatto et al. 2013](#)). In contrast, the [Narayanan et al. \(2012\)](#)’s prescription takes into account the effect of the ISM metallicity and gas surface density in the estimation of the  $\alpha_{CO}$  value. This is, however, a numerical prediction for  $\Sigma_{gas}$  and its effect is parametrized via the luminosity-weighted CO surface brightness quantity ( $\Sigma_{CO}$ ; see [Narayanan et al. 2012](#), for more details).

In order to apply these two  $\alpha_{CO}$  parametrizations, we use the  $\Delta MS$  values calculated by assuming the [Whitaker et al. \(2012\)](#)’s definition of the ‘main-sequence’ of star-forming galaxies and presented in Table 2. The metallicities are estimated from the [NII]/ $H\alpha$  ratio and assuming the [Pettini & Pagel \(2004\)](#) metallicity prescription. The inclination corrected  $\Sigma_{CO}$  values are calculated from the ALMA observations. Based on these assumptions, we list the global  $\alpha_{CO}$  values for each galaxy in Table 2.

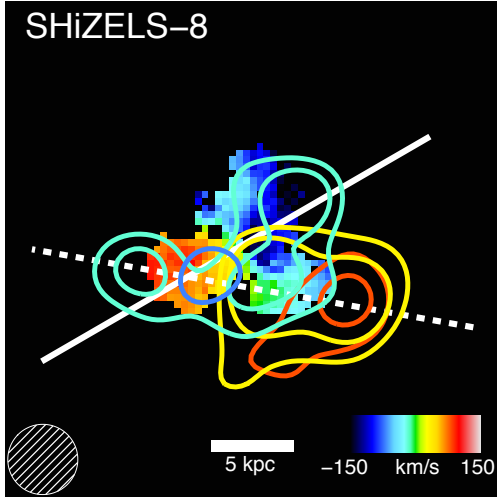
We find little agreement between the two parametrizations. By considering the [Accurso et al. \(2017\)](#)’s prescription, we find higher CO-to- $H_2$  conversion values than the obtained from the [Narayanan et al. \(2012\)](#)’s parametrization (Table 2). This is expected as [Accurso et al. \(2017\)](#)’s prescription does not consider the effect of  $\Sigma_{gas}$  in their estimation of the  $\alpha_{CO}$ , and it has a steeper dependence on metallicity. In the case of the [Narayanan et al. \(2012\)](#)’s parametrization, the low  $\alpha_{CO}$  value obtained for SHiZELS-19 is mainly dominated by its high galactic  $\Sigma_{CO}$ , which is reflected by its high  $\Sigma_{H_2}$  value (Table 4). On the other hand, SHiZELS-8 has an  $\alpha_{CO}$  value closer to that found in Galactic GMCs (Table 2). This is produced by its low (sub-solar) metal content ( $12+\log_{10}(O/H) < 8.12$ ). Although variations of the CO-to- $H_2$  conversion factor within galactic disks have been reported (e.g. [Sandstrom et al. 2013](#)), we note that a global  $\alpha_{CO}$  value seems to be a good approximation for the SHiZELS-19 galaxy (Appendix A).

#### 3.2 The SHiZELS-8 galaxy

The SHiZELS-8  $H\alpha$  observation ([Swinbank et al. 2012a](#)) suggests that this galaxy is consistent with being a turbulent rotating disk hosting three kpc-sized clumps ([Swinbank et al. 2012b](#)). Unfortunately the SHiZELS-8 CO(2-1) observations have too low S/N to allow a detailed dynamical characterization. This galaxy has  $\sim 50\%$  lower velocity-integrated CO(2-1) flux density than SHiZELS-19, but its emission seems more extended, i.e. it has a lower CO surface brightness. On the other hand, our estimated low metallicity for SHiZELS-8 ( $12+\log_{10}(O/H) < 8.12$ ) suggests a lack of dust content which could indicate an efficiently CO molecule photo-dissociation by the far-ultraviolet (far-UV) photons and a higher CO-to- $H_2$  conversion factor ([Bolatto et al. 2013](#)). This implies that SHiZELS-8 could have a larger molecular gas content than SHiZELS-19, albeit similar SFR and  $M_{\star}$  (see Table 2).

From the high-resolution ( $0''.15 \sim$  kpc-scale) datacube we obtain a velocity-integrated peak flux density r.m.s of  $3.4 \text{ mJy km s}^{-1} \text{ beam}^{-1}$ , corresponding a  $\Sigma_{H_2}$  upper limit of  $\sim 1.6 \times 10^3 M_{\odot} \text{ pc}^{-2} \text{ beam}^{-1}$  based on the [Narayanan et al. \(2012\)](#)’s CO-to- $H_2$  conversion factor (see § 3.4). Thus, by considering the beam angular size, we estimate a molecular gas mass  $5-\sigma$  upper





**Figure 2.**  $H\alpha$  velocity map at  $\sim$ kpc-scale for the SHiZELS-8 galaxy. The solid and dashed white lines represent the ionized and molecular gas major kinematic axis, respectively. The coloured contours represent the 3- and 5- $\sigma$  CO(2-1) emission from the 2000 k $\lambda$  tapered datacube in four spectral channels ( $\Delta v = 240 \text{ km s}^{-1}$ ). The synthesized beam size of this tapered observation ( $\theta_{\text{BMAJ}} = 0''.50 \sim 4.3 \text{ kpc}$ ) is shown in the bottom-left corner. We note that the apparent shift between the two maps may be produced by the astrometry inaccuracies of the SINFONI observations. Nevertheless, we note that both observations suggest that the CO(2-1) and  $H\alpha$  major kinematic axes are misaligned by  $\sim 100$ - $120$  deg, which is indicative of a kinematic complex system.

limit of  $\sim 2.8 \times 10^8 M_{\odot}$  to the three  $\sim$ kpc-scale gaseous clumps detected in the  $H\alpha$  observation and reported by Swinbank et al. (2012b) for this galaxy.

From the  $0''.5$  smoothed map we obtain a velocity-integrated peak flux density r.m.s of  $2.5 \text{ mJy km s}^{-1} \text{ beam}^{-1}$ . The lower image noise allows us to marginally detect the CO(2-1) emission in four spectral channels ( $\Delta v = 240 \text{ km s}^{-1}$ ). We show the SHiZELS-8 marginally detection in Fig. 2. We clearly observe the CO emission line spatial and spectral shifts produced by the internal galactic dynamics. Thus, we estimate a rough major kinematic axis position angle (PA) of  $\sim 140$  deg, with a peak-to-peak rotational velocity of  $\sim 145 \text{ km s}^{-1}$  (non-corrected by inclination).

### 3.2.1 SHiZELS-8: a dynamically-perturbed system?

Two pieces of evidence support the idea that SHiZELS-8 is a dynamically complex system. Firstly, the  $H\alpha$  and CO dynamics show that both components rotate in the same direction but have position angles offset by  $\sim 100 - 120$  deg (see Fig. 2), which is in contrast to the negligible offset in the  $H\alpha$  and CO dynamics seen in SHiZELS-19 (Fig. 3). Second, our previous SINFONI observation shows a flat radial  $[\text{N II}]/H\alpha$  metallicity gradient (Swinbank et al. 2012a).

We are possibly witnessing a massive reservoir of gas fuelling the star formation seen in  $H\alpha$  in a similar way to that previously seen in more violent sub-millimetre galaxies (SMGs; Tacconi et al. 2008). Indeed, the complex dynamics evidenced for the different ISM states might be mixing the gas producing the flat metallicity gradient. We conclude that while SHiZELS-8 is a ‘typical’ galaxy that resides in the upper range of the ‘main sequence’ for star-forming galaxies, which follows the Kennicutt-Schmidt law (see Hughes et al. in prep.), it is probably experiencing torques that will eventually drive a flow of gas into the central regions. The SHiZELS-

8 case demonstrates the wide variety of galaxy kinematics within the ‘main-sequence’ (Elbaz et al. 2018). Given the impossibility to describe this source as a virialized rotating disk, in the remaining of this work we focus on the analysis of the SHiZELS-19 galaxy.

### 3.3 The SHiZELS-19 galaxy

We derive the two-dimensional intensity and kinematic maps for SHiZELS-19 by analysing the CO(2-1) emission line following the approach presented in Swinbank et al. (2012a). Briefly, we spatially bin the ALMA data-cube up to a scale given by the synthesized beam and then we perform an emission line fitting approach using a  $\chi^2$  minimization procedure (see Swinbank et al. 2012a, for more details). In each iteration a Gaussian profile is fitted in the frequency domain to estimate the intensity, velocity and velocity dispersion information (Fig. 3). We highlight that for this galaxy, the  $H\alpha$  emission line properties were derived and presented in an analogous manner in Molina et al. (2017).

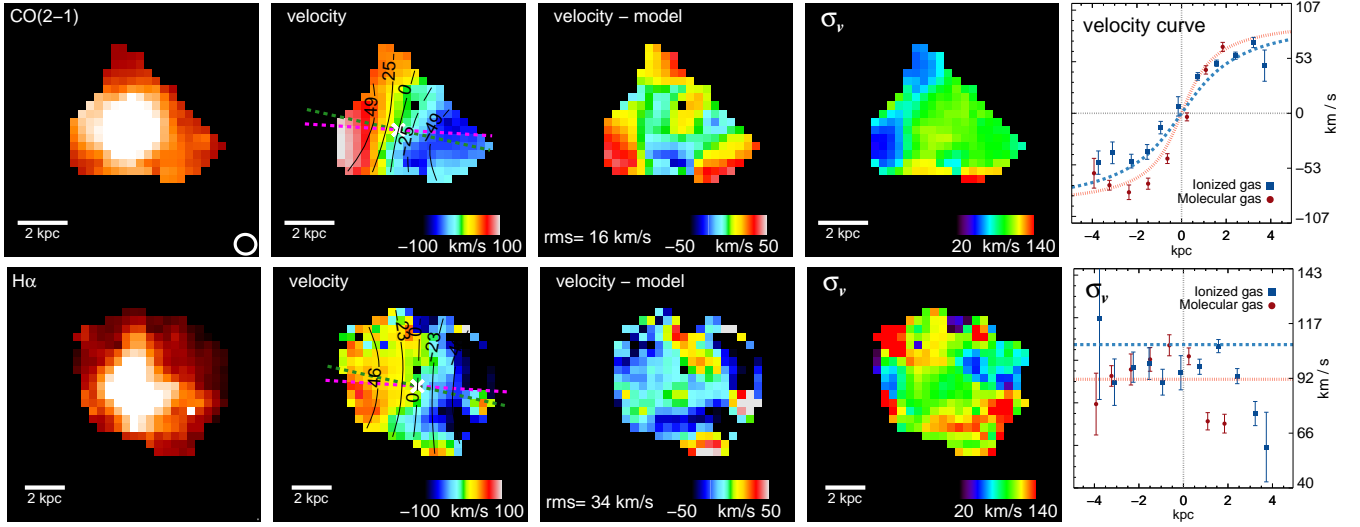
We show the CO(2-1) intensity, velocity and line-of-sight velocity dispersion maps for SHiZELS-19 in Fig. 3, whilst the best-fitted kinematic parameters are listed in Table 3. We observe a smooth CO(2-1) intensity map with no apparent clumpiness, which is consistent with the morphology observed in the  $H\alpha$  intensity map (Molina et al. 2017) and the *HST* F160W-band (rest-frame optical) image. However, this galaxy presents an irregular morphology in the *HST* F814W-band map (rest-frame UV, Fig. 1). The discrepancy between the galaxy morphology seen in the *HST* images suggests that the irregular morphology seen in the *HST* F814W-band image may just reflect a complex dust distribution through the galactic disk (e.g. Genzel et al. 2013).

#### 3.3.1 Global Dynamical Properties

In order to characterise the dynamical properties of SHiZELS-19, we fit the two-dimensional velocity fields for the ionized and molecular gas jointly. We construct two-dimensional models with an input rotation curve following an arctan function [ $V(r) = \frac{2}{\pi} V_{\text{asym}} \arctan(r/r_t)$ ], where  $V_{\text{asym}}$  is the asymptotic rotational velocity and  $r_t$  is the effective radius at which the rotation curve turns over (Courteau 1997). We consider the ‘disk thickness’ by modelling the galaxy as an oblate spheroid system with intrinsic minor-to-major axis ratio of 0.2, a value that seems appropriate for the high redshift galaxy population (Law et al. 2012a). As the CO and  $H\alpha$  velocity fields are consistent (Fig. 3), we also model both velocity fields by coupling the inclination angle parameter. We do not attempt to lock the dynamical centres through RA–DEC coordinates as the SINFONI astrometry is not accurate enough to allow it, nevertheless we are assuming that the ionized and molecular gas ISM phases are co-planar. We also allow the possibility that their rotational motions can be out of phase, i.e. both ISM phases could have different kinematic PA.

This modelling has eleven free parameters ( $V_{\text{asym},H\alpha}$ ,  $r_{t,H\alpha}$ ,  $\text{PA}_{H\alpha}$ ,  $[x/y]_{H\alpha}$ ,  $V_{\text{asym},CO}$ ,  $r_{t,CO}$ ,  $\text{PA}_{CO}$ ,  $[x/y]_{CO}$  and inclination angle; see Table 3) and a genetic algorithm (Charbonneau 1995) is used to find the best-fit model (see Swinbank et al. 2012a for more details). The total  $\chi^2$  of the model is calculated as the sum of the  $\chi^2$  obtained from each two-dimensional modelled map.

In Molina et al. (2017) the kinematic model for SHiZELS-19 was performed without any constraint on the inclination angle value. This adds an additional source of uncertainty as the inclination angle is poorly constrained from the velocity field modelling



**Figure 3.** Intensity, velocity, residual and velocity dispersion maps (1st to 4th columns) for SHiZELS-19 obtained from CO(2-1) (top) and H $\alpha$  (bottom) emission lines. In the 5th column we show the one-dimensional rotational velocity (top) and velocity dispersion (bottom) profiles across each major kinematic axis for both observations. The spatial scale for each observation is showed in each moment map. The CO(2-1) intensity map also shows the synthesized beam size. The velocity maps have over-plotted the kinematic centre and the velocity contours from their best-fit disk model. The green- and pink-dashed lines represent the molecular and ionized gas major kinematic axes, respectively. The residual fields are constructed by subtracting the velocity disk model from the velocity maps: the r.m.s. of these residuals are given in each panel. The velocity dispersion maps are corrected for beam-smearing effects. The one-dimensional profiles are constructed by using the best-fit kinematic parameters and a slit width equal to half of the synthesized beam/PSF FWHM. In each one-dimensional profile, the error bars show the 1- $\sigma$  uncertainty and the vertical dashed grey line represents the best-fit dynamical centre. In the velocity profile panel, the red- and blue-dashed curves show the velocity curve extracted from the beam-smearred CO and H $\alpha$  two-dimensional best-fit models, respectively. In the  $\sigma_v$  one-dimensional profile panel, the red- and blue-dashed lines show the average galactic value (Table 3) for the CO and H $\alpha$  observation, respectively.

alone (Glazebrook 2013). In order to deal with this uncertainty, we constrain the inclination angle by fitting a two-dimensional Sérsic model (Sérsic 1963) to the CO intensity map (moment 0) using GALFIT (Peng et al. 2010). We obtain an observed minor-to-major axis ratio of  $\sim 0.90 \pm 0.05$ , which corresponds to an inclination angle value of  $\sim 26 \pm 6$  deg. However, as GALFIT tends to underestimate the parameter errors, we consider a more conservative inclination angle uncertainty of  $\pm 10\%$  in our fitting procedure (Epinat et al. 2012).

We use the dynamical centres and position angles derived from the best-fit dynamical models to extract the one-dimensional rotation curve and velocity dispersion profile across the major kinematic axes of the ionized and molecular gas. The extracted one-dimensional rotational curves and dispersion velocity profiles are presented in Fig. 3.

We calculate the half-light radius ( $r_{1/2}$ ) for each ISM component by following Molina et al. (2017), and we define the rotational velocity for the ionized and molecular gas component ( $V_{\text{rot,H}\alpha}$ ,  $V_{\text{rot,CO}}$ ) as the inclination-corrected velocity observed at two times the H $\alpha$  and CO half-light radii, respectively (see Table 3).

Even at the  $\sim$ kpc-scales achieved here, there is still a contribution to the derived line widths from the beam-smearred large-scale velocity motions across the galaxy (Davies et al. 2011). In order to correct for these effects, we calculate the velocity gradients ( $\Delta V/\Delta R$ ) across the synthesized beam and Point Spread Function (PSF) in the CO and H $\alpha$  velocity field models, respectively. We subtract them linearly from the corresponding velocity dispersion map by following Eq. A1 from Stott et al. (2016). However, by using this procedure,  $\sim 20\%$  residuals are expected to remain, especially at the centres of each galaxy map where large velocity gradients are expected to be present (Stott et al. 2016). In order to minimize such effects, we define the global velocity dispersion for each gas phase

( $\sigma_{v,\text{CO}}$ ,  $\sigma_{v,\text{H}\alpha}$ ) as the median value taken from the pixels beyond the central galactic zone. This zone is defined as three times the size of the angular resolution of the map.

The best-fit kinematic maps and velocity residuals for the H $\alpha$  and CO derived maps are shown in Fig. 3. The best-fit inclination, position angle and half-light radius values are given in Table 3. The mean deviation from the best-fit model (indicated by the typical r.m.s) is given in each residual map.

The molecular and ionized gas components show similar scale sizes  $r_{1/2,\text{H}\alpha}/r_{1/2,\text{CO}} \approx 1.07 \pm 0.09$ . We stress that the CO and H $\alpha$  analyses are obtained from images created at matched spatial resolution ( $0''.15$ ; corresponding to  $\sim$ kpc-scale at  $z \sim 1.47$ ). Possible loss of the extended CO flux in the high-resolution observation may reduce the  $r_{1/2,\text{CO}}$  value in our calculation. Nevertheless, our estimation of the half-light radius for both ISM components are slightly smaller than the half-light radius value measured from the HST F160W-band image  $r_{1/2,\text{HST-F160W}} = 2.1 \pm 0.5$  kpc (Gillman et al. 2019).

The CO(2-1) velocity map shows a clear rotational pattern, roughly matching the rotational motions traced by the ionized gas component. From the two-dimensional modelling, we find that the kinematic position angles agree ( $\Delta\text{PA} \equiv \text{PA}_{\text{H}\alpha} - \text{PA}_{\text{CO}} = 9 \pm 23$  deg) within the 1- $\sigma$  error range. The velocity curves roughly agree, except in the blueshifted zone where the CO traced rotation curve drops to lower velocity values. However, we note that the ionized gas velocity map is noisier than the molecular gas velocity map, especially in the galaxy outskirts. This may be partly produced by OH line features present in the H-band spectra, whilst the ALMA observation is free from sky-line residuals. We find that, the ionized gas component shows a slightly lower rotational velocity value when compared to that from the molecular gas observations ( $V_{\text{rot,H}\alpha}/V_{\text{rot,CO}} \approx 0.88 \pm$

TABLE 3: KINEMATIC PROPERTIES

**Table 3.** Best-fit kinematic parameters for SHiZELS-19 galaxy. ‘inc.’ is the inclination angle defined by the angle between the line-of-sight (LOS) and the plane perpendicular to the galaxy disk (for a face-on galaxy, inc. = 0 deg.). The velocity dispersion and half-light radii values are corrected for ‘beam smearing’ effects (see § 3.3.1 for more details). The last row shows the reduced chi-squared ( $\chi^2_{\nu}$ ) of the best-fit two-dimensional model.

ID	SHiZELS-19
PA <sub>H<math>\alpha</math></sub> (deg)	176±18
$\sigma_{v,H\alpha}$ (km s <sup>-1</sup> )	107±13
V <sub>rot,H<math>\alpha</math></sub> (km s <sup>-1</sup> )	106±9
r <sub>1/2,H<math>\alpha</math></sub> (kpc)	1.80±0.16
PA <sub>CO</sub> (deg)	167 ± 14
$\sigma_{v,CO}$ (km s <sup>-1</sup> )	91±6
V <sub>rot,CO</sub> (km s <sup>-1</sup> )	121±10
r <sub>1/2,CO</sub> (kpc)	1.68±0.03
inc. (deg)	27.5±0.6
$\chi^2_{\nu}$	3.51

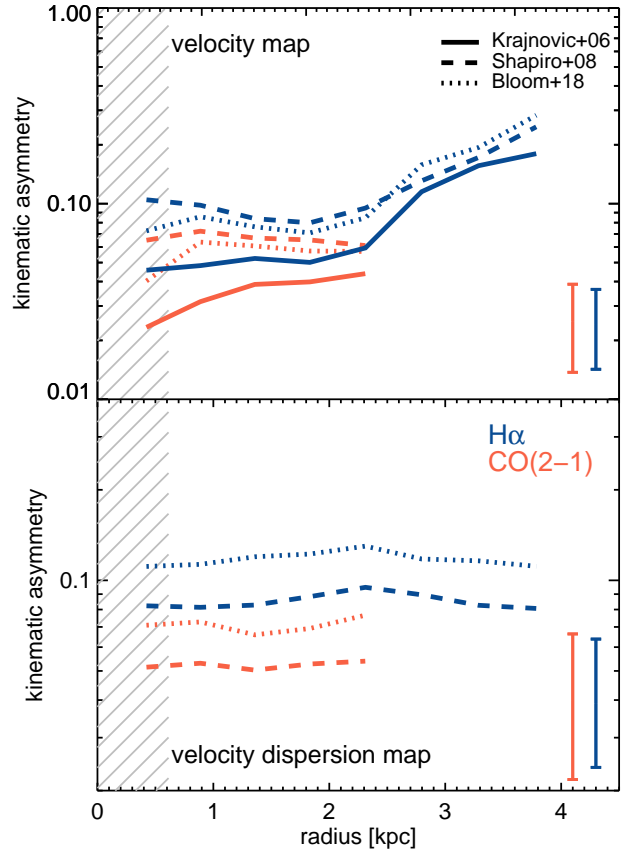
0.10). This might be due to differences in the spatial distribution between the two ISM components.

In terms of velocity dispersion, the CO observation shows a slightly lower average velocity dispersion value than the mean value observed from the ionized gas component ( $\sigma_{v,H\alpha}/\sigma_{v,CO} \approx 1.18 \pm 0.16$ ). The difference between the ALMA (25 km s<sup>-1</sup>) and H–band SINFONI (50 km s<sup>-1</sup>) spectral resolutions should not produce such differences as the intrinsic CO and H $\alpha$  line-widths are significantly broader. The high  $\sigma_v$  values observed at the outskirts of the H $\alpha$  velocity dispersion map may increase the ionized gas average value. In a similar way as the comparison between the velocity maps, the ionized gas velocity dispersion map is noisier than the molecular gas map at larger radii. By considering all the pixels in the mean  $\sigma_v$  estimation, we obtain an average  $\sigma_{v,H\alpha}$  value of  $91 \pm 13$  km s<sup>-1</sup> (Molina et al. 2017), in agreement with the measured  $\sigma_{v,CO}$  value (Table 3). Thus, we suggest that both ISM tracers show similar supersonic turbulence values.

We derive rotational velocity to dispersion velocity ratio (V<sub>rot</sub>/ $\sigma_v$ ) values of  $0.99 \pm 0.14$  and  $1.33 \pm 0.14$  for the ionized and molecular gas ISM phases, respectively. This suggests that the disordered motions of both ISM phases are playing an important role in the galactic support against self-gravity (Burkert et al. 2010).

### 3.3.2 Kinematic Asymmetry Characterization

In order to obtain a detailed characterization of the ionized and molecular gas kinematics, we quantify the kinematic deviations from the ideal rotating disk case by performing a ‘kinemetry’ analysis (Krajnović et al. 2006). Briefly, *kinemetry* proceeds to analyse the two-dimensional kinematic maps using azimuthal profiles in an outward series of best fitting tilted rings. The kinematic profile as a function of angle is then expanded harmonically, which is equivalent to a Fourier transformation which has coefficients  $k_{n,v}$  and  $k_{n,\sigma}$  at each tilted ring for the velocity and velocity dispersion maps, respectively. In the velocity map, the first order decomposition ‘ $k_{1,v}$ ’ is equivalent to the rotational velocity value, and therefore, the ideal rotating disk case is simply described by the cosine law along the tilted rings ( $V(\theta) = k_{1,v} \cos(\theta)$ ). The high-order terms describe the kinematic anomalies with respect to the ideal rotating disk case (see Krajnović et al. 2006 for more details). We note that *kinemetry* stops



**Figure 4.** Kinematic asymmetry radial profiles measured from the SHiZELS-19 velocity (*top*) and velocity dispersion (*bottom*) maps. We plot the CO(2-1) and H $\alpha$  observations. The line, dashed-line and dotted-line represent the kinematic asymmetry estimators presented in Krajnović et al. (2006); Shapiro et al. (2008) and Bloom et al. (2018) for each map (see § 3.3.2 for more details). The colour-coded error bars show the median 1- $\sigma$  uncertainties in each panel. The grey-dashed area represents the resolution element radial extent. Despite of the estimator used, the ionized gas two-dimensional maps tend to show slightly higher kinematic deviations from the ideal rotating disk case than the molecular gas kinematic maps. Although, the measurements agree within 1- $\sigma$  error range.

the radial fitting when there are less than 75% of the pixels sampled along the best-fit tilted ring (Krajnović et al. 2006).

We restrict the inclination and position angles within the 1- $\sigma$  error range given by our best-fit two-dimensional model. The  $k_{n,v}$  and  $k_{n,\sigma}$  errors are derived by bootstrapping via Monte-Carlo simulations the errors in measured velocities, velocity dispersions, and estimated dynamical parameters.

We quantify the kinematic deviations from the ideal disk case by computing three different estimators used in the literature: (1) the  $k_{5,v}/k_{1,v}$  ratio (Krajnović et al. 2006); (2) the  $(k_{2,v} + k_{3,v} + k_{4,v} + k_{5,v})/4k_{1,v}$  and  $(k_{1,\sigma} + k_{2,\sigma} + k_{3,\sigma} + k_{4,\sigma} + k_{5,\sigma})/5k_{1,v}$  fractions (Shapiro et al. 2008); and (3) the  $(k_{3,v} + k_{5,v})/2k_{1,v}$  and  $(k_{2,\sigma} + k_{4,\sigma})/2k_{1,v}$  ratios (Bloom et al. 2018). The first case is the traditional dimensionless ratio that describes the kinematic asymmetries just in the velocity map. It does not consider the low-order coefficients as these are used by ‘kinemetry’ to find the best-fitted tilted rings at a given radius (Krajnović et al. 2006). The second case was defined to classify galaxy mergers which tend to present extremely disturbed kinematic fields (Shapiro et al. 2008). The third

case consists on a slight modification to the second case as it takes into account that in moderately disturbed systems, the even/odd moments contribution measured from the velocity/velocity dispersion maps are negligible (Bloom et al. 2018).

In Fig. 4 we show the different estimators of the kinematic deviations for the CO and H $\alpha$  velocity and velocity dispersion maps as a function of the de-projected radius. We note that the shorter CO radial profiles compared to the H $\alpha$  radial profiles are produced by the stop of the ‘kinemetry’ procedure at shorter radius due to the lack of roundness of the CO two-dimensional maps derived from our observations.

In the case of the velocity map, the  $k_{5,v}/k_{1,v}$  (Krajnović et al. 2006) ratio gives lower values along the galactic disk compared with the other two estimators. We obtain an average  $k_{5,v}/k_{1,v}$  ratio of  $0.04 \pm 0.01$  and  $0.09 \pm 0.05$  for the CO and H $\alpha$  velocity map respectively. This difference is mainly produced by the higher  $k_{5,v}/k_{1,v}$  values found in the H $\alpha$  velocity map at longer radius ( $\gtrsim 2$  kpc). This gradient suggests that SHiZELS-19 suffered a merger event in the past as the outer regions retain better the kinematic perturbations by remaining out of equilibrium while the central region tends to relax faster to a disk-like system (Kronberger et al. 2007).

If we follow the kinematic classification performed to the ATLAS<sup>3D</sup> (Krajnović et al. 2011) and SAMI local galaxy surveys (van de Sande et al. 2017) and we consider their  $k_{5,v}/k_{1,v} = 0.04$  limit value to classify systems as regular rotators, this would imply that SHiZELS-19 corresponds to a ‘non-regular’ rotator, i.e., the velocity field presents significant kinematic deviations that make it not well-described by the cosine law.

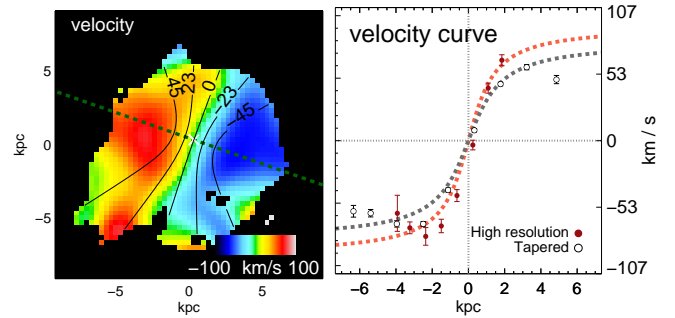
In the case of the velocity dispersion map, we found that the Bloom et al. (2018)’s estimator is higher than the Shapiro et al. (2008)’s estimator at all radii. The additional  $k_{n,\sigma}$  coefficients considered in the latter case contribute little to the kinematic asymmetry estimator. This may also suggest that SHiZELS-19 is a moderate disturbed system. We also note that, as a difference from the velocity map, the kinematic asymmetries in the CO and H $\alpha$  velocity dispersion map tend to be nearly constant along the galactic disk. The kinematic deviations measured from the CO velocity dispersion map tend to be lower than the ones measured from the H $\alpha$  velocity map, however, they agree between the  $1-\sigma$  error range.

The rough agreement between the molecular and ionized gas kinematics suggests that, at  $\sim$ kpc-scales, both phases of the ISM are tracing the galactic dynamics instead of peculiar kinematics (e.g. gas inflows/outflows). This is in agreement with previous studies of massive galaxies (at  $\sim 0.4 - 2.4 \times 10^{11} M_{\odot}$ ) at similar redshift (e.g. Übler et al. 2018; Calistro Rivera et al. 2018).

### 3.4 Dynamical Mass & Dark Matter content

The dynamical mass estimate is a useful tool that allows us to measure the total galactic mass enclosed as a function of radius. It provides a simple way to probe the existence of dark matter haloes (e.g. Gnerucci et al. 2011) or to constrain the CO-to-H<sub>2</sub> conversion factor (e.g. Motta et al. 2018; Calistro Rivera et al. 2018).

By measuring the global kinematics of a galaxy, the dynamical mass can be easily estimated from the rotational velocity (e.g. Genzel et al. 2011) considering a thin-disk dynamical mass approximation ( $M_{\text{dyn,thin}}$ ). On the other hand, if the supersonic turbulence across the galactic disk is comparable to the ordered motions amplitude, then, an additional pressure gradient support contribution against self-gravity has to be considered. In this limit, the galactic disk height is not negligible and a thick-disk approximation ( $M_{\text{dyn,thick}}$ ) should be considered (Burkert et al. 2010).



**Figure 5.** Velocity map, and velocity profile for the CO(2-1) 2000 k $\lambda$  tapered datacube for SHiZELS-19. We use the same colour-coding presented in Fig. 3. In this case, the one-dimensional velocity profile is constructed by using the best-fit kinematic parameters for the tapered datacube and a slit width equal to half of the tapered synthesized beam FWHM. We also overplot the data taken from the  $\sim$ kpc-scale high-resolution observations. The tapered rotation curve extends up to  $\approx 6$  kpc.

We calculate the dynamical mass for the SHiZELS-19 galaxy by using the kinematic information from our CO observations as its velocity map shows lower kinematic asymmetry amplitudes compared to the H $\alpha$  velocity map (§ 3.3.2). Since the CO  $\sim$ kpc-scale observations are more sensitive to the denser and compact emission, we use a tapered version (2000 k $\lambda$ ) of the ALMA observations that allows us to trace the diffuse and more extended CO emission (at  $0''.29$  resolution). This allows us to observe a rotation curve up to a radial distance of  $\approx 6$  kpc or  $\sim 3.5$  times the CO half-light radius (Fig. 5).

Taking into account that the Sérsic index derived from the *HST* image is consistent with unity for this galaxy (Gillman et al. 2019), we assume an exponential disk surface density profile. This implies that, in terms of the disk scale length ( $r_d$ ), we observe the rotation curve up to  $\approx 6r_d$  ( $r_{1/2} \approx 1.67r_d$  for an exponential disk).

By using the inclination-corrected rotational velocity value derived from the tapered rotation curve at radius of  $\approx 6$  kpc ( $V_{\text{rot,tap}} = 112 \pm 6 \text{ km s}^{-1}$ ), we would obtain a total enclosed mass of  $M_{\text{dyn,thin}}(r \lesssim 6 \text{ kpc}) = (1.75 \pm 0.19) \times 10^{10} M_{\odot}$  assuming a thin disk approximation. This dynamical mass estimate is lower but consistent within  $1-\sigma$  range with the estimated stellar mass for this galaxy scaled at the same radius ( $M_{\star}(r \lesssim 6 \text{ kpc}) \approx 0.98 M_{\star} \approx (1.96 \pm 0.90) \times 10^{10} M_{\odot}$ ). However, this ‘thin disk’ dynamical mass value would suggest that this galaxy has almost no gaseous mass content, evidencing an apparent discrepancy with our CO and H $\alpha$  emission line measurements. On the other hand, as the  $V_{\text{rot}}/\sigma_v$  ratio is consistent with unity for both ISM components, this suggests that the  $M_{\text{dyn,thin}}$  quantity may be underestimating the total mass of this galaxy. Additional support against self-gravity needs to be considered.

We follow the analysis by Burkert et al. (2010), and we consider a possible additional pressure support by calculating the dynamical mass in the thick-disk approximation. In the ‘thick-disk’ dynamical mass modelling, the radial pressure gradient term in the hydrostatic equation can not be neglected and it is parametrized by the galactic velocity dispersion and the mass density distributions. This approximation further assumes that  $\sigma_v$  is independent of the galaxy disk radius and height. We use Burkert et al. (2010)’s Eq.11 with  $\sigma_{v,\text{CO}}$  and  $r_{1/2,\text{CO}}$  as input values and we obtain  $M_{\text{dyn,thick}} = (1.59 \pm 0.19) \times 10^{11} M_{\odot}$ . This dynamical mass value is  $\sim 8$  times higher than  $M_{\star}$ , erasing any discrepancy between both



quantities, but allowing the possibility of a non-negligible amount of dark matter content in this galaxy.

In order to test this, we calculate the dark matter fraction by comparing the total mass budget from our dynamical analysis with the luminosity-based total mass content. We consider the total  $M_\star$  value estimated for the SHiZELS-19 galaxy as its difference with the scaled value at 6 kpc ( $M_\star - M_\star(r \lesssim 6 \text{ kpc}) \approx 0.02M_\star$ ) is negligible compared to the stellar mass uncertainty (see Table 2). Therefore, by considering the  $M_\star$ ,  $M_{\text{H}_2}$  and  $M_{\text{dyn}}$  quantities, we define the dark matter fraction as,

$$f_{\text{DM}} \equiv 1 - \frac{M_\star + M_{\text{H}_2}}{M_{\text{dyn,thick}}} = 1 - \frac{\alpha_{\text{CO}} L'_{\text{CO}} + M_\star}{M_{\text{dyn,thick}}}. \quad (2)$$

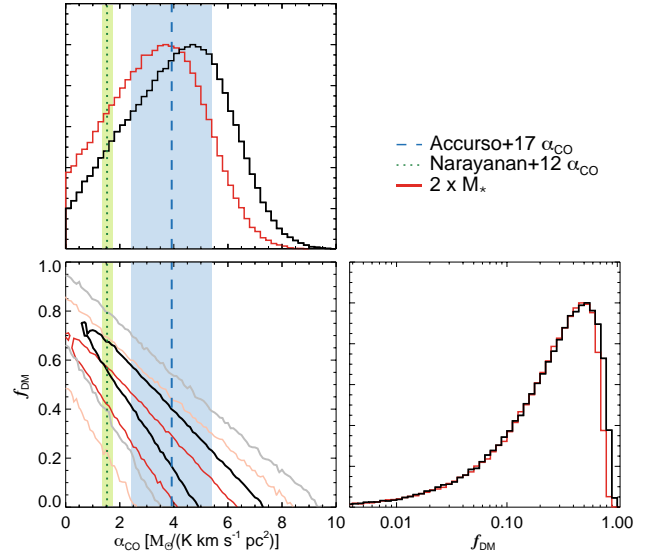
where the molecular mass content is estimated via the CO luminosity ( $M_{\text{H}_2} = \alpha_{\text{CO}} L'_{\text{CO}}$ ). However, this mass sum approach needs additional information about the CO-to- $\text{H}_2$  conversion factor in order to overcome the degeneracy between  $\alpha_{\text{CO}}$  and  $f_{\text{DM}}$ . We also note that strong dependence on the assumptions behind  $M_\star$ ,  $M_{\text{dyn}}$  and  $L'_{\text{CO}}$  may also affect the result from Eq. 2.

Thus, in order to properly consider the  $M_\star$ ,  $M_{\text{dyn}}$  and  $L'_{\text{CO}}$  uncertainties and the degeneracy between  $\alpha_{\text{CO}}$  and  $f_{\text{DM}}$ , we reproduce the parameter space built up in Eq. 2 by applying an MCMC technique following Calistro Rivera et al. (2018). Briefly, based on the likelihood of the measured  $L'_{\text{CO}}$ ,  $M_\star$  and  $M_{\text{dyn}}$  values, we sample the posterior probability density function (posterior PDF) for  $\alpha_{\text{CO}}$  and  $f_{\text{DM}}$  parameters using the EMCEE algorithm (Foreman-Mackey et al. 2013).

We note that SED fitting techniques based on unresolved flux observations may lead to the underestimation of the galactic stellar mass values (Sorba & Sawicki 2018). Thus, we consider an additional case in which we assume that the stellar mass content is being underestimated by a factor of two. This is likely to be an extreme case as suggested by Sorba & Sawicki (2018) for galaxies with similar sSFR.

In Fig. 6 we show the one- and two- dimensional posterior PDFs of the  $\alpha_{\text{CO}}$  and  $f_{\text{DM}}$  parameters. We also show the CO-to- $\text{H}_2$  conversion factor values suggested by following Accurso et al. (2017) and Narayanan et al. (2012). From the two-dimensional posterior PDF we observe the strong degeneracy between both parameters regardless of the  $M_\star$  value assumed. Lower  $\alpha_{\text{CO}}$  values imply higher dark matter fractions. We note that if we assume the Accurso et al. (2017)’s  $\alpha_{\text{CO}}$  value, we obtain  $f_{\text{DM}} \sim 0.3 \pm 0.13$ . Although SHiZELS-19 has a metallicity consistent with being solar, its ISM morphology and kinematics departs strongly from the ISM conditions observed in local galaxies. The high molecular gas velocity dispersion values (Table 3) observed for this system suggest that SHiZELS-19 should have a dense ISM (Papadopoulos et al. 2012) which may lower its CO-to- $\text{H}_2$  conversion factor value (Bolatto et al. 2013). As the Accurso et al. (2017)’s parametrization does not consider the ISM density effects, its  $\alpha_{\text{CO}}$  value should be considered as an upper limit. This is also consistent with the  $\alpha_{\text{CO}}$  upper limit derived from the dynamical mass estimate within the CO half-light radius (see Appendix B, for more details.). Thus, in the remaining of this work, we use the Narayanan et al. (2012)’s parametrization as it does consider the ISM density effect in the estimation of  $\alpha_{\text{CO}}$ .

We find  $f_{\text{DM}} \approx 0.59 \pm 0.10$  for SHiZELS-19. This value is consistent with the dark matter fraction predicted for disk-like galaxies at similar redshift range and stellar mass content from hydrodynamical simulations (Lovell et al. 2018). From our Bayesian approach, we find 3- $\sigma$  range boundaries of  $\sim 0.31 - 0.70$  for the  $f_{\text{DM}}$  value. On the other hand, if we consider the extreme case of a stellar mass



**Figure 6.** One- and two- dimensional posterior PDFs of the  $f_{\text{DM}}$  and  $\alpha_{\text{CO}}$  parameters for SHiZELS-19. The one-dimensional PDFs are represented by the black line in the *top-left* and *bottom-right* panels. The red line represents the inference assuming  $2\times$  the stellar-mass value derived from the spatially unresolved SED fitting, thus we consider a possible underestimation of  $M_\star$  as suggested from spatially resolved studies (Sorba & Sawicki 2018). In *bottom-left* panel we show the two-dimensional PDFs, i.e., the covariance between both parameters. The black and grey lines show the 1- and 3- $\sigma$  regions of the PDF derived by using the stellar mass value obtained from the spatially-unresolved SED fitting. The red and orange lines show the 1- and 3- $\sigma$  regions by assuming a stellar mass correction factor of two. In the *bottom-* and *top-left* panels, the dashed and dotted lines show the CO-to- $\text{H}_2$  conversion factors calculated by following the Accurso et al. (2017) and Narayanan et al. (2012) parametrizations, respectively. The blue- and green-shaded regions show the 1- $\sigma$  uncertainties for each parametrization.

underestimated by a factor of two (Sorba & Sawicki 2018), then the 3- $\sigma$  range boundaries correspond to  $\sim 0.20 - 0.64$ .

To determine if we need to include the  $\text{H I}$  content in our analysis, we note that in local spirals the transition between a  $\text{H}_2$ - to  $\text{H I}$ -dominated ISM ( $\Sigma_{\text{H}_2} \approx \Sigma_{\text{H I}}$ ) occurs at a gas surface density of  $\Sigma_{\text{gas}} \sim 12 \pm 6 M_\odot \text{ pc}^{-2}$  (Leroy et al. 2008). In contrast, from our spatially resolved CO(2-1) observations, we derive an average  $\Sigma_{\text{H}_2} \sim 220 \pm 166 M_\odot \text{ pc}^{-2}$  value from a tilted ring centred at the the same radius at which  $V_{\text{rot,tap}}$  was calculated. This suggests that the  $\text{H I}$  mass content within a radius of  $\approx 6$  kpc is likely to be negligible compared to  $M_{\text{H}_2}$  and therefore, our estimated  $f_{\text{DM}}$  value may be a good approximation. Thus, we suggest that SHiZELS-19 is a ‘typical’ star-forming galaxy which may have a considerable dark matter content.

The dark matter fraction obtained for SHiZELS-19 is consistent with the values reported by Tiley et al. (2019), but in tension with the conclusions reported from Genzel et al. (2017) and Lang et al. (2017). These three studies rely primarily on the analysis of the stacked rotation curve constructed from normalized individual velocity curves from galaxies in the  $0.6 \lesssim z \lesssim 2.6$  redshift range. However, the discrepancy between the obtained  $f_{\text{DM}}$  values from these studies seems to be driven by the way in which the velocity curves are normalized. In Genzel et al. (2017) and Lang et al. (2017) works they normalize the individual velocity curves in both, radial extension through the turn-over radius and velocity amplitude

TABLE 4: SHIZELS-19 FINAL PARAMETERS

**Table 4.** Summary of the SHIZELS-19 galaxy parameters derived in this work using the kinematic modelling. The  $f_{\text{DM}}$ ,  $\Sigma_{\text{H}_2}$  and  $\tau_{\text{dep}}$  values are computed by considering the Narayanan et al. (2012)’s CO-to- $\text{H}_2$  conversion factor (see § 3.4).

$f_{\text{DM}}$	$0.59 \pm 0.10$
$\log_{10} \Sigma_{\text{SFR}} (M_{\odot} \text{ kpc}^{-2})$	$-0.5 \pm 0.3$
$\log_{10} \Sigma_{\text{H}_2} (M_{\odot} \text{ pc}^{-2})$	$3.0 \pm 0.6$
$\tau_{\text{dep}} (\text{Gyr})$	$2.3 \pm 1.2$

through the velocity at the turn-over radius (see Lang et al. 2017 for more details). This normalization procedure tends to favour the contribution of the systems with low  $V_{\text{rot}}/\sigma_v$  values to the stacked rotation curve at longer radii. This bias seems to be produced by the smaller turn over radius values presented in those galaxies which acts as a ‘zoom in’ scaling factor (Tiley et al. 2019). On the other hand, Tiley et al. (2019) normalize the individual velocity curves by the stellar light disk-scale radius and also velocity. In this case, galaxies with different  $V_{\text{rot}}/\sigma_v$  values contribute more uniformly to the shape of the stacked rotation curve. Taking this into account, we note that SHIZELS-19 is a galaxy with  $V_{\text{rot}}/\sigma_v \sim 1.0 - 1.3$ , favouring the scenario in which the conclusions presented in Genzel et al. (2017) and Lang et al. (2017) studies may be biased.

### 3.5 The Kennicutt-Schmidt law at $\sim \text{kpc}$ -scales

First proposed by Schmidt (1959) and extended by Kennicutt (1998a,b), the Kennicutt-Schmidt law is an observational power-law relationship between the galaxy star formation rate surface density ( $\Sigma_{\text{SFR}}$ ) and the gas surface density. It describes how efficiently galaxies turn their gas content into stars. For local galaxies, this correlation is well-fitted by an exponent of  $N = 1.4$  (Kennicutt 1998b).

Since then, latter studies have found that  $\Sigma_{\text{SFR}}$  is better correlated with the molecular gas surface density ( $\Sigma_{\text{H}_2}$ ) rather than  $\Sigma_{\text{gas}}$  (e.g. Bigiel et al. 2008; Leroy et al. 2008). At first order, local disk-like galaxies show a linear correlation between both surface density quantities ( $\Sigma_{\text{SFR}} \propto \Sigma_{\text{H}_2}$ ), with a median depletion time ( $\tau_{\text{dep}} \equiv \Sigma_{\text{H}_2}/\Sigma_{\text{SFR}}$ ) of  $\sim 2.2$  Gyr (e.g. Leroy et al. 2013). Second order departures from this relationship have also been found (e.g. Saintonge et al. 2012; Utreras et al. 2016), although these effects may be related to systematic errors behind the estimation of the molecular gas content and/or local nuclear starburst activity (Leroy et al. 2013).

In Fig. 7 we present the star formation activity of SHIZELS-8 and SHIZELS-19 in the context of the  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  relation. We compare with several local galaxy samples observed at similar spatial scales and galactic averages of galaxies observed at similar redshifts. Briefly, the ‘ $z \sim 0$  spirals’ sample is composed by high spatial resolution ( $\sim 0.2 - 1 \text{ kpc}$ ) observations of small galactic regions taken from Kennicutt et al. (2007); Blanc et al. (2009); Rahman et al. (2011, 2012). The ‘ $z \sim 0$  LIRGs’ sample consist in observations of the NGC3110 and NGC232 galaxies observed at  $\sim 1 \text{ kpc}$  scale (Espada et al. 2018). Both starburst systems have  $\text{SFR} \sim 20 M_{\odot} \text{ yr}^{-1}$ , i.e. comparable with the value reported for SHIZELS-19 ( $\text{SFR} = 23 M_{\odot} \text{ yr}^{-1}$ ). NGC3110 is a barred Sb galaxy interacting with a minor companion (mass ratio  $\sim 14:1$ ), whilst NGC232 corresponds to a barred Sa galaxy which presents a bright compact nuclear region (see Espada et al. 2018, for more details). We also compare with the median trend observed for a

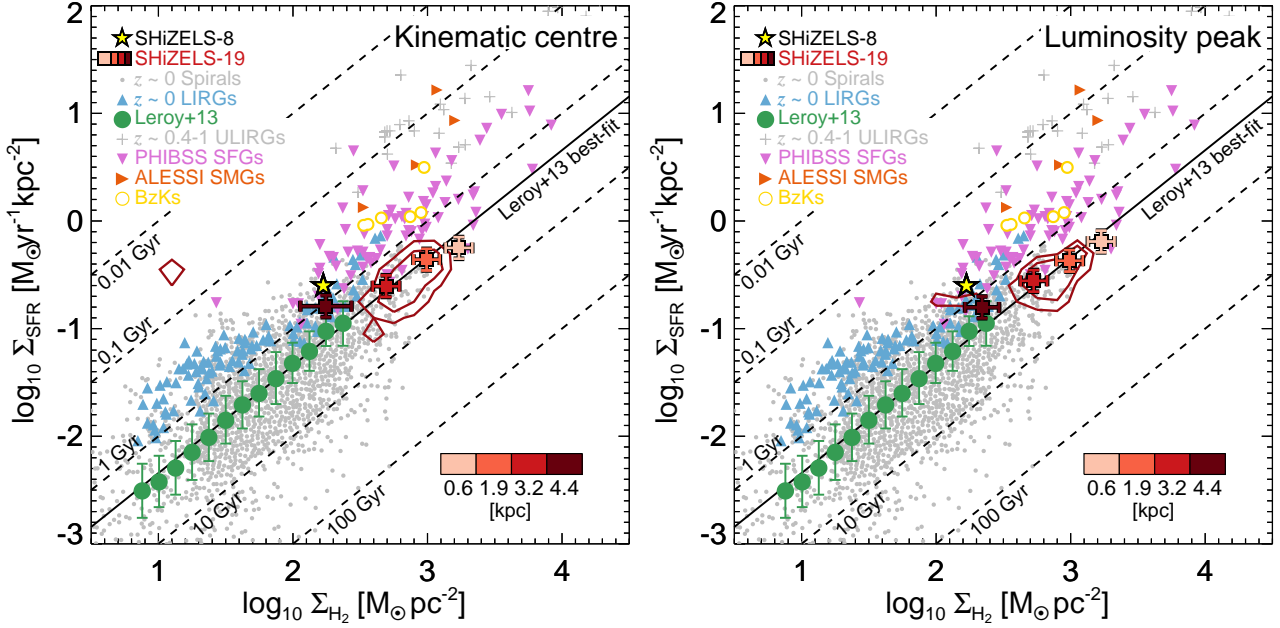
sub-sample of 30 local galaxies taken from the HERA CO Line Extragalactic Survey (HERACLES; Leroy et al. 2013). These data also consist in  $\sim 1 \text{ kpc}$  scale observations of the galactic ISM. The high redshift observations consist in galaxy-integrated estimates from ULIRGs ( $z \sim 0.4 - 1$ ; Combes et al. 2013), four SMGs taken from the ALESS survey ( $z \sim 2.0 - 2.9$ ; Calistro Rivera et al. 2018), ‘typical’ star-forming galaxies observed at  $z \sim 1 - 2.5$  taken from the PHIBSS survey (Tacconi et al. 2013) and five  $BzK$  galaxies ( $z \sim 1.5$ ) presented in Daddi et al. (2010). For the ALESS SMGs we calculate the surface density quantities following Tacconi et al. (2013).

Given our marginally-detected CO observation for SHIZELS-8, we just plot a galactic average estimation ( $\log_{10} \Sigma_{\text{SFR}} \approx -0.61 \pm 0.07 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ ;  $\Sigma_{\text{H}_2} \sim 2.23 \pm 0.08 M_{\odot} \text{ pc}^{-2}$ ). However, we caution that in this particular case,  $\Sigma_{\text{H}_2}$  is a rough estimation as we can not constrain the SHIZELS-8’s CO spatial distribution accurately. For SHIZELS-19, we use the Interactive Data Language (IDL) procedure HASTROM to align the two-dimensional fields using as a reference point the kinematic centre (left panel) and the luminosity peak position (right panel) from  $\text{H}\alpha$  and CO  $\sim \text{kpc}$ -scale observations. For this galaxy, we derive a median  $\log_{10} \Sigma_{\text{SFR}} = -0.5 \pm 0.3 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$  and  $\log_{10} \Sigma_{\text{H}_2} = 3.0 \pm 0.6 M_{\odot} \text{ pc}^{-2}$  values. These estimations indicate that SHIZELS-19 has a somewhat denser ISM compared with local star-forming galaxies. On the other hand, the median  $\Sigma_{\text{H}_2}$  value is consistent with molecular surface density estimations from galaxy-integrated observations of  $BzK$  and ‘typical’ star-forming galaxies at similar redshifts (Daddi et al. 2010; Tacconi et al. 2013), but SHIZELS-19 presents lower  $\Sigma_{\text{SFR}}$  values compared to these systems.

We derive a median  $\tau_{\text{dep}} = 2.3 \pm 1.2$  Gyr for this galaxy, with the pixel-by-pixel distribution between  $\sim 0.003 - 5$  Gyr. SHIZELS-19 presents a median depletion time consistent with the best-fit  $\tau_{\text{dep}} = 2.2 \pm 0.28$  Gyr reported in Leroy et al. (2013) for the median trend observed in local galaxies at similar spatial resolution.

In the left panel of Fig. 7 we show the  $\tau_{\text{dep}}$  values calculated from tilted rings constructed from the two-dimensional best-fit model and centred at the kinematic centre. At first order, we find the same trend suggested from the average  $\tau_{\text{dep}}$  values. But, at second order, we note that the depletion times vary from  $\sim 1.0 \pm 0.3$  Gyr in the outer ring ( $\approx 4.4 \text{ kpc}$ ) to  $\sim 2.9 \pm 0.2$  Gyr in the central kpc of this galaxy, suggesting an apparent decrease in the star formation efficiency ( $\text{SFE} \equiv \tau_{\text{dep}}^{-1}$ ) towards the galactic centre in SHIZELS-19. This is in contradiction with second order effects found in galaxies in the local Universe. Possible variations of the CO-to- $\text{H}_2$  conversion factor through a radial dependence of the dust-to-gas ratio optical depth or gas excitation or nuclear starburst activity in galactic centres favour the opposite  $\tau_{\text{dep}}$  correlation with galactic radius (e.g. Sandstrom et al. 2013; Leroy et al. 2013). However, by using the  $[\text{NII}/\text{H}\alpha]$  ratio as a proxy of the metallicity gradient (Pettini & Pagel 2004), we find a  $\alpha_{\text{CO}}$  radial profile consistent with being flat (see Appendix A).

On the other hand, although the CO and  $\text{H}\alpha$  maps are smooth, the  $\text{H}\alpha$  best-fit kinematic centre does not coincide exactly with the  $\text{H}\alpha$  luminosity peak as it does in the CO observations. Indeed, the projected distance between both centres is  $\sim 0''.11$ , i.e. slightly lower than the spatial resolution of the observations ( $\approx 0''.15$ ). Thus, possible inaccuracies of our best-fit kinematic centres given by the limited spatial resolution of our observations may lead to the apparent outward decrease of the  $\tau_{\text{dep}}$  values obtained from the tilted rings. In order to explore this possibility, in the right panel of Fig. 7 we show the  $\tau_{\text{dep}}$  values calculated from tilted rings constructed from the two-dimensional best-fit model but centred



**Figure 7.** *Left:*  $\Sigma_{\text{SFR}}$  against  $\Sigma_{\text{H}_2}$  for SHiZELS-8 and SHiZELS-19 galaxies compared with spatially-resolved local galaxy observations in the literature. For SHiZELS-8 we just show a global estimate given the limitations of our marginally-detected CO observation. For SHiZELS-19 we centre the CO(2-1) and  $\text{H}\alpha$  two-dimensional intensity maps by using the best-fit kinematic centre. The red contours show the 50th and 90th percentile levels of the pixel-by-pixel distribution. The colour-coded squares represent the  $\Sigma_{\text{SFR}} - \Sigma_{\text{H}_2}$  values calculated within tilted rings of  $0''.15$  ( $\sim 1.2$  kpc) thickness at the radius indicated by the colour bar. The ‘ $z \sim 0$  Spirals’ sample consist in observations of local disks taken from Kennicutt et al. (2007); Blanc et al. (2009); Rahman et al. (2011, 2012) at spatial resolutions between  $\sim 0.2 - 1$  kpc. The ‘ $z \sim 0$  LIRGs’ values consist in  $\sim 1$  kpc scale observations of two galaxies (Espada et al. 2018). The green circles show the median trend observed in the HERACLES survey (Leroy et al. 2013) at  $\sim$ kpc-scales and the black line represents the best-fit for those median values. The error bars represent the  $1-\sigma$  uncertainty. We also present galaxy-integrated estimates of ULIRGs ( $z \sim 0.4 - 1$ ; Combes et al. 2013), four SMGs taken from the ALESS survey ( $z \sim 2.0 - 2.9$ ; Calistro Rivera et al. 2018), ‘typical’ star-forming galaxies observed at similar redshifts (Tacconi et al. 2013) and five  $BzK$  galaxies ( $z \sim 1.5$ ; Daddi et al. 2010). The dashed lines indicate fixed  $\tau_{\text{dep}}$  values. *Right:* The same plot as the showed in left panel, but now the CO(2-1) and  $\text{H}\alpha$  two-dimensional intensity maps are centred by using the CO and  $\text{H}\alpha$  luminosity peaks.

at the luminosity peak. For this case, the  $\tau_{\text{dep}}$  values vary from  $\sim 1.3 \pm 0.3$  Gyr in the outer ring to  $\sim 2.5 \pm 0.1$  in the inner ring. The increase of the  $\tau_{\text{dep}}$  values towards the galactic centre still remains.

The suppression of the star formation in the molecular gas by dynamical effects is a possibility. For example, a morphological quenching scenario in which the bulge stabilises the molecular gas, preventing the star-formation activity but not destroying the gas may explain the observed  $\tau_{\text{dep}}$  trend with galactocentric radius (e.g. Martig et al. 2009; Saintonge et al. 2011). However, this scenario is unlikely as the Sérsic index measured for SHiZELS-19 ( $n \sim 1$ ; Gillman et al. 2019) indicates that this galaxy is consistent with being a disk-like galaxy with no prominent bulge component. Galaxies with a prominent bulge component tend to show Sérsic index values deviated from unity (Lang et al. 2014). On the other hand, Schreiber et al. (2016) found that the increase of  $\tau_{\text{dep}}$  towards the central galactic zone in massive systems ( $M_{\star} \sim 10^{11} M_{\odot}$ ) seems to be independent of the possible mass growth of the bulge component as disk-dominated galaxies tend to present the same  $\tau_{\text{dep}}$  trend with radius.

Another possible effect that adds uncertainty to the calculated  $\tau_{\text{dep}}$  values is a potential spatial variation of the  $\text{H}\alpha$  extinction. We have used an  $A_{\text{H}\alpha}$  correction constant across the galactic disk, but an underestimated galactic extinction in the galactic centre may lower the observed  $\tau_{\text{dep}}$  values in the central kpc zone therefore, producing the observed trend. An increase of the  $\text{H}\alpha$  extinction towards the galactic centre is consistent with findings of  $A_{\text{H}\alpha}$  being correlated with stellar mass surface density (Hemmati et al. 2015)

or the presence of compact density starbursts (e.g. Simpson et al. 2015; Hodge et al. 2016, 2018)

In order to explore the effects of the global galaxy kinematics in the global star formation activity, we compute the orbital timescale ( $\tau_{\text{orb}} = 2\pi R/V_{\text{rot}}$ ) to be compared it with the median depletion timescale (e.g. Kennicutt 1998b; Daddi et al. 2010). By following the analysis of Daddi et al. (2010), we choose  $R$  to be equal to three times the half-light radius. Although this assumes that the rotation curve remains flat beyond two half-light radius (the radius at which  $V_{\text{rot}}$  was estimated), this seems to be a reasonable assumption (see Fig. 5 & Tiley et al. 2019). Thus, we obtain  $\tau_{\text{orb}} = 256 \pm 22$  Myr and  $\tau_{\text{dep}}/\tau_{\text{orb}} \sim 9 \pm 5$ . We find that SHiZELS-19 converts  $\sim 10\%$  of its available gas into stars per orbit. This is consistent with the average value found for local galaxies by Kennicutt (1998b) and with galaxy-integrated studies of  $BzK$  galaxies at similar redshifts (Daddi et al. 2010). Therefore, on average, SHiZELS-19 is a galaxy which follows a similar star formation law to that seen in local spiral galaxies, although in denser environments.

We should stress, however, that our conclusions are highly dependent on the assumed  $\alpha_{\text{CO}}$  value (Table 4) and its variation with radius. We have used the CO-to- $\text{H}_2$  conversion suggested by Narayanan et al. (2012) in order to consider possible variations in the average ISM metallicity and density (see also Appendix A). However, spatially resolved observations of the dust content are desirable as these may help to constrain the  $\alpha_{\text{CO}}$  value through a dust-to-gas-to ratio based approach (Leroy et al. 2013; Sandstrom et al. 2013).



Our work opens the possibility to perform morpho-kinematic analysis of high-redshift galaxies at  $\sim$ kpc-scales using two different ISM tracers, but we stress that more observations of ‘typical’ galaxies are needed to understand the impact of local or global galactic properties on the star formation activity in high-redshift systems.

#### 4 CONCLUSIONS

We present new ALMA Cycle-5 observations tracing the CO(2-1) emission line from two ‘typical’ star-forming galaxies at  $z \sim 1.47$ . These observations were designed to deliver spatially resolved observations of the molecular gas content on  $\sim$ kpc-scales. We combine our ALMA observations with the previous H $\alpha$  SINFONI AO-aided observations (Swinbank et al. 2012a; Molina et al. 2017; Gillman et al. 2019) in order to study and compare the ionized and molecular gas dynamics.

One of our targets, SHiZELS-8, is marginally detected only in the 2000k $\lambda$  tapered datacube ( $0''.5 \sim 4.3$  kpc spatial resolution). For this system the H $\alpha$  and CO dynamics show that both ISM components rotate in the same direction but have position angles offset by 100 – 120 deg. This suggests that SHiZELS-8 is a dynamically perturbed system consistent with its previously observed flat metallicity gradient (Swinbank et al. 2012a). This finding suggests that ‘main-sequence’ galaxies at high-redshift are not exclusively part of a well-behaved morpho-kinematic disk-like population (e.g. Elbaz et al. 2018).

For the other target, SHiZELS-19, we find a good agreement between the CO and H $\alpha$  spatial extent ( $r_{1/2, \text{H}\alpha}/r_{1/2, \text{CO}} \sim 1.07 \pm 0.09$ ) and dynamics at  $\sim$ kpc-scales (Fig. 3). From both ISM phases we derive  $V_{\text{rot}}/\sigma_v \sim 1$  (Table 3). By performing a kinemetry analysis we classify SHiZELS-19 as a ‘non-regular rotator’ (van de Sande et al. 2017). The kinematic analysis suggests that the CO and H $\alpha$  observations are tracing the same galactic kinematics in agreement with previous studies of massive galaxies at similar redshift range (e.g. Übler et al. 2018; Calistro Rivera et al. 2018).

We estimate the total mass budget of the SHiZELS-19 galaxy by assuming a galactic thick-disk geometry (Burkert et al. 2010) and Narayanan et al. (2012)’s CO-to-H $_2$  conversion factor. From the SHiZELS-19 2000k $\lambda$  datacube we are able to trace the CO emission up to  $\approx 6$  kpc (Fig. 5), finding a dark matter fraction of  $f_{\text{DM}} = 0.59 \pm 0.10$  within this aperture. By applying a MCMC technique to sample the posterior PDF and take into account the parameter uncertainties (Fig. 6; e.g. Calistro Rivera et al. 2018) we estimate a  $f_{\text{DM}}$  3- $\sigma$  error range of  $\sim 0.31$ – $0.70$ . The dark matter fraction value is in agreement with hydrodynamical simulations of disk-like galaxies with similar stellar mass (Lovell et al. 2018) and the average dark matter fraction suggested by the stacked rotation curve analysis of galaxies at similar redshift range (Tiley et al. 2019). Thus, we conclude that SHiZELS-19 is a ‘typical’ star-forming galaxy at  $z \sim 1.47$  harbour in a non-negligible amount of dark matter.

By using two-dimensional modelling, we study the star formation activity observed in the SHiZELS-19 galaxy at  $\sim$ kpc-scales. We derive a median  $\tau_{\text{dep}} = 2.3 \pm 1.2$  Gyr. This median value is consistent with the typical value observed in local galaxies at similar spatial scales ( $\tau_{\text{dep}} = 2.2 \pm 0.28$  Gyr; Leroy et al. 2013) and consistent with the the large scatter presented in the  $z \sim 0$  spirals galaxy observations (Fig. 7), suggesting that ‘typical’ high-redshift galaxies (at  $z \sim 1.47$ ) with denser ISM still follow the same star-formation law.

#### ACKNOWLEDGEMENTS

We thank to the anonymous referee for her/his careful read of the manuscript and helpful comments and suggestions. J. M. acknowledges the support given by CONICYT Chile (CONICYT-PCHA/Doctorado-Nacional/2014-21140483). E. I. acknowledges partial support from FONDECYT through grant N $^\circ$  1171710. A.E. acknowledges support from CONICYT project Basal AFB-170002 and Proyecto Regular FONDECYT (grant 1181663). I.R.S. and A.M.S. acknowledge the support from STFC (ST/P000541/1). This paper makes use of the following ALMA data: ADS/JAO.ALMA#2018.1.01740.S, ADS/JAO.ALMA#2012.1.00402.S and ADS/JAO.ALMA#2015.1.00862.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in co-operation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ.

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#### APPENDIX A: $\alpha_{\text{CO}}$ RADIAL PROFILE

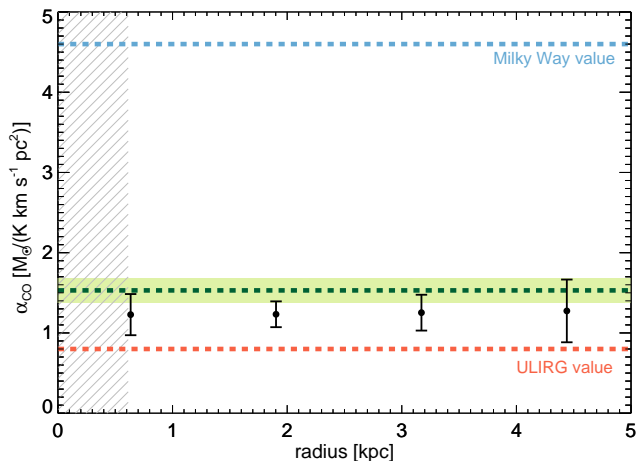
Throughout this work we have used a simple CO-to-H<sub>2</sub> conversion factor to estimate the molecular gas content in SHiZELS-8 and SHiZELS-19 galaxies (§ 3.1). Thus, we have assumed that there is no significant radial variation of the  $\alpha_{\text{CO}}$  value across each galactic disk. In order to test this assumption, we calculate the CO-to-H<sub>2</sub> conversion factor radial profile. This can only be done for the SHiZELS-19 galaxy since we were not able to obtain spatially resolved CO observations for SHiZELS-8. In Fig. A1 we show the  $\alpha_{\text{CO}}$  as a function of the galactocentric radius. It was calculated by using the Narayanan et al. (2012)’s parametrization with the CO surface brightness radial profile and metallicity gradient as input values. We find an  $\alpha_{\text{CO}}$  gradient consistent with being flat. This is mainly produced by the sub-linear dependence of the CO-to-H<sub>2</sub> conversion factor with respect to  $\Sigma_{\text{CO}}$  and metallicity in the Narayanan et al. (2012)’s parametrization. Although SHiZELS-19 has a negative metallicity gradient (Molina et al. 2017) it does not vary enough in order to increase the  $\alpha_{\text{CO}}$  value at larger radii.

We note that the  $\alpha_{\text{CO}}$  radial profile values are slightly lower but still consistent within 1- $\sigma$  uncertainties with the galactic average CO-to-H<sub>2</sub> conversion factor value calculated from the tapered (2000 k $\lambda$ ) map. This is expected as the low spatial resolution data-cube is able to trace CO(2-1) emission from the outskirts of the galaxy where the CO surface brightness is lower and the molecular gas has low metallicity compared to the inner parts. Both effects favour the increase of the average  $\alpha_{\text{CO}}$  value.

It is worth to mention that by considering the large variety of metallicity gradients observed in high redshift galaxies (e.g. Queyrel et al. 2012; Swinbank et al. 2012a; Molina et al. 2017), this result may be particularly applicable to SHiZELS-19 and it might not be used as typical property for the bulk population.

#### APPENDIX B: $\alpha_{\text{CO}}$ UPPER LIMIT FROM DYNAMICS

In § 3.4 we have assumed the Narayanan et al. (2012)’s parametrization to estimate the CO-to-H<sub>2</sub> conversion factor. Using this  $\alpha_{\text{CO}}$  value coupled with our dynamical mass calculus, we have constrained the dark matter content in the SHiZELS-19 galaxy. We



**Figure A1.** CO-to-H<sub>2</sub> conversion factor gradient across SHiZELS-19 from spatially-resolved measurements and as a function of the galactocentric radius derived from the best-fit kinematic model. The green-dashed line represent the galactic  $\alpha_{\text{CO}}$  value derived from the tapered (2000 k $\lambda$ ) map and the green-shaded region show the 1- $\sigma$  uncertainty. The blue- and red-dashed lines indicate the  $\alpha_{\text{CO}}$  values usually adopted for the Milky Way and ULIRG like systems. The grey-dashed area represents the resolution element radial extent. We find a flat  $\alpha_{\text{CO}}$  profile.

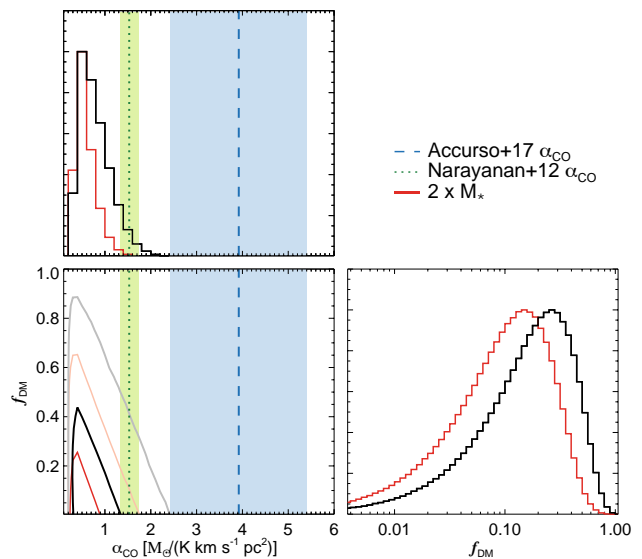
have used the Narayanan et al. (2012)’s parametrization in detriment of Accurso et al. (2017)’s parametrization as the second is likely to be an upper limit for the CO-to-H<sub>2</sub> conversion factor as it does not consider the gas surface density effects (Bolatto et al. 2013). In order to confirm this assumption we use the dynamical mass calculus to constrain the CO-to-H<sub>2</sub> conversion factor (e.g. Tacconi et al. 2008).

We repeat the analysis done in § 3.4, but now we calculate the total and stellar mass content within one CO half-light radius. The stellar mass within this radius is estimated by assuming an exponential stellar surface density profile, as suggested by the best-fitted Sérsic profile presented in Gillman et al. (2019) for the HST-F160W broad-band image. We caution, however, that this calculus also assumes a constant mass-to-light ratio across the SHiZELS-19 galactic disk. We calculate the thick-disk dynamical mass within one  $r_{1/2,\text{CO}}$  by using the  $\sim$ kpc-scale kinematic CO observations (Fig. 3).

Initially we just constrain the  $\alpha_{\text{CO}}$  lower limit value by imposing that the CO emission should be optically thick ( $\alpha_{\text{CO}} \gtrsim 0.34$ ; Bolatto et al. 2013). We do not assume any dark matter content as we allow that the MCMC technique samples  $\alpha_{\text{CO}} - f_{\text{DM}}$  phase-space and fully considers the parameter degeneration introduced in Eq. 2.

In Fig.B1 we show the one- and two- dimensional posterior PDFs of the  $\alpha_{\text{CO}}$  and  $f_{\text{DM}}$  parameters. As in § 3.4, we find that higher  $\alpha_{\text{CO}}$  values imply lower dark matter fractions. In the case of negligible central dark matter content within  $r_{1/2,\text{CO}}$ , we find an  $\alpha_{\text{CO}}$  upper limit of  $1.3(2.4) M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$  by considering 1-(3-) $\sigma$  uncertainties.

This analysis suggests that the Accurso et al. (2017)’s parametrization overestimates the CO-to-H<sub>2</sub> conversion factor in SHiZELS-19 as this value is beyond the 3- $\sigma$  range derived from the  $\alpha_{\text{CO}}$  PDF. Meanwhile, the CO-to-H<sub>2</sub> conversion factor estimated by assuming the Narayanan et al. (2012)’s parametrization is consistent within 1- $\sigma$  uncertainties. We note that an assumed  $\alpha_{\text{CO}} \gtrsim 1$  implies that SHiZELS-19 may be baryon dominated ( $f_{\text{DM}} < 0.5$ ) in



**Figure B1.** One- and two- dimensional posterior PDFs of the  $f_{\text{DM}}$  and  $\alpha_{\text{CO}}$  parameters estimated by considering the total mass content within one CO half-light radius for SHiZELS-19. The data is colour coded in the same way as Fig. 6. This suggests an  $\alpha_{\text{CO}}$  upper limit of  $2.4 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$  in the case of negligible dark matter content within this radius. This result rules out the Accurso et al. (2017)’s CO-to-H<sub>2</sub> conversion factor suggested for SHiZELS-19 by the 3- $\sigma$ .

its central zone, albeit dark matter dominated in its outskirts (§ 3.4; see also Tiley et al. 2019). This is consistent with the ‘compaction’ scenario (e.g. Dekel & Burkert 2014; Zolotov et al. 2015) in which the baryonic matter can cool and condense more efficiently than the collisionless dark matter, and thus, falling into the centre of the dark matter halo where they concentrate.

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