The EDGE-CALIFA Survey: Using Optical Extinction to Probe the Spatially-Resolved Distribution of Gas in Nearby Galaxies

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ABSTRACT
We present an empirical relation between the cold gas surface density (Σgas) and the optical extinction (A_V) in a sample of 103 galaxies from the Extragalactic Database for Galaxy Evolution (EDGE) survey. This survey provides CARMA interferometric CO observations for 126 galaxies included in the Calar Alto Legacy Integral Field Area (CALIFA) survey. The matched, spatially resolved nature of these data sets allows us to derive the Σgas-A_V relation on global, radial, and kpc (spaxel) scales. We determine A_V from the Balmer decrement (Hα/Hβ). We find that the best fit for this relation is Σgas (M⊙ pc^-2) ~ 26 × A_V (mag), and that it does not depend on the spatial scale used for the fit. However, the scatter in the fits increases as we probe smaller spatial scales, reflecting the complex relative spatial distributions of stars, gas, and dust. We investigate the Σgas/A_V ratio on radial and spaxel scales as a function of EW(Hα). We find that at larger values of EW(Hα) (i.e., actively star-forming regions) this ratio tend to converge to the value expected for dust-star mixed geometries (~ 30 M⊙ pc^-2 mag^-1). On radial scales, we do not find a significant relation between the Σgas/A_V ratio and the ionized gas metallicty. We contrast our estimates of Σgas using A_V with compilations in the literature of the gas fraction on global and radial scales as well as with well known scaling relations such as the radial star-formation law and the Σgas-S relation. These tests show that optical extinction is a reliable proxy for estimating Σgas in the absence of direct sub/millimeter observations of the cold gas.

Key words: galaxies: evolution, galaxies: ISM, ISM: molecules

1 INTRODUCTION
The interstellar medium (ISM) is essential to the understand the structure and evolution of galaxies. The cold ISM is the raw material for the formation of new stars, as is evident from the tight relation between the cold gas surface mass density (Σgas) and the star formation surface density (Σ_{SF}) , also known as the Star Formation or Kennicutt-Schmidt law (Schmidt 1959; Kennicutt 1998b).

Radio observations are used to directly trace the mass of the cold gas component in galaxies. The atomic component of the cold gas is observed via the 21 cm line of HI. Even though the main component of the cold molecular gas in the ISM is H2, due to its absence of transitions available at low temperature, emission from CO rotational transitions is used as a proxy for the H2 gas in extragalactic molecular clouds. Large extragalactic single-dish CO and HI surveys have provided estimates of the total molecular and neutral atomic gas mass in galaxies (e.g., FCRAO, COLD GASS surveys; Young et al. 1995; Saintonge et al. 2011) as well as

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their relevance to galactic processes such as chemical enrichment (e.g., Peebles & Shankar 2011). As noted by Bolatto et al. (2017) in the EDGE-CALIFA survey presentation paper, spatially resolved information regarding the gas content in galaxies is fundamental to understanding key processes of galactic evolution such as the star formation rate and gas transport. In this regard, spatially resolved maps of CO and HI exist for samples of local galaxies, such as the THINGS/HERACLES surveys (Walter et al. 2008; Leroy et al. 2008). However, mapping of HI and CO to trace the spatial distribution of neutral and molecular gas is limited and not feasible for large samples of galaxies. This includes the Integral Field Spectroscopy (IFS) surveys (e.g., CALIFA, MaNGA, SAMI; Sánchez et al. 2012; Bundy et al. 2015; Croom et al. 2012) which provide spectral information across their optical extension for a large set of galaxies. Therefore, having an optical tracer for the cold gas distribution for these IFS surveys would be quite useful.

On the other hand, starformation is typically embedded or occurs very close to molecular gas complexes which in turn are mixed with dust that attenuates the light from these newly born stars. How the extinction, due to the dust, and the gas correlate to each other could strongly depend on the geometrical arrangement of the stars and the dust (e.g., Nordon et al. 2013). Generally, the geometrical arrangements that yield the observed optical extinction ($A_V$) can be classified as a foreground dust screen obscuring the starlight or a mix of stars and dust. Depending on the physical scale either of these geometries can be assumed (e.g., Liu et al. 2013; Genzel et al. 2013). Therefore for a given wavelength, for an obscuring dust screen the extinction would be smaller than for a star-dust mixed geometry. Different studies also consider the impact of tracing $A_V$ using different methods in the optical (i.e., emission vs absorption) as well as the spatial distribution of extinction as well as the impact of the diffuse ionized gas in determine $A_V$ in galaxies (e.g., Kreckel et al. 2013; Tomičić et al. 2017). Under the assumption of local thermodynamic equilibrium (LTE), it is also expected that the gas column density ($N(H)$) correlates with $A_V$. This relation has been explored extensively within the Milky Way (e.g., Dickman 1978; Bohlin et al. 1978; Rachford et al. 2009). More recently the relation between the CO emission ($I_{CO}$) and $A_V$ has also been explored, resolving clouds of tens of parsecs in size in near extragalactic objects (Lee et al. 2015; 2018), as well as at kpc scales (e.g., Boguén et al. 2013), Guver & Özel (2009) found a tight relation between these two observables using the extinction derived from the Balmer decrement and the hydrogen column density modelling the continuum and the line features from the spectra of 22 supernova remnants with $N(H) = (2.21 \pm 0.09) \times 10^{21}$ cm$^{-2}$ $A_V$. In terms of the total gas surface mass density ($\Sigma_{gas} = \Sigma_{H_2} + \Sigma_{HI}$) this relation translates to

$$\Sigma_{gas} = 23\left(\frac{A_V}{mag}\right)(M_\odot pc^{-2}).$$

Alternatively, the total gas column density can be obtained assuming an effective gas-to-dust ratio. Assuming a foreground dust screen, Heiderman et al. (2010) derived $A_V$ using Spitzer infrared SEDs of young stellar objects. Using a constant gas-to-dust relation of $N(H) = 1.37 \times 10^{21}$ cm$^{-2}$ $A_V$, with $R_V = 5.5$ (Draine 2003) which includes the helium mass contribution, they found that the gas surface mass density ($\Sigma_{gas}$) is given by

$$\Sigma_{gas} = 15\left(\frac{A_V}{mag}\right)(M_\odot pc^{-2}).$$

Dust-star mixed models will yield twice the above values as they account for the dust in the foreground and the background. Optical studies have also provided the relationship between the gas density and the optical extinction. Using the Sloan Digital Sky Survey single-fiber spectroscopic data, Brinchmann et al. (2013) presented a method to derive the total gas column density from the optical dust attenuation, the dust-to-metal ratio, and the metallicity of the ionized gas for the central region of a large sample of galaxies. In summary, relations between $\Sigma_{gas}$ and $A_V$ can vary depending on the geometry as well as the averaging scale (ranging from pc-size molecular clouds to entire galaxies) (e.g., Tacchella et al. 2018). Despite the above efforts, there is no systematic study using a homogeneous data set to determine the spatially resolved relation between $\Sigma_{gas}$ and $A_V$ relevant for estimating the gas content in galaxies. In this regard, the EDGE-CALIFA survey (Bolatto et al. 2017) provides an ideal data set for quantifying the relation between these two parameters on different scales, including galaxy-integrated, radial, and kpc scales. This survey provides a unique observational data set of spatially resolved CO data cubes as well as Integral Field Unit data cubes from the optical CALIFA survey for 126 galaxies in the nearby universe. The main goal of this article is to determine the relation between $\Sigma_{gas}$ and $A_V$ using a large sample of nearby galaxies and to quantify the impact of averaging these properties on different spatial scales.

This paper is organized as follows: in Section 2 we present the main features of the EDGE-CALIFA survey; in Section 3 we give a description of the main observables we extract from the different data cubes for each galaxy; in Section 4 we present the relation between $\Sigma_{gas}$ and $A_V$ at different spatial scales (from integrated, radial and kpc scales); we compare our results with respect to previous Galactic and extragalactic results in Section 5, and present the main conclusions of this article in Section 6. In this article we assume the following cosmological parameters: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$.

2 SAMPLE AND DATA

The galaxies presented in this study are part of the EDGE-CALIFA survey (Bolatto et al. 2017). The goal of this survey is to provide spatially resolved maps of the molecular $^{12}$C$^1$O ground rotational transition line ($J = 1 \rightarrow 0$) and at optical wavelengths for 126 galaxies. This surveys enables matched resolution comparison of the properties of the molecular gas with those of other galactic components such as the stellar and ionized gas. In this section we briefly describe the main characteristics of the CALIFA and EDGE surveys as well as our target selection.

2.1 The CALIFA survey

The CALIFA survey (Sánchez et al. 2012) was designed to acquired spatially resolved spectroscopic information from more than 600 galaxies in the nearby Universe ($0.005 < z < 0.03$) using the PMAS Integral Field Unit (IFU) instrument (Roth et al. 2005) mounted at the 3.5 m telescope of the Calar Alto Observatory. The main component of this instrument consists of 331 fibers of 27" diameter each, concentrated in a single hexagon bundle covering a field-of-view (FoV) of 74" x 64", with a filling factor of ~ 60%. Three-point dithering allows a full coverage of the FoV. The nominal resolution of this instrument is $\sim 1100$ at $\sim 5000$ Å with a nominal wavelength range from 3745 to 7300 Å. Besides the restriction in redshift, most CALIFA galaxies are expected to match the instrument FoV. Their isophotal diameters in the SDSS r-band are in the range $45 \lesssim D_{25} \lesssim 80$ arcsec (Walcher et al. 2014). The data reduction is performed by a pipeline designed specifically for the CALIFA survey.

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The final data cube for each galaxy consists of more than 5000 spectra with a sampling of 1 arcsec per spaxel. The detailed reduction process is described in Sánchez et al. (2012), and improvements on this pipeline as well as extensions to the original sample (reaching a total of 834 galaxies) are presented by Husemann et al. (2013); García-Benito et al. (2015); Sánchez et al. (2016).

2.2 The EDGE survey

The EDGE survey obtained millimeter-wave interferometric observations for a subsample of galaxies selected from the CALIFA survey. These observations were carried out at the Combined Array for Millimeterwave Astronomy (CARMA, Bock et al. 2006). The EDGE survey provides the first major effort to combine CO data with IFS optical data.

We present a brief description of the survey here. See Bolatto et al. (2017) for a detailed description. Observations took place between November 2014 and April 2015. Galaxies were observed using half-beam-spaced seven-point hexagonal mosaics to optimize et al. (2017) for a detailed description. Observations took place with IFS optical data.

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We present a brief description of the survey here. See Bolatto et al. (2017) for a detailed description. Observations took place between November 2014 and April 2015. Galaxies were observed using half-beam-spaced seven-point hexagonal mosaics to optimize extended flux recovery over the central 1 arcmin region and yielding a half-power field-of-view of radius \( \sim 50'' \). 177 CALIFA galaxies were observed in the E array configuration (each with typically 40 min of integration time and \( \sim 8 \) arcsec resolution). From these galaxies, 126 with detections or possible detections of CO emission were selected for an additional \( \sim 3.5 \) hr integration, this time in the more extended D-array, yielding \( \sim 4'' \) resolution, equivalent to \( \sim 1-2 \) kpc at the typical distances of galaxies in the survey. To maximize observing efficiency, galaxies were observed in different groups according to their redshift. Each of these observation bins used a fixed tuning and correlation set-up. The correlator covers five 250-MHz windows spanning the velocity range where emission is expected to occur for each of the targets. The final maps combined the E and D array observations resulting in velocity resolution of 20 km s\(^{-1}\) with a typical angular resolution of 4.5'' and typical rms sensitivity of 30 mK at the velocity resolution. Assuming a constant CO-to-H\(_2\) conversion factor, the survey is sensitive to an H\(_2\) surface mass density of \( \sim 4-110 \) M\(_{\odot}\) pc\(^{-2}\) (averaged over a \( \sim 1.5 \) kpc scale). The data cubes are smoothed and then masked in order to distinguish CO signal from noise and to reach higher signal to noise (see more details in Bolatto et al. 2017). Projects conducted with EDGE data to date include in-depth studies of the impact of morphology and kinematics on the molecular depletion time (Utomo et al. 2017; Colombo et al. 2018), as well as dynamical comparisons of the cold and ionized gas (Levy et al. 2018) and dynamical modelling of different baryonic components (Leung et al. 2018).

3 ANALYSIS

3.1 CALIFA and EDGE Spatially Resolved Properties

We used the IFU analysis pipeline PIPE3D (Sánchez et al. 2015) in order to extract physical parameters from the CALIFA data cubes. A full description of how the pipeline extracts two-dimensional physical properties from data cubes is described in Sánchez et al. (2016). The pipeline extracts properties from a large variety of emission lines included in the covered wavelength range such as integrated flux, equivalent width, line-of-sight velocity, and velocity dispersion. In particular, for this study we use fluxes from the emission lines H\(_\alpha\), H\(_\beta\), [OIII]\(\lambda\)5007\AA, and [NII]\(\lambda\)6583\AA as well as the H\(_\alpha\) equivalent width (EW(H\(_\alpha\))). The pipeline also provide a myriad of information regarding the stellar component including the stellar mass density \( \Sigma_*(\text{see details in Sánchez et al. 2016}). \) For the resolved analysis, we use the photometric axis ratio for each galaxy (Walcher et al. 2014) to correct the surface densities for inclination effects (Barrera-Ballesteros et al. 2016).

To obtain the velocity-integrated CO surface brightness maps (\( I_{CO} \)), the smoothed and masked EDGE data cubes are integrated along the velocity axis. The uncertainties are also derived from the integrated noise data cubes. We convert \( I_{CO} \) into molecular gas surface density \( \Sigma_{CO} \) via a constant CO-to-H\(_2\) conversion factor \( (\alpha_{CO}) \) of 4.4 M\(_{\odot}\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) (Bolatto et al. 2013), including the mass contribution from helium.

In order to compare properties from the two data sets on a spaxel by spaxel basis, we follow a similar procedure to that described in Utomo et al. (2017). The EDGE maps are centered and regrided to match the spaxel size and grid of the CALIFA maps by using the MIRiad task \texttt{regrid}. The CALIFA maps are also convolved to match the resolution of EDGE maps. In Fig. 1 we show an example of the emission maps used for this analysis.

From the emission line flux maps, we derive the dust attenuation for the H\(_\alpha\) emission line (\( A(H\alpha) \)) following Catalán-Torrecilla et al. (2015). Assuming an extinction-free H\(_\alpha\)/H\(_\beta\) flux ratio of 2.86 (Osterbrock 1989) and \( R_V = 3.1 \) (Cardelli et al. 1989),

\[
A(H\alpha) = \frac{K_{H\alpha}}{-0.4(K_{H\alpha} - K_{H\beta})} \times \log \left( \frac{F_{H\alpha}}{F_{H\beta}} \right) \frac{2.86}{3.1}
\]

where \( F_{H\alpha}/F_{H\beta} \) is the flux ratio between these Balmer lines, and \( K_{H\alpha} = 2.53 \) and \( K_{H\beta} = 3.61 \) are the extinction coefficients for the Galactic extinction curve from Cardelli et al. (1989). The values of \( K_{H\alpha} \) and \( K_{H\beta} \) are similar for both Cardelli et al. (1989) and Calzetti et al. (2000) extinction curves and dust-to-star geometries. Assuming an extinction curve of \( R_V = 3.1 \) (Cardelli et al. 1989), the optical extinction is given by

\[
A_V = A(H\alpha)/0.817.
\]

We use the luminosity of the H\(_\alpha\) emission line to derive the integrated and spatially resolved star formation rates (SFR) presented in this study. We transform this luminosity to SFR following the relation presented in Kennicutt (1998a) which assumes a Salpeter Initial Mass Function and solar metallicity

\[
\text{SFR} (M_{\odot} \text{ yr}^{-1}) = 8 \times 10^{-12} L(H\alpha)(\text{erg s}^{-1})
\]

where \( L(H\alpha) \) is the luminosity of the H\(_\alpha\) emission line obtained using the extinction-corrected integrated flux \( (F_{\text{corr}}(H\alpha)) \) via

\[
L(H\alpha)(\text{erg s}^{-1}) = 1 \times 10^{-16} \times 4\pi D^2 F_{\text{corr}}(H\alpha)
\]

where \( D \) is the luminosity distance for each galaxy in units of cm and \( F_{\text{corr}}(H\alpha) \) has units of \( 10^{-16} \text{erg s}^{-1} \text{ cm}^{-2} \). In Sec. 4.1 we used the H\(_\alpha\) equivalent width measured at an effective radius of one (EW(H\(_\alpha\),\( r_e \)); this value was derived for all the CALIFA galaxies in Sánchez et al. (2018). Finally, we derived the metallicity for each of the selected spaxels in the EDGE-CALIFA galaxies. Here we use the metallicity from the O3N2 empirical calibrator (Marino et al. 2013). A full description of the derivation of metallicity for CALIFA galaxies using this calibrator is presented in Sánchez et al. (2017).

4 RESULTS

Due to the spatially-resolved nature of the EDGE data cubes, we can study the correlation between molecular gas surface density

\[
\Sigma_{CO}(r) \sim \text{co的相关性}
\]

选择合适的数学公式来表示这方面的关系。
\[ \log \left( \frac{\Sigma_{\text{gas}}}{M_\odot \text{pc}^{-2}} \right) = (25 \pm 7) A_V \]

\[ \Sigma_{\text{gas}} = \frac{(25 \pm 7) A_V}{M_\odot \text{pc}^{-2}} \]

For each of the selected spaxels in each galaxy we derived the extinction for each galaxy as the median value obtained for all the spaxels that satisfy the above selection criteria. We note that extinction derived using this method is quite similar to the one derived from the ratio of the integrated H\(\alpha\) and H\(\beta\) fluxes in each galaxy. For the CO datacubes, we derive the total mass of the molecular hydrogen in each galaxy by adding up the mass contributions from individual spaxels assuming a conversion factor of \(\alpha_{\text{CO}} = 4.4 \times 10^{20} M_\odot \text{K km s}^{-1} \text{pc}^{-2} \) \(^{-1}\). To derive the total molecular mass surface density (\(\Sigma_{\text{H}_2}\)), we divide the total mass by the effective area, which is the area of a single spaxel (in pc\(^2\)) times the number of selected spaxels in each galaxy. Finally to compare \(A_V\) to the total hydrogen gas density (\(\Sigma_{\text{gas}} = \Sigma_{\text{H}_2} + \Sigma_{\text{HI}}\)), since resolved HI maps are not available for most galaxies we use a fiducial HI surface density of \(\Sigma_{\text{HI}} = 6 M_\odot \text{pc}^{-2}\). This deprojected surface density is a typical value in disc galaxies where \(H_2\) is detected (Bigiel et al. 2008). To provide robust estimates of the relation, we exclude from our sample galaxies with values of \(A_V < 0.2\). That is, we exclude those galaxies/regions where CO emission likely drops rapidly due to photo dissociation of the CO molecules (van Dishoeck & Black 1988). The final sample consists of 103 galaxies out of the total sample of EDGE galaxies (126 targets).

\[ A_V / \text{mag} = 0.316 \times \log(\Sigma_{\text{gas}} / M_\odot \text{pc}^{-2}) + 1.000 \]

\[ \Sigma_{\text{gas}} = (25 \pm 7) A_V \]

\[ \text{G" uver &"Ozel (2009)} \]

\[ \text{Heiderman et al. (2010)} \]

\[ 0.316 \]

\[ 1.000 \]

\[ 3.162 \]

Figure 1. Example of the maps used for this study. Left and middle panels correspond to maps of the logarithm of the flux from the H\(\alpha\) and H\(\beta\) emission lines for the galaxy NGC 5633. Both in units of \(10^{-19} \text{erg s}^{-1} \text{cm}^{-2}\). The right panel corresponds to the CO intensity in units of K km s\(^{-1}\) for the same object. The CO intensity maps have been centered and regrided to have the same spatial resolution as the CALIFA datacubes (1 arcsec, Utomo et al. 2017). To compare the \(A_V\) derived from the Balmer decrement with the \(\Sigma_{\text{gas}}\) derived from the CO intensity, our selection considers only those regions where both H\(\alpha\) and CO emission are detected.

4.1 Global Properties

Prior to obtaining the integrated properties from the optical and millimeter maps, we select those regions with non-negative flux in both the CO and H\(\alpha\) emission maps. Although this selection criterion may consider spaxels with relatively low signal to noise ratio, or even below the detection limit, it does provide a good compromise between reliable detections and upper limits. Below we consider the effect of different CO flux selection thresholds in estimating the best relation between \(\Sigma_{\text{gas}}\) and \(A_V\). It also provides a reliable way to mimic the integrated properties derived using a single-dish in the millimeter regime or narrow filters in the optical.

For each of the selected spaxels in each galaxy we derived the extinction from the Balmer decrement as described in Sec. 3. In those cases where H\(\alpha\) /H\(\beta\) < 2.86 with CO flux larger than zero, we assume a median extinction derived from those spaxels in the galaxy with H\(\alpha\) /H\(\beta\) > 2.86. Following Sánchez et al. (2018), we derive the extinction for each galaxy as the median value obtained for all the spaxels that satisfy the above selection criteria. We note that extinction derived using this method is quite similar to the one derived from the ratio of the integrated H\(\alpha\) and H\(\beta\) fluxes in each galaxy.

In Fig. 2 we plot the galaxy-averaged gas mass surface density and optical extinction for the selected EDGE galaxies (see Sec. 4.1 for details). Symbols are color-coded by the H\(\alpha\) equivalent width (EW(H\(\alpha\)) \(\AA\)). Horizontal-gray and vertical-blue shaded areas represent the detection limits for \(\Sigma_{\text{gas}}\) and \(A_V\), respectively. The black line represents the best fitted line of the form \(\Sigma_{\text{gas}} = b A_V\), with \(b = 25 M_\odot \text{pc}^{-2} \text{mag}^{-1}\); the green shaded area reflects the uncertainty from CO selection effects (see text for details). The red and blue-dashed lines represent the \(\Sigma_{\text{gas}} - A_V\) relation derived from observations (cf. Eq. (1), Güver & Özel 2009) and a dust-screen model (cf. Eq. (2), Heiderman et al. 2010). Galaxies with larger EW(H\(\alpha\)) \(\text{mag}^{-1}\) tend to have a similar \(\Sigma_{\text{gas}} - A_V\) relation as the one derived from observations.
For our particular selection (CO flux larger than zero) we represent this limit in Fig. 2 with horizontal-gray shading. The upper value of the shading represents the sum of the assumed value of $\Sigma_{\text{gas}}$ and the $3\sigma$ brightness sensitivity of the EDGE-CALIFA survey ($\Sigma_{\text{HI}} \sim 11\, M_\odot\, \text{pc}^{-2}$, Bolatto et al. 2013). On the other hand, for our data we are not able to estimate $A_V$ larger than 3 mag due to the impossibility of measure $H_\beta$ at such large extinction. We indicate this limit with vertical blue shading. Despite the scatter, $\Sigma_{\text{gas}}$ increases with $A_V$.

We also overlap the expected relations presented in Eqs. 1 and 2 (red and blue dashed lines, respectively). We note that in general the integrated $\Sigma_{\text{gas}}$ and $A_V$ follows these two lines. Following this relation, we fit this data set using a linear relation of the form

$$\Sigma_{\text{gas}} = bA_V. \quad (7)$$

with $b = 25\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}$ determined as the best fitting value (see black line in Fig 2). We note that this value is more similar to the one determined from observations by Güver & Özel (2009) than the expected value from a dust-screen geometry obtained by Heiderman et al. (2010). When we repeat the above analysis selecting only low-inclination galaxies (i.e., $i < 65^\circ$), we obtain a similar value for $b$, $b = 23\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}$. To account for the fact that different CO flux selection can lead to different estimates of the best fit $\Sigma_{\text{gas}}$-$A_V$ relation, the green-shaded area in Fig. 2 represents the range of fits using two different selection criteria. By using a conservative selection criteria with CO detection brighter than $2\sigma$ we find the upper envelope of this area (i.e., $b = 29\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}$). This value is significantly larger than the one derived by Güver & Özel (2009). However, it is similar to the expected value for a dust-star mix geometry, where $b$ is expected to be close to twice the value derived for the dust-screen geometry (Nordon et al. 2013). On the other hand, if we loosen this constraint and select all the CO flux, we find values very similar to those reported by Heiderman et al. (2010), $b = 18\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}$.

The equivalent width of the $H\alpha$ emission line ($\text{EW}(H\alpha)$) has been used extensively to quantify the nature of the ionization source responsible for the emission from the ionized gas in extragalactic objects (e.g., Cid Fernandes et al. 2010; Barrera-Ballesteros et al. 2016). Large values of $\text{EW}(H\alpha)$ strongly correlate with underlying young stellar population and thus recent star formation (e.g., Sánchez et al. 2015) whereas low-values are attributed to ionization due to old-stellar population or any other process of ionization such as underlying old stellar population, shocks, etc (e.g., Lacerda et al. 2018, with the exception of ionization due to Active Galactic Nuclei). In Fig. 2 we color-coded the data points according to the $\text{EW}(H\alpha)$ measured at the effective radius for each galaxy ($\text{EW}(H\alpha)_{\text{eff}}$). Althought, we find that the median value of the ratio $\Sigma_{\text{gas}}/A_V$ increases as we select galaxies with larger $\text{EW}(H\alpha)_{\text{eff}}$, the typical value of this ratio for this sample is similar to the best fit of Eq. 7 ($\Sigma_{\text{gas}}/A_V \sim 25\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}$). Selecting galaxies with $\text{EW}(H\alpha)_{\text{eff}} > 6$ (the typical value used to segregate star-forming galaxies) we find a similar median ratio to the one derived using the entire sample. However, when selecting galaxies with $\text{EW}(H\alpha)_{\text{eff}} > 20$ we find that the median value of the $\Sigma_{\text{gas}}/A_V$ ratio agrees with the value expected for a dust-star mixed geometry ($\Sigma_{\text{gas}}/A_V \sim 30\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}$). These results suggest that for actively star-forming galaxies (i.e., galaxies with large $\text{EW}(H\alpha)$ values), the relation between the gas density and the optical extinction is similar to a dust-star mix configuration rather than the commonly assumed dust-screen geometry.

In summary, these results suggest that the galaxy-averaged $\Sigma_{\text{gas}}$ can be derived from the galaxy-averaged $A_V$. However, due to the limits inherent on the detection sensitivity for both gas (at low values of $\Sigma_{\text{gas}}$, CO detection) and extinction (at large values of $A_V$, H$\beta$ detection) the linear relation expected from these two values is affected. Even more, we also note that galaxies without current star formation (i.e., galaxies with small $\text{EW}(H\alpha)$ values) contribute to the scatter of the global $\Sigma_{\text{gas}}$-$A_V$ relation.

The above relation also allows us to compare the estimate of the total galaxy molecular gas mass from the integrated CO flux with the one using extinction as a proxy for gas mass surface density. To derive molecular gas mass from $A_V$ in each galaxy, first we use the relation at spaxel scales to transform $A_V$ to $\Sigma_{\text{gas}}$ (see details in Sec. 4.3). Next, we derived the mass in each spaxel multiplying $\Sigma_{\text{gas}}$ times the spaxel area. Then, we integrate the individual contributions of spaxels to derive the total gas mass for each galaxy. Finally, to obtain the total molecular mass from the extinction ($M_{\text{HI}}(A_V)$), we subtract the contribution of HI to the total gas mass.

In Fig. 3 we plot the total mass of $M_{\text{HI}}$ for each EDGE-CALIFA galaxy using CO (with $M_{\text{HI}}(CO)$ from Bolatto et al. 2017) vs the total mass of $M_{\text{HI}}$, estimated as described above using $A_V$ (i.e., using $\Sigma_{\text{gas}} = 25\, M_\odot\, \text{pc}^{-2}\, \text{mag}^{-1}\, A_V$). Despite the difference in methods for deriving $M_{\text{HI}}$, we find that most galaxies lie near the one-to-one line (dashed-line in Fig. 3).

To further quantify possible differences in the two methods for estimating molecular gas mass, in the inset of Fig. 3 we show the distribution of the ratio of the molecular mass obtained from each method. The distribution is quite tight and close to unity; indeed the average gas mass ratio is 1.1 and its standard deviation is similar to the deviation of the relative errors of the gas masses ($\sim 0.3$ dex). The best fit using an orthogonal distance regression (ODR) between these
two masses (blue line in Fig. 3) is close to a linear relation with a best fitted intercept and slope in logarithm scale of $(0.1 \pm 0.5) \log(M_\odot)$ and $0.98 \pm 0.05$, respectively.

### 4.2 Radial binned properties

The spatially resolved data allows us to study the relationship between $\Sigma_{\text{gas}}$ and $A_V$ in radial bins in our sample of extragalactic objects. We averaged the spatial distribution of each observable in annuli of $0.2 R_{\text{eff}}$ width each out to a radius of $2.5 R_{\text{eff}}$. To account for the effects of inclination, we use the ellipticities and position angles provided for the CALIFA galaxies (Walcher et al. 2014). For our analysis, in each galaxy we select those annuli for which at least 15 per cent of the spaxels included in the annulus have reliable CO detections (> 1σ). To derive the extinction for each of the selected annuli, we compute the average $H\alpha$ and $H\beta$ fluxes within it and estimate the extinction from their ratio, as described in Sec. 3. We derive the integrated CO flux in each selected annulus using all the unmasked CO spaxels to determine its corresponding $\Sigma_{\text{gas}}$. Using a similar procedure described above (Sec. 3). Similar to our procedure for galaxy-integrated properties, we assume a constant density for the neutral gas component. Thus in each annulus $\Sigma_{\text{gas}} = \Sigma_{\text{H}_2} + \Sigma_{\text{HI}}$, with $\Sigma_{\text{HI}} = 6 M_\odot$ pc$^{-2}$. As result, we are able to measure $\Sigma_{\text{gas}}$ and $A_V$ in 893 annuli from 93 EDGE-CALIFA galaxies.

In Fig. 4 we plot the comparison between $\Sigma_{\text{gas}}$ and $A_V$ derived for each annulus. $\Sigma_{\text{gas}}$ increases with $A_V$. As we describe in Sec. 4.1, here we are also limited by our ability to detect CO and $H\beta$ emission line flux in these annuli (horizontal-gray and vertical-blue shades in Fig. 4). We note that $\Sigma_{\text{gas}}$ and $A_V$ follow a similar relation as the one derived at galaxy-integrated scales (see Fig. 2).

We overplot blue and red-dashed lines representing the relations from Heiderman et al. (2010) and Güver & Özel (2009), respectively. We note that a significant fraction of points have values that lies between these two lines. Using orthogonal distance regression (ODR), we fit Eq. 7 to 80 per cent of the sample (see data points enclosed in the blue contour in Fig. 4). This fit results in $b = (27 \pm 5) M_\odot$ pc$^{-2}$. We derived the uncertainty in $b$ by fitting this parameter in a Monte Carlo simulation in which we allow the following parameters to vary: (i) $\Sigma_{\text{HI}} = [3.8] M_\odot$ pc$^{-2}$; these values are typically obtained from $\Sigma_{\text{HI}}$ radial profiles observed in nearby galaxies (Bigiel et al. 2008); (ii) the choice of CO brightness threshold was varied from 0.5 to 2 $\sigma$; and (iii) the minimum percentage of spaxels per annulus with CO flux was varied from 15 to 45 percent.

The best fit radial $\Sigma_{\text{gas}}$-$A_V$ relation is in agreement with the estimates from Güver & Özel (2009) rather than the values expected from a dust-screen model (Heiderman et al. 2010). On the other hand, the scatter of this relation derived for radial bins is larger than the one derived using integrated properties (0.73 dex and 0.55 dex, respectively). Despite the large differences in physical scales, these results indicate that as we measure these two observables at smaller angular scales, the scatter of the $\Sigma_{\text{gas}}$-$A_V$ relation increases, suggesting a complex structure of geometries between the stars and the dust/molecular gas. In Sec. 4.4 we explore the impact of the E/W(H$\alpha$) on the $\Sigma_{\text{gas}}$-$A_V$ relation. In particular, we will quantify whether this parameter can separate the wide range of geometries observed at radial scales. Despite the scatter, we consider that the average $A_V$ measured in radial bins is a good indicator of the gas density of the ISM in nearby galaxies.

#### 4.3 Spaxel-by-spaxel Properties

In Fig. 5 we plot the relationship of $\Sigma_{\text{gas}}$ and $A_V$ derived on a spaxel-by-spaxel basis for the galaxies. For this analysis we select spaxels with reliable CO detections (> 1σ) and reliable measurements of extinction. To determine $\Sigma_{\text{HI}}$ and $A_V$ we follow Sec. 3. We correct $\Sigma_{\text{HI}}$ for inclination following Barrera-Ballesteros et al. (2016). This selection criteria allow us to measure this properties in 34705 spaxels located in 103 EDGE-CALIFA galaxies.

As in Sec 4.2, we use $\Sigma_{\text{gas}} = \Sigma_{\text{HI}} + \Sigma_{\text{HI}}$, with $\Sigma_{\text{HI}} = 6 M_\odot$ pc$^{-2}$. Although, the observed distribution of spaxels in the $\Sigma_{\text{gas}}$-$A_V$ plane shows a large dispersion in comparison to the radial distribution (see Fig. 4), the trend of $\Sigma_{\text{gas}}$ and $A_V$ is similar to those derived at radial and integrated scales. This also implies that bulk of the spaxels have $\Sigma_{\text{gas}}$ and $A_V$ that lies between the relations found in the literature (blue and red dashed lines in Fig. 4). We note that low values of $A_V$ (< 0.5) tend to have a relatively constant value of $\Sigma_{\text{gas}}$ (~ 20 M$\odot$ pc$^{-2}$). A possible explanation for this tail at low $A_V$ is the CO detection limit of (~ 11 M$\odot$ pc$^{-2}$) as well as our assumption of a constant $\Sigma_{\text{HI}}$ which at these scales may not be true for all the galaxies where we detect CO. We also have a lower limit in determining $A_V$ due to the detection of the $H\beta$ emission line. These limitations are represented in Fig. 5 by the horizontal and vertical dashed areas. We fit Eq. 7 to 80 per cent of the data (based on the data density distribution) using ODR. We find the best fitted value to be $b = (25 \pm 7) M_\odot$ pc$^{-2}$ mag$^{-1}$. The uncertainty for this parameter reflects the previous assumptions we made regarding our ability to detect CO and the value of $\Sigma_{\text{HI}}$. We use a Monte Carlo simulation of 1000 random values of the limit in CO detection (0.5 < $\sigma$ < 2) and...
\[ \Sigma_{\text{HI}} = [3.8] \ M_\odot \ pc^{-2}; \text{ which, as we mention above, is the typical range observed in local galaxies.} \]

Despite the scatter, we note that the best fit value at spaxel scales is closer to the relation derived by Güver & Özel (2009). Comparing to the relations derived at other spatial scales (radial and global), this best fit is similar to the other physical scales. These results agree with the previous results at radial scales, meaning that the smaller the physical scale we probe, the larger the scatter we find in the \( \Sigma_{\text{gas}} - \alpha_V \) relation. This large scatter suggests the complex interplay between the distribution of the gas/dust and the location of the stars at kpc scales. As for the radial scales, in Sec.4.4 we explore the impact of the EW(H\(\alpha\)) on the \( \Sigma_{\text{gas}} - \alpha_V \) relation at spaxel scales. In particular, we will quantify whether this parameter can separate the wide range of geometries observed at radial scales.

### 4.4 The impact of EW(H\(\alpha\)) on the resolved \( \Sigma_{\text{gas}} - \alpha_V \) relation

In Sec. 4.1 we note that for galaxies with larger values of EW(H\(\alpha\)) \( \lambda_{\text{eff}} \) (i.e., actively star-forming galaxies) the \( \Sigma_{\text{gas}} - \alpha_V \) ratio is approximately twice larger than the value expected for an obscuring dust geometry (e.g., Heiderman et al. 2010). This suggests that for star-forming galaxies the dust and gas are mixed with stars resulting in an even-mix geometry. Following this study, we explore in this section the impact of the EW(H\(\alpha\)) on the \( \Sigma_{\text{gas}} - \alpha_V \) ratio at radial and spaxel scales.

In Fig. 6 we plot this ratio against EW(H\(\alpha\)) for the radial (top panel) and spaxel (bottom panel) scales. For the radial study, we average the EW(H\(\alpha\)) in each annulus. For both scales, black points represent medians while error bars represent the standard deviation for the \( \Sigma_{\text{gas}} - \alpha_V \) ratio in bins of width of EW(H\(\alpha\)) = 10 Å. In both panels, blue horizontal-dashed lines represent the values of the \( \Sigma_{\text{gas}} - \alpha_V \) ratio expected for an obscuring screen and even-mix geometries \( (b = 15 \text{ and } 30 \ M_\odot pc^{-2} mag^{-1}, \text{ Heiderman et al. } 2010) \) as well as the ratio derived by Güver & Özel (2009) (red-dashed line with \( b = 23 \ M_\odot pc^{-2} \)). We note that in average, regions with larger EW(H\(\alpha\)) tend to have larger \( \Sigma_{\text{gas}} - \alpha_V \) ratios reaching a constant value of \( \sim 30 \ M_\odot pc^{-2} \). This is the ratio expected for a geometry in which dust is distributed both in the foreground and in the background of stars. These results suggest that for star-forming regions (EW(H\(\alpha\)) \( \geq 20 \) Å) the \( \Sigma_{\text{gas}} - \alpha_V \) relation is better represented by an even-mix geometry rather than for a single foreground dust-obscuring screen. On the other hand, for those regions with low EW(H\(\alpha\)) values although we are not probing a \( \Sigma_{\text{gas}} - \alpha_V \) ratio close to a even-mix geometry we cannot rule out that this could be case. As we mention above, our method to determine \( \alpha_V \) relies in the detection of the H\(\beta\) emission line which is quite difficult to measure for \( \alpha_V > 3 \). This may induce a bias towards those regions with low EW(H\(\alpha\)) having low \( \Sigma_{\text{gas}} - \alpha_V \) ratios. It could also be the case that we are underestimating \( \alpha_V \) as our method is not sensitive to \( \alpha_V \geq 3 \) (e.g., Liu et al. 2013). In any case, for those region that we are probing active star formation the prefer geometry seems to be a dust-mixed one.

**Figure 5.** Distribution of \( \Sigma_{\text{gas}} \) versus \( \alpha_V \) at spaxel scales. As in previous figure, the distribution is color-coded to represent its density distribution. The outer and inner blue contours enclose 80% and 60% of the sample, respectively. The black line and green-shaded areas represent the best fit and uncertainties using Eq. 7, with \( b = (25 \pm 7) \ M_\odot pc^{-2} mag^{-1} \). The blue and red-dashed lines represent the relations from Heiderman et al. (2010) and Güver & Özel (2009), respectively. It is evident that as we probe smaller physical scales, the \( \Sigma_{\text{gas}} - \alpha_V \) relation shows larger scatter.

**Figure 6.** Comparison of the \( \Sigma_{\text{gas}} - \alpha_V \) ratio with EW(H\(\alpha\)) for radial (top panel, gray points) and spaxel scales (bottom panel, blue contours). Black circles with errorbars represent the medians and standard deviations of the \( \Sigma_{\text{gas}} - \alpha_V \) ratio in bins of 10 Å of EW(H\(\alpha\)). As EW(H\(\alpha\)) increases, the \( \Sigma_{\text{gas}} - \alpha_V \) ratio increases reaching the value expected for an even-mixed geometry (30 \( M_\odot pc^{-2} \)).
of CO are available for a given set of galaxies. Most of the $F_{\text{H}_2}$ derived using $A_V$ are located within the stripe derived using a large compilation of different data sets. In comparison to other large cold gas surveys like the xCOLD GASS survey, the values of $F_{\text{H}_2}$ in our sample derived using $A_V$ are similar to those derived using single-dish CO observations where the two samples overlap.

4.5 Validation of dust-inferred gas masses

So far in this work we have studied the reliability of using dust attenuation derived from the $A_V$ estimates as a proxy for the amount of cold gas. The EDGE-CALIFA data set allows us to perform such a study on a variety of spatial scales, from galaxy-integrated to spatially resolved scales. In this section, we provide a comparison between our estimates of the gas fraction using $A_V$ and compilations in the literature for both integrated and spatially resolved measurements.

4.5.1 Galaxy-integrated Measurements

In Fig. 7 we present the scaling relation between total molecular gas fraction defined as $F_{\text{H}_2} = M_{\text{H}_2}/M_*$ and stellar mass $M_*$. In this figure we used different estimates for the molecular mass. The red circles show the molecular gas fraction derived from the calibrator presented in Sec. 4.1 using as proxy the dust extinction. Blue crosses represent direct observations of CO for the EDGE-CALIFA galaxies (Bolatto et al. 2017). We also compare these observations with a recent compilation in the literature of the trend of these two observables (Calette et al. 2018). The total stellar mass derived from this compilation assumed the initial mass function (IMF) from Chabrier (2003), whereas the total stellar mass from CALIFA galaxies is derived using a Salpeter (1955) IMF. We transform the relation derived from the compilation to agree with the stellar masses reported for the CALIFA sample. This figure shows that in general the molecular mass derived using $A_V$ is a good proxy for estimating the global molecular gas fraction. Red circles are in good agreement to the blue crosses. This is particularly useful when no direct measurements of CO are available for a given set of galaxies. Most of the $F_{\text{H}_2}$ derived using $A_V$ are located within the stripe derived using a large compilation of different data sets. In comparison to other large cold gas surveys like the xCOLD GASS survey, the values of $F_{\text{H}_2}$ in our sample derived using $A_V$ are similar to those derived using single-dish CO observations where the two samples overlap.

4.5.2 Spatially Resolved Measurements

We also perform a comparison of the gas content derived at radial scales with a sample of spatially resolved data reported in the literature. In Fig. 8 we show the scaling relation between the gas fraction at local scales defined as $f_{\text{gas}} = \Sigma_{\text{gas}}/([\Sigma_{\text{gas}} + \Sigma_*]$ and the stellar mass density $\Sigma_*$. In both panels the gray circles represent the data presented in Stark et al. (2018). They use a subsample of MaNGA galaxies (Bundy et al. 2015) with direct measurements of the cold gas component (Leroy et al. 2008). The blue diamonds in the left panel represent the gas fraction derived using the EDGE-CALIFA CO radial measurements to trace $\Sigma_{\text{H}_2}$ presented in Sec. 4.2 and assuming that $\Sigma_{\text{H}_2} = 6 M_\odot$ pc$^{-2}$. First we note that our sample of galaxies probes larger values of $\Sigma_*$ than those in Stark et al. (2018). We also find that the values of $f_{\text{gas}}$ derived from our sample agree very well with the trend observed by Stark et al. (2018) at small values of $\Sigma_*$; this is that the gas fraction decreases as the stellar mass density increases. In the right panel of Fig. 8 we show in red circles the gas fraction derived using the $\Sigma_{\text{gas}}$ observed from the extinction using the calibrator presented in Sec. 4.2. As in the left-side plot, the gas fraction derived using extinction of Hα and $H\beta$ as a proxy is also in agreement with the trend observed in the direct measurements from Stark et al. (2018). In other words, this plot shows that the extinction is a reliable proxy for probing the gas fraction on local scales.

4.6 Caveats

As we mention throughout this study, in order to determine a relation between $\Sigma_{\text{gas}}$ and $A_V$ it is necessary to consider the sensitivity of our observables. Our ability to determine the optical extinction requires a reliable determination of the $H\beta$ flux. Therefore we cannot measure $A_V$ in regions where it is small enough that it is not affecting the $H\alpha/H\beta$ ratio, but even more importantly in those regions where extinction is large enough to suppress the $H\beta$ emission line. In contrast to Galactic studies (Heiderman et al. 2010; Lee et al. 2018), where they can probe regions with $A_V > 10$ mag, from the $H\alpha/H\beta$ ratio we can only probe regions with $A_V \lesssim 3$ mag. On the other hand, the $3\sigma$ sensitivity of our CO observations is $\Sigma_{\text{H}_2} \gtrsim 11 M_\odot$ pc$^{-2}$ (Bolatto et al. 2017). This may imply a limitation in constraining the $\Sigma_{\text{gas}}-A_V$ relation over a wider range of parameters. Nevertheless, we argue that for the parameters probed by the EDGE-CALIFA in both global and spatially-resolved scales (e.g., Figs 7, 8), the optical extinction derived from the $H\alpha/H\beta$ ratio is indeed a reliable proxy for estimating the amount of cold gas in extragalactic sources. In a future study, we will explore the $\Sigma_{\text{gas}}-A_V$ relation using the optical extinction estimated from the fitting of the stellar continuum.
5 DISCUSSION

5.1 Previous CO and optical extinction measurements

In this work we present the observational relation between the gas mass surface density \( \Sigma_{\text{gas}} \) and the optical extinction \( A_V \) derived from the Balmer decrement for a sample of 103 galaxies included in the EDGE-CALIFA survey. The spatially resolved nature of this dataset allows us to determine this relation at integrated, radial and kpc scales. In other words, we aim to provide a reliable proxy for direct observations of the gas surface density (via CO emission) using optical observables (via the optical extinction derived from the Balmer decrement). On theoretical grounds a relation between CO emission (I_{CO}) and optical extinction (A_V) is expected. The amount of dust shielding between the CO-CII (or HII-HI) transition layer is almost constant (Wolff et al. 2010; Lee et al. 2015). Similar relationships have been also been derived in photo-dissociation regions (PDR) calculations (e.g., Bell et al. 2006) as well as in numerical simulations (e.g., Glover & Mac Low 2011).

Observationally, the relation between gas and dust tracers has been studied on different scales and with different proxies. Lee et al. (2015, 2018) studied how the brightness of I_{CO} and the optical extinction derived from SED fitting of the infrared emission correlated in molecular clouds located in the Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC) and the Milky Way. Broadly speaking, they found that their empirical I_{CO} - A_V relation agrees with the standard Galactic CO-to-H2 conversion factor (\( X_{CO} = 2 \times 10^{20} \text{ cm}^{-2}(\text{K km s}^{-1})^{-1} \), Bolatto et al. 2013) with a mild dependence on the metallicity. Following Lee et al. (2015) this conversion factor can be written as I_{CO}/A_V \sim 4.7 \text{ K km s}^{-1} \text{mag}^{-1}. From our analysis in Sec. 4, we find that this ratio for our sample corresponds to I_{CO}/A_V \sim 5.4 \text{ K km s}^{-1} \text{mag}^{-1}. Although this value is larger by 15% than the I_{CO}/A_V ratio expected from the CO-to-H2 conversion factor, we argue that we are using a more heterogeneous set of CO emitting regions and moreover we are averaging these properties over areas larger than those in studies in the local Volume. It would important to probe this ratio on sub-kpc scales in extragalactic objects. This potentially could be achieved by comparing the optical extinction from MUSE datacube observations with I_{CO} data from ALMA millimeter observations. Despite these caveats, it is clear that in the absence of direct millimeter observations it is still possible to use optical proxies such as the A_V derived from the Balmer decrement to gauge the content of the cold gas in the ISM.

Recently, Concas & Popesso (2019) present a similar analysis as the one presented in this study for global properties by determining the relation between the Balmer decrement and the total molecular mass (M_{HI}(CO)) for a sample of 222 star-forming galaxies included in the xCOLD GASS survey. They indicate that scatter is reduced when highly-inclined galaxies are excluded. We compare our integrated measurements with the best relation derived from their data set. To do this, we transform our global measurements of A_V to Balmer decrement. Our data is in agreement with their best estimates of the M_{HI}(CO) - Balmer decrement relation, with most of the data points lying between their best fit for all the star-forming galaxies and the line derived using only low-inclination targets. These results reinforce the idea that the A_V derived from the Balmer decrement is a reliable proxy for estimating the content of gas in large surveys which have no direct observations in the millimeter.

5.2 The physical interpretation of the scatter of the gas-extinction relation

In Sec. 4 we note that the scatter of the \( \Sigma_{\text{gas}} - A_V \) relation increases as we observe this relation at smaller physical scales (from global, radial and spaxel scales; see Figs. 2, 4, and 5, respectively). We suggest that this could be a consequence of probing smaller scales. The smaller the physical scale, the more complex is the geometrical relation between the amount of gas/dust and stars (e.g., Liu et al. 2013; Tacchella et al. 2018). In other words, when we measure these observables at larger physical scales we are averaging out the complexity in the physical distribution of the stars, dust and gas.

As mentioned above, the simplest dust/star geometry – foreground dust screen – yields the smallest \( \Sigma_{\text{gas}}/A_V \) ratio (15 M_{\odot} pc^{-2} mag^{-1}; Heiderman et al. 2010) whereas a mixed geometry would yield twice the ratio accounting for dust and gas in background and in the foreground of the stars (e.g., Nordon et al. 2013). Although the best fit of the \( \Sigma_{\text{gas}} - A_V \) relation for the probed physical scales for the EDGE-CALIFA galaxies is closer to the ratio reported by Güver & Özel (2009) (i.e., \( \Sigma_{\text{gas}}/A_V = 23 \))
The values center on this dashed-line, reinforcing the idea that, at least for these galaxies, metallicity does not seem to play an important role in shaping the $\Sigma_{\text{gas}} - A_V$ relation. We suspect that the small impact of metallicity relation could also be induced by the fact that we are not probing low-mass galaxies in our sample. The EDGE-CALIFA survey covers a range of relatively massive galaxies (i.e., $10^{10} - 10^{12} M_\odot$; see details in Bolatto et al. 2017); therefore we are not able to probe the gas content, optical extinction and metallicity for low-mass galaxies. We consider that further studies including a deeper analysis between spatially resolved millimetre and optical data such as the EDGE-CALIFA survey are necessary to probe the low-mass regime and quantify the impact of metallicity on the determination of the gas surface density on local scales.

5.4 Scaling relations using the Gas-Extinction calibrator

In this section we discuss whether our proxy of $\Sigma_{\text{gas}}$ derived from optical extinction is sufficiently reliable to obtain spatially resolved scaling relations. In particular, we focus on the star-formation law and the $\Sigma_{\text{gas}} - \Sigma_{\text{gas}}$ relations on radial scales. The star-formation law (also known as the Kennicutt-Schmidt Law, Kennicutt 1998b) describes how the star formation rate density ($\Sigma_{\text{SFR}}$) tightly correlates with $\Sigma_{\text{gas}}$. We determine $\Sigma_{\text{SFR}}$ in each radial bin considered as star-forming following the same selection procedure as described in Section 5.3. The star formation rate (SFR) in each bin is derived using the relation between SFR and H$\alpha$ luminosity presented in Eq. 5. Then, $\Sigma_{\text{SFR}}$ in each radial bin is obtained by dividing the SFR by the area of the radial bin.

In the left panel of Fig. 10 we present the star-formation law using two different estimates of $\Sigma_{\text{gas}}$. Blue diamonds represent $\Sigma_{\text{gas}}$ derived using the CO radial measurements as a proxy for $\Sigma_{\text{H}2}$ as presented in Sec. 4.2 and assuming that $\Sigma_{\text{H}2}$ is $6 M_\odot$ pc$^{-2}$. Red circles represent $\Sigma_{\text{gas}}$ using the best fit of the relation $\Sigma_{\text{gas}} - A_V$ presented in Sec. 4.2. The black line shows the average of the best fit of the Kennicutt-Schmidt law on logarithmic scales for seven spiral galaxies presented by Bigiel et al. (2008) (cf., Eq. 2). We note that even though we are using the same index ($N = 1.85$) as Bigiel et al. (2008), we are using the lowest coefficient reported by their uncertainties in ($A = -2.64$).

We note that both estimates of the star formation law using different proxies for $\Sigma_{\text{gas}}$ are in excellent agreement with each other. Even more, when we compare our estimates with the estimate presented by Bigiel et al. (2008), we find good agreement in both the slope of the law as well as the coefficient. We further provide the best fit of this relation using and ODR fitting. We fit the equation $\log(\Sigma_{\text{SFR}}) = B + m \log(\Sigma_{\text{gas}})$ to the data. In the legend of the left panel of Fig. 10 we show the values from the fit for $B$ and $m$ parameters from both $\Sigma_{\text{gas}}$ estimates. The slopes of the fitted relations are slightly steeper than those derived from Bigiel et al. (2008) with $m = 2.54$ and $2.16$, for $\Sigma_{\text{gas}}$ (CO) and $\Sigma_{\text{gas}}$ (A$\beta$), respectively. On the other hand, the intercept with the log($\Sigma_{\text{SFR}}$) axis is smaller than the one derived by Bigiel et al. (2008) with $B = -5.4$ and -4.9, respectively. Both slopes derived from our ODR fitting are in agreement with the one derived by Bigiel et al. (2008) within the reported uncertainties.

We also compare the scatter of the relations by measuring the standard deviation of the residuals of the data points with respect to the best fitted lines using two quantities: measuring (i) the orthogonal distance of the data points with respect to the best fitted line ($\sigma_d$) and (ii) the difference between the observed and expected $\Sigma_{\text{SFR}}$ ($\sigma_r$). For both of these parameters we find that $\Sigma_{\text{gas}}$ derived from A$\beta$ has a smaller scatter than $\Sigma_{\text{gas}}$ from CO measurements.
As a validation test, we also derive estimates of star formation law. However, we caution that this may not be the case since we are calibrating a similar scatter as the one derived from the ODR best fitting but from optical extinction to be a reliable proxy to trace the gas content in the disk. This is in agreement with the results of previous studies (e.g., Güver & Özel 2009).

We find that the relation increases as smaller scales are probed. We argue that this is an indication of the complexity in geometries or physical processes. To conclude, this analysis suggests that $A_V$ is a reliable calibrator to estimate $\Sigma_{\text{gas}}$ in the absence of direct observations of the cold gas component.

### 6 SUMMARY AND CONCLUSIONS

Thanks to the EDGE-CALIFA survey we are able to determine an empirical relation between the gas surface density $\Sigma_{\text{gas}}$ and $A_V$ inferred from the H$\alpha$/H$\beta$ ratio in a sample of 103 galaxies in the nearby Universe. The angular-resolved nature of the EDGE (in the millimeter) and CALIFA (in the optical) surveys allows us to determine this relation on global, radial, and kpc (spaxel) scales. We summarize the main results of this study as follows:

(i) We measure the best fit relation between $\Sigma_{\text{gas}}$ and $A_V$ at global, radial, and spaxel scales (see Figs. 2, 4, and 5). We find similar relations across these different spatial scales, obtaining $\Sigma_{\text{gas}} (\text{M}_\odot \text{pc}^{-2}) \sim 26 \times A_V \text{(mag)}$. This is in agreement with previous studies (e.g., Güver & Özel 2009).

(ii) We find that even though the best fit relation for the $\Sigma_{\text{gas}} - A_V$ relation is similar on the different spatial scales, the scatter of the relation increases as smaller scales are probed. We argue that this is an indication of the complexity in geometries or physical processes.

(iii) We do not find a significant trend between the $\Sigma_{\text{gas}}/A_V$ ratio and the ionized gas metallicity on radial scales for galaxy properties probed by the EDGE-CALIFA survey (we note however that our range of metallicities is rather small 0.2 dex). It would be worth exploring this relation in galaxies of lower stellar mass.

(iv) We derive the gas fractions using the best value for $\Sigma_{\text{gas}}$ derived from $A_V$ and compare these fractions with compilations in the literature for the global and radial scales (see Figs. 7 and 8). We also derive the star-forming and $\Sigma_{\text{gas}} - \Sigma_*$ scaling relations for radial scales (see Fig. 10) using $\Sigma_{\text{gas}}$ from CO direct measurements and estimates from $A_V$. We find excellent agreement between the two $\Sigma_{\text{gas}}$ estimators. These comparisons show that $A_V$ is a reliable proxy to use in the absence of direct estimates of $\Sigma_{\text{gas}}$. 

Figure 10. Scaling relation for $\Sigma_{\text{gas}}$ using different estimates at radial scales. In both panels blue diamonds represent $\Sigma_{\text{gas}}$ determined using CO to estimate $\Sigma_{\text{gas}}$, whereas red circles represent $\Sigma_{\text{gas}}$ determined using $A_V$ (see details in Sec. 4.2). Left panel shows the star formation rate density ($\Sigma_{\text{sfr}}$) vs $\Sigma_{\text{gas}}$. The black solid line represents the star formation law derived from observations by Bigiel et al. (2008). The right panel shows the $\Sigma_{*} - \Sigma_{\text{gas}}$ scaling relation. In both panels blue dashed and red dot-dashed lines represent the best ODR fitting for these scaling relation using CO and $A_V$ to estimate $\Sigma_{\text{gas}}$, respectively (see details in Sec. 5.4). For each of these fits we also include the dispersion from orthogonal distance ($\sigma_d$) and the dispersion from the residuals ($\sigma_r$). The similarity of the fitting and the residuals using either calibrator indicate that $A_V$ is a reliable calibrator to estimate $\Sigma_{\text{gas}}$ in the absence of direct observations of the cold gas component.
In conclusion, using the galaxies sampled by the EDGE-CALIFA survey we determine that the optical extinction derived from the Balmer decrement is a reliable tracer of the gas component measured from the CO observations. This observational calibrator is quite useful in particular for optical studies of large samples of galaxies using IFS observations which lack spatially resolved observations of the cold gas component (e.g., Barrera-Ballesteros et al. 2018; Sánchez et al. 2018).

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