A panchromatic spatially resolved analysis of nearby galaxies - II. The main sequence - gas relation at sub-kpc scale in grand-design spirals

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ABSTRACT

In the second work of this series, we analyse the connection between the availability of gas and the position of a region with respect to the spatially resolved main sequence (MS) relation. Following the procedure presented in Paper I we obtain 500pc scales estimates of stellar mass and star formation rate surface densities ($\Sigma$\textsubscript{\*} and $\Sigma$\textsubscript{SFR}). Our sample consists of five face-on, grand design spiral galaxies located on the MS. Thanks to HI 21cm and $^{12}$CO(2-1) maps, we connect the gas surface densities and gas fractions to the observed star formation properties of each region. We find that the spatially resolved MS ($\sigma = 0.23$ dex) is the combination of two relations: the Kennicutt-Schmidt law ($\sigma = 0.19$ dex) and the molecular gas MS (MGMS, $\sigma = 0.22$ dex); $\Sigma$\textsubscript{\*}, $\Sigma$\textsubscript{SFR} and the surface density of the molecular gas, $\Sigma$H\textsubscript{2}, define a 3D relation as proposed by Lin et al. (2019). We find that $\Sigma$H\textsubscript{2} steadily increases along the MS relation, varies little towards higher $\Sigma$\textsubscript{SFR} at fixed stellar surface densities (not enough to sustain the change in SFR), and it is almost constant perpendicular to the relation. The surface density of neutral gas ($\Sigma$HI) is constant along the MS, and increases in its upper envelop. $\Sigma$\textsubscript{SFR} can be expressed as a function of $\Sigma$\textsubscript{\*} and $\Sigma$HI, following the Equation: $\log \Sigma$\textsubscript{SFR} = 0.97$log $\Sigma$\textsubscript{\*} + 1.99$log $\Sigma$HI - 11.11. Finally, we show that $f$\textsubscript{gas} increases significantly towards the starburst region in the $\log \Sigma$\textsubscript{\*} - $\log \Sigma$SFR plane, accompanied by a slight increase in SFE.

Key words: galaxies: evolution – galaxies: star formation – galaxies: spirals

1 INTRODUCTION

In the current model of galaxy formation and evolution stars form in dense clouds of molecular gas, thanks to the interplay of different physical mechanisms (magnetic fields, turbulence, shielding, feedback). Despite its complexity, this interplay translates in tight correlations between different physical quantities: i) between the surface density of the star formation rate ($\Sigma$\textsubscript{SFR}) and the surface density of the gas ($\Sigma$\textsubscript{gas}), and ii) between the stellar mass surface density ($\Sigma$\textsubscript{\*}) and $\Sigma$\textsubscript{SFR}. The first relation, originally formulated by Schmidt (1959) using the gas volume density and the number of stars formed in the solar neighborhood, was subsequently derived by Kennicutt (1998) for radially averaged surface densities in external galaxies, and it is thus called the Kennicutt-Schmidt (KS) relation. The second, called main sequence (MS), was initially found using integrated quantities of star-forming galaxies (thus the total SFR and stellar
mass $M_\star$ in Brinchmann et al. (2004) for local galaxies and later confirmed for high-redshift galaxies by several works (e.g. Salim et al. 2007; Noeske et al. 2007; Elbaz et al. 2007; Daddi et al. 2007). As both relations are intrinsically related to the process of star formation and thus to galaxy evolution as a whole, and because they are fundamental ingredients of theoretical models and simulations, they have been intensively studied in the past (e.g. Tan 2000; Boissier et al. 2003; Springel & Hernquist 2003; Krumholz & McKee 2005; Rodighiero et al. 2011; Krumholz et al. 2012; Whitaker et al. 2012; Kennicutt & Evans 2012; Kashino et al. 2013; Speagle et al. 2014; Hopkins et al. 2014; Genzel et al. 2015; Schreiber et al. 2015; Kurzynski et al. 2016; Santini et al. 2017; Tacchella et al. 2016; Orr et al. 2018; Pearson et al. 2018; Popesso et al. 2019; Morselli et al. 2019).

The KS law relates the fuel of star formation to its end product, stars; its shape has important effects on the depletion time of the gas and on the efficiency of the star formation process. In one of the earliest works, Kennicutt (1998) finds that the correlation is super linear (slope $= 1.4 - 1.5$) and stronger when considering the total gas rather than the molecular component alone, that is considered the primary fuel of star formation. Following this result, several papers investigate the relation between star formation and gas availability, considering different gas phases and star formation tracers, as well as exploring this link at different cosmic epochs (e.g. Wyder et al. 2009; Genzel et al. 2010; Tacconi et al. 2010; Genzel et al. 2012). A deeper understanding of the interplay between molecular gas and star formation was reached in recent years thanks to the HERACLES (The HERA CO-Line Extragalactic Survey, Leroy et al. 2008) and THINGS (The HI Nearby Galaxy Survey, Walter et al. 2008) surveys, that emission high resolution images of $^{12}$CO(2-1) and HI 21cm emission in nearby galaxies. The works of e.g. Bigiel et al. (2008), Leroy et al. (2008, 2013) and Schruba et al. (2011) exploit these observations to investigate how the relation between gas and star formation activity varies within nearby galaxies and as a function of local and integrated properties. Globally, their findings indicate that the connection between star formation and molecular gas is a linear relation (at least at first order), thus implying a constant molecular SFE and depletion time (around 2.2 Gyr), also in a regime where the atomic gas dominates over the molecular one (Schruba et al. 2011). Leroy et al. (2013) find second order variations in the molecular gas depletion time and study how some of them can be related to variations in the $q_{H_2}$ conversion factor between CO luminosity and $H_2$ mass, while further variability might arise as a consequence of galaxy properties. Bigiel et al. (2010), instead, study the relation between recent SF activity and HI outside the optical disc, in regions where HI represents the totality of the ISM. They find a significant spatial correlation between FUV and HI intensity on scales of 15 arcsec around $R_{25}$. They also find that the SFE (gas depletion timescale) decreases (increases) with increasing radius. Similarly, Roychowdhury et al. (2015) study the spatially resolved KS relation on sub-kpc and kpc scales in the HI dominated regions of nearby spirals and irregular galaxies and find that gas consumption time-scales are longer compared to $H_2$ dominated regions (lower SFE). While this series of works suggest the existence of a universal KS law, others find galaxy-to-galaxy variations of the molecular gas - star formation relation. In particular, Ford et al. (2013) and Shetty et al. (2013, 2014b,a) find evidence for a sub-linear relation within galaxies and for the combined samples. Also Casasola et al. (2015) find galaxy-to-galaxy variations of the spatially resolved KS relation, and underline that the slope can be both sub-linear and super-linear, depending on the spatial scale.

The second fundamental relation, the MS, relates stars that have already been formed to the ongoing SFR. In the recent years, the advent of large integral field spectroscopic (IFS) surveys revealed that the integrated MS relation originates at smaller scales (up to the sizes of molecular clouds), thus implying that the star formation process is regulated by physical process that act on sub-galactic scales (Cano-Díaz et al. 2016; Hsieh et al. 2017; Lin et al. 2017; Abdurro’uf & Akiyama 2017; Medling et al. 2018; Hall et al. 2018; Cano-Díaz et al. 2019; Valcani et al. 2019; Bluck et al. 2020; Enia et al. 2020). Despite a general consensus on the existence of the spatially resolved MS, the slope, intercept and scatter of the relation vary significantly among different works, depending on the sample selection, indicator, dust correction, and fitting procedure. Moreover, some authors find that the spatially resolved relation vary dramatically from galaxy to galaxy. Recently, thanks to the combination of MaNGA (Mapping Nearby Galaxies at APO, Bundy et al. 2015) and ALMaQUEST (the ALMA-MaNGA QUEnching and STar formation survey), Lin et al. (2019) suggest that the MS relation originates from two more fundamental relations: the molecular KS and the so-called molecular gas main sequence (MGMS), a relation between $\Sigma_*$ and $\Sigma_{H_2}$. Early works on the formation of molecular hydrogen in the ISM, such as Elmegreen (1993) and Blitz & Rosolowsky (2006), have already underlined the role of the disc hydrostatic pressure, and hence of $\Sigma_*$, in triggering the formation of molecules. The existence of the MGMS relation implies that variations in slope and scatter of the spatially resolved MS, as well as the integrated one, might actually be related to variations in the relation between molecular gas and $M_\star$. Dey et al. (2019), exploiting data from the EDGE-CALIFA survey (CARMA Extragalactic Database for Galaxy Evolution Bolatto et al. 2017) find that, while $\Sigma_{\text{MS}}$ is a function of both $\Sigma_*$ and $\Sigma_{H_2}$, the relation with the stellar mass is statistically more significant than the one with the molecular gas, differently from what found in Lin et al. (2019).

In this paper, we build on the work presented in Enia et al. (2020, hereafter Paper I) and analyse the sub-kpc relation between the surface densities of star formation, gas in different phases, and stellar mass in 5 local grand-design spirals. In Paper I we exploit multiwavelength observations in more than 20 photometric bands to obtain spatially resolved estimates of $\Sigma_*$ and $\Sigma_{\text{MS}}$ on different physical scales, from few hundred parsecs to 1.5 kpc, via SED fitting. We use these estimates to study the spatially resolved MS relation and find the slope to be consistent for different spatial scales, as well as with the slope of the integrated relation. Here, we aim at analysing under which gas properties different spatial regions populate different loci of the spatially resolved MS, thus trying to understand whether the SFR is more connected to the gravity of the disc (dominated by stars up to $\sim 2/3$ of the optical radius) or with the availability of fuel, or a combination of both. We exploit observations in more than 20 photometric bands to derive accurate SFR and $M_\star$ maps to compare to HI and $H_2$ maps. We discuss...
the origin of the spatially resolved MS, in terms of its slope and scatter.

The structure of the paper is the following: in Section 2 we give a short description of the data used in this work; in Section 3 we present our results at 500 pc resolution; in Section 4 we analyse the implications of our results on the existence of the MS relation and on how SFE and gas vary with varying SFR. Finally, in Section 5 we summarise our findings. The assumed IMF is Chabrier (2003), cosmology is ΛCDM with parameters from Planck Collaboration et al. (2016).

2 DATA

This work is based on multiwavelength observations of five nearby face-on spiral galaxies: NGC0628, NGC3184, NGC5194, NGC5457, and NGC6946. Four out of five galaxies are in common with Paper I: they are the ones observed in 23 photometric bands, and included in the THINGS and HERACLES surveys. NGC6946 was initially excluded from the Paper I sample since it lacked optical observations (the five Sloan optical filters). We tested for the sample in Paper I how the SED fitting routine results change excluding these five photometric points, finding that they are nearly unchanged. Following this, we are including NGC6946 in this analysis. The observations in 23 different bands (18 for NGC6946) have been collected in the DustPedia archive; more details on the data set can be found in Paper I and references therein. The main properties of the galaxies in this sample are shown in Table I.

2.1 SFRs, stellar mass, and distance from the MS

The spatially resolved measurements at 500 pc resolution of $\Sigma_*$, $\Sigma_{\text{SFR}}$ and distance from the MS ($\Delta \text{MS}$), have been obtained following the procedure presented in Paper I. Briefly, we select 8 nearby, face-on, grand design spiral MS galaxies with log$M_*$ $\sim 10.4-10.6$ $M_\odot$, and perform spatially resolved SED fitting to 23 photometric bands using MAGPHYS (da Cunha et al. 2008). In particular, we performed SED fitting on cells having two different side measurements: 8 arcsec (thus a varying physical scale between 290pc and 700pc, depending on the distance of the galaxies) and 1.5 kpc. Here we implement an improved procedure, and performed SED fitting at a common resolution of 500 pc (as discussed in Paper I, these scales are higher than the ones where the energy-balance criterion holds, $\sim 200-400$ pc). The procedural improvements are the following: i) we estimate the noise on the photometry of each cell from the rms maps (while in Paper I we used the DustPedia photometry signal-to-noise ratio); ii) if a cell has more than 10 bands with SNR $< 2$ it is automatically excluded from the SED fitting procedure, thus reducing computational time. These improvements influence the $\chi^2$ estimation in MAGPHYS, increasing the number of accepted points within the optical radius, and leading to cleaner results in the outer part of galaxies, where the photometry is fainter. The slope and intercept of the spatially resolved MS given in Paper I do not change when these improvements are implemented in the pipeline.

In each cell, the SFR is computed as the sum of unobscured (SFR$_{\text{UV}}$) and obscured (SFR$_{\text{IR}}$) star formation activity, obtained using the relations of Bell & Kennicutt (2001) and Kennicutt (1998) (reported to Chabrier IMF):

$$ SFR = 0.88 \times 10^{-28} L_{\text{UV}} + 2.64 \times 10^{-44} L_{\text{IR}}, $$

where $L_{\text{UV}}$ and $L_{\text{IR}}$ are taken from the best fitting SED and are the luminosity (in erg s$^{-1}$ Hz$^{-1}$) at 150nm and the one (in erg s$^{-1}$) integrated between 8 and 1000μm, respectively. As shown in Fig. 3 of Paper I, the SFR computed following Eq.1 and the one that MAGPHYS gives as output, are highly consistent. Here, for consistency with Paper I, we use the SFRs estimated with Eq.1, but the results would not change when considering the SFRs given as output of the SED fitting procedure.

As the sample of galaxies used here differs from the one of Paper I, we decided to recompute the spatially resolved MS for this sample, but following the same procedure. Thus, we computed the spatially resolved MS by fitting the median values of log$\Sigma_{\text{SFR}}$ in bins of log$\Sigma_*$ or by implementing an orthogonal distance regression (ODR) technique. The slope and intercept of the MS are 0.76(±0.15) and -8.15(±0.63) with the first method, and 0.87(±0.06) and -8.94(±0.06) with the second. These estimates are consistent with the ones in Paper I. In the following analysis we make use of the distance from the MS relation computed with the binning technique, but our results do not change when considering the ODR MS relation.

We compute the distance from the MS as the ratio be-

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1 The DustPedia data base is available at http://DustPedia.astro.noa.gr
between the SFR of a region and the corresponding MS SFR at fixed $M_*$. $\Delta MS = \log(sSFR / sSFR_{MS})$. The left panel of Fig. 1 shows, as an example, the $\Delta MS$ map of NGC0628; cells in red are located below the spatially resolved MS, while the ones in blue are located above the relation. Within the optical radius (the dashed circle) we are able to recover most of the cells, especially at $r < 0.9 R_{25}$.\footnote{R_{25} is defined as the length of the projected semi-major axis of a galaxy at the isophotal level 25 mag/arcsec$^2$ in the B-band and it is taken from the HyperLEDA data base (Makarov et al. 2014).} We refer the reader to Paper I for details on theSED fitting procedure, as well as for how the spatially resolved MS relation is obtained.

2.2 Neutral gas: HI 21cm observations

Neutral hydrogen mass surface densities ($\Sigma_{HI}$) are measured from 21cm maps available from the THINGS survey (Walter et al. 2008). These observation have been carried out with the Very Large Array (VLA) and are characterized by a high angular resolution (6 arcsec and 10 arcsec in the robust and natural weighting, respectively). To compute the HI surface brightness, $\Sigma_{HI}$, we first convolve the 21cm natural-weighted intensity maps, given in Jy beam$^{-1}$ m s$^{-1}$, to the resolution of the worst of the 23 photometric bands used in theSED fitting (the one of SPIRE350, 24 arcsec, see Paper I) using a Gaussian kernel. We used the beam sizes given in Table 2 of Walter et al. (2008) and Eq.1 to obtain the flux in K km s$^{-1}$ and then estimate $\Sigma_{HI}$ from Eq. 5 of Walter et al. (2008) (that does not include a correction for helium). We compute the sensitivity limit from our maps of $\Sigma_{HI}$ at 500 pc resolution and find $\Sigma_{HI,lim} \sim 2 M_\odot pc^{-2}$. The central panel of Fig. 1 shows the distribution of $\Sigma_{HI}$ in NGC0628. As in several other spiral galaxies, the HI is centrally depressed (e.g. Casasola et al. 2017), and it extends on radius that are significantly larger than the optical radius (Swaters et al. 2002; Wang et al. 2013). The values of $M_{HI}$ within $R_{25}$ are reported in Table 1. For the galaxies in our sample, the HI gas fraction ($f_{HI} = M_{HI}/M_*$) within $R_{25}$ varies from 5% to 60%.

2.3 Molecular gas: CO observations

The molecular gas surface density, $\Sigma_{HI}$, is computed using the $^{12}$CO(2 − 1) intensity maps from the HERACLES survey (Leroy et al. 2008). These observations were made with the IRAM 30m telescope and have an angular resolution of 11 arcsec. As for $\Sigma_{HI}$ we convolve the images using a Gaussian kernel to the resolution of SPIRE350. We estimated $\Sigma_{HI}$ using Eq. 4 of Leroy et al. (2008), considering a metallicity independent conversion factor $X_{CO} = N(H_2)/I_{CO}$, where $N(H_2)$ is the $H_2$ column density and $I_{CO}$ is the line intensity) equal to $2 \times 10^{20}$ cm$^{-2}$(K km s$^{-1}$)$^{-1}$ (the typical value for disc galaxies, see e.g. Bolatto et al. 2013), and a CO line ratio $I_{CO2-1}/I_{CO1-0} = 0.8$ (e.g. Leroy et al. 2009; Schruba et al. 2011, Casasola et al. 2015). We divide by a factor 1.36 that is included in Eq. 4 of Leroy et al. (2008) to remove the helium contribution. In Sec. 3 we show that the results presented here remain true when considering a metallicity-dependent $X_{CO}$ factor, using the $X_{CO}=(12+\log O/H)$ relation of Genzel et al. (2011) and the spatially resolved metallicity measurements collected in DustPedia. The sensitivity limit, computed as the rms of our $log \Sigma_{HI}$ maps at 500pc resolution, is $\log \Sigma_{HI,lim} = 0.4 M_\odot pc^{-2}$. For the regions corresponding to a negative flux of $^{12}$CO(2 − 1), in the $\Sigma_{HI,lim}$ map we replace the value with a randomly generated number between 0 and the sensitivity limit, so that $\Sigma_{HI}$ can be computed as an upper limit. While this step does not influence our results concerning $H_2$, it allows us to extend the analysis also to the regions where $H_2$ is not detected. The right panel of Fig. 1 shows the distribution of $\Sigma_{HI}$ in NGC0628. The $H_2$ is centrally concentrated, and mostly below the sensitivity limit for $r > 0.5 R_{25}$. For the galaxies in our sample, the $H_2$ gas fraction ($M_{H_2}/M_*$) within $R_{25}$ is almost constant around 11-14%.

Figure 1. Spatially resolved properties of NGC0628: $\Delta MS$ in the left panel, $\log \Sigma_{HI}$ in the central panel, and $\log \Sigma_{HI}$ in the right panel. The dashed circle has a radius equal to the optical radius of the galaxy, $R_{25}$. In the left and right panel, small dots are the cells where the SED fitting is characterized by a large $\chi^2$ and are thus rejected. In the central panel, the dotted points are the ones with measured $\log \Sigma_{HI}$ but no (or rejected) $\Delta MS$. 

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3 RESULTS

Before analysing the spatially resolved connection between star formation and gas components, we briefly comment on the integrated properties of the galaxies in our sample. It is worth underlying that, within $R_{25}$, three out of five galaxies have similar amount of neutral and molecular gas ($M_{\text{HI}}$ and $M_{\text{H}_2}$), within the uncertainties. This is consistent with the results of Casasola et al. (2020), as they find that, within $R_{25}$, galaxies with morphological type $T = 4, 5, 6$ have $M_{\text{HI}}/M_{\text{H}_2} = 0.91, 1$ and 1.05 respectively. For NGC5457 and NGC5194 the average value associated to their morphological type does not describe well their gas properties. It is well known that NGC5457 is likely to have experienced a recent event of gas accretion (Mihos et al. 2013; Vilchez et al. 2019) which can explain the HI rich outer disc and its high total HI mass. A high molecular gas mass fraction, as for NGC5194, is likely the result of tidal stirring by a companion.

3.1 Dependency of the SFR on gas

With the data set in our hands, we first investigate the spatially resolved relations between the SFR and the different gas phases, by analysing how $\Sigma_{\text{SFR}}$ relates to $\Sigma_{\text{HI}}, \Sigma_{\text{H}_2}$, and $\Sigma_{\text{gas}}$. This last quantity is computed as the sum of the neutral and molecular component for all the regions where the $\Sigma_{\text{HI}}$ is above the sensitivity limit, while it is equal to $\Sigma_{\text{H}_2}$ otherwise, and it is thus a lower limit. The results of this exercise are shown in Fig. 2.

As expected, no correlation is found between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{HI}}$, while tight correlations are present between $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{H}_2}$, and $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$, confirming several results in the literature (e.g. Bigiel et al. 2008; Kumari et al. 2020). In Fig. 2 we add the information on how regions located at different distance from the spatially resolved MS populate the $\log \Sigma_{\text{SFR}} - \log \Sigma_{\text{HI}}/\Sigma_{\text{gas}}$ plane. To do so, we divide the $\Sigma_{\text{SFR}} - \log \Sigma_{\text{H}_2}/\Sigma_{\text{gas}}$ planes in bins colour coded according to the median value of $\Sigma_{\text{MS}}$ in each bin. We observe that regions above the MS are found in correspondence to the highest $\Sigma_{\text{HI}}$, but span a wide range of $\Sigma_{\text{H}_2}$ values. Analogously, regions located below the MS are preferentially found at lower $\Sigma_{\text{HI}}$, while are characterized by $\Sigma_{\text{H}_2}$ spanning the whole range of possible values. For $\log \Sigma_{\text{SFR}} > -2$ the trend between $\Sigma_{\text{H}_2}$ and $\Sigma_{\text{MS}}$ is less evident; this is due to the fact that we are not well sampling the region below the MS, as shown in Fig. 5 of Paper I, and confirmed by the decrease of the scatter of the spatially resolved MS at the larger stellar surface densities. Analogously, the points with $\log \Sigma_{\text{SFR}} < -3$ are mostly found on the MS or below it, thus hiding a possible trend at the lowest SFRs. When considering the total gas, we see that regions closer to the relation that describes local Ultra-Luminous IR Galaxies (ULIRGs) and sub-mm galaxies (dashed black lines, taken from Daddi et al. 2010) are the ones located above the relation. On the other hand, the general behaviour between the distance from the best fit relation and the distance from the MS is less regular than in the case of molecular gas. Indeed, the central panel of Fig. 3 suggests that the spatially resolved MS is intrinsically linked to the molecular KS relation, as MS regions (in white) fall very consistently along the $\log \Sigma_{\text{SFR}} - \log \Sigma_{\text{H}_2}$ relation. Regions that populate the upper (lower) envelop of the molecular KS law are also found in the upper (lower) envelop of the spatially resolved MS relation.

By fitting the average values of $\log \Sigma_{\text{SFR}}$ in bins of $\log \Sigma_{\text{H}_2}$ and $\log \Sigma_{\text{gas}}$ (both above the sensitivity limit of $\log \Sigma_{\text{HI}}$) we find the following scaling relations (slopes $N$ and intercepts $A$) written in the panels. In the central panel, the dotted lines mark constant molecular depletion time-scales of $10^8$, $10^9$, and $10^{10}$ yr from top to bottom. In the right panel, the dashed black line is the fit to local ULIRGs and SMGs taken from Daddi et al. (2010).
A are also written in the corresponding panels):

\[ \log \Sigma_{\text{SFR}} = 0.80(\pm0.12) \cdot \log \Sigma_{\text{HI}} - 3.11(\pm0.87) \] (2)

and

\[ \log \Sigma_{\text{SFR}} = 1.30(\pm0.18) \cdot \log \Sigma_{\text{gas}} - 3.94(\pm1.15) \] (3)

The scatter of the two relations is in both cases smaller than the one of the spatially resolved MS: 0.19 for the log\(\Sigma_{\text{HI}}\) - log\(\Sigma_{\text{SFR}}\) relation and 0.15 for the log\(\Sigma_{\text{gas}}\) - log\(\Sigma_{\text{SFR}}\) relation. The relation between log\(\Sigma_{\text{SFR}}\) and log\(\Sigma_{\text{HI}}\) is sub-linear, but becomes linear when the ODR fitting is applied. We retrieve a molecular depletion time that varies between 1.6 and 3 Gyr. These results are consistent with Bigiel et al. (2008), that exploited THINGS and HERACLES surveys and used a combination of 24\mu m and FUV observations to trace the star formation. In particular, they find a linear molecular KS law, no correlation between log\(\Sigma_{\text{SFR}}\) and log\(\Sigma_{\text{HI}}\), and an average molecular depletion time of \(-2\) Gyr when using a constant XCO conversion factor, when averaging over a sample of 18 galaxies.

Finally, we underline here that the trends observed in Fig. 2 are not driven by one or few of the galaxies in our sample, but by and large are common to all five galaxies in our sample. Slope and intercept of the log\(\Sigma_{\text{HI}}\)-log\(\Sigma_{\text{SFR}}\) and log\(\Sigma_{\text{gas}}\)-log\(\Sigma_{\text{SFR}}\) relations are summarised in Tab. 2.

### 3.2 Dependency of gas distribution on stellar mass

As the trends shown in Fig. 2 with \(\Delta_{\text{MS}}\) are related to variations of the gas content with \(M_\star\), we show in Fig. 3 how the surface densities of neutral, molecular and total gas vary as a function of \(M_\star\). The left panel of Fig. 3 shows that a very weak anti-correlation is found between log\(\Sigma_{\text{HI}}\) and log\(\Sigma_{\text{gas}}\). Indeed, when fitting the average values of log\(\Sigma_{\text{HI}}\) in bins of log\(\Sigma_{\star}\), the slope of the correlation is \(-0.11 \pm 0.07\). We stress that every galaxy shows a trend of decreasing \(\Sigma_{\text{HI}}\) towards the central regions, as in the central region the high pressure favours the HI to H\(_2\) transition and most of the gas is in molecular form, but such a decrease can be more or less pronounced from galaxy to galaxy, and does not follow a universal behaviour. Starbursting regions are preferentially located at \(r > 0.5\) \(R_{25}\), where the surface density of stars falls below \(10^7\) \(M_\odot\) pc\(^{-2}\), and are generally located along the spiral arms.

The relation between log\(\Sigma_{\star}\) and log\(\Sigma_{\text{HI}}\), shown in the central panel of Fig. 3 is consistently common to all five galaxies and gives birth to a very tight correlation, the MGMS (Lin et al. 2019). The MGMS (re-scaled to a Chabrier IMF) of Lin et al. (2019) is indicated with a green dashed line in the central panel of Fig. 3 and has a slope of 1.1. To obtain the slope of our MGMS relation, we fit the average values of log\(\Sigma_{\text{HI}}\) in bins of log\(\Sigma_{\star}\), restricting the analysis to stellar surface densities where the average value of log\(\Sigma_{\text{HI}}\) is above the sensitivity limit. We find:

\[ \log \Sigma_{\text{HI}} = 0.92(\pm0.29) \cdot \log \Sigma_{\star} - 6.05(\pm2.11) \] (4)

This relation has a scatter of 0.22 dex, similar to that obtained for the MS. We find a slope that is consistent within the error with the one of Lin et al. (2019), that is 1.1. The different slopes can be ascribed to different fitting procedures; indeed, if we follow the ODR method, we also retrieve a super-linear slope. Regions with the largest sSFR are located in the upper envelop of this relation; in other words, cells located above the spatially resolved MS are also located above the log\(\Sigma_{\star}\) - log\(\Sigma_{\text{HI}}\) relation.

A correlation is also apparent between log\(\Sigma_{\star}\) and log\(\Sigma_{\text{gas}}\), that is the combination of the two behaviours seen in the left and central panel of Fig. 3. At low log\(\Sigma_{\star}\) (log\(\Sigma_{\star} \lesssim 7\)), the HI tends to dominate over H\(_2\), and the scatter of the relation is larger, while it is slightly narrower at large log\(\Sigma_{\star}\). This combined behaviour results in a slope of \(0.45 \pm 0.14\) and an intercept of \(-2.14 \pm 0.97\). Slope and intercept of the log\(\Sigma_{\star}\)-log\(\Sigma_{\text{gas}}\) and log\(\Sigma_{\star}\)-log\(\Sigma_{\text{HI}}\) relations are summarised in Tab. 2.

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**Figure 3.** Distributions of the regions in the log\(\Sigma_{\star}\)-log\(\Sigma_{\text{HI}}\) plane (left panel), log\(\Sigma_{\star}\)-log\(\Sigma_{\text{gas}}\) plane (central panel) and log\(\Sigma_{\star}\)-log\(\Sigma_{\text{HI}}\) plane (right panel). Each hexagonal bin the the plane has been colour coded according to the average value of \(\Delta_{\text{MS}}\), as in Fig. 2. The purple solid lines are the best fit relations obtained by fitting the average values of log\(\Sigma_{\text{HI},\text{gas}}\) in bins of log\(\Sigma_{\star}\), as marked with black crosses; the slope (N) and intercept (A) of the best fit are written in the panels. The green dashed line in the central panel is the MGMS of Lin et al. (2019), re-scaled to a Chabrier IMF.
Figure 4. HI and H$_2$ in the log $\Sigma_{\ast}$ - log SFR plane. Top-left panel: log $\Sigma_{\ast}$ - log SFR plane color coded as a function of the average value of log $\Sigma_{\text{HI}}$ in each bin. The black solid line marks the location of the spatially resolved MS relation. Top-right panel: $\Delta_{\text{MS}}$, as a function of log $\Sigma_{\text{HI}}$. The average values of $\Delta_{\text{MS}}$ computed in bins of log $\Sigma_{\text{HI}}$ are shown in green. Each bin is colour coded as a function of the number of cells that it contains. Bottom-left panel: log $\Sigma_{\ast}$ - log SFR plane color coded as a function of the average value of log $\Sigma_{\text{H}_2}$ in each bin. The black sold line marks the location of the spatially resolved MS relation. Bottom-right panel: $\Delta_{\text{MS}}$, as a function of log $\Sigma_{\text{H}_2}$. The average values of $\Delta_{\text{MS}}$ computed in bins of log $\Sigma_{\text{H}_2}$ are shown in green. Each bin is colour coded as a function of the number of cells that it contains. In the right panels, the grey shaded area marks the MS region.

3.3 HI and H$_2$ in the $\Sigma_{\ast}$-SFR plane

To further analyse the link between the atomic, molecular and total gas and the star formation properties of a region, we show in Fig. 4 how log $\Sigma_{\text{HI}}$ and log $\Sigma_{\text{H}_2}$ vary across the log $\Sigma_{\ast}$ - log SFR plane. In the two left panels of Fig. 4 we show the log $\Sigma_{\ast}$ - log SFR plane color coded as a function of the average log $\Sigma_{\text{HI}}$ (top) and log $\Sigma_{\text{H}_2}$ (bottom) values in each bin. The spatially resolved MS is indicated with the black solid line. To compute the average value of log $\Sigma_{\text{HI}}$ we also used values below the sensitivity limit, therefore it is important to emphasise that H$_2$ is detected only for $\Sigma_{\text{H}_2}$ above $\sim 3$ $M_{\odot}$pc$^{-2}$ which requires a $\Sigma_{\ast}$ higher than $10^7 M_{\odot}$kpc$^{-2}$. On the other hand H$_2$ column densities below this threshold value are hardly self-shielded and quite rare (e.g. Sternberg et al. 2014).

Interestingly, along the MS relation the average value of log $\Sigma_{\text{HI}}$ is fairly constant and equal to about 7 $M_{\odot}$pc$^{-2}$ which corresponds to an HI column density of about 9-$10^{20}$ cm$^{-2}$. This indicates that for cells on the MS the radiation field is strong enough to require large amount of dust rich HI gas to prevent H$_2$ dissociation (Sternberg et al. 2014). As expected, $\Sigma_{\text{H}_2}$ increases with increasing $M_{\ast}$, following the MGMS relation, suggesting that the gravity dominated by stars compresses and enhances the ISM volume density, thus favoring the formation of molecules. The upper envelop of the MS is populated by cells that, on average, have larger HI
3.4 Dependency of the results on metallicity

A possible source of uncertainty in this work is the dependency of the conversion factor between CO and H₂ on metallicity (XCO). Indeed, several works have shown that XCO varies strongly as a function of the galaxy metallicity (e.g. Bolatto et al. 2013), and strong metallicity gradients have been found in some of the galaxies in this sample, as well as in larger samples of local star forming galaxies (Ho et al. 2014; Chiang et al. 2018; Vilchez et al. 2019), reaching a factor of 10 within the optical radius. From an integrated perspective, instead, Genzel et al. (2015) find that XCO varies little within ±0.6 dex of the MS (thus for the large majority of the cells in this work). Nevertheless, such variations in metallicity need to be addressed properly in order to avoid biased interpretations of spatially resolved results. From the DustPedia archive, we download the table containing all the metallicity measurements available in literature (De Vis et al. 2019) and obtain in regions within R₂₅ of the five galaxies in our sample. For NGC5457 there are 280 estimates of metallicity within the optical radius, while for NGC6946 only 14 are available. In particular, we make use of the metallicities computed exploiting the N2 and O3N2 calibrations of Pettini & Pagel (2004)³. In particular, N2 is defined as log([NII]λ6583/Hα) and O3N2 as log([OIII]λ5007/Hβ)/[NII]λ6583/Hα). With the conversion relations of Kewley et al. (2004) we obtain the metallicities in the Denicolò et al. (2002) calibration. For each galaxy we then build a 1D metallicity profile by fitting the different measurements. We use the 1D metallicity profile to obtain a 2D map of the metallicity dependent αCO factor exploiting the relation of Genzel et al. (2012), that is obtained by fitting the z=0 points of Leroy et al. (2011) with z>1 ones collected in Genzel et al. (2012):  

$$\log \alpha_{\text{CO}} = -1.3 \cdot (12 + \log(O/H)_{\text{Denicolò02}} + 12$$  

(5)

With the 2D map of log αCO we then estimate \(\Sigma_{\text{H}_2}\). Fig. 5 shows a comparison of the molecular gas mass computed considering a constant XCO and the metallicity dependent one (in particular, the one obtained with the O3N2 calibration, but no significant differences are found when considering the N2 one). The highest scatter corresponds to small molecular gas masses, located in the outskirts of the optical disc, where the metallicity is, on average, smaller than in the centre. The source characterized by the largest scatter is NGC5457, that is also the one with the strongest metallicity gradient (Vilchez et al. 2019). We note, nevertheless, that within 0.5 R₂₅ (that is, in first approximation, the distance within which the estimate of M\(_{\text{H}_2}\) is above the sensitivity limit), the maximum difference between the two estimates is around 0.2 dex.

We repeat the previously shown analysis considering \(\Sigma_{\text{H}_2}\) estimated with the metallicity dependent XCO. In Tab. 2 we report the slopes, intercepts and scatter of the various relations discussed above: \(\log \Sigma_{\text{H}_2} - \log \Sigma_{\text{SFR}}\), \(\log \Sigma_{\text{gas}} - \log \Sigma_{\text{SFR}}\), \(\log \Sigma_{\text{SFR}} - \log \Sigma_{\text{HI}}, \) and \(\log \Sigma - \log \Sigma_{\text{gas}}\). With respect to the case of constant XCO, the slope of molecular KS relation slightly increases but not significantly given the errors on the estimates. The slope of the total gas KS law decreases to reach values closer to 1, but again this decrease is not significant when taking the errors into account. Similarly, the variations in slope and intercept of the log \(\Sigma_{\text{SFR}} - \log \Sigma_{\text{HI}}\) relations do not vary significantly with respect to the values found in Sec. 3.2. The scatter of the four relations increases. In particular, the scatter of the log \(\Sigma_{\text{SFR}} - \log \Sigma_{\text{HI, gas}}\) relations

³ We refer the reader to Casasola et al. (2020) and De Vis et al. (2019) for details of the metallicity calibration.
Figure 6. **Left panel**: distribution of the regions having an estimate of $\Sigma_{\text{H}_2}$ above the sensitivity limit in the $\log \Sigma_{\star}$ - $\log \Sigma_{\text{SFR}}$ - $\log \Sigma_{\text{H}_2}$ plane. Each point is colour coded as a function of $\log \Sigma_{\text{H}_2}$. Four projections of this space at different azimuthal angles are shown in Fig. A1. **Right panel**: distribution of the regions having an estimate of $\Sigma_{\text{HI}}$ above the sensitivity limit in the $\log \Sigma_{\star}$ - $\log \Sigma_{\text{SFR}}$ - $\log \Sigma_{\text{HI}}$ plane. Each point is colour coded as a function of $\log \Sigma_{\text{HI}}$. The best fit plane is indicated by the green grid. Four projections of this plane, described by Eq. 7, at different azimuthal angles are shown in Fig. A2.

Table 2. Slope, intercept and scatter of the following relations: molecular KS law, $\log \Sigma_{\text{gas}}$ - $\log \Sigma_{\text{SFR}}$, MGMS and $\log \Sigma_{\star}$ - $\log \Sigma_{\text{gas}}$. We list the best fit parameters for $\log \Sigma_{\text{H}_2}$ computed using a constant XCO factor and a metallicity dependent XCO obtained from estimates of the metallicity that use: 1) the N2 index, and 2) the O3N2 index.

| Correlation          | Slope Const. XCO | Slope O3N2 | Slope N2 | Intercept Const. XCO | Intercept O3N2 | Intercept N2 | Scatter Const. XCO | Scatter O3N2 | Scatter N2 |
|----------------------|------------------|------------|----------|----------------------|----------------|--------------|-------------------|--------------|------------|
| $\log \Sigma_{\text{H}_2}$ - $\log \Sigma_{\text{SFR}}$ | 0.80±0.09        | 0.83±0.12  | 0.83±0.11 | -3.11±0.87           | -3.08±0.93     | -3.04±0.90   | 0.19               | 0.20         | 0.19       |
| $\log \Sigma_{\star}$ - $\log \Sigma_{\text{H}_2}$ | 1.30±0.18        | 1.07±0.18  | 1.06±0.18 | -3.94±1.15           | -3.57±1.15     | -3.57±1.14   | 0.15               | 0.17         | 0.17       |
| $\log \Sigma_{\star}$ - $\log \Sigma_{\text{gas}}$ | 0.92±0.29        | 0.94±0.29  | 0.97±0.27 | -6.05±2.11           | -6.49±2.26     | -6.78±2.2   | 0.22               | 0.24         | 0.23       |

become comparable or larger than the one of the spatially resolved MS. This is expected, as we are adding several sources of uncertainty: the conversion between different metallicity calibrations, the correlation between XCO and metallicity, as well as the fact that we are averaging the metallicity to build a 1D profile. In first approximation, this exercise reveals that the result in this paper are robust against variations of the XCO factor as a function of metallicity, that is the main and most studied dependence of XCO on physical/galaxy properties (e.g., gas temperature and abundance, optical depth, cloud structure, cosmic ray density, and UV radiation field, in addition to the metallicity). This happens because the central metallicities for the galaxies in our sample are similar, and the molecular gas maps are not deep enough to reach the outermost regions where the metallicity decrease with respect to the central value.

4 DISCUSSION

4.1 The origin of the main sequence and its scatter

The spatially resolved MS of galaxies constitutes the building block of the integrated MS relation of star forming galaxies so deeply analysed in literature to understand the star formation processes and the quenching mechanisms. When analysing the molecular gas component of nearby galaxies we find tighter relations than the MS itself, and that may be at the physical origin of it: the KS law a (Eq. 2) and the MGMS (Eq. 4). By combining Equations 2 and 4, we obtain a spatially resolved MS in the form:

$$\log \Sigma_{\text{SFR}} = 0.74 \cdot \log \Sigma_{\star} - 7.95$$

(6)

We find that the $\Sigma_{\text{H}_2}$ - $\Sigma_{\text{SFR}}$ relation is the tightest one, with a scatter of 0.19 dex, followed by the $\Sigma_{\star}$ - $\Sigma_{\text{H}_2}$ relation.
0.22 dex, similar to the scatter of the spatially resolved MS (0.23 dex). Contrary to Lin et al. (2019) we find that the scatter of the spatially resolved MS is significantly smaller than the quadratic sum of the scatter of the $\Sigma_*$ - $\Sigma_{HI}$ and $\Sigma_{HI}$ - SFR relations, indicating that the scatter of these relations is not independent. Indeed, regions located in the upper (lower) envelop of the molecular KS relation also populate the upper (lower) envelop of the MGMS. To further investigate the connection between the three relations (KS, MS, MGMS), we plot in the left panel of Fig. 6 how regions with an estimate of $\Sigma_{HI}$ above the sensitivity limit populate the 3D space constituted by $\log \Sigma_*$, $\log \Sigma_{SFR}$ and $\log \Sigma_{HI}$. The variables define a 3D relation, as found by Lin et al. (2019). This is expected, as we find no dependency of $\Delta_{MS}$ on $\Sigma_{HI}$ (see Fig. 4). On the other hand, the analysis of $\Sigma_{HI}$ in the log $\Sigma_*$-$\log \Sigma_{SFR}$ plane revealed that the spatially resolved MS scatter seems to be connected to the presence of neutral gas. Indeed, when analysing how regions populate the 3D space formed by $\log \Sigma_*$, $\log \Sigma_{SFR}$ and $\log \Sigma_{HI}$, we find that they identify a plane, as shown in the right panel of Fig. 6. The equation of the plane that minimises the perpendicular distance of the points can be written as:

$$\log \Sigma_{SFR} = 0.97 \log \Sigma_* + 1.99 \log \Sigma_{HI} - 11.11 \quad (7)$$

The relation expressed by Eq. 7 has a scatter of 0.14 dex, significantly smaller than the one of the spatially resolved MS relation. Interestingly, when the dependency of the SFR of HI surface densities is taken into account, the relation between $\log \Sigma_{SFR}$ and $\log \Sigma_*$ becomes closer to linear. To better understand the origin of the relation expressed by Eq. 7, in Fig. 7 we show the log $\Sigma_{HI}$ - log $\Sigma_{SFR}$ plane colour coded as a function of $\Delta_{MS}$ (left panel) and $r/R_{25}$ (right panel).

From Fig. 7 we can appreciate that regions with log $\Sigma_{HI}$ higher than 10 M$\odot$ pc$^{-2}$ (that is the typical value for the the HI to H2 transition, Leroy et al. 2008; Lee et al. 2012, 2014) correspond to the upper envelope of the spatially resolved MS and, on average, are preferentially located between 0.3 and 0.8 R$_{25}$. These regions span a wide range of log $\Sigma_{HI}$ values: 1) up to log $\Sigma_{HI} = 2.0 \pm 0.5$ pc$^{-2}$ for 0.3R$_{25} < r < 0.6$ R$_{25}$, and 2) below the sensitivity limit for R$>0.6$ R$_{25}$. In the first case, the stellar surface density and average SFR are moderately high, and high HI surface densities (and dust) are needed to prevent the dissociation of the molecular gas by the intense radiation field. In the outer part of the optical disc, the SFRs are on average lower than in the inner disc, and so is the stellar surface density; nevertheless, the SFRs above the MS reach values that are comparable to SFRs on the MS in the inner part of the disc. Most likely the molecular gas, when formed, is immediately disrupted by the feedback from star formation. Indeed, the scatter of the spatially resolved MS is larger at lower stellar surface densities (see Paper I), as the gas itself contributes significantly to the gravitational field, and episodes of molecular gas formation are regulated by local gas overdensities. The variations of neutral gas content across and along the spatially resolved MS relation (see Fig. 4) are in agreement with what has been recently observed by Wang et al. (2020) when analysing integrated galaxy properties. They conclude that the increase in $\Sigma_{HI}$ above the MS at fixed M$_*$ happens as HI is an intermediate step in the fuelling of star formation. In the resolved MS, instead, the high HI surface density clumps in the outer regions enhance the local gravity and the ISM volume density favoring gas fragmentation and star formation. The low metallicity and weaker arm structure in the outer regions likely support the formation of small molecular clouds, easily dissociated by the light of the newly formed young stellar clusters.

### 4.2 Star Formation Efficiency vs Gas Fraction

The data set in our hands gives us the possibility to analyse the role of SFE and $f_{gas}$ in setting the sSFR of a region, thus deciding its location with respect to the spatially resolved MS relation. As in literature the gas fraction and SFE estimates may or may not include the contribution of neutral gas, depending on how the gas mass is measured, we define a total and molecular SFE and $f_{gas}$: $SFE_{tot} = SFR/(M_{HI}+M_{H2})$, $SFE_{mol} = SFR/M_{H2}$, $f_{gas,tot} = (M_{HI} + M_{H2})/(M_{HI}+M_{H2}+M_*)$, and $f_{gas,mol} = M_{H2}/(M_{H2}+M_*)$. In the left panels of Fig. 8 we show how the average $SFE_{tot}$ (top) and $f_{gas,tot}$ (bottom) vary in the log $\Sigma_*$ - log $\Sigma_{SFR}$ plane. Qualitatively, we observe that $f_{gas,tot}$ varies strongly when moving from the lower to the upper envelop of the MS (in green), both perpendicular to the relation and at fixed log $\Sigma_*$. Regions with log $\Sigma_* < 7.0$ M$_\odot$, that on average correspond to log $\Sigma_{HI}$ below the sensitivity limit, have large gas fractions thanks to the contribution of the neutral gas. On the other hand, the variations of $SFE_{tot}$ are less evident: $SFE_{tot}$ increases slightly at fixed stellar surface densities, and less significantly in the direction perpendicular to the MS relation. In the central panels of Fig. 8 we study how $\Delta_{MS}$ varies as a function of log $SFE_{tot}$ (top panel) and $f_{gas,tot}$ (bottom panel). The correlation between $\Delta_{MS}$ and log $SFE_{tot}$ is weak: a Spearman test reveals a ranking of 0.39, and the average values of $\Delta_{MS}$ in bins of log $SFE_{tot}$ are in the range ±0.4. On the other hand, we observe a stronger correlation between $\Delta_{MS}$ and $f_{gas,tot}$ (Spearman ranking is 0.58). Finally, in the right panels of Fig. 8 we study the dependency of $\Delta_{MS}$ on SFR$_{mol}$ (top) and $f_{gas,mol}$ (bottom): while the former is stronger than in the case of total gas, the latter is weaker.

When considering the different gas phases, our results are in qualitatively good agreement with other works in literature. In fact, there is now convergence of the fact that, from an integrated point of view, an increase in SFR at fixed M$_*$ and cosmic epoch is due to a combination of increasing gas mass and decreasing depletion time (thus, increasing SFE, e.g. Saintonge et al. 2011; Saintonge et al. 2012; Leroy et al. 2013; Huang & Kauffmann 2014). In the recent years, these studies could be carried out with larger and larger samples, using different sub-mm observations to trace gas, and exploring a wide range of cosmic epochs, 0 < z < 4.5. For example, while Scoville et al. (2017) exploit sub-mm continuum observations of 700 COSMOS galaxies and estimated the gas mass from the dust mass, Genzel et al. (2015) used line observations of CO transition in 500 star forming galaxies. Tacconi et al. (2018) added an estimate of dust from FIR SED to increase the sample to ~1500 MS galaxies, and similarly find that only an almost equal increase of gas fraction and SFE can explain an increase in sSFR. We note that the samples cited above are mainly constituted by galaxies at 0.7 < z < 4, for which the total gas fraction is dominated by the molecular gas (e.g. Lagos et al. 2014). Indeed, when
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Figure 7. The $\log \Sigma_{\text{H}_2}$ - $\log \Sigma_{\text{HI}}$ plane, colour coded as a function of $\Delta_{\text{MS}}$ (left panel) and $R/R_{25}$ (right panel). Sensitivity limits are marked with dotted-dashed lines.

Figure 8. SFE and $f_{\text{gas}}$ in the $\log \Sigma_{\star}$ - $\log \Sigma_{\text{SFR}}$ plane. Top left panel: $\log \Sigma_{\star}$ - $\log \Sigma_{\text{SFR}}$ plane color coded as a function of the average SFE$_{\text{tot}}$ = SFR/(M$_{\text{H}_2}$+M$_{\text{HI}}$) in each bin. The spatially resolved MS is indicated with the green solid line. Top central panel: $\Delta_{\text{MS}}$ as a function of logSFE$_{\text{tot}}$. The black points are the average values of $\Delta_{\text{MS}}$ in bin of logSFE$_{\text{tot}}$. The Spearman correlation ranking, computed using the grey points, is indicated in the panel. Top right panel: $\Delta_{\text{MS}}$ as a function of $f_{\text{gas},\text{mol}}$ = log(SFR/M$_{\text{H}_2}$). Bottom left panel: $\Delta_{\text{MS}}$ as a function of $f_{\text{gas},\text{tot}}$ = (M$_{\text{HI}}$+M$_{\text{H}_2}$)/$(M_{\text{HI}}$+M$_{\text{H}_2}$+M$_{\star}$) in each bin. The spatially resolved MS is indicated with the green solid line. Bottom central panel: $\Delta_{\text{MS}}$ as a function of $f_{\text{gas},\text{tot}}$. The black points are the average values of $\Delta_{\text{MS}}$ in bin of $f_{\text{gas},\text{tot}}$. The Spearman correlation ranking, computed using the grey points, is indicated in the panel. Bottom right panel: $\Delta_{\text{MS}}$ as a function of $f_{\text{gas},\text{mol}}$. The black points are the average values of $\Delta_{\text{MS}}$ in bin of $f_{\text{gas},\text{mol}}$. The Spearman correlation ranking, computed using the grey points, is indicated in the panel.
we consider only the molecular gas component, we also find that, on average, the SFE and the gas fraction both increase of comparable amounts when moving from the MS to its upper envelop. Recently, Ellison et al. (2020), using data from the AlMaQUEST survey (median redshift $\sim 0.03$), find that variations of the SFE play a major role in setting the SFR at fixed stellar mass, with differences in $f_{\text{gas}}$ playing a secondary role. The discrepancy between our results and the ones of Ellison et al. (2020) might arise from considering only molecular gas, thus omitting the neutral gas component.

5 CONCLUSIONS

In this manuscript we exploit the combination of highly accurate measurements of $\Sigma_*$ and $\Sigma_{\text{SFR}}$ at 500pc resolution of five nearby, face-on spiral galaxies obtained following the procedure presented in Paper I, with observations of neutral and molecular gas. With this powerful data set we study how the location of a region with respect to the spatially resolved MS is related to the gas in the different phases. We summarise here our main results:

- We find that $\log \Sigma_*$, $\log \Sigma_{\text{SFR}}$, and $\log \Sigma_{\text{HI}}$ define a 3D relation; the three projections are the KS law, the MS and the MGMS. The KS law is the tightest relation, with a scatter of 0.19 dex, followed by the MGMS (0.22 dex) and the spatially resolved MS (0.23 dex). The existence of the MGMS at sub-kpc scales opens up the possibility to study molecular gas content from $\log \Sigma_{\text{SFR}}$ and $\log \Sigma_*$ alone, that are generally easier to obtain and available for large samples;

- We study the distribution of the neutral and molecular gas in the $\log \Sigma_*$ - $\log \Sigma_{\text{SFR}}$ plane and we find that the molecular component steadily increases along the MS relative, but is almost constant perpendicular to it. The neutral gas, instead, is almost constant along the MS, and increases/decreases in its upper/lower envelop. On average, regions located in the upper envelop of the spatially resolved MS have $\Sigma_{\text{HI}} \geq 10 M_{\odot} \text{pc}^{-2}$, that is the typical value for the HI to H$_2$ transition. The three variables $\log \Sigma_*$, $\log \Sigma_{\text{SFR}}$, and $\log \Sigma_{\text{HI}}$ are distributed along a plane that has a scatter of 0.14 dex;

- When moving towards high $\Sigma_{\text{SFR}}$ at fixed stellar surface densities, the molecular gas fraction and molecular SFE both increase. On the other hand, when we consider the total gas, thus also the contribution of the neutral component, we observe a steep increase of the gas fraction towards high SFRs, accompanied by a weak increase of the total SFE.

Our results confirm the intricate interplay between neutral and molecular gas that changes as a function of the distance from the centre of galaxies (ad thus, as a function of $M_*$ and SFR). We speculate that in the outer optical disc, where most of the starburst regions are located, the high HI surface densities favour fragmentation and star formation; the small molecular clouds would then be easily dissociated by the feedback from star formation. At intermediate distances from the center, high HI surface densities could be a necessary ingredient to prevent dissociation of $H_2$ by means of a more intense radiation field. In an upcoming Paper, we will investigate the physical origin behind the molecular and neutral gas interplay at different SFRs and $M_*$. The continuity of trends above the MS, MGMS, and KS relations suggests that regions characterized by a SFR a factor of 4 higher than the MS value at fixed $M_*$ (the usual starburst limit in literature) do not exist because of a bimodality in the SF process, but rather because of a steady variation of total gas fraction and, on a second order, of star formation efficiency. We speculate that this continuity could also explain the existence of high redshift starbursts, as the scatter of the spatially resolved MS is similar to the one of the integrated relation, and this last quantity is observed to be constant with redshift. Thus, the contribution of neutral gas within the optical radius could be significant also at earlier cosmic epochs, and not only in the local Universe. The next generation of radio telescopes like the Square Kilometer Array (SKA), but also ongoing surveys with MeerKAT, such as MIGHTEE (Jarvis et al. 2016) and LADUMA (Bluth et al. 2016), will directly measure the HI content in distant galaxies, finally unraveling its role in the star formation processes at various cosmic epochs.

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APPENDIX A: THE $\log \Sigma_* - \log \Sigma_{SFR} - \log \Sigma_{H_2}$ 3D RELATION

As shown in Fig. 6, the three quantities $\log \Sigma_*$, $\log \Sigma_{SFR}$ and $\log \Sigma_{H_2}$ define a 3D relation. To better visualise this relation, in Fig. A1 we show four different projections of it, corresponding to azimuthal angles of $0^\circ$, $60^\circ$, $120^\circ$ and $180^\circ$. We stress here that we are plotting only the regions that have an estimate of $\Sigma_{H_2}$ above the sensitivity limit. In Fig. A2 we show, instead, the $\log \Sigma_*$, $\log \Sigma_{SFR}$ and $\log \Sigma_{HI}$ 3D plane at four different azimuthal angles, with the aim of better visualise the positioning of the cells along the 3D plane marked in green. We plot in Fig. A2 only the regions that have an estimate of $\Sigma_{HI}$ above the sensitivity limit.
Figure A1. Distribution of the regions with an estimate of $\log \Sigma_{H_2}$ above the sensitivity limit in the $\log \Sigma^* - \log \Sigma_{SFR} - \log \Sigma_{H_2}$ 3D space. For different projections of the plane are shown, corresponding to different azimuthal angles: $0^\circ$ (top left), $60^\circ$ (top right), $120^\circ$ (bottom left) and $180^\circ$ (bottom right). The points are colour coded as a function of $\log \Sigma_{H_2}$. 
Figure A2. Distribution of the regions with an estimate of $\log \Sigma_{\text{H}_2}$ above the sensitivity limit in the $\log \Sigma_{\text{H}_2} - \log \Sigma_{\text{SFR}} - \log \Sigma_{\text{H}_I}$ 3D space. For different projections of the plane are shown, corresponding to different azimuthal angles: 0° (top left), 125° (top right), 175° (bottom left) and 220° (bottom right). The point are colour coded as a function of $\log \Sigma_{\text{H}_2}$. 