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



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The atomic gas sequence and mass–metallicity relation from dwarfs to massive galaxies

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ABSTRACT

Galaxy scaling relations provide insights into the processes that drive galaxy evolution. The extension of these scaling relations into the dwarf galaxy regime is of particular interest. This is because dwarf galaxies represent a crucial stage in galaxy evolution, and understanding them could also shed light on their role in reionizing the early Universe. There is currently no consensus on the processes that dominate the evolution of dwarfs. In this work, we constrain the atomic gas sequence (stellar mass versus atomic gas fraction) and mass–metallicity relation (stellar mass versus gas-phase metallicity) from dwarf ($10^{6.5} M_{\odot}$) to massive ($10^{11.5} M_{\odot}$) galaxies in the local Universe. The combined optical and 21-cm spectroscopic observations of the Dark Energy Spectroscopic Instrument and Arecibo Legacy Fast ALFA surveys allow us to constrain both scaling relations simultaneously. We find a slope change of the atomic gas sequence at a stellar mass of $\sim 10^9 M_{\odot}$. We also find that the shape and scatter of the atomic gas sequence and mass–metallicity relation are strongly linked for both dwarfs and more massive galaxies. Consequently, the low-mass slope change of the atomic gas sequence is imprinted onto the mass–metallicity relation of dwarf galaxies. The mass scale of the measured slope change is consistent with a predicted escape velocity threshold below which low-mass galaxies experience significant supernova-driven gas loss, as well as with a reduction in cold gas accretion onto more massive galaxies.

Key words: galaxies: dwarf – galaxies: general – galaxies: ISM.

1 INTRODUCTION

Galaxy scaling relations are the observable result of a complex network of processes driving galaxy evolution. Many of the processes that dominate the evolution of galaxies relate to the accretion, processing, and ejection of gas from galaxies (Tinsley 1980); combined, these processes are referred to as the baryon cycle. Many of the elements of the baryon cycle, in particular the gas inflow and outflow rates, are unfortunately challenging to accurately measure (Tumlinson, Peebles & Werk 2017). This is a significant hurdle in the understanding of galaxy evolution through the baryon cycle, given the central importance of these processes. Luckily, however, there is significant information about all the components of the baryon

cycle encoded in the much more readily observable cold interstellar medium (ISM) of galaxies (Saintonge & Catinella 2022).

Indeed, the connection between various observables of galaxies through processes in the baryon cycle is reflected in the correlation of the atomic and molecular gas mass of galaxies with other galaxy properties, such as luminosity, stellar mass, baryonic mass, size, morphology, and star formation rate (e.g. Tully & Fisher 1977; Kenney & Young 1988; Sage 1993; Roberts & Haynes 1994; Brinchmann et al. 2004; Bothwell et al. 2013, 2016; Lelli et al. 2017, 2019; Bacchini et al. 2020). Large surveys of the atomic (e.g. extended GALEX Arecibo SDSS Survey (xGASS); Catinella et al. 2018) and molecular [e.g. extended CO Legacy Database for GASS (xCOLD GASS); Saintonge et al. 2017] cold gas content of representative samples of galaxies established gas scaling relations and quantified the role of gas in shaping the observed galaxy distributions as a function of their main observable properties (e.g. Brown et al. 2015, 2018; Maddox et al. 2015; Saintonge et al. 2017;

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Catinella et al. 2018; Romeo 2020). A clear connection between the gas within galaxies and the circumgalactic medium (CGM) has also been established; showing that the HI disc of galaxies is fuelled by the CGM (Borthakur et al. 2015); this further strengthens the picture of the interaction of intergalactic and circumgalactic gas with the gas phase of galaxies through the baryon cycle.

Baryon cycle processes are closely related to the chemical evolution of galaxies. Gas is the fuel of star formation and, therefore, an indirect driver for chemical enrichment. The accretion of (relatively) pristine gas onto galaxies also has a diluting effect on the gas-phase metallicity of the ISM of galaxies. This dilution lowers the metallicity of galaxies that have accreted a large amount of gas, which is imprinted on the scatter of the mass–metallicity relation (MZR, the relation between stellar mass and gas-phase metallicity; Tremonti et al. 2004; Moustakas et al. 2011). In the nearby Universe, where gas mass measurements of representative samples of galaxies are available, the effect of metallicity dilution on the MZR has been measured (Bothwell et al. 2013, 2016; Brinchmann et al. 2013; Hughes et al. 2013; Lara-Lopez et al. 2013; Marino et al. 2013; Brown et al. 2018; Zu 2020; Scholte & Saintonge 2023). These gas mass measurements are not readily available for large samples of galaxies at higher redshifts. Therefore, the scatter (and redshift evolution) of the MZR has more often been studied as a function of star formation rate (e.g. Ellison et al. 2008). The three-parameter relation between stellar mass, gas-phase metallicity, and star formation rate is often referred to as the fundamental metallicity relation (FMR; Mannucci et al. 2010; Mannucci, Salvaterra & Campisi 2011; Brown, Martini & Andrews 2016; Cresci, Mannucci & Curti 2019; Curti et al. 2020). In this work, we study the connection between the baryon cycle and the chemical evolution of galaxies using measurements of the atomic gas sequence and MZR. We refer to the atomic gas sequence as the relation between the stellar mass (M_*) of galaxies and their atomic gas fraction ($f_{\text{HI}} \equiv M_{\text{HI}}/M_*$). We show our results in the form of atomic gas fractions as this quantity is more directly informative of the balance between the stellar content, gas content, metals, and other components of galaxies than the total gas mass.

Constraining galaxy scaling relations in the dwarf galaxy regime is of particular interest. Due to the many orders of magnitude lower mass of dwarfs compared to massive galaxies, it is unclear whether feedback and gas accretion operate similarly over the entire stellar mass range covered in this work (from $10^{6.5}$ to $10^{11.5} M_{\odot}$). These questions so far remain mostly unanswered as observing large representative samples of dwarf galaxies is challenging due to their faintness. However, significant samples have been compiled (e.g. Karachentsev & Kaisina 2019) in the Local Volume and nearby Universe, which suggest that the atomic gas fraction of dwarf galaxies is much higher than for massive galaxies (e.g. Geha et al. 2006; Bradford, Geha & Blanton 2015) and that their gas-phase metallicities are systematically lower (Jimmy et al. 2015). Understanding the physics of dwarf galaxies is also important due to the key role that dwarf galaxies may play in cosmic reionization in the early Universe (e.g. Atek et al. 2024; Wu & Kravtsov 2024).

We use observations from the Dark Energy Spectroscopic Instrument (DESI; Levi et al. 2013; DESI Collaboration 2024a) to study galaxy scaling relations far into the dwarf galaxy regime. DESI is a robotic, multiplexed spectroscopic instrument on the Mayall 4-m Telescope at Kitt Peak National Observatory (DESI Collaboration 2022). DESI can obtain simultaneous spectra of almost 5000 objects (DESI Collaboration 2016b; Silber et al. 2023; Miller et al. 2024) and is currently conducting a 5-yr survey of about a third of the sky (DESI Collaboration 2016a; Schlafly et al. 2023). The DESI survey is the largest spectroscopic galaxy survey to date; it will obtain

spectra of ~ 40 million unique galaxies and quasars at redshifts in the range $0.0 < z < 3.7$ during a 5-yr scientific programme (DESI Collaboration 2016a, 2024c, d, e). In particular, the faint magnitude limits of the DESI Bright Galaxy Survey (BGS; Bright: $r < 19.5$; Faint: $19.5 < r < 20.175$) and LOW-Z Secondary Target Survey ($r < 21.0$) allow us to study a large sample of dwarf galaxies of the nearby Universe (Darragh-Ford et al. 2023; Hahn et al. 2023a). In this work, we measure atomic gas masses using the large shared footprint between DESI and the Arecibo Legacy Fast ALFA (ALFALFA) surveys, which is a blind extragalactic HI survey of the local universe (Giovanelli et al. 2005; Haynes et al. 2018). Using ALFALFA we directly measure the atomic hydrogen content of galaxies through measurements of the 21-cm hydrogen emission line. The combined DESI and ALFALFA data is a valuable homogeneous data set of optical and 21-cm spectroscopy. Our measurements span five orders of magnitude in stellar mass from the dwarf galaxy regime ($10^{6.5} M_{\odot}$) to massive galaxies ($10^{11.5} M_{\odot}$), and we use them to perform a joint analysis of the atomic gas sequence and of the MZR.

This paper is structured as follows. In Section 2, we discuss the observations and data products used in this work. In Section 3, we describe our analysis methods, and in Section 4, we discuss the results. We discuss the implications and possible explanations for our results in Section 5 and summarize our main results in Section 6. We assume the cosmological parameters from the Planck Collaboration VII (2020).

2 OBSERVATIONS AND DATA PRODUCTS

Our main sample is a subset of the DESI BGS validation and Year 1 Main Survey Data (Hahn et al. 2023b). The BGS observes galaxies in the lowest redshift ranges of the DESI survey in the range $0.0 < z < 0.6$. The Year 1 data set of the BGS includes extragalactic spectra for over 10 million galaxies. The spectrographs of the DESI instrument cover a wavelength range between 3600 and 9800 Å, split over three cameras. The resolving power, $R = \lambda/\Delta\lambda$, ranges from approximately 2000 at the shortest wavelengths to 5500 at the longest wavelengths (DESI Collaboration 2024a). The observed spectra are reduced using an extensive spectroscopic reduction pipeline (Guy et al. 2023). Spectra are classified and redshifts are measured using a template fitting pipeline (Anand et al. 2024; Bailey et al., in preparation). The DESI observations (including value-added catalogues) used here will be made publicly available in DESI Data Release 1.¹ Some of the data are already publicly available as part of the DESI Early Data Release (EDR; DESI Collaboration 2024a, b).

Our analysis makes use of several value-added catalogues that have been produced for DESI. The photometric measurements used here are derived from the Data Release 9 of DESI Legacy Imaging Surveys (Dey et al. 2019). The photometry is based on the Mayall z -band Legacy Survey (MzLS), Dark Energy Camera Legacy Survey (DECaLS), and Beijing–Arizona Sky Survey (BASS; Zou et al. 2017). The photometry consists of three optical bands (g , r , and z), which are complemented by observations in four infrared bands (W1–W4) taken from the *Wide-field Infrared Survey Explorer* (WISE; Mainzer et al. 2014).

The emission line fluxes in the DESI spectra are measured using FASTSPECFIT, a stellar continuum and emission line modelling code optimized for DESI, which jointly models the three-camera optical spectrophotometry from DESI and the legacy survey imaging (Moustakas et al. 2023).

¹<https://data.desi.lbl.gov/doc/>

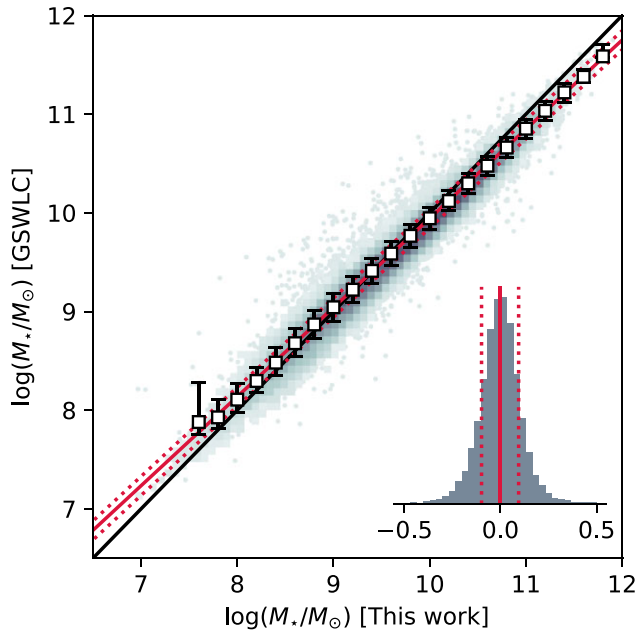


Figure 1. Comparison between the stellar masses used here and stellar masses from the GSWLC catalogue (Salim et al. 2016, 2018). We fit a linear relation to the data of the form $y = 0.90x + 0.91$. The black/white data points show the running median with error bars showing the 16th and 84th percentile values. The red lines show the fit to the data (solid) and the 16th and 84th percentile intervals over all the data (dashed). The black line shows the 1:1 relation. The histogram on the bottom right shows the distribution of the residuals. The 1σ spread in the residuals is 0.09 dex.

The stellar mass measurements are derived from the spectra, Legacy Surveys g -, r -, and z -band photometry, and *WISE* band 1 and 2 photometry using the same approach as in Zou et al. (2024). We use the CodeInvestigatingGALaxyEmission (CIGALE), version 2022.1 (Boquien et al. 2019), to model the spectral energy distributions (SEDs) of galaxies using the Bruzual & Charlot (2003) simple stellar populations and a Chabrier (2003) initial mass function (IMF). We show a comparison between the CIGALE stellar masses and the measurements from the GSWLC-X catalogue (version 2) of the Sloan Digital Sky Survey (SDSS) galaxies for the objects in the overlap between the two samples in Fig. 1 (Salim et al. 2016; Salim, Boquien & Lee 2018). There is overall very good agreement between the two stellar mass measurements. The slope of the stellar mass comparison is slightly shallower than unity, however, within the compared range the systematic offset from the one-to-one relation is at most 0.15 dex. The residual scatter is small at 0.09 dex.

Aside from the DESI spectroscopic observations we also make use of observations from the ALFALFA survey, which is a blind extragalactic HI survey of the local Universe (Giovanelli et al. 2005; Haynes et al. 2018). Due to the significant overlap of the footprints of ALFALFA and DESI, we were able to retrieve ALFALFA spectra capturing the hydrogen 21-cm emission for 69 282 galaxies in our sample (see Section 3.1).

3 METHODS

3.1 Sample selection

Our sample of galaxies is taken from the DESI Survey Validation and Year 1 observations (DESI Collaboration 2024a, b). To ensure we can capture the hydrogen 21-cm line in the ALFALFA observations,

we impose a redshift selection of $0.001 < z < 0.06$. We also impose several quality selections to remove any objects from our sample that are not galaxy spectra or for which the photometry may not be reliable. We only use the primary spectra in the DESI redshift catalogue. This ensures that we use the best spectrum available of each galaxy: `ZCAT_PRIMARY == True`. We also require `SPECTYPE == GALAXY`, `ZWARN == 0` and `DELTA CHI2 >= 40` to ensure we only include galactic spectra in our sample with successful redshift measurements (Hahn et al. 2023b). Using the photometric catalogues we limit the fraction of the flux in each of the optical bands coming from neighbouring objects, `FRACFLUX_G/R/Z < 0.35`. This removes galaxies for which the observed flux is heavily contaminated by nearby sources. The remaining sample consists of 216 333 galaxies. We were able to retrieve ALFALFA observations for 69 282, the remaining DESI galaxies are outside of the ALFALFA survey footprint. In the rest of this section, we will report both the numbers of the DESI sample and combined DESI and ALFALFA observations; the numbers of galaxies observed in both surveys are listed in [square brackets].

We visually inspect the Legacy Surveys imaging of every galaxy with $\log(M_*/M_\odot) < 7.3$ and remove any spectra that are from star-forming regions in large nearby galaxies misclassified as dwarf galaxies; these are called ‘shreds’. Through this inspection, we remove 125/[44] of the 2459/[828] objects below this mass threshold. Above $\log(M_*/M_\odot) = 7.3$ the number of shreds becomes a negligible fraction of the total sample. The remaining 216 208/[69 238] spectra form the base sample for our analysis.

3.1.1 Necessity of using multiple sample selections

The literature sample selection conventions for studies of the atomic gas sequence are different from studies of the MZR. In surveys of the atomic gas content of galaxies volume-limited and mass-complete samples are constructed which allow us to infer the average gas masses of galaxy populations (e.g. Brown et al. 2015; Catinella et al. 2018). However, studies of the MZR require sample selections based on the flux of several emission lines that are required for the metallicity measurement (e.g. Tremonti et al. 2004; Mannucci et al. 2010; Yates, Kauffmann & Guo 2012; Juneau et al. 2014; Kashino et al. 2016; Curti et al. 2020). To allow comparison to literature studies as well as the comparison between these two scaling relations, we use multiple sample selections throughout this work. The two main subsamples in our analysis are (1) a mass-complete sample and (2) a sample with detections of all the optical emission lines needed to derive the gas-phase metallicities for individual galaxies.

3.1.2 Mass-complete sample

We determine a 90 per cent mass-complete sample of galaxies following a similar procedure as in Pozzetti et al. (2010) and Moustakas et al. (2013). We determine the mass each galaxy would have if its magnitude was equal to the magnitude limit of the survey: $\log(M_{\text{lim}}) = \log(M_{*,i}) + 0.4 \times (m_i - m_{\text{lim}})$. Following this, we select the faintest 20 per cent of galaxies in the sample, and in redshift bins of 0.025 dex, we determine the mass below which 90 per cent of the limiting mass measurements of these faint galaxies fall. We define a continuous function $M_{\text{lim}}(z)$ by interpolating between the mass limits in each of the redshift bins. We choose the 90 per cent completeness limit following Hahn et al. (2023a).

Our DESI observations are divided into three categories with different magnitude limits. There is BGS Bright with $r < 19.5$ con-

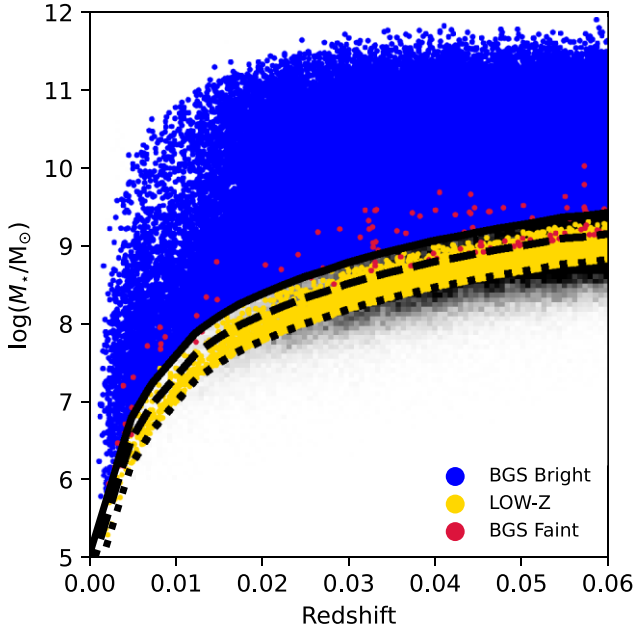


Figure 2. The 90 per cent mass-complete limits for the BGS Bright (blue data points, solid black line), BGS Faint (red data points, dashed black line), and LOW-Z (yellow data points, dotted black line) subsamples.

taining 185 959 galaxies, BGS Faint with $19.5 < r < 20.175$ (8222 galaxies), and the LOW-Z Secondary Target Survey with $r < 21.0$ (22 027 galaxies; Darragh-Ford et al. 2023; Hahn et al. 2023b). We compute the mass completeness limits for each of these categories. Our mass-complete sample includes the 121 918/[39 869] galaxies above the mass completeness limit of the respective categories. The mass completeness selection on these different DESI observations is shown in the redshift–stellar mass plane in Fig. 2.

3.1.3 Emission line flux-limited sample

To measure reliable gas-phase metallicities we require a signal-to-noise ratio (S/N) > 3 for the flux in the [O II] $\lambda\lambda 3726, 3729$, H β , [O III] $\lambda\lambda 4959, 5007$, H α , and [N II] $\lambda\lambda 6548, 6584$ emission lines. We also require the line excitation to be caused by star formation. To ensure this we only include galaxies classed as star forming using the Kauffmann et al. (2003) criterion:

$$\log([\text{O III}]/\text{H}\beta) \leq \frac{0.61}{\log([\text{N II}]/\text{H}\alpha) - 0.05} + 1.3. \quad (1)$$

The remaining sample after these selections includes 76 726/[24 508] galaxies.

3.2 Stacking procedure of DESI spectra

We stack spectra of galaxies to derive high S/N emission line measurements for subsamples of our data set. This allows us to mitigate selection biases against galaxies with weak line emission. Our stacking procedure consists of the following steps:

(i) The spectra are corrected for Milky Way dust attenuation using Galactic extinction measurements from Schlegel, Finkbeiner & Davis (1998) using a Fitzpatrick (1999) extinction curve with $R_V = 3.1$.

(ii) Each spectrum is resampled to a common rest wavelength grid (3600–9800 Å, $\Delta\lambda = 0.2$ Å) using the measured spectroscopic

redshifts. We resample the spectra using linear interpolation (e.g. Andrews & Martini 2013).

(iii) Each spectrum is normalized using the flux of the H α emission line.

(iv) The spectra are then coadded, where the coadded flux is given by the mean flux in each wavelength bin. We coadd the flux in 200 bootstrap samples where the final coadded flux values are the mean flux measurements over the bootstrap samples of each wavelength bin.

(v) The coadded inverse variance is derived from the propagated inverse variance measured for each wavelength bin of each spectrum. The coadded inverse variance values we report are the mean inverse variances of the 200 bootstrap samples of each wavelength bin.

We experimented with several different normalization (e.g. by luminosity or continuum flux) and weighting schemes (e.g. inverse variance or root-mean-square weighting) for the spectral stacking. On test samples with known metallicities of galaxies entering the stacks, the current stacking algorithm most accurately produced stacks with measured metallicities representative of the sample. We measure the emission lines in the coadded spectra using the `stackfit` routine of FASTSPECFIT-v2.4. This applies the same emission line fitting procedure that was used to derive the emission line measurements for the FASTSPECFIT value-added catalogue.²

3.3 Metallicity measurement

We derive gas-phase metallicities for the galaxies in our sample using the R23 ($\{[\text{O II}] 3726, 3729 + [\text{O III}] 4959, 5007\}/\text{H}\beta$) and N2 ($[\text{N II}] 6584/\text{H}\alpha$) strong line diagnostics (Pagel et al. 1979; Calzetti, Kinney & Storchi-Bergmann 1994; Storchi-Bergmann, Calzetti & Kinney 1994). The measured R23 and N2 values are corrected for ISM dust attenuation using the Cardelli, Clayton & Mathis (1989) attenuation prescription and an assumed intrinsic H α /H β flux ratio of 2.86 based on Case-B recombination (Osterbrock & Ferland 2006). We use the calibration from Nakajima et al. (2022) for the R23 diagnostic:

$$\text{R23} = 0.515 - 1.474x - 1.392x^2 - 0.274x^3, \quad (2)$$

where $x = 12 + \log(\text{O}/\text{H}) - 8.69$. To break the degeneracy in the R23 diagnostic we use the N2 diagnostic to derive unique solutions for the metallicities. We use the calibration from Denicoló, Terlevich & Terlevich (2002), which can be written as

$$\text{N2} = -0.589 + 1.370x. \quad (3)$$

The calibration by Denicoló et al. (2002) is described by a linear relation between the N2 diagnostic and metallicity which is in agreement with the expected theoretical relation for this diagnostic over the metallicity range covered as well as with directly measured metallicities. We derive the metallicity using a least-squares approach where we jointly minimize the residuals for the R23 and N2 diagnostics.

We validate our metallicity measurements by comparing them to metallicities derived using measurements of the [O III] 4363 and/or [O II] 7320, 30 auroral emission lines, which constrain the electron temperature and elemental abundances. We do this comparison using three samples with such temperature-sensitive metallicity measurements: the stacked SDSS spectra derived by Liang et al. (2007) and Andrews & Martini (2013) for the higher end of the

²<https://fastspecfit.readthedocs.io/en/latest/index.html>

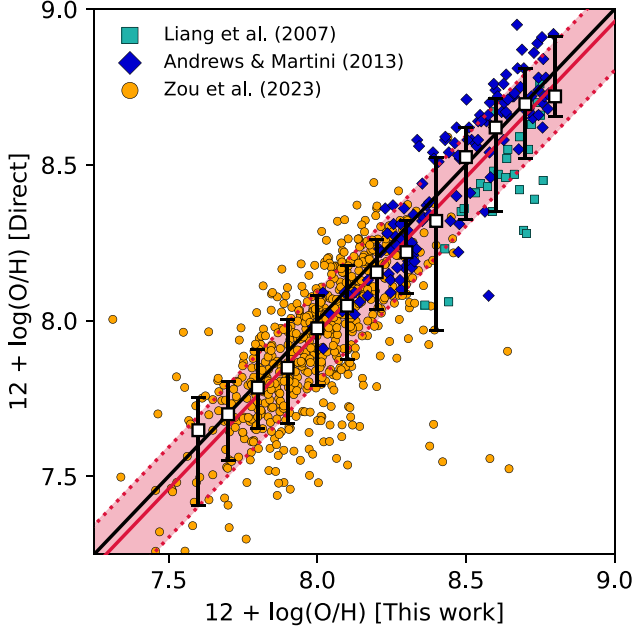


Figure 3. A comparison between direct metallicity measurements and our strong line metallicity measurements. The direct metallicity measurements by Liang et al. (2007), Andrews & Martini (2013), and Zou et al. (2024) are shown in cyan squares, dark blue diamonds, and orange circles, respectively. The black/white data points show the running median with error bars showing the 16th and 84th percentile values. The red lines are not fits to the data but show the median and 16th and 84th percentile intervals over all the data. The black line shows the 1:1 relation.

metallicity range, and the individual galaxies in the DESI EDR from Zou et al. (2024) cover the low metallicity range. We expect one-to-one agreement between our chosen strong line metallicities and these direct measurements because the strong line diagnostics were calibrated using similar metallicity measurements. Fig. 3 shows that our strong line metallicities are in agreement with the direct metallicity measurements with a scatter of ~ 0.3 dex. Due to the small aperture of the fibres of the DESI instrument (diameter ~ 1.5 arcsec; approximately 0.3–1.8 kpc in our redshift range), the observed spectra only capture the emission from the central regions of the galaxies. Therefore, the derived metallicities are representative of these central regions. This may introduce some biases towards higher metallicity in central regions through galactic metallicity gradients, however, this should not affect the overall results as discussed by e.g. Andrews & Martini (2013) and Brown et al. (2018).

3.4 Stacking procedure of ALFALFA spectra and M_{HI} measurement

We measure the HI 21-cm line flux of galaxies in our sample using the ALFALFA survey (Giovanelli et al. 2005; Haynes et al. 2018). ALFALFA was conducted as a blind survey, which means that we can extract an ALFALFA spectrum from any position within the survey footprint. The survey covers the frequency range from 1335 to 1435 MHz, which means the HI 21-cm (~ 1420.41 MHz) line can be recovered at $z < 0.06$. From the unresolved HI line profiles, we can calculate the atomic gas mass of a galaxy:

$$M_{\text{HI}} [M_{\odot}] = \frac{2.356 \times 10^5}{(1+z)^2} [D_L(z)]^2 \int S_{\nu} d\nu, \quad (4)$$

where $D_L(z)$ is the luminosity distance (in Mpc) to the galaxy at redshift, z , as measured from the HI spectrum in the observed velocity frame, and the integral is the HI-line flux density integrated over the line, with S_{ν} in units of Jy and ν in km s^{-1} (Haynes & Giovanelli 1984). These atomic gas masses are sensitive to the total gas mass of galaxies due to the large beam (diameter ~ 3.5 arcmin; approximately 50–250 kpc) of the Arecibo Telescope at these frequencies.

Most of our DESI-selected galaxies are undetected in the HI line; this is highlighted by the fact that only ~ 10 per cent of our sources are catalogued in Haynes et al. (2018). Therefore, we do not derive the M_{HI} for individual galaxies but rather stack the ALFALFA spectra of several galaxies together to increase the S/N of the measurement. Our stacking procedure for the ALFALFA observations has the following steps:

- (i) The 21-cm emission line is centred for each of the spectra using the DESI redshift measurements and each of the ALFALFA spectra is resampled to a common rest-frequency grid with velocity offsets from -800 to 800 km s^{-1} in intervals of 5 km s^{-1} . This is done for both the linear polarizations in the ALFALFA data.
- (ii) The flux arrays are converted to units of luminosity using the luminosity distance: $L_{\nu} = [D_L(z)]^2 S_{\nu}^{\text{rest}}$.
- (iii) We perform median stacking, i.e. we take the weighted median of the luminosity in each velocity channel. The stacking weights are defined as $w_{\text{stack}} = w/\sigma^2$, where w are the ALFALFA spectral weights and σ is the rms noise in the flux measurement. This is done separately for each of the two linear polarizations.
- (iv) We combine the signal of the two linear polarizations by taking the mean flux in each frequency bin.
- (v) We integrate over the 21-cm emission line to measure the luminosity of the emission line. We determine the bounds to integrate over (width of the emission line) using the curve of growth.
- (vi) We convert the measured line luminosities to atomic hydrogen masses (see equation 4 for the conversion).
- (vii) We derive measurement uncertainties using bootstrap resampling of the spectra. We resample the spectra with replacement 200 times and calculate the uncertainty on the derived atomic gas mass as the standard deviation of masses derived in the bootstrap samples.

We use a weighted median to derive our stacked measurements to reduce the impact of abnormalities in some of the spectra in the stacks. These outliers can, for example, be caused by source confusion where the atomic hydrogen content of a galaxy near the target contributes to the measured flux in the 21-cm line.

We also measured the width at 20 per cent of the peak height of the 21-cm line (W_{20}). We correct the W_{20} measurement for the line broadening due to the velocity dispersion induced by redshift uncertainty of DESI BGS ($\sigma_{\text{BGS}} \sim 10 \text{ km s}^{-1}$; Lan et al. 2023) using the Tully & Fouque (1985) correction method:

$$W_{20}^2 = W_{\text{uncorr.}}^2 + W_{\text{rand}}^2 - 2W_{\text{uncorr.}} W_{\text{rand}} \left[1 - e^{-(W_{\text{uncorr.}}/W_c)^2} \right] - 2W_{\text{rand}}^2 e^{-(W_{\text{uncorr.}}/W_c)^2}, \quad (5)$$

where W_{20} is the corrected line width (at 20 per cent of the peak flux) due to the rotational velocity of the atomic gas. $W_{\text{uncorr.}}$ is the uncorrected line width directly measured from the stacks. W_{rand} is the line width due to the random contribution to the line width; we assume $W_{\text{rand}} = 3.78 \times \sigma_{\text{BGS}}$ where the multiplication factor translates the 1σ width to width at 20 per cent of the peak flux based on a Gaussian profile. W_c is the width where the 21-cm line profile changes from a Gaussian shape to a double-horned profile;

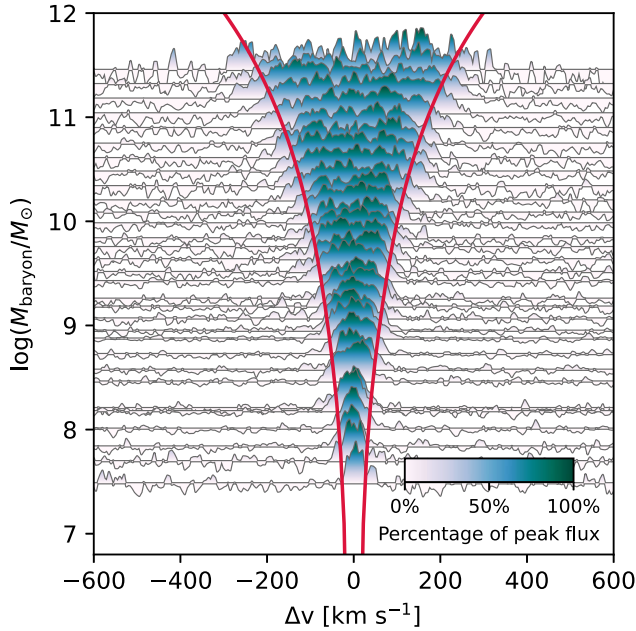


Figure 4. The 21-cm line profiles of stacked spectra from our mass-complete sample in stellar mass bins of 0.15 dex. On the x -axis, we show the velocity offset from the 21-cm line, and on the y -axis, the zero flux point is centred on the median baryonic mass of each stack. In this figure, we computed the baryonic mass as $M_{\text{baryon}} = M_{\star} + 1.33 \times M_{\text{HI}}$. The solid red line shows the baryonic Tully–Fisher relation measured by Lelli et al. (2019), adjusted to our measurements which are not inclination corrected and include an added velocity dispersion due to the average DESI BGS redshift uncertainty (Lan et al. 2023).

we assume $W_c = 120$. We do not perform an inclination correction before stacking the spectra, therefore, we apply also an average inclination correction factor of $\sin(i) = 0.7$ in $W_{20}/(\sin(i))$, assuming a random distribution of inclinations of galaxies in the stacks. These corrections allow us to compare our stacked results with line width measurements of individual galaxies. We use the width at 20 per cent of the peak flux as this reliably traces V_{max} down to the dwarf galaxy regime (Sardone et al. 2024), where $V_{\text{max}} \simeq W_{20,\text{corr}}/2$.

In Fig. 4, we show the stacked spectra we produce for galaxies in 0.15 dex stellar mass bins. We overplot the expected velocity widths according to the measured baryonic Tully–Fisher relation (Tully & Fisher 1977; Lelli et al. 2019), where we have applied the corrections discussed above in reverse to provide a fair comparison between the stacked measurements and literature. On the y -axis, we show the measured baryonic mass of the galaxies in each stack. This is calculated using $M_{\text{baryon}} = M_{\star} + 1.33 \times M_{\text{HI}}$, where we multiply the atomic gas mass measurement by a factor of 1.33 to account for the contribution of helium to the total gas mass (e.g. Lelli et al. 2019). The widths of our 21-cm line measurements align well with the maximum rotational velocities expected from the measured baryonic Tully–Fisher relation from Lelli et al. (2019).

4 RESULTS

4.1 The atomic gas sequence

We measured the atomic gas fraction ($f_{\text{HI}} = M_{\text{HI}}/M_{\star}$) of the galaxies in our full (r -band flux-limited), mass-complete, and emission line flux-limited samples using stacked ALFALFA spectra in stellar mass bins of 0.15 dex. These measurements are shown in Fig. 5. This

figure shows a significant slope change for the atomic gas sequence between the dwarf and massive galaxy regimes. We parametrize the shape of the atomic gas sequence with a broken power law with a smooth transition region using the following functional form:

$$\log(f_{\text{HI}}) = \log(f_{\text{HI},7}) + \gamma_0 \log\left(\frac{M_{\star}}{10^7}\right) + \frac{\gamma_1 - \gamma_0}{\beta} \log\left(1 + \left(\frac{M_{\star}}{M_0}\right)^{\beta}\right). \quad (6)$$

In this equation $\log(f_{\text{HI},7})$ is the atomic gas fraction at $M_{\star} = 10^7 M_{\odot}$, γ_0 is the slope at the low-mass end, γ_1 is the slope at the high-mass end, β determines the width of the transition region between the two slopes, and M_0 is the location of the transition. We fit the function to the data using a weighted least-squares minimization. The best-fitting parameters were found using the EMCEE Markov chain Monte Carlo (MCMC) algorithm (Foreman-Mackey et al. 2013).

We compare our results of the atomic gas sequence to measurements from previous surveys in Fig. 5 (right panel). We compare to results from the r -band flux-limited sample from Geha et al. (2006), the HI-selected sample from Saintonge (2007), the ALFALFA sample of HI-detected galaxies from Maddox et al. (2015), stacked ALFALFA measurements from Brown et al. (2015), the xGASS representative galaxy survey of atomic gas masses (Catinella et al. 2018), and the Local Volume sample composed by Karachentsev & Kaisina (2019). For the Local Volume sample, we calculate the stellar masses from the reported K -band luminosity using a mass-to-light ratio of 0.21, which is the median mass-to-light ratio for our stellar mass measurements at $\log(M_{\star}) \sim 7.5$ in the neighbouring *WISE*-1 band. The large data points connected with dotted lines show the median measured atomic gas fraction as a function of stellar mass.

The median results from these comparison samples are in good agreement with our measurements over the entire mass range. The sample of Maddox et al. (2015) covers a wide stellar mass range, similar to our DESI sample, and detects a similar slope change at a stellar mass of $\sim 10^9 M_{\odot}$. As their sample only includes ALFALFA HI-detected galaxies, it is significantly biased towards the most gas-rich galaxies, explaining the significant offset, especially with our mass-complete sample. At stellar masses above $\sim 10^9 M_{\odot}$, we get an excellent agreement with the median gas masses derived from the representative sample of the xGASS survey. The small systematic offset with the ALFALFA measurements from Brown et al. (2015) is due to a difference in the stacking strategy used. The result from Brown et al. (2015) uses mean stacking (not median stacking as used here), which they show is consistent with the logarithm of the mean atomic gas masses from xGASS. In the dwarf galaxy regime, we compare to samples from Geha et al. (2006), Saintonge (2007), and Karachentsev & Kaisina (2019). Saintonge (2007) derives slightly lower gas fractions compared to our measurements, however, here we have to take into account that their stellar mass calibrations are not matched to ours, which may introduce an artificial offset in both the x - and y -axis. The observed gas fractions and slope of the atomic gas sequence in the dwarf galaxy regime in the Karachentsev & Kaisina (2019) sample are very similar to our measurements over the same mass range. We also note that a turnover of the atomic gas sequence around $\sim 10^9 M_{\odot}$ has previously been described (e.g. Bradford et al. 2015; Maddox et al. 2015).

4.2 The mass–metallicity relation

We use both our emission line flux-limited and our mass-complete sample to study the MZR. The emission line flux-limited sample is

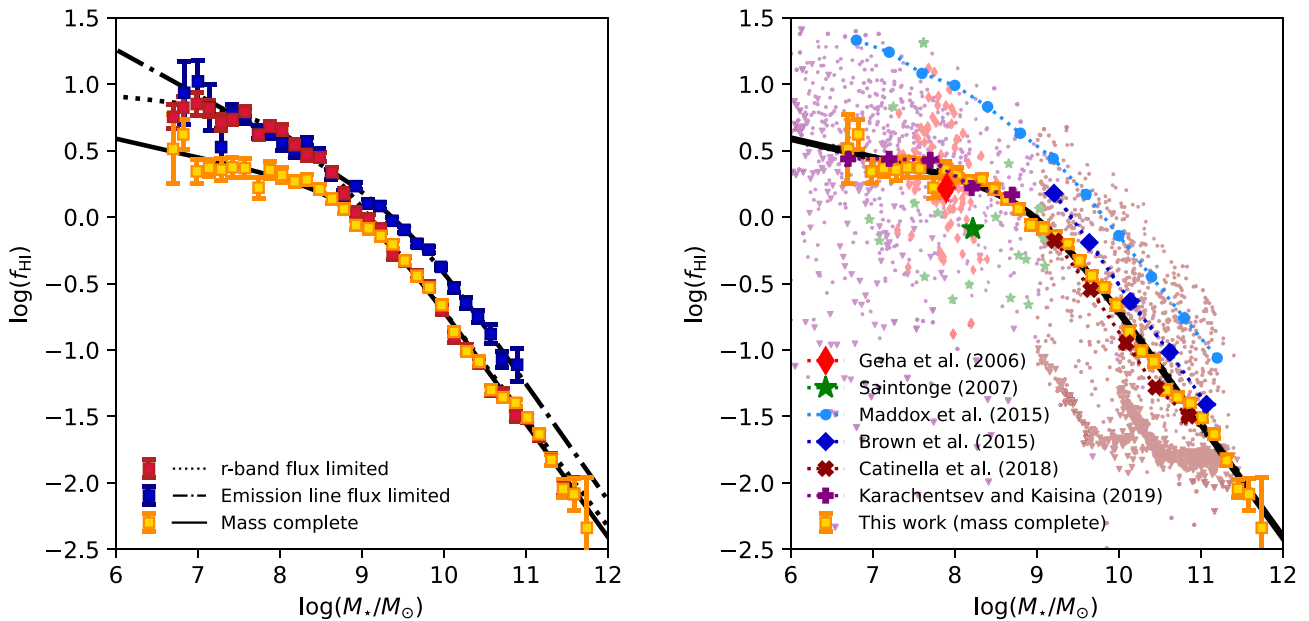


Figure 5. Left: The atomic gas sequence as derived from stacked ALFALFA spectra for the r -band flux-limited (red, black dotted line), emission line flux-limited (blue, black dash-dotted line), and mass-complete samples (yellow, black solid line) together with the best-fitting relations from equation (6) as shown in Table 1. Right: Literature comparisons to the sample from Geha et al. (2006) (red), the H I-selected sample from Saintonge (2007) (green), the ALFALFA H I detections from Maddox et al. (2015) (light blue), stacked ALFALFA measurements (dark blue; Brown et al. 2015), the xGASS representative survey of atomic hydrogen in galaxies (maroon; Catinella et al. 2018), and the Local Volume sample from Karachentsev & Kaisina (2019) (purple). The large data points connected with dotted lines show the median atomic gas fractions within each survey, individual measurements are shown in the small data points, and upper limits in small triangles.

vital to study the scatter in the relation. However, the requirements on emission line S/Ns introduce biases in the sample selection (Yates et al. 2012; Juneau et al. 2014; Kashino et al. 2016). Therefore, we also use our mass-complete sample to verify our measurement of the MZR.

4.2.1 The mass–metallicity relation for individual galaxies

In the left panel of Fig. 6, we show the MZR for the galaxies where we are able to derive gas-phase metallicities. We measure the mean metallicity and standard deviation in narrow 0.15 dex stellar mass bins, which is shown by the blue data points and error bars. The grey data point shows where we have only <25 galaxies in a bin. Our measurements constrain the MZR down to a stellar mass of $\sim 10^6 M_\odot$. We fit the functional form for the MZR from Curti et al. (2020) to the binned stellar mass and metallicity measurements. This function is given by

$$12 + \log(\text{O}/\text{H}) = Z_0 - \frac{\gamma}{\beta} \log \left(1 + \left(\frac{M_\star}{M_0} \right)^{-\beta} \right). \quad (7)$$

In this equation, M_\star is the stellar mass, Z_0 the metallicity at the high-mass end, γ the power-law index of the slope at low stellar masses, β constrains the width of the transition region, and M_0 the turnover stellar mass. We fit the function to the data using a weighted least-squares minimization. The best-fitting parameters are shown in Table 1 and were found using the EMCEE MCMC algorithm (Foreman-Mackey et al. 2013).

In Fig. 7, we compare our results to other measurements of the MZR at low redshift by Tremonti et al. (2004), Pettini & Pagel (2004), Mannucci et al. (2010), Andrews & Martini (2013), and Curti et al. (2020). We get particularly good agreement with the

results derived by Andrews & Martini (2013) and Curti et al. (2020). The metallicity measurements for both these works are (anchored on) ‘direct’ metallicity measurements, which means that we can perform a one-to-one comparison with our measurements. Below $\sim 10^{8.5} M_\odot$ we are seeing some deviations with the result from Andrews & Martini (2013), however, at these stellar masses the SDSS sample has much lower completeness than DESI. The discrepancies with the Tremonti et al. (2004), Pettini & Pagel (2004), and Mannucci et al. (2010) calibrations are due to differences in metallicity calibrations which are well documented (e.g. Kewley & Ellison 2008; Moustakas et al. 2010).

4.2.2 The mass–metallicity relation for a representative sample of star-forming galaxies

We repeat the metallicity measurements for a more representative sample of star-forming galaxies based on our mass-complete sample. Only galaxies with some star formation produce the emission lines used to measure the gas-phase metallicity. Therefore, we exclude quiescent galaxies from our sample by introducing an S/N > 3 selection on the H α flux; below a stellar mass of $10^9 M_\odot$ this excludes only ~ 9 per cent of our sample, above a stellar mass of $10^9 M_\odot$ this increases to ~ 15 per cent. As only a small fraction of the mass-complete sample is excluded through this selection, we make comparisons between the metallicity measurements of this representative sample of star-forming galaxies and gas fraction measurements of the mass-complete sample; the exclusion of this small subset of galaxies does not have a large influence on the median measurement of the atomic gas fraction as we show in Table A1 in Appendix A. As we do not have reliable emission line measurements for the individual galaxies in this sample, we cannot

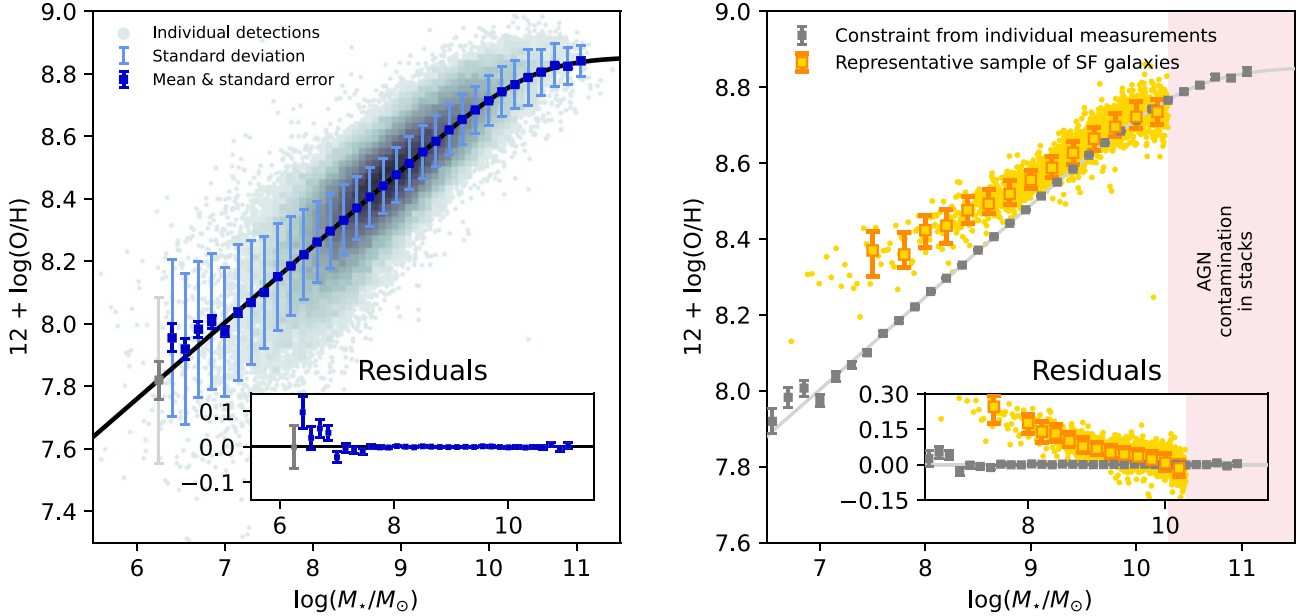


Figure 6. The MZR of star-forming galaxies at $z < 0.06$. Left: The emission line flux-limited sample. The grey-shaded area and data points show the individual measurements. The square data points show the mean MZR, standard error (dark blue/dark grey), and standard deviation (light blue/light grey) in 0.15 dex stellar mass bins for bins with 25 (blue)/10 (grey) or more galaxies. The fitted relation using equation (7) is shown in solid black. Right: The MZR for the mass-complete stacks. The stacked measurements (yellow) are shown together with the fitted relation for the emission line flux-limited sample (black) and binned averages of the stacked measurements (grey).

Table 1. Parameter values for the fitted relations. These parameter values were determined using a weighted least-squares minimization using the EMCEE MCMC algorithm (Foreman-Mackey et al. 2013).

Atomic gas sequence (equation 6)						
Data sample	No. of galaxies	$\log(f_{\text{H}1,7})$	γ_0	γ_1	β	$\log(M_0)$
<i>r</i> -band flux limited	69 238	$0.85^{+0.04}_{-0.04}$	$-0.06^{+0.04}_{-0.07}$	$-0.811^{+0.016}_{-0.018}$	$1.10^{+0.34}_{-0.21}$	$8.17^{+0.10}_{-0.07}$
Line flux limited	24 508	$0.92^{+0.05}_{-0.05}$	$-0.34^{+0.08}_{-0.05}$	$-0.88^{+0.09}_{-0.08}$	$1.1^{+1.0}_{-0.4}$	$9.50^{+0.17}_{-0.19}$
Mass complete	39 869	$0.45^{+0.04}_{-0.03}$	$-0.14^{+0.07}_{-0.06}$	$-0.854^{+0.025}_{-0.033}$	$1.2^{+0.4}_{-0.3}$	$8.98^{+0.11}_{-0.11}$
Mass–metallicity relation (equation 7)						
Data sample	No. of galaxies	Z_0	β	$\log(M_0)$	γ	
Line flux limited	76 726	$8.854^{+0.009}_{-0.008}$	$1.20^{+0.10}_{-0.09}$	$10.49^{+0.03}_{-0.03}$	$0.2439^{+0.0014}_{-0.0013}$	

remove active galactic nucleus (AGN). This population contaminates the sample at high stellar mass and therefore we are only able to make reliable metallicity measurements from the mass-complete stacks at $M_* < 10^{10.3} M_\odot$ (e.g. Kauffmann et al. 2003). For this mass-complete sample, we use spectral stacking to ensure all the required emission lines are detected. We divide the sample into stellar mass bins, each containing ~ 50 galaxies. We show the results from our stacked measurements in the right panel of Fig. 6. These results for what is a much more complete sample show a significantly shallower slope of the MZR at masses $< 10^9 M_\odot$, compared to the emission line flux-limited sample. The difference between these samples is mainly the inclusion in the mass-complete sample of galaxies with a lower star formation rate and gas fraction. As shown by the FMR, at fixed stellar mass, metallicity is inversely correlated with star formation rate, therefore, the inclusion of galaxies with a low star formation rate will increase the average gas-phase metallicity of the sample (e.g. Ellison et al. 2008; Mannucci et al. 2010). This is also reflected in the lower average gas fraction of the atomic gas sequence of the mass-complete sample compared to the emission line flux-limited sample as shown in Fig. 5.

4.3 The connection between the scatter in the mass–metallicity relation and atomic gas sequence

Our results show that sample selection has a significant effect on the measured atomic gas sequence and MZR. At fixed stellar mass, the gas fraction/metallicity of galaxies is systematically higher/lower for the emission line flux-limited sample compared to the mass-complete sample. This shows that the atomic gas mass and metallicity of galaxies are strongly related quantities.

We investigate further this connection between the MZR and the atomic gas sequence, by looking for systematic trends in the scatter around the scaling relations. To do so, we divide the galaxies in our emission line flux-limited sample and ALFALFA coverage into 34 quantile bins in stellar mass and 5 quantile bins in offset from the average MZR (equation 7); this ensures that each bin contains ~ 150 galaxies. The average stellar mass and metallicity of the galaxies in each bin are shown in the left panel of Fig. 8. We stack the ALFALFA spectra in these stellar mass/MZR offset bins to measure the atomic gas mass in each bin; this is shown in the right panel of Fig. 8. Our measurements show that for all stellar mass bins,

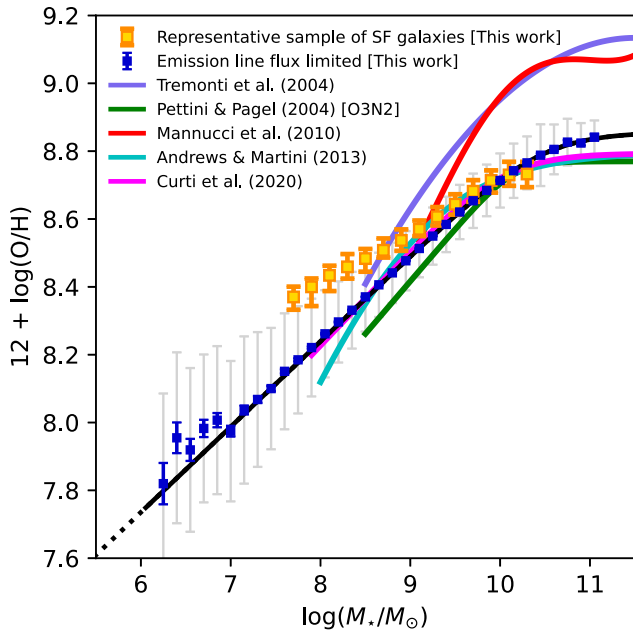


Figure 7. Comparison of our MZR measurements (blue and orange; same as in Fig. 6) to previous results by Tremonti et al. (2004), Pettini & Pagel (2004), Mannucci et al. (2010), Andrews & Martini (2013), and Curti et al. (2020). We find excellent agreement with the measurements from Andrews & Martini (2013) and Curti et al. (2020).

the most metal-poor(rich) galaxies are also the most gas-rich(poor). This result is in agreement with several previous studies that have revealed that gas mass plays an important role in establishing the scatter of the MZR (Bothwell et al. 2013, 2016; Brinchmann et al. 2013; Hughes et al. 2013; Lara-Lopez et al. 2013; Brown et al. 2018; Scholte & Saintonge 2023). In this work, we push these established relations to much lower stellar masses ($10^{7.3} M_{\odot}$) than most previous studies ($\sim 10^9 M_{\odot}$). Qualitatively, we get similar results to the $\text{FMR}_{\text{H I}}$ measurements from Jimmy et al. (2015) in the dwarf galaxy regime, however, here derived using a much larger sample.

5 DISCUSSION

Using the DESI and ALFALFA surveys we constrain the atomic gas sequence and MZR over a stellar mass range from $10^{6.5}$ to $10^{11.5} M_{\odot}$. We find that there is a slope change in both the atomic gas sequence and the MZR at $\sim 10^9 M_{\odot}$ when using a mass-complete sample. We also find that the scatter of the MZR is inversely correlated with the scatter of the atomic gas sequence over the entire mass range. These measurements of the slope change in both the atomic gas sequence and MZR at a similar mass of $\sim 10^9 M_{\odot}$ (see Fig. 5 and the right-hand panel of Fig. 6) provide compelling evidence that there is a transition of the dominant process that regulates the evolution of dwarf galaxies and massive galaxies, respectively.

5.1 A transition of the atomic gas sequence at $\sim 10^9 M_{\odot}$

The measurement of a slope change in the atomic gas sequence indicates a change in the dominant processes that set the atomic gas mass between the dwarf and massive galaxy regimes. The combination of efficient accretion of cool gas onto low-mass galaxies (‘cold-mode accretion’; e.g. Kereš et al. 2005) and efficient removal of gas from the shallow potential well of dwarfs due to supernova

feedback are likely to be dominant processes determining the gas content of dwarf galaxies (e.g. Larson 1974).

Dekel & Silk (1986) predicted that supernova-driven winds efficiently drive a substantial fraction of the gas out of galaxies when the virial velocity is lower than a critical value (V_{crit}) of $\sim 100 \text{ km s}^{-1}$. More recently, simulations with physically motivated supernova feedback models also show a threshold value of the maximum rotational velocity of $\sim 100 \text{ km s}^{-1}$ allowing the removal of a significant fraction of the gas phase of dwarfs (de Rossi, Tissera & Pedrosa 2010). The supernova feedback model in these simulations is able to explain the observed break in the stellar Tully–Fisher relation at $\sim 90 \text{ km s}^{-1}$ (Tully & Fisher 1977; McGaugh et al. 2000). Other simulations have also indicated that there is significant gas removal from dwarfs through feedback; the ISM of dwarf galaxies has a much lower density and is not collapsed into a thin disc as observed at higher masses (e.g. Hopkins, Quataert & Murray 2012; Shen et al. 2014; Rey et al. 2022). This may make the gas phase of dwarf galaxies much more susceptible to feedback. Hopkins et al. (2012) have shown that in the dwarf galaxy regime, a combination of momentum from ultraviolet photons, stellar winds, warm gas pressure from photoionization regions, and supernovae feedback can generate a multiphase outflow that ejects large amounts of gas. The literature results above also show that this process ceases to be efficient at masses above $\sim 10^9 M_{\odot}$.

Measurements of the outflow velocities (V_{out}) in star-forming galaxies at $10^9 M_{\odot}$ show that $V_{\text{out}} \simeq 100 \text{ km s}^{-1} \simeq V_{\text{crit}}$ and that at higher masses $V_{\text{out}} < V_{\text{crit}}$ (Roberts-Borsani & Saintonge 2019). This shows that the outflow velocities of normal star-forming galaxies are not high enough to escape the potential. However, in the shallower potentials of dwarfs, outflows can escape into the intergalactic medium. With decreasing mass, galaxies are significantly more efficient at generating outflows; simulations show us that this is largely driven by the effect of the halo potential well (Christensen et al. 2016).

We can estimate the characteristic stellar mass at which galaxies transition into the regime where significant gas loss is expected. To do this, we calculate the maximum rotational velocity of the galaxies in our sample through the width of the 21-cm emission line in the stacked ALFALFA spectra. The result is displayed in Fig. 9, which shows that the expected transition at a virial velocity of $\sim 100 \text{ km s}^{-1}$ indeed corresponds to a stellar mass of $\sim 10^9 M_{\odot}$. Based on this, we can infer that the change in the efficiency of supernovae-driven outflows in galaxies with virial velocities greater/smaller than 100 km s^{-1} is likely to be a contributing factor to the slope change of the atomic gas sequence observed at $\sim 10^9 M_{\odot}$.

At stellar masses larger than $\sim 10^9 M_{\odot}$, the relation between the stellar mass and H I gas content of galaxies is unlikely to be regulated in most part by supernova feedback. In this higher mass regime, we see a persistent trend where the gas fraction of galaxies decreases with stellar mass, as previously also robustly derived by the xGASS survey (Catinella et al. 2018). If gas removal is unlikely to be the dominant factor regulating this steep declining slope at masses $> 10^9 M_{\odot}$ (at least until significantly higher masses where AGN feedback might play a role), then we should logically look instead for changes in gas accretion.

It has been convincingly argued based on numerical simulations that there is a change in the efficiency of gas accretion onto galaxies at stellar masses of $10^{10} M_{\odot}$ (e.g. Kereš et al. 2005; Dekel & Birnboim 2006; van de Voort et al. 2011). Above such a characteristic mass, infalling gas is shock heated to the virial temperature of the halo. The very long cooling time of shock-heated gas makes the accretion of this gas into the ISM an inefficient process, effectively starving

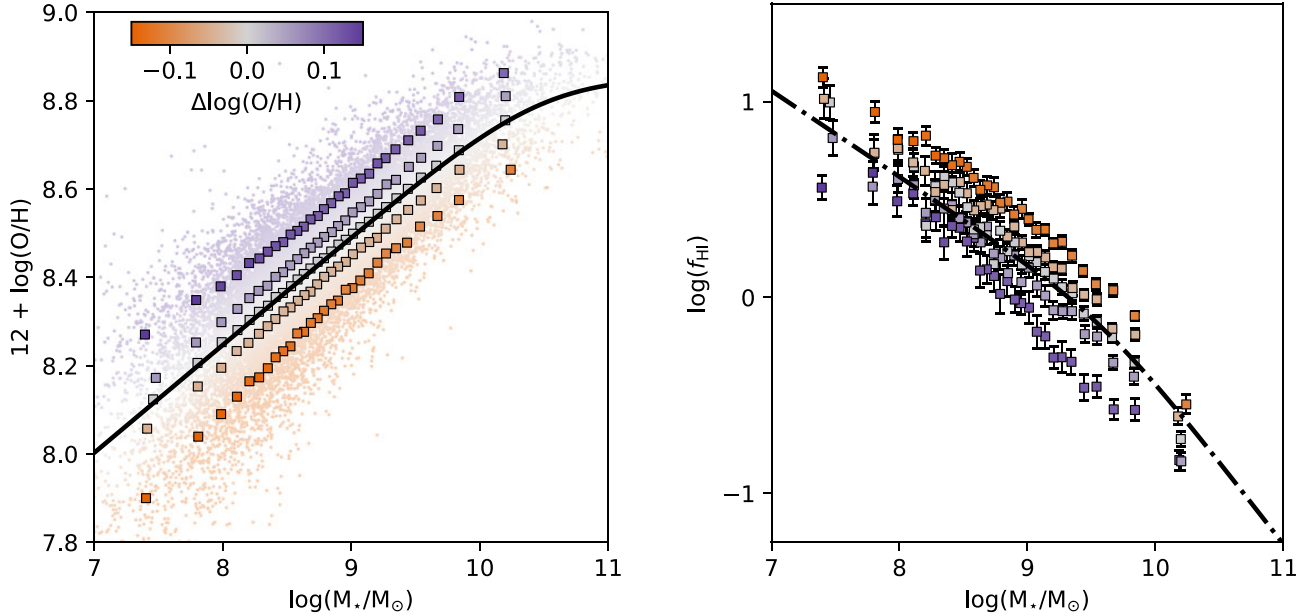


Figure 8. Left: The MZR binned in stellar mass and offset from the average MZR ($\Delta \log(\text{O}/\text{H})$, black, solid, same as in Fig. 6). For each bin the average stellar mass and metallicity is shown (square) coloured by offset from the MZR. Right: The atomic gas sequence (black, dash-dotted, same as in Fig. 5) and measured atomic gas fraction of the galaxies in each stellar mass/MZR offset bin. The binned measurements are coloured by the offset from the MZR as in the left panel.

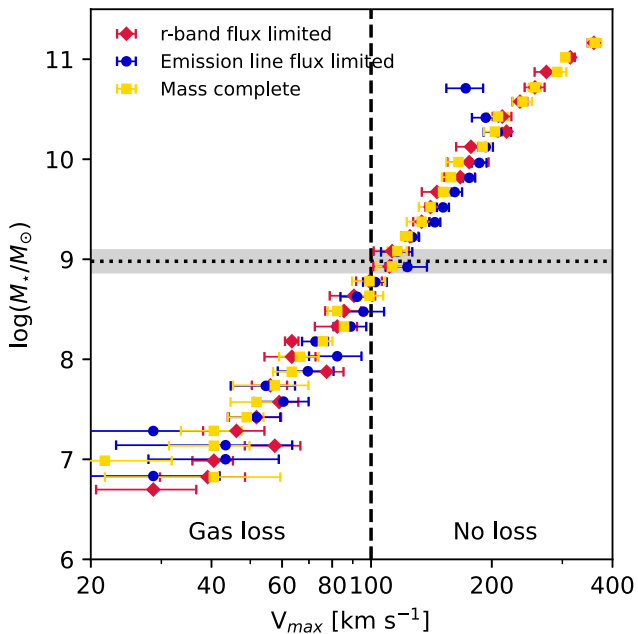


Figure 9. The maximum rotational velocity versus stellar mass of galaxies (stellar Tully–Fisher relation; Tully & Fisher 1977). The data points show the measured maximum rotational velocity inferred from the W_{20} line width of the 21-cm line (see Section 3.4). The vertical dashed line shows the critical value of the maximum rotational velocity below which gas loss is expected according to Dekel & Silk (1986). The horizontal dotted line and grey band denote the location of the slope transition of the atomic gas sequence in our mass-complete sample: $\log(M_*/M_\odot) = 8.98^{+0.11}_{-0.11}$.

the galaxy of fresh gas. This naturally leads to a relative decrease in the total cold gas reservoirs of galaxies as they grow more massive. While the transition between the so-called ‘cold-mode’ and ‘hot-mode’ accretion onto haloes is often reported to occur at stellar

masses of $\sim 10^{10} M_\odot$, a smoother transition between the two modes could explain why the gas reservoirs (relative to the stellar mass) are already starting to decline at $\sim 10^9 M_\odot$. A thorough analysis of the respective roles of gas inflows and outflows in determining the slope of the atomic gas sequence will in the future be enabled through detailed comparisons with modern simulations. These simulations are starting to reach the volumes and resolution required to produce galaxy scaling relations over similarly broad stellar mass ranges (e.g. Feldmann et al. 2023).

5.2 Understanding the link between the atomic gas sequence and the MZR through a simple analytical model

The shape and scatter of the MZR are often attributed to the effects of inflows of pristine gas and the removal of metals from the gas reservoirs of galaxies through feedback. To gain an understanding of how these processes may connect to explain our results on the atomic gas sequence and MZR, we use a simple chemical evolution model (Recchi et al. 2008). This model describes the ISM of galaxies as a gas reservoir in which metals are deposited through star formation. The reservoir can be fuelled by (metal-poor) inflows and metals can be removed through (metal-rich) outflows. The gas-phase metallicity is determined using the following equation:

$$Z = \frac{\Lambda Z_A + y_Z}{\Lambda + (\beta - 1)\lambda} \times \left(1 - [(\Lambda - \lambda) - (\Lambda - \lambda - 1)\mu^{-1}]^{\frac{\Lambda + (\beta - 1)\lambda}{\Lambda - \lambda - 1}} \right), \quad (8)$$

where y_Z is the yield of metals through star formation, μ is the gas fraction $M_{\text{gas}}/(M_* + M_{\text{gas}})$, Λ and λ are the relative strengths of gas inflows and feedback proportional to the star formation rate, Z_A is the metallicity of inflowing gas, and β regulates the preferential ejection of metal-enriched gas. Although simplistic and not encompassing all of the complexity of the underlying physical processes, this kind of simple analytical model is quite successful

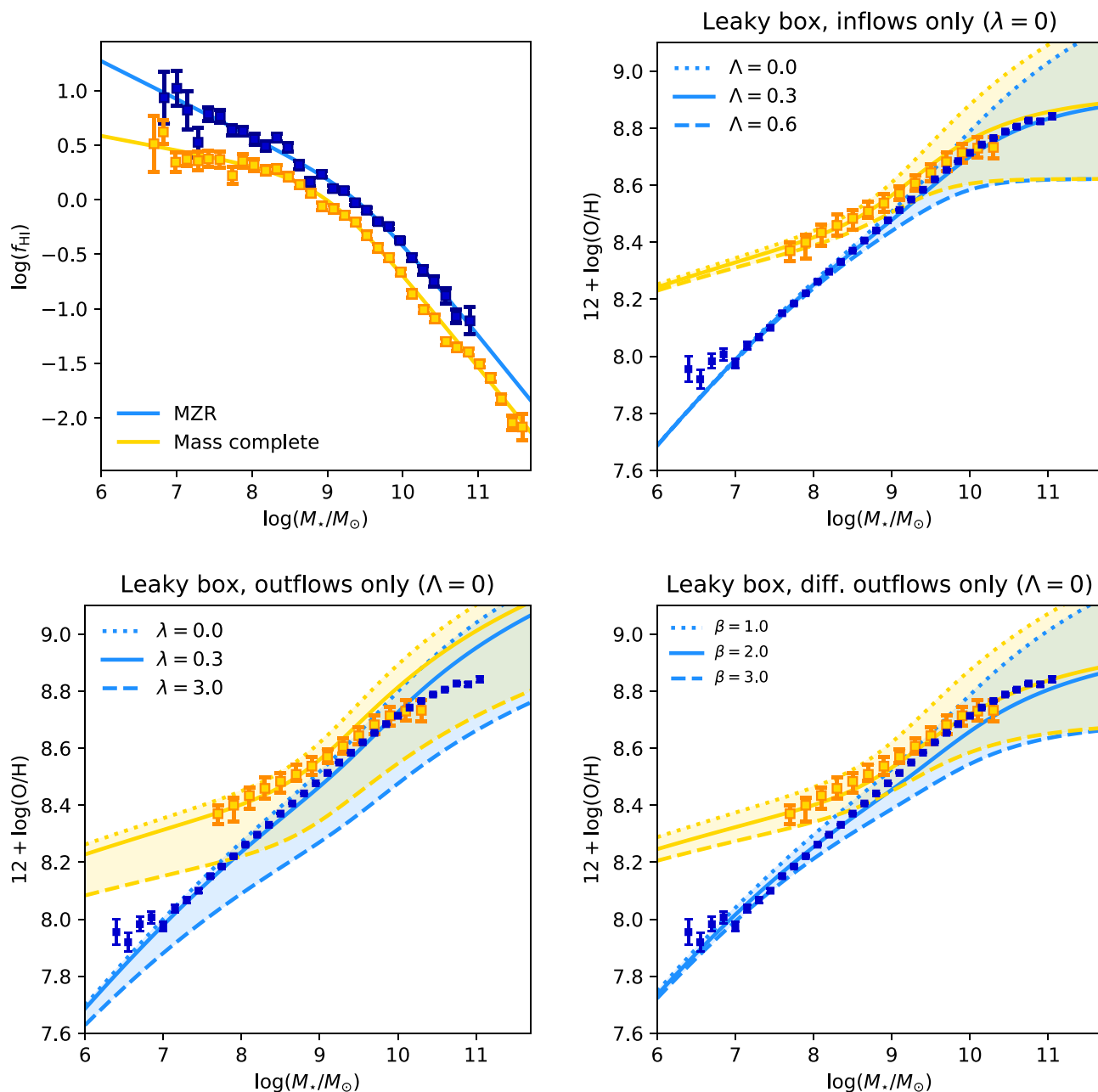


Figure 10. Modelled MZR derived using the analytical model from Recchi et al. (2008). Top-left: The measured atomic gas sequence as in Fig. 6 from the emission line flux-limited sample (dark/light blue) together with the atomic gas sequence of the mass-complete sample (orange/yellow). Top-right: The measured MZR (black, same as in Fig. 6) for the emission line flux-limited (dark blue) and mass-complete (orange) samples shown together with MZR derived using the analytical model using the respective gas sequences coloured according to the top-left panel. These MZR are derived assuming that the metallicity is regulated by inflows of pristine gas and no outflows. Line styles show different values of the inflow parameter strength as explained by the legend. Bottom-left: Same as top-right panel except here showing the results where the metallicity is regulated by outflows. Bottom-right: Same as top-right panel except here showing the results where the metallicity is regulated by differential outflows.

at reproducing the MZR (e.g. Recchi et al. 2008; Lilly et al. 2013; Tortora, Hunt & Ginolfi 2022). Here we use the model to provide us with a qualitative understanding of how different processes affect the shape of the MZR, rather than to try to put quantitative constraints on quantities such as mass-loading factors, metal yields, or IMF variations due to strong degeneracies between model parameters (e.g. Spitoni et al. 2010). The behaviour seen in the analytic model used here can be reproduced using similar analytical prescriptions (e.g. Davé, Finlator & Oppenheimer 2012; Lilly et al. 2013).

We use our measurements of the atomic gas sequence to determine μ and set the following parameters to fixed values for the inflow and outflow models: $y_Z = 0.0084$ and $Z_A = 0.0$. In the differential outflow model, we fix the parameters to $y_Z = 0.010$, $Z_A = 0.0$, and $\lambda = 0.3$. In these models μ represents the gas fraction that is actively involved in the star-forming process and in which the metals are mixed almost instantly. This is not the case for the full atomic gas mass, therefore we assume that 25 per cent of the gas mass is ‘star-forming gas’, which roughly corresponds to the atomic

to molecular gas ratio (e.g. Saintonge et al. 2011; Catinella et al. 2018).

In the top-left panel of Fig. 10, we show the measured atomic gas sequence as in for the emission line flux-limited sample (blue) as well as the mass-complete sample (orange). The remaining panels show the expected MZR using models including outflows (top-right), inflows (bottom-left), and differential outflows (bottom-right), each using the two different atomic gas sequences as input. For each model, we show several values for the inflow (Λ), outflow (λ), and differential outflow (β) parameters, as shown in the legends of the respective graphs. These panels show clearly that the shape of the atomic gas sequence is the main factor responsible for the slope of the MZR at masses $<10^9 M_\odot$. Models with the same parameter values for inflows and outflows can simultaneously describe the MZR slopes of both of these samples, as long as the relevant atomic gas sequence is used as input.

6 CONCLUSIONS

Using combined observations from the DESI and ALFALFA surveys we constrained the atomic gas sequence and MZR from dwarfs ($10^{6.5} M_\odot$) to massive galaxies ($10^{11.5} M_\odot$). This is made possible due to the faint magnitude limit of the DESI survey in comparison with previous generations of large spectroscopic surveys such as SDSS. Summarized our main findings are as follows:

(i) We find a slope change of the atomic gas sequence at $\sim 10^9 M_\odot$. In the dwarf galaxy regime, the slope of the atomic gas sequence becomes shallower. We show that the mass range at which we see a shallow slope of atomic gas sequence change is consistent with predictions of supernova-driven gas loss in the dwarf galaxy regime (e.g. Larson 1974; Dekel & Silk 1986; de Rossi et al. 2010).

(ii) We measure the MZR using individual galaxies that are characterized by a high-mass plateau at $\sim 10^{10.5} M_\odot$ and a power-law relation with a constant slope of ~ 0.24 at a lower mass. Our results are in excellent agreement with other works using similar metallicity measurements (e.g. Andrews & Martini 2013; Curti et al. 2020). However, the faint magnitude limit of the DESI survey allows us to constrain the MZR down to galaxies with $M_* \sim 10^{6.5} M_\odot$.

(iii) We show that the slope of the MZR is, however, significantly shallower at stellar masses $<10^9 M_\odot$ when measured for a much more complete and representative sample of star-forming galaxies. Using the chemical evolution model of Recchi et al. (2008) to argue that the slope change of the MZR at $\sim 10^9 M_\odot$ is directly linked to the behaviour of the atomic gas reservoir.

The joint constraints on these scaling relations over five orders of magnitude in stellar mass provide compelling evidence that there is a transition of the dominant processes that regulate the evolution of dwarf galaxies and massive galaxies, respectively. Further DESI data releases will significantly increase the number of low-mass galaxies and the overlap with the ALFALFA survey, allowing us to better constrain the joint behaviour of galaxy scaling relations, and to interpret the observations through a combination of analytic models and large volume simulations.

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DATA AVAILABILITY

The data from the DESI Survey Validation period is publicly available at <https://data.desi.lbl.gov/doc/> (DESI Collaboration 2024a). The full DESI Survey Year 1 data set used in this work will be made public at the same location in 2025. This includes spectra and derived data such as emission line flux measurements from FASTSPECFIT (Moustakas et al. 2023). The Legacy Survey imaging is available at <https://www.legacysurvey.org/>. Data products from the ALFALFA Survey are available at <https://egg.astro.cornell.edu/index.php/>. Other derived data generated in this research will be shared on reasonable request to the corresponding author.

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APPENDIX A: MEASUREMENTS OF THE ATOMIC GAS SEQUENCE AND MASS–METALLICITY RELATION

This appendix contains tables of the measured atomic gas sequences and MZR for the samples used in this paper. The atomic gas sequence measurements are shown in Table A1. The measurements of the MZR derived from individual galaxies in the emission line flux-limited sample are shown in Table A2. The measurements of the MZR derived from stacked spectra of the representative sample of star-forming galaxies are shown in Table A3.

Table A1. The atomic gas fraction measurements of the samples used in this paper.

$\log(M_*/M_\odot)$	$\log(F_{\text{HI}})$			
	Flux limited	Line flux limited	Mass complete	Representative SF
6.675	0.75 ± 0.09	–	0.5 ± 0.3	–
6.825	0.82 ± 0.09	0.94 ± 0.24	0.62 ± 0.11	0.70 ± 0.08
6.975	0.85 ± 0.09	1.02 ± 0.16	0.34 ± 0.09	0.35 ± 0.10
7.125	0.82 ± 0.06	0.82 ± 0.17	0.37 ± 0.06	0.38 ± 0.07
7.275	0.71 ± 0.06	0.53 ± 0.14	0.36 ± 0.09	0.39 ± 0.08
7.425	0.74 ± 0.04	0.79 ± 0.06	0.37 ± 0.08	0.39 ± 0.07
7.575	0.79 ± 0.04	0.76 ± 0.06	0.37 ± 0.07	0.40 ± 0.07
7.725	0.62 ± 0.04	0.64 ± 0.05	0.22 ± 0.08	0.28 ± 0.08
7.875	0.68 ± 0.04	0.63 ± 0.04	0.35 ± 0.06	0.35 ± 0.06
8.025	0.65 ± 0.04	0.55 ± 0.05	0.32 ± 0.05	0.34 ± 0.05
8.175	0.54 ± 0.04	0.49 ± 0.04	0.27 ± 0.04	0.31 ± 0.04
8.325	0.47 ± 0.04	0.57 ± 0.03	0.28 ± 0.03	0.31 ± 0.03
8.475	0.45 ± 0.04	0.48 ± 0.04	0.21 ± 0.04	0.29 ± 0.03
8.625	0.34 ± 0.04	0.32 ± 0.04	0.14 ± 0.03	0.19 ± 0.03
8.775	0.17 ± 0.04	0.16 ± 0.04	0.06 ± 0.03	0.16 ± 0.03
8.925	0.03 ± 0.04	0.23 ± 0.03	-0.06 ± 0.04	0.04 ± 0.03
9.075	-0.01 ± 0.04	0.10 ± 0.03	-0.09 ± 0.04	0.045 ± 0.024
9.225	-0.09 ± 0.03	0.08 ± 0.03	-0.14 ± 0.03	-0.016 ± 0.023
9.375	-0.28 ± 0.04	-0.028 ± 0.023	-0.21 ± 0.03	-0.09 ± 0.03
9.525	-0.33 ± 0.03	-0.097 ± 0.023	-0.33 ± 0.03	-0.23 ± 0.03
9.675	-0.43 ± 0.03	-0.201 ± 0.022	-0.44 ± 0.03	-0.35 ± 0.03
9.825	-0.51 ± 0.03	-0.245 ± 0.022	-0.53 ± 0.03	-0.39 ± 0.03
9.975	-0.70 ± 0.04	-0.375 ± 0.021	-0.66 ± 0.03	-0.56 ± 0.03
10.125	-0.91 ± 0.04	-0.53 ± 0.03	-0.86 ± 0.04	-0.70 ± 0.03
10.275	-1.00 ± 0.04	-0.65 ± 0.04	-1.01 ± 0.03	-0.84 ± 0.03
10.425	-1.10 ± 0.03	-0.75 ± 0.05	-1.09 ± 0.04	-0.90 ± 0.03
10.575	-1.31 ± 0.04	-0.88 ± 0.07	-1.30 ± 0.03	-1.11 ± 0.03
10.725	-1.33 ± 0.04	-1.07 ± 0.06	-1.36 ± 0.04	-1.18 ± 0.03
10.875	-1.50 ± 0.04	-1.11 ± 0.12	-1.40 ± 0.03	-1.31 ± 0.03
11.025	-1.51 ± 0.03	–	-1.51 ± 0.03	-1.43 ± 0.03
11.175	-1.64 ± 0.04	–	-1.63 ± 0.04	-1.53 ± 0.03
11.325	-1.82 ± 0.04	–	-1.83 ± 0.04	-1.71 ± 0.04
11.475	-2.03 ± 0.06	–	-2.05 ± 0.07	-1.93 ± 0.07
11.625	-2.08 ± 0.12	–	-2.08 ± 0.12	-1.88 ± 0.12
11.775	-2.3 ± 0.4	–	-2.3 ± 0.4	–

Table A2. The metallicity measurements of the emission line flux-limited sample.

$\log(M_*/M_\odot)$	$12 + \log(\text{O}/\text{H})$		
	Mean	Standard deviation	Standard error
6.40	7.955	0.252	0.0453
6.55	7.919	0.241	0.0325
6.70	7.983	0.218	0.0255
6.85	8.007	0.218	0.0210
7.00	7.974	0.207	0.0159
7.15	8.037	0.217	0.0133
7.30	8.068	0.199	0.0099
7.45	8.100	0.179	0.0076
7.60	8.151	0.171	0.0058
7.75	8.185	0.158	0.0044
7.90	8.221	0.144	0.0033
8.05	8.262	0.129	0.0024
8.20	8.297	0.120	0.0018
8.35	8.331	0.113	0.0015
8.50	8.370	0.102	0.0012
8.65	8.406	0.095	0.0011
8.80	8.441	0.089	0.0010
8.95	8.477	0.087	0.0010
9.10	8.513	0.085	0.0010
9.25	8.550	0.084	0.0011
9.40	8.584	0.082	0.0012
9.55	8.621	0.080	0.0013
9.70	8.654	0.080	0.0015
9.85	8.684	0.076	0.0017
10.00	8.714	0.080	0.0023
10.15	8.742	0.080	0.0030
10.30	8.766	0.078	0.0034
10.45	8.788	0.091	0.0050
10.60	8.805	0.073	0.0053
10.75	8.827	0.069	0.0058
10.90	8.824	0.059	0.0070
11.05	8.841	0.049	0.0093

Table A3. The metallicity measurements of the representative sample of star-forming galaxies.

$\log(M_*/M_\odot)$	$12 + \log(\text{O}/\text{H})$
7.8	$8.37^{+0.03}_{-0.04}$
8.0	$8.40^{+0.03}_{-0.06}$
8.2	$8.43^{+0.03}_{-0.05}$
8.4	$8.46^{+0.04}_{-0.04}$
8.6	$8.48^{+0.03}_{-0.04}$
8.8	$8.508^{+0.035}_{-0.021}$
9.0	$8.54^{+0.03}_{-0.03}$
9.2	$8.570^{+0.026}_{-0.020}$
9.4	$8.61^{+0.03}_{-0.03}$
9.6	$8.64^{+0.03}_{-0.03}$
9.8	$8.68^{+0.03}_{-0.03}$
10.0	$8.71^{+0.03}_{-0.04}$
10.2	$8.73^{+0.04}_{-0.03}$

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