Star Formation and Quenching of Central Galaxies from Stacked HI Measurements

Hong Guo1,5, Michael G. Jones2,3,5, Jing Wang4,5, and Lin Lin1

1 Key Laboratory for Research in Galaxies and Cosmology, Shanghai Astronomical Observatory, Shanghai 200030, People’s Republic of China
2 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Rm. N204, Tucson, AZ 85721-0065, USA; jonesmg@arizona.edu
3 Institute of Astrophysics of Andalucía, Glorieta de la Astronomía s/n, SE-18008 Granada, Spain
4 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, People’s Republic of China; jwang_astro@pku.edu.cn

Received 2021 April 5; revised 2021 May 20; accepted 2021 May 26; published 2021 September 7

Abstract

We quantitatively investigate the dependence of central galaxy HI mass (M_{HI}) on the stellar mass (M_*), halo mass (M_h), star formation rate (SFR), and central stellar surface density within 1 kpc (Σ_{1}), taking advantage of the HI spectra stacking technique using both the Arecibo Fast Legacy ALFA Survey and the Sloan Digital Sky Survey. We find that the shapes of M_{HI}-M_* and M_{HI}-M_h relations are remarkably similar for both star-forming and quenched galaxies, with massive quenched galaxies having constantly lower HI masses of around 0.6 dex. This similarity strongly suggests that neither halo mass nor stellar mass is the direct cause of quenching, but rather the depletion of the HI reservoir. While the HI reservoir for low-mass galaxies of M_* < 10^{10.5} M_☉ strongly increases with M_*, more massive galaxies show no significant dependence of M_{HI} with M_h, indicating that the main effect of halo is to determine the smooth cold gas accretion. We find that the star formation and quenching of central galaxies are directly regulated by the available HI reservoir, with an average relation of SFR ∝ M_{HI}^{0.75}/M_*^{0.40}, implying a quasi-steady state of star formation. We further confirm that galaxies are depleted of their HI reservoir once they drop off the star formation main sequence and there is a very tight and consistent correlation between M_{HI} and Σ_{1} in this phase, with M_{HI} ∝ Σ_{1}^{-2}. This result is consistent with the compaction-triggered quenching scenario, with galaxies going through three evolutionary phases of cold gas accretion, compaction and post-compaction, and quenching.

Unified Astronomy Thesaurus concepts: H I line emission (690); Galaxy quenching (2040); Galaxy evolution (594); Quenched galaxies (2016); Circumgalactic medium (1879); Galaxy dark matter halos (1880); Star formation (1569); Interstellar atomic gas (833)

1. Introduction

Galaxies in the local universe are known to consist of two broad categories of early and late types, and their color and star formation rate (SFR) distributions are found to be bimodal (see, e.g., Baldry et al. 2004; Balogh et al. 2004; Brinchmann et al. 2004). Galaxies are then naturally separated into the red/blue or the star-forming/quenched populations. One of the fundamental questions in modern extragalactic astronomy is how galaxies evolve from the bluer and younger population to that of the redder and older one, i.e., how galaxies quench their star formation.

Various physical mechanisms have been proposed to understand this process, such as the virial shock heating (e.g., Rees & Ostriker 1977; Silk 1977; White & Rees 1978; Birnboim & Dekel 2003; Kereš et al. 2005), stellar feedback (e.g., Dekel & Silk 1986; Murray et al. 2005), active galactic nucleus (AGN) feedback (e.g., Fabian 2012, and references therein), violent disk instabilities (e.g., Gammie 2001; Dekel et al. 2009; Cacciato et al. 2012), and morphological quenching (Martig et al. 2009). As discussed in the review of Man & Belli (2018), most of these mechanisms are trying to explain the cooling, inflow, and outflow of the gas.

Most of the cold gas in the universe is in the form of neutral hydrogen. While the molecular neutral hydrogen (H_2) is thought to serve as the fuel of star formation, the atomic neutral hydrogen (HI) is indirectly connected to star formation through its conversion to H_2 (see, e.g., Bigiel et al. 2008, 2010; Krumholz 2012). However, HI in the local universe is more abundant and much easier to observe with the 21 cm hyperfine emission line than H_2. It is therefore of great interest to explore the HI reservoir through large 21 cm surveys, e.g., the HI Parkes All-Sky Survey (Barnes et al. 2001; Meyer et al. 2004), the Arecibo Fast Legacy ALFA Survey (ALFALFA; Giovanelli et al. 2005; Haynes et al. 2011, 2018), and the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010, 2018). Along with the surveys measuring the H_2 content through the CO emission lines (e.g., the COLD GASS survey; Saintonge et al. 2011, 2017), we will be able to answer whether the galaxy quenching is due to the lack of HI or the low conversion efficiency from HI to H_2.

In order to explore the role of HI in the galaxy quenching, it is necessary to measure the HI masses for both the star-forming galaxies (SFGs) and quenched galaxies (QGs). However, individual source detection in blind HI surveys like ALFALFA depends on the instrument flux limit (Haynes et al. 2011). Since QGs typically have low HI fluxes, their detection rate in ALFALFA is therefore much smaller than that of the SFGs (Huang et al. 2012). Although the HI detection rate still encodes useful information about the HI reservoir in different populations (see, e.g., Catinella et al. 2013), accurate average HI masses can be directly measured by stacking all the HI signals for QGs and SFGs separated in bins of different properties.

Such an HI spectral stacking technique has been applied to measure the HI scaling relations with galaxy stellar mass, color, SFR, and stellar surface density (see, e.g., Verheijen et al. 2007;
Fabello et al. 2011; Geréb et al. 2015; Brown et al. 2015). Saintonge et al. (2016) stacked the GASS and COLD GASS galaxy samples over the SFR–$M_*$ plane. They found that both the HI and H$_2$ fractions decrease for SFGs when their stellar masses increase, while the star formation efficiency and HI-to-H$_2$ ratios remain roughly constant, indicating that the decrease of the cold gas reservoir is the main cause of the galaxy quenching. Brown et al. (2017) stacked the overlap regions between the Sloan Digital Sky Survey (SDSS) DR7 Main Galaxy Sample (Albareti et al. 2017) and the spring area of the ALFALFA 70% sample. They showed that the HI depletion in satellite galaxies depends more on the halo mass than local density.

Taking advantage of the completed ALFALFA 100% sample, Guo et al. (2020a) directly measured the total HI mass in halos ranging from $10^{11}$ to $10^{14} h^{-1} M_\odot$, by stacking the HI signals of entire groups from SDSS DR7. They found that the total halo HI gas depends on both the halo mass and halo richness, which confirms the finding of Guo et al. (2017) that the galaxy HI gas is closely related to the halo accretion history. They proposed that the measured HI reservoir is consistent with a three-phase scenario, i.e., smooth HI accretion in halos of $\log(M_{hi}/h^{-1}M_\odot) < 11.8$, reduction of HI supply in halos of 11.8 $< \log(M_{hi}/h^{-1}M_\odot) < 13$, and slow HI growth by (dry) mergers in more massive halos.

In observation, phenomenological classifications of galaxy quenching mechanisms have been proposed to separate the internal and external causes, e.g., the mass quenching and environment quenching (or halo quenching; Peng et al. 2010). In this paper, we will explore the cause of galaxy quenching by extending the work of Guo et al. (2020a) and stacking the HI signals for SFGs and QGs in different stellar and halo mass bins, which naturally separates the contributions from mass and halo quenching. We also present an improved HI mass map in the SFR–$M_*$ plane, based on the work of Saintonge et al. (2016). We will only focus on the HI gas of the central galaxies, complementary to the study of Brown et al. (2017).

The structure of the paper is as follows. We describe the galaxy samples and stacking method in Section 2. We present the results in Sections 3 and 4. We summarize and discuss the results in Sections 5 and 6. Throughout the paper, the halo mass is in units of $h^{-1} M_\odot$, while the stellar and HI masses are in units of $M_\odot$. We assume a Hubble constant of $h = 0.7$.

2. Data and Method

2.1. HI and Optical Samples

We use the same galaxy samples as in Guo et al. (2020a), with the HI data from the spring sky of ALFALFA 100% complete catalog (Haynes et al. 2018; Jones et al. 2018), which encompasses most of the optical galaxy sample from SDSS DR7. We adopt the galaxy group catalog from Lim et al. (2017) for the identification of central and satellite galaxies, as well as the halo mass estimates, with the redshift range limited to 0.0025 $< z < 0.06$. We refer the readers to Guo et al. (2020a) for more details. The measurements of HI mass functions of this catalog have been presented in Jones et al. (2020). As a result, our final sample consists of 22,810 central galaxies in the HI spectral stacking. We note that this sample includes many isolated central galaxies in low-mass halos.

The $M_*$ and SFR measurements for the central galaxies are obtained from the GSWL-C2 catalog of Salim et al. (2018), which used state-of-the-art UV/optical spectral energy distribution fitting techniques. We note that for galaxies below the star formation main sequence (SFMS), with a low specific SFR (sSFR, defined as SFR/$M_*$), there are nonnegligible measurement errors, and their sSFR estimates can only be considered as upper limits (Salim et al. 2016), as these galaxies are truly quiescent. It does not affect our HI stacking for the overall populations of SFGs and QGs. However, when we stack the HI gas in the SFR–$M_*$ plane, we only focus on galaxies with log(sSFR/yr$^{-1}$) $> -12$. As will be shown in the following sections, our conclusions are not affected if we use a more conservative cutoff of log(sSFR/yr$^{-1}$) $> -11.5$ or even slightly higher sSFRs.

We show in Figure 1 the distribution of central galaxies from our sample in the SFR–$M_*$ plane. We fit a simple power-law relation to classify the SFGs and quenched central galaxies as follows (shown as the black line):

$$\log\text{SFR}_{\text{cut}} = 0.65 \log M_* - 7.25,$$

with the same power-law slope of 0.65 as that of Salim et al. (2007). As the SFMS tends to be flattened for the massive galaxies (e.g., Karim et al. 2011; Whitaker et al. 2012; Saintonge et al. 2016), we follow the method of Saintonge et al. (2016) by fitting a third-order polynomial (shown as the blue line) to the mean SFRs of the SFGs as

$$\log\text{SFR}_{\text{MS}} = -2.6121 x + 0.4605 x^2 - 0.0201 x^3,$$

where $x = \log M_*$. For galaxies in the range of 9 $< \log(M_*/M_\odot) < 10.5$, the SFMS can be well approximated by a power law of logSFR$_{\text{MS}} = 0.65 \log M_* - 6.65$, which is also very similar to that of Janowiecki et al. (2020) using galaxies...
from the low-mass extensions of GASS (xGASS; Catinella et al. 2018).

As shown in Figure 1, this cut ensures that it is wide enough to include the majority of the main-sequence galaxies in the star-forming population, as the typical SFGs are within ±0.3 dex of the SFMS. The limit of reliable SFR measurements with log(sSFR/yr⁻¹) = −12 is shown as the red line (Salim et al. 2016). There are still about 15% of the galaxies below this limit.

In addition, we also calculate the central stellar surface density within 1 kpc, Σ₁, for these central galaxies to compare with other studies following the method introduced in Fang et al. (2013). The central compactness Σ₁ is thought to be an important indicator of the galaxy quenching (Cheung et al. 2012; Fang et al. 2013; Zolotov et al. 2015; Barro et al. 2017; Wang et al. 2018, 2020). We use the surface brightness profiles in ugriz bands from SDSS DR7 and have corrected for Galactic extinction. The k-corrections are applied in each annulus using version 4.2 of the kcorrect code from Blanton & Roweis (2007). The corrected surface brightness profiles are then accumulated and interpolated smoothly to compute the total light within 1 kpc. Finally, the stellar mass surface density within 1 kpc is calculated using the total light within 1 kpc and i-band mass-to-light ratios calibrated by Fang et al. (2013).

2.2. Stacking Method

We follow the same stacking procedure as detailed in Guo et al. (2020a), based on the method outlined in Fabello et al. (2011). In Guo et al. (2020a), the angular size of the square stacking aperture used to extract the spectrum of each central galaxy from the ALFALFA data cubes was set as max(200 kpc/DA, 8′), where DA is the angular diameter distance of the galaxy. As that work was focused on the global properties of the groups, the aperture selection was not optimal and led to significant contributions to the HI flux from confusion, particularly for centrals in massive halos or with large distances. In this paper, we improve the method in Guo et al. (2020a) by using a smaller and adaptive aperture size for each central galaxy, as detailed below.

In order to create an adaptive aperture size, a scaling between stellar mass and HI diameter is needed, as the majority of the stacking targets are undetected in ALFALFA. To do this, we combine the Mₖ-M_HI relation of Huang et al. (2012) with the HI size–mass relation (Wang et al. 2016). Here we note that for a stellar-mass-selected sample of galaxies the average HI mass (and therefore HI diameter) is weakly dependent on the stellar mass (e.g., Catinella et al. 2010; Brown et al. 2015). We therefore have intentionally constructed our relation based on the HI-rich ALFALFA population in order to ensure that apertures are large enough. We approximate the Mₖ-M_HI relation from Huang et al. (2012) for galaxies with Mₖ > 10¹⁰.₅ M☉ as a straight line: log(M_HI/Mₖ) = 0.256 log(Mₖ/M⊙) + 7.263. We then add a 0.5 dex offset to this relation so that it lies above most of the scatter in the ALFALFA population, again to ensure that apertures are large enough for even galaxies with exceptionally rich gas content. Combining this with the Wang et al. (2016) size–mass relation gives the final relation that we use to set our aperture widths: log(D aperture/kpc) = 0.130 log(Mₖ/Mₖ) + 0.635.

We note that due to the resolution of Arecibo (~3′/8 in L band with ALFA), we limit the minimum aperture size to 4′. In practice, the aperture sizes for the vast majority (almost 96%) of the centrals in our catalog are determined by this limit, and the relation above is only relevant for the centrals closer than ~100 Mpc. It should also be noted that all apertures were extracted by rounding up to the next integer number of arcmin, as an ALFALFA pixel is 1′ × 1′ and the extraction procedure does not allow partial pixels.

After all the extracted spectra in a particular stacking bin have been aligned in the rest frame and co-added, the spectrum is re-baselined following the same procedure as in Guo et al. (2020a). The HI mass of the centrals in the stack is then finally estimated by integrating all emission within ±300 km s⁻¹. We confirm from the stacked spectra that there is not much emission outside this velocity range for our results in this paper, as shown similarly in Figure B2 of Guo et al. (2020a).

The statistical uncertainties in stacked HI masses were estimated as σrms/√Nchan, that is, the rms noise in the stacked spectrum divided by the square root of the number of channels summed over. We found that the bootstrap uncertainty estimates from Guo et al. (2020a) were well correlated with the statistical uncertainty estimates, with the bootstrap errors larger by a factor of around 1.5. For simplicity, we therefore multiply the statistical uncertainty estimates calculated here by 1.5 in order to mimic the bootstrap uncertainties estimated previously.

Following the prescriptions for estimating the contribution of confused HI emission to a stack from Jones et al. (2016), we estimate that at the highest redshift (z = 0.06), where confusion is most severe, the expected HI mass from confused emission in a stack of SFGs would be log(M_HI/Mₖ) ~ 8.8, which is negligible compared to the expected HI masses for massive galaxies observed at these large distances. As confirmed by a careful investigation of stacking systematics using mock galaxy catalogs in Chauhan et al. (2021), the choices of aperture size and velocity width in a reasonable range do not significantly affect the stacked HI mass measurements.

3. HI Stacking in the Mₖ–M_HI Plane

3.1. Halo Mass Dependence

We show in the top panel of Figure 2 the average HI masses (M_HI) of central galaxies in halos of different masses, for both the star-forming (blue line) and quenched (orange line) populations. The measurement for all centrals is also shown as the black line. The most straightforward conclusion is that in all halo mass environments, QGs have much lower HI gas content than the SFGs. The HI–halo mass relation for all the centrals can be simply understood as the combination of SFGs and QGs, along with the quenched fractions at different halo masses.

For halos of Mₖ > 10¹² h⁻¹ M⊙, the HI masses in QGs have a roughly constant lower offset of 0.6 dex (i.e., about four times smaller) compared to those of the SFGs, shown as the blue dashed line in the bottom panel of Figure 2. At lower halo masses, the offset becomes larger. It is remarkable to note that the shapes of the central HI–halo mass relations for SFGs and QGs are quite similar. The HI mass is smoothly increasing with the halo mass at the low-mass end and becoming flat for halos of Mₖ > 10¹².₅ h⁻¹ M⊙. For example, the HI mass of SFGs increases by 1 dex from halos of 10¹¹ h⁻¹ Mₖ to that of 10¹².₅ h⁻¹ Mₖ, but there is almost no growth from 10¹².₅ to 10¹₄ h⁻¹ Mₖ. This implies that the smooth HI accretion is impeded in massive halos of Mₖ > 10¹².₅ h⁻¹ Mₖ, irrespective of the star
formation status of the central galaxies. It is potentially related to the effect of the virial shock heating in these massive halos. As suggested by hydrodynamical simulations (Birnboim & Dekel 2003; Kereš et al. 2005), gas falling into halos above a critical mass of around $10^{12} \, M_\odot$ will be shock-heated to the virial temperature, and the hot accretion mode will then dominate the growth of massive galaxies. This is consistent with our finding of the flat gradient of the HI–halo mass relation for the massive halos.

3.2. Joint Stellar and Halo Mass Dependence

We show in Figure 3 the HI stacking in different stellar and halo mass bins, with $8 < \log(M_*/M_\odot) < 11.5$ and $11 < \log(M_*/h^{-1}M_\odot) < 13.5$, and the bin sizes are both set as 0.25 dex. The same measurements of $(M_{HI}/M_*)$, $(M_{HI}/M_h)$ are shown in both the left and right panels of Figure 3. The left panel shows the HI–halo mass relation color-coded with $M_*$, and the right panel is the HI–stellar mass relation color-coded with $M_h$. The SFGs are represented by the filled circles with solid lines, while the QGs are displayed with open circles and dotted lines. Measurements for galaxies in the same stellar (halo) mass bins are connected with lines in the left (right) panel.

The measurements of HI–halo mass relations in Figure 2 are also shown as the black dotted lines for the SFGs and QGs in the left panel. By decomposing the contribution to the HI signals from galaxies with different stellar masses, we find that for galaxies with $M_*>10^{10.5} \, M_\odot$ the dependence of $M_{HI}$ on $M_*$ at a given stellar mass bin is very weak, which is the same for both SFGs and QGs. The halo mass dependence seen in Figure 2 for halos of $11.8 < \log(M_h/h^{-1}M_\odot) < 13.5$ just reflects the dependence on galaxy stellar mass. For galaxies with $M_*<10^{10.5} \, M_\odot$, the halo mass dependence is much stronger than that of the stellar mass.

It is clear that one effect of halo (or environment) quenching is to impede the accretion of cold gas, thus ensuring a long-term quenched state (Dekel & Burkert 2014). It takes effect for galaxies with a lower mass limit of $10^{10.5} \, M_\odot$, which roughly corresponds to a halo mass around $M_h\sim10^{11.8} \, h^{-1} \, M_\odot$ (e.g., Moster et al. 2010; Yang et al. 2012). However, the roughly constant offset between the HI masses of SFGs and QGs in all halo masses indicates that the halo mass is not the direct cause of quenching.

From the HI–stellar mass relation in the right panel of Figure 3, we find that SFGs tend to form a tight HI main sequence (HIMS), which is fitted with a straight line as follows (shown as the black dashed line):

$$\log M_{HI,MS} = 0.42 \log M_* + 5.35.$$  (3)

It is similar to the definition in Janowiecki et al. (2020), with a slightly shallower slope. We note that for low-mass halos, $M_{HI}$ tends to slightly decrease with stellar mass before arriving at the HIMS. The resulting HI fraction, $f_{HI} = M_{HI}/M_*$, on the HIMS would scale as $f_{HI} \sim 3 \times 10^{-2}$, i.e., the HI fraction would decrease with increasing $M_*$ even for SFGs. It is consistent with the result of Saintonge et al. (2016), with the flattening of the SFMS due to the overall reduction of the gas reservoirs.

For QGs, the behavior is still very similar. At a given halo mass, there is a very weak, if not negligible, dependence of $M_{HI}$ on $M_*$ for $M_*<10^{10.5} \, M_\odot$. For more massive QGs, the $M_{HI}$–$M_*$ relation has a similar slope to the HIMS, i.e., the HI gas of QGs has the same relative growth rate $\langle M_{HI} \rangle / \langle H_{MS} \rangle$ as that of SFGs. This remarkable similarity of the HI–stellar mass relations for SFGs and QGs again confirms that the stellar mass is also not the direct cause of quenching.

Due to the tight correlation between central stellar and halo masses at the low-mass end (e.g., Moster et al. 2010; Yang et al. 2012), the average trend of halo mass dependence at the low-mass end can be reasonably reproduced when we combine the stellar mass dependence of $M_{HI} \propto M_*^{0.42}$ with an average stellar–halo mass relation. This is not affected by the algorithm of the halo mass assignment in the group finder. For example, we can adopt the independent stellar–halo mass relation from Moster et al. (2010) as

$$\langle M_* \rangle = 0.056 M_h \left[ \frac{M_h}{M_*} \right]^{1.07} \left[ \frac{M_h}{M_*} \right]^{0.61},$$  (4)

where $M_*=10^{11.9} \, M_\odot$. Therefore, given that $M_{HI} \propto M_*^{0.42}$, the HI–halo mass relation would scale as $M_{HI} \propto M_h^{0.87}$ and $M_{HI} \propto M_h^{0.16}$ at the low and high halo mass ends, respectively, consistent with our measurements. Despite the strong degeneracy between $M_*$ and $M_h$, as shown in the left panel of Figure 3, for galaxies with $M_*<10^{10.5} \, M_\odot$, $M_{HI}$ is clearly dominated by the halo and stellar mass dependence, respectively.

3.3. Global Star Formation Law

As the HI gas provides the reservoir for star formation, we investigate the corresponding dependence of SFR on $M_*$ and $M_h$.

Figure 2. Top: measurements of HI masses for central galaxies in halos of different masses. We show the measurements for all central galaxies (black), SFGs (blue), and QGs (orange). Bottom: offsets between the HI masses from the SFGs and QGs, i.e., $\Delta \log M_{HI} = \log M_{HI, SFG} - \log M_{HI, QG}$. The measurements of HI masses at the low-mass end can be reasonably reproduced when we combine the stellar mass dependence of galaxies with a lower mass limit of $10^{10.5} \, M_\odot$. For more massive QGs, the $M_{HI}$–$M_*$ relation has a similar slope to the HIMS, i.e., the HI gas of QGs has the same relative growth rate $\langle M_{HI} \rangle / \langle H_{MS} \rangle$ as that of SFGs. This remarkable similarity of the HI–stellar mass relations for SFGs and QGs again confirms that the stellar mass is also not the direct cause of quenching.

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Mh in the left panel of Figure 4, which is similar to the right panel of Figure 3. We measure the mean SFR in the same M* and Mh bins as the Hi mass. The SFMS of Equation (2) is denoted as the dotted black line. We find that the trends of SFR with M* and Mh are very similar to those of MHI for both SFGs and QGs. As expected, most of the data points for SFGs lie on the SFMS, while there is similar halo mass dependence to that seen in the Hi mass at the low-mass end. The SFMS indeed tends to be flattened for log(M*/M⊙) > 10.6, similar to that of Saintonge et al. (2016). We note that the gap between SFRs of SFGs and QGs is larger than that of the Hi mass.

We show, in the right panel of Figure 4, the relation between SFR and MHI for galaxies with different M* (color-coded) and different Mh. Galaxies in more massive halos are shown with larger symbols. The filled and open circles are for the SFGs and QGs, respectively. The black arrow indicates the example of SFR ∝ MHI2 for galaxies with M* ∼ 1011 M⊙. For clarity, we only show the errors on MHI.
the Kennicutt–Schmidt law with $\alpha = 1.4$ (Schmidt 1959; Kennicutt 1998), which is, however, based on the relation between SFR surface density and total cold gas surface density.

The QGs with $M_\bullet < 10^{9.5} M_\odot$ still lie close to the bottom tail of the power-law relation, as these galaxies are still not far from the SFMS, likely related to the selection effect when we get close to the detection limit of the SFR measurements. As will be discussed in the following sections, these galaxies are likely not fully quenched and would possibly return back to the star-forming population in their later evolution, accompanying the cold gas accretion during the halo growth. For more massive galaxies, their SFR–$M_\bullet$ relation can still be reasonably fitted with the same power-law index of $\alpha = 1.547$, shown as the black dotted line in the right panel of Figure 4. This indicates that even for QGs, the SFR is still closely related to the available HI mass, but the star formation efficiency $\text{SFE} = \text{SFR}/M_{\text{HI}}$ is significantly reduced.

It is generally conceived that the SFR is more correlated with the molecular hydrogen $H_2$ than HI, with $\Sigma_{\text{SFR}} \sim \Sigma_{\text{HI}}$ (e.g., Bigiel et al. 2008; Leroy et al. 2008), where the SFR and $M_{\text{HI}}$ are expressed in surface densities. It makes $M_{\text{HI}}$ a poor indicator of SFR, which seems to contradict with our results above. However, it is simply because the variation of SFR in the relation $\text{SFR} \propto M_{\text{HI}}^{1.547}$ is mainly caused by the change of stellar mass, rather than the star formation status. If we compare the SFR–$M_{\text{HI}}$ relations for galaxies with the same stellar mass, e.g., $M_* \sim 10^{11} M_\odot$, the change of SFR from SFGs to QGs would roughly scale as $\text{SFR} \propto M_{\text{HI}}^{3.4}$ (shown as the black arrow in the right panel of Figure 4), in very good agreement with Bigiel et al. (2008). It can also be understood from the global relation among the three physical parameters of SFR, $M_{\text{HI}}$, and $M_*$, as follows.

According to our measurements, we assume the following power-law scaling relation:

$$\log \text{SFR} = \alpha \log M_{\text{HI}} + \beta \log M_\bullet + \gamma,$$

where $\gamma$ is a constant coefficient. We can estimate $\alpha$ and $\beta$ from Figure 4. As shown in the left panel, at the massive end galaxies with the same stellar mass have a roughly constant offset of $\Delta \log \text{SFR} \sim 1.6$ from SFGs to QGs, and the corresponding HI mass changes by $\Delta \log M_{\text{HI}} \sim 0.6$ as in Figure 2, which means that $\alpha \sim 2.7$. In the right panel, at a given $M_{\text{HI}}$, the vertical offset between the blue dashed and black dotted lines is $\Delta \log \text{SFR} = -0.65$, while the stellar mass offset is around $\Delta \log M_\bullet \sim 1.25$, so $\beta \sim -0.52$. Therefore, we have $\text{SFR} \propto M_{\text{HI}}^{2.7}/M_*^{0.52}$, consistent with our rough estimate before. At a given $M_{\text{HI}}$, more massive galaxies would actually have lower SFRs, due to the reduction in gas fraction. This indicates that the SFR is determined by a global star formation law that depends on both the HI reservoir and the stellar mass.

### 3.4. Atomic Gas Depletion Time

We define the atomic gas depletion time as, $t_{\text{dep}} = M_{\text{HI}}/\text{SFR}$, which is the timescale for the galaxy to consume all the HI gas with the current SFR. We show in Figure 5 the dependence of $t_{\text{dep}}$ on $M_\bullet$ and $M_*$ in the same format as in Figure 3. The SFGs have much smaller gas depletion time than those of the QGs, and the dependence on $M_\bullet$ and $M_*$ is very weak for massive galaxies with $M_* > 10^{10.5} M_\odot$. Saintonge et al. (2017) found an average HI gas depletion time of $\log(t_{\text{dep}}/\text{Gyr})$ around $0.65 \pm 0.44$ for galaxies in the SFMS using xGASS, which is consistent with our measurements.

The weak dependence on $M_\bullet$ and $M_*$ is expected, as we find $\text{SFR} \propto M_{\text{HI}}^{1.5}$ for galaxies on the SFMS, which means that $t_{\text{dep}} \propto M_{\text{HI}}^{0.5} \propto M_*^{-0.21}$. The increase of $t_{\text{dep}}$ toward the low-mass end (also seen in Saintonge et al. 2017) is due to the different slope of the SFR–$M_\bullet$ relation at a given halo mass bin compared to the SFMS (left panel of Figure 4).

For QGs, $t_{\text{dep}}$ is typically much larger than 10 Gyr, indicating that the HI gas is not actively involved in the star formation. However, the scaling relation as in Equation (5) is still valid, as the HI gas still provides the reservoir for star formation, though with very low efficiency. It may seem that the HI reservoir is already large enough compared to the SFR of QGs, and the quenching appears to be caused by the bottleneck of the conversion from HI to $H_2$. However, as we show in Equation (5), the star formation efficiency would be significantly decreased with the decreasing of the HI reservoir when $\alpha$ is larger than unity. There is positive dependence on $M_\bullet$ and
negative dependence on $M_*$ for low-mass QGs below $10^{10.5} M_\odot$, due to the similar behavior of HI mass to that in Figure 3.

As will be further confirmed in the next section, both the SFGs and QGs follow the very similar global star formation law of Equation (5). This implies that galaxies at low redshifts tend to live in a quasi-steady state in which the star formation is directly regulated through the fueling and depletion of the cold gas (Bouché et al. 2010; Lilly et al. 2013; Dekel & Mandelker 2014).

4. HI Stacking in the SFR–$M_*$ Plane

We show in the above sections the HI stacking in different stellar and halo mass bins, for the SFGs and QGs. To fully investigate the smooth evolution of HI gas in the transition from SFGs to QGs, we show in this section the stacking in bins of SFR and $M_*$, with $8 < \log (M_*/M_\odot) < 11.5$ and $-3.5 < \log \text{SFR} < 1.5$, and the bin sizes are 0.25 and 0.5 dex, respectively.

4.1. Dependence on SFR and $M_*$

We show in the left panel of Figure 6 the stacked HI signals as a function of SFR and $M_*$. For fair comparisons with the literature, we show here the HI gas fraction defined as $f_{\text{HI}} = M_{\text{HI}}/M_*$, while the original stacking is still made for $M_{\text{HI}}$ rather than $f_{\text{HI}}$. The lines of SFMS, the demarcation line between SFGs and QGs, and the limit of $\log (\text{sSFR}/\text{yr}^{-1}) = -12$ are also shown, the same as in Figure 1. We note that the stacking measurements for galaxies with $\log (\text{sSFR}/\text{yr}^{-1}) < -12$ are less reliable owing to the large uncertainties of SFR. But we still show them in the figure for consistency.

There are two apparent trends in this figure. For SFGs, $f_{\text{HI}}$ is decreasing with increasing $M_*$ along the main sequence, consistent with the finding of Saintonge et al. (2016). For QGs, most of their HI fractions are below 0.1, and $f_{\text{HI}}$ is continually smaller when the galaxies are farther away from the SFMS. It further confirms our previous conclusion that galaxy quenching is directly caused by the decreasing of the HI gas content. This is also seen in the right panel of Figure 6, where we show the dependence of $f_{\text{HI}}$ on sSFR for different stellar masses. The filled and open circles are for SFGs and QGs, respectively. The Measurements are only reliable for galaxies with $\log (\text{sSFR}/\text{yr}^{-1}) > -12$.

As will be further confirmed in the next section, both the SFGs and QGs follow the very similar star formation law of Equation (5). This implies that galaxies at low redshifts tend to live in a quasi-steady state in which the star formation is directly regulated through the fueling and depletion of the cold gas (Bouché et al. 2010; Lilly et al. 2013; Dekel & Mandelker 2014).

The other important systematic trend is that the slope of $\log f_{\text{HI}}/\log \text{sSFR}$ at a given $M_*$ is consistent with our previous estimate of a scaling relation of $\text{SFR} \propto M_{\text{HI}}$, i.e., $\Delta \log \text{SFR} = \log (\text{SFR}/\text{SFR}_{\text{MS}})$ and $\Delta \log M_{\text{HI}} = \log (M_{\text{HI}}/M_{\text{HI,MS}})$. As shown in Figure 7, the galaxies drop below the SFMS when their HI masses decrease from the HIMS. While the SFGs have the apparent trend of increasing slope of $\alpha$ with $M_*$, they drop below the SFMS at almost the same rate with $\alpha \sim 1.5$, forming a very tight relation between SFR and $M_{\text{HI}}$ irrespective of the stellar mass. For massive SFGs, the significantly increased slope $\alpha$ is likely caused by two reasons.
First, those most massive galaxies with high SFRs tend to efficiently consume the HI reservoir and form the molecular gas (Catinella et al. 2018). The other is that the HI accretion in these systems is slowed down, as manifested by the significantly decreased $f_{\text{H}I}$. These two effects make the slope between SFR and $M_{\text{HI}}$ much flatter, consistent with the results of Jaskot et al. (2015). This overall trend further confirms our previous conclusion that the central galaxies are quenched by the overall reduction of the HI gas reservoir by an amount of $\sim 0.6$–1.0 dex.

Taking advantage of the stacking method, we are able to quantitatively trace the change of the relation between SFR and $M_{\text{HI}}$ above and below the SFMS, improving the similar investigation shown in Janowiecki et al. (2020) using the xGASS sample (their Figure 5). However, our measurements for $\Delta \log \text{SFR} < -1$ suffer from large uncertainties of the SFR measurements, making it hard to predict the slope $\alpha$ for these truly quiescent galaxies.

### 4.2. Connection to the Central Stellar Surface Density

Increasing evidence of the structural differences between the SFGs and QGs suggests that the formation of a dense core (represented by the measurement of $\Sigma_1$) is the prerequisite for galaxy quenching (see, e.g., Kauffmann et al. 2003; Schiminovich et al. 2007; Barro et al. 2013; Fang et al. 2013; van Dokkum et al. 2014). We show in Figure 8 the distribution of $\Sigma_1$ as a function of $M_*$ in our sample. We also fit the average of $\Sigma_1$ on the main sequence ($\Sigma_{1,\text{MS}}$) using only the SFGs as

$$\log \Sigma_{1,\text{MS}} = 0.810 \log M_* + 0.607,$$

which is shown as the solid line in the figure. The ridgeline of QGs from Fang et al. (2013; $\log \Sigma_1 = 0.64 \log M_* + 2.73$) is displayed as the dotted line. More massive galaxies have significantly denser cores, and the QGs have even higher $\Sigma_1$ values. We focus on the measurements of $\Sigma_1$ for $M_* > 10^{8.5} M_\odot$ to ensure enough S/N.

We show in Figure 9 the dependence of $\Sigma_1$ on SFR and $M_{\text{HI}}$ in different stellar mass bins. All the measurements are scaled by their values on the main sequence, with the additional definition of $\Delta \Sigma_1 \equiv \log (\Sigma_1/\Sigma_{1,\text{MS}})$. There are strong correlations among these measurements. We find a similar trend between $\Delta \Sigma_1$ and $\Delta \log \text{SFR}$ to that in the literature. The SFGs evolve along with the $\Sigma_{1,\text{MS}}$ ($\Delta \Sigma_1 \sim 0$) when their SFRs gradually fall on the main sequence. As the galaxies leave the SFMS with $\Delta \log \text{SFR} < 0$, $\Delta \Sigma_1$ also increases until a plateau of $\Delta \Sigma_1 \sim 0.4$, which is the so-called compaction process (Dekel & Burkert 2014). The sharp decrease of SFR, with $\Delta \Sigma_1$ remaining roughly constant, identifies the final state of quenching. For our definition of QGs with $\Delta \log \text{SFR} \lesssim -0.6$ as in Figure 1, the quenching happens along with the compaction.

The $\Delta \Sigma_1 - \Delta \log M_{\text{HI}}$ relation appears quite different for the SFGs compared to that of the QGs, as the majority of the SFGs are located around $\Delta \Sigma_1 \sim 0$ and $\Delta \log M_{\text{HI}} \sim 0$. This indicates that the HI gas increases consistently with central core density. As we have seen in Figure 7, most massive SFGs lie very close to the HIMS. Similar behavior is seen for $\Sigma_1$, i.e., as galaxies evolve along the $\Sigma_1$ main sequence, their HI masses also follow the HIMS closely. The trend of $\Delta \Sigma_1$ with $\Delta \log M_{\text{HI}}$ for QGs shows very similar slopes for different stellar masses, with $\Sigma_1 \propto M_{\text{HI}}^{-0.5}$.

We note that the scale lengths of these three parameters are quite different, ranging from 1 kpc to a few tens of kpc for the HI disks. The tight correlations among their values imply that the same physical mechanisms are regulating their joint evolution. Our results are in good agreement with the compaction evolutionary scenario suggested in theory and
simulations (e.g., Dekel & Burkert 2014; Zolotov et al. 2015; Tacchella et al. 2016). The dense SFGs (also called blue nuggets) could be formed from the wet (gas-rich) compaction induced by intense cold gas inflow due to dissipative processes such as mergers and violent disk instability, which is consistent with our finding in the right panel of Figure 9. The onset of galaxy quenching is typically associated with the maximum gas compactness in hydrodynamical simulations (e.g., Zolotov et al. 2015). We find that as the compaction starts, the HI reservoir is also decreased along with $\Sigma_1$, potentially due to the gas consumption, outflows, and stellar or AGN feedback. In this model, the process of galaxies moving toward a compaction is relatively gradual, and the drop of central gas density and SFR following the maximum of compaction is relatively quick. The increased $\Sigma_1$ away from the HIMS is consistent with such a scenario.

We show in Figure 10 the dependence of $M_{\text{HI}}$ on $\Sigma_1$ for galaxies in different $M_*$ and SFR bins. Galaxies in the same $M_*$ bins are connected with dashed lines of different colors. The positions of the main sequences of $M_{\text{HI}}$ and $\Sigma_1$ at different stellar masses are shown as the solid blue line. As expected, there is a tight relation between $M_{\text{HI}}$ and $\Sigma_1$ for the SFGs, due to their strong dependence on $M_*$. It is interesting that the quenching routes for galaxies with different $M_*$ are all perpendicular to the main sequence, with a slope of $M_{\text{HI}} \propto \Sigma_1^{-2}$. The different $\Sigma_1$ values for QGs suggest that there is not a fixed quenching threshold in $\Sigma_1$ and it increases with stellar mass (Barro et al. 2017).

While we do not have accurate measurements for galaxies with $\log(\text{sSFR}/\text{yr}^{-1}) < -12$, it is not clear whether they would form another tight quiescent sequence. But as predicted from the hydrodynamical simulations (Zolotov et al. 2015), $\Sigma_1$ will remain roughly constant after the quenched cores are formed (the so-called red nugget phase). The HI mass would possibly further decrease with the SFR until sSFR drops to an extremely low value, where a very minor amount of the HI reservoir is involved in the star formation activity. To guide the eye, we show the red solid line as assuming $\Delta \log M_{\text{HI}} = -0.7$ (corresponding to $\Delta \log \text{SFR} \sim -1.2$) and the $\Sigma_1$ ridgeline of Fang et al. (2013). It roughly marks the positions where the quenched cores are formed. The trend of quenching is seen in some stellar mass bins in Figure 10, with the sharp drop of $M_{\text{HI}}$ at roughly constant $\Sigma_1$ in the QGs.

4.3. Dependence on Morphology

The structural evolution from the SFGs to QGs usually accompanies the change of morphology from disk-dominated to bulge-dominated systems. The morphological quenching has been proposed in Martig et al. (2009), emphasizing the effect of the bulge in stabilizing the gas disk and preventing the cold gas from collapsing and forming stars. While such a mechanism could be contributing in some bulge-dominated galaxies, we
find that the major reason for the central quenching is the depletion of the HI reservoir, which also increases the Toomre instability parameter $Q$ (Toomre 1964) in stabilizing the disk by decreasing the cold gas surface density (Dekel & Burkert 2014).

Galaxies can be generally separated into four categories, according to the morphology (disk or bulge dominated) and the star formation status (star-forming or quenched). While star-forming disk galaxies and quenched spheroidal galaxies are typically observed, the star-forming bulge-dominated and quenched disk galaxies are much less abundant. The quenched disk galaxies or red spiral galaxies have raised lots of interest recently (e.g., Masters et al. 2010; Cortese 2012; Tojeiro et al. 2013; Schawinski et al. 2014; Bremer et al. 2018; Hao et al. 2019; Guo et al. 2020b; Luo et al. 2020b; Mahajan et al. 2020; Zhou et al. 2021).

Quantifying the HI reservoir for these quenched disk galaxies is a key step toward understanding their formation history. However, whether these galaxies have enough gas reservoir to support their star formation is still under debate. Zhang et al. (2019) found a surprisingly large amount of cold HI reservoir for nearly all massive quenched disk central galaxies ($10 < \log(M_\text{HI}/M_\odot) < 11$), comparable to that expected for their star-forming counterparts. Cortese et al. (2020) argued that the underestimation of the aperture-corrected SFR from the MPA/JHU SDSS DR7 catalog, as used in Zhang et al. (2019), will wrongly classify a significant fraction of SFGs as quenched.

To complement our understanding of the quenching processes along with the change of morphology, we also investigate the HI reservoir for the star-forming/quenched disk- and bulge-dominated central galaxies. We stack the HI signals for the four categories of galaxies in our sample. We adopt two methods of morphology classifications. One is the 2D photometric two-component bulge/disk decomposition of Meert et al. (2016) for the SDSS DR7 galaxies. The catalog galaxies flagged as low quality are discarded. We use 0.5 as the cut for the bulge-to-total light ratio ($B/T$) to divide the bulge- and disk-dominated galaxies. The other is the concentration index (defined as $R_{90}/R_{50}$ of the Petrosian flux) from the SDSS pipeline, which does not suffer from the uncertainties of the disk/bulge decomposition. As shown in Luo et al. (2020a), the cut of $R_{90}/R_{50} = 2.5$ provides a reasonable demarcation line for the classic and pseudo-bulges, as well as no-bulge and elliptical galaxies. We adopt the same cut of $R_{90}/R_{50}$ for our sample. A similar cut of $R_{90}/R_{50} = 2.6$ was used in the HI stacking of Fabello et al. (2011).

To ensure enough S/N, we only stack the HI signals for the stellar mass range of $10 < \log(M_\odot/M_\odot) < 11.5$ for the four populations. We show in the top panels of Figure 11 the $M_{\text{HI}}$ measurements for the morphology classifications of Meert et al. (2016) (left panel) and $R_{90}/R_{50}$ (right panel). The filled symbols with solid blue lines are for the SFGs, and the open symbols with red dashed lines are for the QGs. The disk- and bulge-dominated galaxies are displayed with triangles and circles, respectively. The black dotted lines represent the HIMS as in Figure 3.

We note that the results from the two different morphology classifications are in very good agreement with each other, with only minor differences in the quenched disk galaxies. For SFGs, there is only weak dependence of $M_{\text{HI}}$ on morphology, with bulge-dominated galaxies having a slightly smaller HI reservoir. The fact that the bulge- and disk-dominated galaxies lie close to each other is consistent with the tight HIMS seen in the whole sample. It also implies that the morphological transition during the star-forming phase, e.g., through compaction, does not significantly affect the overall HI reservoir. This is in very good agreement with the results from Cook et al. (2019) using an independent bulge/disk decomposition method for the xGASS sample (see also Cook et al. 2020).

For QGs, the differences in $M_{\text{HI}}$ between disk- and bulge-dominated galaxies increase with $M_\star$, with the more massive quenched disk galaxies approaching their star-forming counterparts. As will be shown below, the HI masses conform to their SFRs, with quenched disk galaxies having slightly higher SFRs. However, for the mass range studied in Zhang et al. (2019) ($10 < \log(M_\odot/M_\odot) < 11$), the quenched disk galaxies have on average $0.35-0.5$ dex lower HI masses compared to the star-forming disks, depending on the morphology classification methods. Even for more massive quenched disk galaxies, they have consistently lower HI fractions relative to the star-forming ones. This again suggests that central galaxies are quenched by the depletion of the HI reservoir, even for the disk galaxies.

But the large difference seen in the quenched disk and bulge galaxies is still intriguing. It is helpful to compare their distributions in the SFR–$M_{\text{HI}}$ and $M_{\text{HI}}$–$\Sigma_\text{SFR}$ diagrams as shown in the bottom panels of Figure 11, where the symbols are the same as in the top panels. We only show the results for the morphology classification of Meert et al. (2016). The results of using $R_{90}/R_{50}$ are quite similar. The blue dashed and black dotted lines in the left panel are the power-law relations of $\text{SFR} \propto M_{\text{HI}}^{1.547}$ for the SFGs and QGs, respectively, as also shown in the right panel of Figure 4.

We find that there is no significant difference between the global star formation scaling relations for the disk- and bulge-dominated galaxies in the star-forming and quenched populations. This means that their HI masses are consistent with their observed SFRs and the global star formation law of Equation (5) applies to both the disk- and bulge-dominated galaxies.

We note that the quenched disk galaxies all have higher $\Sigma_\text{S}^{*}$ than star-forming disk and bulge galaxies with the same $M_\star$. This indicates that these quenched disk galaxies have already undergone the compaction processes, with a strong central bulge. There is no substantial difference in the HI mass for the quenched disk and bulge galaxies with $M_\star < 10^{11} M_\odot$. As also found in a detailed study of Guo et al. (2020b), the quenched disk galaxies are very similar to the quenched bulges in age, metallicity, and halo environment, indicating a very similar formation scenario (see also Zhou et al. 2021). Future HI observations for larger samples would provide more insights into their formation scenario.

### 4.4. HI Scaling Relations

The HI scaling relations have been intensively studied in the literature to understand the connection between the cold gas and other galaxy properties (see, e.g., Zhang et al. 2009; Catinella et al. 2010, 2018; Fabello et al. 2011; Li et al. 2012; Brown et al. 2015; Wang et al. 2015, 2016). Although we are stacking in the 2D plane of SFR–$M_\star$, we can still compare our results with previous scaling relations of the HI fraction by summing our measurements of $M_{\text{HI}}$($M_\star$, SFR) in one dimension weighted by the corresponding number of galaxies in each bin.
We show in Figure 12 the comparisons of our measurements with literature for the $f_{\text{HI}}$–$M_*$ (left panel) and $f_{\text{HI}}$–sSFR relations (right panel). In the left panel, all the measurements shown are made with the HI stacking technique for the ALFALFA samples at different completion stages, including the studies of Fabello et al. (2011), Brown et al. (2015), and Brown et al. (2017). We note that the former two studies used all galaxies in the stacking, while the last one only stacked the satellite galaxies selected from a similar group catalog of Yang et al. (2007). Our measurements are in very good agreement with these studies, despite the fact that we are only using the central galaxies. With the larger volume of the ALFALFA 100% sample, we are now able to extend this relation to the lower stellar masses of $M_* \sim 10^8 M_\odot$.

This comparison shows that the average scaling relations of $f_{\text{HI}}$–$M_*$ for central and satellite galaxies are very similar, except that the satellite galaxies have slightly smaller gas fractions at the massive end. However, as shown in Brown et al. (2017), $f_{\text{HI}}$ of the satellite galaxies strongly depends on the hosting halo mass, with satellite galaxies in massive halos suffering from severe cold gas depletion (see also Stevens et al. 2019). It is different from what we find in Figure 3 for central galaxies. The HI fraction of central galaxies of $M_* < 10^{10.5} M_\odot$ will increase with halo mass, while $f_{\text{HI}}$ for more massive centrals show no strong dependence on the halo mass.

We compare our measurements of $f_{\text{HI}}$–sSFR in the right panel of Figure 12 with the individual HI detection from the xGASS sample (gray circles). The weighted averages of xGASS galaxies in Catinella et al. (2018) are also shown as
the black stars with dotted line. Our measurements are shown as circles with solid lines as in the right panel of Figure 6, and the filled pink circles with dotted line are our averaged measurements of different stellar mass bins, where we extend our measurements to a lower limit of \( \log(\text{sSFR/yr}^{-1}) > -13 \). The overall agreement with the xGASS sample is quite good, while the individual observations have larger scatters. Thanks to the much larger sample size and the HI stacking technique, we are able to reconstruct the clear trends with the stellar mass. The smaller scatters of \( f_{\text{HI}} \) for QGs are clear evidence of the HI reduction happening in galaxies of different \( M_\ast \).

Using stacked HI data of GASS galaxies, Saintonge et al. (2016) found a three-dimensional scaling relation of \( \log(f_{\text{HI}}) = 0.588 \log \text{ SFR} - 0.902 \log M_\ast + 8.57 \), which naturally explains the strong dependence of \( f_{\text{HI}} \) on \( M_\ast \) for SFGs, as shown in the right panel of Figure 12. Following the same practice, we fit Equation (5) using all our stacked data with \( \log(\text{sSFR/yr}^{-1}) > -12 \) (59 data points weighted by the number of galaxies in each stacking), and we find a scaling relation of

\[
\log f_{\text{HI}} = 0.363 \log \text{ SFR} - 0.854 \log M_\ast + 8.159, \tag{7}
\]

which would translate to \( \text{SFR} \propto M_{\text{HI}}^{2.75}/M_\ast^{0.40} \), in good agreement with our estimate in Section 3.3. However, the scatters of this relation are significantly larger in the QGs. This is due to the fact that the slope between \( f_{\text{HI}} \) and sSFR is changing as galaxies quench, as clearly seen in Figure 12. As the sSFR decreases, the galaxy HI content is less correlated with the star formation activity, as also seen in Figure 7.

Therefore, to find a reasonable scaling relation between the three parameters of \( f_{\text{HI}}, \text{SFR}, \) and \( M_\ast \), we fit the relations for SFGs and QGs separately and obtain

\[
\log f_{\text{HI},\text{SFG}} = 0.265 \log \text{ SFR} - 0.794 \log M_\ast + 7.554 \tag{8}
\]
\[
\log f_{\text{HI},\text{QG}} = 0.453 \log \text{ SFR} - 0.624 \log M_\ast + 5.688. \tag{9}
\]

We note that the fitting is based on the stacked measurements, not the individual measurements as in ALFALFA and xGASS.

Therefore, it is not minimizing the variation of individual measurements on purpose, as done in Zhang et al. (2009) and Li et al. (2012).

It is noteworthy that we are still assuming a constant slope between \( f_{\text{HI}} \) and SFR for the SFGs, while we know that the slope is changing with \( M_\ast \) as shown in Figure 12. It should be regarded as an average slope for the SFGs. But the corresponding slope for the QGs does not seem to change much with \( M_\ast \). For galaxies at a given \( M_\ast \), it means that the global star formation law would vary from \( \text{SFR} \propto M_{\text{HI}}^{2.77} \) in the star-forming population to \( \text{SFR} \propto M_{\text{HI}}^{2.21} \) in the quenched population, consistent with our rough estimate of the transition slope as \( \text{SFR} \propto M_{\text{HI}}^{1.7} \) in Section 3.3. At a given sSFR, the relation would vary from \( f_{\text{HI}} \propto M_\ast^{-0.53} \) to \( f_{\text{HI}} \propto M_\ast^{-0.17} \), i.e., the scatters with \( M_\ast \) in the relation of \( f_{\text{HI}}-\text{sSFR} \) become much smaller in the QGs.

5. Star Formation, Quenching, and the Relation to HI Gas

Our HI stacking measurements establish the key role of HI in sustaining star formation in low-redshift galaxies. It weakens the necessity to invoke additional mechanisms that suppress or prevent the HI from streaming in, or from cooling and forming molecular gas and stars. As we show in Sections 3.3 and 4.4, the star formation and quenching of these low-redshift central galaxies are generally governed by the global star formation law of \( \text{SFR}(M_{\text{HI}}, M_\ast) \) as in Equation (5). We note that the scaling coefficients in this equation only vary slightly with the star formation status. With an average scaling relation of \( \text{SFR} \propto M_{\text{HI}}^{2.75}/M_\ast^{0.40} \), it emphasizes the important role of the HI reservoir in regulating the star formation.

These results are consistent with recent works based on the ALMaQUEST survey quantifying the role of molecular gas in regulating the star formation at low redshifts with resolved observations (Lin et al. 2019; Ellison et al. 2020a, 2020b, 2021a, 2021b), as well as the xCOLD-GASS survey using the global molecular measurements (Saintonge et al.)

**Figure 12.** Comparison of the HI scaling relations with the literature for the \( f_{\text{HI}}-M_\ast \) (left panel) and \( f_{\text{HI}}-\text{sSFR} \) relations (right panel). Left: our combined measurements (open circles) are compared with results from Fabello et al. (2011), Brown et al. (2015), and Brown et al. (2017), using different symbols. The error bars are omitted for clarity. Right: our measurements are shown as the circles with solid lines as in the right panel of Figure 6, with the filled pink circles with dotted line for our averaged measurements of different stellar mass bins. The individual HI detections from xGASS are shown as the open circles, which would translate to the much larger sample size and the HI stacking technique, as also seen in Figure 7. We note that the fitting is based on the stacked measurements, not the individual measurements as in ALFALFA and xGASS.
et al. 2016). They found that both the resolved and integral SFMS can be fully explained by a combination of the molecular abundance and the molecular star formation law. As HI needs to be converted to H₂ before forming stars, these results on the molecular gas perfectly fit and fill the physical gap between HI and SFR in our relations. The similar behaviors of our global SFR–HI scaling relation to the resolved ones (Bigiel et al. 2008, 2010), and to the SFR–molecular gas scaling relations, strongly infer the quasi-equilibrium baryonic flow where HI is smoothly converted to H₂ and then to stars (as also suggested in Saintonge et al. 2016) for the majority of SFGs at low redshifts. This suggests that the star formation and quenching are regulated by the availability of the HI reservoir, rather than the stellar or halo masses.

However, the detailed physics involved in changing the HI reservoir is hard to clearly identify in observation. It may include HI accretion, outflow, cooling of hot gas, compaction, mergers, and stellar and AGN feedback, as suggested in the literature (see Péroux & Howk 2020; Tacconi et al. 2020, for reviews). From HI measurements of the bulge- and disk-dominated galaxies, we do not find any strong evidence of morphological quenching, as both populations follow the same global star formation law as shown in Figure 11. There is no significant difference between the HI reservoir in bulge- and disk-dominated SFGs (Figure 11), as also found by Cook et al. (2019) and Cook et al. (2020). The massive quenched disks show relatively higher HI masses than those of the quenched bulges, due to their slightly higher SFRs.

The scaling relations of M_{HI} with Σ_1 and M_B seem to be consistent with the compaction-triggered quenching scenario presented in earlier studies (see, e.g., Dekel & Burkert 2014; Zolotov et al. 2015). But the increasing of Σ_1 is not equivalent to gradual dominance of the bulge. Due to the large scatters between Σ_1 and B/T, many disk galaxies can still have large values of Σ_1. As shown in Figure 11, the correlation between M_{HI} and Σ_1 persists in the disk galaxies, with a very similar slope and intercept to those of the bulge-dominated systems. The consistent slopes between M_{HI} and Σ_1 in the transition from SFMS to the quiescent phase at all stellar masses (Figure 10) further confirm that their correlation is not simply caused by the bulge growth.

However, we emphasize that the strong correlation between M_{HI} and Σ_1 does not necessarily indicate the causal relation of compaction and quenching, because other physical mechanisms may possibly cause the quenching, as well as the compaction. We only treat the compaction-triggered quenching as a potential candidate to summarize the scaling relations presented in this paper. The overall possible evolutionary picture of central galaxies can be reasonably described using the parameters of M_{HI}, Σ_1, and M_B, as illustrated in Figure 13. The galaxies starting from a low mass of around 10^8 M☉ will potentially undergo three phases before they finally quench, unified in the scenario as follows.

1. **Cold gas accretion.** As we see in Figure 3, galaxies with M_s ≈ 10^8 M☉ will increase their HI reservoir smoothly with increasing halo mass, in a rate around M_{HI} ∝ M_h. Their HI mass is less correlated with the stellar mass, when the gas inflow timescale becomes smaller than the star formation timescale (Tacchella et al. 2016). The dependence of M_{HI} on Σ_1 in this stage is mainly driven by the stellar mass growth, with the diffuse star-forming cores gradually becoming dense (Barro et al. 2017).

   The uniformity of Equation (5) throughout the sample space suggests that such an inflow almost always happens, possibly with a flow rate proportional to the abundance of HI. A positive correlation of Δ log SFR with the mass and averaged surface density of HI in the inner optical disks is found by Wang et al. (2020) using disk-dominated galaxies of xGASS.

2. **Compaction and post-compaction.** The increase of the gas surface density, as well as the slow bulge growth, will make the Toomre instability parameter Q quickly decrease, leading to the disk compaction. The compaction of gas naturally results in the significant increase of star formation because SFR is super-linearly correlated with HI mass density in the star-forming regions. The galaxy central core is built up, as can be seen from the slightly positive slope of the ∆Σ_1–Δ log M_{HI} relation when Δ log M_{HI} > 0 (Figure 9). We do not measure the HI surface densities here, but Wang et al. (2020) showed that for at least the disk-dominated galaxies the averaged HI surface density increases with ∆Σ_1 at a given Δ log SFR.

   The end of compaction leads to the decrease of HI mass due to the quick depletion from star formation, outflow, and feedback mechanisms. The galaxy thus moves to the phase of post-compaction, and star formation gets suppressed to a local minimal level before the next round of compaction (unless the current round results in permanent quenching), as determined by the star formation law. The slope of dM_{HI}/dΣ_1 becomes much steeper in this phase (M_{HI} ∝ Σ_1^2 when Δ log M_{HI} < 0; Figure 9). We note that such a relation does not necessarily link to a continuous evolutionary track along this slope. As suggested in Tacchella et al. (2016), low-mass galaxies may experience a couple of gas replenishment, compaction, and depletion cycles before they finally quench. Galaxies going through different phases in their evolution cycles may mix up
together in this area to form the relation of \( M_{\text{HI}} \propto \Sigma^2 \). That is, the position of those post-compaction galaxies may mix with newly replenished galaxies before the next round of compaction, which would smooth the \( \Delta \Sigma_{\text{HI}} \propto \Delta \log M_{\text{HI}} \) relation.

The compaction result is slightly different for galaxies reaching the critical mass of \( 10^{10.5} M_{\odot} \). These galaxies live in halos of masses larger than around \( 10^{12} M_{\odot} \), where the virial shocking heating and AGN feedback will take effect to shut down the cold gas supply to the halo center (Dekel & Birnboim 2006; Dekel & Burkert 2014), as seen in Figure 3.

3. Quenching. Once the galaxy center reaches the maximum gas compactness, it will start to quench. The slope between SFR and \( M_{\text{HI}} \) will gradually change during the compaction and quenching phase (shown in Figure 6), with an average slope around \( SFR \propto M_{\text{HI}} \). Thus, the SFR will be significantly decreased even if \( M_{\text{HI}} \) is only lowered by around 0.6 dex. As shown in Figure 3, galaxies below \( 10^{10.5} M_{\odot} \) might experience rejuvenation due to the growth of the HI reservoir with the halo mass (represented by the dotted blue lines in Figure 13), when the gas replenishment timescale is smaller than the depletion timescale (see also Tacchella et al. 2016).

The above scenario has been presented with more sophisticated details in the previous theories and simulations (e.g., Dekel & Birnboim 2006; Dekel & Burkert 2014; Tacchella et al. 2016). But here, for the first time, we put the three steps coherently together based on one observational data set, uniquely linking the \( M_{\text{HI}}-M_{\text{b}} \) relation (which sets the HI abundance in the accretion and quenching phases) with the \( M_{\text{HI}}-\text{SFR}-M_{*} \) scaling relation (which determines the rate of HI converting into stars at a given abundance in the compaction and post-compaction phase). It is interesting that the combination of physics on the very large (halo) and very small (star-forming clouds) scales basically determines the integral star-forming status of a galaxy.

6. Conclusions

With accurate stacked measurements of the HI signals in the overlap regions between ALFALFA and SDSS DR7, we make it possible to quantitatively investigate the dependence of HI mass on halo mass, stellar mass, SFR, and central stellar surface density, for both the SFG and quenched central galaxy populations.

Our main conclusions are summarized as follows:

1. The shapes in the \( M_{\text{HI}}-M_{\text{b}} \) and \( M_{\text{HI}}-M_{*} \) relations are remarkably similar for SFGs and QGs, with the QGs having consistently lower HI masses around 0.6–1 dex. This indicates that neither the stellar mass nor the halo mass is the direct cause of quenching. The HI masses of galaxies with \( M_{*} < 10^{10.5} M_{\odot} \) strongly increase with \( M_{\text{b}} \), while for more massive galaxies the HI reservoir does not vary with \( M_{\text{b}} \). The SFGs form a tight HMS, with \( M_{\text{HI}} \propto M_{*}^{0.42} \), while the QGs show similar dependence with slightly larger scatters.

2. Central galaxy star formation and quenching are generally regulated by the HI reservoir, following an average global star formation law of \( \text{SFR} \propto M_{\text{HI}}^{2.75}/M_{\odot}^{0.40} \). The correlation would be better fitted when separating the relations for SFGs and QGs as in Equations (8) and (9), due to the slight slope changes in the two populations. The observed gas fraction \( f_{\text{HI}} \) shows large scatters with sSFR for the SFGs, mainly caused by the stellar mass dependence.

3. The HI masses of central galaxies are decreased once they drop off the SFMS, confirming that the cold gas depletion is the main culprit of quenching. There is also a strong and consistent correlation of \( M_{\text{HI}} \propto \Sigma^2 \) for quenching galaxies in this phase, supporting the idea of compaction-triggered quenching.

4. There are no significant differences in the HI reservoir for the bulge- and disk-dominated galaxies in both the star-forming and quenched populations. Galaxies with different morphology types both follow the same global star formation law and corroborate that depletion of the HI reservoir is the sufficient and necessary requirement for quenching, regardless of morphology.

5. Our results are consistent with the compaction-triggered quenching scenario, suggesting that the evolution of central galaxies generally goes through three different phases of cold gas accretion, compaction, and quenching.

This work is supported by the National Key R&D Program of China (grant No. 2018YFA0404503), National SKA Program of China (grant No. 2020SKA0110100), National Science Foundation of China (Nos. 119222305, 11773049, 12073002, 11721303), and Spanish Science Ministry “Centro de Excelencia Severo Ochoa” program under grant SEV-2017-0709. M.G.J. was supported by a Juan de la Cierva formación fellowship (FJCI-2016-29685). M.G.J. also acknowledges support from the grants AyA2015-65973-C3-1-R and RTI2018-096228-B-C31 (MINECO/FEDER, UE).

We thank the anonymous reviewer for the helpful comments that significantly improved the presentation of this paper. We acknowledge the work of the entire ALFALFA team for observing, flagging, and performing signal extraction. We thank Xiaoyang Xia and Cheng Li for helpful discussions. We acknowledge the use of the High Performance Computing Resource in the Core Facility for Advanced Research Computing at the Shanghai Astronomical Observatory.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/.

Facilities: Arecibo, Sloan.

ORCID iDs
Hong Guo @ https://orcid.org/0000-0003-4936-8247
Michael G. Jones @ https://orcid.org/0000-0002-5434-4904
Jing Wang @ https://orcid.org/0000-0002-6593-8820
Lin Lin @ https://orcid.org/0000-0003-1138-8146

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