Star Formation and Quenching of Central Galaxies from Stacked HI Measurements

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Abstract

We quantitatively investigate the dependence of central galaxy HI mass ($M_{\rm HI}$) on the stellar mass (M_*), halo mass ($M_{\rm h}$), 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 $M_{\rm HI}$–$M_{\rm h}$ and $M_{\rm HI}$–M_* 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 HI reservoir. While the HI reservoir for low-mass galaxies of $M_* < 10^{10.5}M_\odot$ strongly increases with $M_{\rm h}$, more massive galaxies show no significant dependence of $M_{\rm HI}$ with $M_{\rm h}$, indicating the effect of halo 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 $\propto M_{\rm HI}^{2.75}/M_*^{0.40}$, 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 $M_{\rm HI}$ and Σ_1 in this phase, with $M_{\rm HI} \propto \Sigma_1^{-2}$. This result is in consistent with the compaction-triggered quenching scenario, with galaxies going through three evolutionary phases of cold gas accretion, compaction and post-compaction, and quenching.

1. INTRODUCTION

Galaxies in the local Universe are known to consist of two broad categories of early and late types and their color and 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

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,

Проблема би-модальности «цвет-светимость»

- 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.

Предлагавшиеся объяснения:

Various physical mechanisms have been proposed to understand this process, such as

- gas consumption
- the virial shock heating
- stellar feedback
- active galactic nuclei (AGN) feedback
- and morphological quenching при наличии газа (Martig et al. 2009).

Zhang et al. (2019) found a surprisingly large amount of cold Hi reservoir for nearly all massive quenched disk central galaxies (10.6 < log(M=M) < 11)

Анализ содержания газа позволит понять, связан ли quenching с потерей газа, или с остановкой SF в результате низкой эффективности перехода HI – H2.

Accurate average Hi masses can be directly measured by
stacking all the Hi signals for quenched and star-forming
galaxies 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.

Предыдущая работа: HI-selected galaxies

- **Direct Measurement of the H I-halo Mass Relation through Stacking**
- Hong Guo[1], Michael G. Jones[2], Martha
  and Jian Fu[1] , 2020

Для групп галактик найдена зав

ме

$$M_h = 200\bar{\rho}_m(1+z)^3\frac{4\pi}{3}r_{200}^3,$$

The smooth cold gas accretion is driving the H i mass growth in low-mass halos having them more H i accreted.
In halos of **11.8<logMhalo<13** the virial halo shock-heating and AGN feedback will take effect to reduce the H i supply. The H i mass in halos more massive than 10^13   generally grows by mergers, with the dependence on halo richness becoming much weaker.

Guo et al.

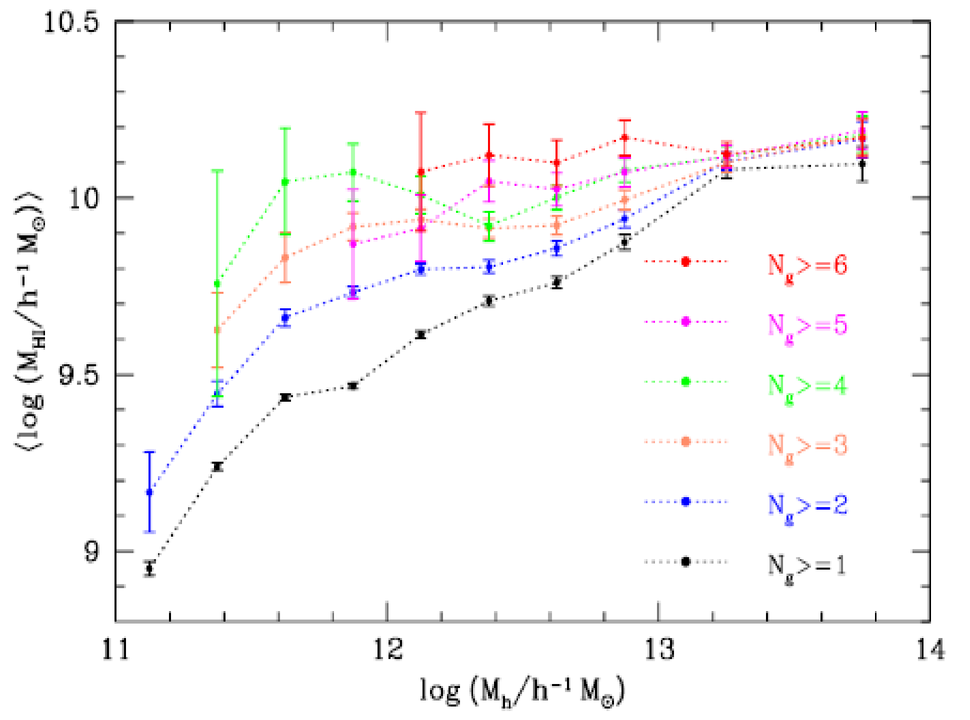


Figure 2. Measurements of total H I masses for halos in different mass bins. We show the measurements for different richness groups in different colors, as labeled. There is an increasing turnover feature with larger group richness around the halo mass scale $\sim 10^{12} M_{\odot}$.

Цель данной работы:

- Используя тот же метод HI stacking, сравнить галактики главной последовательности SF и красные галактики в зависимости от массы гало в группах галактик.

Рассматривались только центральные галактики групп (со звездообразованием)

Исходные данные

- HI catalogue ALFALFA
- We use the surface brightness proles in ugriz bands from SDSS DR7
- Galaxy group catalog from Lim et al. (2017) for the identification of central and satellite galaxies, as well as the halo mass estimates.

ИТОГ:

- our final sample consists of 22 810 central galaxies $0.0025 < z < 0.06$.

The M and SFR measurements for the central galaxies are obtained from the GSWLC-2 catalog of Salim et al. (2018), which used UV/optical spectral energy distribution fitting techniques.

Масса гало – из каталога Lim et al 2017 (калибровка по WMAP cosmol.)

- STACKING: Due to the resolution of Arecibo (3.8’) we limit the minimum aperture size to 4’.

Процедура оценки масс гало – метод с опорой на космологический “halo-mass abundance” (Lim et al 2017)

- After the membership of a group is determined, we define the stellar mass-weighted centre of member galaxies as the group centre, if stellar masses are available. Otherwise, we use luminosity-weighted centre as the group centre.
- To assign masses to groups, we use abundance matching between the mass function of the preliminary groups and an adopted theoretical halo-mass function

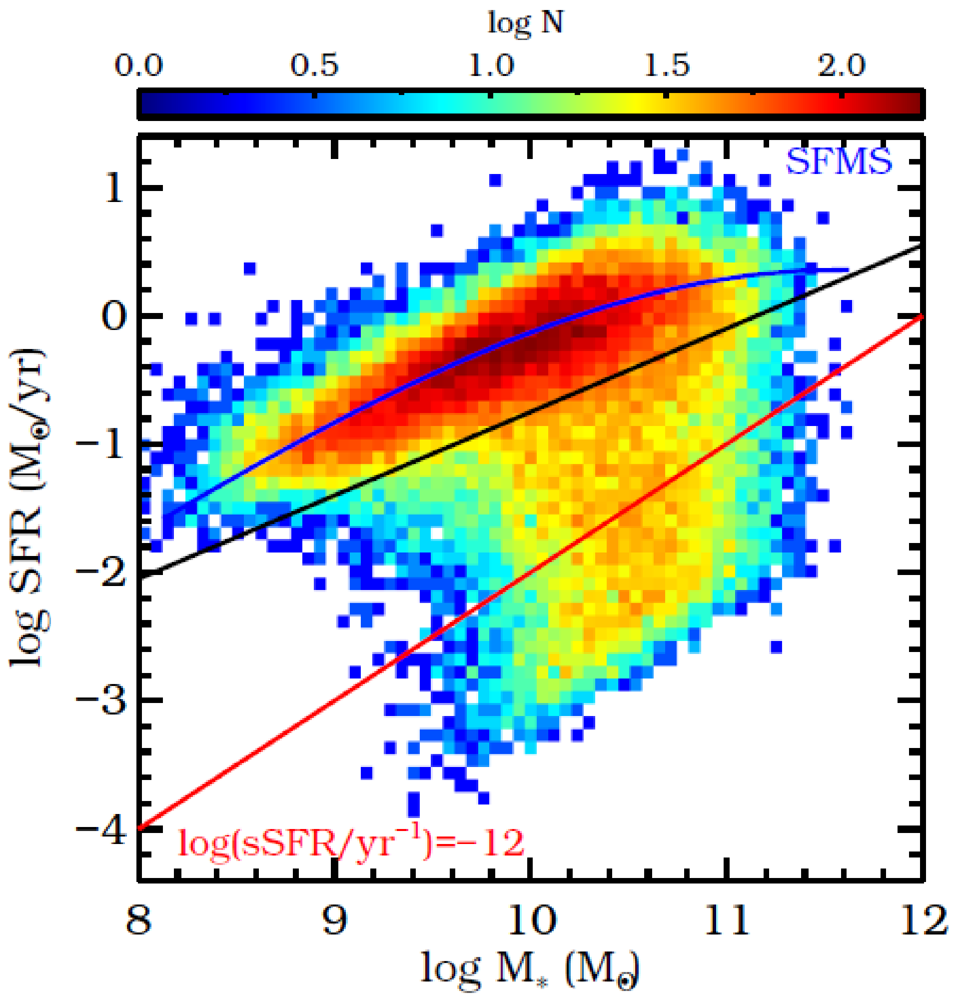


Figure 1. Distribution of the central galaxies as a function of SFR and M_*. The color scales represent the logarithmic number counts at the SFR and stellar mass intervals. The black line separates the star-forming and quenched populations, while the blue line is our definition of the SFMS and red line shows the positions of $\log(\mathrm{sSFR/yr^{-1}}) = -12$. The color scale shows the logarithmic number counts.

- The Hi mass is smoothly increasing with the halo at the low mass end and becoming flat for halos of Mh > 10^12Ms. In all halo mass, quenched galaxi (hereafter QGs) have much lower Hi gas content th the star-forming galaxies.

СВЯЗЬ МАССЫ ГАЗА С МАССОЙ ГАЛО ИСЧЕЗАЕТ ДЛЯ НАИБОЛЕЕ МАССИВНЫХ ГАЛО

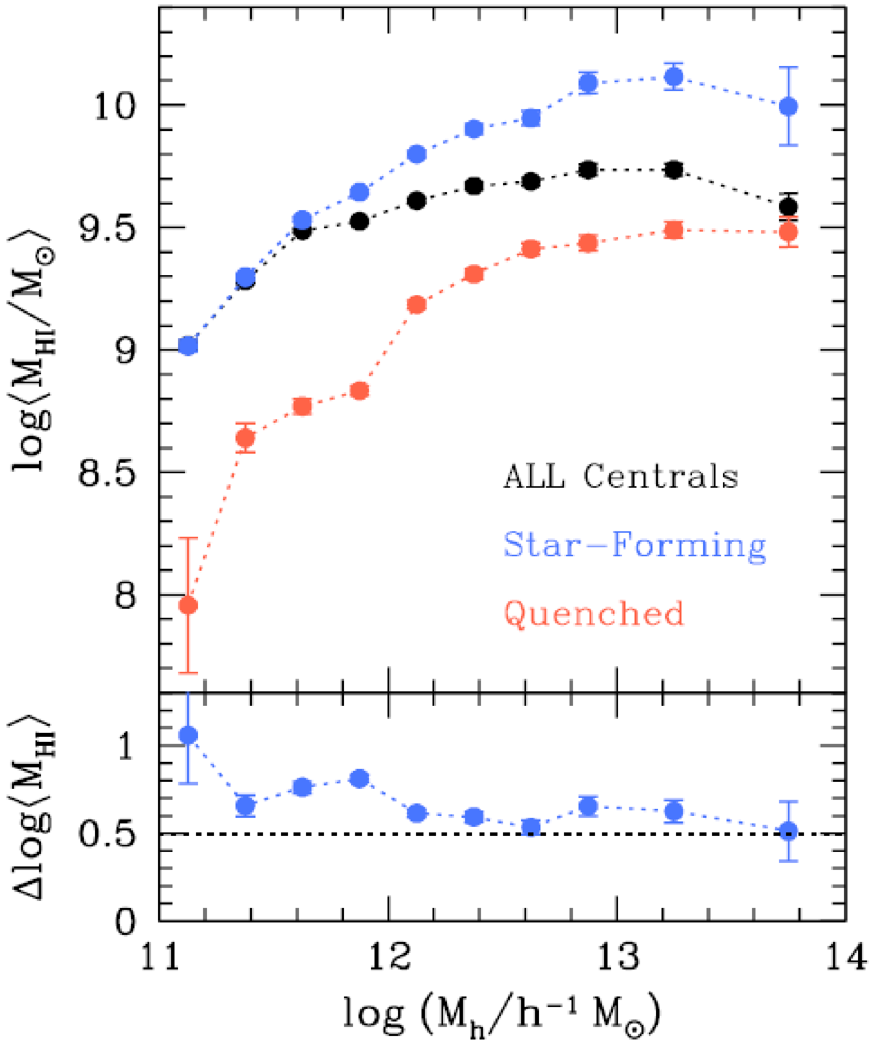
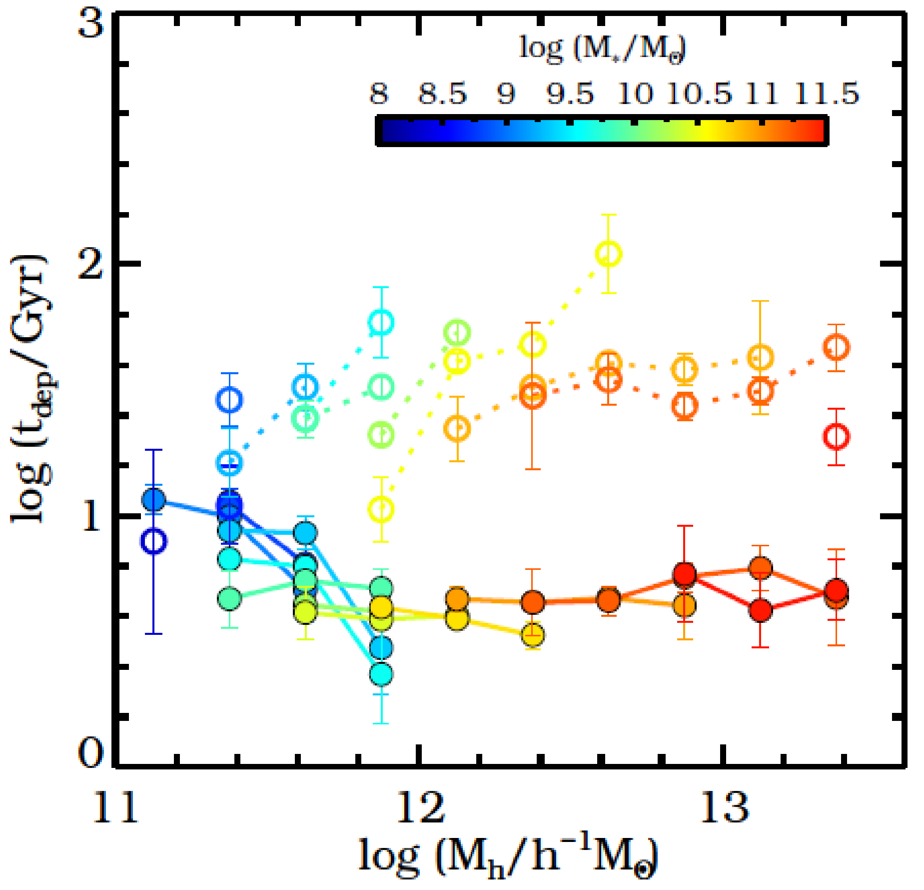


Figure 2. Top: measurements of HI masses for central galaxies in halos of different masses. We show the measurements for all central galaxies (black), star-forming galaxies (blue) and quenched galaxies (orange). Bottom: offsets between the HI masses from the star-forming and quenched galaxies, i.e. $\Delta\log M_{\rm HI} = \log M_{\rm HI,SFG} - \log M_{\rm HI,QG}$.

SFG – заполненные кружки, QGs – открытые кружки



For QGs, t_{dep} is typically much larger than 10 Gyrs,
indicating that the Hi gas is not actively involved in the
star formation. However, the scaling relation is still valid, as the Hi gas still provides the reservoir
for star formation, though with very low efficiency.

$$\log \mathrm{SFR} = \alpha \log M_{\mathrm{HI}} + \beta \log M_{*} + \gamma,$$

Калибровка по средним значениям для гл.последовательности SFR

The galaxies drop below the SFMS when their Hi mas

decrease from the HIMS, forming a very tight relatio

SFR and MHI irrespective of the stellar mass.

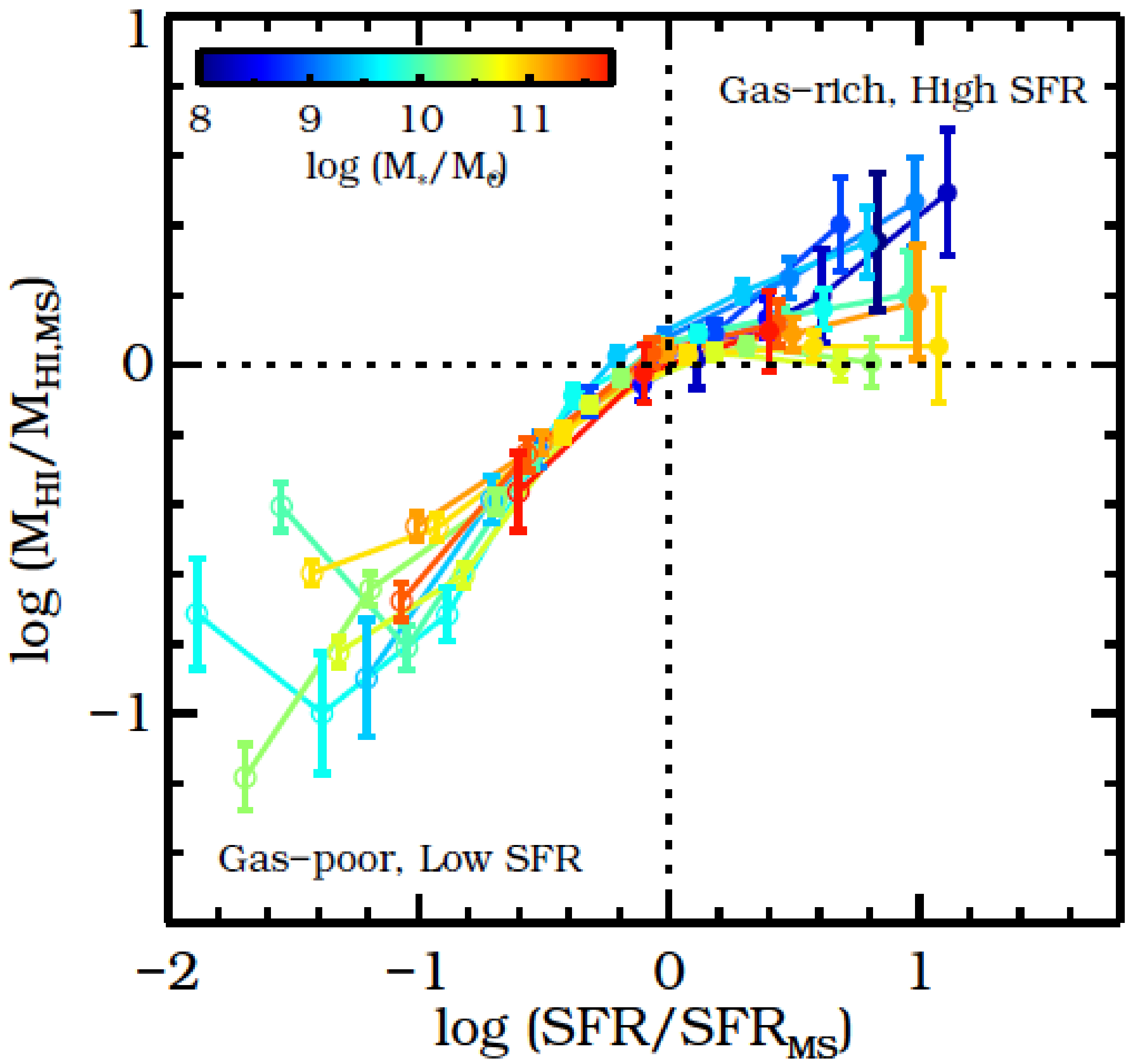
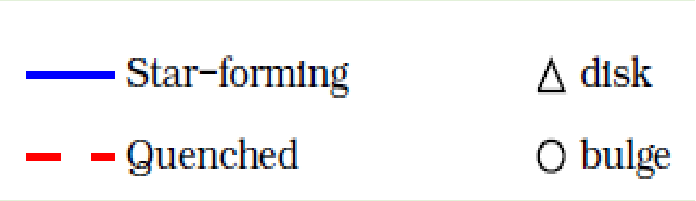
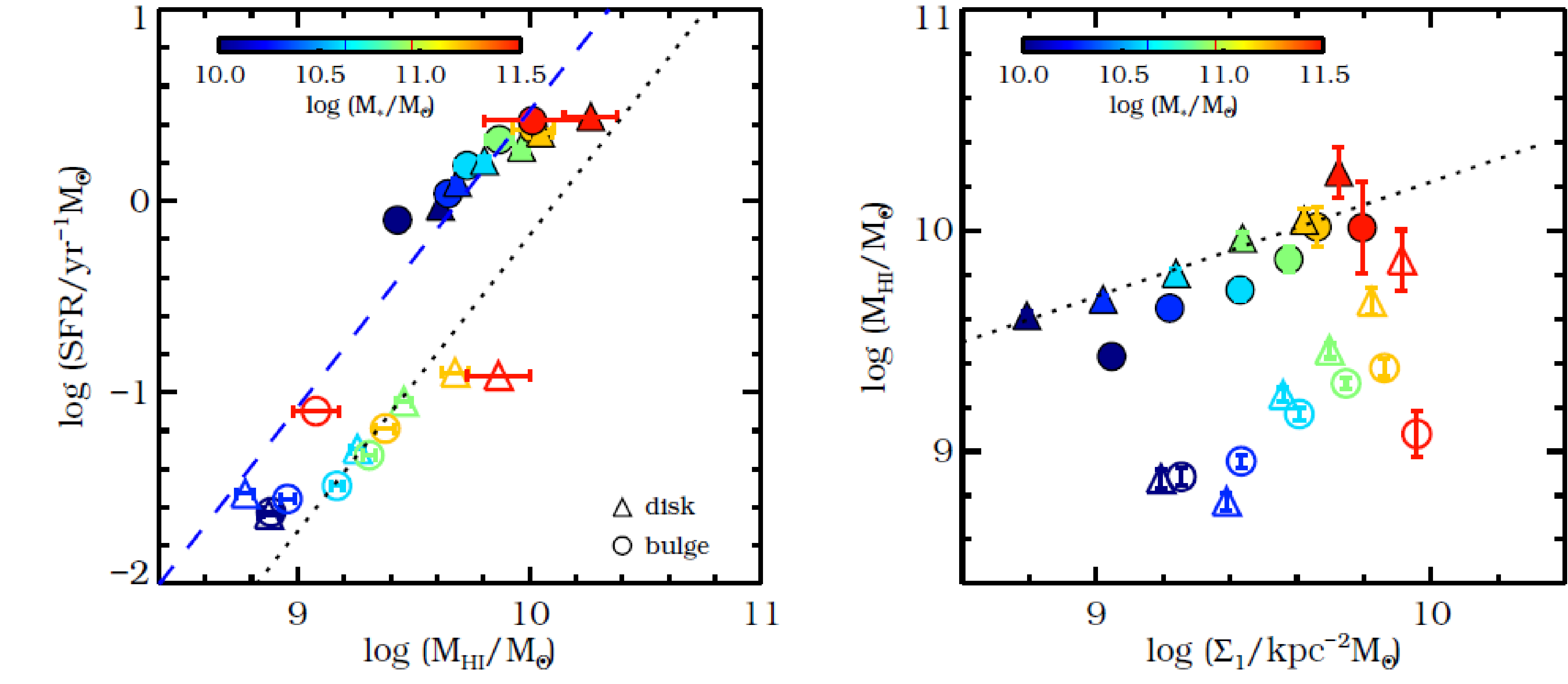


Figure 7. Similar to the right panel of Figure 6, but we scale the SFR and $M_{\rm HI}$ by the corresponding values at the SFMS, i.e. SFR/SFR$_{\rm MS}$ and $M_{\rm HI}/M_{\rm HI,MS}$. The horizontal and vertical dotted lines represent the positions of $M_{\rm HI} = M_{\rm HI,MS}$ and SFR = SFR$_{\rm MS}$, respectively. Measurements are

Сравнение галактик с балджами и без ба





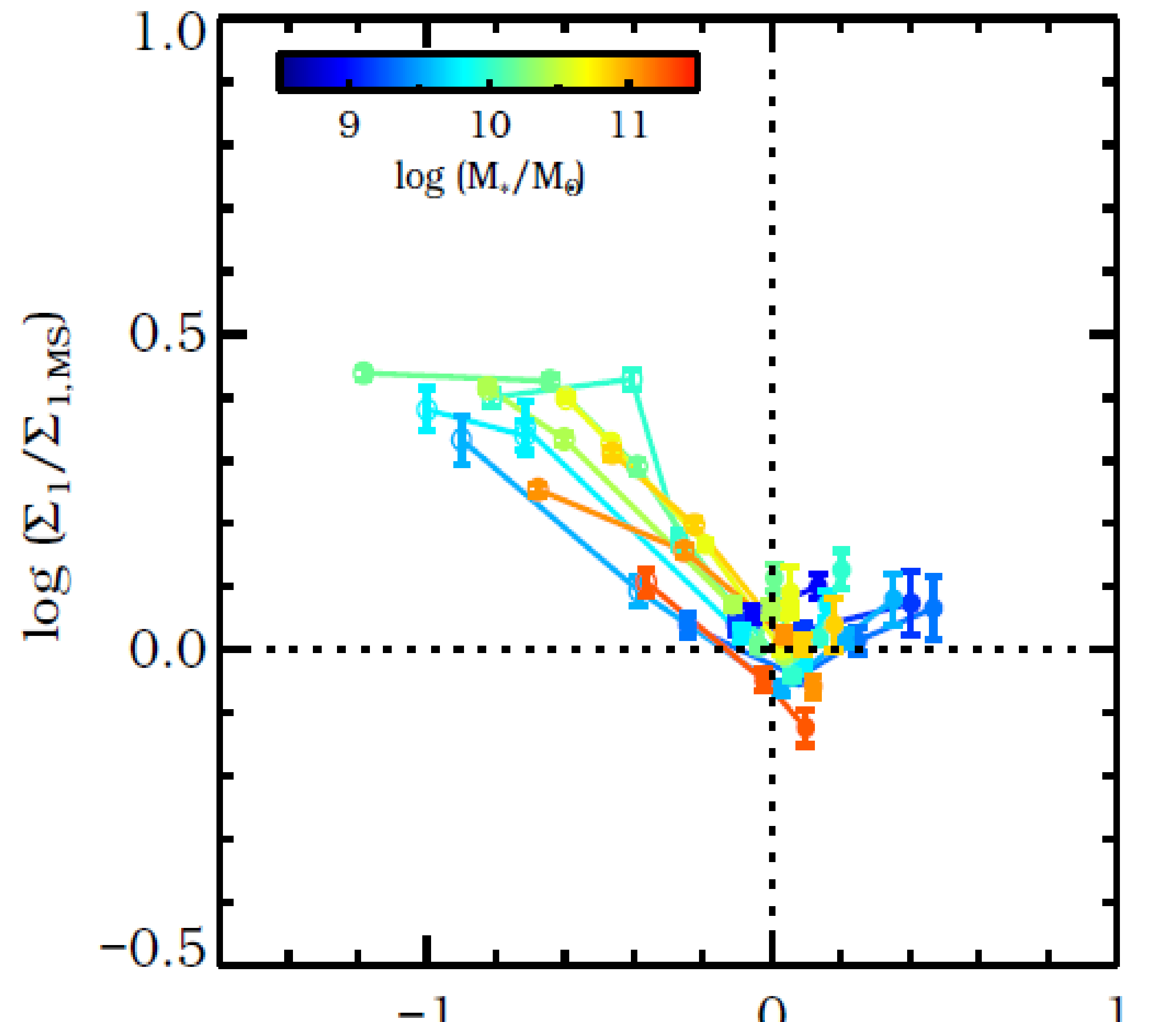
We find that there is no significant difference between the global star formation scaling relations between the disk- and bulge-dominated galaxies in the star-forming and quenched populations. It means that their Hi masses are consistent with their observed SFRs

We treat the compaction-triggered quenching as a potential candidate (идея Dekel,Burkert, 2014).

he formation of a dense core (represented by he measurement of $\sum_1$) is the prerequisite for galaxy quenching.
he filled and open circles are for the SFGs nd QGs, respectively.

he end of compaction leads to the decrease f Hi mass due to the quick depletion from tar formation, outflow and feedback mechanisms. he galaxy thus moves to the phase of post-ompaction, and star formation gets suppressed o a local minimal level.

he strong correlation between MHI and $\sum_1$ does ot necessarily indicate the causal relation of ompaction and quenching, because other physical mechanisms may possibly cause the uenching, as well as the compaction.



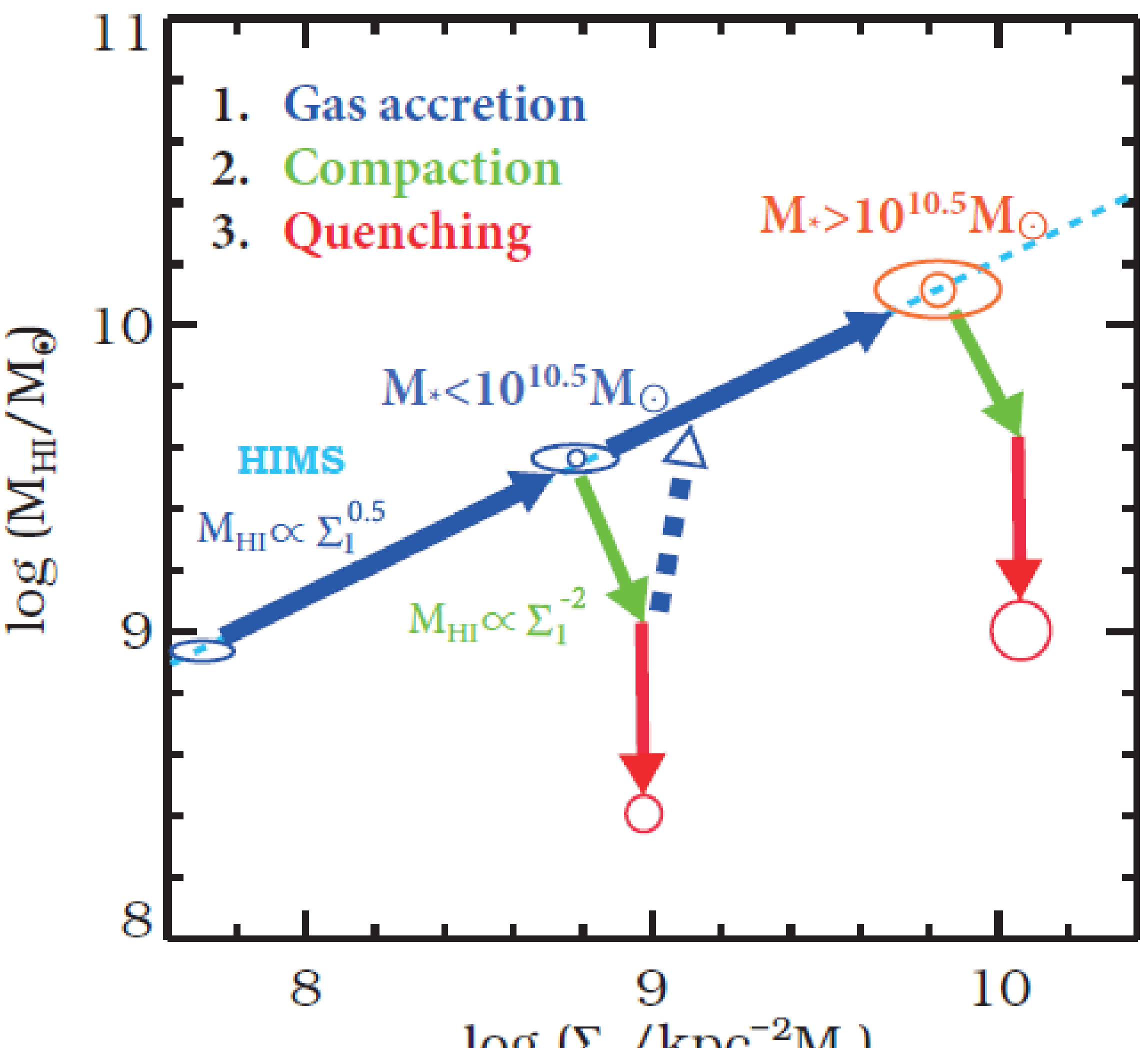


Figure 13. Illustration of the possible evolution tracks of the star-formation and quenching of central galaxies, using M_{HI} and Σ_1. A galaxy starting with a low mass around $10^8 M_{\odot}$ will potentially undergo three phases before they fully quench, i.e. the gas accretion (blue), compaction (green) and quenching (red). The blue dotted lines represent the possible rejuvenation of the quenched low mass galaxies through new gas accretion. The results of the compaction and quenching phases are different for galaxies with masses below and above $10^{10.5} M_{\odot}$, because the environmental effect of halo quenching will take effect to shutdown the cold gas supply to the center, when their host halo masses grow above the critical value of $10^{12} M_{\odot}$. See text for details.

Наиболее важные выводы

- The shapes in the MHI-Mh and MHI-M_* relations are remarkably similar for SFGs and QGs, with the quenched galaxies having consistently lower Hi masses around 0.6 -1 dex. It indicates that neither the stellar mass nor the halo mass is the direct cause of quenching.
- Central galaxy star formation and quenching are generally regulated by the Hi reservoir, following an average **global star formation law of SFR ~ MHI^2.75/M_*^0.40**
- 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 MHI ~ $\sum_1^{-2}$ for quenching galaxies in this phase, supporting the idea of compaction-triggered quenching.
- There is no significant differences in the Hi reservoir for the bulge- and disk-dominated galaxies in both the star-forming and quenched populations.
- **The star formation and quenching is 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 observations.