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# Strong Correlation Between Galactic H I-to-stellar Mass Ratio and Halo Spin Explored by H I-rich Galaxies

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## Abstract

Using a semi-analytic approach, we estimate halo spins for a large sample of H I-rich galaxies from the Arecibo Legacy Fast ALFA Survey and examine the correlation between H I mass fractions and halo spins. Our analysis reveals a strong correlation between halo spin and the H I-to-stellar mass ratio in both low-mass and massive galaxy samples. This finding suggests a universal formation scenario: higher halo spin reduces angular momentum loss and gas condensation, leading to lower star formation rates and weaker feedback, which in turn help retain gas within dark matter halos.

*Key words:* galaxies: statistics – galaxies: evolution – galaxies: formation – galaxies: halos

## 1. Introduction

In the Lambda cold dark matter framework, the characteristics of galaxies are determined by the properties of their host dark matter halos. Factors such as gas accretion mode, gas temperature, angular momentum, and star formation efficiency within a galaxy are influenced by the characteristics of the dark matter halos (e.g., Fardal et al. 2001; Rubin et al. 2010, 2015; Lehner et al. 2014; Kereš et al. 2005; Silk 1977; Behroozi et al. 2010; Guo et al. 2011; van de Voort et al. 2012; Yang et al. 2012; Nelson et al. 2013; Girelli et al. 2020; Noguchi 2023). While various halo properties like halo mass and concentration play a role in empirical galaxy formation models, the influence of halo spin on galaxy features may be particularly significant but is not yet fully understood. It is believed that the spin of parent dark matter halos affects, and possibly determines, the distribution of stars (Mo et al. 1998; van den Bosch 1998; Diemand et al. 2005; Desmond et al. 2017). The prevailing theoretical expectation is that gas in halos with higher spin will exhibit faster rotation, resulting in a more dispersed distribution and lower stellar density during star formation.

Previous hydrodynamical simulations (e.g., Kim & Lee 2013; Jiang et al. 2019) and semi-analytic galaxy formation models (e.g., Mo et al. 1998; van den Bosch 1998) have shown that halo spin strongly influences the size and density of stellar matter distribution, especially in massive late-type galaxies. However, recent studies based on high-resolution simulations suggest that the role of halo spin in low-mass galaxies is still debated: for most typical dwarf galaxies, their stellar distributions may be unaffected by or only weakly correlated with halo spin (Di Cintio et al. 2019; Yang et al. 2023), while for specific dwarf galaxy populations like ultra-diffuse galaxies (Amorisco & Loeb 2016; Rong et al. 2017; Liao et al. 2019; Benavides et al. 2023), halo spin could significantly impact their stellar distributions.

In addition to the influence of halo spin on the distribution of stars (Rong et al. 2025), the H I fraction within halos may also be impacted by spin (e.g., Obreschkow et al. 2016; Rong et al. 2024b). Cosmological simulations (e.g., Nelson et al. 2015; Lagos et al. 2016) suggest that the H I fraction provides insights into a galaxy's history and plays a significant role in its future growth and morphology. For example, Rong et al. (2024b) discovered that excessive halo spin could impede gas from shedding angular momentum, making it challenging for the gas to accumulate at the halo's core and form stars. This often results in a decreased star formation rate, weakening stellar feedback mechanisms (such as supernova feedback) and inadequately expelling gas from the halo, ultimately leading to an increased gas fraction within galaxies.

The impact of halo spin on H I fractions and H I-to-stellar mass ratios in galaxies remains inconclusive, especially in observational studies where determining halo spin poses a challenge. Measurements of halo spin in galaxies have primarily focused on a limited number of samples with resolved H I observations (e.g., Hunter et al. 2012; Oh et al. 2015), which are insufficient for statistically analyzing the relationship between halo spin and stellar distribution in galaxies. Large-sample integral field unit (IFU) observations like MaNGA mainly concentrate on regions within halos dominated by stellar matter, making accurate estimation of halo spin challenging with IFU data (e.g., Cappellari et al. 2006, 2013; Rong et al. 2018; Wang et al. 2020). Furthermore, due to constraints in observation time and telescope sensitivity, IFU observations tend to target galaxies with higher surface brightness and stellar masses, leading to sample selection bias. Even with accurate measurements of halo spin parameters, studying the correlation between halo spin and H I-to-stellar mass ratios within galaxies accurately and without bias remains challenging.

Alternatively, H I surveys, conducted with single-dish telescopes such as the comprehensive Arecibo Legacy Fast ALFA (ALFALFA) survey (Giovanelli et al. 2005; Haynes et al. 2018) and the ongoing FAST All Sky H I survey (FASHI; Zhang et al. 2024), provide valuable opportunities to obtain H I spectra from numerous galaxies. These surveys offer essential dynamical information on galaxies, enabling the estimation of spin parameters across a large galaxy sample and facilitating comparisons of halo spins in galaxies with diverse mass distributions. Galaxy samples selected by H I surveys have an unbiased stellar mass distribution, making them suitable for studying the correlation between halo spin and H I-to-stellar mass ratios.

In this study, we first utilize a semi-analytic approach to estimate halo spin for each H I-bearing galaxy cataloged in ALFALFA, and then investigate the potential correlation between halo spins and H I-to-stellar mass ratios of galaxies. Section 2 presents the sample data and outlines the methodology for estimating halo spin. Section 3 provides a statistical analysis of the dependence of H I-to-stellar mass ratios of galaxies on their halo spins. Our conclusions are presented in Section 4.

## 2. Data

### 2.1. Sample

The galaxy sample is sourced from the ALFALFA extragalactic H I survey, covering approximately 6600 $\deg^2$ at high Galactic latitudes. The comprehensive ALFALFA catalog ($\alpha$. 100; Haynes et al. 2018), contains around 31,500 sources with radial velocities below 18,000 $\mathrm{km\,s^{-1}}$, providing properties for each source, including H I spectrum signal-to-noise ratio (SNR), cosmological distance, H I line width at 50% peak ($W_{50}$) corrected for instrumental broadening, and H I mass ($M_{\rm H\,I}$).

### 2.2. H I-to-stellar Mass Ratio

ALFALFA galaxies are cross-matched with Sloan Digital Sky Survey (SDSS) data (Alam et al. 2015). Following Durbala et al. (2020), stellar masses ($M_\star$) of ALFALFA galaxies with optical counterparts are estimated using three methods: ultraviolet (UV)-optical-infrared spectral energy distribution (SED) fitting, SDSS $g - i$ color, and infrared $W_2$ magnitude. This study primarily uses stellar mass from SED fitting, and for galaxies lacking UV or infrared data for SED fitting, $g - i$ color is used to estimate stellar mass. Discrepancies among methods are considered negligible.

The H I-to-stellar mass ratio, $\eta$, is then calculated as $\eta = \log M_{\rm HI} - \log M_\star$, where both $M_\star$ and $M_{\rm H\,I}$ are in units of $M_\odot$.

### 2.3. Rotation Velocity and Halo Spin

The rotation velocity is calculated as $V_{\rm rot} = W_{50}/2/\sin\phi$, where $\phi$ represents the inclination of the H I disk. When resolved H I data are unavailable, we estimate the H I disk inclination $\phi$ using the optical axis ratio $b/a$ from Durbala et al. (2020) as $\sin\phi = \sqrt{(1-(b/a)^2)/(1-q_0^2)}$, where $q_0 \sim 0.2$ (Giovanelli et al. 1997; Tully et al. 2009; Li et al. 2022) for massive galaxies, and $q_0 \sim 0.4$ (Rong et al. 2024a) for low-mass galaxies with $M_\star < 10^{9.5} M_\odot$. If $b/a \leqslant q_0$, we set $\phi = 90°$.

To improve rotation velocity accuracy, we exclude galaxies with inclinations $\phi < 50°$ and those with low H I SNRs (SNR $< 10$) due to high velocity uncertainties.

Some H I-bearing galaxies may exhibit velocity dispersion-dominated kinematics rather than regular rotation, often characterized by "single-horned" H I line profiles (El-Badry et al. 2018), which complicates accurate rotation and halo spin measurements. Following Hua et al. (2025), we distinguish single-horned from double-horned H I spectra using the kurtosis parameter $k_4$, classifying spectra as single-horned if $k_4 > -1.0$. Our analysis focuses exclusively on isolated galaxies with double-horned profiles, excluding potentially dispersion-dominated systems.

For rotation-dominated galaxies with high H I SNR and inclinations, we estimate halo spin following Hernandez et al. (2007)

$$\lambda_{\rm h} \simeq 21.8 \frac{R_{\rm HI,d}/{\rm kpc}}{(V_{\rm rot}/{\rm km\ s^{-1}})^{3/2}}. \tag{1}$$

Here, the galaxy's dark matter halo is assumed to follow an isothermal sphere model, with baryonic gravitational effects neglected. The H I disk scale length, $R_{\rm H\,I,d}$, is derived assuming a thin, rotationally supported gas disk with an exponential surface density profile (Mo et al. 1998)

$$\Sigma_{\rm HI}(R) = \Sigma_{\rm HI,0} \exp(-R/R_{\rm HI,d}), \tag{2}$$

where $\Sigma_{\rm H\,I,0}$ is the central surface density. Total H I mass $M_{\rm H\,I}$ relates to $R_{\rm H\,I,d}$ as

$$\int_0^\infty \Sigma_{\rm HI}(R) 2\pi R {\rm d}R = 2\pi\Sigma_{\rm HI,0} R_{\rm HI,d}^2 = M_{\rm HI}. \tag{3}$$

We define the H I radius $r_{\rm H\,I}$ as the radius where H I surface density reaches 1 $M_\odot\,{\rm pc^{-2}}$. Empirical studies provide $r_{\rm H\,I}$ in terms of H I mass $M_{\rm H\,I}$ as $\log r_{\rm HI} = 0.51 \log M_{\rm HI} - 3.59$ (Wang et al. 2016; Gault et al. 2021). Thus, at $r_{\rm H\,I}$

$$\Sigma_{\rm HI,0} \exp(-r_{\rm HI}/R_{\rm HI,d}) = 1\ M_\odot\ {\rm pc^{-2}}. \tag{4}$$

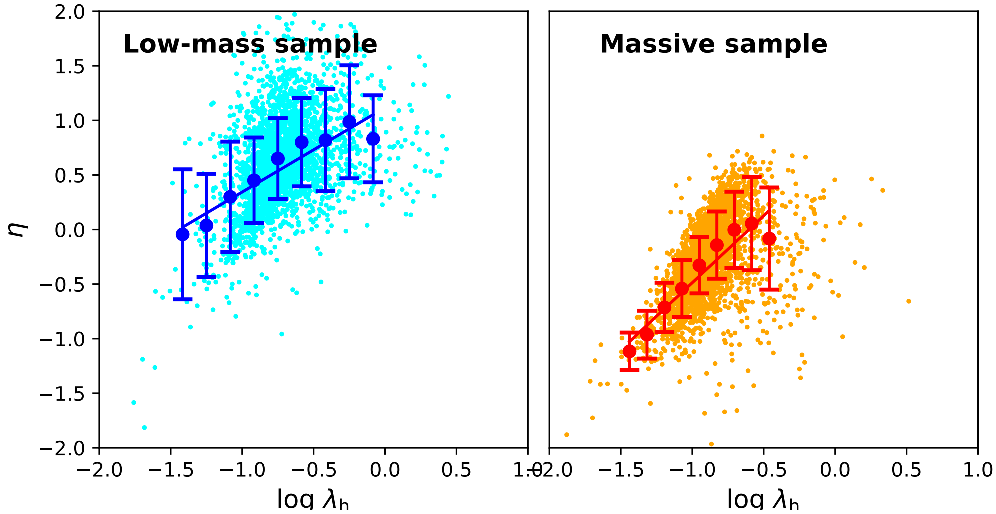


**Figure 1.** The $\eta$–$\lambda_h$ relationships for low-mass (panel (a)) and massive (panel (b)) galaxies. Median $\eta$ values with $1\sigma$ error bars are shown in blue and red for bins in log $\lambda_h$. The best linear fitting results are highlighted by the corresponding lines.

Using the equations above, we compute $R_{\rm H\,I,d}$ for each galaxy, allowing halo spin estimation.

### 2.4. Environment Control

Environmental factors exert a profound influence on the H I fractions within galaxy halos (Kawata & Mulchaey 2008; Yozin & Bekki 2015; Davies et al. 2019). Overdense environments, such as clusters, groups or even close pairs (Patton et al. 2011; Robotham et al. 2014; Davies et al. 2016) can significantly impair or entirely inhibit the inflow of gas essential for sustained star formation, thereby triggering quenching events (Peng et al. 2010; Schaefer et al. 2017). Observational studies have established that the gas fractions, star formation rates, and colors, indicators of star formation activity, of galaxies exhibit a correlation with local galaxy density within groups and clusters (Peng et al. 2012; Treyer et al. 2018; Davies et al. 2019), as well as with their positions relative to the center of these systems (Martínez et al. 2008; Wolf et al. 2009; Wetzel et al. 2012; Woo et al. 2015; Barsanti et al. 2018). Furthermore, previous investigations, alongside our recent analyses, have indicated that halo spin is contingent upon environmental factors and the effects of tidal fields (Hahn et al. 2007a, 2007b; Wang et al. 2011; Wang & Kang 2017; Hua et al. 2025; Xue et al. 2024). Consequently, any potential correlation between halo spin and the H I-to-stellar mass ratio may be obscured or entirely negated by environmental influences. Therefore, it is imperative that we account for environmental variables when examining the dependence of the ratio $\eta$ on halo spin. We employ the galaxy group and cluster catalog developed by Saulder et al. (2016), derived from SDSS Data Release 12 (DR12; Alam et al. 2015) and the 2MASS Redshift Survey (Huchra et al. 2012), which is constructed using the friends-of-friends algorithm and rigorously corrects for observational biases, such as the Malmquist bias and the "Fingers of God" effect.

To eliminate environmental influences, we select only isolated galaxies, defined as those located beyond three times the virial radius from any galaxy group or cluster (Guo et al. 2020; Rong et al. 2024b). This threshold effectively excludes regions subject to tidal or ram pressure stripping associated with dense environments (Mamon et al. 2004; Gill et al. 2005; Oman et al. 2013; Zinger et al. 2018).

## 3. Results

Di Cintio et al. (2019) identify a stellar mass $\sim 10^9 M_\odot$ as a transition point between feedback-dominated and angular momentum-dominated galaxy formation regimes. This suggests that for low-mass galaxies, H I-to-stellar mass ratios $\eta$ may be less dependent on halo spin. To investigate, we divide the sample into low-mass ($M_\star < 10^9 M_\odot$) and massive ($M_\star > 10^9 M_\odot$) subsamples, analyzing their respective $\eta$-$\lambda_h$ relationships.

Figure 1 presents $\eta$ as a function of $\lambda_h$ for low-mass (left panel) and massive (right panel) galaxies. Median $\eta$ values with $1\sigma$ error bars are shown in blue and red for bins in log $\lambda_h$. Our findings indicate that massive galaxies have generally lower H I fractions than low-mass galaxies; however, in both subsamples, $\eta$ increases significantly with halo spin. The correlation coefficients are 0.40 for low-mass and 0.50 for massive galaxies, demonstrating a strong $\eta$–$\lambda_h$ correlation. Linear fits yield $\eta \simeq (0.73 \pm 0.37)\log \lambda_h + (1.09 \pm 0.30)$ for low-mass galaxies and $\eta \simeq (1.39 \pm 0.31)\log \lambda_h + (0.91 \pm 0.36)$ for massive galaxies.

While our estimates of rotation velocities and halo spins are derived from optical inclinations, this approach may introduce uncertainty due to minor misalignments ($d\phi$) between optical and H I inclinations in certain galaxies (Hunter et al. 2012; Oh et al. 2015; Nelson et al. 2018, 2019). Nonetheless, this discrepancy does not undermine the robust correlation observed between $\eta$ and $\lambda_h$. Previous studies have demonstrated that the stellar and gas disks within galaxies may not be perfectly co-planar, frequently exhibiting a small inclination difference of $\delta\phi < 20°$ (Starkenburg et al. 2019; Guo et al. 2020; Gault et al. 2021). However, while this inclination uncertainty may contribute to an increased scatter in the halo spins within our galaxy sample, it does not uniformly bias the measurements, resulting in either overestimation or underestimation of all spins.

## 4. Conclusion

Using a semi-analytic approach, we estimate halo spins for the ALFALFA H I-bearing galaxy sample and investigate the potential dependence of H I-to-stellar mass ratios $\eta$ on halo spins $\lambda_h$ for isolated low-mass and massive galaxies. We find a strong correlation between $\eta$ and $\lambda_h$ in both samples, suggesting that halo spin plays a central role in regulating gas cooling, star formation, and feedback in galaxies. This finding aligns with our previous results in Rong et al. (2024b).

As proposed by Rong et al. (2024b), a galaxy halo with increased spin would likely lead to high-spin gas accretion, where angular momentum loss is difficult. This high-spin gas resists infall toward the galactic core, slowing the condensation and cooling processes essential for central star formation (Peng & Renzini 2020). Consequently, gas inflow and star formation proceed at a moderated, continuous rate, reducing supernova feedback intensity compared to low-spin halos. This mitigated feedback prevents significant H I gas loss from the halo, thereby sustaining a higher H I fraction.

Compared to Rong et al. (2024b), a study which concentrated on ultra-diffuse galaxies, we find that the $\eta$–$\lambda_h$ correlation and formation mechanism appear applicable to galaxies across a broad mass range.

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