The Origin of the Stellar Angular Momentum-Mass Relation: Connecting Galaxies and Halos in IllustrisTNG

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ABSTRACT

The IllustrisTNG simulations reproduce well the observed scaling relation between specific angular momentum ($j_s$) and mass ($M_s$) of galaxies, i.e., the $j_s$-$M_s$ relation. This relation develops in disk galaxies at redshift $z \lesssim 1$ via forming disk structures whose $j_s$ are nearly conserved from their parent dark matter halos. We provide a simple model that describes well the connection between halos and galaxies, giving $\log j_s = 0.54 \log M_s - 2.53 + b$, where $b$ quantifies how well $j_s$ is retained. This model suggests that the power law index 0.54 of the $j_s$-$M_s$ relation is determined by (i) the change of the halo angular momentum-mass relation $j \propto M^\alpha$, whose index $\alpha$ grows from 0.68 to 0.80 under the effect of baryonic processes, and (ii) the mass dependence of the luminous-dark mass ratio. This model is different from the traditional expectation using a constant luminous-dark mass ratio and $\alpha = 2/3$. We further suggest that a significant loss of $j_s$, which manifests as a decrease in $b$, leads to the parallel offset of elliptical galaxies (relative to disk galaxies) in the $j_s$-$M_s$ relation.

Keywords: Scaling relations (2031); Galaxy kinematics (602); Galaxy evolution (594); Spiral galaxies (1560); Galaxy dark matter halos (1880)

1. INTRODUCTION

The relation between the properties of galaxies and their parent dark matter haloes, as well as the physical processes that regulate such properties, is a long-standing puzzle. In a cosmological framework, the angular momentum of a dark matter halo is initially acquired through tidal torques from neighbouring perturbations (e.g. White 1984). Theoretical models predict that the specific angular momentum $j_s$ (hereafter) of haloes follows $j \propto M^{2/3}$ where $M$ is the halo mass. If angular momentum is conserved throughout the formation of galaxies via accreting gas that decoupled from their host dark matter halos, a similar relation should also apply to galaxies. Observations show that stellar masses $M_s$ and $j_s$ of disk galaxies are correlated by a power law with index 0.5-0.6 (e.g. Fall 1983; Romanowsky & Fall 2012; Fall & Romanowsky 2013; Posti et al. 2018; Hardwick et al. 2021; Mancera Piña et al. 2021), i.e., the so-called Fall relation. This relation with an index close to 2/3 has been thus considered as a strong evidence of the conservation of angular momentum. Yet, the interplay between properties of dark matter haloes and those of the baryons is not fully understood.

The angular momentum of galaxies plays a crucial role in many stages of their formation and evolution (e.g. Fall & Efstathiou 1980; Dalcanton et al. 1997; Mo et al. 1998). But the correspondence between stellar and dark components is complex after taking the detailed loss and gain of angular momentum into consideration. For example, it is well known that the stellar angular momentum can be significantly lost during major mergers, thus forming spheroidal structures. Consistently, local surveys have shown that the scatter of the $j_s$-$M_s$ relation correlates strongly with galaxy morphology (e.g. Obreschkow & Glazebrook 2014; Cortese et al. 2016; Sweet et al. 2018). Elliptical galaxies have about five times less $j_s$ than spirals for a given stellar mass. Disky structures grow at $z \lesssim 2$ by accreting cold gas inflows from a vast reservoir of the circum-galactic medium (e.g. Tacchella et al. 2019; Renzini 2020; DeFe-
lippis et al. 2020; Du et al. 2021). During this phase, it is commonly assumed that the angular momentum of gas is conserved, thus forming galaxies with angular momenta tightly correlated with their parent dark matter halos. Numerical simulations have shown that the angular momentum vectors of disk galaxies are well aligned with the angular momentum vectors of haloes with a median misalignment angle of $\sim 20^\circ$-$30^\circ$ (Bailin et al. 2005; Bett et al. 2010; Shao et al. 2016). Motloch et al. (2021) further find the correlation between galaxy spin directions and the halo spin reconstruction by the cosmic initial conditions (Yun et al. 2019; Wu et al. 2021).

No agreement is fully reached in studies that examined the link of angular momentum amplitude between halos and galaxies. Zavala et al. (2016) and Lagos et al. (2017) found remarkable links between the sAM evolution of the dark and baryonic components in the EAGLE simulation. A similar correlation is suggested in Teklu et al. (2015) using the Magneticum Pathfinder simulations. However, Jiang et al. (2019) found no/weak correlation using the NIHAO zoom-in simulation. Danovich et al. (2015) argued that cold gas inflows that form galactic disks cannot conserve angular momentum when they fall into the inner region to form stars. Recent numerical simulations, however, suggested that galactic winds and AGN feedback can regulate the angular momentum distribution of gas (e.g. Genel et al. 2015; DeFelippis et al. 2017), which contributes to angular momentum conservation in disk galaxies.

In this paper, we revisit a longstanding open question of how the $j_s-M_s$ relation develops in disk galaxies using IllustrisTNG (Nelson et al. 2018, 2019; Naiman et al. 2018; Marinacci et al. 2018; Pillepich et al. 2018a, 2019; Springel et al. 2018). We aim to address: (i) whether or not there is a prevalent connection of angular momentum between dark halos and the galaxies they host; (ii) how does $j_s - M_s$ evolve in disk galaxies; and (iii) how well does a simple, theoretical model explain the evolution of $j_s$ despite the complexities of baryonic physics.

2. TNG50 SIMULATION

IllustrisTNG is a popular suite of cosmological hydrodynamical simulations that were run with gravomagnetohydrodynamics (MHD) and incorporate a comprehensive galaxy model (see Weinberger et al. 2017; Pillepich et al. 2018b, for details). The TNG50-1 run of the IllustrisTNG has the highest resolution. It includes 2×2160³ initial resolution elements in a ~50 comoving Mpc box, corresponding to a baryon mass resolution of $8.5 \times 10^4 M_\odot$ with a gravitational softening length for stars of about 0.3 kpc at $z = 0$. Dark matter is resolved with particles of mass $4.5 \times 10^5 M_\odot$. Meanwhile, the minimum gas softening reaches 74 comoving parsec. The galaxies are identified and characterised with the Friends-of-Friends (Davis et al. 1985) and SUBFIND (Springel et al. 2001) algorithms. Resolution elements (gas, stars, dark matter, and black holes) belonging to an individual galaxy are gravitationally bound to its host subhalo.

In this paper, we mainly focus on how the $j_s-M_s$ relation develops in central galaxies dominated by disks. In such cases, neither mergers nor environmental effects have played an important role. We use the galaxies over the stellar mass range $10^9 - 10^{11.5}$ from the TNG50-1 run. Disk-dominated galaxies are identified by $\kappa_{\text{rot}} \geq 0.5$, where $\kappa_{\text{rot}} = K_{\text{rot}}/K$ (Sales et al. 2012) is the relative importance of cylindrical rotational energy $K_{\text{rot}}$ over the total kinetic energy $K$. Du et al. (2021) showed that $\kappa_{\text{rot}} \geq 0.5$ selects galaxies whose mass fractions of kinematically-derived spheroidal structures are $\lesssim 0.5$. The other galaxies are classified as spheroid-dominated galaxies that correspond to elliptical galaxies or slow rotators in observations. We further divide disk-dominated galaxies into two subgroups with $0.5 \leq \kappa_{\text{rot}} < 0.7$ that correspond to the cases with strong rotation and with relatively moderate rotation, respectively. The former ones are likely to have more disky morphology.

All quantities in this paper are calculated using all particles belonging to subhalos identified with the SUBFIND algorithm. No limitation on the radial extent is made to obtain the overall properties. The radial variation is ignored to simplify our discussion.

3. THE $j_s - m_s$ RELATION IN IllustrisTNG

In Figure 1, we show the $j_s - M_s$ relation of galaxies at $z = 0$ from TNG50, in comparison with those measured in observations. The disk galaxies of Romanowsky & Fall (2012) follow a nice linear scaling relation with slope $\alpha = 0.52$ and a root-mean-square scatter of $\sim 0.22$ dex (black-dashed line with error bar). The latest studies of Mancera Piña et al. (2021) and Posti et al. (2018) obtained a similar result, shown by the gray lines (see also Hardwick et al. 2021). It is clear that TNG50 reproduces the $j_s-M_s$ relation that agrees well with the observations for the disk-dominated galaxies (blue and cyan dots). The linear fitting (cyan line) of all disk-dominated central galaxies of TNG50 gives $\log j_s = 0.54 \log M_s - 2.69$ with a similar scatter $\sim 0.23$ dex as the observations. Moreover, the galaxies dominated by spheroids (red dots) are also consistent with the observations (black-dotted line) of ellipticals from Romanowsky & Fall (2012), though they have a fairly large scatter. The satellite galaxies, shown using gray
It is worth mentioning that there is a big uncertainty in the observational estimation of $j_s$ because of the limited radial extent of the kinematic data. In Romanowsky & Fall (2012), the total sAM of galaxies $j_s$ is estimated using approximate deprojection factors and density profiles described by the Sرسic function. The stellar mass fraction of bulges cannot be accurately obtained, though their contributions are calculated in an independent way. Furthermore, the usage of constant mass-to-light ratios may also generate uncertainty. Fall & Romanowsky (2013) gave $\alpha = 0.6$ after making the correction of stellar mass-to-light ratio based on colors, which still matches the relation from the TNG simulations well. Despite the big uncertainty in observations, a nice scaling relation of $j_s - M_s$ is found in TNG50.

4. THE ORIGIN OF THE $j_s - M_s$ RELATION

4.1. The halo-galaxy angular momentum connection at $z = 0$

The existence of the $j_s - M_s$ relation suggests that, despite the complexity of galaxy formation in a cosmological context, a fundamental regularity still exists. We then need to understand it better.

The $j_s - M_s$ relation is expected to be an important output of the related $j - M$ relation of dark matter halos. We have verified that the dark matter-only runs in the TNG simulations indeed result in $j \propto M^{2/3}$ (not shown here) that is consistent with the theoretical expectation. However, the $j - M$ relation gradually deviates from this relation since $z = 2$ in the presence of baryons, as shown in the first row of Figure 2. At $z = 0$, fitting the central galaxies dominated by disks (blue and green dots) from TNG50 gives

$$j_{\text{tot}} = 10^{-6.37} M_s^{0.80},$$

where $j_{\text{tot}}$ and $M_s$ are the sAM and mass of all components, which are little different from those of dark matter components. It is clear that the slope gradually grows larger than $2/3$ at $z < 1.5$ in the logarithmic space. It is thus not enough to use the dark matter-only $j \propto M^{2/3}$ relation to explain the $j_s - M_s$ relation. The effect of that central halos gain angular momenta under the effect of baryonic processes should be taken into account. It is worth mentioning that such an evolution of the halo $j - M$ relation has no significant correlation with galaxy morphology, quantified by $\kappa_{\text{rot}}$ in this paper. In previous studies, Zhu et al. (2017) showed that the presence of baryonic component is able to induce net rotation in the inner regions of dark matter halos, which may lead to the increase of their angular momenta. Pedrosa et al. (2010) suggested that central galaxies may acquire angular momentum from their satellites that are disrupted by dynamical friction. Similarly, Lu et al. (2022) showed that galaxy interactions can inject angular momentum to the circumgalactic medium, possibly also to the dark matter. The mechanism is still not well known, which is out of the scope of this Letter.

From equation (1), we assume that the average sAM of the stars in a galaxy can be directly determined by the retention factor of angular momentum $f_j \equiv j_s / j_{\text{tot}}$ that is the ratio of the average sAM of the stars in one galaxy to that of the halo. A simple derivation thus gives

$$\log j_s = 0.8 \log M_{\text{tot}} - 6.37 + \log f_j = 0.8 \beta \log M_s + 0.8a - 6.37 + \log f_j,$$

where we define $M_{\text{tot}} = 10^a M_s^\beta$ that is slightly different from the mass ratio $f_m = M_s / M_{\text{tot}}$ that has been
widely used in previous studies. In the second row of Figure 2, we can see clearly that $M_s$ is tightly correlated with $M_{\text{tot}}$. During $z = 0$ to 1.5, linear fitting results give nearly constant $a = 4.8$ and $\beta = 0.67$ for disk-dominated galaxies. There are some galaxies offset from the main sequence in the massive cases with $\log M_s/M_\odot \gtrsim 11$. But it has a small effect on the overall trend, as the number of such cases is relatively small.

Figure 3 shows the $j_s-M_{\text{tot}}$ relation of central galaxies. This relation can be described by

$$\log j_s = \log j_{\text{tot}} + b,$$

where the offset $b = \log f_j$ decreases with $\kappa_{\text{tot}}$ following a nearly parallel sequence. The $j_s-M_s$ relation of the disk-dominated galaxies is determined by $b$, the $j_{\text{tot}}-M_{\text{tot}}$, and the $M_{\text{tot}}-M_s$ relations. At $z = 0$, equation 2 can thus be written as

$$\log j_s = 0.54 \log M_s - 2.53 + b. \quad (4)$$

It is clear that the galaxies with $\kappa_{\text{tot}} \geq 0.7$ at $z = 0$ match the dotted line of $b \sim 0$ (marked with $y = x$) best. The angular momentum thus is retained well in such galaxies, giving $\log j_s = 0.54 \log M_s - 2.53$. For all disk-dominated galaxies where the median value of $b$ is about $-0.5$, equation (4) gives $\log j_s \approx 0.54 \log M_s - 2.6$, which predicts perfectly the outcome of the $j_s-M_s$ relation of disk-dominated galaxies at $z = 0$ shown in Figure 1. Apparently, the decrease of $b$ leads to a parallel shift of the $j_s-M_s$ relation from disk- to spheroid-dominated galaxies following a nearly parallel sequence.

Our model suggests that the slope ($\sim 0.54$) of the $j_s-j_{\text{tot}}$ relation is well accounted for the $j_{\text{tot}}-M_{\text{tot}}$ and $M_{\text{tot}}-M_s$ relations that are weakly dependent galaxy morphology. The intercept is determined by the retention factor of angular momentum that is strongly correlated with galaxy morphology, thus leading to a $j_s-j_{\text{tot}}$ relation with a parallel offset from disk to elliptical galaxies. There is no need to assume that $f_j$, $f_m$, and spin parameter $\lambda$ are constant, which has been widely used in previous works (e.g. Jiang et al. 2019). We improve the traditional idea that the $j_s-M_s$ relation is a direct outcome of the $j \propto M^{2/3}$ relation of halos. The conservation of angular momentum in disk galaxies further suggests that neither galactic winds nor fountains (e.g. Governato et al. 2007; DeFelippis et al. 2017) can induce sufficient removal of angular momentum.

4.2. The generation of the $j_s - M_s$ relation: assembly of disks

Figure 4 shows that the $j_s-M_s$ relation of disk galaxies in the local Universe develops at $z \lesssim 1$. Its slope becomes shallower to high redshifts, for example, $\log j_s = 0.35 \log M_s - 1.02$ at $z = 1.5$. At high redshifts, the disk- and spheroid-dominated galaxies follow a similar $j_s-M_s$ relation with a large scatter, indicating that they form via a similar violent, gas-rich evolutionary pathway, thus losing angular momentum at a similar rate.

The deviation from the local $j_s-M_s$ relation is partially explained by the evolution of the $j_{\text{tot}}-M_{\text{tot}}$ relation and the retention factor of angular momentum, as the $M_{\text{tot}}-M_s$ relation has almost no change since $z = 1.5$. The $j_{\text{tot}}-M_{\text{tot}}$ and $M_{\text{tot}}-M_s$ relations at $z = 1.5$ give $\log j_s = 0.46 \log M_s - 1.86$ in the case of $j_{\text{tot}} = j_s$, which still cannot fully explain the index 0.35 of the $j_s-M_s$ relation at high redshifts. This may be due to the fact that galaxies have experienced much more serious losses of angular momentum at $z > 1.5$, during which gas-rich mergers and clumpy instabilities happen frequently. As a consequence, the retention factor $b$ is smaller at high redshifts, as shown in the right-most panel of Figure 3.

The generation of the $j_s-M_s$ relation of disk-dominated galaxies coincides well with the assembly of their disk structures. In Figure 5, we show the relation between sAM of dark matter component $j_{\text{dm}}$ and that of young stars $j_{\text{ys}}$ that form within 1 Gyr in each galaxy for given snapshot. Young stars are considered as tracers of how well angular momentum is conserved when a new star forms from cold gas inflows decoupled from its host dark matter halo. Such young stars contribute significantly to the growth of disks during $z < 1$. Their angular momentum loss due to galaxy mergers is not important during this epoch. In Figure 5, we see that $j_{\text{ys}}$ roughly follows the dashed line corresponding to $y = x$ in disk-dominated galaxies. The retention factor of angular momentum $b$ generally varies between -0.5 to 0.5, corresponding to $f_j \sim 0.3 - 3$. It is worth mentioning that the angular momentum vectors of dark matter and that of stars are roughly aligned with angles peaking at $\sim 20^\circ$ (generally $\lesssim 60^\circ$) in TNG50, which is consistent with the result in Teklu et al. (2015). We therefore ignore the orientation misalignment here. Thus, we can draw a conclusion that angular momentum is roughly conserved in disk galaxies, which leads to the $j_s-M_s$ relation in the local Universe.

Many phenomena have been suggested to induce angular momentum losses or gains in previous works, e.g., dynamical friction, hydrodynamical viscosity, galactic winds (e.g. Governato et al. 2007; Brook et al. 2011), and galactic fountains (e.g. Brook et al. 2012; DeFelippis et al. 2017). Our results indicate such processes mainly redistribute angular momenta rather than reducing them. Moreover, the fact that young stars at $z = 1.5$ have lower angular momentum than those at $z = 0$ may be partially explained by the biased collapse (e.g. van
Figure 2. Evolution of the $j_{\text{tot}}$-$M_{\text{tot}}$ and $M_{\text{tot}}$-$M_*$ relations of central galaxies (colored dots) from $z = 1.5$ (right) to $z = 0$ (left) in TNG50. The redshift is given at the top-left corner. The black and cyan lines correspond to the linear fitting results of all and disk-dominated galaxies, respectively.

Figure 3. Evolution of the $j_*$-$j_{\text{tot}}$ relation of central galaxies in TNG50. This figure uses the same convention as Figure 2. Here the dotted lines highlight the $\log j_* = \log j_{\text{tot}} + b$ scaling relation in an interval of 0.5.
It leads to the result that gas with small angular momenta collapse earlier, then gas inflows later have somewhat higher angular momenta. Disk-dominated galaxies then overall correlate with their parent halos, given a long time evolution. It is also worth emphasizing that the difference of $j_s$ between disk- and spheroid-dominated galaxies is much smaller than that of $j_s$ shown in Figure 3. It suggests that young stars of spheroid-dominated galaxies form disks in a somewhat similar manner to those of disk-dominated galaxies.

5. CONCLUSIONS

In this paper, we show that the TNG50 simulation reproduces the scaling relation between specific angular momentum $j_s$ and mass $M_s$ of galaxies, i.e., the so-called Fall relation, as measured in the local Universe. The disk-dominated central galaxies in TNG50 follow log$_{10}$[$j_s$] = 0.54 log$_{10}$[$M_s$]−2.69, which matches observations perfectly.

Our result confirms that the observed Fall relation is evidence showing that the formation of disk galaxies is tightly correlated with dark matter halos. However, the theoretical $j$-$M$ relation, i.e., $j \propto M^{2/3}$, from dark matter-only simulations is not adequate to explain the $j_s$-$M_s$ relation. We suggest that the $j_s$-$M_s$ relation of disk galaxies at the local Universe can be well explained by a simple model giving $j_{tot} \propto M_{tot}^{0.8}$, $M_{tot} \propto M_s^{0.67}$, and $j_s \propto j_{tot}$, where $j_{tot}$ and $M_{tot}$ are the overall specific angular momentum and mass of halos. The index 0.54 of the $j_s$-$M_s$ relation comes from the indices of the $j_{tot}$-$M_{tot}$ and $M_{tot}$-$M_s$ relation that are almost independent of the galaxy morphology. The retention factor of angular momentum $j_s/j_{tot}$ is $\sim 1$ in galaxies with strong rotation, while it anti-correlates with the spheroid’s mass. This leads to the morphological dependence of the $j_s$-$M_s$ relation from disk to elliptical galaxies.

We further show that the local $j_s$-$M_s$ relation develops at $z \lesssim 1$ in disk galaxies. Disk- and spheroid-dominated galaxies follow a similar $j_s$-$M_s$ relation with index 0.35 at $z = 1.5$. Disk structures form or grow massive later, thus leading to the $j_s$-$M_s$ relation at the local Universe. Angular momentum is roughly conserved during the formation of new stars in disk galaxies. It is worth emphasizing that the power law index of the $j_{tot}$-$M_{tot}$ relation increases from $\sim 0.68$ to $\sim 0.8$ from $z = 1.5$ to 0, which plays an important role in generating the $j_s$-$M_s$ relation. This is inconsistent with the expectation of dark-matter-only simulations.

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Figure 4. The evolution of $j_s - M_s$ (Fall) relation in TNG50 from $z = 1.5$ to $z = 0$. This image uses the same convention as Figure 2. The observations of Romanowsky & Fall (2012) (black lines) are overlaid to compare with the evolution of the $j_s - M_s$ relation of disk-dominated galaxies (cyan lines).

Figure 5. The evolution of the $j_{ys} - j_{dm}$ relation in TNG50 from $z = 1.5$ to $z = 0$. This image uses the same convention as Figure 2. We exclude the cases with small star formation rate of $< 0.1 M_{\odot}/yr$ in the last 1 Gyr, i.e., quenched galaxies, which only contribute a small fraction ($\sim 1/4$ at $z = 0$) of even spheroid-dominated galaxies.

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