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Galaxy Group Ellipticity Confirms a Younger Cosmos

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Abstract: We present an analysis of the ellipticities of galaxy groups, derived from the spatial distribution of member galaxies, revealing a notable incongruity between the observed local galaxy groups and their counterparts in the Lambda cold dark matter cosmology. Specifically, our investigation reveals a substantial disparity in the ellipticities of observed groups with masses $10^{13.0} < M_{\rm h} < 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$ exhibiting significantly higher ellipticities (at a confidence level of approximately 4σ) compared to their simulated counterparts. Notably, the consistent use of the same group finder for identifying galaxy groups in both observational and simulated datasets underscores the robustness of this result. This observation may imply a potential incongruence between the inferred age of the Universe from observations and the predictions of the model, which aligns with the younger Universe hypothesis suggested by the elevated fraction of observed satellite pairs with correlated line-of-sight relative velocities compared to simulations. Our findings significantly strengthen the plausibility of a younger age for our Universe.

Keywords: methods; statistics methods; observational galaxies; groups; general (cosmology); large-scale structure of Universe

1. Introduction

Over the past several decades, the Lambda cold dark matter (ΛCDM) paradigm has emerged as the predominant model for structure formation in our Universe. Given the initial amplitude of perturbations, structures form hierarchically within the ΛCDM cosmology, through gravitational collapse and mergers of smaller objects. The collapse amplifies the initial anisotropy of matter distribution, giving rise to a complex pattern of sheets, filaments, and knots, delineating large under-dense voids e.g., [1–5]. Galaxies adhere to this network, undergoing a sequence of clustering, interaction, and merging, gravitating towards denser regions along well-defined paths, from the voids to the sheets, the sheets feeding the filaments, and the filaments ultimately channeling galaxies towards the knots, culminating in the formation of galaxy groups [6–12]. Consequently, the motions of member galaxies in galaxy groups encapsulate valuable information about the growth of host structures e.g., [13]. Furthermore, the distribution and alignment of member galaxies also encode essential information about their assembly history and the dynamical states of their host large-scale structures [14–20].

Therefore, the investigation of the motions and distributions of member galaxies in galaxy groups holds the potential to provide insights into the understanding of structure formation and the testing of the ΛCDM model. In the local group, the preferential co-planar and co-rotating arrangement of satellite dwarf galaxies around the Milky Way and M31 suggests a possible origin related to galaxy interactions [21–23], or an isotropic accretion of satellite galaxies along cosmic web filaments [24–27]. The spatial distribution of member galaxies in loose galaxy groups such as galaxy pairs and triplets has been observed to align with large-scale filamentary structures, indicating a tendency for clustering along filaments [8,9], while the absence of alignment in compact pairs and triplets implies multiple interactions and a potentially equilibrium state within the systems [28]. Similarly,

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an anisotropic distribution of galaxies in a galaxy cluster is often accompanied by structural interaction, clumpy hot gas distribution, and non-virilized velocity distribution [29–36]; in contrast, a more relaxed galaxy group is expected to exhibit a more isotropic distribution of galaxies and radial alignment of satellites [14–17], as violent relaxation misanthropizes objects through the time-dependent gravitational potential. Furthermore, the satellite pairs on both sides of the central galaxies in galaxy groups have been found to display correlated line-of-sight velocities relative to the central galaxies, with their relative velocities tending to be either positive or negative, indicating a history of infalling for the member galaxies. Drawing on these insights, a comparison of the distribution and motions of member galaxies in observations and simulations can aid astronomers in testing the ΛCDM cosmology and in evaluating the age and state of the large-scale structure in which the current member galaxies reside.

In a recent study, Gu et al. (2024) [13] made a noteworthy discovery, revealing that the proportion of satellite pairs exhibiting correlated velocities in observational data significantly exceed that predicted by simulations based on the ΛCDM framework. This intriguing finding raises the possibility that our Universe may be younger than anticipated or, alternatively, that the ΛCDM model may not be as robust as previously thought. Motivated by the implications of this study, we endeavour to explore the distributions of member galaxies within galaxy groups and group ellipticities in the present work. Given that both the analyses of member galaxy motions and distributions within groups are minimally contingent on galaxy formation models and intrinsic properties, it is anticipated that observed galaxy groups would manifest greater ellipticities in comparison to simulations if our Universe is indeed younger. This expectation arises from the premise that a younger Universe corresponds to a shorter duration since the accretion of galaxies into the galaxy groups, thereby rendering the groups less dynamically relaxed.

In Section 2, we will provide an introduction to the galaxy group catalogues utilized in both observational and simulated analyses, obtained using the same group finder. Section 3 will encompass a comparative analysis of the ellipticities of groups in observational and simulated datasets. Our findings will be discussed and summarized in Section 4. In this paper, we use "log" to represent "$\log_{10}$", and use $h = H_0/100$ to denote the Hubble constant.

2. Galaxy Group Samples in Observation and Simulation

In our observational analysis, we utilize the galaxy group catalogue developed by Yang et al. (2007) [37], which is derived from the Sloan Digital Sky Survey (SDSS) DR7 data [38] and selected using a "halo-based" group finder. The galaxy sample utilized for identifying galaxy groups is selected from the New York University Value Added Galaxy Catalogue (NYU-VAGC) [39] of the SDSS DR7, with redshifts in the range of $0.01 < z < 0.20$, spectroscopic completeness greater than 0.7, and r-band flux-limited of $r < 17.77$ mag, where r denotes the extinction-corrected Petrosian magnitude in the r-band. The stellar mass of each galaxy is estimated from the r-band absolute magnitude and colour between the g and r bands, $g - r$, by applying the mass-to-light ratio of Bell et al. (2003) [40]. When identifying galaxy groups, the halo-based group finding algorithm developed by Yang et al. (2007) [37] is implemented, which identifies groups based on dark matter halo properties, such as mass and velocity dispersion, expected from the CDM cosmogony. We refer the reader to Yang et al. (2005) [41] and Yang et al. (2007) [37] for details. This particular group catalogue has demonstrated its efficacy in the examination of large-scale structures and the properties of member galaxies e.g., [42–46]. In order to reduce boundary effects, in this study, we exclude the galaxy groups with $0 < f_{\rm edge} < 0.7$, where $f_{\rm edge}$ is the fraction of the volume of a group that lies within the survey boundary.

For comparative purposes, we turn to the galaxy groups within the cosmological L-GALAXIES simulation and conduct a comparison of their ellipticities with those observed. L-GALAXIES is chosen due to its expansive simulation box, spanning approximately 500 Mpc. The galaxy formation model, as detailed in Henriques et al. (2015) [47], implemented in L-GALAXIES represents an updated iteration of the Munich semi-analytic

model e.g., [48,49] established upon the Millennium Simulation [50]. L-GALAXIES employs a Markov Chain Monte Carlo (MCMC) method to explore the high-dimensional parameter space, aiming to replicate the observed galaxy abundance and properties as a function of stellar mass from redshift z∼3 to z∼0.

Within L-GALAXIES, halos, or galaxy groups, are identified using the friends-of-friends (FOF) group algorithm, which links particles separated by 0.2 times the mean inter-particle separation [3] at each redshift snapshot. The SUBFIND algorithm [51] is subsequently utilized to identify the self-bound subhalos within each halo. It is important to note that due to the disparate methods employed for group identification, a direct comparison of the shapes of the simulated and observed galaxy groups may introduce systematic bias in the estimation of ellipticity.

In order to facilitate a reliable comparison with the observational data, we constructed a mock catalogue of galaxy groups for L-GALAXIES to account for potential observational selection effects by following the method described in Lim et al. (2017) [52]. We refer the reader to Lim et al. (2017) for details. This involved stacking duplicates of the original simulation box alongside each other to create a suitably large volume. Subsequently, we designated an observer location within the constructed volume, and calculated the redshift and apparent magnitude for each galaxy based on its luminosity, distance, and relative motion with respect to the observer. Finally, we selected a flux-limited sample ($r < 17.77$ mag) of galaxies from a light cone covering the redshift range $0.01 < z < 0.2$, similar to the ranges covered by the SDSS data, and applied the same group finder used in the study by Yang et al. (2007) [37] to identify galaxy groups.

3. Ellipticity of Galaxy Groups

In this investigation, we leverage the spatial distribution of member galaxies to infer the ellipticities of galaxy groups in both observational and simulated datasets. To mitigate the influence of redshift-induced distortions, we calculate the ellipticity in the projected sky plane. The configuration of a galaxy group comprising N member galaxies is approximated using the inertia tensor,

$$I_{\alpha\beta} = \Sigma_{i=1}^{N} w_i x_{i,\alpha} x_{i,\beta}, \quad (1)$$

where w_i denotes the weight assigned to the i-th member galaxy, α and β are the inertia tensor indices taking values of 1 or 2, and $x_{i,\alpha}$ represents the position of the i-th galaxy relative to the centroid of the galaxy group in the projected sky plane (for this study, we adopt the luminosity-weighted group center). Subsequently, the axis lengths a and b ($a \geq b$) of the ellipsoidal group are derived from the eigenvalues λ_1 and λ_2 ($\lambda_1 \geq \lambda_2$) of the inertia tensor, where $a = \sqrt{\lambda_1}$ and $b = \sqrt{\lambda_2}$.

In this investigation, we employ three distinct methods to estimate the ellipticity of galaxy groups. Method (1), akin to the approach used by Wang et al. (2008) [53], involves setting $w_i = 1$ for all member galaxies, signifying equal weights for different member galaxies within a group. Method (2), akin to the approach proposed by Wang et al. (2020) [54], entails setting $w_i = 1/R_i^2$, where R_i represents the distance from the i-th member galaxy to the group center. In this method, greater weight is assigned to members in closer proximity to the group center. Method (3), similar to the approach adopted by Shao et al. (2016) [55], involves setting $w_i = m_{\star,i}$, where $m_{\star,i}$ denotes the stellar mass of the i-th member galaxy, thereby assigning greater weight to more massive member galaxies.

To ensure accurate estimation of the ellipticity ($\epsilon = 1 - b/a$) of a galaxy group, we exclude groups with low richness ($N < 20$) or low masses ($M_{\rm h} < 10^{13.0}$ $\mathrm{M}_{\odot}$ h^{-1}). Subsequently, we partition the groups in both the simulation and observation datasets into distinct mass bins and compute the average ellipticity, $\langle\epsilon\rangle$, of groups within each mass bin, along with the error of the average axis ratio (i.e., $\sigma_\epsilon/\sqrt{K}$, where σ_ϵ represents the standard deviation of axis ratios of groups within a mass bin, and K denotes the number of groups in the corresponding bin). The average group axis ratio as a function of group mass for the simulated and observed galaxy groups is depicted in Figure 1.

Our findings indicate that across all mass bins where $M_{\rm h} < 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$, the observed galaxy groups exhibit a higher average ellipticity compared to the simulated groups, irrespective of the method employed for ellipticity estimation. Specifically, the observed groups with $M_{\rm h} < 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$ are found to be more elliptical than the simulated counterparts at confidence levels of 4.7σ, 3.8σ, and 4.2σ for estimation methods (1), (2), and (3), respectively. Notably, the disparity in ellipticity between the simulation and observation appears to diminish as the group mass exceeds $M_{\rm h} > 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$.

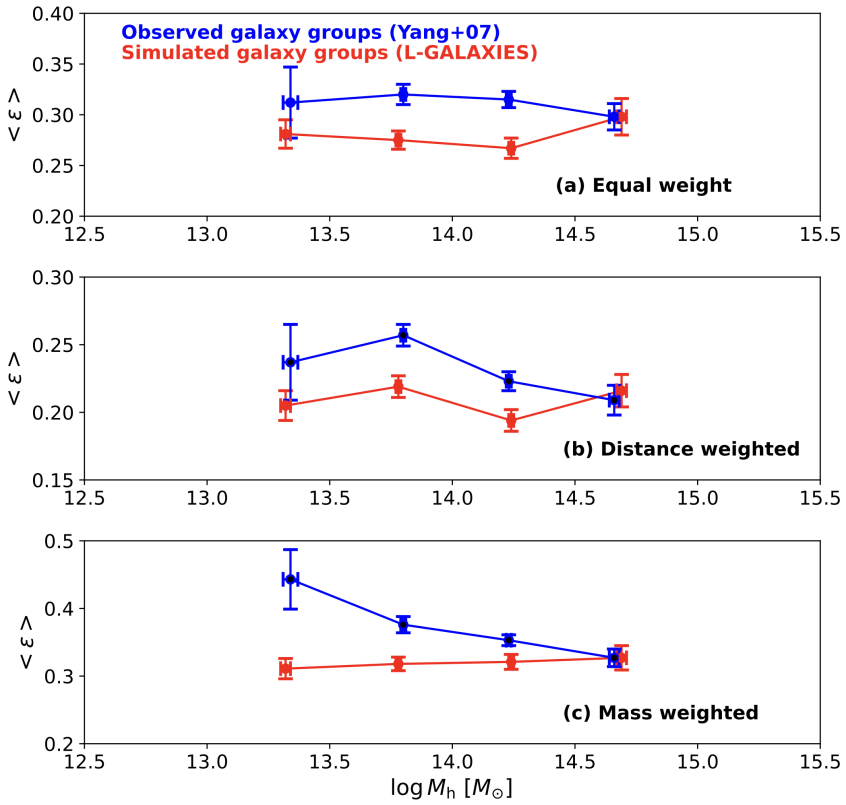


Figure 1. The comparison between average ellipticities of the observed (depicted in blue colour) and simulated (depicted in red colour) galaxy groups with the same group finder. Panels (**a**–**c**) correspond to Method (1), (2), and (3), respectively. The galaxy group samples are split into the different mass bins, within $10^{13.0} < M_{\rm h} < 10^{13.5}\,{\rm M}_{\odot}\,h^{-1}$, $10^{13.5} < M_{\rm h} < 10^{14.0}\,{\rm M}_{\odot}\,h^{-1}$, $10^{14.0} < M_{\rm h} < 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$, and $M_{\rm h} > 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$. Each point and the corresponding error bar represent the average ellipticity and error of the average value.

4. Discussion

We find that the observed galaxy groups with masses of $M_{\rm h} < 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$ exhibit a statistically significantly higher degree of ellipticity compared to their simulated counterparts. Notably, to ensure robustness and reliability, we have employed three distinct weighting methodologies for estimating group ellipticities and, strikingly, our findings remain consistent and independent of the chosen estimation approach. The discernible disparity in ellipticities between observed galaxy groups and simulation outcomes may indicate that the dynamical states of the observed galaxy groups are potentially younger than anticipated. Notably, the most massive groups in both simulations and observations, characterized by masses exceeding $M_{\rm h} > 10^{14.5}\,{\rm M}_{\odot}\,h^{-1}$, exhibit minimal differences in ellipticity, as evidenced by their closely aligned average ellipticity values (differing at a confidence level of less than 1σ). This convergence in ellipticity could plausibly be attributed to the faster relaxation and advanced dynamical age of these massive groups.

Our findings align with the notion of a Universe that is younger than originally postulated, a conclusion that resonates with the findings of Gu et al. (2024) [13] regarding

the heightened fractions of satellite pairs in galaxy groups displaying correlated line-of-sight velocities relative to the central galaxies. Importantly, both our investigations and the aforementioned study by Gu et al. (2024) [13] draw upon N-body cosmological simulations, which are minimally contingent on galaxy formation models and chemical enrichment models. Consequently, the convergence of our conclusions significantly strengthens the plausibility of a younger age for our Universe.

On the contrary, it is important to consider that a warm dark matter (WDM) cosmology also has the capacity to engender heightened infalling velocities of member galaxies, which in turn correspond to an elevated proportion of satellites exhibiting substantial and co-oriented velocities relative to the central galaxy [56] (we refer the reader to Figure 10 and Section 3.6 of [56]), as compared to the predictions of the ΛCDM cosmology. It is worth noting that a WDM cosmology, with an appropriate particle mass, could feasibly account for the observations reported by Gu et al. (2024) [13]. Nevertheless, it is also worth to acknowledge that a WDM cosmology would concurrently yield a more isotropic distribution of member galaxies within a galaxy group (we refer the reader to Figure 6 of [56]), a trend that contradicts our own findings. Consequently, it is evident that WDM cosmology does not present a viable framework to reconcile these disparate results.

It is also worth considering that the lower density fluctuations, denoted as σ_8 in the early Universe, may also account for the more elliptical galaxy groups detected in observations [15]. Particularly, the σ_8 of L-GALAXIES is high, with $\sigma_8 \sim 0.9$, whereas the Planck measurements of the cosmic microwave background give $\sigma_8 \sim 0.8$ [57,58]. Therefore, the ellipticity difference between the observed and simulated galaxy groups may be explained as the different σ_8. However, the lower σ_8 cannot account for the results of Gu et al. (2024) [13] (in [13], the fractions of satellite pairs with correlated velocities in TNG300 [59,60], which applies $\sigma_8 \sim 0.8$, are still much lower than the observables). Consequently, it is evident that the lower σ_8 also does not present a viable framework to reconcile these disparate results.

We also acknowledge the potential influence of background or foreground interlopers, introduced by the group finder, which could conceivably contribute to a more spheroidal group shape. However, it is crucial to emphasize that in this study, the identical group finder was uniformly applied to identify both the observed and simulated groups. Consequently, the level of contamination in both the observational and simulated datasets should theoretically be comparable, rendering it implausible for this factor alone to account for such a substantial disparity.

Furthermore, we systematically varied the threshold for selecting groups, transitioning from a richness criterion of $N > 20$ to $N > 10$, or $N > 30$, among others, and consistently arrived at a similar overarching conclusion. Additionally, we conducted an analysis utilizing the brightest galaxies or most massive galaxies as the group centres and, remarkably, the adjustment yielded no discernible changes in ellipticity difference.

Finally, it is worth noting that the recent observational research on globular clusters by Llorente de Andrés (2024) [61] suggests that the age of the Universe may be older than theorized. Furthermore, observations with the James Webb Space Telescope (JWST) have also revealed the presence of numerous high-redshift massive galaxies, e.g., [62,63]. Given that galaxies require sufficient time for star formation, these findings may also indicate that the Universe is somewhat older than expected. However, it should be pointed out that these observational studies heavily depend on the assumed galaxy formation models and chemical evolution models, which are quite uncertain, particularly for the cases in the early Universe. In contrast, our work and that of Gu et al. (2024) [13] are primarily based on the hierarchical structure formation theory within the framework of ΛCDM, with little relevance to galaxy formation models. Therefore, our work and that of Gu et al. (2024) may be more credible.

5. Conclusions

Taking advantage of the galaxy group catalogue derived from observational data in conjunction with the mock group catalogue generated from cosmological simulations,

both obtained through the application of a consistent group finder, our analysis reveals that observed galaxy groups with masses of $M_{\rm h} < 10^{14.5}$ $M_\odot$ h^{-1} exhibit a statistically significantly higher degree of ellipticity compared to their simulated counterparts at a confidence level of approximately 4σ.

We find that the discernible disparity in ellipticities between the observed galaxy groups and simulation outcomes cannot be explained by a warm dark matter cosmology or lower density fluctuations in the early Universe, but suggest that the observed galaxy groups are potentially younger than anticipated and, thus, that the observed cosmic age may be younger than the theoretical prediction.

Our conclusions are consistent with those of Gu et al. (2024), further confirming that the actual age of the Universe may be younger than expected based on theory.

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Abbreviations

The following abbreviations are used in this manuscript:

ΛCDM	Lambda cold dark matter
FOF	Friends-of-friends
MCMC	Markov Chain Monte Carlo
WDM	Warm dark matter
JWST	James Webb Space Telescope
SDSS	loan Digital Sky Survey

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