Formation of the Large Nearby Galaxies

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ABSTRACT

Observations of the nearby \( L \sim L_* \) galaxies that can be examined in particularly close detail suggest that many have small luminosity fractions in bulges and haloes. Simulations of galaxy formation tend to place star particles in orbits seriously different from circular in numbers far greater than seem reasonable for the bulges and haloes of these nearby spirals. I offer an example of how the situation might be improved: a prescription for non-Gaussian initial conditions on the scale of galaxies.

Key words: galaxies: bulges – galaxies: haloes – galaxies: formation – cosmology: large-scale structure of universe

1 INTRODUCTION

The ΛCDM cosmology was convincingly established in part because most of its predictions can be computed from first principles by perturbation theory. It is essential that observations agree with predictions, of course, but equally essential that we can trust the predictions. This is not a value judgement, it is just to say that establishing a persuasive case for the ΛCDM theory proved to be relatively straightforward.

Galaxy formation cannot be analyzed from first principles. It is impressive that large-scale numerical simulations based on the ΛCDM cosmology produce good approximations to real galaxies. And it is inevitable that there are differences between model and observation because galaxy formation is a complex process. The differences are guides to better ways to model the complexity.

The possibility that motivates the present study is that theory and observation disagree because some aspect of the physical situation is significantly different from the standard ΛCDM theory. This cosmology was assembled out of the simplest assumptions I could get away with (Peebles 1982, 1984), and it is not at all surprising to find that some are oversimplifications. An example is the tilt from scale-invariant initial conditions. The length scale issue may be another hint to a better theory (Verde, Treu, & Riess 2019). The example discussed here is that simulations of galaxy formation tend to produce a much larger fraction of star particles in far from circular orbits than seems reasonable for a typical close to pure disc \( L \sim L_* \) galaxy.

The challenge of reconciling thin galaxies with the hot distributions of orbits found in model galaxies is noted by Kautsch, Grebel, Barazza, & Gallagher (2006): “Cosmological models do not predict the formation of disc-dominated, essentially bulgeless galaxies, yet these objects exist.” Elias, Sales, Creasey, et al. (2018) put it that “To first order, galaxies with little or no stellar halo are difficult to find in cosmological simulations within ΛCDM where mergers are a prevalent feature” but “How can a galaxy avoid merging and disrupting satellites throughout its entire history?” (Italics in the original). A discussion of the possible lessons for cosmology seems to be in order.

Section 3 reviews the natures of the stellar haloes and bulge types in the large galaxies that are close enough that they can be examined in best detail. These observations are compared to what might be expected from numerical syntheses of galaxy formation in Section 4. Section 4.5 presents a summary in the form of five challenges to accepted ideas, along with cautions about the limitations of the evidence. The conclusion offered in Section 4.6 is that a more promising picture for galaxy formation would be closer to the Eggen, Lynden-Bell & Sandage (1962) near monolithic collapse. Section 5 offers examples of non-Gaussian initial conditions that change the situation in this direction. Non-Gaussianity is small on scales probed by the cosmic microwave background radiation, but may be significant on the smaller scales of galaxies. For simplicity I use the warm dark matter initial mass fluctuation power spectrum. Again, it has challenges that may be met by suitably contrived initial conditions. We must be wary of contrived models, but we must be aware of the evidence.

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2 STELLAR HALOES AND HOT OR COLD BULGES

Properties of classical bulges, pseudobulges, and stellar haloes are well discussed in the literature. This review explains my understanding of some fundamental issues.

2.1 Classical Bulges and Pseudobulges

I take it that a classical bulge of a spiral galaxy is largely supported by a roughly isotropic distribution of stellar velocities, a situation similar to that of an elliptical galaxy. I take it that a pseudobulge is largely supported by a well-ordered flow of stars, perhaps in the manner of the disc stars in a spiral galaxy. The more cautious Kormendy & Kennicutt (2004) statement is that pseudobulges may “have one or more characteristics of discs [such as] large ratios of ordered to random velocities.” My working assumption is that this large ratio is the defining feature. Cold streaming flow in a pseudobulge would allow formation of the observed spiral arms, rings, and bars, just as the cold flow of stars in a disc allows spirals. A classical bulge may be significantly flattened by angular momentum. The same is true of an elliptical galaxy of similar luminosity (Davies, Efstathiou, Fall, & Schechter 1983; de Zeeuw & Franx 1991). The hot distribution of orbits in an elliptical tends to discourage pattern formation, but ellipticals can exhibit shells presumed to be sheets in phase phase produced by dry mergers. The hot orbits in classical bulges seem to make them featureless, but I am not aware of a search for shells.

The categories, hot and cold, tell us something about how bulges formed. Stars that formed in subhaloes before merging with the protogalaxy are not likely to have joined the cold distribution of orbits in a pseudobulge. Pseudobulges more likely formed from gas and plasma that settled to support by streaming flow before being incorporated in stars. Classical bulges could have grown out of stars that formed in subclusters before merging, if in concentrations compact enough to have resisted tidal disruption until joining the bulge. Or diffuse matter may have tumbled toward the center of the growing galaxy and collapsed to stars before it could have settled to organized streaming motion. Or classical bulge stars may have formed in a disc that contracted to a bar that was so violently unstable that gravity rearranged the stars into the cuspy radial distribution characteristic of a classical bulge. I take the point to be that classical bulges likely formed in conditions far from dynamical equilibrium, while pseudobulges likely formed in conditions close to organized flow in dynamical equilibrium.

2.2 The Circularity Parameter

Model galaxy discs and bulges often are characterized by the distributions of the circularity parameter \( \epsilon \) of a star particle orbit,

\[
\epsilon = J_z/J_c.
\]

The component of the angular momentum of the star particle normal to the disc is \( J_z \), and \( J_c \) is the angular momentum of a particle in a circular orbit in the plane of the disc with the same energy as the star particle.

Abadi, Navarro, Steinmetz, & Eke (2003) introduced the elegant decomposition of the frequency distribution of \( \epsilon \) into a spheroid component centered near \( \epsilon = 0 \) that could include a classical bulge and stellar halo; a thick disc that would have values of the circularity parameter closer to \( \epsilon = 1 \); and a thin disc with circularity parameters quite close to \( \epsilon = 1 \). Other early applications of this statistic include Governato, Willman, Mayer, et al. (2007) and, in a variant of this statistic, Scannapieco, Tissera, White, & Springel (2008). The distribution of circularity parameters in the Guedes, Mayer, Carollo, & Madau (2013) Eris simulation (in the middle panel in their fig. 5) has a prominent peak at \( \epsilon = 1 \) from star particles that are in close to circular orbits, as in a disc, and a local maximum at \( \epsilon = 0 \), as from stars in a slowly rotating classical bulge or stellar halo. Most star particles in the range \( 0 < \epsilon < 0.8 \) are within 2 kpc of the center. They are moving in the direction of rotation of the disc, but not close to support by circular motion. These star particles are good candidates for a classical bulge. I take the Eris distribution to be a useful standard for comparison to the later progress in simulations reviewed in Section 4.4.

It is helpful to have an illustration of the relation between values of \( \epsilon \) and the natures of the orbits. Consider a model galaxy with a spherically symmetric mass distribution, in an approximate to a dark matter halo, a flat rotation curve at circular speed \( v_c \), and a massless disc of stars. The galactocentric radius and angular position of a particle moving in the plane of the disc at circularity parameter \( \epsilon \) satisfy

\[
(dr/dt)^2 = v_c^2 \left( 1 - 2 \log \frac{r}{R} - (\epsilon R/v)^2 \right),
\]

\[
d\theta/dt = \epsilon R v_c/|R|.
\]

The circular orbit with the same energy has radius \( R \).

If \( \epsilon \) is close to unity then in lowest nonzero order in perturbation theory the maximum departures from a circular orbit, where \( dr/dt \) vanishes, satisfy

\[
r_x = R(1 \pm \delta_x), \quad \delta_x^2 = (1 - \epsilon^2)/2.
\]

At \( \epsilon = 0.8 \) the extrema of the galactocentric distances in this approximation are \( r = R(1 \pm 0.4) \). For a simple measure of the radial velocity note that at radius \( r = R \) equation (2) is

\[
(dr/dt) = \pm v_c \sqrt{1 - \epsilon^2}, \text{ at } r = R.
\]
At circularity parameter \( \epsilon = 0.8 \) the radial speed at \( r = R \) is 60% of the circular velocity \( v_c \).

A numerical solution to equation (2) is shown in Fig. 1. The computed maximum and minimum radius and the rms radial velocity at this value of the circularity parameter, \( \epsilon = 0.8 \), are
\[
\begin{align*}
\max \frac{dr}{dt} & = 1.40 R, \quad \min \frac{dr}{dt} = 0.53 R, \quad (\langle \frac{dr}{dt}\rangle)^2 = 0.43 v_c. \quad (5)
\end{align*}
\]
At \( \epsilon = 0.9 \) the numbers are
\[
\begin{align*}
\max \frac{dr}{dt} & = 1.30 R, \quad \min \frac{dr}{dt} = 0.67 R, \quad (\langle \frac{dr}{dt}\rangle)^2 = 0.31 v_c. \quad (6)
\end{align*}
\]
These numerical results are reasonably consistent with equations (3) and (4).

Under the assumption of a spherically symmetric mass distribution we can let the orbit in Fig. 1 be tilted from the disc by angle \( \theta = 25^\circ \). Then the orbit occasionally rises normal to the disc by maximum distance \( h = \max \sin \theta = 0.6R \). The eccentricity parameter in this tilted example is \( \epsilon = 0.8 \cos \theta = 0.72 \). A common choice of the disc particles in a model galaxy is \( \epsilon \geq 0.7 \).

The point of this model is that a distribution of orbits with \( \epsilon \sim 0 \) to 0.9 includes fractional departures \( 30 \) to 40 per cent from circular motion in radius and radial velocity, and possibly rising out of the disc by like amounts. The model is an approximation, but the indicated departures from circular flow at the values of \( \epsilon \) conventionally assigned to the disk are large enough to motivate inclusion in the list of challenges in Section 4.5.

### 2.3 Other Measures

Bulge types of spiral galaxies often are defined by the fit of the surface brightness \( i \) normal to the disc as a function of galactocentric radius \( r \) to the sum of an exponential to represent the disc and a Sérsic function to represent the bulge component,
\[
\log i = A - Br - C r^{1/n}. \quad (7)
\]
The constants \( A, B, C \), and \( n \) are fitting parameters. De Vaucouleurs (1948) introduced the third term with \( n = 4 \) to describe the surface brightness run in an early-type galaxy; Sérsic (1963) proposed the generalization to a free value of \( n \); Freeman (1970) pioneered application of the sum of de Vaucouleurs’ form and the exponential to measured surface brightness runs in spirals, and Andreadakis, Peletier, & Balcells (1995) used the generalization to the free parameter \( n \) in equation (7). A fit of the measured surface brightness run with Sérsic index \( n > 2 \), meaning a cuspy central concentration of starlight, is taken to indicate a classical bulge. A pseudobulge defined by this fit has Sérsic index \( n < 2 \), meaning a less cuspy central peak, maybe approaching the exponential \( n = 1 \) characteristic of the radial distribution of disc stars.

Gadotti (2009) introduced another bulge classification. Classical bulges are taken to be those with bulge half-light radius \( r_e \) and average surface brightness \( (\mu_e) \) consistent with the correlation observed for elliptical galaxies, and pseudobulges are taken to be the lower surface brightness outliers. Gadotti’s measure is a helpful indicator that elliptical galaxies are more similar to classical bulges than pseudobulges. The Sérsic index \( n = 1 \) is a helpful indicator of whether the bulge star distribution bears a natural relation to the disc, with Sérsic index closer to \( n = 1 \), or more naturally to an elliptical-like bulge with index closer to \( n = 4 \). Gadotti (2009) applied this criterion to SDSS images, and Gao, Ho, Barth, & Li (2020) used it in analysis of the Carnegie-Irvine Galaxy Survey (CGS).

As remarked in Section 2, another kind of pseudobulge may be indicated by the presence of a bar that grew out of the instability of a cold circular flow of disc stars.

I do not know how reliably the nature of bulge support, whether hot or cold, can be determined by these or other indicators applied to real galaxies. But close observations of the nearby \( L \sim L_\star \) galaxies seem to be a promising place to start.

### 3 BULGES OF NEARBY LARGE GALAXIES

Table 1 is a list of measurements of the ratios \( B/T \) of bulge to total luminosity for 34 galaxies at distances less than 10 Mpc and luminosities \( L \sim L_\star \). It includes the 27 galaxies with K-band luminosities \( L_K > 10^{10} \) and distances \( D \leq 10 \) Mpc in the Local Universe catalog maintained by Brent Tully et al.\(^1\) The other 7 galaxies with absolute magnitudes \( M_B < -19.6 \) are drawn from the list in Fisher & Drory (2011). The different wavelengths mean different bounds on stellar masses. The most extreme case, NGC 2787, has K-band luminosity above the cut and B-band luminosity well below the optical cut. The situation may be related to the impression of considerable dust across the face of this galaxy. The other galaxies with listed values of \( L_K \) and \( M_B \) would be included by either cut, or reasonably close to it.

The last column in Table 1 is the bulge type, C or P for classical or pseudobulge, and the source for the bulge type and measured \( B/T \) are \( K \) for Kormendy, Drory, Bender, & Cornell (2010) and \( F \) for Fisher & Drory (2011). Where both papers give a measurement of \( B/T \) I use the Kormendy et al. value. The two are not very different. The 19 measurements from Kormendy et al. were meant to be a reasonably complete sample to 8 Mpc distance. The Fisher & Drory measurements are largely at distances 8 to 10 Mpc, the few nearer than 8 kpc a result of the use of different distance measurements.

Kormendy et al. give luminosities of both a classical bulge and a pseudobulge in M94 and NGC 2787; the sums of the luminosities are entered in Table 1. I do not include three galaxies with Kormendy et al. B/T measurements: M82, because the definition of its stellar bulge seems likely to be awkward; M51b, which is the spread of stars at the edge of the otherwise elegant M51a spiral galaxy; and NGC 4490, which looks like a galaxy in the process of merging or falling apart. Six of the \( L_\text{U} \) galaxies that pass the cuts \( D < 10 \) Mpc and \( L_K > 10^{10} \) do not have bulge luminosities listed in either source. Three of them, NGC 2640, NGC 1023, and NGC 2784, look like early types. Three, NGC 4517, NGC 4631, and NGC 891, look like normal close to edge-on discs in which dust may or may not obscure significant bulge luminosities. But these six galaxies do not seem to be seriously atypical of what I take to be the local \( L \sim L_\star \) sample.

\(^1\) Available at the Extragalactic Distance Database, http://edd.ifa.hawaii.edu as the catalog ‘Local Universe (LU)’.
The considerable fraction of nearby classical bulges. But to my mind the striking observation is Nebula M 31, and the spiral M 81, have relatively prominent puffed-up elliptical; the other half is a disc. The Andromeda Sombrero Galaxy M 104 is a stellar bulge or halo, maybe a lies with larger values of B/T are named. The three with total luminosities in the local L* sample. The galax-

ty D, Mpc B/T type
M31 0.01 0.19 ± 0.02 P K
NGC4945 3.4 0.073 ± 0.012 P K
Maffei1 3.4 1 C K
IC342 3.4 0.030 ± 0.001 P K
Maffei2 3.5 0.16 ± 0.04 P K
CenA 3.6 1 C K
M81 3.6 0.34 ± 0.02 C K
NGC253 3.7 0.15 P K
Circinus 4.2 0.30 ± 0.03 P K
M64 4.4 0.20 CP K
M94 4.4 0.36 ± 0.01 P K
M83 4.9 0.074 ± 0.016 P K
NGC6946 6.2 0.024 ± 0.003 P K
NGC3621 6.6 0.01 P F
M101 7.0 0.027 ± 0.008 P K
M96 7.2 0.26 P F
NGC2787 7.5 0.39 CP K
M106 7.6 0.12 ± 0.02 C K
NGC2683 7.7 0.05 ± 0.01 C K
M63 7.9 0.19 P F
M66 8.3 0.10 P F
M51 8.4 0.095 ± 0.015 P K
NGC2903 8.5 0.10 P F
M74 9.0 0.08 P F
NGC4096 9.2 0.08 P F
NGC6744 9.2 0.15 C F
NGC925 9.4 0.07 P F
M108 9.6 0.21 P F
Sombrero 9.8 0.51 C F
NGC3344 9.8 0.08 C F
M105 10.0 1. C F
M95 10.1 0.16 P F
M65 10.1 0.16 P F

Table 1. The Nearby Galaxy Sample

There are no massive cD or LRG galaxies with luminosities L ∼ 10L* in this sample, but they are rare. Since L ∼ L* galaxies contribute most of the global starlight it is reasonable and customary to consider them the dominant galaxy class. I have attempted to make Table 1 a reasonably close to fair sample that offers close-up looks at typical dominant galaxies outside rich clusters. The galaxies in Table 1 have been characterized by seasoned observers, but it may be well to bear in mind that I cannot offer much support for my assumption that these galaxies constitute a fair sample of the L ∼ L* galaxies outside rich clusters.

Fig. 2 shows the distribution of ratios B/T of bulge to total luminosities in the local L ∼ L* sample. The galaxies with larger values of B/T are named. The three with B/T close to unity are ellipticals. Half the luminosity of the Sombrero Galaxy M 104 is a stellar bulge or halo, maybe a puffed-up elliptical; the other half is a disc. The Andromeda Nebula M 31, and the spiral M 81, have relatively prominent classical bulges. But to my mind the striking observation is the considerable fraction of nearby L ∼ L* galaxies that are close to pure discs. An example is M 101. Kormendy et al. (2010) showed, and Peebles (2014, fig. 3) used their results to illustrate, the spiral pattern that runs quite close to the ∼ 10^9 M_☉ nuclear star cluster. This pattern suggests the stellar velocity dispersion relative to the mean in the inner parts of this galaxy is small enough to allow the formation of features, down to the star cluster that I suppose is supported by near isotropic motions. We might say this galaxy has a classical bulge with luminosity four orders of magnitude less than the disc. Fisher & Drory (2008) present HST images of other examples of the fascinating phenomenon of compact nuclear star clusters.

We can compare the measured distribution of the luminosity fraction B/T in Figure 2 to other samples. Gadotti’s (2009, fig. 8) distribution of B/T for pseudobulges with Sérsic index n < 2, based on SDSS images, used the radius-surface brightness measure discussed in Sec. 2.3. Gao, et al. (2020 fig. 2d) applied Gadotti’s pseudobulge criterion to their CGS sample. All three distributions peak at B/T < 0.1 but modest tails to B/T ∼ 0.5. A larger fraction of the CGS galaxies are found to have classical bulges than in the local sample, but the criteria differ (Sec. 2).

Gadotti’s (2009) distribution of B/T for classical bulges taken together with elliptical galaxies points to considerably larger bulge fractions. Perhaps this is in line with the second peak at B/T close to unity in the distribution in Figure 2. The CGS selects disc galaxies, so it does not check the presence of a second peak.

Tasca & White (2011) measured bulge luminosity fractions by fitting equation (7) to SDSS images. They showed that the mean bulge luminosity fraction is an increasing function of luminosity, as displayed in their fig. 13. But their analysis does not offer a check of the bimodal distribution of B/T seen in the local L ∼ L* sample.

Many of the local sample galaxies with B/T < 0.1 certainly look like nearly pure discs, to judge by images to be seen on the web. I conclude that there is a good case that this phenomenon is real and common among the nearby dominant galaxies. The reasonable consistency with the other two measurements supports the idea that the phenomenon is common in the field.
4 COMPARISONS OF MODELS AND OBSERVATIONS

It is understood that numerical simulations of galaxy formation are a work in progress aimed at exploring how best to model stellar formation and feedback while striving for ever better mass and position resolution. Discrepancies between theory and observation may only indicate the need for more work. But the thought pursued here is that discrepancies may suggest clues to a better cosmology to serve as the basis for simulations.

4.1 Distributions of Bulge to Total Ratios

Fig. 3 shows distributions of ratios of bulge to total stellar mass in the analysis by Gargiulo, Monachesi, Gómez, et al. (2019) of the 30 model galaxies from the Auriga project (Grand, Gómez, Marinacci, et al. 2017). These galaxies formed in dark haloes about as massive as the Milky Way, comparable to that of an $L \sim L_*$ galaxy. The Gargiulo, et al. analysis uses the fit of the model galaxy surface brightness run normal to the disc to equation (7), the sum of an exponential for the disk and the Sérsic function for the bulge. In the measure $B/T_{\text{sim}}$, the bulge star particles are those at galactocentric distance less than two effective radii $R_{\text{eff}}$ and with circularity parameters $\epsilon < 0.7$. A second measure, $B/T_y$, is the ratio of the Sérsic component to the total in the fit to equation (7). The solid and dashed lines in Fig. 3 mark the distributions of $B/T_{\text{sim}}$ and $B/T_y$.

It is encouraging that the observed and model distributions of bulge fractions $B/T$ in Figs. 2 and 3 are reasonably similar. It may be significant that the measure $B/T_y$ is closer to the observations, because the observations also make use of the fit to equation (7). Also, the model and Sérsic indices both tend to be characteristic of pseudobulges. However, at the bulge cut $\epsilon < 0.7$ in the measure $B/T_{\text{sim}}$ the bulge star particle orbits are far from circular, as illustrated in equation (5), and discussed further in Sec. 4.4. This assigns star particles with far from circular orbits to the disk, and it seems contrary to the picture discussed in Sec. 2 that fractional departures of motions from the mean are small for stars in a pseudobulge. But there are other tests to consider, beginning with stellar haloes.

4.2 Stellar Haloes and Bulges

Many nearby $L \sim L_*$ spirals have quite small luminosity fractions in stellar haloes (Merritt, van Dokkum, Abraham, & Zhang 2016; Harmsen, Monachesi, Bell, et al. 2017). Sanders, Garrison-Kimmel, Wetzel, et al. (2018) point out the difficulty of applying these observations to test and constrain model galaxies. But a simple and I think useful measure is the stellar fraction in orbits close enough to circular to qualify as parts of a disc. The remainder has to be the sum of a stellar halo and bulge.

The solid lines in Fig. 4 show the distribution of the sum of bulge plus halo masses relative to the total stellar mass for the 25 Auriga galaxies with tabulated measures of both bulge and halo masses: the sum of the bulge mass listed in the second column in table 1 in Gargiulo et al. (2019) and the in situ plus accreted halo masses in columns 5 and 6 in table 1 in Monachesi, Gómez, Grand, et al. (2019). It is normalized by the stellar masses listed in column 4 in Monachesi et al. This estimate of $(B+H)/T$ may miss some star particles on noncircular orbits close to the disk, but it seems to be a reasonable lower bound. I do not include models Au29 and Au30, which Monachesi et al. do not consider promising, and I exclude Au28, which does not look that much better. (The total stellar masses Gargiulo et al. 2019 use in their measure of $B/T$ are in some cases a few tens of percent lower than what Monachesi et al. 2019 use, but the difference is small at the level of this discussion.)

Garrison-Kimmel, Hopkins, Wetzel et al. (2018) define the disc mass in a FIRE-2 model galaxy by the fraction of star particles with circularity parameters $\epsilon > 0.5$, along with a cut on galactocentric distance. The discussion in Section 2.2 indicates that this allows a seriously hot distribution of star particles in the disc. So for the present discussion I take the disc star particles to have the more commonly used cut $\epsilon > 0.7$. The fraction in hot distributions of orbits in bulge plus stellar halo would then be

$$(B+H)/T = 1 - f_{\epsilon < 0.7}.$$  

The fraction $f_{\epsilon < 0.7}$ with $\epsilon \geq 0.7$ is listed in column 9 in ta-
Table 2. Stellar Halo and Bulge Fractions

| galaxy     | H/T  | B/T  | (B+H)/T | type   |
|------------|------|------|---------|--------|
| Milky Way  | 0.01 | 0.19 ±0.02 | 0.20   | P H    |
| M31        | 0.15 | 0.32 ±0.02 | 0.47   | C H    |
| NGC4945    | 0.09 | 0.07 ±0.01 | 0.16   | P H    |
| NGC2903    | 0.010 ±0.007 | 0.10   | 0.11   | P M    |
| M81        | 0.02 | 0.34 ±0.02 | 0.36   | C H    |
| NGC253     | 0.08 | 0.15      | 0.23   | P H    |
| M101       | 0.001 ±0.001 | 0.03 ±0.01 | 0.03   | P M    |
| M96        | 0.00 ±0.03 | 0.26    | 0.26   | P M    |
| M106       | 0.00 ±0.02 | 0.12 ±0.02 | 0.12   | C M    |
| NGC891     | 0.05 | —        | —      | —      |
| M95        | 0.00 ±0.02 | 0.16    | 0.16   | P M    |

Table 1 in Garrison-Kimmel et al. (2018). The distribution of (B+H)/T defined by equation (8) for the 15 FIRE-2 galaxies is plotted in long dashes in Fig. 4.

The (B+H)/T distributions in the FIRE-2 and Auriga simulations are computed in different ways, but the approaches seem to be similar enough that comparisons of these measures to each other and to the observations are meaningful.

Table 2 lists measured halo fractions H/T of galaxies in the local sample from Merritt et al. (2016) and Harmsen et al. (2017). The former used surface brightness measurements for the estimates in their table 1 of the fraction $f_{\text{halo}(>5R_p)}$ of the stellar mass outside $5R_p$, where $R_p$ is the half-mass radius of the galaxy. Harmsen et al. used counts of detected red giant stars outside galactocentric distance 10 kpc with the assumption that the initial mass functions of stellar haloes are at least roughly similar to what is observed in our galaxy. I use the estimates in Harmsen et al. table 1 of the stellar halo and total stellar masses, and their assessments of reasonable values for the Milky Way and M31. (I take the liberty of aiding clarity by reducing the number of significant figures.) The third column in Table 2 lists the bulge fractions B/T from Table 1. The fourth column is the sum of central values, and the last column lists the bulge type and the source of the halo measurement, M or H for Merritt et al. (2016) or Harmsen et al. (2017).

The galaxy NGC7814 in the Harmsen et al. study is outside the local sample at $D \sim 17$ Mpc, but worth noting because it resembles the Sombrero Galaxy, a mix of elliptical and spiral. The entry for the Sombrero Galaxy in Table 1 might be rewritten (B+H)/T $\sim 0.5$. Harmsen et al. find halo fraction H/T $= 0.14$ in NGC7814, and there seems to be room for an inner component at $r < 10$ kpc for a total comparable to that of the Sombrero Galaxy.

The galaxy NGC891 is in the local sample, and the Harmsen et al. (2017) halo fraction is entered in Table 2, but the bulge is obscured by dust and not measured. The central value of the measured distance to NGC 4565 puts it just outside the local sample. Harmsen et al. find H/T = 0.03. Kormendy & Bender (2019) argue that the bright central region of this galaxy is a pseudobulge, a bar seen close to edge on.

The nearby face-on galaxy M 101 shows little evidence of starlight in a bulge or halo. Van Dokkum, Abraham, & Merritt (2014) report that the ratio of the luminosity of the halo of this galaxy to its total luminosity is $H/T < 0.01$. Jang, de Jong, Holwerda, et al. (2020) put the fraction at $H/T < 0.003$. Recall that the rotationally supported disc of this galaxy seems to run all the way to a nuclear star cluster that is in effect a classical bulge with luminosity fraction $B/T \sim 10^{-4}$. This plus the faint stellar halo makes M 101 a beautiful example of a most interesting phenomenon that is not seen in the models.

The lesson I draw from the sample in Table 2 and the model results in Fig. 4 is that many $L \sim L_*$ galaxies have much smaller mass fractions in stellar haloes plus bulges than might be expected from the models. Centaurus A is an elliptical; it might be best to say that it has (B+H)/T $\approx 1$. The galaxies M31 and M81 have large bulge plus stellar halo fractions, (B+H)/T $= 0.46$ and 0.36. All the rest in this still limited sample have (B+H)/T $\leq 0.25$. The Auriga and FIRE-2 simulations put the median fraction outside the disc (with the definition used here for FIRE-2) at (B+H)/T $\sim 0.4$ to 0.5. Both have no examples at (B+H)/T $< 0.25$. The theory seems to be well separated from the observations.

Are the stellar halo and classical bulge of a spiral galaxy parts of the same phenomenon, artificially separated by an observationally convenient cut in surface brightness or distance from the center of the galaxy? The usual thinking is that the large bulge and stellar halo of M31 are the results of quite significant mergers. But M81 has a substantial classical bulge and a much more modest stellar halo. If pseudobulges have cold distributions of orbits, and stellar haloes hot, then one might not expect to find a correlation of halo and pseudobulge luminosities. Indeed, images of the galaxy NGC 253 on the web look wonderfully flat, but Harmsen et al. (2017) assign it a considerably more luminous halo than M 101. It may be significant, however, that Table 2 includes examples of low luminosity fractions in both pseudobulge and stellar halo.

4.3 The Bimodal Field Galaxy Population

The two great classes of $L \sim L_*$ galaxies are spirals and ellipticals, a bimodal situation. The details are more complicated. The Sombrero Galaxy M 104 is a striking example of a mixed spiral and elliptical, and another, NGC 7814, is not far outside the local sample. There are the varieties of S0 galaxies. NGC 3115 is a large relatively nearby one; the Local Universe catalog puts it at $D \sim 11$ Mpc. S0s in clusters of galaxies may be normal spirals that were stripped of gas by the ram pressure of the intracluster plasma. But since NGC 3115 is not near a rich cluster how was it so neatly stripped of gas? The most luminous galaxies at optical wavelengths, $L \sim 10^9 L_\odot$, tend to be cDs, the extended ellipticals in rich clusters (Tasca & White 2011). But Li & Chen (2019) find that some first-ranked members of less rich clusters are unclassifiable, or resemble spirals. And some galaxies are exceedingly luminous in the infrared. All these kinds of objects have something to teach us about how the galaxies formed, but all are rare and not part of the considerations of what we might learn from the $L \sim L_*$ galaxies. There is an exception, however, merging spirals (Schweizer 1990). Lahen, Johansson, Rantala, et al. (2018) argue that in about 3 Gyr the Antennae Galaxies will resemble the elliptical M 105 in Table 1. Naab & Ostriker (2009) dispute this; they see problems with the patterns of chemical abundances. But mergers produce galaxies of some sort. A far future version of Table 1
might include such galaxies produced by mergers of the blobs associated with the galaxies M 51a and NGC 4490.

What determines whether a protogalaxy precursor to an $L \sim L_*$ galaxy in the field outside rich clusters will become a spiral or an elliptical? The statement that ellipticals grow by dry mergers only changes the question to why the mergers are dry in some haloes in the field, wet in others. Since the global mean ratio of ellipticals to spirals increases with increasing stellar mass (Tasca & White 2011), the protogalaxy mass is an important determining factor (Johansson, Naab, & Ostriker 2012; Clauwens, Schaye, Franx, & Bower 2018). Consistent with this, the three ellipticals in the local sample have luminosities $L_\mathrm{K} \sim 0.7 \times 10^{11}$ to $2 \times 10^{11}$, toward the upper end of the range of values of $L_\mathrm{K}$ in the local sample. But in the local sample the three spirals NGC 253, 6744, and 6946, which look like rotationally supported discs with modest bulges, have luminosities in the same range as the three ellipticals. And recall that there are low mass ellipticals as well as spirals. That is, there seems to be a true bimodality.

The Fall & Romanowsky (2018) relation among galaxy stellar mass, angular momentum, and bulge fraction shows the importance of angular momentum. The tidal torque picture for the origin of the rotation of galaxies does not appear to be likely to have produced a bimodality of specific angular momentum, however. It seems then that there is a bistability somewhere in the complexities of evolution given the protogalaxy mass and angular momentum.

The distributions of $(B+H)/T$ in the model galaxies in Fig. 4 suggest a single peak with tails toward the two most common types, close to pure disc spirals and disc-free ellipticals. That is, the simulations do not seem to have captured the bistability, whatever it is. Section 5 offers an example of what might have happened.

### 4.4 Distributions of the Circularity Parameter

The star particle circularity parameter diagnostic $\epsilon$ is discussed in Section 2.2. If the bulge and stellar halo in a simulation are not rotating then the mass in these components may be taken to be double the count of star particles with negative $\epsilon$. For example, by this measure the two models presented by Murante, Monaco, Borgani, et al. (2015) have $B/T = 0.20$ and $0.23$. But the authors are not claiming that these are useful measures of bulge masses. Their distributions of $\epsilon$ have the same broad band as Eris in the interval $0 < \epsilon < 0.7$, which indicates a considerable mass fraction in something like a bulge with substantially less than full rotational support.

There has been impressive progress since Eris in the spatial and mass resolutions of simulations of galaxy formation, and in the modeling of the complexities of the evolution, by a variety of groups. And it is notable that the distributions of $\epsilon$ continue to show the large mass fractions that do not seem to belong in a realistic disc or pseudobulge. In the recent example from Kretschmer, Agertz, & Teyssier (2020) the distribution of $\epsilon$ in the left-hand panel in their fig. 5 looks quite like the Eris distribution from seven years earlier. The less familiar-looking distribution in the right-hand panel of Kretschmer et al. might be a useful approximation to an irregular galaxy, or maybe a first step to an elliptical.

Most of the distributions of $\epsilon$ in the 30 Auriga model galaxies (in fig. 7 in Grand et al. 2017) have a local peak or discontinuous change of slope at $\epsilon = 0$, usually a prominent peak at $\epsilon = 1$, and generally a considerable mass fraction with circularity parameters in the range $0.1 \lesssim \epsilon \lesssim 0.7$. This would seem to be consistent with the substantial mass fractions in bulges and stellar haloes in the Auriga galaxies (Figs. 3 and 4).

The distributions of $\epsilon$ in the Buck, Obreja, Macciò et al. (2019) NIHAO Ultra High Definition suite (their fig. 10) have the usual significant mass fractions at $0.1 \lesssim \epsilon \lesssim 0.7$. The same is true of the mean in the EAGLE simulations (fig. 14 in Trayford, Frenk, Theuns, et al. 2019) at low redshift.

Among the FIRE-2 galaxy simulations by Garrison-Kimmel, et al. (2018) some of the distributions of the circularity parameter in their fig. 1 have at most a slight feature at $\epsilon = 0$. The authors term these galaxies nearly bulgeless. In the two most pronounced examples, the models named Romeo and Juliet, the authors assign disc fractions $f_{\mathrm{disc}}^* = 0.8$ based on a disc cut at $\epsilon > 0.5$. But in these two galaxies 35 and 41 per cent of the model star particles are at $\epsilon < 0.7$. This is a considerable departure from circular orbits, as illustrated in Fig. 1. There does not seem to be room for this much mass in stars with large departures from rotational support in the close to bulgeless galaxies in the local sample.

#### 4.5 Five Challenges

I offer a summary of these considerations in the form of challenges that seem reasonably well founded and for the most part possibly simple enough for productive contemplation. Cautions are to be noted. This discussion compares stellar mass fractions in bulges and haloes in model galaxies to luminosity fractions in observations. I cannot assess how much room for error that allows. The roughly 30 galaxies (depending on how you count) in Table 1 at distances $D < 10$ Mpc have been characterized by seasoned observers; but a second point to bear in mind is my assumption that these galaxies constitute a fair sample of the $L \sim L_*$ population outside clusters. Third, I am assuming that pseudobulge stars move with velocity dispersion smaller than the mean. I do not know whether that may only be true for some subset of pseudobulges. We should bear in mind also the Governato, Brook, Mayer, et al. (2010) model with a close to exponential run of surface brightness with radius; it leaves little room for a bulge or stellar halo with $n > 1$. The interpretation is difficult, however, because we do not have the distribution of $\epsilon$ for this model.

1. Pseudobulges. Model galaxies are said to have pseudobulges because fits of the exponential plus Sérsic function in equation (7) tend to indicate Sérsic index $n < 2$. But in these model pseudobulges the distributions of star particle circularity parameters, $\epsilon \lesssim 0.7$, indicate the considerable departures from circular motions illustrated in equation (5). When a bar is present the star particles may have small values of $\epsilon$ because they are moving in organized noncircular patterns. Otherwise it seems that the motions of stars in model pseudobulges are hot. That not what would be expected of pseudobulges from the considerations in Sec. 2.1. And we see in Table 1 that pseudobulges are common among nearby $L \sim L_*$ galaxies. Thus the challenge is to explain why the simulations fail to predict the apparently
cold flows of stars in the pseudobulges commonly observed in \( L \sim L_c \) galaxies, or else to demonstrate that the notion of well-ordered flows of pseudobulge stars is wrong.

2. Bulge Fractions. If the run of model surface brightnessness fitted to the exponential plus Sérsic function yields a good measure of the bulge fraction then the distribution of Auriga bulge fractions \( B/T \), in Fig. 3 is not far from the observed distribution in Fig. 2, within reasonable uncertainties. But the distribution \( B/T_{\text{sim}} \) based on a cut in \( \epsilon \) is significantly further from the observations. And \( B/T_{\text{sim}} \) seems to be an underestimate because it assigns a hot distribution of orbits to the disk. The more natural home for star particles with \( 0.7 < \epsilon < 0.9 \) is a classical bulge or the inner parts of a stellar halo. How might the model bulge fractions be reduced? Guedes et al. (2013) fig. 3 and Gargiulo et al. (2019) fig. 5 show models in which most bulge stars formed at about the same range of galactocentric distances that they are now. If so, it seems that too much mass in diffuse baryons made its way to the central regions before being converted to stars (e.g. Governato et al. 2010). The generations of models since then for the evolving distribution of the diffuse baryons may not have been specifically designed to reduce typical values of \( B/T \), but the challenge is implicit in the program of improving model galaxies. And this challenge to model bulge fractions does not seem to have been met.

3. Stellar Haloes. The evidence reviewed in Sec. 4.2 is that the stellar halo mass fraction \( H/T \) in models tends to be considerably larger than the luminosity fractions \( H/T \) in nearby \( L \sim L_c \) spiral galaxies. The observed sample is not large but the discrepancy merits consideration. The substantial mass fractions in model stellar haloes are at least in part a result of the prediction of the standard ΛCDM cosmology that galaxies grew by merging of a hierarchy of subhaloes within subhaloes. Stars that formed in subhaloes before merging with the main halo of the growing galaxy would seldom end up joining a cold flow in the disc or in the adopted picture of a pseudobulge; they are far more likely to contribute to the stellar halo. That is, if a protogalaxy grew by the merging of subhaloes then the challenge would be to show how the subhaloes could have “known” which was to be the single one in which nearly all the visible stars would be forming, so as to place an acceptably small fraction of star particles in the stellar halo.

4. Velocity Dispersions in Disks. In the simple model in equation (2) the circularity parameter \( \epsilon = 0.9 \) translates to \( \pm 30\% \) maximum departures from a circular orbit in the plane of the galaxy, and the rms radial velocity dispersion is 30\% of the circular velocity (eq. [6]). This is uncomfortably large if the Milky Way disk is typical. And model disk star particles commonly are taken to be those with \( \epsilon > 0.7 \) and the still larger departures from circular orbits illustrated in equation (5). Perhaps violations of conservation of particle energy and angular momentum inflate the departures from quiet flow derived from equation (2). That could be checked by more direct measures of the velocity dispersion of model disk star particles. (If that has been done I have not found it.) Or perhaps the approximations required to deal with the complexities of star formation introduce artificially large dispersions of star velocities at formation. But the several generations of improvements of simulations since Eris have failed to change the apparent prediction of large velocity dispersions in model disks. O take the challenge to be to demonstrate reasonable consistency of the actual star particle velocity dispersions in model disks with what is known about velocity dispersions of stars in disks of the Milky Way and other nearby spiral galaxies.

5. The Spiral–Elliptical Duality. The evidence from observations and simulations is that the most massive protogalaxies naturally tend to evolve into massive elliptical galaxies. But we see in Fig. 2 that most nearby \( L \sim L_c \) galaxies are either spirals with modest stellar haloes or ellipticals with at most modest disks. There are irregular galaxies of many sorts, but they are less common in the local sample. If this is true of the field outside rich clusters then the challenge and opportunity is to identify a bistability somewhere in the course of evolution of the galaxies.

### 4.6 What do the Challenges Suggest?

The phenomenology suggests that many \( L \sim L_c \) galaxies grew by a gentle rain of diffuse matter that dissipatively settled into rotational support in a single growing disc before being incorporated in stars. This brings to mind the Eggen, Lynden-Bell & Sandage (1962) picture for formation of the Milky Way by a roughly monolithic collapse of initially diffuse baryons. Eggen et al. pointed out that the contracting mass distribution has to have had enough substructure to have allowed some star formation as matter was settling, so as to account for the high-velocity stars. We can add the stellar streams indicative of shredding of merging subclusters. But weaker subclustering than the ΛCDM prediction could help avoid accumulation of an unacceptably luminous stellar halo, and a scarcity of stars in the diffuse matter as it was settling would help avoid disturbing the growing disc (e.g. Tóth & Ostriker 1992; Kazantzidis, Zentner, Kravtsov, et al. 2009).

Galaxies do merge, and mergers can change morphologies (Toomre 1977). While M 101 seems to have suffered no significant accretion of subhaloes containing stars, it is reasonable to add to the empirical picture the standard idea that M 31 and M 81 owe their classical bulges to more serious mergers after formation of their first generations of stars. The idea that ellipticals were assembled by dry mergers is supported by the shells seen in some ellipticals, and suggested by the concentration of early-type dwarfs in the outskirts of the elliptical galaxy Centaurus A (Karachentsev, Sharina, Dolphin, et al. 2002; Crnojević, Grebel, & Koch 2010). But the phenomenology allows us to imagine instead that the elliptical in the Centaurus group formed by an early merger of two nearly monolithic haloes that happened to be unusually close to each other. This merger would have to have been violent enough to have triggered rapid star formation, which could have scattered debris, producing the early-type satellites of Centaurus A. It would be a bistable process of sorts: Centaurus A grew out of a merger at high redshift that produced the early-type debris that gives us the impression of growth by dry mergers. The other large galaxy in this group, M 83, with its pseudobulge, would have grown out of near star-free accretion. This spiral has the usual concentration of satellites, most late-types. Their presence certainly requires departures from monolithic protogalaxies, as does the rather substantial stellar halo around the near pure disc galaxy NGC 253. But lesser departures than in the conventional ΛCDM theory could be helpful.
A consideration reviewed in Peebles & Nusser (2010), and to be added to the issues, is the evidence that the properties of $L \sim L_*$ galaxies are insensitive to environment. This is a starting assumption for the Halo Occupation Distribution model (Berlind, Weinberg, Benson, et al. 2003), but it is curious. Apart from occasional mergers, $L \sim L_*$ galaxies seem to have evolved as island universes, independent of the environment, yet the ratio of early to late types of galaxies is a function of environment. Perhaps that is because violent mergers at high redshift that produced early-type galaxies were more frequent in higher density regions. What would we make of less violent mergers? That is among the considerations that would have to be addressed by simulations with initial conditions that encourage more nearly monolithic galaxy formation.

5 ADJUSTING INITIAL CONDITIONS

The $\Lambda$CDM cosmology certainly might be improved by some more realistic model of the dark sector. But the simpler idea considered here is an adjustment of initial conditions.

In the warm dark matter (WDM) model, primordial mass density fluctuations are suppressed on scales less than a chosen comoving value $M_{WDM}$. The idea has a long history (Blumenthal, Pagels, & Primack 1982; Bond, Szalay, & Turner 1982), it still is discussed (e.g. Adhikari, Agostini, Ky, et al. 2017; Lovell, Hellwing, Ludlow, et al. 2020; Leo, Theuns, Baugh, et al. 2020), and it can suppress substructure within protogalaxies. It still allows unwanted promiscuous merging on scales $\sim M_{WDM}$; however, I have experimented with remedying this by changing the shape of the primordial mass density fluctuations. The normalization of $\delta$ in equation (9) is

$$\langle \delta_1 \delta_2 \rangle = \langle \delta_1 \delta_2 \rangle_G \frac{1 + 2F^2 (\langle \delta_1 \delta_2 \rangle/L^2)}{1 + 2F^2},$$

where $\langle \delta_1 \delta_2 \rangle_G$ is the two-point function for the Gaussian process. The two-point function for the cubic model in equation (10) is

$$\langle \delta_1 \delta_2 \rangle = \langle \delta_1 \delta_2 \rangle_G \frac{1 + 6F + 9F^2 + 6F^2 (\langle \delta_1 \delta_2 \rangle/G^2)}{1 + 6F + 15F^2}.$$  

At $F \ll 1$ the functions are changed from that of $\delta_G$ only by terms of order $F^2$.

I hesitate to apply equations (9) or (10) to a near scale-invariant power law power spectrum truncated at some very small scale because that places considerable substructure within protogalaxies, which may encourage excess structure prior to merging, and excess mass in a hot distribution of orbits. But it certainly might be considered.

In the examples in Figs. 5 and 6 the Gaussian function with period $L_*$ along the line $x$ is computed as

$$\delta_G(x) = 2 \sum_{k \geq 1} \delta_k \cos(2\pi \frac{x}{L_*} + \phi_k), \quad \delta_k \propto \exp^{-k^2/2\Gamma^2} / \sqrt{k}.$$  

The normalization of $\delta_k$ does not affect the ratios of the Gaussian and non-Gaussian terms in equations (9) and (10). The phases $\phi_k$ are random, as usual. The length of the plot is $L_*$ in units we may choose. (In the computation $L_*$ is $10^8$ and $k$ is the positive integers.) The exponential factor in $\delta_k$ approximates the WDM cutoff of the power spectrum at the length scale $\sim L_*/k$.

The dotted curves in Figs. 5 and 6 are the same realization of the random Gaussian process, and the solid curves are the non-Gaussian processes in equations (9) and (10) with the same non-Gaussian parameter $F = 0.3$. Since realizations of the cubic model are statistically unchanged by a change of sign of $\delta$ we get two examples by plotting only positive values in one panel of Fig. 6 and only negative values with the sign changed, in the other.

The skewness of initial conditions in Fig. 5 and the excess kurtosis in Fig. 6 both have the effect of increasing $2\sigma$ upward density fluctuations. This is in the direction of the Eggan, Lynden-Bell, & Sandage (1962) picture, which I have argued is suggested by the observations. The cubic model in Fig. 6 is closer to what seems to be indicated, because it increases density fluctuations above the $2\sigma$ line and

$$\delta(x) = \frac{\delta_G(x) + F \langle \delta_1 \delta_2 \rangle_G (\langle \delta_1 \delta_2 \rangle_G^{-1/2} - \langle \delta_1 \delta_2 \rangle_G^{1/2})}{(1 + 2F^2)^{1/2}},$$

$$\delta(x) = \frac{\delta_G(x) + F \delta_0 \langle \delta_1 \delta_2 \rangle_G}{(1 + 6F + 15F^2)^{1/2}}.$$  

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Figure 5. The dotted curve is a realization of the Gaussian process $\delta_G$. The solid curve is the primeval density contrast $\delta(x)$ with the quadratic term in eq. (9) and $F = 0.3$. The vertical axis is the contrast in units of standard deviations of $\delta_G$.

Figure 6. As in Fig. 5 for the cubic term in eq. (10) with the same $\delta_G(x)$ and $F = 0.3$.

decreases them below the line. That is, it suppresses sub-clustering around a growing mass concentration, which may offer a better approximation to a real protogalaxy. It may even help account for the presence of hosts for quasars at high redshift, as in downsizing (Cowie, Songaila, Hu, & Cohen 1996), and for the impressive scarcity of dwarf galaxies in the Local Void (Peebles & Nusser 2010 fig. 1).

6 CONCLUDING REMARKS

We must be cautious about adjusting a theory to fit what is wanted; it may only produce a “just-so story.” But recall that CDM and then Einstein’s cosmological constant were added to the cosmological model to make the theory fit reasonably persuasive evidence. We have argued that there is reasonably persuasive evidence that simulations of galaxy formation based on the $\Lambda$CDM theory with Gaussian initial conditions produce unacceptably large fractions of stars in hot distributions of orbits. It is appropriate to seek an adjustment of the theory that might relieve the problem, and natural to look first at the sub-grid physics. But this has been examined in several generations of models by several groups. The stability of the gross form of the distribution of the circularity parameter $\epsilon$, with the substantial mass fraction in what looks like hot distributions of orbits, suggests this is characteristic of $\Lambda$CDM in a considerable range of ways to treat the baryon physics. The adjustment of initial conditions proposed here is more contrived than the introductions of CDM and $\Lambda$, but it is in the same spirit. Whether it would remedy any of the challenges listed in Section 4.5 remains to be examined, perhaps by comparison of numerical simulations already run to what results when run again with initial conditions adjusted to a degree of non-Gaussianity.

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