Disk and Bulge Intensity Profile Evolution During the MW-M31 Major Merger

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1. INTRODUCTION

1.1. *Topic*

A galaxy merger occurs when two galaxies collide. Major mergers, those between large galaxies of comparable luminosities, are the most transformative events that galaxies may undergo after their formation (Lambas, D. G. et al. 2012). It is understood that the predominant members of our Local Group, the Milky Way (MW) and Andromeda (M31) galaxies, will likely merge in several billion years. This will cause the two now-spiral galaxies to ultimately coalesce into a single elliptical galaxy. The Local Group is a galaxy group containing over 100 gravitationally bound galaxies, most satellites of the MW and M31. Using measurements of the velocities of the centers of mass (COMs) of the MW and M31 (van der Marel et al. 2012b), van der Marel et al. (2012a) found an expected merger of the MW and M31 in ∼6 Gyr after a first pericenter in ∼4 Gyr. Collisionless interactions between the stars of the MW and M31 lead to largely random orbits, in line with field elliptical galaxies and juxtaposed with the ordered rotation of the present MW and M31 spirals.

The stellar bodies of disk galaxies are broken down into bulges and disks. Stellar bulges are relatively dense groups of stars found within the central regions of their galactic hosts. Bulges generally come in one of two forms: classical bulges or pseudobulges. M31 has a large classical bulge (Kormendy et al. 2010), which is similar in form to an elliptical galaxy. The MW has a smaller pseudobulge. Pseudobulges are not spherically symmetric, are rotation-supported, and have Sérsic indices $n \leq 2$.

We can examine the evolutions of the MW and M31 disks and bulges by studying their radial intensity profiles throughout a simulated merger. Radial intensity profiles describe how the luminosity per unit area in a 2-dimensional projection of a galaxy varies as a function of radius from its galactic center. These can be fit in terms of Sérsic profiles (see Equation 1) to quantify the rate of radial falloff with a Sérsic index n (Sérsic 1963; Sérsic 1968).

1.2. *Motivation*

The evolutions of disks and bulges during major mergers are important to understanding the galaxies that we see today, including those in the Local Group. From Willman & Strader (2012): "A galaxy is a gravitationally bound set of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity." Galaxy evolution involves how galaxies change with time, which we can see by observing galaxies at varied look-back times (redshifts z) to get statistical or population-level results for how galaxies have come to their current forms at $z = 0$ ("now"). The field of galaxy evolution includes studying how galaxies may lose gas ("quenching"), form stars, change in color (a proxy for the age of stellar populations), grow their central supermassive black holes, and, importantly, merge.

We require simulations to study how galaxies may continue to evolve in the future, and many of the details of major mergers are still ill-understood. While we can directly observe some galaxy mergers in progress, e.g. NGC 4678 A&B (The Mice Galaxies), we cannot measure the proper motions of these merging galaxies. The MW-M31 system is unique in that we can directly measure the proper motions of stars in each galaxy (Sohn et al. 2012), which has informed our simulated merger model. At the beginning of the simulation, we have two large spiral galaxies ($M \approx 10^{12}$, ignoring M33). Understanding how spiral galaxies may evolve to form ellipticals through major mergers can help inform our understanding of elliptical galaxy formation, beyond our wanting to understand the fate of our own galaxy and the Local Group as a whole. By analyzing the evolutions of the disks and bulges of the MW and M31

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through their future simulated merger, we can track the bulk migrations of these galaxies' stars over billions of years to see how they redistribute themselves in a major merger.

1.3. *Contemporary Understanding*

It is thought that many elliptical galaxies are formed through major mergers. Additionally, major mergers are thought of as a means to transform spiral galaxies into S0 galaxies. This is an alternative explanation from S0s being viewed as "faded spirals" which cannot explain all their observed properties (Querejeta et al. 2015b). See Fig 1 for a showcasing of the striking similarities between simulated merger remnants and observed S0 galaxies. Further, it is believed that mergers (including minor mergers) could be the source of classical bulges (Brooks & Christensen 2016)—though major mergers often destroy the original bulge and disk structures of the merging galaxies. It is possible that these structures are then rebuilt by secular processes to create S0 galaxies (Querejeta et al. 2015a). In addition, galaxy mergers have been examined as possible creators of elliptical galaxies for a long time (Toomre 1977), but there are still concerns that mergers by themselves may be unable to reproduce all relations observed for elliptical galaxies (Brooks & Christensen 2016). In sum, examining major mergers of spiral galaxies is important to understand the formation of elliptical galaxies, S0 galaxies, and classical bulges in spiral galaxies, all of which can often be characterized and distinguished by their intensity profiles/Sérsic indices.

1.4. *Open Questions*

This simulated merger has implications for our understanding of field elliptical galaxies, and there are many open questions concerning galaxy evolution and major mergers: did some field elliptical galaxies form from major mergers like that of the future MW-M31 merger? If so, could *all* of them have formed this way? Are some or all classical bulges formed from galaxy mergers? Are some or all S0 galaxies formed by major mergers? How do bulges and disks evolve during mergers? How do stars redistribute *during* mergers? Further examination of simulated major mergers will help to bring us closer to answering some or all of these questions. Querejeta et al. (2015b) explore the possibility of mergers are progenitors of S0 galaxies is investigated by the comparison of properties of simulated merger remnants with those of observed S0 galaxies. Meanwhile, Brooks & Christensen (2016) examine how merger may produce classical bulges—though minor mergers may be more likely to do this than their major counterparts. There the effects of gas and subsequent star formation are modeled in contrast with our purely stellar-dynamical simulation.

2. THIS PROJECT

2.1. *Project Introduction*

In this paper, we will examine the evolution of the radial intensity profiles of the MW and M31 galaxies throughout their simulated future merger. My analysis includes the bulge and disk only, with M33 and dark matter particles not considered. The simulated merger is constructed from a collisionless N-body simulation described in van der Marel et al. (2012a). The evolutions of the bulge and disk components of the MW and M31 *throughout* the merger were not explored in detail by van der Marel et al. (2012a), where the final state of the merged remnant was a larger focus of the analysis. Radial intensity profiles will be fit in terms of Sérsic profiles at different time snapshots throughout the course of the merger. Here we will fit only to the Sérsic index n, as the other functional parameters, effective radius and total luminosity, See Figures 2 and 3 for examples of what a luminosity profile plot at a *single snapshot* may resemble. In Figure 3, Sérsic profiles were fit explicitly, and in Figure 2 the surface mass density Σ was plotted against $R^{1/4}$ to show a straight line indicating a de Vaucouleurs profile (de Vaucouleurs 1948). A de Vaucouleurs profile can be described with a Sérsic index $n = 4$, indicative of an elliptical galaxy or classical bulge. Assuming a particular mass-to-light ratio allows the conversion $\Sigma \rightarrow I$. We will assume a mass-to-light ratio of 1 for our bulge and disk particles to make our surface mass density and intensity nominally identical.

2.2. *Questions to Address*

We will address the evolution of the luminosity profiles of the bulge and disk components of the MW and M31 throughout the merger, by fitting to Sérsic Profiles where Sérsic indices n are allowed to vary. This describes one aspect of the evolution of disks and bulges *during* mergers. Of particular interest will be the question of how these Sérsic indices change throughout the simulated merger, and *when* they change the most. We may expect the greatest changes to be at pericenters or just after pericenters. An increase in Sérsic index indicates that more stars are being concentrated in the center of a galaxy. These higher concentrations in galactic centers yielding $n > 2$ are indicative of elliptical galaxies and classical bulges, where lower Sérsic indices ($n \sim 1$) better describe spiral galaxies with more of their light distributed further out in disks. Changes in Sérsic indices for the bulges and disks of the MW and M31 throughout the simulated merger will help describe how two spiral galaxies can come to form an elliptical galaxy.

2.3. *Importance, Project Relevance*

`**Why is this open question an important problem to solve for our understanding of Galaxy Evolution? How will your study help us to address the open question?**` The galaxies we observe in the sky may have never undergone a major merger, may have already undergone a major merger, or for very few, are currently undergoing a major merger. To understand how un-merged galaxies transform into the remnant that we observe, we need to understand the processes that occur in the process, during the merger. Observing actively merging systems can only tell us so much, so we rely on simulations like those used in this paper to better study the dynamics of these events. Sérsic profile evolution is also a proxy for the evolution of stellar density as a function of radius and will tell us how exactly disks with relatively low Sérsic indices become an elliptical galaxy with a relatively high Sérsic index. Major mergers are the most transformative events that galaxies may undergo as part of their evolution, and understanding the specifics of how stars redistribute through this process will help us to understand how galaxies evolve through mergers, in detail.

3. METHODOLOGY

3.1. *Methods Introduction*

`**Start with an introduction to the simulations you are using. You must reference the paper and describe what is meant by an \N-body" simulation.**`

We use an N-body simulation from (van der Marel et al. 2012a) for analysis. This simulation follows collisionless massive particles which interact only through gravity. These particles are meant to represent stars, though due to computational limitations, it is not feasible to simulate all $\sim$200 Billion stars in each of the MW and M31 galaxies. Instead, we restrict our resolution to particles each of masses on the order of 10^7 $M_\odot$. In essence, each particle represents a few dozen million Sun-like stars, or even more when accounting for the popularity of stars in the Milky Way being smaller M-dwarfs. The MW, M31, and M33 (the Triangulum galaxy) are each modeled with disk, bulge, and dark matter particles. In this paper, we examine only the disk and bulge particles of the MW and M31, through the gravitational effects of dark matter and the particles of M33 are affecting the dynamics, if not the intensity profiles of the MW, M31, and their future remnant. Here the MW is modeled with a classical bulge more similar to that of M31, as opposed to its true pseudobulge. By the end of the simulation, we have a single merger remnant which is well described by this de Vaucouleurs, $n = 4$ surface density profile, making it most similar to an elliptical galaxy (van der Marel et al. 2012a).

3.2. *Proposed Methods*

Sérsic profiles will be fit similarly to the method of Lab 6, but will be made more robust by using `scipy.optimize.curvefit()`, potentially only fitting profiles to data beyond a cut-off radius so as to neglect the innermost components that do not follow well Sérsic profiles. Sérsic profiles as a function of radius r are given by the equation,

$$I(r) = I_e \exp\left(-7.67[(r/R_e)^{1/n} - 1]\right) \tag{1}$$

where $L = 7.2 I_e \pi R_e^2$ for the galaxy, and I_e and R_e are the equivalent (half-light) intensity and radius, respectively. I_e and R_e can be calculated at each snapshot from the surface brightness profile, and n can then be varied to best fit the simulated data. When only considering simulated stellar particles, we can take $M_{\mathrm{stellar}}/L = 1$ to get an intensity profile from an area mass density profile.

To actually compute the intensity profile, we begin by reading in the simulation data that is stored in a .txt file at each snapshot, and for each galaxy. These data files contain information on the particle types, masses, positions, and velocities for the given galaxy at the snapshot. The positions and velocities are with respect to the initial position of the MW, where x and y are in the initial plane of the disk of the MW, and z is therefore orthogonal to this plane. We then restrict the data to only the particle type we are interested in for any given calculation (either bulge or disk stellar particles). We then move to center-of-mass coordinates for each galaxy, so that we can compute radial intensity profiles with respect to the centers of each galaxy at each snapshot, which move with time as the galaxies merge. We then compute the *cylindrical* radius of each particle in the snapshot-dependent plane of its disk and bin them into annuli that span radius intervals out to a maximum radius (too far from a galaxy's center there are too few particles to meaningfully compute an intensity). Calculating the mass enclosed in each annulus then gives us the luminosity in each annulus with our mass-to-light ratio of 1, and by dividing this annulus-enclosed intensity by the area of the annulus in projected cylindrical coordinates gives us an intensity at the geometric mean (midpoint radius) radius of the given annulus. We can then plot these intensity values as a function of their annulus midpoint radii to show our intensity profiles graphically. These will be compared and contrasted with the fit Sérsic profiles.

This will be attempted at *all* snapshots using for loops through snapshot data files, but if that proves too computationally intensive then snapshots of particular interest will be selected to best show the evolution. All programming and plotting will be done in Python with the `Matplotlib`, `Numpy`, and `SciPy` modules. Refer again to Figures 2 and 3 for examples of what my plots at a single snapshot may resemble. We will create animations of these Sérsic profile–fit plots as the simulation progresses. This would allow for the changes in the luminosity profile and Sérsic indices to be more easily seen. Additionally, we may create a plot of n versus t. An animation could be created by importing plots into Adobe Premiere.

3.3. *Calculations*

`**Describe the calculations your code will compute. You must include all relevant equations and citations, and describe the meaning behind every parameter in the equation (e.g. The circular speed is defined as Vc2 = GM/r, where M is the Mass of the host galaxy (Msun) and r is the Galactocentric radius (kpc)). Note that the reference for the Hernquist profile is Hernquist 1990 ApJ 356.**`

3.4. *Plots*

`**Describe the plots you will need to create and explain why those plots will answer your question. Note that later your results section must feature at least two figures that you created. One Figure can be generated entirely by code from Homeworks or In Class Labs (e.g. phase diagrams, density plots). The other figure must be generated by code that includes one new function or method that YOU created BY YOURSELF.**`

3.5. *Hypothesized Results*

We expect the Sérsic indices for both the bulge and disk particles of M31 and the MW to generally increase with time as the merger comes to form a single elliptical galaxy. Relaxation over time through collisionless two-body interactions should drive this process of increasing n overall. We would also expect the change in the luminosity profiles/Sérsic indices to be greatest at or just after pericenters in the merger, where it seems that the most dramatic changes in the galaxies' structures occur. It is possible that some Sérsic indices do actually lower, however, possibly due to something like initially-centralized bulge particles being redistributed to outer parts of the galaxy. In this case, it may be more informative to also fit Sérsic profiles to the galaxies as a whole to account for the net radial migration of bulge *and* disk stars taken together.

4. RESULTS

See figures 4–12 for some big-time science results.

5. DISCUSSION

REFERENCES

Brooks, A., & Christensen, C. 2016, in Astrophysics and Space Science Library, Vol. 418, Galactic Bulges, ed. E. Laurikainen, R. Peletier, & D. Gadotti, 317, doi: 10.1007/978-3-319-19378-6_12

Chilingarian, I. V., Di Matteo, P., Combes, F., Melchior, A. L., & Semelin, B. 2010, A&A, 518, A61, doi: 10.1051/0004-6361/200912938

de Vaucouleurs, G. 1948, Annales d'Astrophysique, 11, 247

Kormendy, J., Drory, N., Bender, R., & Cornell, M. E. 2010, ApJ, 723, 54, doi: 10.1088/0004-637X/723/1/54

Lambas, D. G., Alonso, S., Mesa, V., & O´Mill, A. L. 2012, A&A, 539, A45, doi: 10.1051/0004-6361/201117900

Querejeta, M., Eliche-Moral, M. C., Tapia, T., et al. 2015a, A&A, 573, A78, doi: 10.1051/0004-6361/201424303

—. 2015b, A&A, 579, L2, doi: 10.1051/0004-6361/201526354

Sánchez, S. F., Kennicutt, R. C., Gil de Paz, A., et al. 2012, A&A, 538, A8, doi: 10.1051/0004-6361/201117353

Sérsic, J. L. 1963, Boletin de la Asociacion Argentina de Astronomia La Plata Argentina, 6, 41

Sérsic, J. L. 1968, Atlas de Galaxias Australes

Sohn, S. T., Anderson, J., & van der Marel, R. P. 2012, ApJ, 753, 7, doi: 10.1088/0004-637X/753/1/7

Toomre, A. 1977, in Evolution of Galaxies and Stellar Populations, ed. B. M. Tinsley & D. C. Larson, Richard B. Gehret, 401

van der Marel, R. P., Besla, G., Cox, T. J., Sohn, S. T., & Anderson, J. 2012a, ApJ, 753, 9, doi: 10.1088/0004-637X/753/1/9

van der Marel, R. P., Fardal, M., Besla, G., et al. 2012b, ApJ, 753, 8, doi: 10.1088/0004-637X/753/1/8

Willman, B., & Strader, J. 2012, AJ, 144, 76,
doi: 10.1088/0004-6256/144/3/76

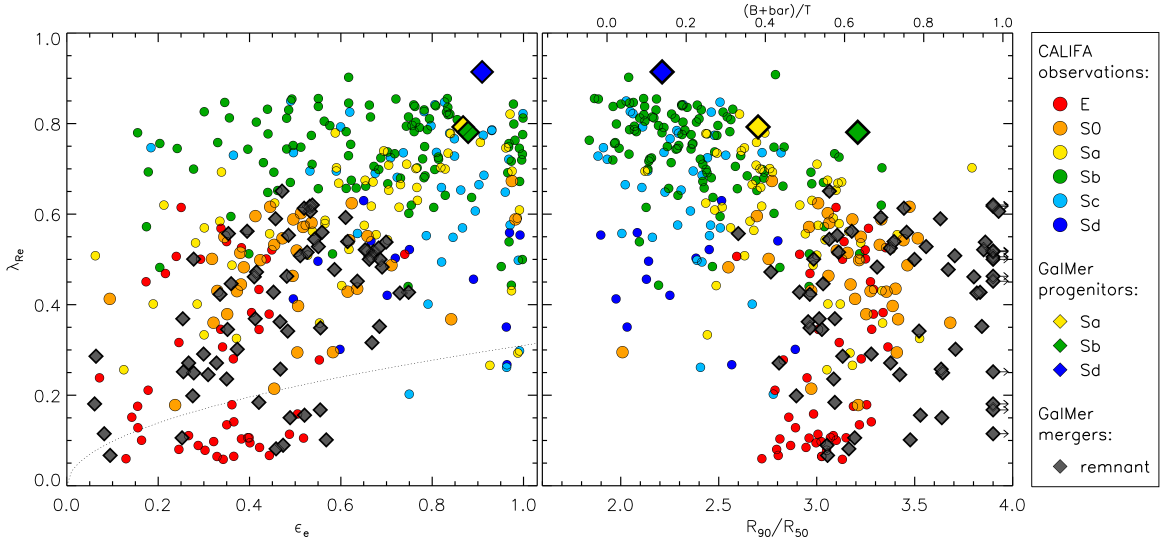

Figure 1. Figure 1 from Querejeta et al. (2015b). Here we see the stellar angular momentum $\lambda_{\mathrm{R_e}}$ plotted against both the ellipticity ϵ_{e} and concentration R_{90}/R_{50} for simulated merger progenitors and remnants from the GalMer (Chilingarian et al. 2010) simulations (galmer.obspm.fr) as well as observed Calar Alto Legacy Integral Field Area Survey (CALIFA) galaxies (Sánchez et al. 2012). We see that the observed CALIFA S0 galaxies as orange circles generally coincide well with the GalMer merger remnants as grey diamonds in these regions of galactic parameter space.

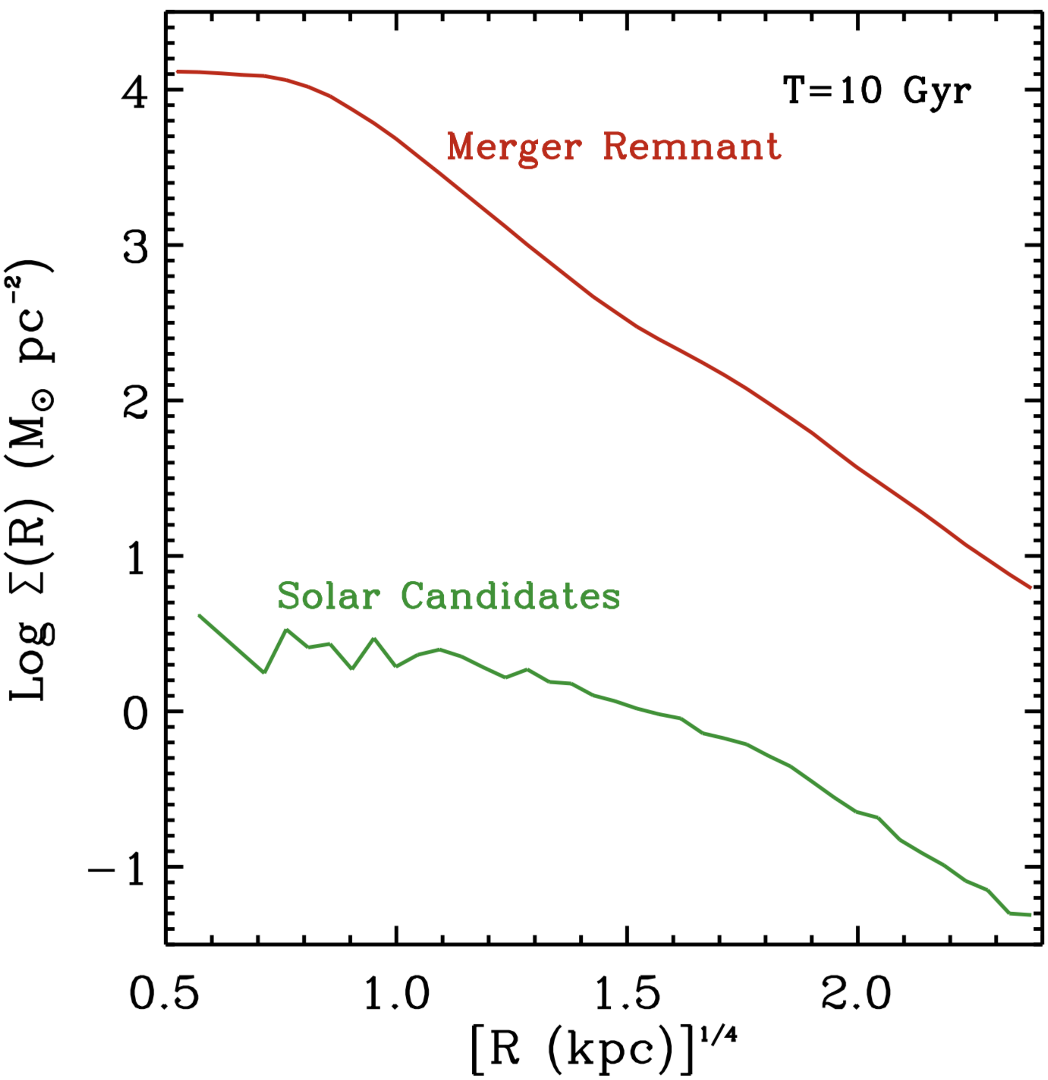

Figure 2. Figure 7 from van der Marel et al. (2012a). Here we see a surface mass density profile for the remnant and its solar candidates specifically plotted against the radius from the galactic center to the power of 1/4, with a semi-log plot. Surface mass density Σ can be converted to intensity I by assuming a mass-to-light ratio. The straight lines past $\sim$1 kpc indicate accordance with a de Vaucouleurs, $n = 4$ Sérsic profile.

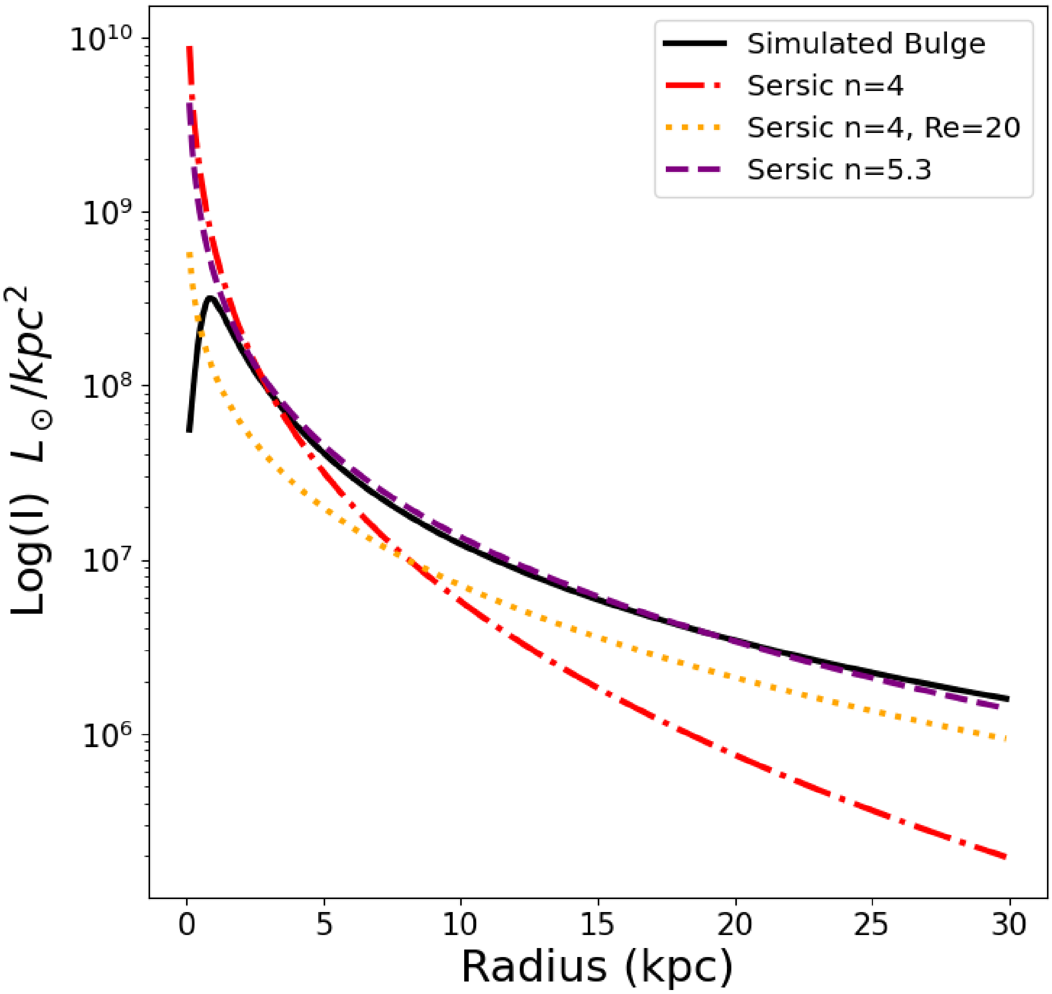

Figure 3. Plot from Lab 6 showing Sérsic profiles fit to the simulated bulge of M31 at the snapshot for $t = 0$ (the present epoch), with a semi-log plot of Intensity I versus distance from the M31 galactic center. Here we see how the effective radius (half-light radius) R_e affects the form of Sérsic profiles.

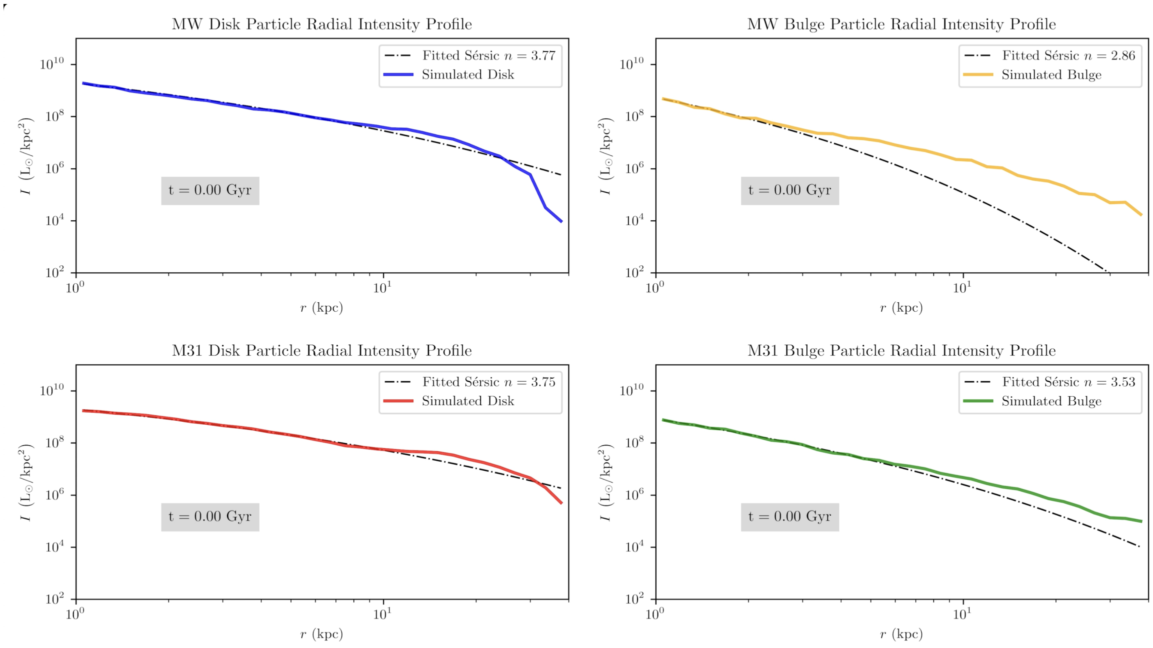

Figure 4. 0.00 Gyr

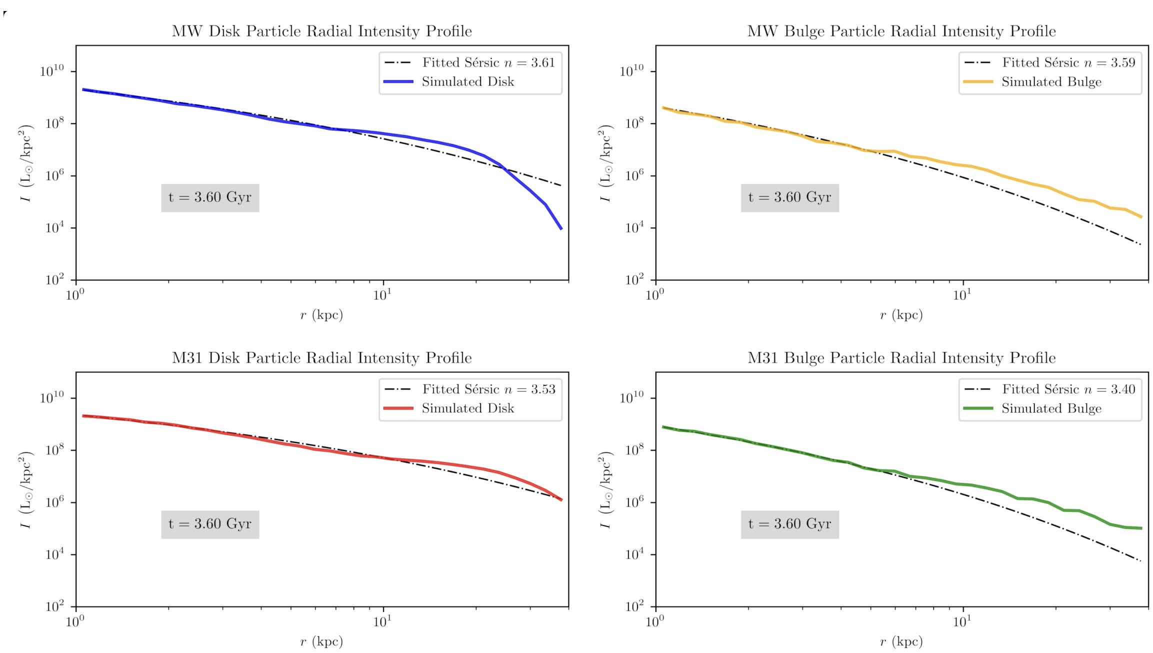

Figure 5. 3.60 Gyr labelfig:3.60

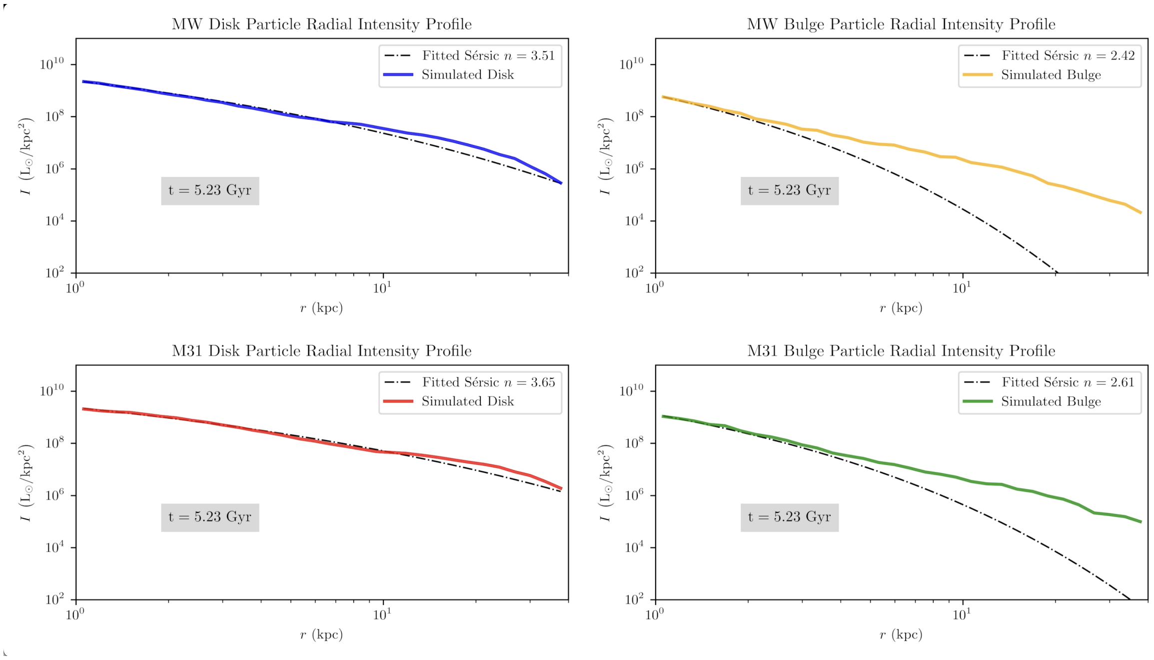

Figure 6. 5.23 Gyr

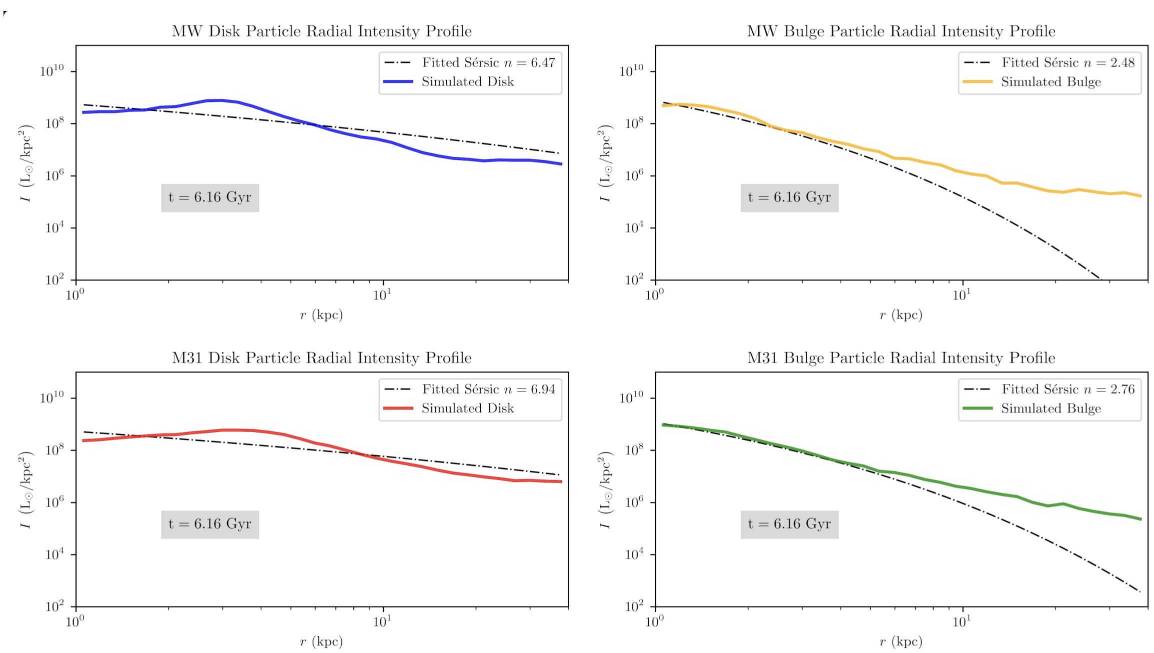

Figure 7. 6.16 Gyr

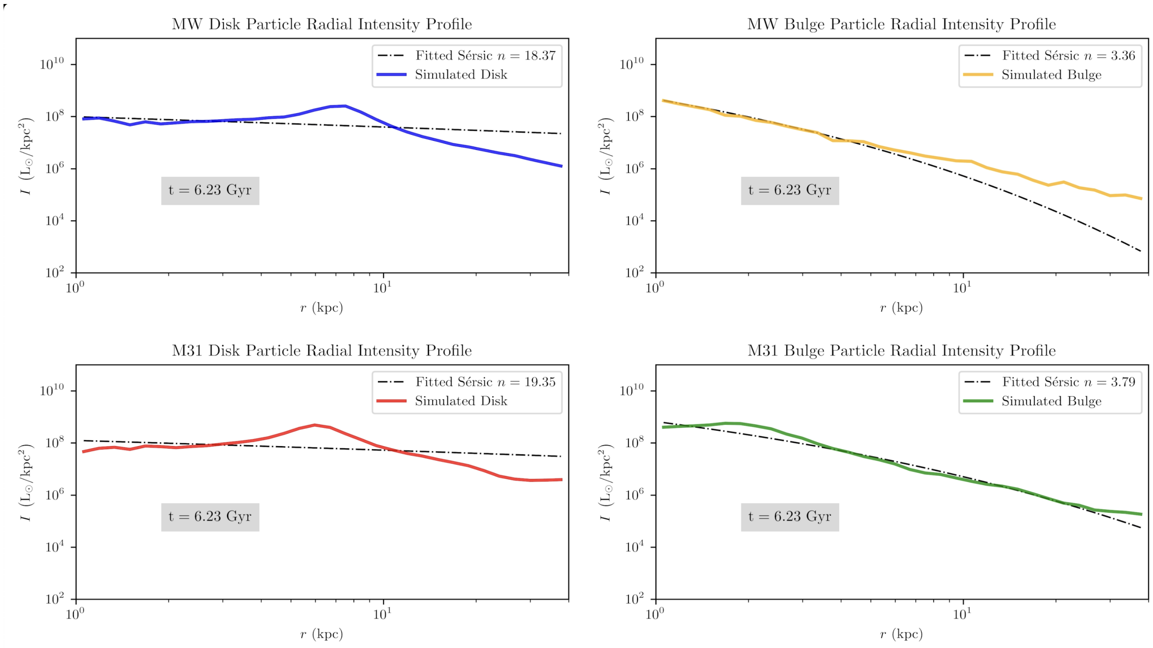

Figure 8. 6.23 Gyr

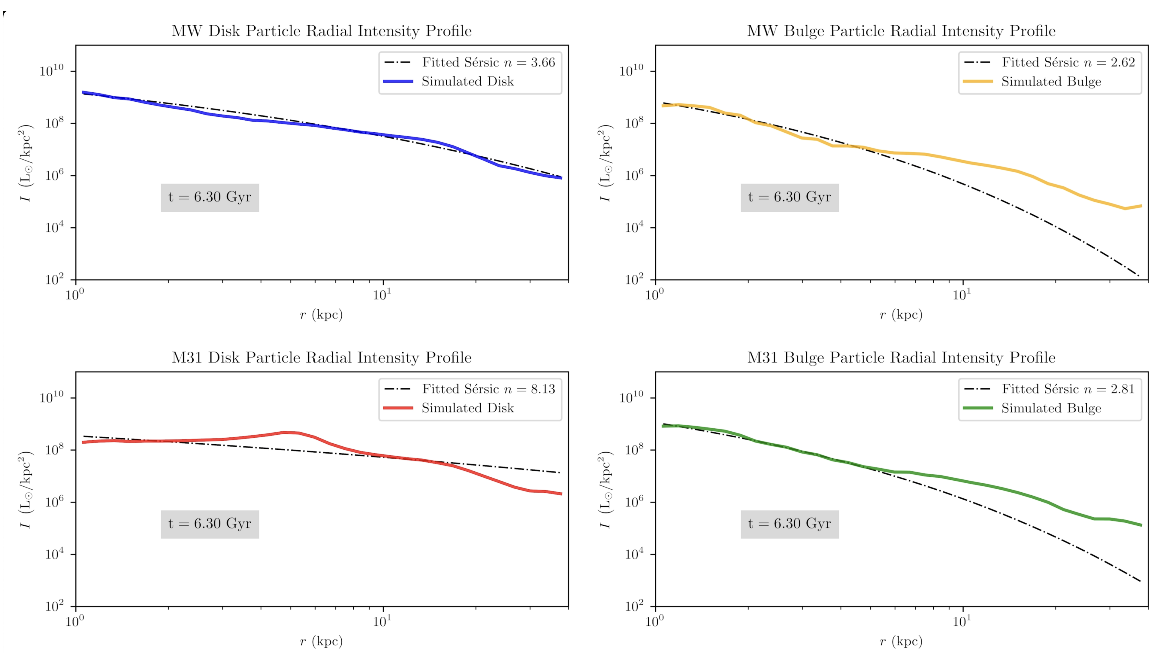

Figure 9. 6.30 Gyr

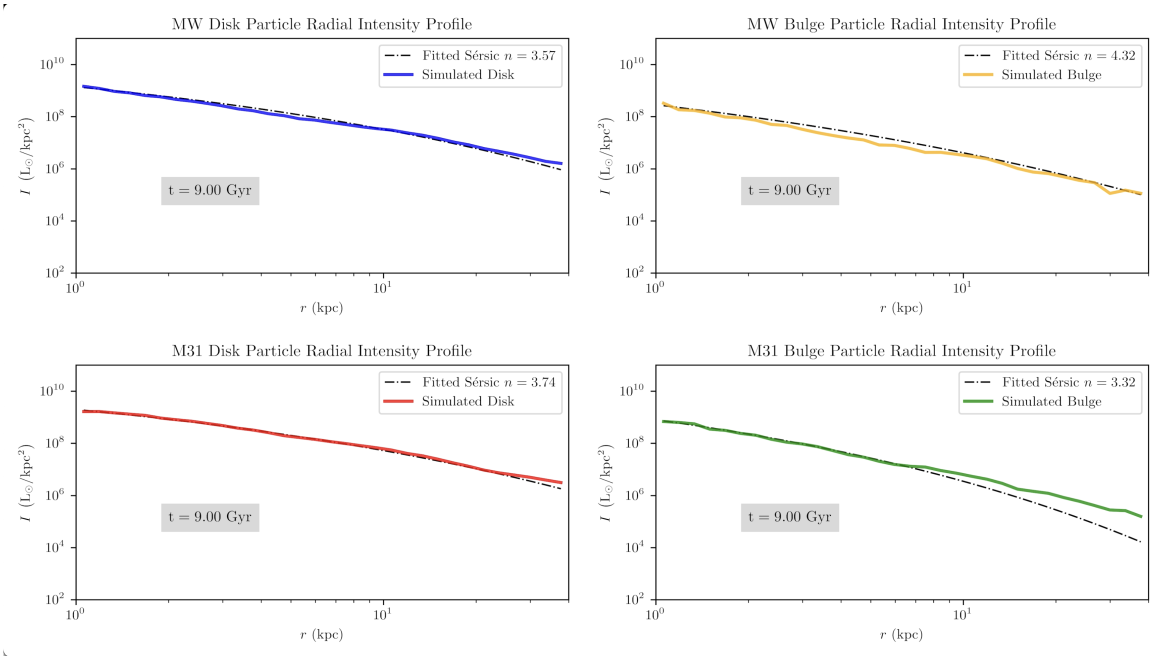

Figure 10. 9.00 Gyr

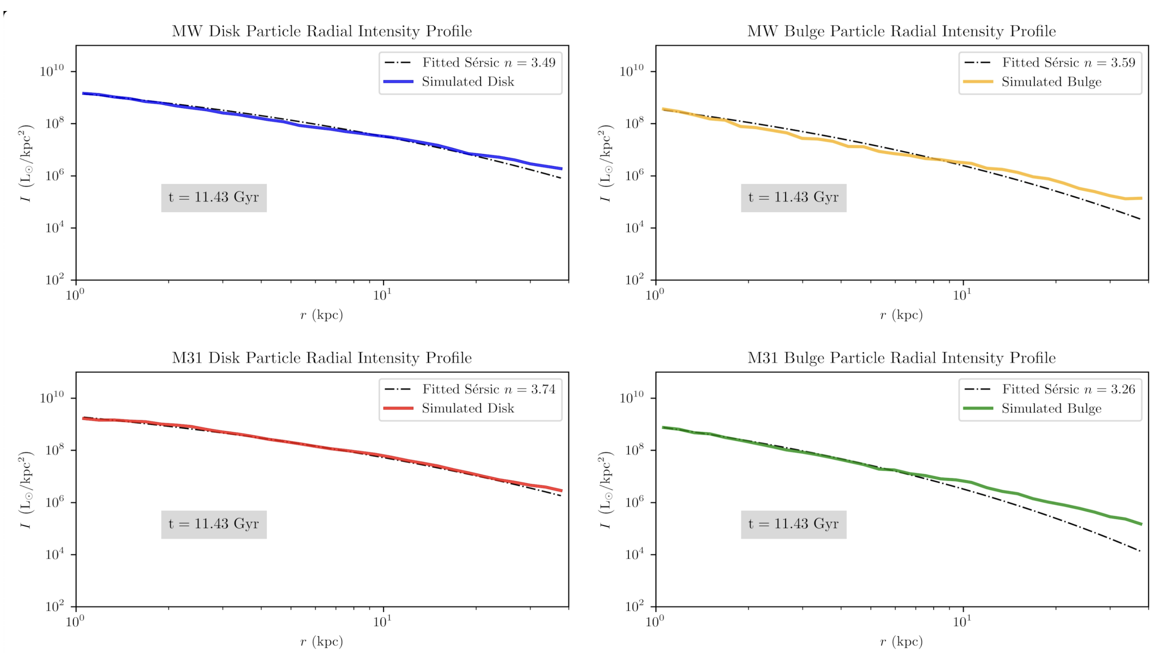

Figure 11. 11.43 Gyr

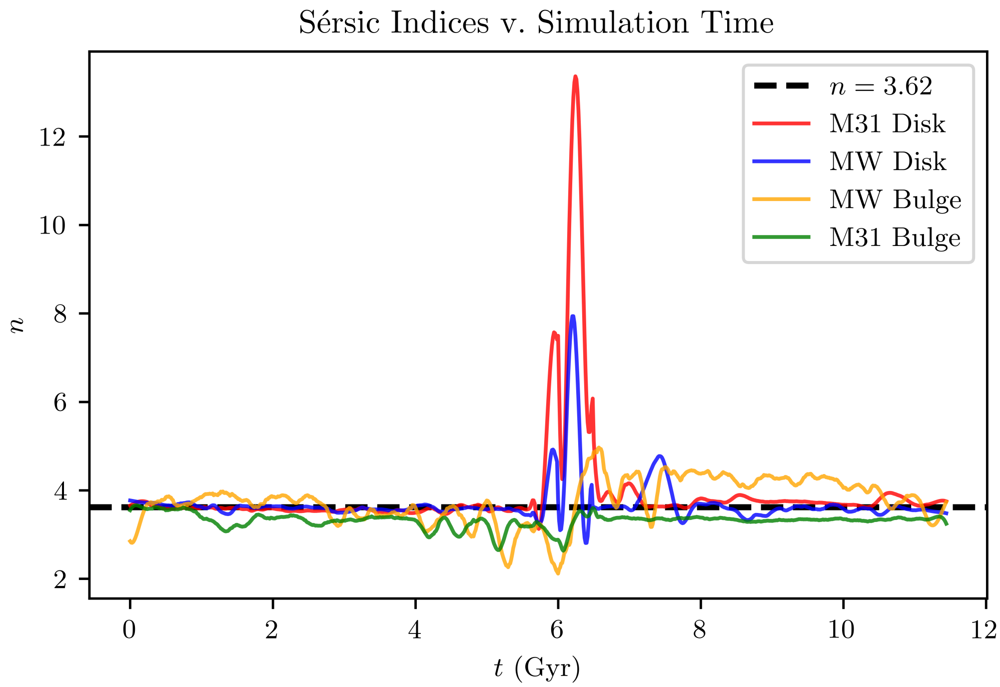

Figure 12. Indices v. time