**Title: Ellicular galaxies**

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**Abstract:**

The classification “early-type” galaxies includes both elliptical and lenticular galaxies. Lenticular galaxies are composed of a central spheroid (or “bulge”) of stars encased in a larger stellar disk. When performing bulge/disk decomposition of a galaxy’s light, the spheroidal component is typically described with a Sérsic [Sersic 1963] model, while the disk is modeled with an exponential function. Theoretically, the bulge-to-disk flux ratio can assume any positive value. However, several studies only consider bulge/disk decompositions in which the disk neatly dominates over the spheroid at large galaxy radii, creating an inner bulge, and reject those decompositions in which the disk remains embedded within the spheroid, labeling them as unphysical [Allen+2006]. Here we show that these rejected models correctly reproduce the photometric and kinematic properties of a class of early-type galaxies intermediate between that of elliptical and lenticular galaxies, which we name *ellicular*. Ellicular galaxies have often been confused with lenticular galaxies and, consequently, their disk luminosities have been considerably overestimated and their bulge luminosities underestimated. This mistake has led to some wrong conclusions, such as the claim that a number of ellicular galaxies (Mrk 1216 [Yildirim+2015], NGC 1277 [van den Bosch+2012], NGC 1271 [Walsh+2015], and NGC 1332 [Rusli+2011]) host a central black hole whose mass is abnormally large compared to expectations from its (underestimated) bulge luminosity. When ellicular galaxies are properly modeled, they no longer appear as extreme outliers in the (black hole mass) – (spheroid mass) diagram, resolving previous “anomalies”. This nullifies the need for invoking different evolutionary scenarios [Ferre-Mateu+2015] for these galaxies and their non-extraordinary black holes. Furthermore, it strengthens the significance of the observed (black hole mass) – (spheroid mass) correlation and confirms its importance as a fundamental ingredient for theoretical and semi-analytic models used to describe the coevolution of spheroids and their central supermassive black holes.

**Main:**

There are currently two well-known types of stellar disks in galaxies. The first are the large-scale disks (with sizes of a few kiloparsec) that dominate the light at large radii in spiral and lenticular galaxies; the second are the small (tens to a couple of hundred parsec) nuclear disks observed in both early- and late-type galaxies [Scorza & Van den Bosch 1998, Rest+2001, Balcells+2007, Ledo+2010]. The origin of the nuclear disks has been speculated to arise from the infall of small satellite galaxies or gas clouds. The origin, or at least the on-going feeding and growth, of the large-scale disks has been attributed to cold gas flows, gas rich mergers and halo accretion events [Khochfar & Silk 2006, Dekel+2009, Ceverino+2010, Conselice+2012]. A puzzling question, which has been unspoken for decades, is why are there not intermediate-sized disks: why are there not accretion events which create disks larger than the typical nuclear disks but which are not large enough to dominate at large radii? Here we report on the existence of these intermediate-sized stellar disks.

The majority of stellar disks have some level of inclination with respect to our line-of-sight, which makes them appear elliptical in projection on the sky, and helps us distinguish them from the more spherical bulges. Yet, other few disks are close to face-on, making their detection from images a difficult task. However, their presence can still be discerned from a galaxy’s one-dimensional radial “light profile”. Identifying the extent of these disks with respect to their bulge can be subtle. Two-dimensional kinematic maps represent an extremely powerful diagnostic tool for this purpose. Most early-type galaxies are classified as central fast rotators [atlas3d], that is, they are rapidly rotating within one galaxy half-light radius (the half-light radius of a galaxy is the radius that contains half of the galaxy light). However, more extended kinematic maps [Arnold+2014] reveal that some of the central fast rotators continue to be fast rotating well beyond one or two half-light radii, which proves the presence of a large-scale disk, whereas other central fast rotators become slow rotators in their outer regions, which indicates the presence of an intermediate-scale disk. Unfortunately, such extended kinematic maps are not yet available for a large sample of galaxies in the local Universe. Nevertheless, there is another powerful tool that can help identify the extent of stellar disks in early-type galaxies, and has the advantage of requiring only galaxy images (even photometrically uncalibrated), which are cheaper to acquire in terms of telescope time than spatially resolved two-dimensional kinematic maps. This tool is the radial “ellipticity profile” of a galaxy's isophotes.

The isophotes of a galaxy are curves along which the intensity of light is constant, and that can be modeled with a series of concentric ellipses (see Figure 1). These ellipses can have varying ellipticity, which means that they can be more or less “squeezed”. An ellipse with zero ellipticity corresponds to a circle, whereas an ellipse with large ellipticity is similar to a cigar. The toy model shown in Figure 1 illustrates the typical ellipticity profile of (i) a lenticular galaxy, comprised of a large-scale disk and a smaller encased bulge, (ii) an elliptical galaxy with a nuclear stellar disk, and (iii) a galaxy composed of an intermediate-scale disk embedded in a larger spheroid. We refer to the last case as a *ellicular* galaxy. Stellar disks are intrinsically flat and circular; they typically have fixed ellipticity, dictated by their inclination to our line of sight. Bulges, instead, can have their ellipticities varying with radius, but they are often rounder than the observed projection on the sky of inclined disks, thus their average ellipticity is lower than that of an inclined disk. If the ellipticity profile of a galaxy increases with radius, this can be ascribed to an inclined disk that becomes progressively more important at large radii, whereas a radial decrease of ellipticity signifies the opposite case.

The awareness that many “elliptical” galaxies actually contain embedded stellar disks dates back at least three decades [Capaccioli1987, Carter1987, Rix & White1990, Scorza & Bender 1990]. However, the class of ellicular galaxies has been missed by many galaxy modelers, who labeled as “unphysical” those bulge/disk decompositions in which the disk does not dominate over the spheroid at large radii [Allen+2006]. Such a concern is appropriate for late-type spiral galaxies, but not for early-type galaxies. This unspoken bias has led them to reject any bulge/disk decomposition with an outcome similar to that illustrated in the middle panel of Figure 1. Unsurprisingly, studies affected by this bias have found that the bulge-to-total ratio of lenticular galaxies is never larger than ~0.5 [Mendez-Abreu 2015].

Examples of ellicular galaxies are Mrk 1216, NGC 1271, NGC 1277, NGC 1332, and NGC 3115. Their distribution of light can be easily described and explained with a Sérsic-spheroid plus an intermediate-sized exponential-disk. Our bulge/disk decomposition for the galaxy NGC 3115 is presented in Figure 2. The radial light profile (μ) extends out to five times the galaxy half-light radius (5 x 50 arcsec). Not only does the photometric bulge/disk decomposition for NGC 3115 match the galaxy’s light profile and the ellipticity profile, but it is in excellent agreement with the galaxy’s kinematic properties [Arnold+2011].

Our two-component models (intermediate-sized disk embedded within a larger spheroidal component), match the observed light distributions and explain the kinematic maps [Arnold+2014] (when available) and the ellipticity profiles of ellicular galaxies. Figure 3 reveals that when ellicular galaxies are properly modeled, they no longer appear as extreme outliers in the (black hole mass) – (spheroid stellar mass) diagram. That is, when they are incorrectly modeled, they appear as outliers. Obviously, having both the black hole mass and the spheroid mass correct is important for placing systems in the (black hole mass) – (spheroid stellar mass) diagram.

For early-type galaxies, the bulge luminosity and the total galaxy luminosity can be used to predict the black hole mass with the same level of accuracy [Savorgnan+2015]. If a galaxy hosts a black hole that is over-massive compared to expectations from the bulge luminosity, but is “normal” compared to expectations from the total galaxy luminosity, then the bulge luminosity may have been underestimated due to inaccurate bulge/disk decomposition. Indeed, none of the five ellicular galaxies mentioned here is a noticeable outlier in the (black hole mass) – (total galaxy luminosity) diagram [Savorgnan+2015].

The existence of intermediate-scale stellar disks reveals that a continuum of disk sizes exists, rather than a dichotomy of nuclear versus large-scale disks. The presence of intermediate-scale disks also blurs the distinction between elliptical and lenticular galaxies. The existence of such disks is not only important for our understanding of disk growth in general, but accounting for such structure will impact on our understanding of galaxy structure and surely see the reclassification of many “disky elliptical” galaxies and lenticular galaxies as ellicular galaxies. It’s been argued [Graham 2014] that the classification scheme for early-type galaxies should not be their apparent axis ratio as seen on the plane of the sky, but instead their bulge-to-disk flux ratio, with a continuum from pure elliptical galaxies to disk-dominated lenticular galaxies.

We also note that the local Universe is populated by an abundance of compact, massive spheroids [Graham+2015], with the same physical properties as the high-redshift compact quiescent galaxies [van Dokkum+2008], named red nuggets [Damjanov+2009]. Some of these local compact massive spheroids are encased within a large-scale disk, that is to say they are the bulges of lenticular and spiral galaxies. Over the last 9-11 billion years, their spheroids have evolved by growing a relatively flat disk, rather than a three-dimensional envelope, which has increased the galaxy size but preserved the bulge compactness. The other compact massive spheroids in the nearby universe belong to ellicular galaxies, whose galaxy size is roughly equivalent to the spheroid size because these are spheroid-dominated systems. This implies that, among the local descendant of the high-redshift red nuggets, compact ellicular galaxies are those that have undergone the lowest degree of disk growth. Indeed, the galaxies Mrk 1216, NGC 1271, NGC 1277, NGC 1332, and NGC 3115 are all high-dispersion, compact ellicular galaxies.

**Method:**

Figure 3 was populated using a galaxy decomposition technique extensively described in [Savorgnan & Graham 2015]. Briefly, we obtained Spitzer/IRAC 3.6 μm images for 45 early-type galaxies with a dynamical detection of their black hole mass and we extracted their one-dimensional light profiles. We modeled the light profiles with a combination of analytic functions, using one function per galaxy component. Spheroid luminosities were converted into stellar masses using individual, but almost constant mass-to-light ratios (0.60 ± 0.02) [Savorgnan+2015]. The ellicular galaxies NGC 1332 and NGC 3115 are included in the sample of 45 early-type galaxies. In addition, we show the ellicular galaxies Mrk 1216, NGC 1271 and NGC 1277, which were not a part of the original sample of 45.

For the galaxy NGC 1271, we use the black hole mass measurement and the mass-to-light ratio obtained by [Walsh+2015]. The luminosity of the spheroidal component of this galaxy comes from the one-dimensional bulge/disk decomposition of [Graham+2015], who used an archived Hubble Space Telecope (HST) image taken with the Wide Field Camera 3 (WFC3) and the near-infrared F160W filter.

For the galaxy NGC 1277, we use the black hole mass measurement and the mass-to-light ratio obtained by [van den Bosch+2012]. The luminosity of the spheroidal component of this galaxy comes from our one-dimensional bulge/disk decomposition using an archived HST image taken with the Advanced Camera for Surveys (ACS) and the F550M filter (V-band).

For the galaxy Mrk 1216, we use the upper limit on the black hole mass and the mass-to-light ratio obtained by [Yildirim+2015]. The luminosity of the spheroidal component of this galaxy comes from our one-dimensional bulge/disk decomposition, using an archived HST image taken with the WFC3 and the F160W filter (H-band).

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**Contributions:**

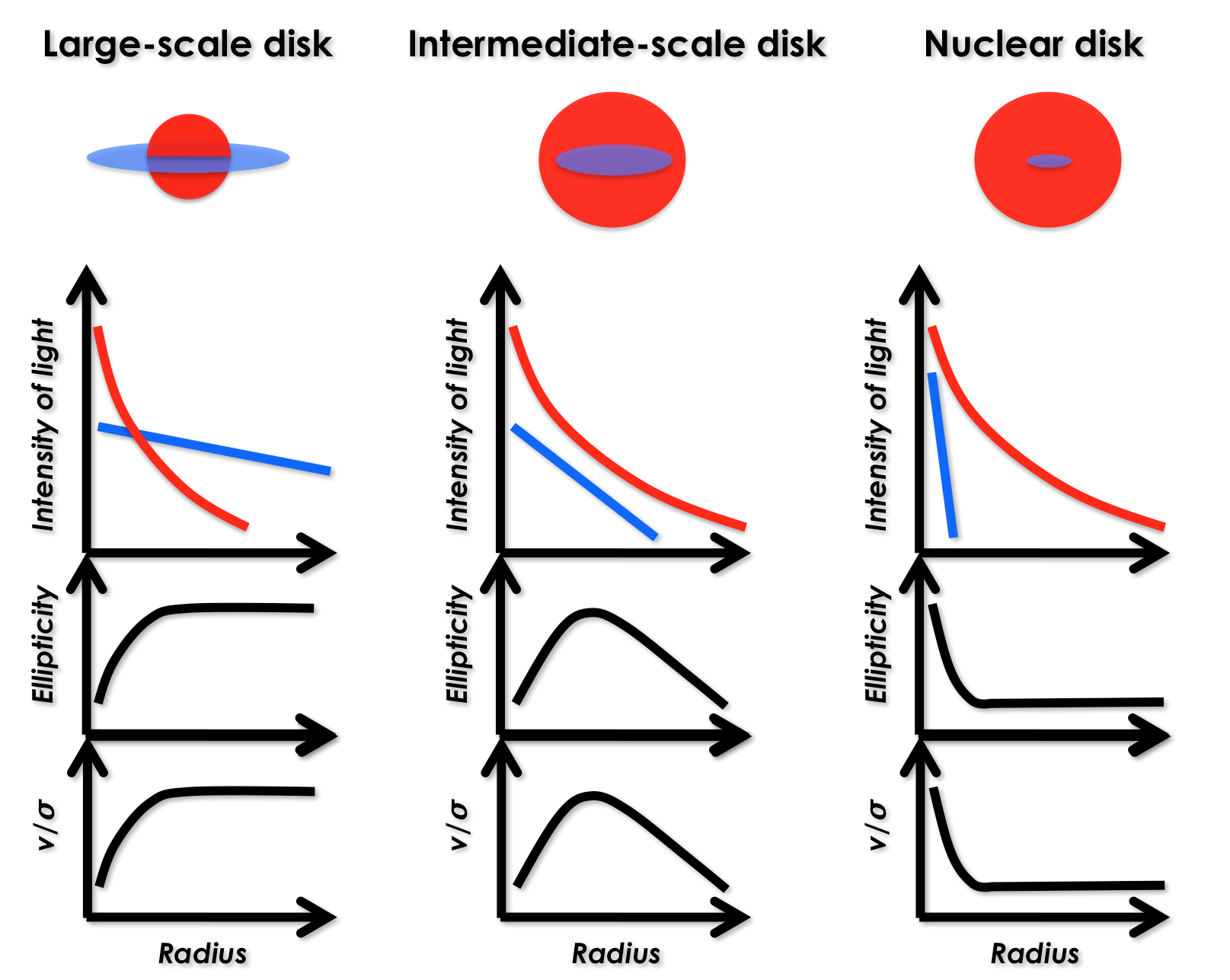
G.A.D.S. collected the data, and performed the data reduction and analysis. G.A.D.S. wrote the Python code used to perform the fitting of the one-dimensional surface brightness profiles. A.W.G. conceived and supervised the project. G.A.D.S. wrote the manuscript and produced the figures. All authors provided contribution to the interpretation of the results and the writing of the manuscript.

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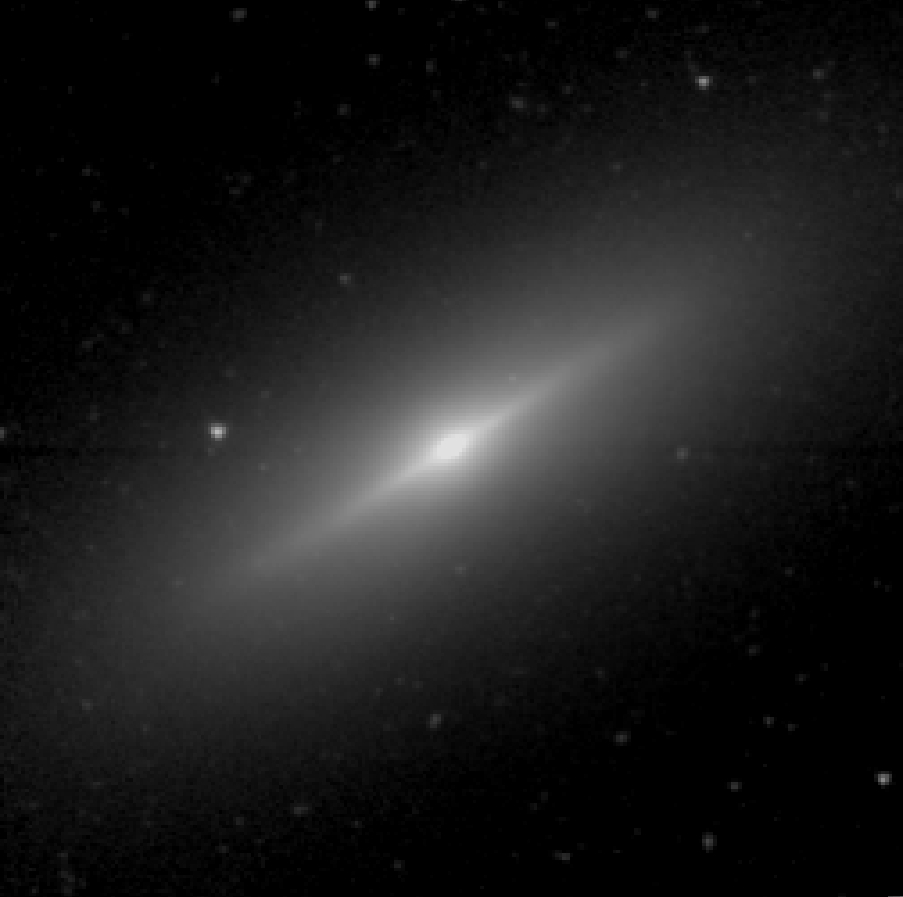
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*Figure 1*

Simple illustration of the bulge/disk decomposition, the ellipticity profile and the v/σ (rotation of the disk / dispersion of the spheroid) profile of three prototype early-type galaxies. In the decompositions, the spheroid (or bulge) and the disk are shown with the red and blue color, respectively. The left panel shows a lenticular galaxy, composed of a bulge encased in a large-scale disk. The right panel displays an elliptical galaxy with a nuclear stellar disk. The middle panel presents a “ellicular” galaxy with an intermediate-sized disk embedded in the spheroid.

a)  b) 

*Figure 2*

The galaxy NGC 3115. **a)** Near-infrared (3.6 μm) image of the galaxy obtained with the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope. **b)** Unsharp mask of the galaxy image. First the original image is smoothed through convolution with a Gaussian filter. Then the original image is divided by the smoothed image. The result is the unsharp mask. This technique highlights the asymmetric features of the original image. The unsharp mask of NGC 3115 reveals the presence of a faint edge-on nuclear ring.

Macintosh HD:Users:gsavorgnan:galaxy_vivisection:papers:lentiptical:images:n3115_decomposition.eps

*Figure 3*

Bulge/disk decomposition of the light profile, and ellipticity profile for the galaxy NGC 3115. The left panels refer to the major-axis Rmaj, while the right panels refer to the geometric mean of the major (a) and minor (b) axis (Req = √ab), equivalent to a circularized profile. The top panels display the observed galaxy light profiles (μ) with black points. The color lines represent the individual model components: red = Sérsic (spheroid); blue = exponential (disk). A faint nuclear ring, identified in the unsharp mask of the galaxy image, is additionally modeled with a Gaussian function (gray line). The residual profile (data – model) is shown as Δμ in the second row. The bottom panels show the ellipticity (ε) profiles.

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*Figure 4*

Early-type galaxies: black hole mass plotted against spheroid stellar mass for 42 galaxies (black) plus the galaxies Mrk 1216, NGC 1271, NGC 1277, NGC 1332, NGC 3115, and NGC 4291. The black solid line is the bisector linear regression for early-type galaxies [Savorgnan+2015]. The dashed lines mark the 1σ and 3σ deviations, where σ (0.51 dex) is the total rms scatter of the correlation in the black hole mass direction. The red color is used for five ellicular galaxies: NGC 1271, NGC 1277, NGC 1332, NGC 3115 and Mrk 1216 (for which only an upper limit on its black hole mass has been reported). Five galaxies (Mrk 1216 [Yildirim+2015], NGC 1271 [Walsh+2015], NGC 1277 [van den Bosch+2012, Yildirim+2015], NGC 1332 [Rusli+2011], and NGC 4291 [Bogdan+2012]), that were claimed to be extreme outliers in this diagram, all lie within the 3σ deviation from the correlation.

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