

The Stellar Kinematics of Extragalactic Bulges

Jesús Falcón-Barroso

Abstract Galactic bulges are complex systems. Once thought to be small-scale versions of elliptical galaxies, advances in astronomical instrumentation (spectroscopy in particular) has revealed a wealth of photometric and kinematic substructure in otherwise simple-looking components. This review provides an overview of how our perspective on galactic bulges has changed over the years. While it is mainly focused on aspects related to the dynamical state of their stars, there will be natural connections to other properties (e.g. morphology, stellar populations) discussed in other reviews in this volume.

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1 Introduction

Galactic bulges have been generally assumed to be simple components that, morphologically, closely resemble elliptical galaxies. First photometric decompositions of lenticular and spiral galaxies (e.g. Caon et al., 1993) established that the radial behaviour of their surface brightness followed a de Vaucouleurs (de Vaucouleurs, 1948) or a Sérsic profile (Sersic, 1968) with typically high n values. In the mid 90s, we discovered that bulges in late-type, spiral galaxies were smaller and displayed exponential profiles (Andredakis et al., 1995; Courteau et al., 1996; Carollo, 1999). This difference observed in the light profiles was also present in their colours, with exponential bulges displaying bluer colours than those with larger Sérsic n (e.g. MacArthur et al., 2004; Ganda et al., 2009). Despite the marked distinction in their light profiles, the variation of colour between bulges and their surrounding disks is rather smooth (e.g. Balcells & Peletier, 1994).

Our view of the location of bulges in the major scaling relations (e.g. Faber-Jackson [Faber & Jackson 1976], Kormendy relation [Kormendy 1977], or Fundamental Plane [Dressler et al. 1987; Djorgovski & Davis 1987]) has also evolved over time. The sample selection biases introduced in the first studies (e.g. predominantly early-type galaxies) showed no significant differences between bulges and elliptical galaxies (e.g. Kormendy & Djorgovski, 1989; Jorgensen et al., 1996; Balcells et al., 2007). With samples nowadays including large numbers of spiral galaxies, our understanding of the situation of bulges in those relations has now drastically changed (e.g. Gadotti, 2009; Laurikainen et al., 2010; Erwin et al., 2015).

One aspect in the study of galactic bulges that has radically changed our understanding of their nature (i.e. merger-driven structures around which disks are formed) is their kinematics. While the photometric properties of some bulges already pointed to a high degree of structural similarity with disks (e.g. exponential profiles), this can only be confirmed if their kinematics also follows that displayed by disks (e.g. significant rotation and low velocity dispersions). In a pioneering study Kormendy & Illingworth (1982) investigated the degree of rotational support of a small sample of bulges compared to elliptical galaxies. Figure 1 presents an updated version, from Kormendy & Fisher (2008), of the original figure published in 1982. The figure shows that bulges display a much larger degree of rotation than the elliptical galaxies at a given apparent ellipticity. This was the first piece of evidence in the literature indicating that bulges differed dynamically from their otherwise similarly looking, slow rotating, massive early-type counterparts. While we know now that this picture is not accurate, at the time it led to the realisation that some bulges are actually disks and therefore may not have formed in merger episodes, as most scenarios would assume, but rather formed from internal material through secular processes (Kormendy, 1993). These ideas evolved over time and gave rise to the definition of pseudobulges. We refer the reader to Falcón-Barroso & Knapen (2013) for an extensive review, produced by the lecturers of the *XXIII Canary Islands Winter School of Astrophysics*, of bulge formation and evolution in the context of secular evolutionary processes.

In this review I will give an overview of the kinematic properties observed in extragalactic bulges, establish their connection to the dynamical features produced by bars, and briefly discuss the similarities with the Milky Way bulge. I will also summarise our yet limited knowledge of the kinematics of bulges at high redshift and end with future prospects yet to be explored in this field.

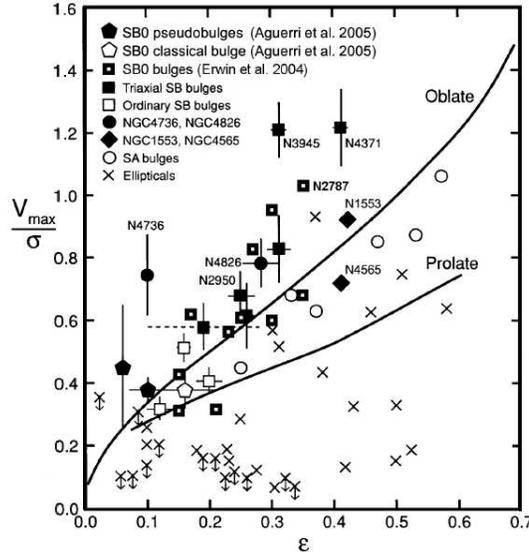


Fig. 1 Historical view of the level of rotational support and anisotropy of a sample of elliptical galaxies (crosses) and bulges (remaining symbols) from Kormendy & Fisher (2008). This is an updated version of the original figure presented in Kormendy & Illingworth (1982). While the physical interpretation of this figure has evolved over time, it was the first piece of evidence suggesting that bulges and massive early-type galaxies were intrinsically different.

2 Kinematic Properties of extragalactic Bulges

The central regions of galaxies are complex environments often displaying multiple coexisting structural components. It is thus important to define what we mean by a bulge in this context. In this chapter I will consider as a bulge the stellar structures in the central regions of galaxies that “bulge” vertically over the disk. The modern view is that there are three type of bulges: classical bulges (with properties akin to elliptical galaxies), disky bulges (with properties akin to disks), and Boxy/Peanut bulges (which are related to bars, see §3). In addition to bulges, the central regions of galaxies can also host smaller structures such as nuclei, black holes, or nuclear rings (that do not extend vertically beyond the main disk of the galaxy).

The study of bulges is often hampered by the contamination from different sources¹. In general there are two main components that can affect our measurements: (1) the underlying main disk of the galaxy, as so far there is no indication of truncation of disks in the inner parts of galaxies; (2) dust, that will prevent the full integration along the line-of-sight and thus will only allow to measure properties of stars in front of the dust lanes. These issues are usually solved by observing galaxies in edge-on or face-on configurations. The first one will give a clear view of the bulge above the disk and avoid dust obscuration. It is most useful for prominent bulges in early-type galaxies. The face-on orientation will minimize the effects of the underlying disk. It is best for small bulges in late-type systems, which have higher surface brightness than the disk. The drawback is that if bulges are rotating, their signature will be likely minimal in that orientation.

In the following subsections I will summarize the main kinematic properties of bulges paying particular attention to those works in the literature that have considered these issues more carefully.

2.1 Rotational support and level of anisotropy

Kormendy & Illingworth (1982) were the first to describe the level of rotational support specifically in bulges of galaxies. This was achieved by measuring the maximum rotational velocity observed in the regions above the main disk where the light of the bulge dominates over the central velocity dispersion of the system (V_{\max}/σ). The work by Kormendy not only concluded that the level of rotation observed in galactic bulges was larger than that displayed by elliptical galaxies but also, with the aid of model predictions (Binney, 1981), concluded that bulges were very likely oblate, have isotropic velocity dispersions, and are flattened by rotation. This study was quickly followed up by Kormendy himself (Kormendy, 1982), but also other authors (Davies et al., 1983; Davies & Illingworth, 1983) reaching similar conclusions. Our current view on the level of anisotropy of bulges is, however, different (e.g. Cappellari et al., 2007).

The V_{\max}/σ - ϵ diagram has been very popular for its power to classify dynamically different kind of galaxies, but most studies have focused on the study of the entire systems and not in their bulge components specifically (e.g. Bender, 1988b; Prugniel & Simien, 1994; Kormendy & Bender, 1996; Rix et al., 1999; van Zee et al., 2004). With the advent of integral field spectroscopy (IFS), this diagram has evolved and led to a parameter (i.e. λ_{Re} , Emsellem et al. 2007) that allows a more robust (and less inclination dependent) kinematic classification of galaxies. λ_{Re} quantifies the level of specific angular momentum in a galaxy within its half-light radius. Applied to large samples of early-type galaxies it allowed the distinction between Slow

¹ It is important to remember that properties observed in galaxies are result of integrating along the line of sight. This averaging depends greatly on the number of components as well as the type of stars contributing most to the light in that direction.

and Fast rotating galaxies (Emsellem et al., 2007, 2011). Together with model predictions for oblate/prolate, (an)isotropic systems, it can also be used to establish the level of anisotropy of galaxies. This aspect was explored by Cappellari et al. (2007) for the SAURON sample (de Zeeuw et al., 2002) of early-type galaxies. This study shows that the family of Slow Rotators are weakly triaxial, while the Fast Rotators (with V_{\max}/σ values similar to those observed in bulges) are typically oblate and display a wide range of anisotropy values. The results of this study indicate that the anisotropy observed in Fast Rotators is mainly due to a flattening of the velocity ellipsoid in the meridional plane ($\sigma_R \geq \sigma_z$), with clear indications that anisotropy is larger for intrinsically flatter galaxies. Given the significant contribution of the bulge to the light in these regions, this result suggests that bulges are actually anisotropic. This is consistent with the level of intrinsic flattening observed in different kind of bulges (see Méndez-Abreu in this volume). In this context, the study of larger samples of bulges in late-type galaxies will be very important to fully characterize their dynamical properties (e.g. CALIFA survey, Falcón-Barroso et al., 2014).

There has been very few attempts in the literature to extract a *clean* measurement of the anisotropy of bulges and are mostly focused on the analysis of the Milky Way bulge. The complications to decompose accurately the contributions of the disk to the velocity ellipsoid in the bulge dominated areas still remains the major hurdle. The best way forward in this topic has come from the use of detailed dynamical modelling fitting the observed stellar kinematics (e.g. Bottema et al., 1991; Pignatelli & Galletta, 1999; Kregel & van der Kruit, 2005). Nevertheless, the main limitation of those studies is that often the shape of the velocity ellipsoid is a property imposed in the fitting. The natural step forward is the use of orbit-based dynamics models (e.g. Schwarzschild, 1979) to separate the contributions of the bulge, disk, and any other components present in a galaxy and thus obtain their intrinsic properties. These models are quite demanding and require a large number of kinematic constraints. With many IFS surveys providing data for vast amounts of galaxies, it is only a matter of time that we exploit these analysis tools more routinely to study the intrinsic properties of bulges.

2.2 *Scaling relations*

Many of the scaling relations used to study galaxy evolution are, in essence, different manifestations of the Virial Theorem (Clausius, 1870), and relates the kinetic energy of a galaxy with the one provided by its gravitational potential. The relationship between different structural parameters of galaxies (e.g. absolute magnitude, half-light radius, mean surface brightness), are discussed at length in other reviews in this volume. Here we concentrate only on those relations that involve the velocity dispersion of the galaxy (σ).

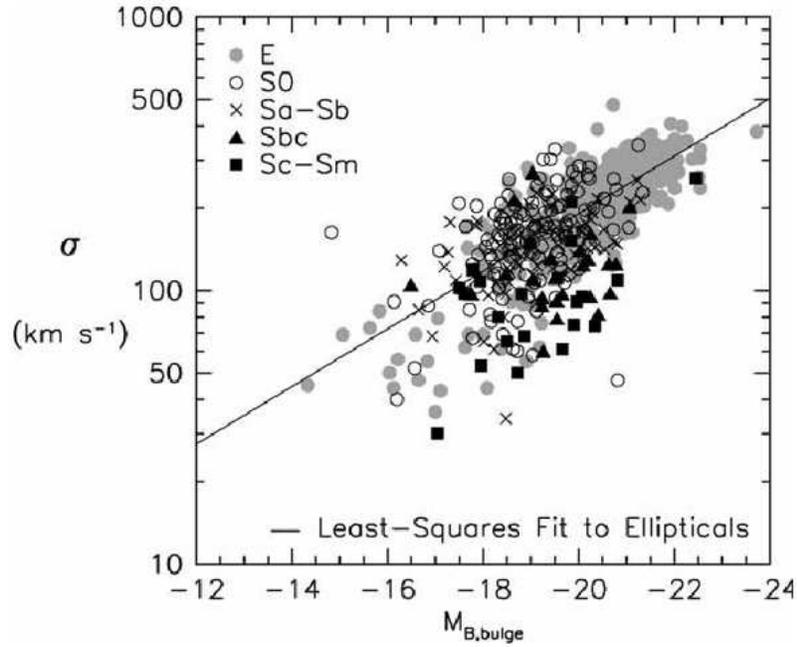


Fig. 2 Faber-Jackson relation for galaxies of different morphological types from Kormendy & Cornell (2004). Bulges of late-type galaxies deviate systematically from the relation defined by ellipticals.

2.2.1 Faber-Jackson relation

The Faber-Jackson relation establishes the link between the absolute magnitude of a galaxy with its central velocity dispersion (Faber & Jackson, 1976). Early-type galaxies form a well defined sequence where more luminous galaxies are also those exhibiting larger velocity dispersions. When it comes to the bulges in particular, the inclusion of bulges of lenticular galaxies hardly introduces any changes in the relation. Bulges of disk dominated spiral galaxies, however, seem to populate different regions in this parameter space, with largest offsets more from the relation defined by the ellipticals for those galaxies with latest morphological types (see Figure 2). The observed offset implies that: (1) either the bulges of later-types are brighter at a given velocity dispersion, which would suggest the presence of younger stellar populations (as they are also typically bluer) and/or (2) the dynamics of late-type bulges, at a given absolute bulge luminosity, is closer to that observed in their surrounding disks. Both cases are likely possible given that the velocity dispersion is biased towards the younger population present along the line-of-sight. Note, that despite the potential disk origin of those late-type bulges, the observed relation is not driven by the luminosity of the disk but of the bulge itself (e.g. Balcells et al., 2007).

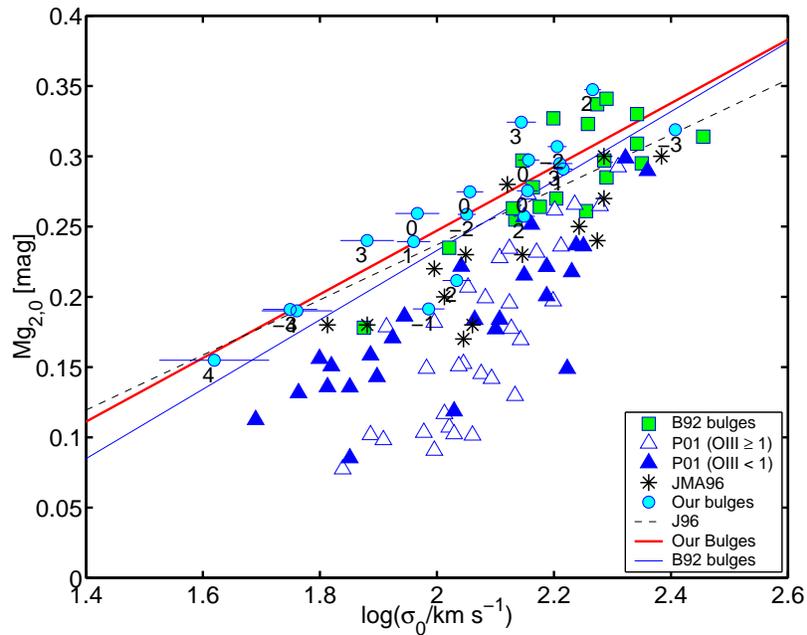


Fig. 3 $Mg_2 - \sigma$ relation for galactic bulges presented in Falc3n-Barroso et al. (2002). The figure includes samples from this work as well as Bender et al. (1992), Jablonka et al. (1996), and Prugniel et al. (2001). Dashed line marks the reference relation for early-type galaxies observed by Jorgensen et al. (1996). Bulges of later-type galaxies, e.g. with larger amounts of ionised-gas and younger stellar populations, deviate most from the reference line.

2.2.2 $Mg_2 - \sigma$ relation

A more direct connection with stellar populations is made in the $Mg_2 - \sigma$ relation (e.g. Terlevich et al., 1981). In Figure 3 we show the compilation made by Falc3n-Barroso et al. (2002) using their own sample together with that of Bender et al. (1992), Jablonka et al. (1996), and Prugniel et al. (2001) against the reference relation defined for early-type galaxies by Jorgensen et al. (1996). Galaxies displaying larger amounts of ionised gas (i.e. [OIII] equivalent width) are also the ones deviating most from the relation for early-types. This relation is usually considered as a mass–metallicity relation. This is however only true in the absence of young stellar populations. If present, the Mg_2 index is no longer a good metallicity indicator and it becomes quite sensitive to age (e.g. Vazdekis et al., 2010). Galaxies with large amounts of ionised-gas are also typically the ones experiencing more intense star formation and thus result into overall younger stellar populations. It is therefore not surprising that the bulges in those galaxies are the ones deviating most from the relation described by the early-type galaxies. Similar conclusions have been reached using much larger samples (e.g. Chiappini et al., 2002), although exploring the dependence with maximum rotational velocity rather than morphological type.

2.2.3 Fundamental Plane relation

The Fundamental Plane is one of the most studied scaling relations. It relates the half-light radius of galaxies to the mean surface brightness within that radius and the central velocity dispersion of the galaxy. As many other scaling relations, early-type galaxies have been studied extensively (e.g. Dressler et al., 1987; Djorgovski & Davis, 1987; Jorgensen et al., 1996; Pahre et al., 1998; Mobasher et al., 1999; Bernardi et al., 2003; D’Onofrio et al., 2008; Hyde & Bernardi, 2009; La Barbera et al., 2010; Magoulas et al., 2012; Cappellari et al., 2013). In contrast, the specific location of bulges in the relation has not been explored much and has been limited to galaxies with prominent bulges.

One of the first studies in this respect was carried out by Bender et al. (1992). They showed that bulges of lenticular galaxies followed the relation defined by elliptical galaxies. This result was later confirmed by Falcón-Barroso et al. (2002), who also found that bulges of later-type galaxies (e.g. Sbc) were slightly displaced with respect to the main relation. Bulges presenting the largest offsets were those with younger stellar populations and lower velocity dispersions. These authors showed that the offsets could be removed if one considers the missing rotational support expected in these late-type bulges. As the rotational support of some bulges increases, the measured velocity dispersion is no longer a reliable tracer of their motion. In those cases rotational velocity is a much better probe of those motions. For purely rotationally supported systems the Tully–Fisher relation (Tully & Fisher, 1977) is the one often the one invoked. Several studies have confirmed that when the full kinetic energy is accounted for and differences in the stellar populations are considered, galaxies of all morphological types form a single relation (e.g. Prugniel & Simien, 1994, 1996; Cappellari et al., 2006; Graves & Faber, 2010; Falcón-Barroso et al., 2011), with remaining scatter typically driven by changes in their mass-to-light ratios (e.g. Cappellari et al., 2013).

2.3 Radial behaviour

The study of the kinematic radial properties of galaxies has been one of the most prolific areas in astronomy. Mainly for bulges of early-type galaxies (e.g. Kormendy & Illingworth, 1982; Fisher, 1997; Héraudeau & Simien, 1998; Héraudeau et al., 1999; Falcón-Barroso et al., 2003; Emsellem et al., 2004; Spolaor et al., 2010), over time we quickly started to routinely explore the motions of stars in late-type systems (e.g. Bottema, 1989, 1992; Vega Beltrán et al., 2001; Pizzella et al., 2004; Kregel & van der Kruit, 2005; Pizzella et al., 2008; Fabricius et al., 2012). More recently, we have started expanding our understanding of bulges through IFS (e.g. SAURON [Ganda et al. 2006], DisKMass [Martinsson et al. 2013]). While at first only rotational velocity and velocity dispersion was extracted, the arrival of new parametrizations of the line-of-sight velocity distributions (e.g. Gauss-Hermite expansions, van der Marel & Franx 1993) allowed us to identify the presence of kine-

matic subcomponents in galaxies (see §2.4 for a detailed discussion). Despite displaying clear signatures of rotational support, it is very hard to distinguish between the signal of the bulge and underlying disk in typical rotation curves. A much more fruitful avenue to explore is the study of the radial behaviour of the stellar velocity dispersion. With many bulges still having a high degree pressure support (e.g. dynamical support by random motions), it is easiest to identify the contrast between the velocity dispersion of the disk and the bulge-dominated regions.

Fisher (1997) is one of the first studies to correlate the slope of the observed velocity dispersion profile with general properties of their host galaxies (e.g. central velocity dispersion, absolute magnitude, or Mg_2 and Fe line-strength indices). He analysed a sample of 18 lenticular galaxies and computed the velocity dispersion gradients along the major and minor axes of the galaxies. Compared to bright elliptical galaxies, the velocity dispersion profiles of lenticulars in his sample were much steeper. This is expected given that the profiles reached the low dispersion regimes observed in the disk dominated regions. The contrast between the velocity dispersion in the bulges and disks of his galaxies was therefore large. The intriguing result of this study was to discover that there was no correlation between these gradients and central velocity dispersion (σ_0), absolute magnitude or gradients of metallicity sensitive line-strength indices. The lack of correlation with central velocity dispersion was particularly surprising, as one would expect a larger contrast (i.e. steeper gradient) between the very high central dispersion galaxies and their surrounding disk. At face value, this result suggests that: (1) the sample used in this study did not cover a sufficiently large range of central velocity dispersion values, which could be true as the lowest σ_0 was above 100 km s^{-1} or (2) galaxies with dynamically hotter bulges (i.e. with larger σ_0) have also hotter disks. At this point, with the current sample it was not possible to discern between the two scenarios.

The next natural step in this direction was to extend the sample to later-type galaxies. Falcón-Barroso et al. (2003) studied the radial kinematic profiles (along the minor axis) of 19 galaxies with morphological types expanding between S0 and Sbc. The sample was carefully chosen to have intermediate inclinations and thus permit access to the bulge with minimal contamination of the disk on one side of the galaxy. Central velocity dispersions ranged from 50 to over 300 km s^{-1} . The analysis of their sample did show remarkably different σ radial profiles. While about half of the sample displayed very steep profiles, the remaining set showed mainly flat profiles. The lack of velocity dispersion gradient in a fair amount of galaxies in the sample was yet another piece of evidence pointing to the disky nature of some galactic bulges. In relation to the properties of the host galaxy, there was a slight tendency for galaxies with flatter profiles to display higher disk central surface brightness. A trend was also found with the ellipticity of the bulge component in the sense that more flattened bulges showed shallower gradients. Despite analysing galaxies covering a wider range of morphological types, no correlation was found with either morphological type index, bulge Sérsic index n , bulge and disk scale lengths and bulge effective surface brightness. It appears that the disky nature of bulges cannot be es-

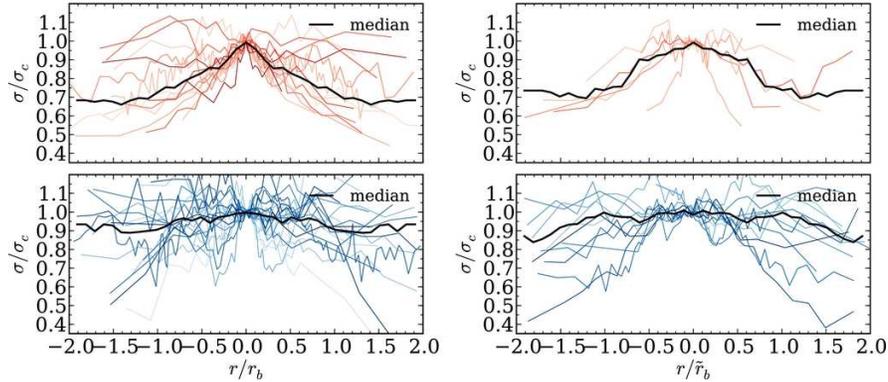


Fig. 4 Radial velocity dispersion profiles for a sample of 45 lenticular to spiral galaxies from Fabricius et al. (2012). Profiles have been normalised to their central velocity dispersion and bulge radius. Profiles of classical bulges are plotted in red and pseudobulges in blue. Major axis profiles are shown on the left and minor axis on the right columns respectively. The thick black lines correspond to the median of the individual profiles.

tablished on the basis of spheroid luminosity, as velocity dispersion gradients do not seem to correlate with bulge luminosity or with central velocity dispersion either.

Fabricius et al. (2012) presents the most recent effort in the literature trying to address these issues. In this work 45 S0 to Sbc galaxies were studied with the goal of relating the kinematic information with photometric properties typical of classical and pseudobulges². The sample contained a fair fraction of barred galaxies and displayed a wide range of central velocity dispersions (between ~ 50 to 200 km s^{-1}) and absolute magnitudes (from -18 to -21 mag). The galaxies were also moderately inclined with allowed access to the bulge region without being significantly affected by dust in the disk. Figure 4 shows the radial behaviour of the velocity dispersion along the major and minor axes of the galaxies in the sample. Similarly to Falc3n-Barroso et al. (2003), bulges exhibit two types of profiles: steep and flat velocity dispersion profiles. This work provides first tentative evidence for a correlation between the slope of the velocity dispersion profile and the bulge’s Sérsic index n .

The study of the stellar kinematics of late-type galaxies has usually been hampered by complex, often dusty, morphologies. Furthermore, bulges in those galaxies are not particularly bright which makes the extraction of any spectroscopic measurement (kinematic in particular) specially harder. With the advent of integral-field spectroscopy, a few studies have allowed a kinematic characterisation of bulges in galaxies from Sb to Sd types. Ganda et al. (2006) carried out SAURON observations of 18 spiral galaxies with good *Hubble Space Telescope* photometry available. The

² Note that in this work the definition of a bulge differs from the one used in this review. While Fabricius et al. (2012) define bulges as structures with flux above the disk surface brightness profile, here they are also required to extend vertically above the disk.

velocity dispersion profiles of the galaxies were mostly flat or with positive gradients. Very few galaxies displayed negative gradients. When looking for correlations between these gradients and the morphological type of the galaxies, there was only a slight tendency for earlier types to displayed negative gradients. Positive gradients were not strongly correlated with latest Hubble types.

The study of velocity dispersion gradients will be soon expanding thanks to the large number of IFU surveys (DiskMass, Bershady et al. 2010; CALIFA, Sánchez et al. 2012]; SAMI, Croom et al. 2012; MaNGA, Bundy et al. 2015). However, it is important to remember that not all of them will allow the study of bulges in late-type galaxies due to restrictions in the spatial sampling or their spectral resolution.

2.4 Amount of substructure

So far in this review we have exposed the properties of different kind of bulges, and yet this has gone as far as showing that some bulges exhibit kinematics closer to what it is observed in a disk (e.g. rotation dominated) instead of the classical idea of bulges being pressure supported. Here we will revise the kinematic properties of the different structural components dominating the light in the inner regions of galaxies.

Counter-rotating components are common in galaxies. Large, kpc-scale, kinematically decoupled components (KDCs) are typically found in bright elliptical galaxies (e.g. Bender, 1988a; Franx et al., 1989; Carollo et al., 1997; Hau et al., 1999; Davies et al., 2001; Emsellem et al., 2014). They usually contain old stellar populations and are almost indistinguishable from the remaining body of the galaxy. Smaller decoupled components are, however, harder to identify, are made of young stars and reside in lower luminosity early-type galaxies (e.g. McDermid et al., 2006). Large-scale counter-rotation of disk components seems also not so rare: NGC 4550 (e.g. Rubin et al., 1992; Rix et al., 1992), NGC 4138 (Jore et al., 1996), NGC 4473 (Cappellari et al., 2004). See Krajnović et al. (2011) for other cases detected through a *kinemetry* analysis (Krajnović et al., 2006). The detection of such extreme cases keeps increasing as new kinematic decomposition techniques are developed (e.g. Coccato et al., 2013; Johnston et al., 2013; Pizzella et al., 2014).

Counter-rotation of bulges is an odd phenomenon. There are very few cases reported in the literature of bulges rotating around a completely different axis than their surrounding disks. One of those striking cases is NGC 4698 (Bertola et al., 1999), where the bulge appear to rotate perpendicular to the stellar disk. Another unusual case is that of NGC 7331, where the bulge was reported to counter-rotate with respect to the disk (Prada et al. 1996, but see Bottema 1999). Numerical simulations suggest mergers of galaxies as the only viable path for the formation of such structures (e.g. Balcells & González, 1998; Thakar & Ryden, 1998).

A common feature is the presence of co-rotating components (e.g. a nuclear disk) embedded in an otherwise pressure supported spheroidal bulge . The key kinematic

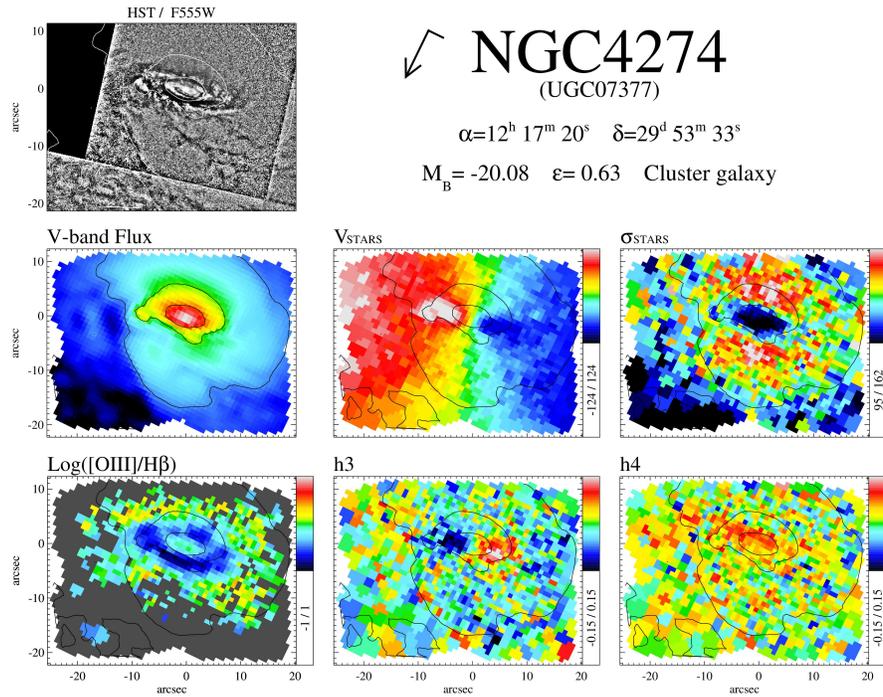


Fig. 5 Stellar kinematic maps for NGC 4274 from Falcón-Barroso et al. (2006). The arrow and its associated dash at the top of each figure mark the north and east directions, respectively. (*First row*) HST unsharp-masked image of the galaxy and some basic information. (*Second row*) reconstructed total intensity (in mag/arcsec² with an arbitrary zero point), stellar mean velocity V , and stellar velocity dispersion in km s⁻¹. (*Third row*) $[\text{OIII}]/\text{H}\beta$ emission line ratio map (in logarithmic scale), and Gauss-Hermite moments h_3 and h_4 of the stellar line-of-sight velocity distribution.

signature of these inner disks is a steep rise of the rotation velocity in the inner parts (i.e. faster than the expected rise of the main disk) accompanied by low velocity dispersions values. There is often also an anti-correlation between the velocity and h_3 moment in the locations with lowest velocity dispersion, which is usually an indication of multiple kinematic components. All these features are shown in Figure 5 using the two-dimensional kinematic maps of NGC 4274 from Falcón-Barroso et al. (2006) as an example. The *Hubble Space Telescope* unsharp-masked image reveals the presence of a dusty disk in the inner regions of the galaxy, which is not so obvious in the reconstructed image of the galaxy. The disk has a clear signature in the velocity map, and even more so in the velocity dispersion which is much lower than the values of the surrounding dynamically hot bulge. In this particular case, the very low $[\text{OIII}]/\text{H}\beta$ emission line ratio suggests star formation is taking place in the inner disk. The presence of these co-rotating components do not always imply associated young stellar populations. The stellar population analysis carried out by Peletier et al. (2007) of the Falcón-Barroso et al. (2006) sample of 24 Sa galaxies

concluded that about half of the galaxies displaying low central velocity dispersion values (so called σ -drops, Emsellem et al. 2001; Wozniak et al. 2003) have mean luminosity weighted ages above 5 Gyr. The incidence of σ -drops in this sample was about 50%. σ -drops are not only produced by nuclear disks, but can also be caused by nuclear dust spirals and star-forming rings (Comerón et al., 2008). The origin of these components is often related to the inflow of gas, driven by bars, towards the inner regions of galaxies (e.g. Athanassoula, 2005). Note, however, that minor mergers could be also responsible for the formation of inner disks and rings in spiral galaxies (e.g. Eliche-Moral et al., 2011).

3 Relating Bars and Bulges

Bars are prominent components of galaxies, produced by disk instabilities, that can pump disk material above the plane generating central structures that also *bulge* over the thin disk (e.g. Hasan et al., 1993). As we discuss in this section, the kinematic properties of these bars are different from those observed in common bulges. The origin of some type of bulges (e.g. pseudobulges) appears to be tightly connected to secular evolutionary processes induced by bars (see Athanassoula, 2005, for a theoretical view of bulge formation in the context of bars). Bars are active agents in the inflow of gas towards the inner regions of galaxies (e.g. Sakamoto et al., 1999). This naturally allows the formation of new structures (e.g. bulges, rings, inner disks, central mass concentration).

The vertical extent of bars is best observed in edge-on galaxies. When the long axis of the bar is perpendicular to our line-of-sight bars are usually called Boxy/Peanut (BP) bulges due to their peculiar shape. Most of the material outside the disk plane has been elevated through bar buckling episodes early in the evolution of the bar (e.g. Martinez-Valpuesta et al., 2006). Kinematically, BP bulges produce a characteristic signature (i.e. a “figure-of-eight”) in the Position–Velocity Diagram (PVD). This was first predicted by Kuijken & Merrifield (1995) (see Figure 6, top row). With the aid of analytical models, they determine the location of particles in this diagram for barred and non-barred galaxies. In their view, the gap observed in the PVD of barred galaxies is produced for a lack of available orbits near the corotation radius of the bar. This effect should affect both the stellar and gas components of galaxies. This prediction was nicely confirmed with larger samples of galaxies (e.g. Merrifield & Kuijken, 1999; Bureau & Freeman, 1999). In the case of Bureau & Freeman (1999), they produced PVDs for a sample of 30 edge-on spiral galaxies with prominent BP bulges. Figure 6, bottom row, shows the observed PVD for NGC 5746 that clearly displays the predicted gap.

Another typical kinematic feature of BP bulges predicted by numerical simulations is cylindrical rotation (e.g. Rowley, 1988; Combes et al., 1990). The first evidence for cylindrical rotation in galaxies was revealed by (Kormendy & Illingworth, 1982) for NGC 4565 when studying the stellar kinematics of galactic bulges. Ref-

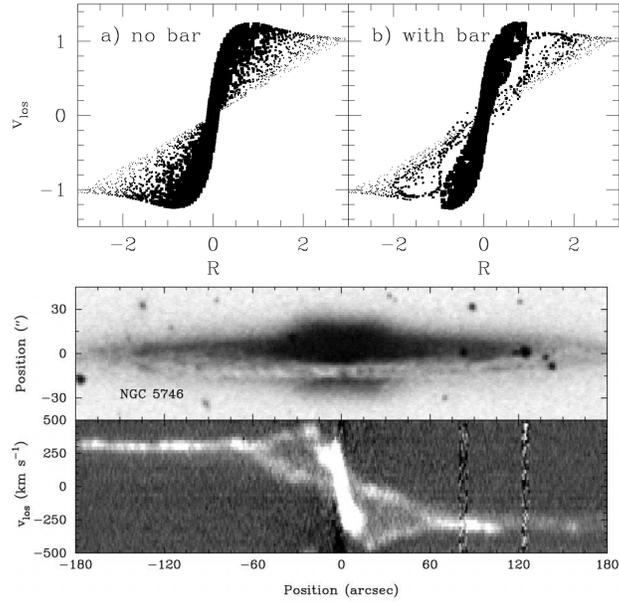


Fig. 6 Position–Velocity diagrams (PVDs) of barred galaxies. (*Top*) Model prediction for the observed line-of-sight velocity distribution as a function of radius for non-barred and barred galaxies (Kuijken & Merrifield, 1995). (*Bottom*) Observed PVD for the boxy/peanut bulge of NGC 5746 (Bureau & Freeman, 1999). The kinematic signature of a bar in the observations is very evident.

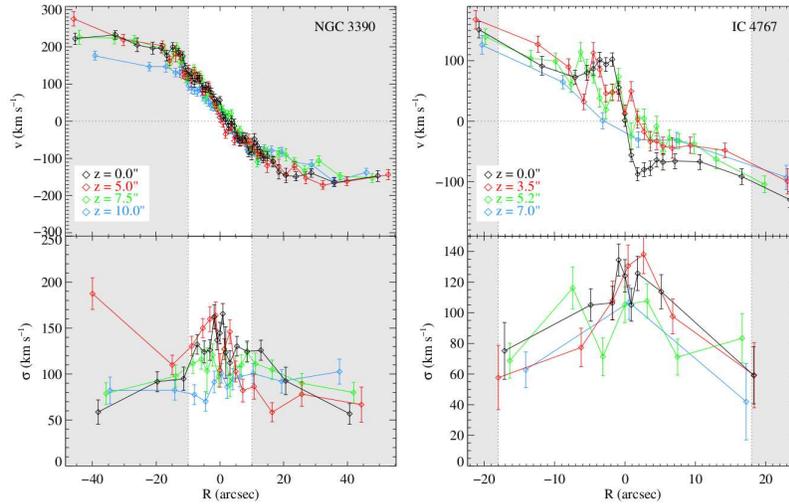


Fig. 7 Stellar line-of-sight rotation curves and velocity dispersion profiles for two Boxy/Peanut, edge-on galaxies in the Williams et al. (2011) sample. NGC 3390 shows clear signatures of cylindrical rotation, while IC 4767 does not (i.e. kinematics at increasing distance from the main disk shows different behaviour). The shaded regions mark the disk dominated regions.

erences of cylindrical rotation in other galaxies are rather scarce in the literature: IC 3370 (Jarvis, 1987), NGC 1055 (Shaw, 1993), NGC 3079 (Shaw et al., 1993), NGC 5266 (Varnas et al., 1987), NGC 7332 (Fisher et al., 1994). This lack of cases is likely due to: (1) inclinations effects. Cylindrical rotation is best observed in edge-on galaxies (e.g. Athanassoula & Misiriotis, 2002), (2) the fact that most observations with long-slit spectrographs targeted the major and/or minor axes of the galaxies, which makes it difficult to detect. The most recent work addressing this aspect of BP bulges is that of Williams et al. (2011). This study placed long slits parallel to the major axis of five known BP bulges. The surprising result of this study is that not all BP bulges displayed cylindrical rotation. Figure 7 shows the analysis for two distinct cases in their sample. While NGC 3390 displays clear signatures of solid-body rotation, IC 4767 presents shallower major axis velocity profiles as we move away from the disk. This outcome requires further confirmation using larger samples of edge-on galaxies. It will also benefit from studies making use of integral-field spectrographs to map the full two-dimensional kinematics over the BP dominated region. A glimpse of what this kind of studies can bring is presented in Falcón-Barroso et al. (2004) for the known case of NGC 7332.

Bars are also capable of producing other distinct features in the stellar kinematics of galaxies, which are often related to resonances induced by the bar itself in the host galaxy. Bureau & Athanassoula (2005) established, using N-body simulations, a series of kinematic diagnostics for bars of different strength and orientations in highly-inclined galaxies (see Figure 8): (1) a “double-hump” rotation curves, (2) velocity dispersion profiles with a plateau at moderate radii, and often displaying a σ -drop in the centre, (3) a positive correlation between the velocity and the h_3 Gauss-Hermite moment over the length of the bar. Some of these features have been recognised observationally in several studies (e.g. Pence, 1981; Kormendy, 1983; Bettoni & Galletta, 1997; Emsellem et al., 2001; Márquez et al., 2003; Pérez et al., 2009). While having the most potential to unravel the presence of bars, the $V-h_3$ correlation has been hardly studied observationally (e.g. Chung & Bureau, 2004). These diagnostics work best for edge-on galaxies. The kinematic tracer of BP bulges in face-on systems is the h_4 Gauss-Hermite moment. Simulations carried out by Debattista et al. (2005) predict that a negative double minima around the centre of the galaxy is an excellent indicator of a BP bulge for a wide range of bar strengths and inclinations. Although the observational requirements to measure this parameter are very demanding, this feature has been nicely confirmed observationally by Méndez-Abreu et al. (2008). Interestingly, Laurikainen et al. (2014) suggest that the barlenses observed in the face-on view of many disk galaxies (e.g. Laurikainen et al., 2011) are effectively the thick part of the BP bulge when seen face-on. See also Athanassoula et al. (2014) for a theoretical interpretation.

There are strong indications that large bulges can have an effect in the strength of a bar. Stronger bars appear in galaxies with low bulge-to-total ratios and central velocity dispersions (Das et al., 2008; Aguerri et al., 2009; Laurikainen et al., 2009). What it is not well established yet, observationally, is the effect a bar would have on the dynamics of a pre-existing bulge. Numerical simulations by Saha & Gerhard

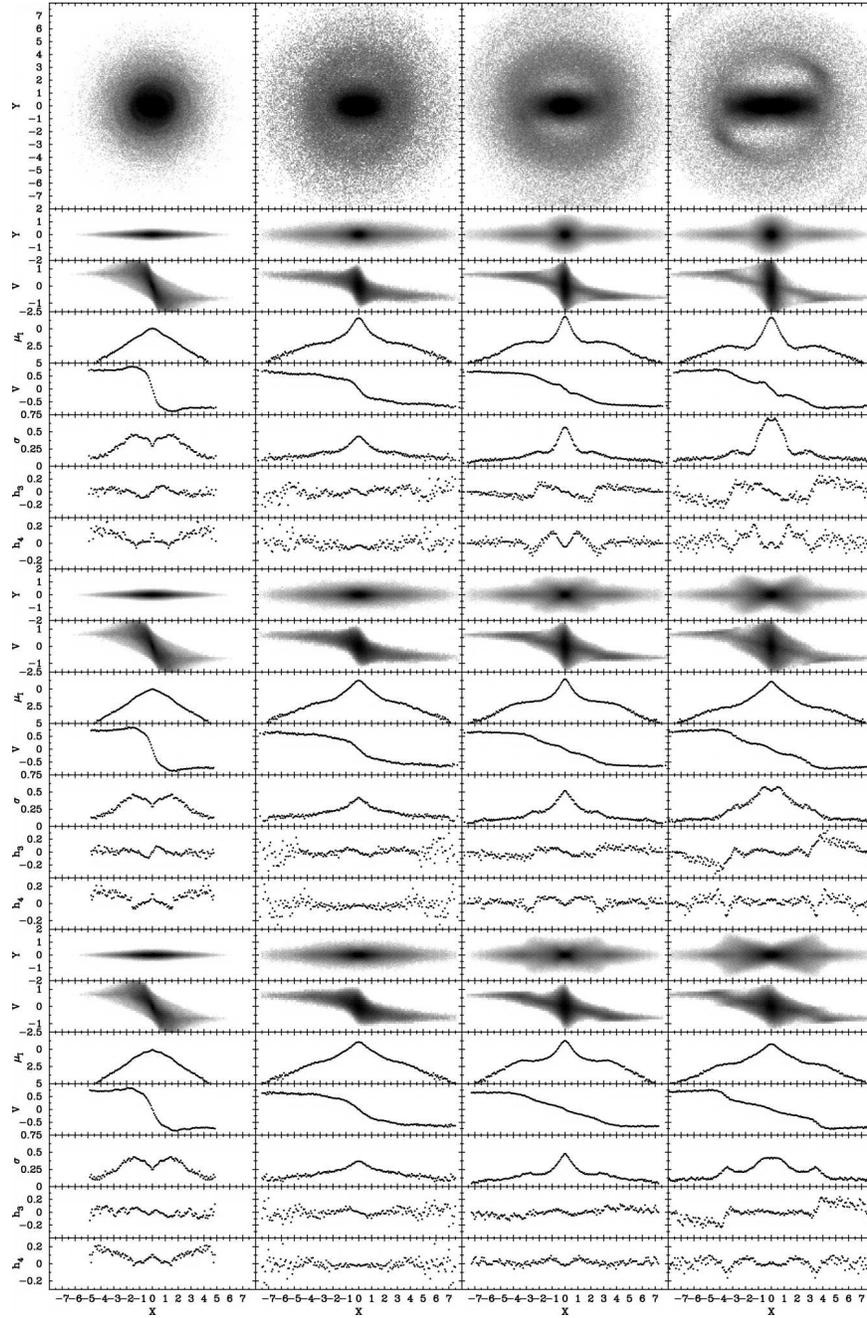


Fig. 8 Stellar kinematic diagnostics for barred galaxies in N-body simulations from (Bureau & Athanassoula, 2005). (Left to right) No-bar, weak-bar, intermediate-bar, and strong-bar case. (Top to bottom) image, PVD, surface brightness, and kinematic parameters (velocity, velocity dispersion, h_3 and h_4 Gauss-Hermite moments) as a function of bar orientation, from end-on to side-on.

(2013) suggest that a pressure supported bulge would gain net rotation as a result of angular momentum exchange with the bar. Rotation of the final composite classical and BP bulge would be close to cylindrical, with small deviations in the early phases of the secular evolution. Therefore, untangling the intrinsic properties of bulges in barred galaxies is a very difficult task that will require detailed dynamical modelling of high quality observations. Numerical tools like the NMAGIC code (de Lorenzi et al., 2007) applied to high-quality, integral-field data (e.g. De Lorenzi et al., 2013) seems the way forward.

The Milky Way bulge is the most vivid example of a complex system. Besides cylindrical rotation, it displays many of the other kinematic signatures of bars summarised above. The origin of the multiple substructures present at the centre of our Galaxy (possibly including other types of bulges, e.g. Ness et al. 2014) cannot be solved by inspecting the kinematics alone, as angular momentum transfer is expected between them. Most of the efforts today to solve this puzzle come from relating the observed kinematics to the distinct stellar populations present in those regions. We refer the reader to Oscar González and Dimitri Gadotti’s review in this volume for a comprehensive summary of the properties observed in the Galactic bulge, but also Juntao Shen’s chapter for a theoretical view on the possible paths for its formation and evolution.

4 Kinematics of Bulges at High Redshift

With typical sizes of a few kiloparsecs, bulges in nearby galaxies would be very difficult to resolve spatially at intermediate to high redshifts even with the best instruments on board of *Hubble Space Telescope*. In addition, the morphologies of galaxies are known to deviate from the standard Hubble sequence from redshift ~ 1 onwards (e.g. Elmegreen et al., 2008), so we should probably not think of bulges at high-redshift in the same way we think of them in the local Universe. Nevertheless knowing the conditions, in terms of rotational support, of the galaxies that will eventually lead to lenticular and spiral galaxies nearby, can help us understand the kind of progenitors that will host the variety of bulges we see today.

In the light of the large amount of pseudobulges observed in the nearby Universe, a logical question to ask is: do we see the signatures of secular evolution in bulges at high- z ? Numerical simulations reproducing the clumpy galaxies from redshift $z \sim 1$ suggest that bulge kinematics is not very different from the values observed for pressure-supported systems, with (V/σ) values below 0.5 (e.g. Bournaud et al., 2007; Elmegreen et al., 2008). This is likely due to the turbulent nature of clumps merging at the centre of galaxies (e.g. Ceverino et al., 2012). Note, however, that the merging and migration of clumps towards the inner regions is an internal process, as it takes place in the disk of galaxies. The physical conditions, in terms of gas supply, for bulge formation at high redshifts are very different from the ones observed in the local Universe. Secular evolution takes place at a much faster pace at high- z .

Integral-field observations of galaxies at increasing redshifts confirm the turbulent nature of disks, as revealed by the systematically high velocity dispersion values (e.g. Newman et al., 2013; Wisnioski et al., 2014). Nevertheless, galaxies show a wide range of kinematic properties: from well behaved rotating disks, to dispersion dominated systems, and galaxies with chaotic motions (e.g. Yang et al., 2008; Genzel et al., 2008; Wisnioski et al., 2011; Buitrago et al., 2014). Recent results from the KMOS3D survey (Wisnioski et al., 2014) show that most galaxies, in the main star forming sequence, between redshifts 1 and 2 are rotationally-supported. When combined with other datasets, they measure an evolution of the ionised-gas velocity dispersion which is consistent with the observed changes in the gas fractions and specific star formation rates of galaxies as a function of redshift. This results favours an 'equilibrium' model where the amount of turbulence of a disk is defined by the balance between gas accretion and outflows.

The physical conditions between redshifts 1 and 4 appear to be particularly favourable for the formation of bulges, and yet it appears that it cannot be the only channel to build the (pseudo)bulges observed in the nearby Universe. Mergers seem to be required too (e.g. Ceverino et al., 2014). To complicate the issue further, the analysis of the star formation histories of different types of bulges (e.g. Seidel et al., 2015) suggest that at least 60% of the stellar mass of those bulges formed at redshifts beyond 4 (see Figure 9). All these results together indicate that bulge formation most likely happens in a two stage process (e.g. Obreja et al., 2013), with an initial period of rapid build-up (with possible influence of mergers) and a secondary phase (between redshifts 1 and 2) of high star formation activity that would lead to the younger pseudobulge components we see today.

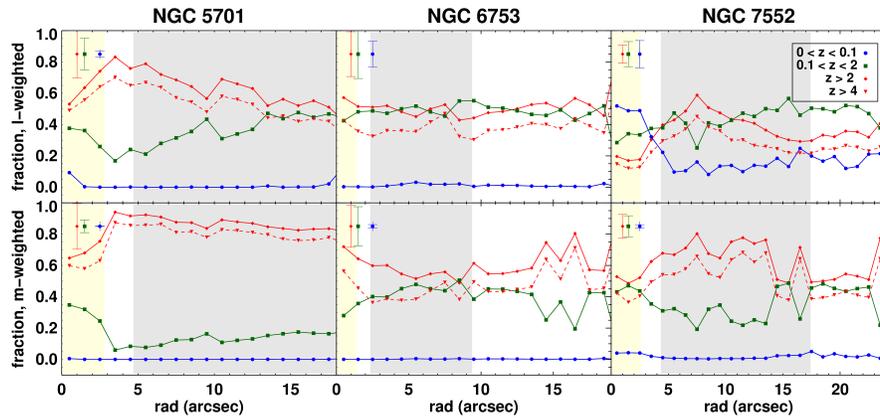


Fig. 9 Relative light (top row) and mass (bottom row) fractions of young, intermediate and old stellar populations as a function of radius present in three galactic bulges studied in Seidel et al. (2015). Uncertainties in the analysis are indicated in the top left corner. Shaded regions mark the regions where the average light and mass fractions of this study are computed. More than 60% of the stellar mass in those bulges was already in place beyond $z \sim 4$.

5 Concluding Remarks & Future Prospects

Lying at the centre and denser regions of galaxies, bulges are a keystone in our understanding of galaxy formation and evolution. It is also their location, shared with other components of galaxies what makes them so difficult to study. In this review I have tried to provide an overview of the main kinematic features observed in extragalactic bulges.

Identifying the formation scenario for bulges based solely on kinematic grounds is a very difficult task. The orbits of the different structural components in galaxies (e.g. bulges, disks, bars, spiral arms, nuclear disks rings, etc) are not necessarily well separated in phase-space. The best example of this complexity come from the observations of the Milky Way bulge. As nicely illustrated in other contributions to this volume (e.g. González & Gadotti, or Sánchez-Blázquez), the combined study of kinematics and stellar populations provides one of the best ways to discern between different formation scenarios. While this coupling can be achieved relatively easy in the Milky Way (because it is possible to measure the properties of individual stars) this is no easy task in bulges of other galaxies where all we get is the integrated light along the line-of-sight. Fortunately, with better data, models, and numerical tools we are at the verge of being able to treat other galaxies in the same way we study our own Galaxy. Studies of the coupling between kinematics and stellar populations in external galaxies are now flourishing (e.g. Ocvirk et al., 2008). Initially restricted to galaxies with known distinct counter-rotating components, they are now exploring more regular galaxies (e.g. Johnston et al., 2014).

As remarked many times throughout this review, this new step in the 3D decomposition of galaxies can only be achieved with datasets that allow the uniform exploration of galaxies in the two-dimensions they project in the sky. The first generation of IFU surveys and instruments (e.g. SAURON, ATLAS3D, DiskMass, SINFONI, VIMOS, PPaK) showed us the potential of these datasets to reveal the intrinsic properties of galaxies. The currently ongoing IFU surveys (e.g. CALIFA, SAMI, MaNGA, KMOS3D) will allow the exploitation of these new techniques for very large, morphologically and mass unbiased samples of galaxies. We should not forget though that we can still learn a lot of the physical processes governing galaxies, and bulge formation and evolution in particular, with unique instruments like MUSE. The Milky Way is a unique case, as we will be able to probe the 3D nature of the Galaxy directly thanks to the Gaia space mission.

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