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The Role of Inner Density Waves in Fueling Galactic Nuclei

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Abstract
I present here a heterogeneous selection of galaxies in which inner density waves (bars, spirals, $m = 1$ modes) have been observed, and which are presumed to host a supermassive black hole.

1.1 Introduction

Density waves the presence of which can be witnessed in structures such as bars, spirals and lopsided distributions are ubiquitous in disk galaxies. If we believe that central massive dark objects are present in most nearby galaxies, then density waves and black holes should often be concomitant. This paper is intended as an attempt to illustrate this issue by providing a few examples of inner ($R < 1$ kpc) density waves in galaxies which are presumed to host a supermassive black hole. We have found that inner density waves are often easily tracable via a combined simple morphological and dynamical analysis, but often ignored in the subsequent dynamical modeling. We also briefly mention some evidence for gas fueling in the central few tens of parcsecs via density waves.

1.2 The Prototype Seyfert 2: NGC 1068

One of the best evidence for gas streaming towards the centre of a nearby galaxy hosting a central dark mass is given by the well-studied Seyfert 2 galaxy NGC 1068. Indeed, a near-infrared bar is well visible in the central 20 arcseconds of this spiral galaxy, and streaming motions have been uncovered in the gas kinematics (see e.g. Schinnerer et al. 2000 and references therein). Note that an outer oval structure has been advocated by Schinnerer et al. to be a large-scale (weak) primary bar, implying that the inner bar is in fact a secondary bar. Although this is one of the best studies active galactic nucleus, it is surprising to realize how little we know about the gravitational potential in the central few kpc of this galaxy.

We have recently obtained integral field spectrography of this inner region using SAURON at the WHT. We first had to carefully disentangle the respective contributions of the ionized gas and of the stellar component. This was achieved by performing an optimal stellar template fit using an iterative procedure and a library of synthetic stellar spectra kindly provided by Alexandre Vazdekis (see Vazdekis 1999 and references therein).

This allowed us to probe both the stellar and gaseous kinematics with unprecedented field coverage. The signature of the so-called near-infrared bar is clearly observed in the SAURON stellar velocity map in the form of an "S-shaped" isovelocity curve. The ionized

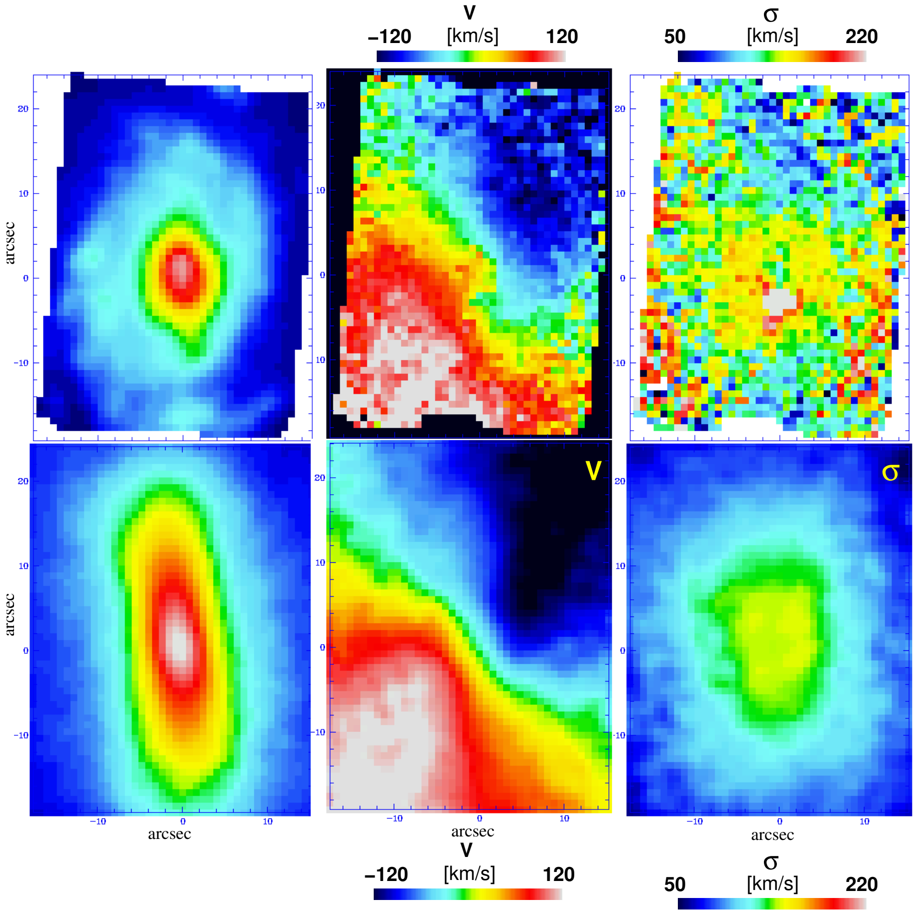

Fig. 1.1. Two-dimensional stellar kinematics of NGC 1068 as observed with the SAURON spectrograph (top panels), and from a numerical N-body + SPH simulations (bottom panels, see text). From left to right: surface brightness reconstructed image, stellar velocity and velocity dispersion maps. From Emsellem, Fathi, Wozniak et al., in preparation. [Note that the central 5 arcsec should be taken with caution as the stellar kinematics is strongly perturbed by wide and strong emission lines].

gas distribution and kinematics is complex, particularly in the central 5 arcseconds or so, where the influence of the AGN is dominant, with the presence of e.g. strong outflows and scattered light. We can however still trace the gas streaming on the leading edge of the inner bar, along spiral structures directed towards the outer two-arms spiral observed in the CO maps (Schinnerer et al. 2000).

We have then conducted a small series of numerical N-body + SPH simulations using up to 2400000 and 30000 particles for the stellar and gas components respectively. Starting from axisymmetric initial conditions, the goal was to trigger the formation of a bar system which would look like the one seen in the inner region of NGC 1068. Tuning the initial conditions (proper mass distribution and dynamics), we have thus obtained a time-evolving model the snapshots of which were compared to the observed SAURON maps. The first attempt at doing this is presented in Fig .1.1 where the observed and modelled stellar kinematics are presented. We could easily reproduce the overall shape as well as the amplitudes of the stellar velocity and dispersion fields. Obviously the surface brightness image reconstructed from the SAURON datacube does not exhibit the strong bar present in the numerical model as the former is perturbed by strong stellar populations gradients, star formation and emitting line regions.

Apart from a detailed study of the kinematics of NGC 1068, the main goal is to now use these data and models to quantify the gas fueling rate in the central few hundreds of parcsecs. Resonances in tumbling potential acts as boundaries where the orbital structure can abruptly change. For $m = 2$ modes such as bars and spirals, the presence and strength of the Lindblad Resonances are critical in determining the dynamical characteristics of the system. Also, depending on the properties of the supporting medium (dissipative or collisionless), density waves are allowed (or not) to cross such bariers. In this context, bars are efficient at driving gas toward their Inner Linbdlad Resonance (if present). In the case of NGC 1068, the location of the ILR has been estimated by Schinnerer et al. (2000) to be at a radius of about 5 arcsec, or 350 pc. Gas indeed seems to be funneled towards this region, but the blending of numerous and complex gas emitting components prevented us to investigate the fate of the gas further in.

1.3 Bars in the Sombrero Galaxy and NGC 3115

In order to probe the region inside the ILR, we should focus onto less active objects. One galaxy hosting a weakly active nucleus, and a candidate for the presence of a $\sim 10^9$ $M_\odot$ black hole (Emsellem et al. 1996 - note the different distance used in that paper - , Kormendy et al. 1996), is the Sa spiral M 104 (NGC 4594) known as the Sombrero: its uncommon appearance is due to its high inclination, its large bulge, and its prominent dust lanes at large radii. This spiral galaxy exhibits strong evidence for the presence of a large-scale bar as emphasized in two papers of a series (Emsellem 1995; Emsellem et al. 1996). This argument was initiated by the analysis of a resonance diagram (Emsellem et al. 1996, Fig. 22) which associated the different rings (CO, HI, ionized gas, stellar) to different resonances (OLR, UHR) of a tumbling bar. In this context, the ILR is situated at about 20 arcsec outside the bright inner secondary disk.

Double disk structures such as the one in the Sombrero galaxy are common in early-type spirals, and have been suggested to be formed via bar driven evolution (see e.g. van den Bosch & Emsellem 1997). In this scenario, the inner disk was mainly built from gas accretion inside the ILR of the bar and subsequent star formation. In the case of the Sombrero galaxy, there is a spiral-like gaseous component inside this inner disk, tentatively interpreted by Emsellem & Ferruit (2000) on the basis of high resolution photometry and two-dimensional spectroscopy to be the signature of a secondary bar driven structure. The ILR of this secondary bar would thus be located at about 1 arcsec or 47 parcsec. If confirmed, this would obviously have important consequences on the estimate of the central black hole mass in this galaxy. Although the Sombrero galaxy may be a rather unique object in the nearby Universe, this would also have implications on our understanding of the way gas can be funneled towards the nuclear region.

As emphasized above, early-type disk galaxies with double disks are rather common, one of the best known example being the quiet S0 galaxy NGC 3115. It exhibits a very thin

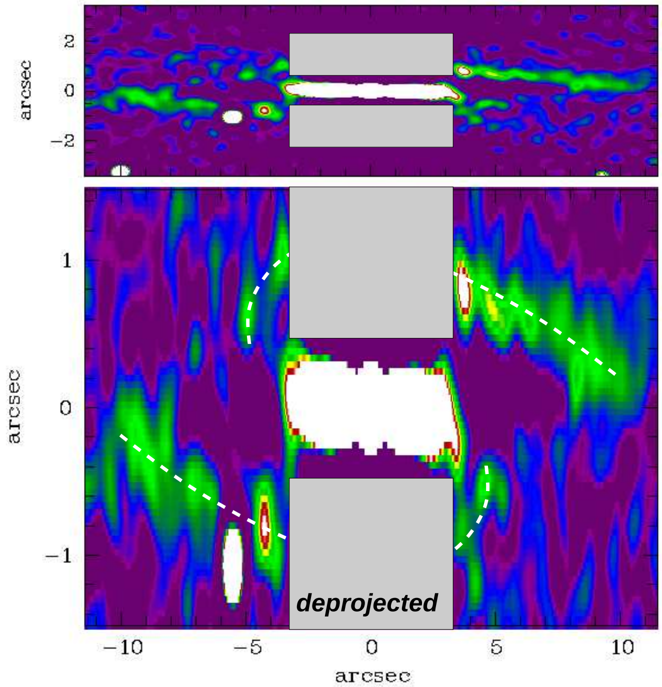

Fig. 1.2. Evidence for an inner stellar spiral in NGC 3115. Top panel: unsharp masking of a WFPC2/F555W (V band) image of NGC 3115. Bottom panel: same image but deprojected using an inclination of 86 deg (Emsellem et al. 1999) and assuming the residual intensity lies in the equatorial plane. An hypothetic sketch for a two-arm spiral is superimposed on the deprojected image. High frequency structures could not be derived in the grey areas due to the presence of the bright inner disk.

and bright disk inside its central 3 arcsec (Kormendy et al. 1996). The central value of its stellar velocity dispersion is on the high side (about 450 km/s as measured with FOS), which has been used to argue for the presence of a central dark mass (Kormendy et al. 1996 and references therein). We have used both integral field spectroscopy and high resolution FOS data to better constrain the mass of the presumed black hole (Emsellem, Dejonghe, Bacon 1999): two and three-integral models provided a range of acceptable masses of [4.5 – 13] 10^8 $M_\odot$ with an overall best fit three-integral model with 6.5 10^8 $M_\odot$ (note that the best fit two-integral model has $M_{bh} = 9.4\ 10^8\ M_\odot$).

Is the bright and thin disk the consequence of bar-driven gas accretion as sketched above, and is there a link between the central massive black hole (if present) and this disk? Isophotes in the inner region of NGC 3115 have varying shapes: they are (obviously) disky in the central 3 arcsec, and become slightly boxy when the luminosity profile of the inner disk drops. This is qualitatively similar to what is observed in another edge-on S0, NGC 4570, where the signature of a tumbling potential was advocated. In NGC 3115, the boxyness is in fact partly due to the presence of a weak centrally symmmetric structure resembling a two-arms stellar spiral. This is illustrated in Fig. 1.2 where a simple unsharp masking of a WFPC2 image reveals this spiral, which seems connected to the inner disk. Although a complete stability analysis should be conducted before concluding too hastily, such a weak (non self-gravitating) structure should require a driver, a forcing tumbling term in the potential, namely a bar. This picture would be consistent with the hypothesis that observed double disk morphologies are linked to a bar driven secular evolution. Again, this would be an important issue to take into account when estimating the mass of the central dark object. And the question of whether or not the central dark object has grown significantly during this evolutionary process would then remain.

1.4 Remnant Signatures of Gas Fueling

In our search for signatures of past or present gas fueling, we have conducted a small study of the stellar kinematics of galaxies hosting active galactic nuclei, mostly Seyfert 2 ones. This was originally intended as a tool to look for possible links between the gravitational potential and the activity of the nucleus. Our first observations included ISAAC/VLT near-infrared spectroscopy of 3 Seyfert 2 galaxies with photometrically detected double bars. We first confirmed the expected kinematical decoupling of the inner structure. A surprising result came from the stellar velocity dispersion profiles, which, in all three cases, exhibits a significant drop at the centre. These central dispersion drops (CDDs) could not be explained via simple dynamical models which all predicted rising or flat dispersion profiles.

We therefore suggested that these drops are transient features due to the presence of a dynamically cold stellar component formed during an episode of central gas accretion driven by a bar. This scenario has to be confirmed with further observational and theoretical evidences. However, we have already conducted a series of numerical N-body + SPH simulations, including star formation, which indeed show that these CDDs naturally appear when gas is driven towards the centre by a bar and a new stellar disk of young stars forms (Wozniak, Combes, Emsellem, Friedli, in preparation). We have also looked more systematically for CDDs in published data. Although most of the stellar kinematics available in the literature is of medium quality and resolution, we have found a few instances of such drops, almost always in active, barred galaxies. We just obtained new spectroscopic observations in the near-infrared, where dust extinction is a less severe problem: we should be soon able to test the link between the activity of the nucleus (AGN or starburst) and the inner potential (barred or not). We provide here a beautiful example of a CDD discovered in the barred galaxy NGC 3623 in the course of the SAURON survey (see Bacon et al. 2001, de Zeeuw et al. 2002): the drop in the dispersion is clear (although there is some extinction due to dust), and is coincident with a cold component detected in the stellar velocity field.

1.5 Lopsided Density Distributions

I should finally say a word about the so-called $m = 1$ modes, associated with lopsided density distributions (see Combes 2001, Emsellem 2002). I will focus on the very striking case of M 31 which has been discussed as a candidate for the presence of a supermassive black hole since almost 15 years (Kormendy 1988; Dressler & Richstone 1988). The nucleus of M 31 has been known to harbour a double peaked structure since the Stratoscope II images (Light et al. 1974), and has been studied in detail with WFPC/HST images by Lauer et al. (1993). Many papers have been published since, attempting to build a physical picture for this puzzling morphology.

Two-dimensional kinematics were obtained by Bacon et al. (1994), showing a clear offset

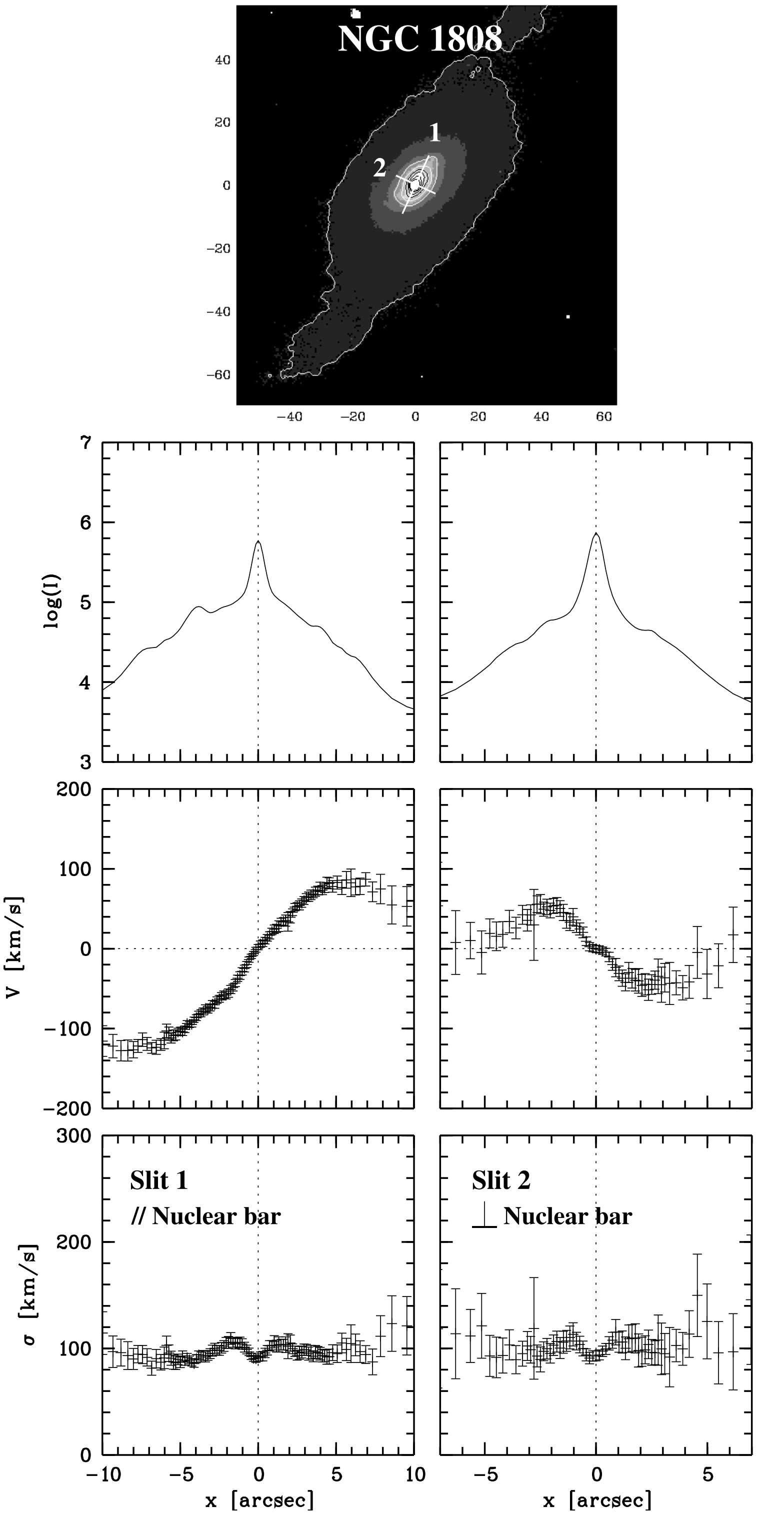

Fig. 1.3. ISAAC/VLT stellar kinematics of NGC 1808 along the major (left panels) and the minor (right panels) axis of the inner bar. An *H* band image is presented at the top with a sketch of the extent of the slits. The central dispersion drop is clearly visible along both directions. Adapted from Emsellem et al. (2001).

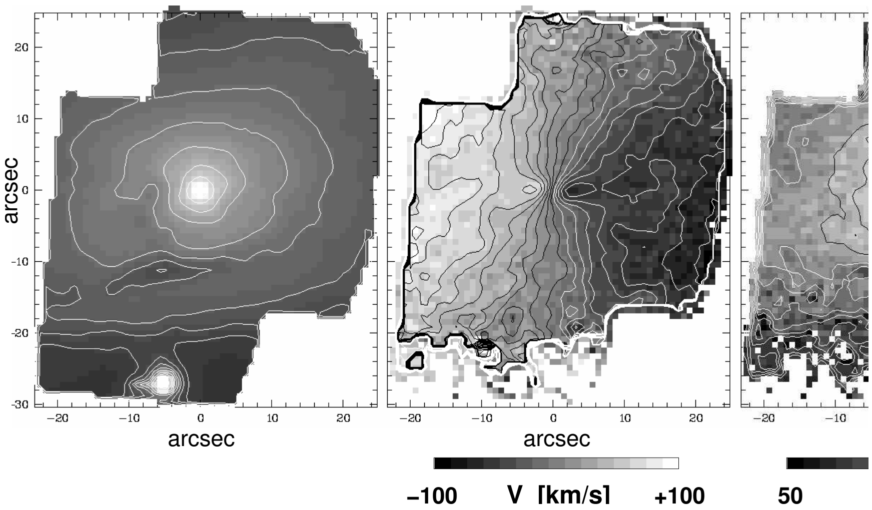

Fig. 1.4. Two-dimensional stellar kinematics of NGC 3623 obtained with the SAURON spectrograph mounted at the WHT. From left to right: reconstructed surface brightness image, stellar velocity and stellar velocity maps. Note the drop in the dispersion as well as the clear signature of a disk in the velocity map.

of the dispersion maximum with respect to the centre of the outer isophotes (P2), already hinted in the previous long-slit works. Bacon et al. (1994) also built simple dynamical Jeans (axisymmetric) models estimating the mass of the central dark object to be $\sim 7\ 10^7\ M_\odot$. The first serious attempt at modeling the lopsided luminosity distribution was conducted by Tremaine (1995) who proposed to explain the offset luminosity (P1) and dispersion peaks by a set of aligned eccentric orbits around a dominating massive black hole. The hypothesis of a decaying cluster destroyed via the tidal forces of the black hole has also been examined (Emsellem & Combes 1997): although it provided good fits to the existing data with the first self-consistent models for this nucleus (black hole masses between 7 and 10 $10^7\ M_\odot$), the overall lifetime of the secondary peak was too short lived for this scenario to be a viable

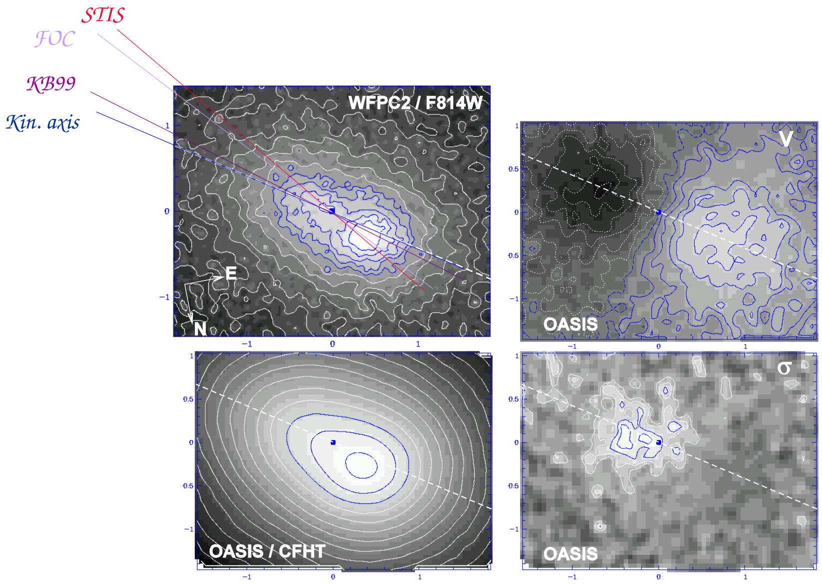

Fig. 1.5. The nucleus of M 31. The top left panel shows a WFPC2/HST image with overimposed isophotes, and a sketch of some long-slit used to probe the kinematics of this nucleus. The three other panels show OASIS integral field spectroscopy of M31's nucleus: (bottom left) reconstructed image, (top right) stellar velocity map, (bottom right) stellar velocity dispersion map. Adapted from data presented in Bacon et al. (2001).

alternative. This hypothesis was fully rejected when detailed spectroscopic analysis demonstrated that, besides a UV excess at the presumed location of the black hole (P2), the stellar population within the nucleus was rather homogeneous (Kormendy & Bender 1999). Subsequent high resolution spectroscopy (Statler et al. 1999), and modeling efforts (e.g. Statler 1999; Salow & Statler 2001; Jacobs & Sellwod 2001) further constrained the detailed dynamical structure of this nucleus. Then Bacon et al. (2001) reexamined most of the available data, also adding new OASIS integral field spectroscopy, to reconcile the different photometric and kinematical profiles. As shown in Fig. 1.5, only two-dimensional spectroscopy can really probe the complex structure of this nucleus.

Bacon et al. (2001) also built numerical self-consistent models to fit the photometry as well as the stellar velocity profile. We found that indeed a slowly rotation prograde $m = 1$ mode could reproduce the observed photometry. Such a mode exists when the gravitational potential is nearly keplerian (in the limit of which the epicyclic frequencies are equal to the circular frequency). However, the central dark mass should not fully dominate the potential, to allow the self-gravity to act and help the mode to grow. In the case of M 31, the mass of the disk should thus be between 20 and 40% of the mass of the central black hole, consistent with the advocated value of 7 10^7 $M_\odot$. As suggested in Emsellem (2002a,b), the nucleus of M 31 is probably the result of gas accretion, which may be related to the present overall structure of the galaxy (bar, inner dust lanes).

1.6 Conclusions

I hope this eclectic selection of illustrations helps to demonstrate that density waves are indeed present in the central regions of galaxies, and that there is probably a link between these waves and the central dark massive object. This link runs in both directions: inner density waves can help bringing gas in the central 10 or 50 parcsecs, closer to seed black holes which may ultimately grow, and central dark masses can strongly influence the dynamical state of this very same region. In this context, bars and $m = 1$ (non-keplerian) may play a significant role. Signatures for such fueling can be found in the stellar kinematics, with the so-called CDDs being presumably rather common in disk galaxies. Finally, we should keep all this in mind, when modeling the dynamics of nearby galaxies in our search for supermassive black holes.

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