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Supermassive Black Holes in Bulges

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Abstract

It is now commonly accepted that supermassive black holes (SMBHs) are an integral part of galaxies and that their black-hole mass ($M_{\rm BH}$) accretion history is tightly linked to the formation and evolution of their hosts. Still, the demography of SMBHs is not complete, and in order address central open issues to our understanding of the coevolution of SMBHs and galaxies such as the real scatter of the popular $M_{\rm BH}$–$\sigma_\star$ relation or the $M_{\rm BH}$ content of classical and "pseudo" bulges, more and accurate $M_{\rm BH}$ measurements are needed. In this context, we show that ionized gas in galactic nuclei provides a relatively easy way to measure $M_{\rm BH}$ with the required accuracy to answer these questions, given that the assumption of circular disk-like motions for the gas is tested. With this respect, we demonstrate that having regular dust lanes considerably boosts the probability of finding regular gas velocity field, providing an excellent criterion for selecting targets of future observing programs. We also show how in the absence of regular motions it is possible to use the central emission-line widths and derive interesting upper-bounds on $M_{\rm BH}$ that can help unveiling trends or exceptions in the $M_{\rm BH}$ content of bulges, or potential problems in using the ionized gas tracer. We indeed present preliminary evidence that for smaller systems non-gravitational forces may be important in explaining the observed line widths.

1.1 Introduction

More than seven years after Kormendy & Richstone (1995) first pointed out that the mass of SMBHs is related to the luminosity of the spheroidal component of their host galaxies , the demography of SMBHs is still not complete. Indeed, even in the latest compilation of Tremaine et al. (2002) the SMBHs census is still strongly biased toward early-type host galaxies: among the 31 $M_{\rm BH}$ measurements that were deemed accurate enough for their demographic study, 18 ($\sim 60\%$) were derived in elliptical galaxies, 9 in lenticulars, and only 4 in spirals.

Still, many patterns have emerged so far, all pointing toward a tight link between galaxy formation and $M_{\rm BH}$ accretion. The mass of SMBHs has been found to correlate with bulges luminosity and mass (see Ho 1999 for a review), light concentration (Graham et al. 2001), and stellar velocity dispersion (Gebhardt et al. 2000, Ferrarese & Merritt 2000). In particular this last two relations stand as real benchmarks for for galaxy formation and evolution models, as they appear to be much tighter than previously discovered ones, although this has already been questioned by McLure & Dunlop (2002). Besides, a very small scatter in the

M_{BH}–$\sigma_\star$ relation would be rather surprising also from a theoretical point of view (see M. Haehnelt's contribution).

Presently it would also look like SMBHs do not "know" if they live in a disk galaxy because, as noticed by Kormendy & Gebhardt (2001), M_{BH} correlates much better with the bulge luminosity than with the total galaxy light. The finding that in pure disks SMBHs are considerably undermassive with respect to their relatives living in bulges of the same luminosity, further points toward a scenario where the growth of SMBHs is linked *only* to the formation of galaxies spheroids. This is however a problematic point, as in fact the high-density central components of galaxies, or bulges, fall in two distinct classes that are believed to form in radically different ways. On one hand we found, mostly in early type disk galaxies (S0-Sa), the classical bulges that are thought to be like little ellipticals. They have surface brightness profiles following a de Vaucouleurs law (Andredakis, Peletier, & Balcells 1995), red colours indicating that they are old (Peletier et al. 1999), and they have long been known to have kinematical properties (e.g., Kormendy & Illingworth 1982) similar to those of faint ellipticals (Davies et al. 1983). Consequently they are also thought to form through a sequence of acquisitions and merger events. On the other hand the high-density components of most late-type disk galaxies tend to have a disk-like dynamics (e.g., Kormendy 1993), exponential surface brightness profiles (Andredakis, Peletier, & Balcells 1995; Courteau, de Jong, & Broelis 1996), and are thought to form via a secular evolution of the disk from gas material driven toward the center by bar or oval distortions (e.g., Pfenninger & Norman 1990). *HST* imaging studies by Carollo et al. (1997, 1998a, b) have further strengthen the evidence for this separate class of objects. The properties of classical and "pseudo" bulges are discussed in more detail in the contributions of J. Kormendy and M. Carollo, but it is already clear that it would be rather surprising to find these two classes of bulges, which presumably formed through very different processes, sharing the same M_{BH} content, although preliminary evidence along these lines exist (Kormendy & Gebhardt 2001).

Clearly, with only four spiral galaxies with secure SMBHs detections, more M_{BH} measurements are needed not only to address whether or not normal and "pseudo" bulges follow the same M_{BH}–$\sigma_\star$ relation, but also to confirm that ellipticals and disk galaxies in general do so. Furthermore there is also a need for *precise* M_{BH} determinations, in order to address the real scatter of the M_{BH}–$\sigma_\star$ relation.

1.2 The SUNNS Survey

The Survey for Nearby Nuclei with STIS, is a completed an *HST* spectroscopic survey (GO-7361, P.I. Rix) meant to understand the relative role of accretion onto SMBHs and star formation in powering the different forms of nuclear activity in galaxies. Blue low-resolution and red high-resolution spectra were obtained for 23 galaxies, to study both their nuclear stellar populations and emission-line kinematics and detect very young stars or SMBHs. The targets were drawn from the Palomar spectroscopic survey (Filippenko & Sargent 1985, Ho, Filippenko & Sargent 1995, 1997) and include all the S0, Sa, and Sb galaxies within 17 Mpc known to have strong emission lines from ground-based observations and that are not too inclined.

Hence the SUNNS sample represented an good opportunity to study SMBHs in bulges, but as other gas-dynamical programs it faced the main drawback of relying on the ionized gas as a tracer of the gravitational potential when in reality gas is also subject to other forces than gravity. In fact the vast majority of the SUNNS galaxies turned out to display irregular rotation curves, and a number of objects did not even show emission lines in their very central parsecs, although they were selected to do so within the resolution limit of ground-based surveys, typically encompassing few hundreds parsecs. Only 4 galaxies out of 23 (17%) were suited for dynamical modeling, leading to 3 $M_{\rm BH}$ measurements and one upper limit (Sarzi et al. 2001).

1.3 Precise $M_{\rm BH}$ from Ionized Gas Kinematics

The interpretation of well-behaved gas kinematics in galactic nuclei generally relies on the assumption that the emitting clouds reside on a coplanar disk and move at the local circular velocity dictated by the stellar mass distribution and a putative SMBH. The contribution to this conference by A. Barth fully details this kind of modeling and shows, for instance, how a reliable spatial description of the gas emissivity and a number of technical details mimicking the instrumental setup considerably help in reproducing the data and in tackling down precisely $M_{\rm BH}$. Still, the biggest impact on such measurement and its associated uncertainties is due both to our limited ability to recover the intrinsic stellar mass distribution from the observed surface brightness, in particular when the stellar gravitational influence within our resolution limit is the greatest, and to our limited knowledge of the nuclear disk orientation, usually decoupled from that of the main stellar body. The finding that gas emission is generally very concentrated in the central parsecs of galaxies (see Fig. 1 of Sarzi et al. 2002) can help circumventing limited spatial resolution, but the broadening of the confidence limits around the best $M_{\rm BH}$ because of the larger parameter space to explore when the nuclear disk orientation is uncertain, cannot be avoided unless more observing time is invested to obtain narrow-band images or multiple slit exposures. Dust absorption features can further help constraining the nuclear disk orientation, as dust is normally associated to gas (e.g., Pogge et al. 2000). This has long been known for early-type (E and S0) galaxies where circumnuclear gas disks have been found to be common (van Dokkum & Franx 1995; Tran et al. 2001) and already targeted by a number of gas-dynamical *HST* programs aimed at deriving $M_{\rm BH}$ in elliptical galaxies (see A. Barth's contribution for a review).

Now among all the disk galaxies in the SUNNS survey, it turned out that the 4 galaxies with regular and extended rotation curves suitable for modeling also display well-ordered circular symmetric dust patterns, which were used to constrain their ionized disk orientation as shown in Fig.1.1. Exploiting such information greatly improved the accuracy of the $M_{\rm BH}$ measurements in these galaxies, as shown in Fig.1.2 for the barred S0 NGC 2787. It is indeed clear how the *constrained* models, where the orientation of the disk was fixed to the one inferred from Fig.1.1, lead to a much narrower χ^2-curve with respect to the *unconstrained* case, where at each $M_{\rm BH}$ the orientation of the disk was optimized to better match the data.

Ultimately, the high degree of precision (25%) attainable by gas dynamical measurements of $M_{\rm BH}$ has been demonstrated by Barth et al. (2001) in the case of NGC 3245, which not only set the standard reference for modeling the ionized gas kinematics but also support the case for trusting disk orientations inferred from the dust-lane morphology. In fact for NGC 3245 the orientation of the ionized gas disk determined by matching the observed kinematics along five parallel slit position is consistent with the one suggested by its visible disk-like dust pattern.

It is worth noticing how the ionized-gas $M_{\rm BH}$ measurements for disk galaxies obtained so far presently place themselves in a special position in the demographic context of the $M_{\rm BH}$–$\sigma_\star$ relation, as to its latest version by Tremaine et al. (2002). Figure 1.3 shows indeed

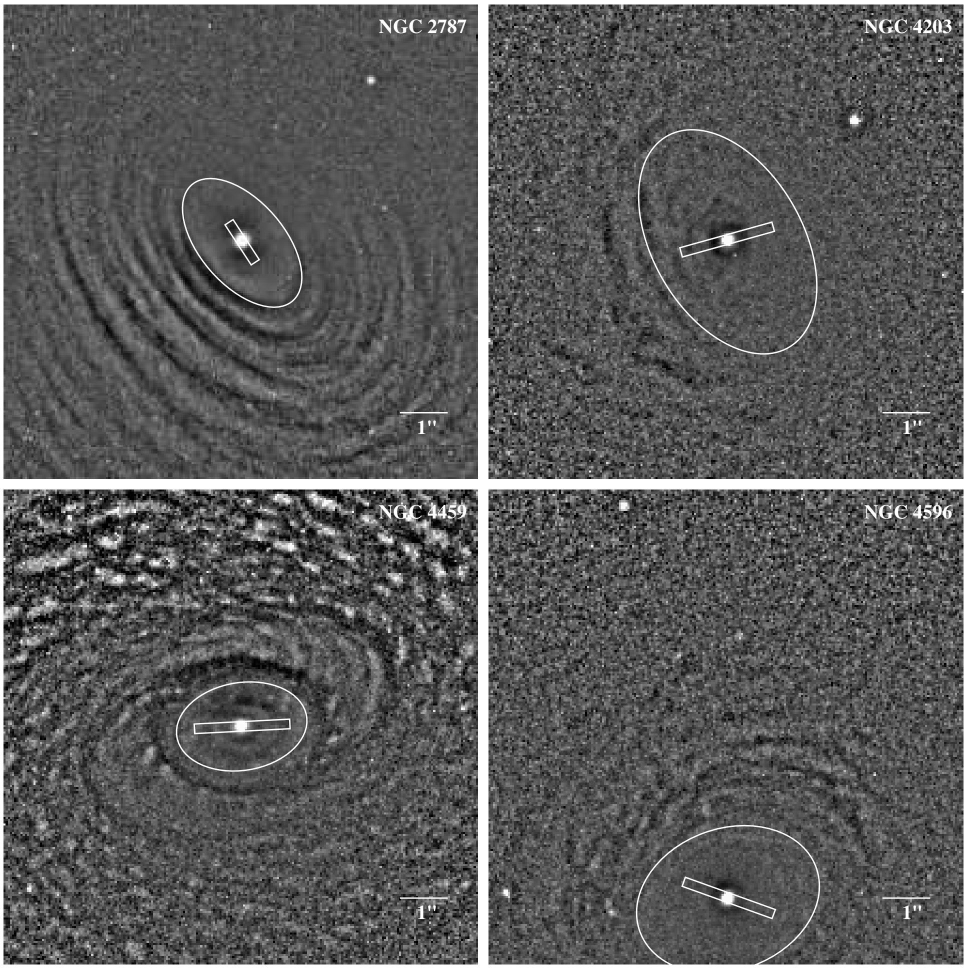

Fig. 1.1. $10'' \times 10''$ unsharp-masked WFPC2 images for the central regions of the galaxies modeled by Sarzi et al. (2001). North is up, east is to the left. Superimposed on each frame is the ellipse showing the assumed gaseous disk orientation and the STIS slit aperture, where the depicted length corresponds to the maximum extent of their kinematic measurements.

that the 4 S0 galaxies (two of which barred) of Sarzi et al. (2001) and Barth et al. (2001) constitute more than 30% of all precise $M_{\rm BH}$ in disk galaxies (4/13), almost half (4/9) of those in lenticular ones, and half (2/4) of those in the poorly surveyed class of barred galaxies. Furthermore they provide the only $M_{\rm BH}$ measurements based on the gas kinematics in galaxies with $150\,{\rm km\,s^{-1}} < \sigma_\star < 250\,{\rm km\,s^{-1}}$, bridging the gap between water-maser based determinations in spiral galaxies and ionized-gas ones in ellipticals. These $M_{\rm BH}$ values are also accurate enough to enable, in combination with the gas-dynamical measurements obtained in ellipticals, an independent estimation of $M_{\rm BH}$–$\sigma_\star$ relation which slope is consistent with the one given by Tremaine et al. ($\beta = 4.02 \pm 0.32$) but with a smaller scatter. Indeed a simple weighted (only in $M_{\rm BH}$) least-square fit of their whole sample gives a consistent slope of

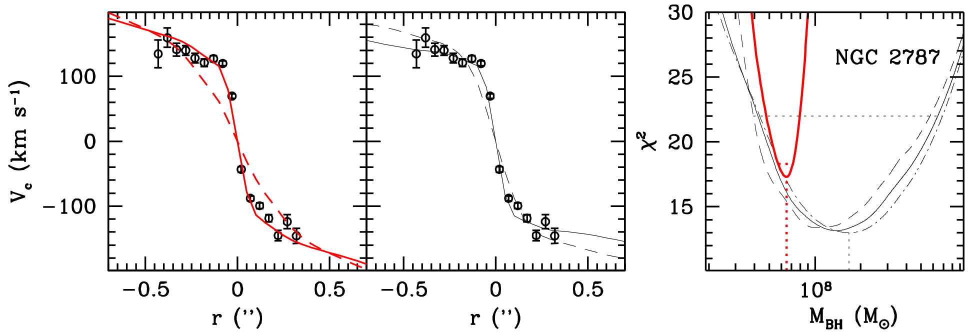

Fig. 1.2. Observed gas kinematics and modeling results for NGC 2787. *Left Panel:* Observed rotation curve and *constrained* models without a black hole (red dashed lines) and with the best $M_{\rm BH}$ (red solid lines). *Middle Panel:* Same as *left* but now for the *unconstrained* models with no black hole (dashed lines), and the best $M_{\rm BH}$ (solid lines). *Right panel:* Model χ^2 values in the *constrained* (red thick line) and *unconstrained* (thin lines) cases as a function of $M_{\rm BH}$. The effect of varying the stellar mass-to-light ratio Υ by 30% is shown in the *unconstrained* case by the thin dashed, solid, and dotted-dashed lines. The vertical and horizontal dotted lines show, respectively, the best and 1σ confidence limit on $M_{\rm BH}$ for the *constrained* case and the best and 3σ confidence limit on $M_{\rm BH}$ for the *unconstrained* one.

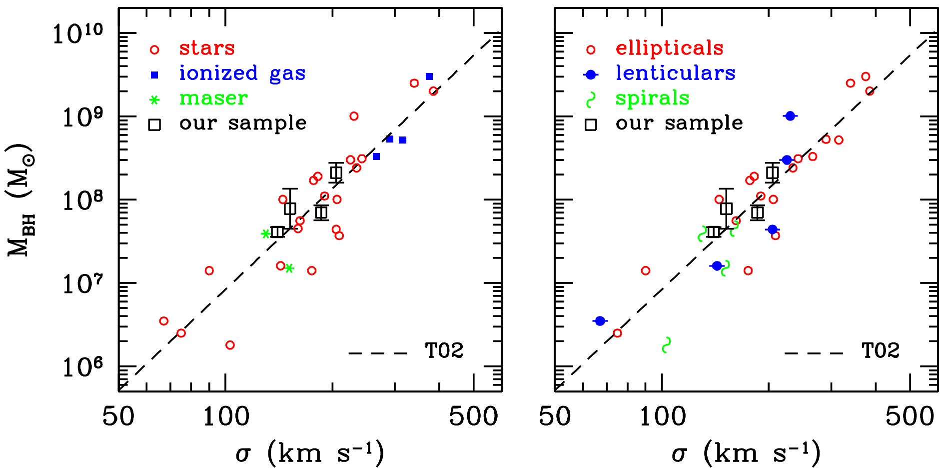

Fig. 1.3. Ionized gas $M_{\rm BH}$ measurements in disk galaxies (open squares) in the $M_{\rm BH}$–$\sigma_\star$ relation . *Left Panel:* Latest version of the $M_{\rm BH}$–$\sigma_\star$ relation (dashed line, Tremaine et al. 2002) along with the $M_{\rm BH}$ measurements that were deemed accurate enough to derive it, coded according to the used tracer for the gravitational potential. *Left Panel:* Same as *left*, but with different symbols representing different types of SMBHs host galaxies.

$\beta = 4.05 \pm 0.41$ with a RMS scatter in $M_{\rm BH}$ of 0.36 dex, while the ionized gas measurements are better aligned along a slope of $\beta = 3.67 \pm 0.48$ with a scatter of 0.17 Dex.

1.4 Regular Dust Lanes Trace Regular Gas Motions

Although well-behaved ionized gas motions can provide the needed accurate $M_{\rm BH}$ determination in disk galaxies, it must be faced that *HST* spectroscopic surveys such as SUNNS have been quite inefficient in terms of their $M_{\rm BH}$ detection rate. Today however, we have learned our lesson.

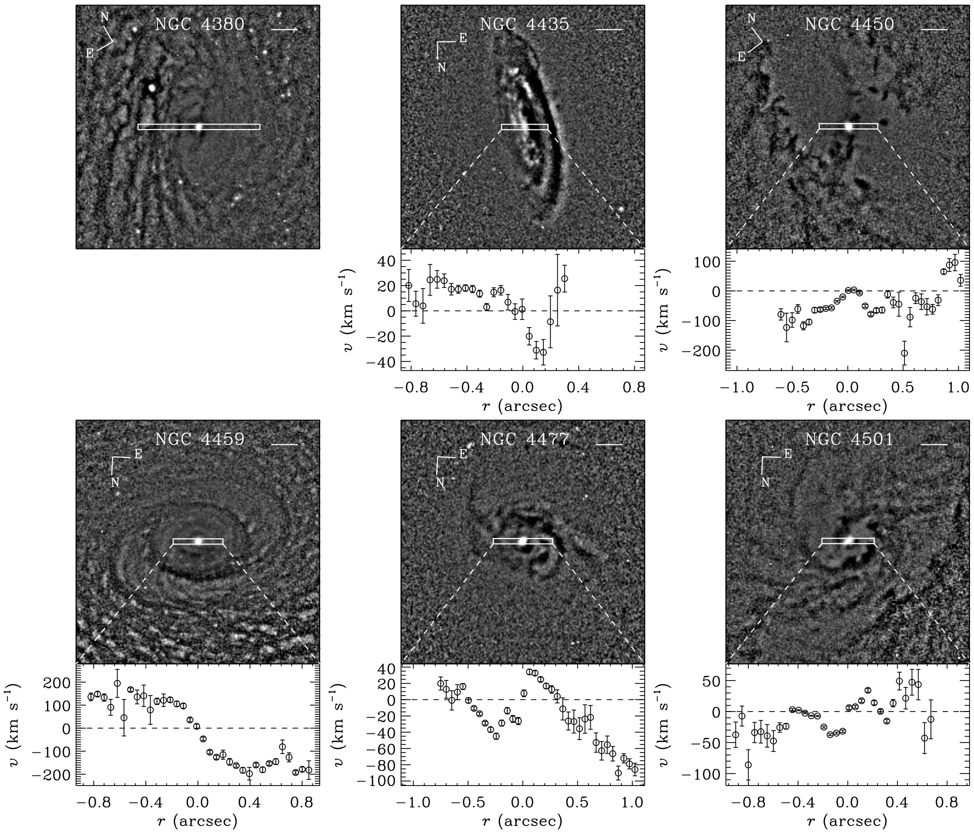

Fig. 1.4. Dust morphology and gas kinematics for NGC 4380, 4435, 4450, 4459, 4477, and 4501. For each galaxy, the *top panel* shows the unsharp-masked, central $9''1 \times 9''1$ region of a V-band WFPC2 image. The horizontal bar on the upper right corner gives the scale of $1''$. The rectangular region superposed on the nucleus outlines the position of the slit. The *bottom panel* shows the Hα velocity curve of the central $\sim 0''5 - 1''0$. The velocity curve is omitted for galaxies lacking extended emission. Adapted from Ho et al. (2002).

Indeed it was not by accident that the only galaxies in the SUNNS survey to display regular gas motions also exhibited circular symmetric dust patterns, as it turned out that none of the galaxies showing irregular dust morphologies had well-behaved rotation curves. Figure 1.4 gives an example of this situation for 6 typical targets of the SUNNS survey, showing also objects where no nuclear emission was detected and where unfortunately the operationally determined position of the STIS slit happen to fall close to the minor axis of a clearly visible nuclear disk. Based on all the SUNNS sample, Ho et al. (2002) concluded that the morphology of the dust lanes can be used as an efficient and relatively reliable predictor of the gas kinematics, boosting the probability of finding regular gas motions in galaxies with circular symmetric dust lanes up to 70%, or even more if nearly face-on configurations are excluded. Supporting this result, in retrospective we notice that also NGC 3245 is the only galaxy among those targeted by its observing program (GO-7403, P.I. Filippenko) to display regular gas kinematics or regular dust-lanes. Furthermore, J. Noel-Storr contribution shows that also in radio-loud early-type galaxies, regular rotation curves are always coupled to sufficiently inclined disk-like dust features.

Even if having regular dust-lanes can boost the probability of finding regular velocity field in galaxies nuclei, it does not preclude to observe very high and problematic gas velocity dispersions, as in the case of the radio-loud elliptical NGC 4335 (Verdoes Klein et al. 2002). Indeed when the observed velocity dispersions exceed the gas velocities as in this case, it is not even possible to explore the asymmetric-drift hypothesis for the gas dynamics and its usually limited impact on $M_{\rm BH}$ (Barth et al. 2002, van der Marel & van den Bosch 1998). Hence without knowing if the gas turbulence also affects its bulk motion, the mass distribution inferred from it is highly uncertain. It remains to be addressed if the exceptional gas turbulence of NGC 4335 is connected to its radio loudness.

1.5 $M_{\rm BH}$ Upper Limits from Central Emission-Line Widths

If the observed ionized gas kinematics is irregular, it is still possible to derive an upper-bound on $M_{\rm BH}$ by explaining the observed central emission-lines width in terms of gas motions dominated by gravity. Clearly the smallest the aperture within which the central emission is collected, the more the observed line-width is affected by the central SMBH and therefore the more interesting the derived upper-bound on its mass. On the other hand, the unsettled importance of non-gravitational forces in contributing to the observed line widths and the lack of spatially resolved information on the gas emissivity constitute the ultimate reasons why it is not possible to also set a lower limit on $M_{\rm BH}$ from central emission-line widths. Different assumptions on the dynamical status of the unresolved central gas translate into different $M_{\rm BH}$ for a given line width, but as shown by Sarzi et al. (2002) the most conservative upper limits are always found for gas participating in Keplerian rotation in a disk-like configuration. Strictly speaking to a perfectly face-on disk would correspond an infinite $M_{\rm BH}$, but as luckily such extreme configurations are statistically rare it is possible to derive sensible 68% confidence upper and lower limits on $M_{\rm BH}$ corresponding to nearly face-on and edge-on disks, respectively.

Figure 1.5 shows the result of this exercise for the 16 galaxies in the SUNNS sample with measurable emission lines within $0''25 \times 0''2$. Remarkably, with one exception, the $+1\sigma$ upper limits are consistent with the $M_{\rm BH}$–$\sigma_\star$ relation and suggest that for galaxies with $\sigma_\star \geq 100\,{\rm km\,s^{-1}}$, SMBHs with exceptionally high $M_{\rm BH}$ must be rare. In this $\sigma_\star$-regime the derived limits on $M_{\rm BH}$ are also quite close to the actual measured values in galaxies (see Fig 6 of S02), as shown in Fig. 1.5 for the SUNNS galaxies with $M_{\rm BH}$ obtained from resolved kinematics. If non-gravitational forces would substantially contribute to the observed line widths, this comparison would fail more often, with the derived upper-limits well exceeding the secure measurements. In fact this seems to be the case for the three galaxies with the smallest $\sigma_\star$ in Fig. 1.5, which $M_{\rm BH}$ upper limits lie systematically above the $M_{\rm BH}$–$\sigma_\star$ relation that for low $\sigma_\star$ is based on $M_{\rm BH}$ obtained by studying the stellar kinematics, such our Milky-Way, Andromeda, or M32.

To further investigate if in low-mass bulges non-gravitational forces can considerably af-

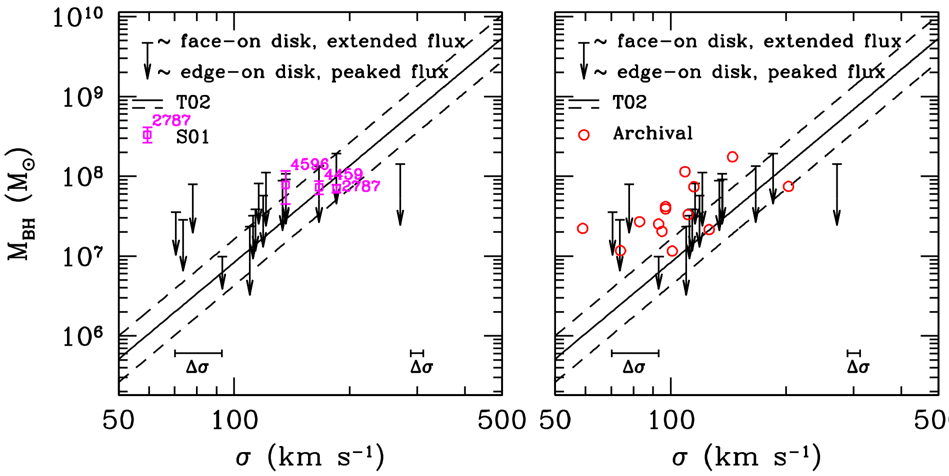

Fig. 1.5. $M_{\rm BH}$ upper limits in the $M_{\rm BH}$–$\sigma_\star$ relation. The 1σ upper and lower limits on $M_{\rm BH}$ (thick downward arrows) obtained by the Keplerian disk modeling of Sarzi et al. (2002) are compared with the range of black hole masses expected as a function of $\sigma_\star$ from the $M_{\rm BH}$–$\sigma_\star$ relation and its absolute scatter in $M_{\rm BH}$ (solid and dashed lines, from Tremaine et al. (2002)). For comparison on the *left panel* the violet open squares show the $M_{\rm BH}$ measurements obtained from extended kinematics in four these galaxies by Sarzi at al. (2001), while on the *right panel* the red open circles show a preliminary extension of this upper-limits exercise using *HST* archival data.

fect the nuclear gas motions, we extended this exercise to more spiral galaxies with archival *HST* spectra, using data from the largest sample of them, that of GO-8228, P.I. Axon. For the galaxies with clearly detectable emission lines and published $\sigma_\star$, Tab. 1.1 lists the central line widths measured within the same aperture, and the corresponding preliminary $M_{\rm BH}$ upper-limits. Indeed the information on the emission spatial distribution of each galaxy has not yet been folded in the models as described by S02, but so far the mean flux extension from the SUNNS sample has been adopted ($\sigma_{gas} = 0''06$). Nevertheless these upper limits appear to be robust as for NGC4321 and NGC4041 the values of Tab. 1.1 are reassuringly consistent with the upper bounds derived by S02 ($2.7 \times 10^7 M_\odot$) and Marconi et al. (2003, $2.0 \times 10^7 M_\odot$), respectively. Figure 1.5 finally shows how these archival $M_{\rm BH}$ upper limits fit into the previous picture. All upper limits are consistent with the $M_{\rm BH}$–$\sigma_\star$ relation, but still the objects with smaller $\sigma_\star$ appear to depart more from it, an impression that will be reinforced once the adopted $\sigma_\star$ values should be corrected to the usually smaller ones at one R$_e$. Finally, while accounting for the stellar influence may be important for addressing the exact $M_{\rm BH}$ in these systems, this is not the case for this kind of upper limits, as shown by S02 for the three lowest $\sigma_\star$ galaxies in their sample, or here in the case of NGC 4303 where Colina et al. (2002) find a central super star cluster of only $10^5 M_\odot$.

1.6 Conclusions

When well-behaved, ionized gas kinematics can provide $M_{\rm BH}$ measurements that are accurate enough to address SMBHs demographic questions such as the exact slope and scatter of the $M_{\rm BH}$–$\sigma_\star$ relation and the $M_{\rm BH}$ content of normal and “pseudo” bulges. Gas-

Table 1.1. *Preliminary $M_{\rm BH}$ upper limits from HST archival data*

Galaxy (1)	Type (2)	B_T (mag) (3)	D (Mpc) (4)	$\sigma_\star$ (km s^{-1}) (5)	Ref. (6)	σ_{gas} (km s^{-1}) (7)	$M_{\rm BH,lim}$ ($M_\odot$) (8)
NGC 613	SBbc	11.00	17.5	126	1	59	2.1×10^7
NGC 1300	SBbc	11.22	18.8	145	2	163	1.8×10^8
NGC 2903	SBbc	9.56	6.3	101	1	72	1.2×10^7
NGC 2964	SBbc	12.26	21.9	97	3	74	3.9×10^7
NGC 3021	Sbc	12.56	25.1	59	4	65	2.2×10^7
NGC 3310	SBbc	11.08	18.7	111	5	71	3.3×10^7
NGC 3642	Sbc	11.68	27.5	109	5	112	1.1×10^8
NGC 4041	Sbc	11.80	19.5	95	6	57	2.0×10^7
NGC 4258	SBbc	9.10	6.8	115	3	175	7.4×10^7
NGC 4303	SBbc	10.18	15.2	74	3	50	1.2×10^7
NGC 4321	SBbc	10.07	16.8	83	1	71	2.7×10^7
NGC 4536	SBbc	11.14	13.3	203	2	125	7.4×10^7
NGC 5879	Sbc	12.18	16.8	93	1	67	2.5×10^7
NGC 6951	SBbc	12.00	24.1	97	1	73	4.2×10^7

Note: Col. (1): Galaxy name. Col. (2): Hubble type from de Vaucouleurs et al. (1991). Col. (3): Total apparent *B* magnitude from de Vaucouleurs et al. (1991). Col. (4): Distance from Tully (1988) and from Marconi et al. (2003) for NGC 4041, both assuming H_0 = 75 km s^{-1} Mpc^{-1}. Col. (5): Ground-based central stellar velocity dispersion. Col. (6): Reference for $\sigma_\star$. Col. (7): Measured gas velocity dispersion within the central $0''25 \times 0''2$. Col (8): Upper limit on $M_{\rm BH}$ obtained with a rotating disk model ignoring the stellar gravitational potential.
References: (1) Schechter 1983; (2) McElroy (1995); (3) Héraudeau & Simien 1998; (4) Héraudeau et al. 1999; (5) Terlevich, Diaz, & Terlevich (1990); (6) Marconi et al. (2003)

dynamical programs have already made important steps in broadening the range of surveyed Hubble-types for galaxies containing SMBHs, but have also been affected by very low SMBHs detection rates. In the future this can be fixed by selecting targets with regular, circular-symmetric, dust lanes, as this considerably boosts the probability of finding regular gas velocity fields. Central emission-line widths obtained with *HST* can already be used to derive astrophysically interesting upper limits on $M_{\rm BH}$ for a wider range of SMBHs host galaxies. Presently these limits support the picture wherein $M_{\rm BH}$ and the overall galaxy structure are closely linked and indicate that non-gravitational forces may substantially affect nuclear gas motions in the smallest bulges. This would prevent $M_{\rm BH}$ measurements based on gas kinematics and leave open only the path for near-IR stellar kinematical measurements with 8m-class telescopes and adaptive optics.

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