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Observation of black holes and extreme gravitational events/Observation des trous noirs et des événements gravitationnels extrêmes

Supermassive black holes in local galaxies

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Abstract

Over the past decade we have learned that probably all ellipticals and bulges of galaxies contain central supermassive black holes (SMBH). SMBH masses correlate well with the luminosities, and in turn the stellar masses of the bulges harboring them, with about 0.15% of the bulge mass being found in the SMBH. Pure disk galaxies, on the other hand, do not, in general, seem to contain SMBHs. Here we review the best cases for SMBH detection in galaxies, discuss methods and associated uncertainties, summarize correlations between SMBH masses and host galaxy properties, and finally address possible future developments. ***To cite this article: R. Bender, R.P. Saglia, C. R. Physique 8 (2007).***

Résumé

Des trous noirs très massifs dans les galaxies proches. Durant la dernière décennie, nous avons appris que probablement toutes les galaxies elliptiques et les bulbes contiennent un trou noir central très massif (SMBH). Les masses des SMBH se corrèlent très bien avec les luminosités, et donc avec les masses, des bulbes dont ils sont les hôtes. Ils représentent environ 0.15% de la masse du bulbe. A l'inverse, les galaxies disques ne semblent pas contenir de SMBH. Nous résumons ici les meilleurs cas de mise en évidence de SMBH dans les galaxies. Nous discutons ensuite des méthodes et de leurs incertitudes, des correlations entre les masses des SMBH et les propriétés de leurs galaxies hôtes et, enfin, des développements futurs possibles. ***Pour citer cet article : R. Bender, R.P. Saglia, C. R. Physique 8 (2007).***
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1. Introduction

With the discovery of quasars (Schmidt [1]) and the proposal that accretion onto compact objects, such as black holes, provided the only efficient and plausible way to generate their required luminosities (Zel'dovich [2] and Salpeter [3]) the idea of the presence of supermassive black holes (SMBHs) at the centers of galaxies was born. A little later, Lynden-Bell [4] elaborated the picture, which came to be known as the black hole paradigm for active galactic nuclei (AGN).

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The evidence for supermassive black holes in AGN has been strong for a long time, but crucial questions remained unanswered until about 10 years ago; e.g., it was unclear whether the black hole density in local galaxies matched the energy requirements set by the total integrated AGN luminosities. Moreover, it was not known whether all galaxies contained black holes and how their masses correlated with galaxy properties. Finally, even for the most nearby galaxies, including our own, it had not been conclusively demonstrated that the dynamically discovered central dark objects were indeed black holes (or just dark clusters of neutron stars, white dwarfs or stellar mass black holes). Tremendous progress has been made in the last decade, especially concerning these questions, mostly thanks to new facilities (especially the Hubble Space Telescope and the adaptive optics at Keck and VLT) and the development of new theoretical tools for the analysis of stellar dynamical data. We have learned that probably all bulges of galaxies contain central dark objects (see Richstone et al. [5], Kormendy and Gebhardt [6]). In the Milky Way, NGC 4258 and M 31, it is virtually certain that these dark objects are indeed SMBHs, because alternatives to SMBHs in the form of clusters of stellar remnants or brown dwarfs can be ruled out (Maoz [7], Schödel et al. [8], Bender et al. [9]). In several cases where independent methods for the estimate of the black hole masses are applicable, the SMBH masses largely agree within the errors (Gebhardt et al. [10]). Moreover, the masses of these dark objects are approximately consistent with the expected mass density of quasar remnants in the local universe (e.g., Richstone et al. [5], Yu and Tremaine [11]).

In the past three years, many reviews and whole conferences (Ho [12]) have been devoted to the subject of SMBHs in nearby galaxy centers. Therefore, this article can only present a brief summary of key results, recent developments and future prospects. The structure of the article is as follows. In Section 2 we review the evidence for a SMBH in the Galactic Center. In Section 3 we address the case of the Andromeda galaxy. In Section 4 we summarize the search for SMBHs in nearby galaxies, discussing the different methods of mass estimates and their uncertainties, the global relations between SMBHs and their host galaxies, and, finally, the perspectives of ground-based, adaptive optics developments. We draw our conclusions in Section 5.

2. The Galactic Center

The best evidence for the existence of SMBHs in galaxies comes from the observations of the Galactic Center (GC) of the Milky Way. Thanks to the development of diffraction limited imaging and spectroscopy, two groups (e.g. Schödel et al. [8], Ghez et al. [13]) were able to measure the positions of several stars near Sag A*, the radio source at the center of our Galaxy possibly coinciding with the MW SMBH (Lo et al. [14]), and to follow their motions with time with subarcsecond precision. Moreover, the radial velocities and spectral types of some of these stars were also secured. This dataset allows one to simultaneously fit the (Keplerian) orbits of the stars, constraining the mass of the central dark object to $(3.67 \pm 0.19) \times 10^6\ M_\odot$ (for a GC distance of 8 kpc). This is the second smallest SMBH detected dynamically in a galaxy (the smallest being M32 with $2.5 \times 10^6\ M_\odot$, Verolme et al. [15], but with much larger error bars, see Section 4). This mass appears somewhat smaller than what one would predict using the global $M_\bullet$–σ relation discussed in Section 4.2, partially because the velocity dispersion of the MW bulge is still not well determined.

The fact that the pericenter of one of the stars is as small as 45 AU (or 600 Schwarzschild radii) implies a minimum density of $8 \times 10^{16}\ M_\odot\,\mathrm{pc}^{-3}$ for the central dark object. This essentially excludes any alternative to a SMBH in the GC. Any cluster of dark objects would have a lifetime of only $\approx 10^5$ yr (Maoz [7]), much shorter than the age of the Galaxy, while a fermion ball would have to be made out of highly unlikely particles with masses ≈ 74 keV (Ghez et al. [13]). Moreover, the multiple orbital fit limits the SMBH motions on the plane of the sky to 2 mas/yr, excluding possible BH companions with masses larger than $\approx 5 \times 10^5 M_\odot (R/16\,000AU)^{1/2}$, where R is the distance of the companion from the central BH.

Spectroscopy of the Sgr A* cluster stars shows that they have hot photospheres (Genzel et al. [16]), similar to massive young main sequence stars. The implication that recent star formation took place in the vicinity of a SMBH, where strong tidal fields are at work, is, at first sight, difficult to accept, and several alternatives have been proposed. Merging of old stars might produce stars massive enough to appear as main-sequence OB stars, or they might have formed outside the central regions of the MW in a massive cluster that spiraled inward quickly through dynamical friction (Gerhard [17]). However, the recent discovery that also the nucleus of M31 shows the presence of a disk of young stars (see Section 3) has re-invigorated the debate on the possibility of star formation near a SMBH.

3. The center of M31

The next nearest SMBH is found in M31, at a distance almost 100 times larger than the GC. The loss in spatial resolution due to the increased distance ($D \approx 760$ kpc) is almost compensated by the increase in the mass of the SMBH detected in M31 ($\sim 1.4 \times 10^8\ M_\odot$, Bender et al. [9]). This means that the angular size of the event horizons of the SMBHs in the Galaxy and M31 differ by only a factor 2–3. Unlike the Galactic SMBH, the M31 SMBH is massive enough to have powered a serious quasar. Current technology does not yet allow one to probe directly the motions of single stars near the BH, as in the MW (but this may become possible in the future, see Section 4.3). The strong evidence for a SMBH in M31 relies on diffraction limited images and integrated kinematics of its central regions obtained with HST, similar to what is available for other nearby galaxies (see Section 4.1).

The nucleus of M31 harbours three nuclei, called P1, P2 and P3. P1 and P2 are dominated by red stars as M31's bulge. P1 is the brightest and offset by ∼0.5 arcsec from the bulge center, P2 is fainter and very closely centered on the bulge. Within P2 resides the blue nucleus P3, which has an exponential brightness profile and a scale length of 0.1 arcsec (Lauer et al. [19], Bender et al. [9]). Tremaine [20] proposed that P1 and P2 are largely made of the same stars orbiting the SMBH in an excentric disk, P1 presenting the apocenter of the disk, where stars loiter, and P2 the pericenter. Both ground-based and HST imaging and spectroscopy have since confirmed Tremaine's model (Peiris and Tremaine [21], Bender et al. [9]). Unresolved remains the long-term stability of the system, as self-gravity of the stars is not negligible (Bacon et al. [22], Salow and Statler [23]).

Analysis of HST STIS spectra shows that the P3 light is dominated by A-stars that likely formed in a star burst about 200 Myrs ago (Lauer et al. [19], Bender et al. [9]). Alternative explanations, like A-stars formed in collisions, are largely ruled out by the environmental conditions in P3 (Bender et al. [9]). As in the case of the MW, the presence of young stars in the vicinity of a SMBH is a puzzle that indicates that star formation near a SMBH may not be an uncommon phenomenon (Goodman [24], Nayakshin and Sunyaev [25], Nayakshin [26]).

The absorption lines of the A-stars are kinematically broadened to a gigantic 977 ± 106 km/s within the inner 0.02 arcsec, the largest value ever observed in a galaxy (see Fig. 1). This value is mostly, maybe exclusively, due to unresolved circular motion of the stars in a circular disk. A kinematic model fitting the available photometric and

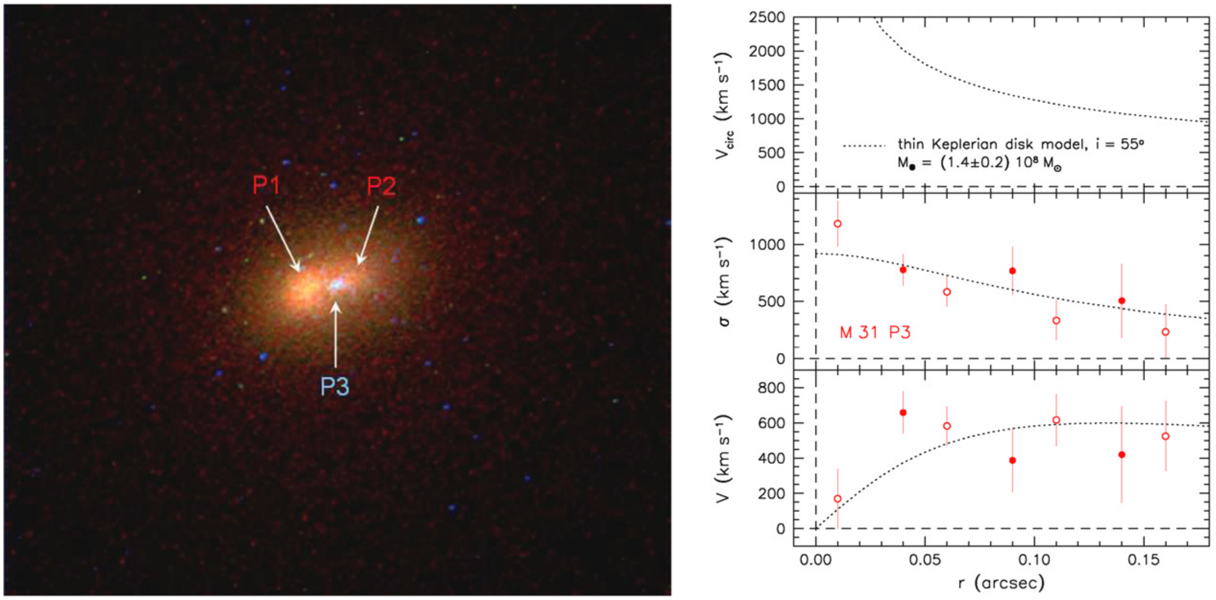

Fig. 1. Left: Real-color image of the three nuclei P1, P2 and P3 of M31, constructed from HST filters F300w, F555W, and F815W, see Kormendy and Bender [18]. P1 and P2 are separated by about 0.5 arcsec, corresponding to about 1.8 pc. Right: The rotation and velocity dispersion curve of the blue nucleus P3 as measured with HST STIS. The data are very well modeled by a thin exponential Keplerian disk of ∼200 A-type stars orbiting a supermassive black hole of $M_\bullet = 1.4 \times 10^8\ M_\odot$. The measured velocity dispersion σ is mostly caused by integration over the slitwidth of STIS (0.2 arcsec) and the point-spread function of the HST-STIS system. The intrinsic circular velocity V_{circ} is shown in the top panel, the bottom panel shows the actually observed rotation velocity V.

spectroscopic data of P3 predicts a circular velocity of $\sim$1700 km/s at 0.05 arcsec = 0.19 pc, implying a BH mass of $1.4^{+0.9}_{-0.3} \times 10^8\ M_\odot$. The data set a 1-$\sigma$ upper limit on the half-mass radius of the massive dark object in M31 of 0.03 arcsec. This rules out astrophysical alternatives to a SMBH, like clusters of brown and white dwarfs, neutron stars or stellar-mass black holes (Bender et al. [9]). Therefore, the M31 provides the third strongest case for a SMBH after the MW and NGC 4258 (see Section 4.1).

4. SMBHs in the nearby universe

Inactive SMBHs can only be found if they noticeably influence the motion of stars or gas at radii that can be resolved observationally. The radius of influence R_i of a SMBH of mass $M_\bullet$ can be defined as:

$$R_i = \frac{GM_\bullet}{V_G^2}$$

where V_G is a rotation velocity or velocity dispersion characteristic for the inner parts of the galaxy. At a distance D of the object, this translates into an angular radius of influence α_i of:

$$\alpha_i \sim 1''\left(\frac{M_\bullet}{10^8\ M_\odot}\right)\left(\frac{V_G}{100\ \mathrm{km\,s^{-1}}}\right)^{-2}\left(\frac{D}{10\ \mathrm{Mpc}}\right)^{-1}$$

While the radius of influence of the SMBH in the Milky Way is large (40″), it already shrinks to 2″ for the SMBH in M31, or 0.5″ for a giant elliptical in the Virgo cluster (assuming a $10^9\ M_\odot$ black hole for the latter). SMBHs at a few Mpc distance with masses below $10^8\ M_\odot$ require HST resolution or adaptive optics on the ground for the resolution of their sphere of influence. If the spatial resolution is much too low, SMBH masses can be biased towards higher masses; see the discussion in Kormendy [27] or Magorrian et al. [28]. However, once spatial resolution is getting close to adequate, lower spatial resolution does in general not bias SMBH mass estimates (Gebhardt et al. [29], Kormendy [27]) but just makes it less reliable and increases the error bars.

4.1. Methods

Different techniques have been used to detect and measure SMBHs, also depending on whether the galaxies under study are quiescent or active: ionized gas dynamics, stellar dynamics, maser gas dynamics, reverberation mapping and Iron Kα emission. All these methods have strengths and weaknesses.

4.1.1. Water masers

Apart from our own Galaxy and the Andromeda galaxy, the best detection of a SMBH in an external galaxy has been obtained for NGC 4258 (Miyoshi et al. [30]). The water masers emit at 22 GHz and can be studied with the VLBI, delivering 0.5 mas precision. NGC 4258 is the best of the few known objects with central water masers, since its emitting clouds are confined to a thin, regular annulus within 0.14 and 0.28 pc from the center. They rotate, following closely the expected Keplerian behaviour $v = \sqrt{GM_\bullet/r}$. The inferred mass $M_\bullet = 3.9 \times 10^7\ M_\odot$ for a distance of 7.2 Mpc implies a mass density $\rho > 4 \times 10^9\ M_\odot\,\mathrm{pc}^{-3}$, virtually excluding any option other than the SMBH solution. Unfortunately, the other few cases with known central water maser emission are not as clear cut (see discussion in Ferrarese and Ford [31]). For example, in NGC 1068, the prototype of Seyfert 2 galaxies, the water maser source possibly is a thin, flat disk, but its rotation declines more gradually than Kepler's law (Greenhill and Gwinn [32]).

4.1.2. Ionized gas

The inner regions of many early-type galaxies harbour dusty, gaseous disks whose kinematics have been used to probe their central masses. Ferrarese and Ford [31] quote observations of 11 galaxies (mostly with HST) with evidence for central SMBHs. These objects have central, optically emitting gaseous regions with morphology regular enough to claim that the gas is in a thin disk, its kinematics is compatible with simple circular motions and the spatial resolution is high enough to probe the sphere of influence of the putative SMBH. Although simpler to obtain and to analyse compared to the stellar dynamical approach, gas dynamical measurements are prone to errors by non-circularity or non-gravitational forces.

4.1.3. Stellar dynamics

Most of the measurements of SMBHs in external galaxies come from stellar dynamics that, in contrast to the ionized gas cases discussed above, are governed by gravitational forces only. However, they require a much larger effort, both in terms of observational time and theoretical modeling. The first step is to measure the stellar kinematics of the central regions of a galaxy from integrated spectra with as high spatial resolution as possible (e.g. with HST or adaptive optics on the ground, see Section 4.3). The goal is to come as close as possible to, or even resolve, the sphere of influence of the BH. The dynamical information is contained in the line-of-sight velocity distribution (LOSVD) of the stars. The latter can be determined from direct fitting of the absorption lines (Rix and White [33]) or deconvolution in Fourier space (Bender [34]). The LOSVD not only measures the mean and random motions of the stars along the line of sight, but also contains the imprints of the orbit distribution. It is conveniently parametrized as a Gauss–Hermite series (van der Marel and Franx [35]; Gerhard [36]; Bender, Saglia and Gerhard [37]), with the 4th order coefficient particularly sensitive to the orbital anisotropy. In the second step, the kinematics (along several slit positions or possibly on a two-dimensional field) are combined with high resolution imaging to construct a dynamical model of the galaxy. State-of-the-art dynamical models are based on orbit superposition following Schwarzschild [38]; see Thomas et al. [39] for axisymmetric models, and van de Ven et al. [40] for triaxial ones. In short, the light distribution is deprojected to compute the gravitational potential generated by the stellar component of the galaxy, assuming a constant mass-to-light ratio (M/L). The Keplerian potential generated by a BH of a given mass $M_\bullet$ is added. Several thousands of orbits are computed in the total potential and combined to optimally reproduce the measured LOSVDs and the observed light distribution. The minimal χ^2 model delivers the best estimate of M/L and $M_\bullet$ with confidence limits and the orbital structure of the galaxy. Here the main uncertainties come from the unknown appropriate degree of regularization needed to find the optimal model between a maximum entropy solution and a solution that overfits the data. It is also non-trivial to estimate the correct number of degrees of freedom of the problem, which makes it difficult to assess the quality of the fit in an objective way.

4.1.4. Reverberation mapping

According to the ‘standard model’ of AGN (Antonucci [41]), the broad line region (BLR) surrounding the SMBH is visible in Seyfert 1 galaxies. Any variation in the ionizing continuum flux produced by the black hole accretion disk should cause a flux variation of the lines of the BLR, with a time delay directly proportional to the size r of the BLR. This is the principle of reverberation mapping (Blandford and McKee [42]), which is distance-independent. The continuum and the line fluxes are best monitored either in the ultraviolet (e.g. with IUE) or in the blue optical range from the ground. When combined with the mean velocity σ of the clouds (assumed to have gravitational origin and measured from the width of the lines), one gets an estimate of the central mass from the Virial Theorem $M = fr\sigma^2/G$, where the factor f encapsulates the assumptions about the structure and geometry of the emission line regions near the SMBH (Onken et al. [43]). In principle, these estimates are very interesting, since r probes regions only 1000 Schwarzschild radii in size, implying such high enclosed mass densities to automatically rule out any alternatives to a SBMH (see above). However, the uncertainties related to the unknown geometry can be large (Horne et al. [44]).

4.1.5. Iron Kα emission

The iron Kα line is an intrinsically narrow fluorescent line at 6.44 KeV. However, in almost all Seyfert I galaxies it is observed to be extremely broad (the full width at zero intensity exceeds $\sim 0.3c$) and strongly skewed to the red (Nandra et al. [45]). Very good fits to the line are obtained assuming that it originates in a rapidly rotating (accretion) disk very near the central BH. The rotation produces the ‘double horn’ line morphology typical of HI disks of spirals, but relativistic beaming enhances the blue component, while gravitational redshift spreads the emission from the inner components of the disk to the red wing. Despite the potentially very interesting sensitivity to the regions nearby the BH (the line can in principle be used to determine the inclination of the accretion disk and even the spin of the BH), systematic effects are very difficult to control.

4.1.6. Consistency checks and reliability

Although the above mentioned methods are affected in different degrees by possibly large systematic errors, careful analysis seems to have kept them largely under control. In fact, they yield virtually indistinguishable $M_\bullet$–$M_{B,\mathrm{bulge}}$ and $M_\bullet$–σ correlations (e.g., Laor [46], Gebhardt et al. [47]); see below. In addition, for some galaxies SMBH masses

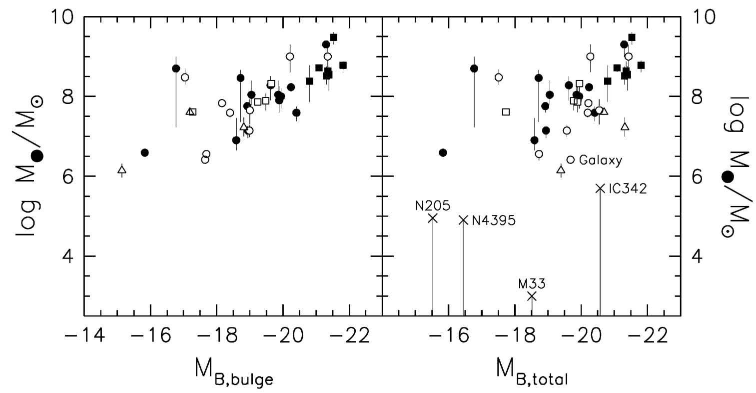

Fig. 2. Left: correlation of black hole mass $M_\bullet$ versus bulge luminosity $M_{B,\mathrm{bulge}}$; right: $M_\bullet$ against the total absolute magnitude of the host galaxy $M_{B,\mathrm{total}}$. Filled symbols denote elliptical galaxies, open symbols denote bulges of disk galaxies. Crosses denote galaxies that do not contain a bulge: M 33 is from Gebhardt et al. [58]; IC 342 is from Böker et al. [72], and NGC 4395 is from Filippenko and Ho [60] (from Kormendy and Gebhardt [6]).

have been derived with independent methods producing largely consistent results (Milky Way: Schödel et al. [48]; NGC 4258: Siopis et al. [49]; M31: Bender et al. [9]; NGC 3379: Shapiro et al. [50]; NGC 5128: Silge et al. [51], Marconi et al. [52]; NGC 3227: Davies et al. [53], see also Section 4.3).

4.2. Global relations

If we assume that the dynamically detected dark objects are SMBHs, then we find that their masses correlate well with the bulge luminosities or bulge masses of their host galaxies (Kormendy [54]; Kormendy and Richstone [55]; Magorrian et al. [28], Marconi and Hunt [56], Häring and Rix [57]). The most reliable observations (Kormendy and Gebhardt [6], see Fig. 2) yield:

$$M_\bullet \sim 0.0013 \cdot M_{\mathrm{bulge}}$$

It is important to note that SMBH mass does not correlate with the luminosity of galaxy disks. Fig. 2 shows how the correlation of $M_\bullet$ with bulge luminosity (left) is destroyed for disk galaxies (right: open symbols and crosses) when the disk luminosity is included. Especially evident is the case of the bulgeless spiral M 33 (Gebhardt et al. [58]; Merritt et al. [59]). On the other hand, some pure disks seem to have Seyfert nuclei and so presumably do contain SMBHs (Filippenko and Ho [60]). However, their masses appear to be *much* smaller than the canonical 0.13% of the bulge mass implied by the left panel of Fig. 2. It will be crucial to improve the statistics on small SMBHs in disk galaxies. Recently, three independent groups (Côté et al. [61], Ferrarese et al. [62], Wehner and Harris [63]) suggested that the relation might extend to lower luminosities and disks when the mass of the BH is replaced by the mass of central nucleus often present in late type galaxies or dwarf ellipticals.

There also is a tight correlation between SMBH mass and the velocity dispersion σ of the bulge (measured at radii much larger than the radius of influence of the SMBH, Gebhardt et al. [10], Ferrarese and Merrit [64]). The scatter is almost as small as the measurement errors (typically a factor of $\sim$2 in $M_\bullet$):

$$\frac{M_\bullet}{M_\odot} \sim 0.1 \left(\frac{\sigma}{\mathrm{km\,s^{-1}}} \right)^4$$

(Tremaine et al. [65]). Based on these data, $M_\bullet$ seems to correlate better with velocity dispersion than with bulge luminosity. This would imply that, at a given bulge luminosity, more massive black holes live in more compact bulges. On the other hand, a recent analysis by Häring and Rix [57] shows that, if bulge masses are derived from dynamical modeling and only galaxies with reliable black holes are considered, then the black hole mass versus bulge mass correlation may be as tight as the black hole mass versus bulge dispersion relation. Finally, note that systematic differences between Narrow-Line and Broad-Line Seyfert 1 galaxies may possibly indicate that not all galaxies follow a single $M_\bullet$–σ relation (e.g. Grupe and Mathur [66]).

Since the velocity dispersion of elliptical galaxies correlates with the circular velocity of their dark matter halos (Gerhard et al. [67]), a relation between the formation of dark matter halos and black holes was proposed by Ferrarese [68]. However, such a scenario does not provide a satisfactory explanation why massive disk galaxies do not contain SMBHs. Finally, the correlation between the Sersic index and the total luminosity of elliptical galaxies (Caon et al. [69]) suggests a correlation between the concentration index of the galaxy luminosity profiles and their central BH mass (Graham et al. [70]). Environmental influences and the presence of sub-components suggest that the latter correlation should not be as tight as the potentially primary correlations of BH mass with bulge mass or bulge velocity dispersion.

A further interesting question is whether galaxies with pseudobulges (PBs) follow the $M_\bullet$–$M_{B,\mathrm{bulge}}$ and $M_\bullet$–σ relations. PBs (Kormendy [86], Kormendy and Kennicutt [71]) are mostly found in late-type galaxies and are physically unrelated to ellipticals. Their defining characteristica are the following: (i) their velocity dispersion σ is smaller than predicted by the Faber–Jackson relation; (ii) they have rapid rotation V such that V/σ values are well above the oblate line describing rotationally flattened isotropic spheroids in the V/σ-ellipticity diagram; (iii) their surface brightness profile is closer to exponential than to an $r^{1/4}$ profile; (iv) their isophotes are mostly *boxy* or peanut-like; and (v) their often bluer colors are indicative of lower ages than those normal bulges. While normal bulges are thought to form like ellipticals, in a partly dissipative collapse during a merger, PBs should form by secular evolution in disks, e.g., through bar instabilities. In mergers black holes can grow via merging with another black hole *and* gas accretion in a fluctuating triaxial potential. In PB black holes can only grow through accretion of gas in a triaxial potential. Investigating systematic differences between the $M_\bullet$–M_{Bulge} relation of massive spheroids and PB can thus provide interesting constraints on the models of black hole growth. The handful of cases already investigated (with the MW and NGC 4258 being the best examples) seem to follow the same $M_\bullet$–$M_{B,\mathrm{bulge}}$ and $M_\bullet$–σ relations as classical bulges and ellipticals (Kormendy and Gebhardt [6]), which would imply that the formation of bulges and the growth of SMBHs have proceeded in lockstep.

4.3. *Current and future developments*

With the failure of the STIS spectrograph on HST we lost the capability to get diffraction-limited spectra from space. However, one can argue that its further availability would not have added too much to the search of SMBHs. In fact, most of the nearby early-type galaxies that could have been observed spectroscopically by HST have been already observed. What remains is either too faint for a 2 m class telescope, or, is so dusty (e.g., pseudobulges, late-type spirals or the star-forming regions near AGNs) that an optical spectrograph, like STIS, would not deliver useful data. Therefore, in the near future progress is more likely going to be achieved using near-infrared (NIR) spectrographs (possibly with two-dimensional field capabilities) on 8 m class ground-based telescopes equipped with Adaptive Optics (AO) systems. The NIR wavelengths are less affected by dust, and AO under good atmospheric conditions can deliver spatial resolutions comparable to HST, combined with a much larger light collecting power. In this spirit, several groups have started programs to exploit the capabilities of ground-based AO. E.g., we are using SINFONI, the integral field NIR spectrograph operating at the VLT (see http://www.eso.org/instruments/sinfoni/), equipped with PARSEC (see http://www.mpe.mpg.de/ir/parsec/index.php), the newly commissioned laser guide star for AO. We have observed a number of pseudo-bulges and bulge-less galaxies to explore the $M_\bullet$–σ relation at the, as yet, poorly known (see above) low-mass end, and test the bulge-BH formation scenarios. Using the strong CO absorption bands at ≈21 µm and the highest spectral resolution grism available, one can probe galaxies with central velocity dispersions as low as ≈30 km/s.

We were able to constrain, for the first time, the BH mass of the Seyfert 1 galaxy NGC3227 with a stellar dynamical analysis and show that it agrees with reverberation mapping techniques (Davies et al. [53]). For the low-luminosity elliptical NGC 4486a we demonstrated the reliability of AO-assisted kinematics by showing that SINFONI and OSIRIS (a spectrograph with AO at Keck, see http://www2.keck.hawaii.edu/inst/osiris/) give the same results at the highest resolution (Nowak et al. [73]). For this galaxy we derive a BH mass in agreement with the $M_\bullet$–σ relation.

In the medium term, a number of further key advances in the studies of SMBHs seem possible thanks to the development of infrared astrometry with 10 micro-arcsecond accuracy and phase referenced imaging with 4 mas resolution. For example, GRAVITY is a near-infrared instrument assisted by adaptive optics, proposed for the VLT Interferometer. With an accuracy of 10 micro-arcseconds, GRAVITY will be able to study motions of stars to within a few times the event horizon size of the Galactic Center SMBH. This will potentially test General Relativity in its strong field limit (see http://www.mpe.mpg.de/ir/gravity/index.php).

M31 is also an interesting target for future interferometric observations. The ≈200 A-type, 200 Myr old stars detected at the P3 center of M31 (see Section 3) could be accompanied by 5–10 red giant stars, expected to be bright enough ($K \approx 19$) to be detectable as single objects given a spatial resolution of $\leqslant$0.05 arcsec and the sensitivity of a 10 m class telescope. This might be already within the current capabilities of OSIRIS in its integral field mode (see link above) and will be resolvable by the interferometric imaging facilities of the Large Binocular Telescope, such as Linc-Nirvana (see http://www.mpia-hd.mpg.de/LINC/). This opens in principle the possibility to repeat the success of the GC monitoring campaigns to detect the proper motions and possibly orbits of stars around the SMBH of M31.

5. Discussion and conclusions

Several models make predictions for the $M_\bullet$–σ or the $M_\bullet$–$M_{\rm Bulge}$ relation (e.g. Burkert and Silk, [74]; Haehnelt and Kauffmann [75] and others), but the slopes of the observed relations are still too uncertain to rule out any of the proposed models. Presumably the earliest massive black holes were formed in the collapse of either massive dense gas clouds or dense star clusters at redshift $z > 3$. Neither of these processes is likely to succeed in the direct formation of seed black holes above $10^5\ M_\odot$ (Rees [76]). Some of these seed objects should have survived in low luminosity galaxies or may live in the halos of massive galaxies. So far, these seed objects have escaped detection. Another major puzzle in understanding the origin of SMBHs is the fact that pseudo-bulges, which are supposed to form via secular evolution of disks, lie on the same $M_\bullet$–σ relation as luminous bulges and ellipticals (see, e.g. Kormendy and Gebhardt [6]). However, this result is based on only very few pseudo-bulges so far and errors in their black hole masses are relatively large.

Having established that SMBHs are probably ubiquitous at the centers of spheroids (at least above the minimal mass probed by current observations), it is interesting to assess the influence of SMBHs on the galaxies harboring them. On the one hand, there are dynamical effects. Stars that come close to the SMBH maybe be captured and/or tidally disrupted (events that have been possibly observed as X-ray flares, Komossa et al. [77]), creating 'loss cones' where only centrophobic orbits survive. Binary black holes that are expected to form during galaxy mergers and have been observed in NGC 6240 (Komossa et al. [78]) and at the center of the cluster A400 (Hudson et al. [79]), destroy dense nuclei (Merritt [80] and references therein), possibly explaining why massive ellipticals have flat cores (Faber et al. [81]). These effects influence the stellar anisotropy structure of the inner regions of galaxies and could be compared with observational results, once the model regularization issues discussed in Section 4.1 will be under control.

On the other hand, there is growing evidence that SMBH are intrinsically linked to the formation and evolution of galaxies. The newest cosmological modeling attempts (Bower et al. [82]; Croton et al. [83]) suggest a 'cosmic cycle' (see Fig. 1 of Hopkins et al. [84]) that offers a natural explanation for the apparently 'anti-hierarchical' formation history of galaxies (e.g. Thomas et al. [85]). The SMBHs regulate star formation, become active (i.e. shine as a quasar) and grow in mass when gas inflow happens after galaxy merger events, and they prevent extended star formation by their activity. Why this should happen, an order of magnitude estimate of Hopkins et al. [84] elucitades. The feedback energy produced by the SMBHs is $E_{\rm feed} \sim \varepsilon_f M_\bullet c^2$, where the efficiency factor is of order 1%. This exceeds the binding energy of the galaxy $E_{\rm bind} \sim M_{\rm sph}\sigma^2$: since $M_\bullet/M_{\rm sph} \approx 0.002$ (see Section 4.2), one gets $E_{\rm feed}/E_{\rm bind} \sim 10(\varepsilon_f/0.01)(\sigma/300\ {\rm km/s})^{-2}$. If just a fraction of the energy that SMBHs can emit is coupled to the intergalactic medium, then SMBHs are bound to have a decisive role in the evolution of galaxies.

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