EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

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APPLICATION FOR OBSERVING TIME — PERIOD: **78A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of COIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title — Category: **B–2**

A Survey of Black Holes in Different Environments

2. Abstract

We propose to carry out a spatially resolved spectroscopic survey of the centers of elliptical and early type galaxies with very low and very high central velocity dispersions. The goal of the survey is to resolve the Sphere of Influence (SoI) of the suspected black holes (BHs) in those galaxies and thereby investigate the low and hi-mass end of the M_{BH}-σ relation. Our sample includes galaxies in a broad range of clusters as well as field galaxies. The centers of all galaxies in our sample have previously been imaged by HST and/or JWST, and expected BH masses have been estimated based on the cusp brightness and velocity dispersion. The survey will for the first time resolve the SoI of BH with masses M_{BH} of around 10^6 outside the local Universe, and at the same time yield spectroscopic data of a significant sample of the most massive BHs currently known. The survey also might discover supermassive BHs with masses of up to about 10^{10} $M_{\odot}$.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	79	FORS2	200h	any	d	$\leq 0.4''$	CLR	v
B	79	FORS2	3h	any	d	$\leq 0.4''$	CLR	v

4.

Number of nights/hours	Telescope(s)	Amount of time
a) already awarded to this project:		
b) still required to complete this project:		

5. Special remarks:

In order to establish feasibility we need detailed simulations which included the expected s/n.

6. Principal Investigator: **Wolfram Freudling** (ESO, D, wfreudli@eso.org)

CoI(s): Eric Ensellem (U. Lyon, F), Alessandro Marconi (Arcetri, I), The Rest (Elsewhere, ESO)

7. Is this proposal linked to a PhD thesis preparation? State role of PhD student in this project

8. Description of the proposed programme

A) Scientific Rationale:

The relationship between host galaxy bulge mass and black hole (BH) mass is well established for both active and currently inactive galaxies (McLure & Dunlop, 2002, MNRAS, 311, 795). Wyithe (2006, MNRAS 365, 1082) and Greene & Ho (2006, ApJ 641, L21) have recently argued that the linear M_{BH}-σ relation steepens at high black hole masses and flattens at low black hole masses. Lauer et al. (2006, ApJ, astro-ph/0606739) argue that cusp brightness might in fact be a better estimator of the black hole masses than σ for the most massive BHs with $M_{BH} > 10^9 M_\odot$. If confirmed, this might explain why it has been so difficult to find the supermassive black holes in the local Universe, which are expected to exist as the counter parts of the high-z QSOs. It is currently not known whether the M_{BH}-σ relation depends on environment or if and how it evolves.
To study the M_{BH}-σ relation at its extreme ends, it is necessary to directly determine the BH masses for statistical significant samples. To confidently detect and measure the mass of a nuclear BH, we need to probe the volume within which the BH dominated the galactic dynamics. Called the 'Sphere of Influence', this region has a radius defined as:

$$r_i = GM_{BH}/\sigma^2 = 4.3pc(M_{BH}/10^7 M_\odot)/(\sigma/100km/s)^2 \quad (1)$$

where σ is the stellar velocity dispersion. A typical scale for BH masses of $\approx 10^7 M_\odot$ is about 7 pc.
Unfortunately, it is quite difficult to probe the SoI in galaxies at the extreme ends of the M_{BH}-σ relation. There are currently only two cases where this region has been probed directly to show that a massive BH is the only physical possibility: our Galaxy and NGC4258. The projected diameter of the SoI for a BH with masses of $\approx 10^7 M_\odot$ is significantly smaller than 100mas at the distance of the Virgo cluster. Because of the low volume density of high-mass BHs, studying the high-mass end of the M_{BH}-σ relation requires samples at moderately high redshifts out to $z \approx 0.4$. At such distance, the SoI is again smaller than 100mas. In addition, the onset of significant surface brightness dimming at such redshifts makes it impossible to obtain spatially resolved spectroscopy of the cores of such galaxies with 8m class telescopes. Therefore, progress in this field will be moderate before the arrival of the ELT.
However, the high angular resolution and sensitivity of an ELT will allow:
1. to resolve nuclear sub-structures down to a few pc at distances of tens of Mpc (depending on aperture and PSF). This will allow mass determination of BHs with masses similar to the one in the center of the Milky Way out to the distance of Virgo.
2. resolve the sphere of influence for the most massive BHs with masses of greater than $10^9 M_\odot$ at cosmological redshifts. Mass determination of black holes will be limited by the available light only. Mass determination for $10^9 M_\odot$ BHs will be possible out to a redshift of about 0.4, allowing the collection of statistical samples of such objects.
Such measurements are fundamental to the understanding of the relationship between the evolution of the BH and the host galaxy, including the possible connection between AGN and starburst activity.
A rough estimate of the maximum redshift at which BHs can be spectroscopically resolved is shown in Fig. 1. For each BH mass, the size of the SoI was computed. Subsequently, the maximum distance at which the projected diameter of the SoI is more than 10 mas was determined. An additional complication is that the most massive BHs tend to be in galaxies with relatively low surface brightness in the center. This effect was taken into account by assuming that the central surface brightness is related to the BH mass as given in Equ. 10 of Lauer et al. (2006). It can be seen that accurate mass determination will be limited to redshifts less than $z \approx 0.6$ even for the most massive BHs.

B) Immediate Objective: We propose to carry out 2 distinct spatially resolved spectroscopic surveys of the nucleus of early type galaxies. The first survey targets galaxies with estimated BH masses of more $10^{9.5} M_\odot$. Candidate galaxies have been extracted from the SDSS, and are at redshifts up to $z \approx 0.4$.
The second survey targets BH with masses less than $10^{6.5} M_\odot$ in a variety of environments. This includes galaxies in the Virgo Cluster and galaxies at similar redshift.

C) Telescope Justification: The program needs the ELT both for the spatial resolution and the light collection power. The most efficient way to map the full velocity field around the nucleus is to use an IFU. If an IFU is not available, several long slit positions could be used.
In order to determine the feasibility to detect BHs with spatially resolved spectroscopy, we have simulated the shape of spectral lines based on a kinematic model of NGC 3377.
We first fit a multi-Gaussian expansion to the density and velocity fields of that galaxy (see Emsellem et al., 1994, AA 285, 739). We then projected the density and velocity field to a given redshift, convolved the fields with a I-band LTAO PSF (provided by Jochen Liske), and finally dispersed the light. To illustrate the results, we present in Fig. 2 a single slice through such a position-velocity cube perpendicular to the rotation axis. For real observations, the optimal position angle of such a long-slit spectrum is not know a priory, but can be determined from IFU observations or alternatively require several slit positions.

8. Description of the proposed programme (continued)

The simulated spectrum in Fig. 2 shows that the proposed project requires very high s/n and Nyquist sampling of the PSF. A more rigorous simulation should include a realistic galaxy spectrum and noise estimate. Such a simulated spectrum could then be used with existing programs to estimate the BH mass.

D) Observing Mode Justification (visitor or service): Would like to visit the ELT.

E) Strategy for Data Reduction and Analysis:

8. Attachments (Figures)

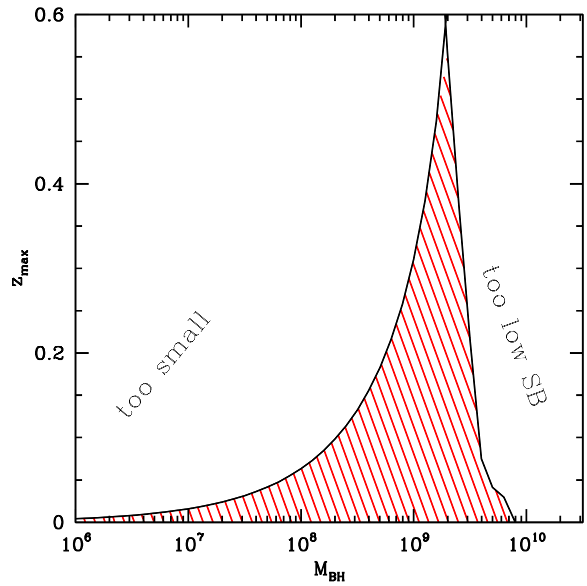

Fig. 1: Maximum observable distance of black holes.

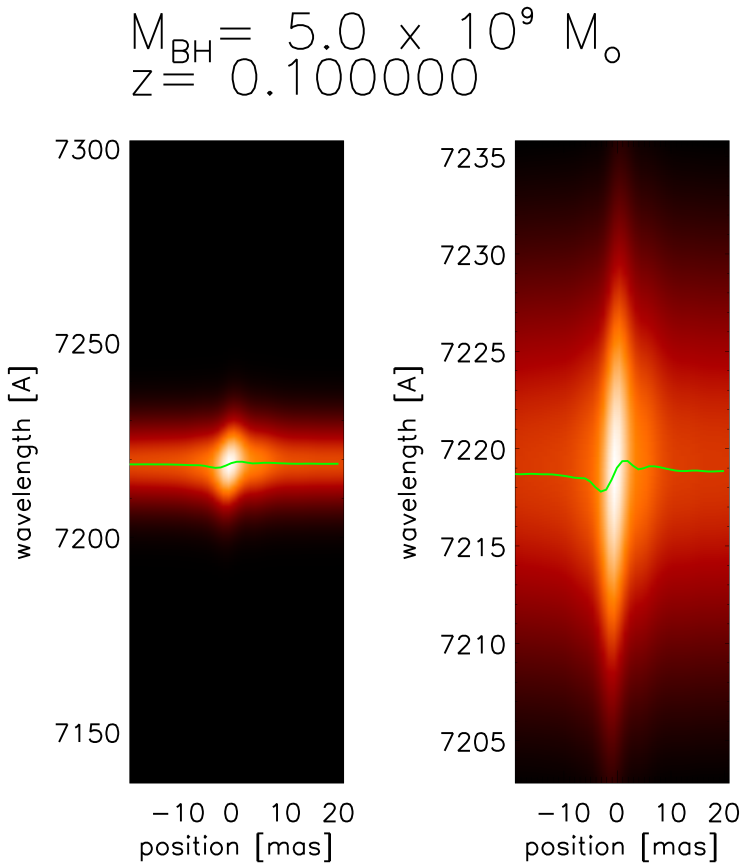

Fig. 2: Simulation of the imprint of a BH on one spectral line at z=0.1. Both panels show the same spectral line at a different wavelength scale. The green line is the center of mass of the spectral line determined for different position along a slit.

9. Justification of requested observing time and lunar phase

Lunar Phase Justification: Grey time would probably be acceptable.

Time Justification: (including seeing overhead) We estimated the exposure times using the ELT ETC, assuming a necessary S/N of 30 **per 5 mas pixel** and a spectral resolution of 5000. We believe such a high s/n will be necessary to accurately determine the center of the broad spectral line as a function of position (see Fig. 2.). In box 15, we list for each target the exposure time for a single spectrum. This corresponds to the time requirement with an IFU. The total exposure time for the hi-z sample is about 200h. For the low-z sample, the actual exposure time for each target is small, the total for the full sample is about 3h. If a longslit spectrograph is used instead the required observing time would triple assuming three position angles on each target.

Calibration Request: Standard Calibration

10. Report on the use of ESO facilities during the last 2 years

11. Applicant's publications related to the subject of this application during the last 2 years

12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	J03081586-234128	030815	-234129	1.0		76	z=0.07	
A	J09481931+00471	094819	+004717	4.4		49	z=0.21	
A	J112604.67-00280	112604	-002809	4.6		35	z=0.34	
A	J122927.38+00584	122927	+005849	5.9		41	z=0.26	
A	J154647.81-00321	154647	-003219	5.7		42	z=0.25	
A	J01415759-01062	014157	-010626	2.5		61	z=0.16	
A	J02114830+00164	021148	+001640	4.1		36	z=0.30	
A	J01035416+14481	010354	+144814	5.1		46	z=0.23	
A	J040316.96-05162	040316	-051622	9.8		37	z=0.30	
A	J091254.53-00092	091254	-000926	5.2		37	z=0.30	
A	J10383663+01174	103836	+011749	2.3		73	z=0.13	
A	J11463450+02214	114634	+022147	4.4		50	z=0.19	
A	J121430.79+01221	121430	+012212	4.2		52	z=0.19	
A	J13315353+03175	133153	+031750	2.9		56	z=0.18	
A	J08533336+02433	085333	+024334	4.7		41	z=0.27	
A	J10494034+05030	104940	+050306	4.8		34	z=0.31	
A	J15322891+02391	153228	+023916	3.1		73	z=0.13	
A	J23233141-10255	232331	-102551	4.6		37	z=0.29	
A	J002750.60-10052	002750	-100524	7.1		30	z=0.40	
A	J002627.47-09260	002627	-092602	7.2		36	z=0.32	
A	J00413973-10544	004139	-105449	5.4		36	z=0.32	
A	J004450.76-09415	004450	-094158	6.1		30	z=0.39	
A	J210656.09+09373	210656	+093734	5.3		35	z=0.34	
A	J13012184+05201	130121	+052016	5.6		46	z=0.23	
A	J13281513+05521	132815	+055210	8.7		35	z=0.32	
A	J134613.21-02160	134613	-021600	5.7		34	z=0.33	
A	J21000912-00324	210009	-003249	5.7		42	z=0.25	
A	J09183893+05280	091838	+052803	2.4		55	z=0.18	
A	J100548.18+06424	100548	+064241	3.2		45	z=0.23	
A	J10421721+07153	104217	+071539	4.8		36	z=0.30	
A	J12022628+10334	120226	+103344	4.2		46	z=0.23	
A	J095327.04+10493	095327	+104933	6.4		37	z=0.31	
A	J10000065+09204	100000	+092044	5.7		35	z=0.32	
A	J112712.60+11563	112712	+115637	7.4		40	z=0.26	
A	J131746.33+12453	131746	+124536	9.1		31	z=0.40	

Following targets moved at the end of the document ...

Target Notes: 1. Run A is for the high-mass BHs, run B for the low-mass BHs. 2. The given diameter the expected one for the sphere of influence in mas.

12b. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If yes, explain why the need for new data.

13. Scheduling requirements

14. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
79	FORS2	A	SPEC	R

15. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
	...continuing from box 3							
A	J13313548+12503	133135	+125032	4.0		43	z=0.25	
A	J155209.36+07475	155209	+074751	4.9		35	z=0.32	
A	J093904.29+11130	093904	+111306	6.1		32	z=0.38	
A	J093653.30+10395	093653	+103958	9.6		33	z=0.36	
A	J09343336+10431	093433	+104312	0.7		77	z=0.12	
A	J100446.38+12200	100446	+122003	3.6		38	z=0.27	
A	J08083058+07201	080830	+072011	0.6		91	z=0.10	
A	J121859.87+14251	121859	+142516	4.6		41	z=0.27	
B	NGC0516	01 24 08.2	+09 33 05	0.1		12	z= 2456 km/s	
B	ESO545G040	02 38 11.3	-20 10 01	0.1		48	z= 1474 km/s	
B	IC1919	03 26 02.0	-32 53 45	0.1		19	z= 1327 km/s	
B	ESO358G006	03 27 17.6	-34 31 37	0.1		23	z= 1254 km/s	
B	ESO548G033	03 32 28.6	-18 56 53	0.1		43	z= 1652 km/s	
B	NGC1373	03 34 59.1	-35 10 15	0.1		35	z= 1383 km/s	
B	NGC1369	03 36 45.0	-36 15 22	0.1		31	z= 1414 km/s	
B	NGC1390	03 37 52.0	-19 00 32	0.1		20	z= 1211 km/s	
B	MCG-06-09-023	03 42 45.5	-33 55 13	0.1		25	z= 1268 km/s	
B	ESO358G059	03 45 03.5	-35 58 22	0.1		32	z= 1042 km/s	
B	ESO250G005	04 04 35.1	-46 02 35	0.1		34	z= 1230 km/s	
B	NGC2328	07 02 35.8	-42 04 07	0.1		25	z= 1187 km/s	
B	UGC05467	10 08 12.8	+18 42 25	0.1		24	z= 2883 km/s	
B	NGC3457	10 54 48.5	+17 37 13	0.1		59	z= 1161 km/s	
B	ESO440G038	12 01 42.5	-31 42 12	0.1		21	z= 2320 km/s	
B	NGC4415	12 26 40.5	+08 26 09	0.1		34	z= 933 km/s	
B	NGC4467	12 29 30.4	+07 59 38	0.1		33	z= 1423 km/s	
B	NGC4587	12 38 35.5	+02 39 25	0.1		49	z= 913 km/s	
B	NGC4612	12 41 32.6	+07 18 52	0.1		28	z= 1781 km/s	
B	NGC4733	12 51 06.9	+10 54 45	0.1		50	z= 929 km/s	
B	NGC5206	13 33 43.9	-48 09 08	0.1		42	z= 555 km/s	
B	NGC5666	14 33 09.3	+10 30 38	0.1		32	z= 2224 km/s	
B	IC4653	17 27 07.1	-60 52 50	0.1		23	z= 1551 km/s	
B	ESO286G050	21 06 41.0	-42 33 26	0.1		20	z= 2672 km/s	
B	NGC7077	21 29 59.6	+02 24 50	0.1		39	z= 1166 km/s	
B	ESO466G046	22 02 44.1	-31 59 26	0.1		22	z= 2326 km/s	
B	NGC7351	22 41 26.8	-04 26 40	0.1		45	z= 890 km/s	
B	IC5267B	22 56 57.1	-43 45 35	0.1		15	z= 1758 km/s	