# Future research directions of VLTI for the Galactic Center and Active Galactic Nuclei

Final report of the "AGN and the Galactic Center Working Group" of the European Interferometry Initiative

The "AGN and the Galactic Center Working Group" within the European Interferometry Initiative has the following composition: Vitor Cardoso, Mark Casali, Ric Davies, Francoise Delplancke, Moshe Elitzur, Frank Eisenhauer, Laura Ferrarese, Paulo Garcia, Stefan Gillessen (deputy chair), Roberto Gilmozzi, Alessandro Marconi (chair), Bruno Lopez, Roberto Maiolino, Klaus Meisenheimer, Thibaut Paumard.

The activities of the working group were finalized during a workshop held in Lisbon (Portugal) on November 28-30, 2011.

The schedule of the final workshop and the PDF files of the presentations are available at the dedicated web page. (The schedule with links to PDF files is also available in the appendix.) The workshop was divided in three parts, the first the on scientific background and recent results, the second on present and future VLT and VLTI Instruments with focus on the science goals, and the third on the synergies with future large facilities like E-ELT, ALMA and submm-VLBI, JWST.

The scientific background on Active Galactic Nuclei was presented by Laura Ferrarese (Supermassive Black Holes and Broad Line Region) and Moshe Elitzur (Dusty torus and the Unified Model) while Franck Eisenhauer presented that on the Galactic Center. The science background was completed by a résumé on the main observational results from optical interferometry by Klaus Meisenheimer and from Adaptive Optics observations by Ric Davies.

The science goals of PRIMA, GRAVITY and MATISSE were presented by Francoise Delplancke, Thibaut Paumard and Bruno Lopez, respectively.

For the synergies with future facilities, Roberto Gilmozzi presented the E-ELT project, Roberto Maiolino presented ALMA and JWST, and Heino Falcke presented the submm VLBI.

## The Galactic Center

The Galactic Center (GC) is a scientifically extremely fruitful, astrophysical laboratory. It allows observing a massive black hole (MBH) in unprecedented detail. The stellar cluster around is resolved allowing for astonishing measurements. Gas is observed on all scales in the GC, down to the event horizon scale. A recent comprehensive overview of Galactic Center science is given Genzel et al. (2010, RvMP, 82, 3121). Key results in the last years have been:

- The outstanding, main result is the proof of existence of an astrophysical MBH, beyond any reasonable doubt. Sgr A* is the MBH in the Milky Way.
- Sgr A* was discovered in X-rays and in the infrared as a flaring source.
- The mass of the MBH has a statistical uncertainty of just 1.5.
- The size of Sgr A* was determined with mm-VLBI, yielding an intrinsic size of just 4 times the size of the event horizon.
- The distance $R_0$ to the GC was determined geometrically to an accuracy of 3%.

- More than 30 stellar orbits around Sgr A* are known.
- There are at least two populations of young stars in the GC - both of which came as a surprise. Firstly, there are the so-called 'S-stars' in the central arcsecond - spectroscopically they are B dwarfs, and they revolve around Sgr A* on randomly oriented orbits with high eccentricities. Second, most of the brighter O/WR-stars at $r > 1''$ orbit Sgr A* in a disk with low eccentricities. These stars formed probably in-situ from a massive, infalling cloud ≈ 6 Myr ago.
- Most recently, a gas cloud falling on a very elliptical orbit towards Sgr A* is getting a lot of attention, since in summer 2013 it will reach pericenter with a distance of a few thousand Schwarzschild radii only.

The basis of these discoveries are high-angular resolution techniques, in the near-infrared this is mainly the availability of adaptive optics at the 8m-class telescopes. Hence, one can expect that using the VLTI with its even higher resolution will yield many exciting measurements in the GC. While for the current VLTI sensitivity the sources are faint (mK = 15 typically), they are not for future instruments that provide robust fringe-tracking. The following potential future observations are ordered roughly according to distance from Sgr A*, going from outer scales inwards:

- The astrometric reference frame in the GC is defined by the observations of SiO maser sources. The VLTI has the potential to significantly improve here in two ways:
  - Currently the infrared positions of the SiO masers are measured from a large-scale image and thus subject to image distortions, which cannot be corrected perfectly. The VLTI will allow measuring the distances between these NIR-bright stars much more accurately, thus allowing to improve the coordinate system. That in turn improves the overall precision of stellar orbit fits, since the position of the radio-source Sgr A* can be used as a prior.
  - The VLTI has the potential to check, whether the SiO emission occurs exactly at the NIR photocenter position, i.e. it is might offer a way to check the basic assumption for the coordinate system definition.
- The disk of stars is defined mostly in a statistical sense. For only eight of the stars the explicit orbits are known. The limitation is the measurement of the spatial acceleration, which further out gets more and more challenging. Improved astrometry will thus allow pushing out the regime over which orbits can be determined far into the stellar disk.
- Binarity of GC stars is a key in many dynamical processes explaining the presence of the young stars, yet there is only one star for which binarity has been reported in the literature (Martins et al. 2006, ApJ, 649, L103). More precise astrometry will allow searching for the photocenter wobble of binaries, ultimately leading to a radial distribution of the binary fraction.
- The increased resolution with the VLTI will help overcome the current crowding-limited observations of the central arcsecond. Thus, more stars on short-period orbits will be discovered, improving the robustness of the mass measurement and the distance estimates further.
- Stars on even short period orbits (down to 1 year) are expected to be detectable with VLTI. That offers very unique chances of measuring relativistic effects, such as Schwarzschild precession, Lense-Thirring precession or even the quadrupole

moment of the metric around the MBH. This opportunity has caught the attention of theorists already (Will 2008, ApJ, 674, L25).

- The smallest scales accessible with VLTI surprisingly match the event horizon scale of Sgr A*: 10µas. Flares of Sgr A* are known to be compact emission regions very close to the event horizon. They thus might constitute test particles in the extreme vicinity of the MBH. With VLTI one will not be able to resolve that, but the astrometric accuracy might be good enough to follow the photocenter motion of flares. Not only a spin measurement would come from that, but one might hope to detect strong relativistic effects such as lensing.

## Active Galactic Nuclei

Active Galactic Nuclei (AGN) are highly luminous (up to $L \sim 10^{15}\ L_\odot$), very compact sources (at less than sub-pc scales) powered by accretion onto supermassive black holes (BH; $M_{BH} \sim 10^6 - 10^{10}\ M_\odot$). One of the most striking achievements in the last decade has been the realization that AGN are key actors in the formation and evolution of galaxies. This important fact is based on several seminal discoveries:

- the detection of supermassive black holes in the nuclei of nearby galaxies;
- the discovery that BH masses are strictly correlated with the structural parameters of the host spheroids (galaxies in the case of ellipticals);
- the realization that local BH were grown through efficient accretion during bright AGN phases.

In order to be established, $M_{BH}$-host galaxy correlations require a physical mechanism linking the pc-scale region surrounding the BH with the kpc-scale galaxy. The feedback from the actively accreting BH, i.e. the AGN, is believed to be such mechanism which also allows to explain the apparently anti-hierarchical growth of galaxies and supermassive black holes, the low fraction of baryons condensed into stars and the low number density of massive galaxies observed. The resulting coevolution of supermassive black holes and their host galaxies is currently a key ingredient for understanding galaxy evolution.

Our current picture of an AGN is provided by the so-called Unified Model according to which the differences between the several observed classes of AGN can be ascribed to different orientation of the line of sight. The supermassive BH is surrounded by an accretion disk, which is responsible for the emission of UV radiation, and by a hot corona, which emits X-rays. These two components are very compact, on scales smaller than a light-day. At larger distances, from a few light-days to several light-months, there are dense gas clouds responsible for the emission of Broad Lines: these are permitted recombination lines with very large widths (Full Width at Half Maxima, FWHM, of ~ 1000 − 10000 km/s). Accretion disk and Broad Line Region (BLR) are surrounded by a thick dusty torus, whose symmetry plane is that of the accretion disk and which is extended at pc-scales, depending on luminosity. The inner edge of the torus is conventionally identified with the dust sublimation radius, which scales as $\sim L^{0.5}$. The torus allows the escape of ionizing photons only in a conical region whose axis is perpendicular to the accretion disk. Strong narrow (FWHM< 1000 km/s) emission lines are emitted from this conical region which extends from 100pc to kpc scales within the host galaxy and which is dubbed Narrow Line Region (NLR). Whether the line of sight intercepts the dusty torus or not determines the different AGN classes as it establishes whether the accretion disk and BLR are directly observed. Clearly, to fully understand the physics of AGN one must observe at sub- pc scales and this is not possible with conventional telescopes but only with interferometers with baselines of the order of ~100m. Optical interferometry with VLTI and Keck has provided important results in the last ~10 years:

- Dusty tori have been spatially resolved in the mid-infrared (MIR) with MIDI@VLTI and with AMBER@VLTI and Keck-I in the NIR;
- MIDI has allowed to study the dust distribution in nearby Seyfert galaxies with 15 ms (~pc) resolution revealing the presence of dusty disks and possibly clumpy media;
- Keck-I and AMBER have so far only allowed to estimate the size of the inner torus edge (dust sublimation radius), demonstrating that this size scale as $\sim L^{0.5}$ i.e. the expected dependence of dust sublimation radius from luminosity;
- Lacking imaging capabilities, detailed dust radiative transfer models have been used to interpret interferometric observations of dusty tori but with the common degeneracies typical of this kind of approaches;
- The BLR has been tentatively resolved with AMBER@VLTI through differential phase measurements, but only using very short exposures since observations are severely hindered by vibrations.

With the second generation of VLTI instruments, and future long-baseline interferometers it will be possible to tackle the following scientific goals.

The imaging capabilities allowed by observations with 4 telescopes (GRAVITY, MATISSE) and the fainter limiting magnitudes reachable will allow to go beyond visibility fitting of the data and will provide much larger samples of fainter objects than currently available.

From the small to the larger scales:

- Although it will still not be possible to spatially resolve the BLR, differential phase measurements (e.g. with GRAVITY) will allow to study the spatial variation of the emission line centroid as a function of wavelength; this information will constraint geometry and kinematics of the BLR and will allow BH mass measurements; such measurements are fundamental to calibrate the virial method which uses Broad Emission Lines to estimate BH masses and which currently is the only way to estimate BH masses at all redshifts.
- It will be possible to definitely establish the nature of the obscuring torus: is it a diffuse or clumpy medium? Is it part of the accretion flow or a different structure? Is it a puffed up part of an extended accretion disk, or is it caused by a warp of that disk?
- It will be possible to disentangle emission from dusty tori and circum-nuclear star forming regions in NIR and MIR, and thus to study the direct connection between circum-nuclear star formation and nuclear activity which is at the base of the co-evolutionary picture.

## Recommendations

This wealth of scientific questions, which the VLTI can address is mirrored in the design of the 2nd generations instrument GRAVITY, which is optimized for the GC, and MATISSE. One key element for successful AGN and GC observations with the VLTI is the infrastructure at Paranal. There are a number of technical hurdles for the infrastructure, which might put the proposed observations at risk. The following list is thus also a list of recommendations, which aspects should be worked on.

- Vibrations of the telescopes modulate the optical path lengths at a frequency, which might seriously harm the fringe-tracking loops. It is not easy to define the maximum tolerable vibration level, but rms values of around 250nm are considered to be the limit.
- The current operational model of the VLTI might not be optimal for the future generation of instruments, since probably there will be a limit of atmospheric conditions below which VLTI observations are not feasible at all anymore - and thus visitor mode is not optimal, and service-mode, block-scheduled VLTI runs are neither. Instead a VLTI visitor mode with over-riding priority should be implemented to guarantee the best observing conditions for this most precious observing mode utilizing 4 telescopes at a time.
- The high density of stars makes the use of adaptive optics at the telescopes mandatory for GC observations with the VLTI. While new wavefront sensors will be deployed with GRAVITY, the deformable mirrors will be reused, and thus their aging might be a concern.
- Polarization is a critical issue for interferometry, and a model of the polarization characteristics of the full VLTI train is needed in order to reach highly accurate astrometry.
- Crucial to astrometry is the knowledge of the interferometer baselines. These will need to be calibrated to a sufficient degree of accuracy, and sufficient telescope time should be allocated to the baseline calibration.

## Appendix. Workshop Schedule and Links to Presentations

**November 28**

14:00 Opening Remarks ***Paulo Garcia***

14:15 Talk (40+15) "Supermassive black holes & the broad line region in AGN" ***Laura Ferrarese***

15:10 Talk (40+15) "The dusty torus and the AGN unified model" ***Moshe Elitzur***

16:05 Coffee break

16:40 Talk (40+15) "Science from VLT (AO observations)" ***Ric Davies***

17:35 Talk (40+15) "Highlights from Optical Interferometry (recent AGN/GC VLT-I & Keck-I science)" ***Klaus Meisenheimer***

18:30 End of day

**November 29**

09:30 Talk (40+15) "The Galactic center" ***Frank Eisenhauer***

10:25 Coffee Break

11:10 Talk (40+15) "PRIMA science" ***Francoise Delplancke***

12:05 Talk (40+15) "GRAVITY science" ***Thibaut Paumard***

13:00 Lunch

15:00 Talk (40+15) "MATISSE science" ***Bruno Lopez***

15:55 Talk (40+15) "Future VLT instruments" ***Mark Casali***

16:50 Coffee break

17:35 Talk (40+15) "E-ELT" ***Roberto Gilmozzi***

18:30 End of day

**November 30**

09:30 Talk (40+15) "ALMA" ***Roberto Maiolino***

10:25 Talk (40+15) "JWST" ***Roberto Maiolino***

11:20 Coffee Break

12:05 Talk (40+15) "Submm VLBI" Part-I and Part II ***Heino Falcke***

13:00 Discussion and concluding remarks ***Alessandro Marconi & Stefan Gillessen***

13:30 End of workshop