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The Core of the Matter — Spatially Resolving Active Galactic Nuclei with GRAVITY

GRAVITY Collaboration

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Thanks to the superb sensitivity and resolution of GRAVITY, ESO's near-infrared beam combiner for the Very Large Telescope Interferometer, our Large Programme study of the inner regions of active galactic nuclei (AGN) has delivered several recent break-throughs. We have spatially resolved the broad line region (BLR) for three nearby AGN, supporting the rotating disc model, directly measuring the masses of their supermassive black holes (SMBHs), and testing the BLR radius-luminosity (*R*-*L*) scaling relation. We have measured the hot dust sizes for eight AGN and fully imaged the hot dust structure for two AGN. Our dust sizes also test the hot dust *R*-*L* scaling relation, revealing the first evidence for luminosity-dependent deviations from the expected relation. The novel GRAVITY data provide unique insight into the physics around SMBHs. In addition, they test the basic assumptions behind mass measurements based on the *R*-*L* scaling relation and reverberation mapping, which is currently the only method for measuring black hole masses in large surveys and out to high redshift. Our observations provide an entirely new, independent method for measuring SMBH masses. With GRAVITY+, we will be able to vastly expand to both larger samples and higher redshifts with the ultimate goal of tracing black hole growth and galaxy coevolution through cosmic time.

The circumnuclear environment of AGNs

Since their discovery in the 1960s astronomers have wanted to know what exactly goes on in the nuclei of quasars (or more generally in active galactic nuclei [AGN]). It became clear early on that AGN come in many different flavours, constituting a veritable zoo of AGN phenomenology. For instance, Type 1 AGN show very broad emission lines in their spectra (with widths of several 1000 km s^{-1}), while Type 2 AGN have only narrow emission lines. Studies in the late 1980s and early 1990s (for example, Antonucci & Miller, 1985) suggested that the different AGN flavours were not due to fundamental intrinsic differences or to evolution, but that perhaps many AGN are the same except for orientation effects. For example, Type 2 AGN often show broad emission components in polarised light, i.e., in light scattered from clouds further out. In Type 2 AGNs the direct view of the broad-line region (BLR) would then be blocked by some dusty structure (often referred to for historical reasons as "the torus").

Obscuring dust and a broad-line emitting region are thus two fundamental ingredients of most contemporary AGN models. If we attribute the enormous widths of broad emission lines to the Doppler motion of gas clouds, then motion in the deep gravitational potential of the central SMBH is the likely explanation. The high velocities and the fact that the BLR is unresolved in high-resolution images and varies rapidly in brightness all suggest that the BLR must be very close to the SMBH. But despite their importance as a hallmark feature of AGN, and although BLRs have been studied for almost 60 years, many basic properties like structure, kinematics and inclination remain elusive. In some models the BLR arises as continuous, outflowing gas distribution in an accretion-disc wind. Other models employ large numbers of small gas clouds, for instance in a spherical or disc-like distribution. The BLR clouds might originate in torus clumps that col-

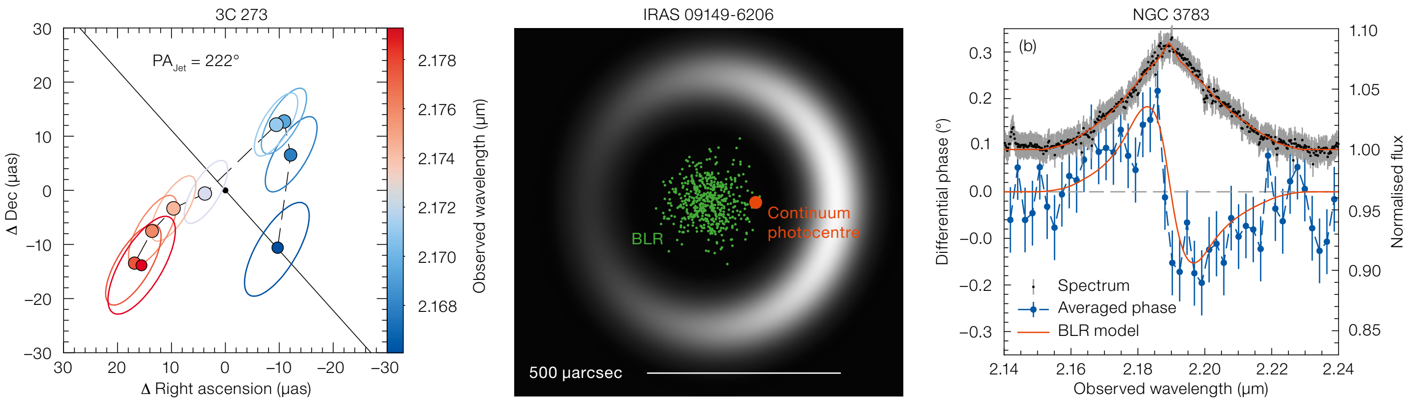

Figure 1. Left: Observed velocity-resolved photocentres for 3C 273 indicating a kinematic axis nearly perpendicular to the radio jet axis (black line) (GRAVITY Collaboration et al., 2018). Middle: Cartoon illustrating a possible cause of the observed offset between the near-infrared continuum photocentre and the BLR for IRAS 09149-6206 (GRAVITY Collaboration et al. 2020c). Right: Observed BLR differential phase signal (a signature of the photocentre distribution) for NGC 3783 (blue points) together with the best-fit model (red lines) and emission line flux profile (black points) (GRAVITY Collaboration et al., 2021a).

lide, get scattered inside the sublimation radius and are then disrupted. Or, perhaps, is the BLR just the puffed-up inner edge of the torus (see, for example, Baskin & Laor, 2018; Wang et al., 2017)?

Measuring SMBH masses

This lack of understanding of the true nature of these components is, to say the least, very unfortunate. Accurate knowledge of the size, distribution and kinematic properties of the BLR gas would not only constrain the transport mechanism of material onto the accretion disc and into the jet or the onset of outflows, but also provide more precise black hole mass measurements.

To date, studies of the BLR structure have relied mostly on reverberation mapping (RM). The reverberation technique uses the time variability observed in the AGN continuum emission (from the accretion disc) and the subsequent response of the gas in the BLR. The time delay between continuum and BLR gas emission translates directly into a radius for the BLR. The width of the BLR lines, assuming the BLR consists of clouds moving in the gravitational potential of the SMBH, provides the velocity of these clouds. Black hole masses can then be inferred from these two observations via the virial theorem. Importantly, RM programmes established a size-luminosity (*R*-*L*) relation ($R_{BLR} \sim L^{\alpha}$; for example, Dalla Bontà et al., 2020; Kaspi et al., 2000), that allows black hole mass estimates even from a single AGN spectrum (and a measurement of the AGN luminosity). This is the only available method for measuring black hole masses in large surveys and out to high redshift and plays a key role in our understanding of black hole growth over cosmic time.

However, the method has well-known limitations: the inclination and the detailed velocity field of the BLR are very hard to extract from RM data. Moreover, recent investigations of the *R*-*L* relationship suggest that a third parameter must be taken into account, the Eddington ratio (i.e., the SMBH accretion rate relative to the theoretical maximum for a given black hole mass). Application to AGN at higher redshift requires the assumption that the locally calibrated *R*-*L* relation still holds at high redshift. The general approach taken towards these uncertainties has been, in the absence of other data, to absorb them into the black hole mass uncertainties. Typically, it is assumed that AGN follow the same M_{BH}–σ relation as quiescent galaxies, and this provides a calibration of the AGN black hole mass scale.

Obviously, better knowledge of the BLR size, kinematics, and orientation, from direct constraints bypassing the *R*-*L* and M_{BH}-σ relations, is crucial for improving our understanding of all AGN black hole masses and their uncertainties. In turn, this would advance our understanding of the evolution of black holes over cosmic time. This is a primary goal of the GRAVITY AGN programme.

The GRAVITY AGN Large Programme

GRAVITY, the near-infrared beam combiner for the Very Large Telescope Interferometer (VLTI), provides images with 3-milliarcsecond angular resolution as well as 10-microarcsecond astrometric accuracy in the range 1.98 to 2.40 μm. Spectro-astrometry (SA) with GRAVITY provides a new, direct probe of the BLR spatial and velocity structure which can independently test and break degeneracies in RM studies. This technique measures the flux-weighted spatial offset from the continuum of each velocity channel across an emission line (Figure 1, left). In interferometry such spatial offsets result in phase differences in the fringe pattern, which can be measured very precisely. In this way, precise phase measurements from interferometric SA provide spatial information on scales much smaller than the interferometric beam. Combining the six independent VLTI baselines, we can then kinematically model the velocity structure of the BLR (Figure 1, right) and measure both the BLR radius and, ultimately, the SMBH mass.

We achieved the first demonstration of the power of SA in this context in 2018, by spatially resolving a velocity gradient across the BLR of the quasar 3C 273 (z = 0.158, Figure 2, GRAVITY Collaboration et al., 2018). The gradient revealed rotation perpendicular to the jet, and is

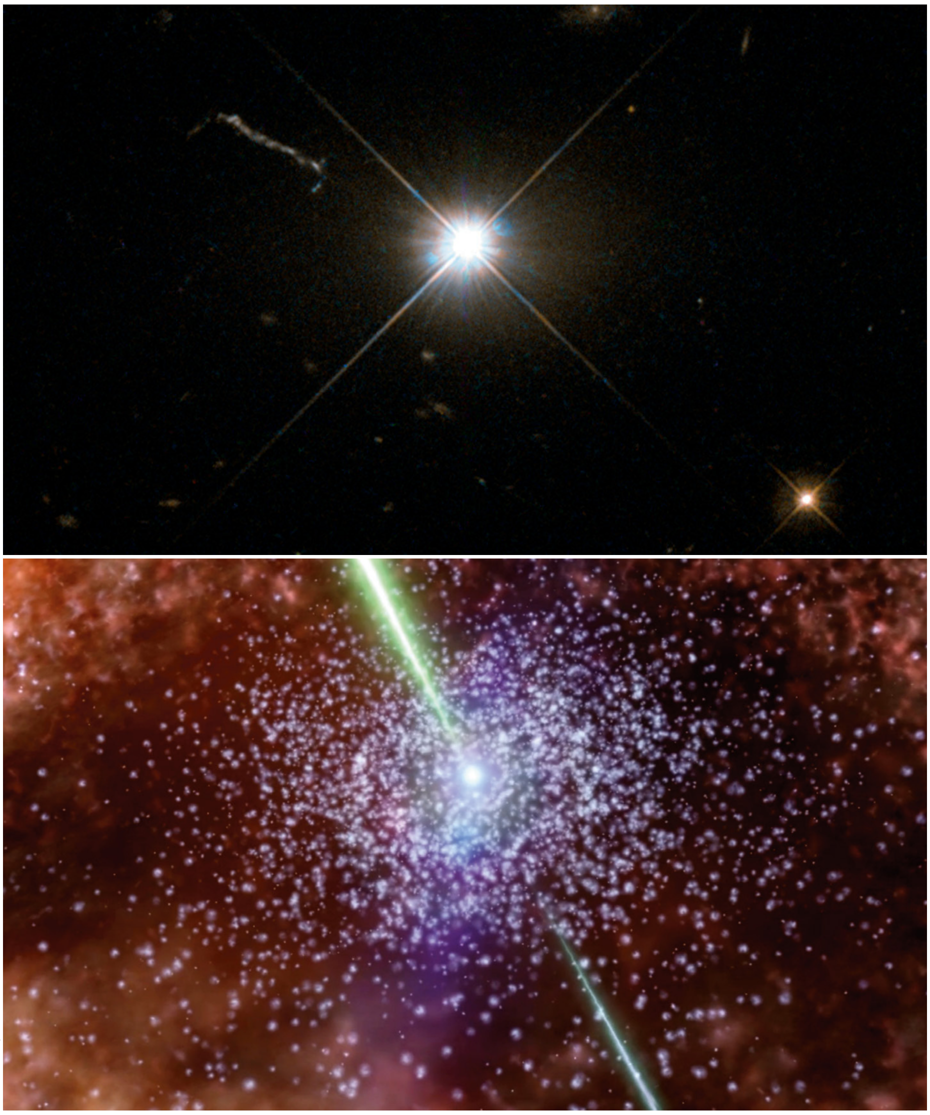

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Figure 2. Top: Hubble Space Telescope image of the quasar 3C 273. Bottom: Zooming in, we are now able to spatially resolve the BLR, where gas clouds whirl around the central black hole and a jet of material is ejected at high speeds from the black hole's poles (artist's impression).

consistent with line emission from a thick disc of gravitationally bound material around a black hole of 3×10^8 solar masses. We measured a disc radius of 150 light-days confirming the size of 130–200 light-days derived from RM.

Following up on this exciting result (resolving a structure of the size of ~ 0.15 pc at a distance of 550 Mpc!) we have been granted by ESO an open-time Large Programme (17 nights over 4 semesters, starting in April 2019) to observe with VLTI/GRAVITY 11 nearby AGN that span four orders of magnitude in luminosity. GRAVITY's exquisite performance opened the door to resolving the innermost regions of the brightest AGN: the BLR and surrounding hot dust. Through our Large Programme we address three key questions: How reliable are RM-based BLR sizes and black hole masses? Are BLR kinematics always dominated by ordered rotation? What are the size and shape of the obscuring structure? We further aim to establish a new, GRAVITY-based *R-L* relation to form the basis for more robust black hole mass measurements in large samples in both the local and distant Universe.

Resolving the broad-line region

The Large Programme has already yielded two further published spectro-astrometric BLR measurements, for IRAS 09149–6206 and NGC 3783. Our study of IRAS 09149–6206, a Type 1 AGN at $z = 0.0573$, led to a much-improved phase calibration method that reduced the instrumental uncertainty of the differential phase to better than 0.05 deg per spectral channel in each baseline[a]. Armed with the improved data reduction, we significantly detected the BLR differential phase signal across the hydrogen Br-γ line. Surprisingly, the signal primarily represented a systematic offset of ~ 120 microarcseconds (0.14 pc) between the BLR and the centroid of the hot dust distribution traced by the 2.3-μm continuum. This offset is well within the dust sublimation region, which matches the measured ~ 300-microarcsecond (0.35 pc) diameter of the continuum and can be explained by an asymmetric hot dust continuum such that the photocentre of the continuum is shifted towards the brightest side of the dust structure (see middle panel of Figure 1). Including this effect in our BLR model, we then measured a BLR size of 65 microarcseconds (0.075 pc) and SMBH mass of 1×10^8 solar masses (Gravity Collaboration et al., 2020c).

In NGC 3783, a galaxy only ~ 40 Mpc away that hosts a bright Type 1 AGN, we again detected the BLR differential phase signal (see right panel of Figure 1). The systematic offset to the continuum is smaller than for IRAS 09149–6206, thus enhancing the rotational signature. For this AGN, we measure a BLR size of 71 microarcseconds (0.013 pc) and SMBH mass of 5×10^7 solar masses. In this case, the physical BLR size is almost a factor of two larger than the one measured by RM, and is consistent with a radial distribution of clouds that peaks in the inner regions but is significantly extended to large radii. This brings to light a discrepancy between RM measurements — which are variability-weighted and thus biased towards the inner regions — and interferometric measurements — which are flux-weighted and more sensitive to outer radii (GRAVITY Collaboration et al., 2021a).

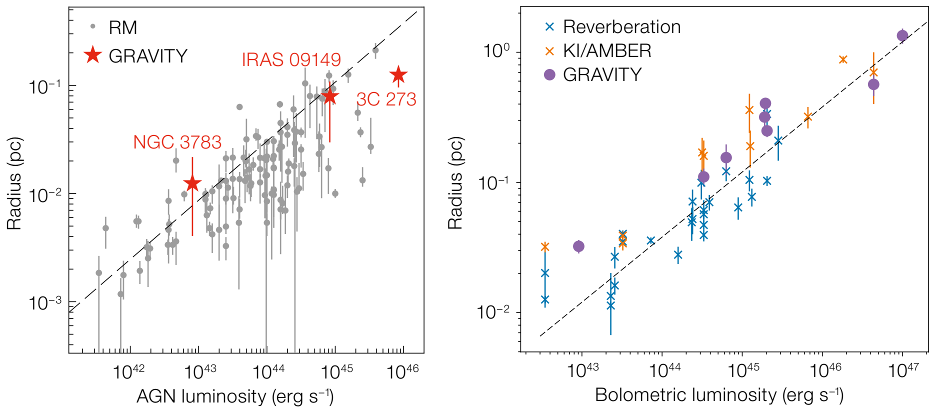

Figure 3. Left: BLR *R-L* relation with our new GRAVITY measurements (red) plotted with RM data points (grey points) and RM relation (black dashed line) (GRAVITY Collaboration et al., 2021a). Right: Hot dust *R-L* relation with our new GRAVITY measurements. Our interferometric hot dust sizes match previous Keck interferometer sizes. They seem to follow a flatter relationship than $R \propto L^{0.5}$ (which would be the expected relationship if hot dust radiation peaks near the dust sublimation radius) (GRAVITY Collaboration et al., 2020b).

With these published BLR size measurements, we have begun constructing our own GRAVITY-based *R-L* relation. The left panel of Figure 3 shows as red stars the locations of our measurements compared to the RM-based measurements and relation (grey points with black dashed line). We begin to see the recently observed deviation towards smaller size in high-luminosity AGN that may be partly due to the high accretion rate (GRAVITY collaboration et al., 2021a). From the Large Programme we have BLR data for another four AGN that are under analysis and will be used to expand our GRAVITY-based BLR *R-L* relation.

Imaging and sizing-up the innermost hot dust

Another long-standing issue of AGN models is the size and structure of the obscuring, dusty region: is it a torus or a disc, clumpy or not, inflowing or outflowing? The near- and mid-infrared luminosity associated with AGN originates in dust surrounding the AGN and heated by it. However, like the BLR, the innermost circumnuclear dust emission cannot be resolved in single-dish images. In the past decade infrared interferometry has begun to shed light on the physical structure of this component. Tens of AGN have been observed in the mid-infrared with the MID-infrared interferometric Instrument (MIDI) at the VLTI. Detailed results from Circinus and NGC 1068 show evidence for an inner disc, but have also revealed dust in the polar regions indicative of outflow (López-Gonzaga et al., 2016). The presence of multiple components could have a severe impact on dust-RM methods that assume a torus origin. The near-infrared is thought to trace hot dust just beyond the sublimation limit at the inner edge of the torus. Measuring the emission size can therefore test the assumptions on which dust-RM methods are based. GRAVITY observations (in the *K* band) provide the first resolved view of the shape and structure of the hot dust emission region whose size and orientation can be compared directly with that of the BLR. With its superior sensitivity compared to previous near-infrared interferometers, GRAVITY also allows for more accurate size measurements for a larger sample of AGN. Consequently, through our Large Programme, we have been able to both image the hot dust structure of individual AGN and measure sizes for the whole sample.

The data set on NGC 1068, the archetypical Type 2 AGN, permitted us for the first time to image and spatially resolve the nuclear hot dust in the sublimation region of an AGN, i.e., the inner edge of the putative torus (GRAVITY Collaboration et al., 2020a). Surprisingly, we found a thin, clumpy, ring-like structure of emission with a radius $r = 0.24$ pc and an inclination $i = 70$ degrees, which we associate with the dust sublimation region (Figure 4 left). The observed morphology is inconsistent with the expected signatures of a geometrically and optically thick torus. Instead, the infrared emission shows a striking resemblance to the 22-GHz maser disc, which suggests they share a common region of origin. The dust structure and photometry are consistent with a simple model of hot dust at $T \sim 1500$ K that is behind $AK \sim 5.5$ mag ($AV \sim 90$ mag) of foreground extinction. This amount of screen extinction could be provided by the dense and turbulent molecular gas distribution observed (for example by ALMA) on scales of 1–10 pc. Radiative transfer modelling of the same dataset was done by Vermot et al. (2021). We note that an alternative interpretation of the geometry is offered by Gámez Rosas et al. (2022), based on a different absolute registration which aligns the 12-µm cool dust continuum of recent MATISSE images with 256-GHz bremsstrahlung from hot ionised gas.

In NGC 3783, the non-zero closure phases allowed us to reconstruct an interferometric image of the dust sublimation region using exactly the same dataset as the one to resolve the BLR. The reconstructed image of the hot dust (see right panel of Figure 4) reveals a faint (5% of the total flux) offset cloud which we interpret as an accreting or outflowing cloud heated by the central AGN.

Even in cases where the hot dust cannot be directly resolved, the interferometric technique allows us to derive at least the size of the emitting region. We now have tantalising results about the size of the hot dust structure in eight AGN, which suggest that the 2.2-µm continuum does not follow the expected size-luminosity relation: continuum reverberation experiments (measuring the time delay between the emission from the accretion disc and the hot dust located at the sublimation radius, i.e., the inner torus rim) find correlated variability between the optical and near-infrared emission with a lag that is consistent with reprocessing. The inferred emission radius scales with luminosity as $R \propto L^{0.5}$, as expected if hot dust

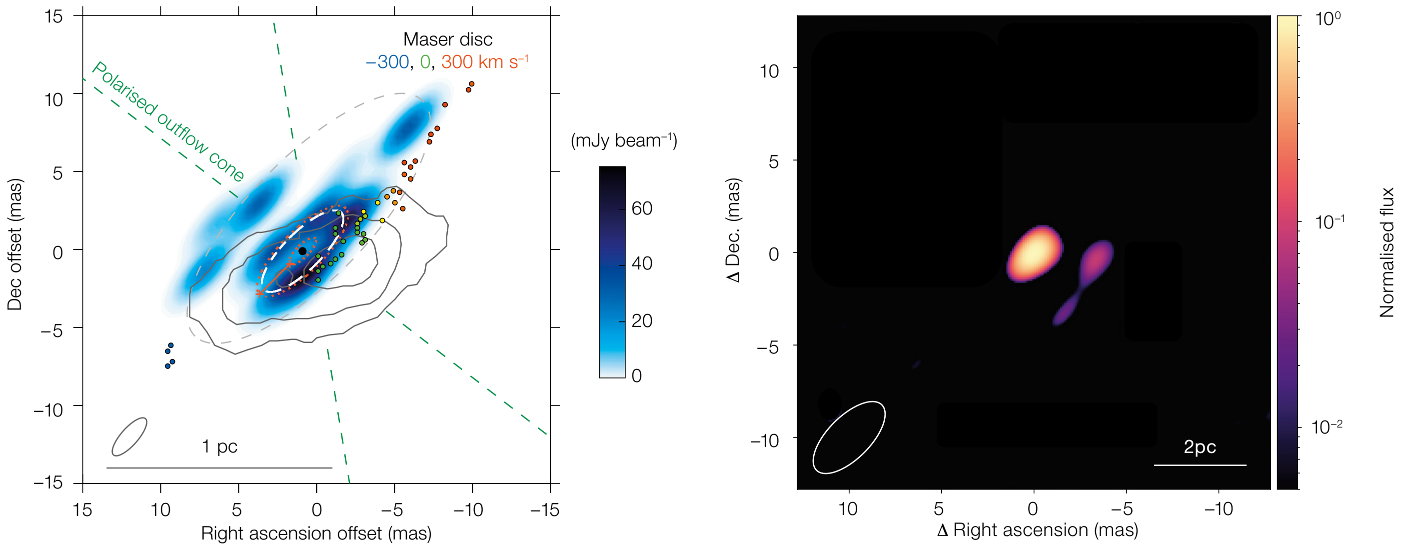

Figure 4. Left: Reconstructed hot dust image of NGC 1068. GRAVITY observes primarily a thin clumpy ring at the expected dust sublimation radius given NGC 1068's AGN luminosity. The bright near side of the ring is cospatial with the megamaser disc, indicating a common origin (GRAVITY Collaboration et al., 2020a). Right: Reconstructed hot dust continuum image of NGC 3783 showcasing the offset cloud 0.6 pc away from the central hot dust at the dust sublimation radius (GRAVITY Collaboration et al., 2021a).

radiation peaks near the dust sublimation radius. The observed normalisation of the relation is smaller than predicted for standard dust composition and grain sizes in the interstellar medium, which may imply the presence of large graphite dust grains near AGN (Kishimoto et al., 2007; GRAVITY collaboration et al., 2020b). Using our robust size measurements, the right panel of Figure 3 shows that the data for the eight AGN yield a rather flatter *R-L* relation ($R \propto L^{0.40}$) at slightly over 2σ significance. There are two important conclusions: (i) the scatter amongst the objects seems to be larger than the measurement uncertainties, potentially indicating real physical differences between objects; and (ii) the sizes derived are larger for lower-luminosity AGN, suggesting a systematic effect in terms of dust emissivity or perhaps related to Eddington ratio, or even an inclination bias at high luminosity. At the same time, new results from RM also show that the relation is flatter than previously thought (at about 2σ significance). We have recently been awarded more time on GRAVITY to measure the dust sizes for a further 16 AGN which we will use to fill out our dust *R-L* relation. All of these data will allow us to explore possible scenarios for the underlying physical cause of the flattening using state-of-the-art models of dust structures around AGN.

Combined SA and RM and geometric distances

The previous sections illustrate the complementarity of the two techniques — SA and RM — and how SA can be used to test the assumptions of RM. We have now also developed the methods necessary for a combined SA+RM analysis of the BLR structure. The joint analysis provides new opportunities to study the BLR structure, with improved accuracy, in particular of black hole masses. It is also a promising new and direct method by which to measure the geometric distance to AGN. The distances to even nearby AGN are remarkably uncertain: the measured redshift is strongly affected by peculiar motions, but other methods often do not agree. Therefore, distance becomes the dominant source of error in estimating properties such as size, luminosity, and mass. By combining the angular size from SA with the linear size from RM, geometric distances can be derived directly via simple trigonometry. The SA+RM method provides as good a distance measurement for NGC 3783 as other more standard methods such as the Tully-Fisher relation (GRAVITY Collaboration et al., 2021b).

GRAVITY+: the evolution of supermassive black holes and their host galaxies over cosmic time

The examples given above demonstrate the significant progress and enormous potential of GRAVITY in the study of the innermost environment of AGN, including BLR structure and kinematics, 2D velocity-resolved joint analysis of RM and SA, *R-L* relations, dust imaging, and improvements to tools and models, to name just a few. While our analysis of the Large Programme data is ongoing[b], the Large Programme has already paved the way for many similar and innovative future studies. The results and experience gained by our team have been instrumental in shaping one of the main science cases (AGN) for GRAVITY+, demonstrating the great potential for future applications (GRAVITY+ collaboration et al., in preparation). A significant upgrade of GRAVITY and the VLTI, GRAVITY+ will boost our understanding in detail of the BLR structure and kinematics over a large range of luminosity and redshifts, thereby overcoming another limitation of RM: a comprehensive study of fast-growing systems at cosmic noon by means of RM is impractical, as the time lag increases both with luminosity (~ $L^{0.5}$) and redshift (~1 + *z*). High-*z* luminous quasars have time lags from months to years.

In addition, GRAVITY+ will make significant contributions to other sub-fields of AGN research, including detecting SMBH binaries (Dexter et al., 2020), resolving the dust continuum and emission-line-emitting gas around tidal disruption events, or probing super-Eddington accretion (GRAVITY+ collaboration et al., in preparation).

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Notes

[a] Improved data reduction methods and recipes resulting from this Large Programme have already been incorporated into the official GRAVITY pipeline, or are in preparation for this in the context of the GRAVITY+ upgrade.
[b] We plan to release processed data within two years of the completion of the observations (i.e., by the end of 2023). We will make available via the ESO Science Archive Facility our reduced and calibrated (fringe-tracker) visibilities and spectra, time-averaged phase data, and reconstructed continuum images.

Zdenek Bardon/ESO

This picture, taken from ESO's La Silla Observatory in Chile, shows bright red streaks known as red sprites. These are an elusive form of lightning that occurs well-above storm clouds, discharging electricity high up in Earth's atmosphere at an altitude of 50–90 km. In addition to occurring much higher in the sky than regular lightning, they are cooler than the white lightning we usually see and appear much fainter. Red sprites are very difficult to catch: the first photographic evidence for them was only taken in 1989.