Black Hole Winds at All Scales
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The sub-parsec structure of AGN with VLTI / GRAVITY

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Abstract. The central parsec of AGN is a key region for the launching of winds, and near-infrared interferometry is a unique tool for its study. With GRAVITY at the VLT interferometer, we can now spatially resolve not just the hot dust continuum on milliarcsecond 'torus' scales through imaging but also the broad-line region (BLR) on microarcsecond scales through spectro-astrometry. We have mapped the kinematics of the BLR in seven nearby AGN, measured sizes of the hot dust for seventeen AGN, and reconstructed dust images for two AGN. BLR kinematics has allowed us to measure the BLR size and supermassive black hole mass independent of reverberation mapping. The ongoing GRAVITY+ upgrade will greatly enhance the sensitivity and sky coverage of GRAVITY, and first results demonstrate its power for AGN science at z∼2 and beyond.

Keywords. galaxies:active, galaxies:nuclei

The commissioning of the GRAVITY instrument (GRAVITY Collaboration 2017) at ESO's Very Large Telescope Interferometer has dramatically improved the sensitivity of near-infrared K-band interferometric observations. This has converted the decades old dream of interferometric studies of the broad-line region of AGN into a reality. Fig. 1 (GRAVITY Collaboration 2018) shows results for the quasar 3C273 and their fit with a broad-line region cloud model based on the model of Pancoast et al. (2014). The data are well represented by a thick almost face-on disk rotating around a supermassive black hole with $log(M_{\rm BH}/M_\odot) = 8.41$.

Of in total seven local universe BLRs studied in this way (GRAVITY Collaboration 2020, 2021, 2023), five are well fit with rotating thick disks. In two cases, introducing outflow motion within the disk, again following the Pancoast approach, provides an improved fit. A BLR radius-luminosity relation with directly measured radii starts to build up, with indication for high luminosity and/or high Eddington ratio AGN falling below the default $R \propto L^{0.5}$ scaling.

Combination of angular radii from GRAVITY spectroastrometry with linear radii from reverberation mapping can provide geometric distances to AGN, albeit with noticeable uncertainties (Wang et al. 2020; GRAVITY Collaboration 2021a).

Continuum emission from host dust close to the dust sublimation radius has been mapped in the prototypical Type 2 AGN NGC 1068 (GRAVITY Collaboration 2020a).

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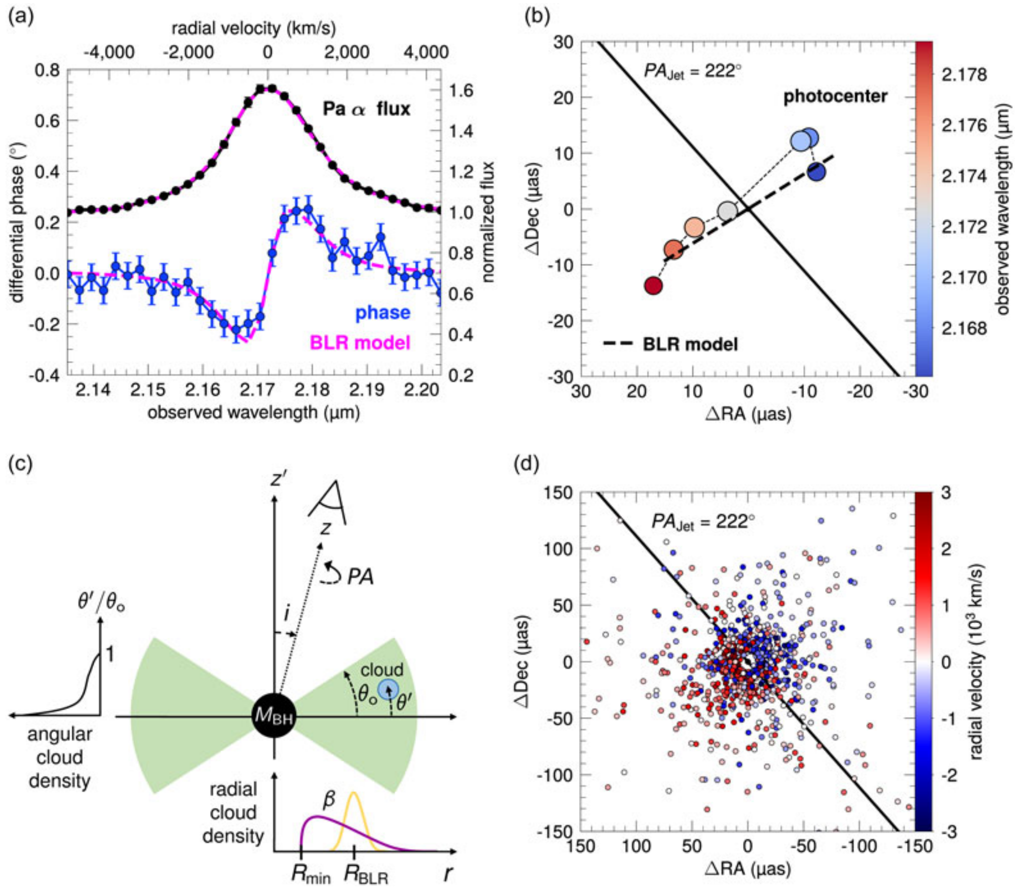

Figure 1. GRAVITY observations and modelling for 3C273 (GRAVITY Collaboration 2018). (a) Paschen α line profile and differential phases, as observed and as modelled by a thick rotating broad-line region disk. (b) Model-independent photocenters measured for different velocity slices. (c) Schematic representation of the adopted thick disk cloud model and its parameters. (d) Velocities in best fit model.

Rather than a thick torus donut, the results prefer a thin ring that is cospatial with the maser emitting clouds (Fig. 2). This clumpy ring is surrounded by thicker molecular material further out, as has been observed with ALMA. In NGC 3783, an illuminated dust cloud is visible in addition to the main K-band component (GRAVITY Collaboration 2021).

Simple hot dust sizes (rather than maps with detection over several resolution elements) have been obtained for up to now 17 local AGN (GRAVITY Collaboration 2020b, 2023a), indicating a radius-luminosity relation that is flatter than $R \propto L^{0.5}$. Such observations are quick, and a tight relation of BLR and dust size (GRAVITY Collaboration 2023b) permits the use of the inferred dust size as a proxy to BLR size in Black Hole mass measurements.

The next step in near-infrared interferometry, towards wide sky coverage, yet fainter science, and high contrast will be obtained by the GRAVITY+ project (GRAVITY+ Collaboration 2022) which will equip the VLTI 8m unit telescopes with state of the art adaptive optics, laser guide stars, and other upgrades. As a first step, the GRAVITY wide functionality is already available to the community. This makes it

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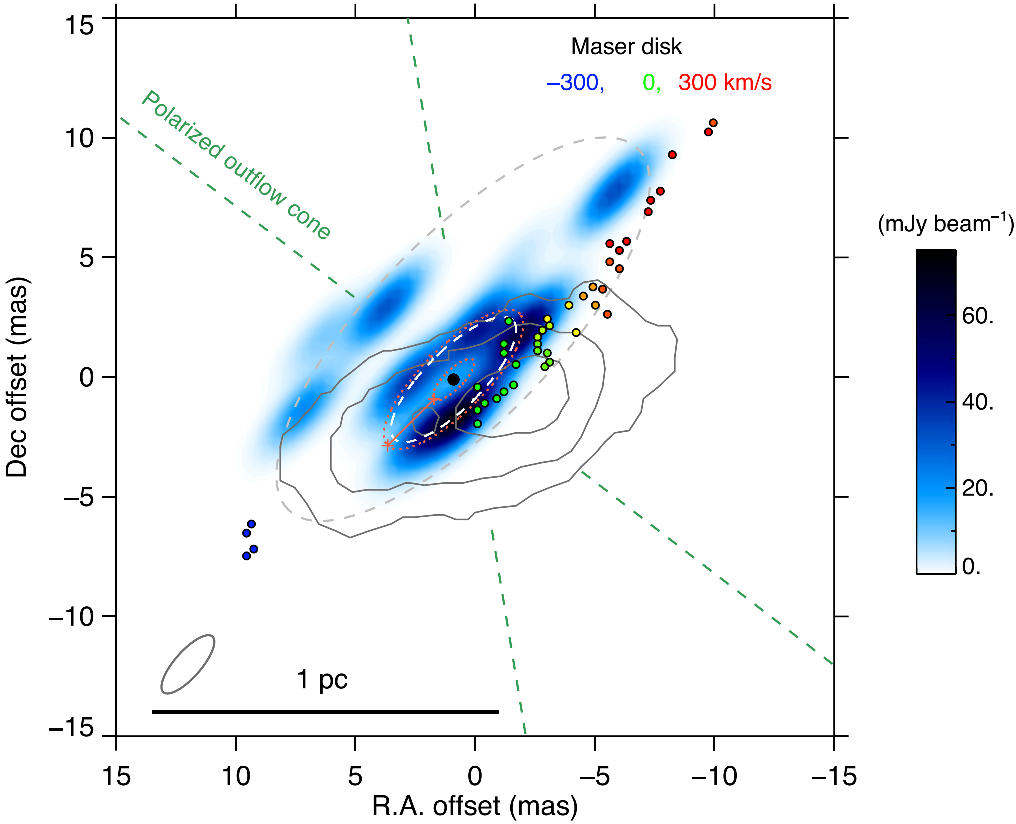

Figure 2. K-band image of circumnuclear hot dust in NGC 1068 (GRAVITY Collaboration 2020a). The best fit radius of the observed clumpy ring (dashed white) is close to the sublimation radius for hot dust (dotted orange).

possible to observe faint AGN making use of bright fringe tracking star at larger separation than before, and has already led to the first BLR detection and direct SMBH measurement of a luminous QSO at z ∼ 2.3 (GRAVITY+ Collaboration 2023).

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