DOI: 10.18727/0722-6691/5376

The GRAVITY+ Project: GRAVITY-Wide and the Beam Compressor Differential Delay Lines

GRAVITY+ Collaboration
Roberto Abuter[8]
Fatme Allouche[17]
Antonio Amorim[6,10]
Christophe Bailet[17]
Jean-Philippe Berger[5]
Philippe Berio[17]
Azzurra Bigioli[14]
Olivier Boebion[17]
Ralf Böttcher[20]
Marie-Lena Bolzer[1,11]
Henri Bonnet[8]
Guillaume Bourdarot[1]
Pierre Bourget[8]
Wolfgang Brandner[3]
Amit Brara[1]
Yann Clénet[2]
Benjamin Courtney-Barrer[8,16]
Ric Davies[1]
Denis Defrère[14]
Alain Delboulbé[5]
Francoise Delplancke[8]
Roderick Dembet[2]
Subo Dong[21]
Antonia Drescher[1]
Andreas Eckart[4,12]
Clemence Édouard[2]
Frank Eisenhauer[1]
Maximilian Fabricius[1]
Helmut Feuchtgruber[1]
Gert Finger[1]
Natascha Förster Schreiber[1]
Robert Frahm[8]
Enrique Garcia[8]
Paulo Garcia[7,10]
Eric Gendron[2]
Reinhard Genzel[1,9]
Juan Pablo Gil[8]
Stefan Gillessen[1]
Tiago Gomes[7,10]
Frederic Gonté[8]
Vishaal Gopinath[1,8]
Jonas Graf[1]
Patricia Guajardo[8]
Sylvain Guieu[5]
Maximilian Häberle[3]
Michael Hartl[1]
Xavier Haubois[8]
Frank Haußmann[1]
Thomas Henning[3]
Sebastian Hönig[13]
Matthew Horrobin[4]
Norbert Hubin[8]
Lieselotte Jochum[8]
Laurent Jocou[5]
Andreas Kaufer[8]
Pierre Kervella[2]
Laura Kreidberg[3]
Sylvestre Lacour[2,8]
Stephane Lagarde[17]
Olivier Lai[17]
Vincent Lapeyrère[2]
Romain Laugier[14]
Jean-Baptiste Le Bouquin[5]
James Leftley[17]
Pierre Léna[2]
Dieter Lutz[1]
Felix Mang[1,11]
Antoine Mérand[8]
Florentin Millour[17]
Nikhil More[1]
Przemek Mroz[22]
Hugo Nowacki[5]
Matthias Nowak[15]
Nadine Neumayer[3]
Sylvain Oberti[8]
Thomas Ott[1]
Hakan Özdemir[1]
Laurent Pallanca[8]
Thibaut Paumard[2]
Karine Perraut[5]
Guy Perrin[2]
Romain Petrov[17]
Oliver Pfuhl[8]
Nicolas Pourré[5]
Hagen Prowatke[20]
Sebastian Rabien[1]
Christian Rau[1]
Christian Rehm[19]
Miguel Riquelme[8]
Sylvie Robbe[17]
Sylvain Rochat[5]
Muhammad Salman[14]
Jonas Sauter[1,3]
Joseph Schubert[1]
Nicholas Schuhler[8]
Jinyi Shangguan[1]
Taro Shimizu[1]
Silvia Scheithauer[3]
Daniel Schuppe[1]
Ferreol Soulez[18]
Eric Stadler[5]
Christian Straubmeier[4]
Eckhard Sturm[1]
Matthias Subroweit[4]
Calvin Sykes[13]
Linda J. Tacconi[1]
Konrad Tristram[8]
Frédéric Vincent[2]
Sinem Uysal[1]
Patrick Wessely[1]
Felix Widmann[1]
Eckhard Wieprecht[1]
Erich Wiezorrek[1]
Lukas Wimmer[1]
Julien Woillez[8]
Senol Yazici[1]
Gérard Zins[8]

[1] Max Planck Institute for Extraterrestrial Physics, Garching, Germany
[2] LESIA, Paris Observatory, Meudon, France
[3] Max Planck Institute for Astronomy, Heidelberg, Germany
[4] 1st Institute of Physics, University of Cologne, Cologne, Germany
[5] Grenoble Alpes University, CNRS, IPAG, Grenoble, France
[6] Faculty of Sciences, University of Lisbon, Portugal
[7] Faculty of Engineering, University of Porto, Portugal
[8] ESO
[9] Departments of Physics and Astronomy, University of California, Berkeley, USA
[10] Centre of Astrophysics and Gravitation, University of Lisbon, Portugal
[11] Department of Physics, Technical University of Munich, Garching, Germany
[12] Max Planck Institute for Radio Astronomy, Bonn, Germany
[13] School of Physics & Astronomy, University of Southampton, UK
[14] Institute of Astronomy, KU Leuven, Belgium
[15] Institute of Astronomy, Cambridge, UK
[16] Research School of Astronomy and Astrophysics, Australian National University, Canberra, Australia
[17] Côte d'Azur Observatory, Lagrange Laboratory, France
[18] University of Lyon 1, ENS de Lyon, CNRS, Lyon, France
[19] ISKON, Ing. Büro, Isen, Germany
[20] Steinmeyer Mechatronik GmbH, Dresden, Germany
[21] Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China
[22] Astronomical Observatory, University of Warsaw, Poland

One of the primary goals of the GRAVITY+ upgrade is to significantly improve the sky coverage of GRAVITY and the Very Large Telescope Interferometer. With the successful commissioning and start of operations of the GRAVITY-Wide mode and the new Beam Compressor Differential Delay Lines, GRAVITY+ has opened up the sky to deep interferometric observations. These include the first dynamical black hole mass measurements at

cosmic noon, vastly increased observable samples of microlensing events, and a step towards the first detection of an intermediate-mass black hole through stellar orbits.

Introduction

The GRAVITY+ project will bring the next revolution in near-infrared interferometry through a phased upgrade of both the GRAVITY beam combiner instrument and the Very Large Telescope Interferometer (VLTI) infrastructure itself. A unique feature of GRAVITY is its dual-field mode, which allows for simultaneous observations of a faint science target and a nearby bright star. The star is then used to correct for the fast-changing optical paths of each telescope induced by the atmosphere during long exposures of the science target. A critical limitation of GRAVITY and the VLTI was the requirement that the fringe-tracking star and science target be within 2 arcseconds of each other for the Unit Telescopes (UTs). This severely constrained the sky coverage, especially for faint extragalactic targets that are primarily located away from the Galactic plane. To improve the sky coverage, the first phase of GRAVITY+ was to implement wide-angle off-axis fringe tracking and allow for separations between the fringe-tracking star and the science target out to the atmospheric limit (~ 30 arcseconds) as well as to upgrade the beam compressors (BCs) and differential delay lines (DDLs). The GRAVITY-Wide upgrade was carried out in two steps: first with the activation of wide-angle off-axis fringe tracking using the pre-existing PRIMA DDLs and second with the installation and commissioning of a new combined system (BCDDL). Both steps have now been completed with the successful commissioning of the BCDDL system at the end of April 2024.

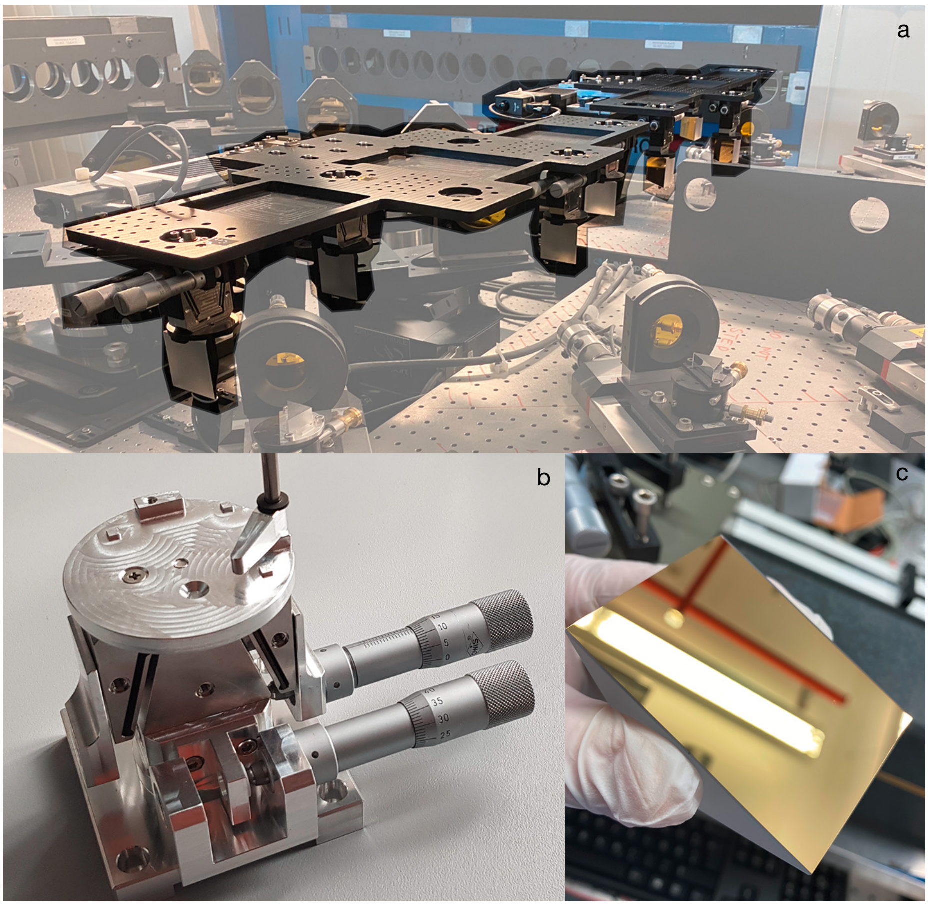


Figure 1. The four-fold periscope that overlaps the beams of the fringe tracking object with those of the science object (a). As the optical bench was already quite crowded, the prism-based mirrors (b) from two motorised bridges that allow the periscope to be moved in and out of the beams to switch automatically between on-axis and off-axis operation (c) were suspended hanging upside down.

Phase 1: GRAVITY-Wide

The light from the 8-metre UTs or the 1.8-metre Auxillary Telescopes (ATs) is routed via a long optical train down to the VLTI laboratory. In fact, the light undergoes more than 20 reflections before even entering the instrument. Within this chain are the VLTI main delay lines that compensate for Earth's rotation and, as a result, the optical path between the observed science object and the telescope changes with time. Mirrors mounted on carts travel along some 100-metre-long rails constantly and very precisely throughout each observation. Bringing the full field of view of the telescopes down to the laboratory would have required prohibitively large optics. Instead, a 2-arcsecond cutout is picked up at the telescopes and propagated along the long delay lines under the VLT platform until they finally are directed to the VLTI laboratory. The beam diameter is about 80 millimetres, and the first optical system encountered by this light in the VLTI Lab comprises the beam compressors, which turn those into 18-millimetre beams with a three-mirror system. After two more reflections, the light enters, for instance, GRAVITY. GRAVITY was built with a dual feed capability. So instead of observing just one object through four telescopes, it is able to observe two objects simultaneously. A brighter object (star) is used to track the motions of the fringe pattern inside GRAVITY. Fast piezo-driven mirrors inside the instrument then allow for the stabilisation of the pattern, such that the second, much fainter, object can be observed with long exposure times.

Unfortunately, nature was not kind enough to place sufficiently bright fringe-tracking stars in the vicinity of all interesting science objects. This severely limits the ability of GRAVITY to observe, for example, faint and highly redshifted active galactic nuclei (AGN) or microlensing targets. This limitation was, however,

Figure 2. The left panel shows the enclosure of the beam compressor delay line optical bench; the right panel shows a bird's-eye view with the protective panels removed. The eight newly activated beam compressors can be seen towards the right of the images; they stretch, however, the entire length of the bench. The two grey laser heads on the top feed the laser distance metrology system that monitors the optical path length to better than 2 nm precision at all times.

foreseen since the early days of the VLTI, which was designed to bring two 2-arcsecond field cutouts per telescope to the interferometric laboratory. This capability was implemented under the umbrella of the Phase-Referenced Imaging and Micro-arcsecond Astrometry (PRIMA) project which delivered star separators (STS) and DDLs to the VLTI. Although this dual-field capability never succeeded in transitioning to science operations, the DDLs and STSs remained in place, largely unused.

To implement the first phase of GRAVITY-Wide, in a close collaboration between ESO, the Max Planck Institute for Extraterrestrial Physics (MPE), and the University of Cologne, our team first reactivated the PRIMA dual-field infrastructure. A minor optical modification had to be carried out on the DDLs to project the optical pupil at the correct location for GRAVITY. Secondly, periscopes were installed (see Figure 1) on the optical bench of the VLTI switchyard to merge the two beams of each of the respective four telescopes and feed the GRAVITY instrument. The STSs can pick up two targets more or less arbitrarily inside a 2-arcminute field of view. But atmospheric turbulence sets a limit on the separation to around 30 arcseconds when operating in the *K* band. This is 15 times larger than the 2 arcseconds of an individual beam and consequently increases the probability of finding a sufficiently bright fringe-tracking star by a factor of 225. In return, the number of observable targets multiplies by the same factor, significantly increasing the science grasp of GRAVITY.

GRAVITY-Wide was commissioned in December 2021 and, since period P110, has been offered to the community. A full description of phase 1 of GRAVITY-Wide was given by GRAVITY+ Collaboration et al. (2022a).

Phase 2: BCDDL

We mentioned above the large number of reflections that the light path undergoes before entering the science instruments. Reintroducing the PRIMA DDLs added five further reflections to the beam path. Any such reflection inevitably results in the loss of light. Also, while the optical path length between telescopes and the science object varies very slowly and smoothly with time, the VLTI optical train is subject to a number of different sources of vibration such as compressors from other cryogenic instruments. These vibrations ultimately affect the fringe contrast. The vibrations from the telescopes' primary, secondary and tertiary mirrors are measured with accelerometers and then partially compensated in open-loop by forwarding appropriate correction signals to fast actuators in the main delay lines. This MANHATTAN vibration control system is upgraded as part of the GRAVITY+ project with additional vibration sensors on the other mirrors of the coudé train, and with improved control algorithms that compensate for these vibrations in a very similar fashion as noise-cancelling headphones. But this requires fast actuators that can be driven directly by MANHATTAN.

The second phase of GRAVITY-Wide (see Figure 2) removed the PRIMA DDLs entirely and instead moved their functionality directly to the aforementioned beam compressors. These formerly statically mounted three-mirror systems were placed on 2-metre-long rails that ride on top of high-precision, directly driven linear stages for low frequency but larger stroke corrections (+/– 35 millimetres, which corresponds to the maximum differential optical path length difference over a 24-hour period). The secondary mirror of the system is now mounted on a piezoelectric stage that we took over from the PRIMA DDL system. We also transferred and augmented the laser metrology system from the PRIMA DDLs to these newly activated beam compressors, called BCDDLs, which provides a very precise feedback signal for the closed-loop control of the optical path length.

Figure 3. Left: The installation of the new BCDDLs was completed on 16 April by the combined team from ESO, MPE and the University of Cologne. Right: The occasion of first light on 17 April.

A direct bypass feed from MANHATTAN to the BCDDLs allows us to take advantage of the full bandwidth of the piezo system and to correct for vibrations.

The new BCDDLs were commissioned in April 2024 by a collaboration of ESO, MPE, and the University of Cologne (see Figure 3). They saw first light on the ATs on 17 April and then on the UT on 22 April. The change to this new system is entirely transparent to the user and available to the community immediately.

Exploring black holes across cosmic time and mass range

Quasars at cosmic noon

One of the first science cases achievable with GRAVITY-Wide involved deep observations of quasars at high redshift. Direct measurements of the broad line region (BLR) and ultimately the supermassive black hole (SMBH) mass are impossible with single-dish facilities, but the VLTI with GRAVITY+ can achieve the necessary spatial and astrometric accuracy for these unique observations. Black hole mass measurements at cosmic noon ($z \sim 1$–3) are particularly important for tracking and testing the co-evolution of SMBHs and their host galaxies, as suggested by the strong correlations between SMBH mass and host galaxy properties in the local Universe.

GRAVITY+ Collaboration et al. (2022a, 2022b) showed the potential of GRAVITY-Wide observations to measure the SMBH mass at $z = 2$ with the first observations of a cosmic noon quasar and a clear detection of the coherent flux and differential phase across the redshifted H-alpha line. Since then, the GRAVITY+ AGN team has published the first $z = 2$ dynamical SMBH mass measurement of the quasar J0920 (Abuter et al., 2024). Combined with complementary measurements of the host galaxy mass from the Northern Extended Millimeter Array (NOEMA) interferometer, J0920's SMBH was found to be undermassive compared to the expectation from the $z = 0$ M_{BH}–$M_{stellar}$ relationship.

Following the first successful detection, the team has been using the GRAVITY-Wide mode and the BCDDL as a workhorse for building a sizable sample of $z = 2$ quasars with combined high-precision SMBH masses and host galaxy masses. Two more BLR signals have now been detected (Figure 4) and deep observations have been completed on a total of five quasars. This allows both for testing the use of local scaling relations (i.e., the BLR radius–luminosity relation) for quick SMBH masses and for establishing a dynamically based M_{BH}–$M_{stellar}$ relationship at $z = 2$.

Gravitational Microlensing

Isolated dark objects such as stellar-mass black holes or free-floating planets are thought to be abundant throughout the Galaxy. Detecting and measuring their masses is critical for understanding the formation mechanisms, mass functions, and evolution of their full population. Because they are isolated, however, the only way to find them is through gravitational microlensing when a foreground object (star, planet, black hole, etc.) passes in front of a more distant star. Lensing due to the gravitational potential of the foreground object then magnifies the star and causes a rapid brightening of its light. These microlensing events are therefore found through constant, wide-field monitoring of Milky Way stars.

However, the light curve by itself does not measure the mass of the lens because it is also dependent on the lens–source relative parallax and proper motion. One method to recover these parameters is to spatially resolve the two microlensed images of the source star and measure the Einstein radius. For Galactic microlensing events, the Einstein radius is on the order of a milliarcsecond and therefore only interferometry has the power to resolve the microlensed images. Dong et al. (2019) showed the power of GRAVITY and near-infrared interferometry by measuring the Einstein radius of a bright and nearby microlensing event for the first time using the single-field on-axis mode (see Figure 5, left panel).

The majority of microlensing events, though, are much fainter and require off-axis fringe tracking and increased sensitivity. GRAVITY-Wide has therefore provided a revolution in the number of microlensing events that can be followed up with interferometry, from a few per year to several dozen per year (see Figure 5, middle panel). Taking advantage of target-of-opportunity observations, the GRAVITY microlensing team, a collaboration between astronomers primarily at ESO, Peking University, and the University of Warsaw, have already observed four microlensing events with GRAVITY-Wide. The first GRAVITY-Wide event measured a lens mass of ~ 0.5 $M_\odot$ (i.e., likely a main sequence star) with an unprecedented precision of 2.5% (see Figure 5, right panel). It is therefore only a matter of time before the first black holes are discovered.

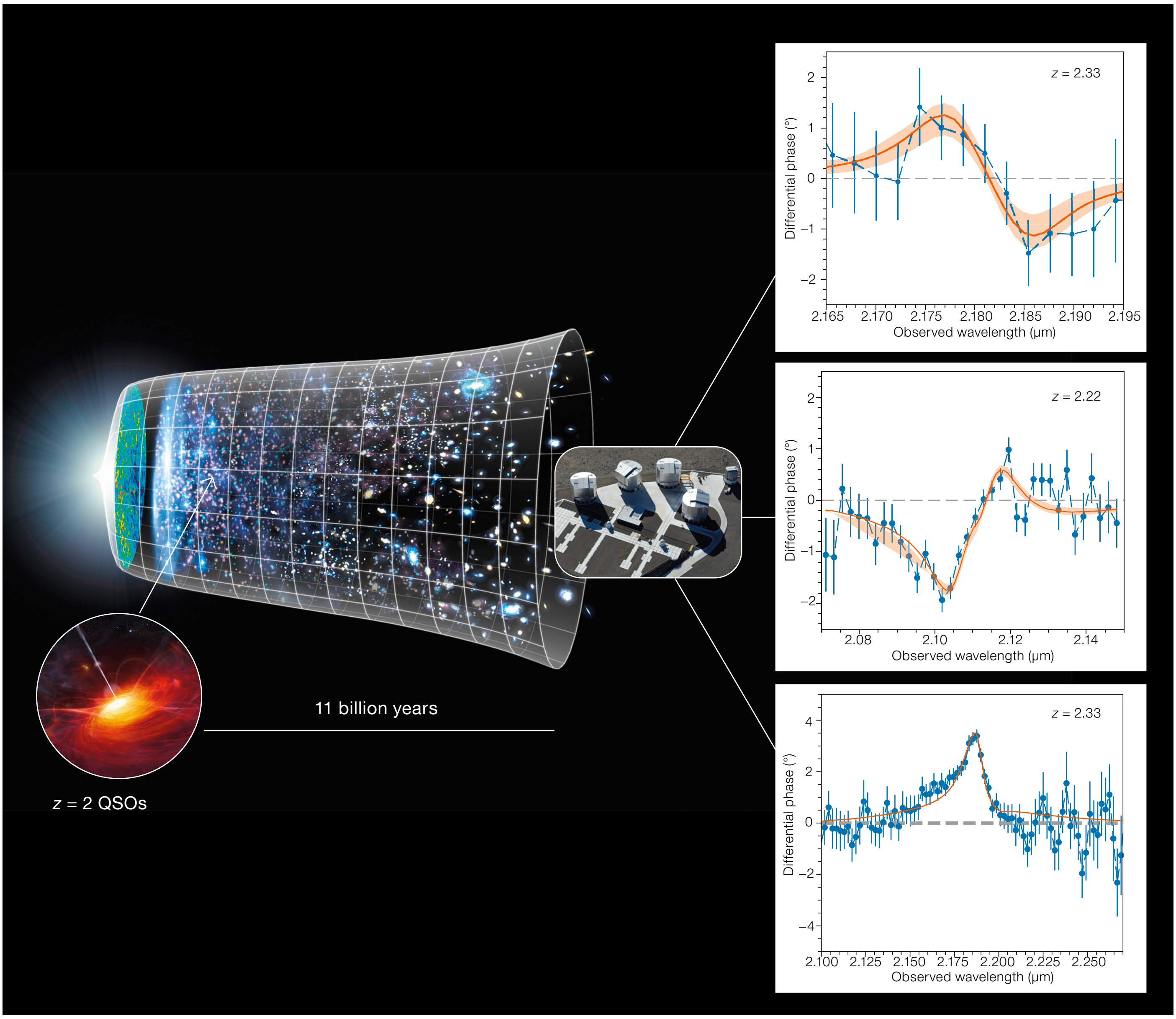


Figure 4. GRAVITY-Wide has now been used to detect the broad-line region differential phase signal in three $z > 2$ quasars. This allows us to measure the supermassive black hole mass with unprecedented precision and helps to disentangle the coevolution of black holes and the galaxies they live in at a time when the Universe was only two billion years old.

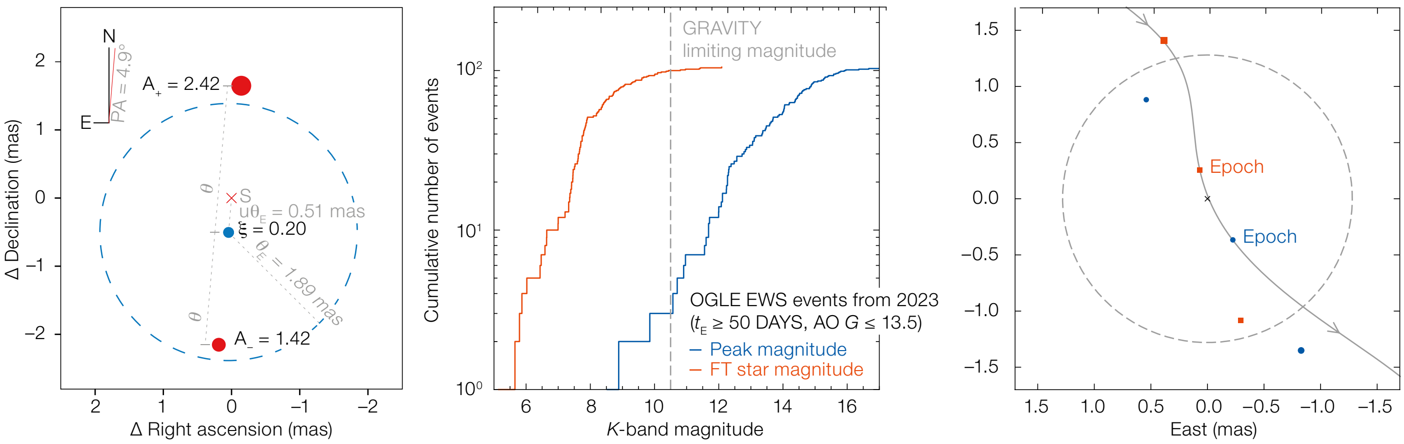


Figure 5. Left: First resolved microlensed images from Dong et al. (2019). Middle: Cumulative distribution of microlensing events in 2023 as a function of *K*-band magnitude (blue curve) along with their potential fringe-tracking stars (red curve). With GRAVITY-Wide, ~ 100 events were available to be followed up, compared to only a few in the single-field on-axis mode. Right: First resolved microlensed images using GRAVITY-Wide. This event was observed in two epochs showing the motion of the images.

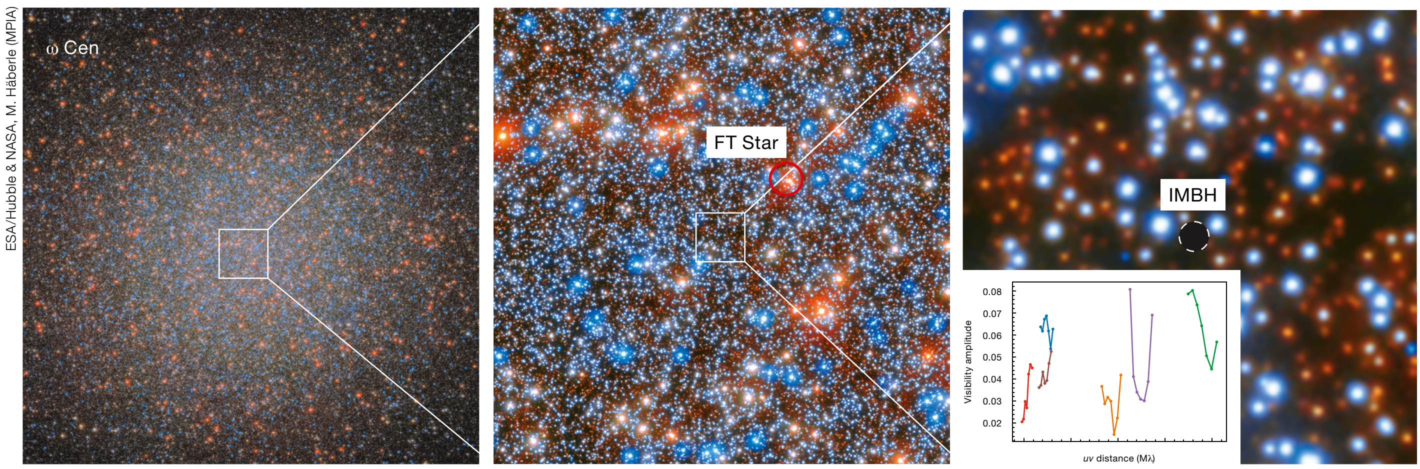
ω Cen and the search for IMBHs

While many black holes in the stellar and supermassive black hole mass ranges have been discovered, only a few candidates in the so-called 'intermediate-mass' range ($10^2 – 10^5\ M_\odot$) exist. Finding intermediate mass black holes (IMBHs) would provide strong constraints on the seeding and formation of SMBHs. Extrapolating from the well-studied black hole mass – bulge mass relation, one possible location of IMBHs is at the centres of stellar clusters. Recently, Häberle et al. (2024) discovered fast-moving stars at the centre of the globular cluster ω Cen that provide strong evidence for an IMBH with a mass of at least 8200 $M_\odot$. Definitive proof of an IMBH and a precise measurement of its mass would come from astrometric monitoring of these fast stars to determine their orbits, similarly to what has been done for the Galactic centre.

However, no bright stars are available for fringe tracking within 2 arcseconds of the centre of ω Cen — but there are several brighter than K = 11 within 11 arcseconds. During the commissioning of the BCDDLs, we tested the performance and sensitivity of GRAVITY-Wide by observing several stars within 1 arcsecond of the proposed location of the IMBH including the brightest fast-moving star (K = 18.1 mag) from Häberle et al. (2024). We could for the first time detect interferometric fringes from the star and measure the visibility (see Figure 6). Absolute astrometry is currently not possible with GRAVITY-Wide owing to the lack of a metrology system but will be investigated in the near future to permit the measurement of the acceleration of the central fast-moving stars of ω Cen and other globular clusters similarly to the discovery and characterisation of the Galactic centre SMBH.

With the next phases of GRAVITY+ that include the adaptive optics systems and laser guide stars, the sensitivity will be

Figure 6. Hubble Space Telescope images of the nearby globular cluster ω Cen showing successively zoomed-in views of the central region. The middle panel highlights the fringe-tracking star used for the GRAVITY-Wide observations during BCDDL commissioning. The right panel highlights the expected location of the IMBH with an inset showing the detected fringes and visibility amplitude of one of the fast-moving stars discovered by Häberle et al. (2024).



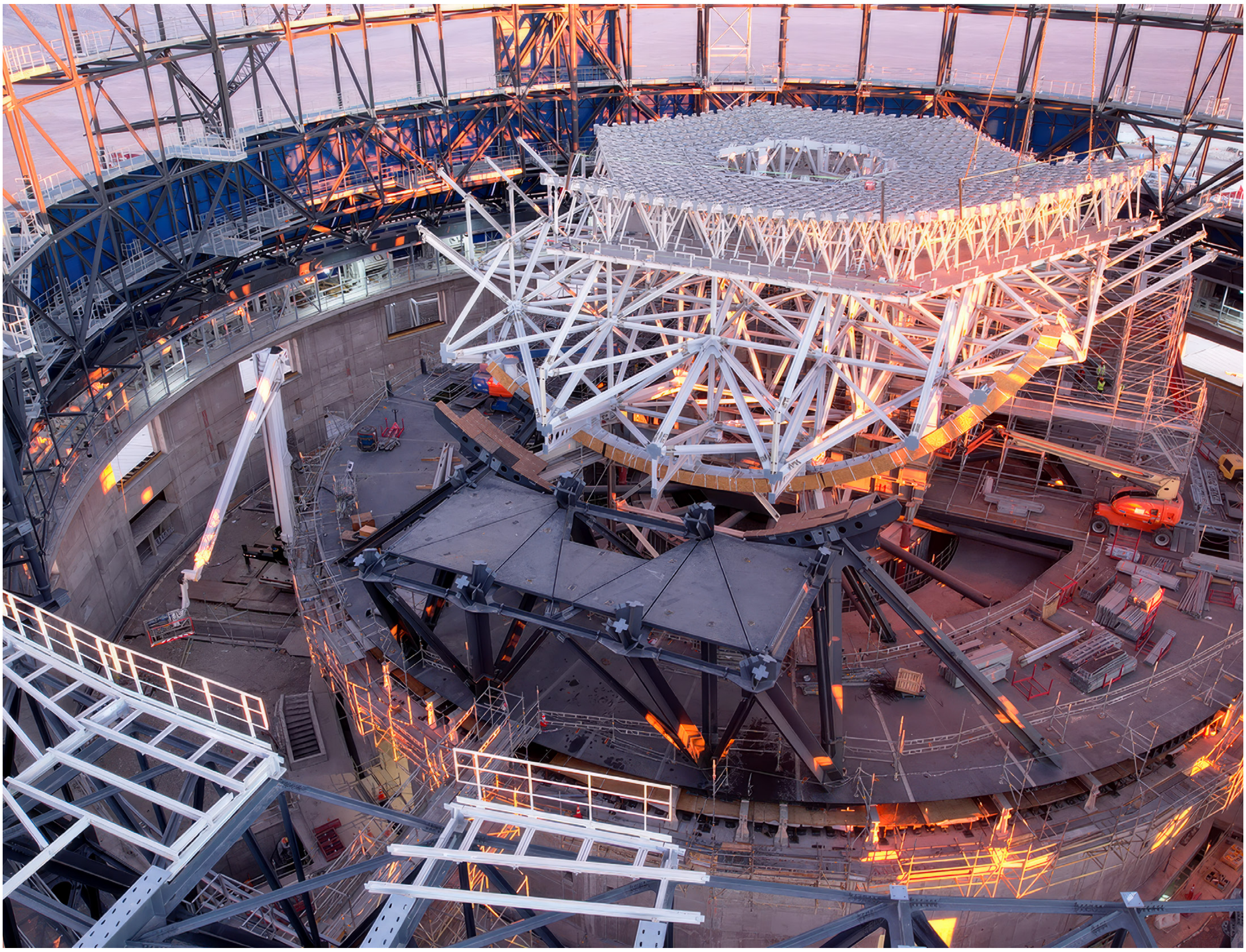
greatly improved and it will be possible to rapidly assemble fainter and larger samples for all three science cases presented. Even higher redshift quasars will be accessible (out to $z \sim 7$ with the MgII line), the first isolated stellar-mass black hole through microlensing will be detected, and more IMBH detections will become possible in the local Universe. This is an exciting time for GRAVITY+ and the VLTI and we look forward to the unexpected science that will be done once GRAVITY+ is completed.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004719.

References

Abuter, R. et al. 2024, Nature, 627, 281
Dong, S. et al. 2019, ApJ, 871, 70
GRAVITY+ Collaboration et al. 2022a, A&A, 665, A75
GRAVITY+ Collaboration et al. 2022b, The Messenger, 189, 17
Häberle, M. et al. 2024, Nature, 631, 285



This drone image from June 2024 shows progress in the construction of ESO's Extremely Large Telescope (ELT), located on Cerro Armazones in the Atacama Desert, Chile. The white lattice structure under construction is a support structure that will eventually hold the ELT's primary mirror, M1. Notice the cranes and vehicles at the bottom, which illustrate just how enormous the ELT is!