Science with GRAVITY
the NIR interferometric imager

Thibaut Paumard[1] for the GRAVITY consortium
[1]LESIA Observatoire de Paris/CNRS

PROJECT STATUS

GRAVITY is currently under construction. Integration has stared in the MPE premises. Shipment to Paranal is expected in 2014.

INSTRUMENT'S BASICS

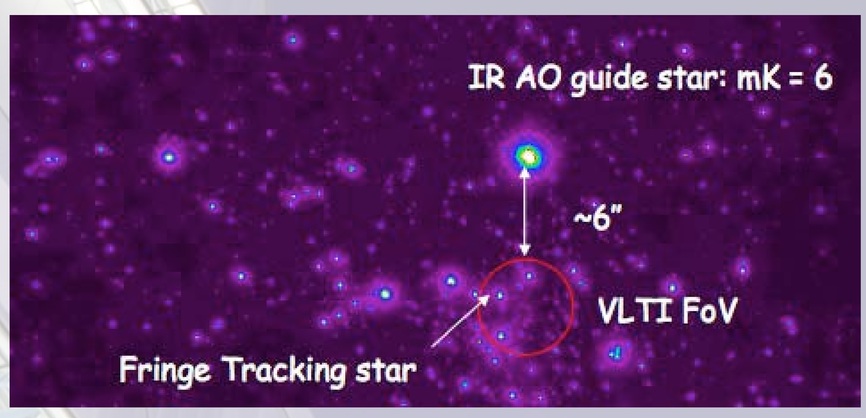
GRAVITY is an interferometric instrument that will be able to recombine light from the four 8.2-m Unit Telescopes (Uts) or of the four 1.8-m Auxiliary Telescopes (ATs) of the Very Large Telescope Interferometer (VLTI) located on mount Paranal in Chile.

GRAVITY is based on an integrated optics beam combiner. One of its key subsystem is a fringe tracker which can either operate directly on the science target (single-field mode) or on a distinct source located less than 2" away for UT observations or 6" for AT observations (dual-field mode). The fringe tracker allows integrating for several minutes instead of being limited by coherence time. In single-field mode, this allows for observing at a higher spectral resolution than would be possible without the fringe-tracker. In dual-field mode, this allows observing very faint targets in the vicinity of a brighter reference star. In addition, in dual-field mode, one can retrieve relative astrometry between the two targets with the astonishing precision of about 10 µas in a couple of minutes integration time. GRAVITY also provides four infrared wavefront sensors for the UTs and controls the VLTI MACAO deformable mirrors.

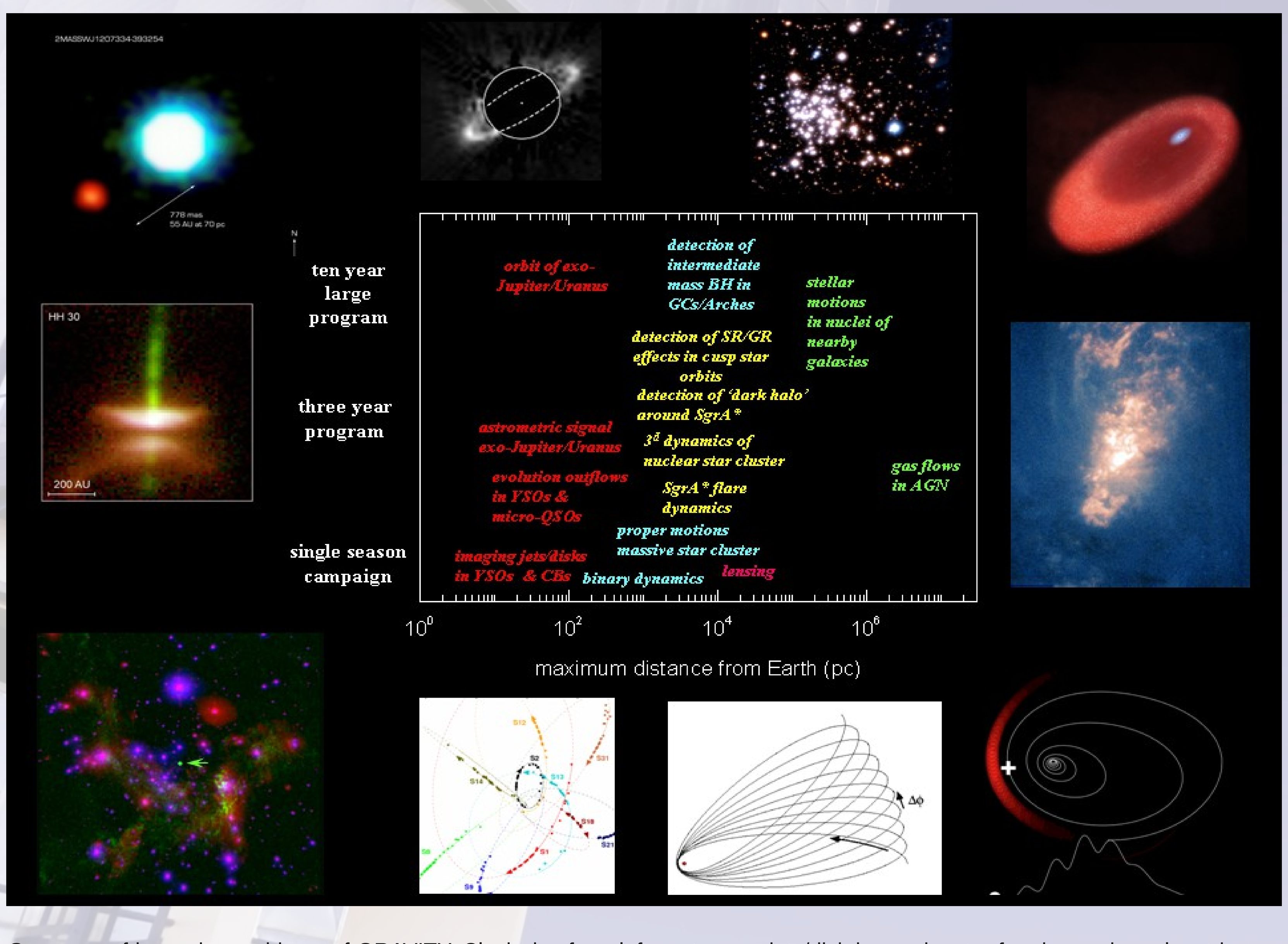
Spectral domain: K-band (mid-infrared, 2–2.4 µm).
Spectral resolution: R=22, 500 or 4000
Field of view: 70 mas
Limiting magnitude: K=10 (UTs, fringe-tracker),
K=16 (UTs, science object)

GRAVITY cryostat in the integration hall

Integrated optics beam combiner



GRAVITY setup for observing Sgr A*: UT infrared AO on IRS7, dual-field mode with fringe tracker on IRS 16CC



Summary of key science drivers of GRAVITY. Clockwise from left centre are: jets/disk in nearby star forming region, planet-brown dwarf binary, dust disk with central gap, Arches star cluster, M31 star disks, NGC1068 outflow/narrow line region, modelling of Galactic Centre flare, radial precession of stellar orbits, S-star orbits, nuclear star cluster and radio emission in the Galactic Centre. In the central insert the horizontal axis denotes the maximum distance from the Earth to which a particular project can be carried out with the capabilities of GRAVITY. The vertical axis represents the time required for such measurements, separated into three rough categories of one season, three and ten years. All entries are based on modeling and simulations with the requirement of a 5 σ or greater detection.

From Paumard et al. 2011

ABSTRACT :

10-m class telescopes have brought a wealth of advances in high resolution science: orbits of stars in the Galactic Center, mrophology of Active Galactic Nuclei, imaging of protostellar accretion disks are but a few of them. The very same telescopes used in interferometric mode and equipped with new instrumentation will provide us with another order of magnitude in spatial resolution and even more in astrometric accuracy. We are currently building GRAVITY, a second generation instrument for the VLT Interferometer. We summarize the basic instrumental concepts behind GRAVITY as well as the many science cases that the instrument will undertake.

INTRODUCTION

Astrometry is a powerful tool for carrying out fundamental measurements and for unveiling the laws of Nature and the structure of the Universe. Precision astrometry by Tycho Brahe allowed Kepler to deduce that the planets orbit the Sun on elliptical orbits. Kepler's work in turn provided the observational basis for the Newtonian revolution. During the past three to four decades sub-milliarcsecond radio astrometry with intercontinental long baseline interferometry (VLBI) led to the discoveries of super-luminal motions in relativistic radio jets of distant quasars and of molecular gas outflows in star forming regions. VLBI also yielded precision measurements of the dynamics of a warped accretion disk around the super massive black hole (SMBH) in the external galaxy NGC 4258 and provided primary distance measurements throughout the Milky Way and reaching several external galaxies. Hipparcos astrometry of stars in the solar neighbourhood revolutionized our knowledge of the dynamics of the Milky Way. Speckle and adaptive optics, near-infrared (NIR) astrometry of stars with the European Southern Observatory (ESO) New Technology Telescope (NTT) and Very Large Telescope (VLT) demonstrated that Sgr A*, the compact radio source at the centre of the Milky Way must be a SMBH of about 4 million solar masses, beyond any reasonable doubt.

Current NIR imagers on 10-m telescopes (such as NACO on the VLT or the NIRC cameras on the Keck telescope) are reaching their limitations: they are already tracking thousands of stars within the central few tens of arcseconds. The detection limit is set by spatial crowding, so only few stars remain to be detected by these instruments, and systematic effects, inherent to the instruments and already reduced to a minimum, dominate the error budget for many Galactic Center (GC) applications. To write the next chapter of the success story that GC research has proven to be so far, new technology developments are in order. For this purpose, we are designing GRAVITY (Eisenhauer et al. 2008), a second generation instrument for the VLT Interferometer (VLTI). GRAVITY will recombine the light of four telescopes simultaneously (either the four 8-m Unit Telescopes or the smaller, 1.8-m Auxiliary Telescopes) thus providing a large u–v coverage for image reconstruction. GRAVITY also feature an internal fringe tracker and phase referencing device. This is crucial for image reconstruction since it allows reconstructing non-point-symmetrical images. Phase referencing is also the fundamental concept for high-accuracy, narrow-angle astrometry as discussed below for Sgr A*'s flares. GRAVITY will operate in the K band and have polarimetric and spectroscopic capabilities.

A DESIGN DRIVER: THE GALACTIC CENTER

Observations of the GC with GRAVITY aim at detecting the effects of Special and General Relativity (SR/GR) on the dynamics of test particles (stars and gas). In addition, GRAVITY measurements will give unique insights into the three-dimensional structure, dynamics and evolution of the unique nuclear star cluster. Three possible observations, in order of increasing power for testing SR/GR but also of increasing technical difficulty, are:

- Precision measurements of the peri-passages of the relatively bright known orbiting stars in the central ≈ 0.5" (the 'S-stars': m_K ≈ 14–17; Ghez et al. 2008; Gillessen et al. 2009). Typically once every 5–10 years one of these stars passes through peribothron (e.g., S2 in 2002 and 2017) where the post-Newtonian corrections due to SR and GR to the orbital parameters to order $\beta^2 = (v/c)^2$ are most pronounced. Observations with SINFONI will detect the respective terms in their radial velocity curves (Zucker et al. 2006) but GRAVITY for the first time allows determination of the astromeric terms;
- Orbit measurements of fainter stars orbiting still closer to Sgr A* than the S-stars (Paumard et al. 2008; Vincent et al. 2011). Such stars provide frequent (≈ 1 yr^{-1}) opportunities for studying peri-passages, with some potentially occurring much closer than the best S-stars so far (10–15 light hours from Sgr A*), and with orbital periods possibly much shorter than 10–20 years. Effects of strong gravity, such as radial precession in the Schwarzschild term and potentially even frame dragging (Lense-Thirring precession) may become observable;
- Time resolved, 10-µas astrometry of the NIR 'flares' from Sgr A* itself (Hamaus et al. 2009; Vincent et al. 2011). Given the growing evidence that these flares originate in the innermost accretion zone on scales of a few to ten times the event horizon, where orbital velocities are a significant fraction of the speed of light and dynamical time scales are ≈ 10 min, astrometry of these flare events offer the unique opportunity of exploring the dynamics at (R/R_S) < 10, in the regime of strong gravity (R_S is the Schwarzschild radius of the event horizon).

A VERSATILE COMMUNITY INSTRUMENT

In addition to the GC, members of the GRAVITY consortium are interested in a wide variety of science cases, and the GRAVITY Science Group has devoted time to study science cases that we believe are of general interest to the ESO community. GRAVITY will allow probing scales of 100 pc at any redshift, which was only possible for the nearset active galactic nuclei (AGNs) in the seeing limit. The resolution in the closest AGNs (e.g. Circinus and Cen A) will be as small as 0.1 pc, equivalent to that of seeing-limited observations of the GC 10 years ago. Imaging protoplanetary disks or measuring the motion of bright spots in protostellar jets will become possible. Hundreds of possible targets are available in e.g. the Trapezium cluster. Jets in close star–compact object systems are also at hand. The astrometric capabilities of GRAVITY will allow weighing black holes at the center of globular clusters and finding substellar (brown dwarfs or planets) components in multiple star systems. Of course, GRAVITY will be an instrument of choice for continuing what has been a standard and fundamental application of interferometry: measuring the properties of binary stars. The mass of stars derived from astrometry is a crucial input parameter of evolution and structure models.

SUMMARY

GRAVITY, an interferometric imager with 10-µas astrometric capability, coupled with spectroscopic and polarization modes and optimized to exploit the exquisite sensitivity of the 4 × 4 VLTI system, will revolutionize dynamical measurements of celestial sources interacting by gravity. GRAVITY will carry out the ultimate empirical test whether or not the GC harbours a 4 × 10^6 M black hole, without resorting to theoretical assumptions. If the current interpretation of the NIR flares from Sgr A* is correct, GRAVITY has the potential of directly determining the space-time metric around this black hole. GRAVITY thus may be able test General Relativity in the presently unexplored strong curvature (R/R_S ≈ a few) limit. GRAVITY will also be able to unambiguously detect and measure the mass of black holes in massive star clusters throughout the Milky Way and in many active galactic nuclei to z ≈ 0.1. It will make unique measurements on gas jets in young stellar objects and active galactic nuclei. It will explore binary stars, exoplanet systems and young stellar disks. Because of its superb sensitivity GRAVITY will excel in milli-arcsecond phase-referenced imaging of faint celestial sources of any kind. Because of its outstanding astrometric capabilities, it will detect motions throughout the local Universe and perhaps beyond. Because of its spectroscopic and polarimetric capabilities it is capable of detecting gas motions and magnetic field structures on sub-milliarcsecond scales.

REFERENCES

Eisenhauer, F. et al. 2008, SPIE Conf. Ser. 7013
Ghez, A. M. et al. 2008, ApJ 689, 1044
Gillessen, S. et al. 2009, ApJ 707, L114
Hamaus, N. et al. 2009, ApJ 692, 902
Paumard et al. 2008, in *The Power of Optical/IR Interferometry...*, p 313
Paumard et al. 2011, ASP Conf. Ser. 439 267
Vincent, F. H. et al. 2011, ASP Conf. Ser. 439 275
Zucker, S. et al. 2006, ApJ 639, L21