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KILOMETER-BASELINE INTERFEROMETRY: SCIENCE DRIVERS FOR THE NEXT GENERATION INSTRUMENT

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Abstract. Infrared interferometry has seen a revolution over the last few years. The advent of GRAVITY+ is about to enable high-contrast observations, all-sky coverage and faint science up to $K_{\mathrm{mag}} = 21$, with the implementation on 8m-class telescope of extreme adaptive optics, wide-field observations, and soon laser guide stars, following a long-term vision of technological and infrastructure development at VLTI. This major progress in sensitivity lift a fundamental limitation of infrared interferometry, namely the brightness temperature achievable with this technique down to milli-arcsecond resolution imaging. This change of paradigm is a crucial element for the expansion of current arrays to a facility up to one to ten kilometer baselines. Micro-arcsecond scales imaging in the infrared on thermal objects, reaching the highest angular resolution possible even compared to VLBI, could offer a unique window in observational astronomy for the next generation instrument.

Keywords: high-angular resolution, infrared interferometry, high-contrast, kilometer baseline

1 Sensitivity

The fundamental limit in resolution of any high-angular resolution instrument is ultimately set by the brightness temperature, and therefore by the sensitivity achieved by a given instrument. In the case of VLBI, functioning at radio-wavelength, this limit is largely in the non-thermal domain, which fundamentally confines this technique to the study of quasars and the synchroton emission around a few object classes. In the O/IR domain, this limit is typically in the range of 1500K to 30,000K, corresponding to thermal objects. Therefore, the brighter the star - for a given surface brightness - the bigger in angular size it is ("bright stars tend to be big"). Based on the relation between angular diameters and temperature (Kervella et al. 2004; Boyajian et al. 2012), one can thus associate the maxium baseline, as defined by $B = \lambda/2\theta$, assuming a given brightness temperature. This criterion represents the limit for fringe-tracking for a single long-baseline (Fig 1). This highlights the fact that for high-angular resolution observations, there is necessarily a trade-off between sensitivity and angular resolution.

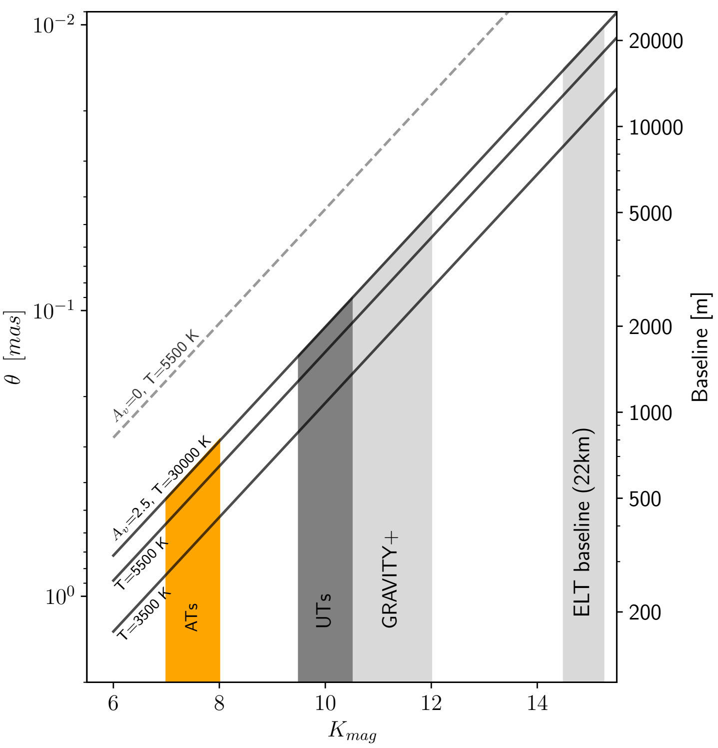

Fig. 1: Parameter space of infrared interferometery: baseline reachable as a function of sensitivity, computed at $\lambda = 2.2\mu m$.

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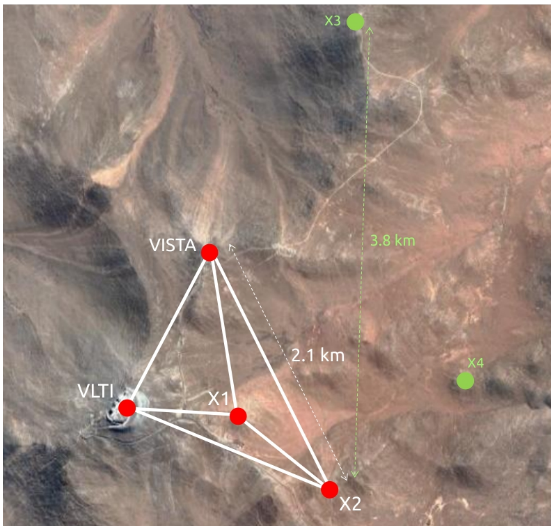

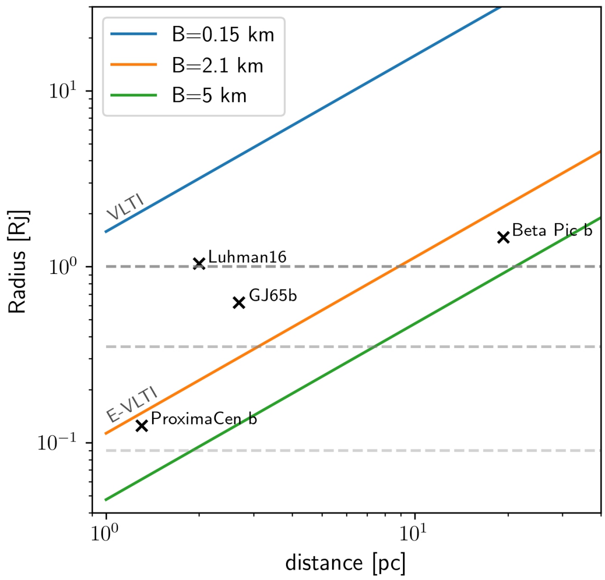

Fig. 2: a) Potential array layout of an Extended VLTI configuration, using the hills sourrounding the existing infrastructure of Paranal. b) Brown-dwarf and exoplanet radii in our Solar system neighborhood which could be resolved by a kilometer baseline interferometer.

In the recent years, a fundamental limit in sensitivity has been overcome with GRAVITY, which now routinely achieves $K_{\mathrm{mag}} = 11$ in fringe-tracking (FT) and $K_{\mathrm{mag}} = 19$ in science limiting magnitude. For the Galactic Center, the FT limiting magnitude is compatible with baselines up to 5 km assuming a large extinction A_v=2.5. For stars located in an environment with no extinction or in the solar neighborhood, the baseline reaches up to 10 km assuming the sensitivity GRAVITY+ on a G-type star.

2 Science drivers

The 50-100 μas imaging resolution and sub-μas astrometry with interferometry would open up a new parameter space in observational astronomy, in a similar fashion to the transformation between single arrays and VLBI in the radio-domain. In the following, we highlight major science topics that a kilometer array could address.

Early Universe up to redshift $z = 10$
The formation of supermassive black-holes (SMBH) and their evolution across cosmic time is a key element in our comprehension of galaxy evolution and black-hole physics. Recent observations with JWST have shown that SMBH are numerous and massive at the earliest stage of the Universe, with a dozen detections of broad line Active Galactic Nuclei (AGNs) between $z = 4$ and 10 (Maiolino et al. 2024). How do these objects form, are they direct collapse black holes? What is their exact mass, and how do they relate to the formation of SMBH seeds? Recently, GRAVITY+ provided the first dynamical measurement of a black hole mass at redshift $z = 2$ (Abuter et al. 2024), which is the only direct method allowing the measurement of black-hole dynamical masses at high-redshift. Kilometer-wide interferometry, with its $< 100\,\mu$as imaging resolution and sub-microarcsecond differential astrometry, would probe the mass and the evolution of SMBH up to redshift $z = 10$, and allow for full resolution imaging of the BLR region. The imaging capability of a kilometer array could hint at potential changes of its structure at high-redshift and allow the direct imaging of potential binary SMBH. The census of the binary SMBH population and its comparison with LISA (Amaro-Seoane et al. 2023) would be a key element to answer the final parsec problem and the coalescence of SMBH. The study of particular objects, such as OJ 287, which is thought to consist of a binary SMBH where the companion is plunging in the accretion disk of

the primary with a period of 12 years, offers the opportunity of spatially resolved observations and temporal monitoring over several years.

Black Hole accretion & No-Hair theorem

In our own Milky Way, the Galactic Center is a unique laboratory for experimental black-hole studies (Genzel et al. 2024). The monitoring of the stellar orbits of the S-stars with adaptive optics (Gillessen et al. 2009; Ghez et al. 2005) and infrared interferometry (GRAVITY Collaboration et al. 2017), allowed the measurement of the black-hole mass with an unmatched accuracy and general relativity tests, including the Schwarzschild precession around SgrA*, relativistic gravitational redshift or the local position invariance tests. Kilometer baseline interferometer will allow to directly resolve the accretion region of SgrA* and IR flare activity at the innermost circular orbit radius with a resolution $< 100\,\mu$as. In addition, the astrometric accuracy of interferometry would allow to constrain the black-hole spin and no-hair theorem tests. This could already be achieved by combining ELT-MICADO spectroscopy (Davies et al. 2021) and an upgraded version of GRAVITY with $< 20\mu$as astrometry, if an S-star is found with a pericenter 2 to 4 times smaller than S2.

Exoplanet Coverage

In the past two decades, ground-based and space observations have transformed our understanding of exoplanet atmospheres, showing a great diversity in composition and dynamics. Directly imaged brown dwarfs and exoplanets offer a key case for giant planets studies, and are expected to create large atmosphere circulation and clouds due to rapid rotation and strong interior convection. Yet, our knowledge of cloud coverage and properties, despite their profund influence on the atmosphere dynamic and radiative transfer, is largely limited. Brown-dwarf in particular exhibit patchiness on regional to global scales, as traced with doppler imaging, photometry, or spectroscopic monitoring (Crossfield et al. 2014; Biller et al. 2024). However, these techniques are intrisically non-resolved and limited by strong spatial degeneracies. Kilometer-baseline interferometry is the only technique able to spatially resolve these angular scales, an array with 2km to 5km being able to resolve the surface of brown dwarf and exoplanets in the Solar System neighborhood (Fig 2), including Luhman 16 (Fig 3). These observations also allow the direct measurement of the radius, placing a calibration point on the

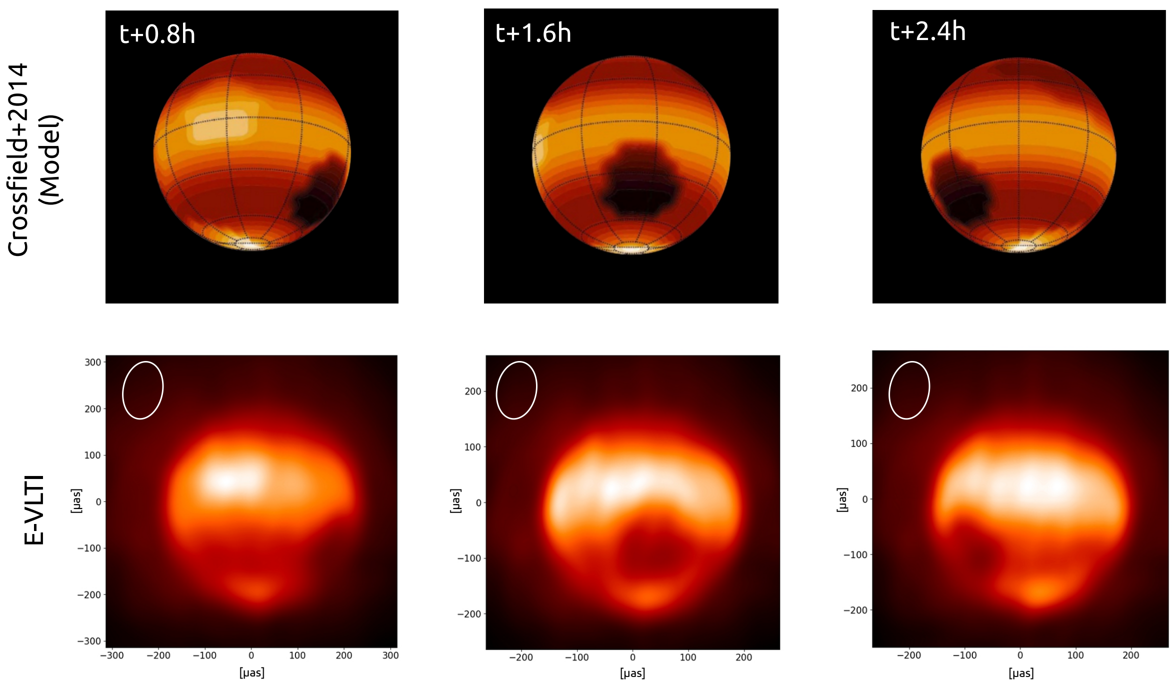

Fig. 3: Simulated image of Luhman 16B with a E-VLTI, based on the model of Crossfield et al. (2014).

evolutionary models of brown dwarfs and exoplanets. The imaging and astrometry resolution has also proven to constrain the potential presence of satellites in these systems, as recently demonstrated with GRAVITY (Xuan et al., accepted in Nature). Finally, for young planets, a 100 μas resolution directly constrains the size of the circumplanetary disk (CPDs) in the near-infrared (Rab et al. 2019).

3 Extended Very Large Telescope Interferometer

The Very Large Telescope Interferometer (VLTI) located at Paranal Observatory is the most sensitive interferometry facility to this day (Eisenhauer et al. 2023). Based on the current sensitivity of GRAVITY+, the addition of telescopes with 4m to 8m diameter is compatible with the recombination of baselines up to 2 km to 5 km (Fig 1), offering the opportunity to leverage the existing infrastructure of the VLTI to larger angular resolution. The site of Paranal itself and its surrounding infrastructure (VISTA, SPECULOOS) has an array configuration with a few kilometer width (Fig 2). The recombination would rely on more than three decades of developments in that area, and the development of key technologies, which includes:

- dual-field observations, to allow for long integration on faint targets.
- delay lines of the order of 1m/s speed (up to 10km baseline), and a total stroke covered by double-pass or incremental steps for the DC part.
- propogation including either optical fiber as explored initially at Mauna Kea in the 'OHANA project (Mariotti et al. 1998), free-space propagation with adaptive optics (Horst et al. 2023), or vacuum pipes (Mozurkewich et al. 2016).

4 Conclusions

The major breakthrough of near-infrared interferometry and the current sensitivity in the range of GRAVITY+ era open up a fundamentally new parameter space in high-angular resolution observations. Building upon the existing facility, the current sensitivity would be compatible with the extension of the interferometry facility to kilometer-wide baseline, based on 4m to 8m-class telescopes. Such an array would provide an imaging resolution of the order of 50-100μas in the infrared and sub-μas astrometric resolution in the near-infrared, addressing a unique domain of fundamental physics and astrophysics.

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