Science Prospects for Kilometers-Baseline Interferometry

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The future of optical/IR telescope – analogy to radio astronomy

The upcoming extremely large telescopes (ELTs) are analogs to the Green Bank- and Effelsberg radio telescopes, the last of their kind of fully steerable single dish telescopes. Because the technical challenges and costs for a single-dish telescope scale approximately with $D^{2\text{-}2.5}$ [1], much larger effective diameters require arrays of telescopes. At radio wavelengths, this transition occurred for single telescopes with a diameter of 100 meters. Kilometer-sized radio telescopes are implemented as interferometers [2], with the VLA an early example, and ALMA the currently most advanced. For optical/IR telescopes, the 39 m ELT and the 200 m VLT Interferometer mark this transition. Without doubt, future kilometers-sized optical/IR telescopes will be interferometric arrays. 130 years after the pioneering work of Michelson, classical interferometry, directly combining the electric fields from multiple telescopes, has reached maturity [3] and is scalable to large arrays. Fast progress in quantum optics, with multi-billion-euro investments and expected Moore's law performance growth, opens up even prospects for quantum interferometry [4] in the next few decades.

Optical/IR interferometry – a unique wavelength range for high-angular resolution astronomy

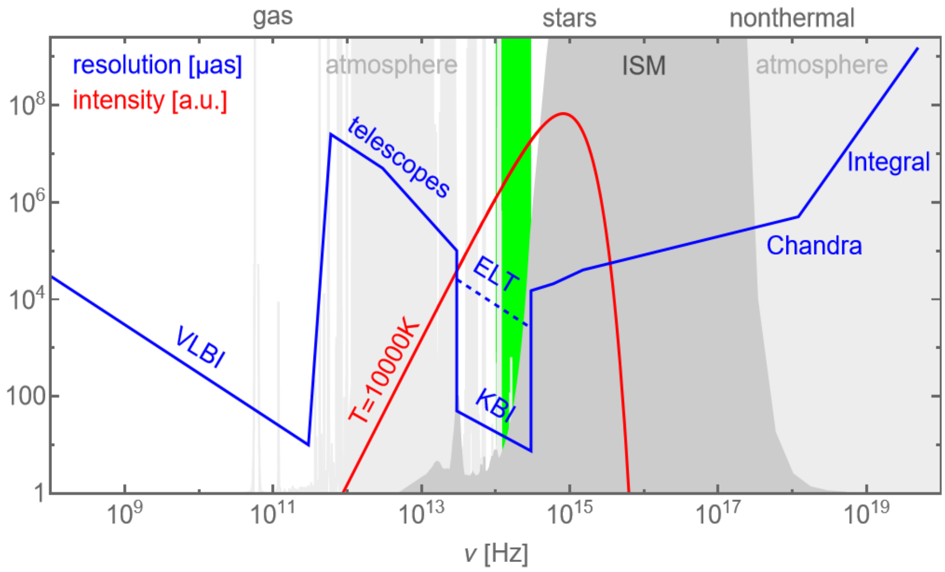


Fig. 1: The optical/NIR (green) is a sweet spot for observing at highest angular resolution. It is close to the peak of the thermal emission from stars, planets, and gas (red), (3) shortward of the Earth atmosphere absorption (light grey) and longward of the interstellar absorption (dark grey). The angular resolution (blue) is only matched by radio VLBI, but here observations are restricted to non-thermal emission.

The optical/near-infrared (NIR) waveband regime is unique in astronomy (Fig. 1). It is the combination of the highest angular resolution and the sensitivity to the thermal emission dominating the visible Universe, which traces the rich physics and chemistry through atomic and molecular lines. The infrared offers a largely unobscured view towards embedded and enshrouded regions not observable at shorter wavelength. Because the Earth's atmosphere is transparent at these wavelengths, it also allows for cost-efficient ground-based facilities and operation. Within only a few years, VLTI/GRAVITY has revolutionized high angular resolution astronomy with milli-arcsecond resolution imaging, a sensitivity-increase of thousands over previous interferometers, 30-100 micro-arcsecond astrometry, and micro-arcsecond spectro-astrometry. Its transformative observations span a very wide range of astrophysics, e.g., spatially resolving the line emission from quasars in the distant universe, probing general relativity in the orbits of stars around the Galactic Center black hole, tracing motions close to its event horizon, the direct detection and spectroscopy of exoplanets not observable by other techniques, and resolving the images of Galactic microlensing events.

Astronomy with 10 µas resolution, ELT sensitivity, and 0.1 µas astrometry

The angular resolution of a future optical/IR interferometer with baselines up to ten kilometers length (**K**ilometer **B**aseline **I**nterferometer) reaches a stunning $\Theta = \lambda/2B = O(1\mu m/2 \times 10km) \approx 10\ \mu as$. The astrometric precision for small separation objects and for spectro-astrometry – differential astrometry across the spectrum of the object – will be even better ≈ 0.1 µas. The point source sensitivity will be comparable to a telescope with the same total collecting area. E.g., when including the ELT in the interferometer, it will be about 28 mag_{AB} for broadband imaging and about 23 mag_{AB} for $R \approx 3000$ resolution spectroscopy. Here, we present exemplary science perspectives, ranging from the solar system (Fig. 2) to the distant universe (Fig. 3).

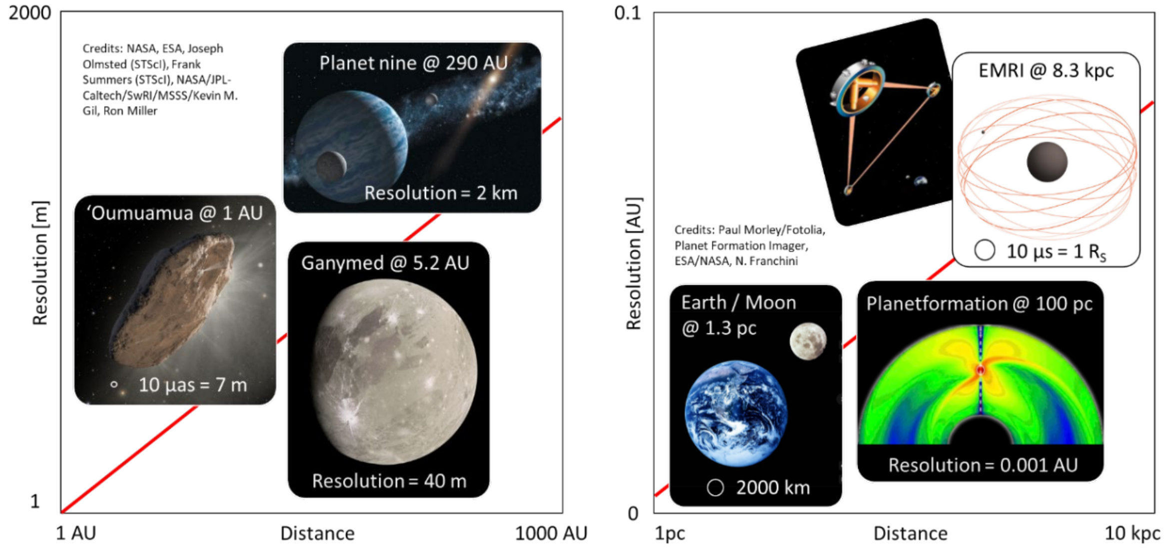
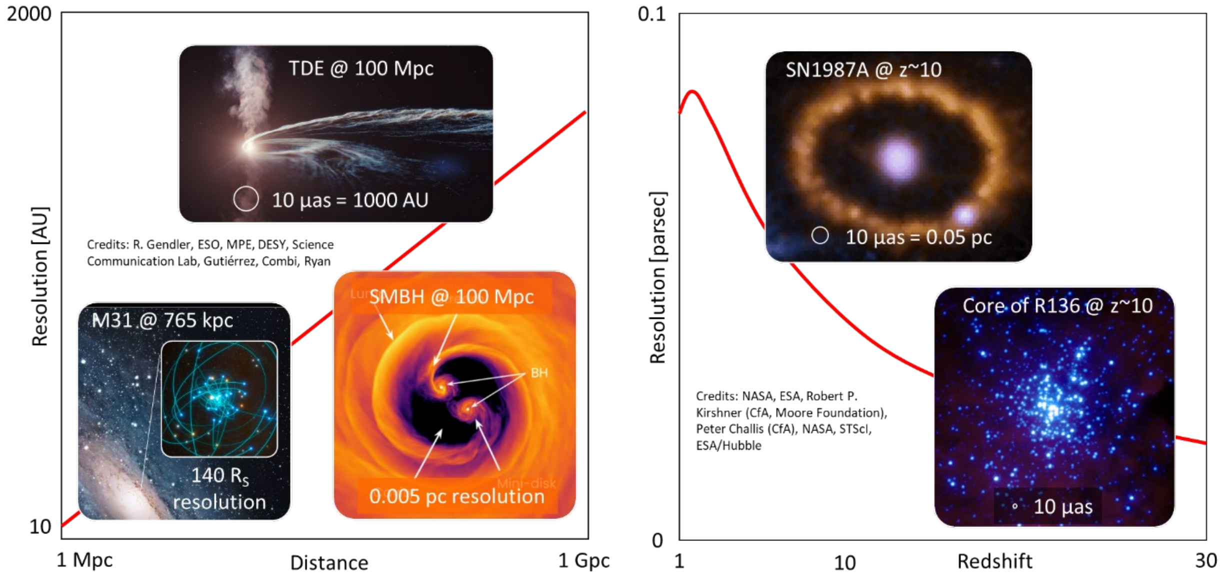


Fig. 2: Science prospects for kilometers-baseline Interferometry in the solar system (left) and the Milky Way (right)

- Interstellar objects passing through the solar system: so far, only three such objects have been observed, but several are expected to pass inside Earth's orbit each year. The first confirmed was 'Oumuamua [5], approaching the Sun as close as 0.25 AU. From the observed light curve, it is likely cigar- or disc-shaped, with a size of a few hundred meters; however, its surface structure is unknown. KBI's resolution at closest approach to Earth (0.22 AU) corresponds to 1.6 m, allowing to image the surface, clarifying the origin and nature of this interstellar interlopers.
- Moons in the outer solar system: they are potential habitats of extraterrestrial life and prime targets for upcoming space missions, e.g., JUICE [6], which will map Jupiter's icy moons Ganymede, Callisto, and Europa. The angular resolution of KBI at the distance (5.2 AU) of Jupiter corresponds to 40 m, and will serve parallel and follow-up observations for future missions.
- Planet nine: the orbits of distant trans-Neptunian objects hint towards a so far not-detected planet in the outer solar system [7] with a predicted orbit at 200-800 AU. Mass predictions range from 4 – 10 Earth masses, and its diameter is estimated to be around 46.000 km or about 0.2" (at 290 AU), barely resolvable by single telescopes. At such a large distance, no space mission will be able to visit planet nine soon. KBI will therefore offer a unique possibility to uncover its nature.
- Exoplanets: most stars have multiple planets. With a resolution of 15000 km at a distance of 10 pc, KBI will resolve the cloud coverage and circulation on giant planets. For the nearest stars, KBI will even image planet surfaces at the scale of continents, and give weather maps for Earth-sized planets.
- Star- and planet-formation: the formation of the solar system and its rocky planets is the result of a complex interplay between star-accretion and disk-evolution [8]. For young stars within 100 pc, KBI will have a resolution to better than the diameter of Jupiter, resolving all scales down to the Hill's radius and circumplanetary disks, and even the accretion onto planetary surfaces themselves.
- Exomoons: our solar system hosts 18-19 major moons and many smaller ones. Life might be more frequent on moons than planets. Also, for spectroscopic exoplanet studies, which probe life through abundance ratios of various molecules [9], one needs to ensure that the spectrum is not a mix of the planet's and its moons' atmospheres, each without a signature of life. The angular separation between Earth and Moon at a distance of 10 pc is 260 µas, resolvable with KBI, allowing to measure the spectrum of each of them.
- Directly tracing gravitational wave sources in the Galactic center: white dwarfs, neutron stars, stellar black holes, and even brown dwarfs, are so compact that they can approach the black hole down to the innermost last stable (60 µas diameter) orbit without tidal disruption. Their orbital periods can be sufficiently short to fall within the detection band of the LISA gravitational wave interferometer [10]. KBI will be able to directly see and follow these LISA sources of gravitational waves on their complex orbits in the rotating space-time.



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Credits: NASA, ESA, Robert P. Kirshner (CfA, Moore Foundation), Peter Challis (CfA), NASA, STScI, ESA/Hubble

Fig. 3: Extragalactic (left) and cosmological (right) science prospects for kilometers-baseline interferometry

- Galactic centers in Andromeda and nearby galaxies: at a distance of 765 kpc, the Andromeda galaxy hosts a black hole with about 10^8 M_{Sun} [11]. The KBI resolution will be ≈140 Schwarzschild radii (R_S), comparable or even better than the angular resolution of GRAVITY in the Galactic Center, which is about 175 R_S. We will finally have a second benchmark system to repeat the Galactic Center experiments and probe the diversity of black hole astrophysics.
- Tidal disruption events out to the Coma cluster: while the tidal disruption radius is only about 1 AU for a sun-like star and a 10^7 M_{Sun} black hole, the fallback stream and its self-interaction have sizes up to several 1000 AU or a few 10 mpc [12]. This stream will be resolved with KBI, for which the resolution is about 5 mpc in, e.g., the Coma cluster with a distance of 100 Mpc.
- Massive binary black holes and the final parsec problem: when two galaxies merge, their central black holes sink to the center. At a separation of about 1 pc, when there are not enough stars and gas available anymore to remove angular momentum, the black hole merger is expected to drastically slow down [13]. However, there is so far little observational evidence for this. KBI will directly image and resolve these massive binary black holes, and with sub-µas spectro-astrometry of their broad-line region, trace the late stages at the smallest separations before gravitational wave emission takes over.
- Supernovae as geometric probes throughout the universe up to the highest redshift: because of the cosmic magnification, objects at a redshift larger than $z \approx 2$ appear ever larger with increasing distance. The physical resolution of a KBI will be better 0.1 pc at $z = 2$, and as good as 0.02 pc at $z = 30$. The circumstellar rings around supernovae – as we know from HST images of SN 1987A [14] – will be fully resolved, thereby providing a geometric ruler to directly measure the expansion of the universe without systematic biases, resolving possible tensions and inconsistencies in other cosmological probes.
- First stars and black holes at redshift 10 – 30: the JWST discoveries of extremely compact galaxies, star clusters, and massive black holes at the highest redshift are challenging our understanding of the early universe [15]. Many of the phenomena and objects are unresolved at the angular resolution of JWST and probably the ELT. This will be different for KBI, for which even extremely dense star clusters like R136 in the Magellanic Cloud will be resolved into individual stars at these extreme redshifts.

References

[1] van Belle et al. 2019 [2] Thompson, Moran, Swenson 2024 [3] Eisenhauer, Monnier, Pfuhl 2023 [4] Bland-Hawthron et al. 2021 [5] Meech et al. 2017 [6] JUICE definition study report 2014 [7] Batygin et al. 2019 [8] Armitage 2024 [9] Schwieterman et al. 2018 [10] Amaro-Seoane et al. 2017 [11] Bender et al. 2005 [12] Ryu et al. 2023 [13] Merritt & Milosavljević 2005 [14] Panagia et al. 1991 [15] Adamo et al. 2025