

# Beyond the Pale Blue dot: Resolving Exoplanet Surfaces in the 2040s

ESO Expanding Horizons White Paper

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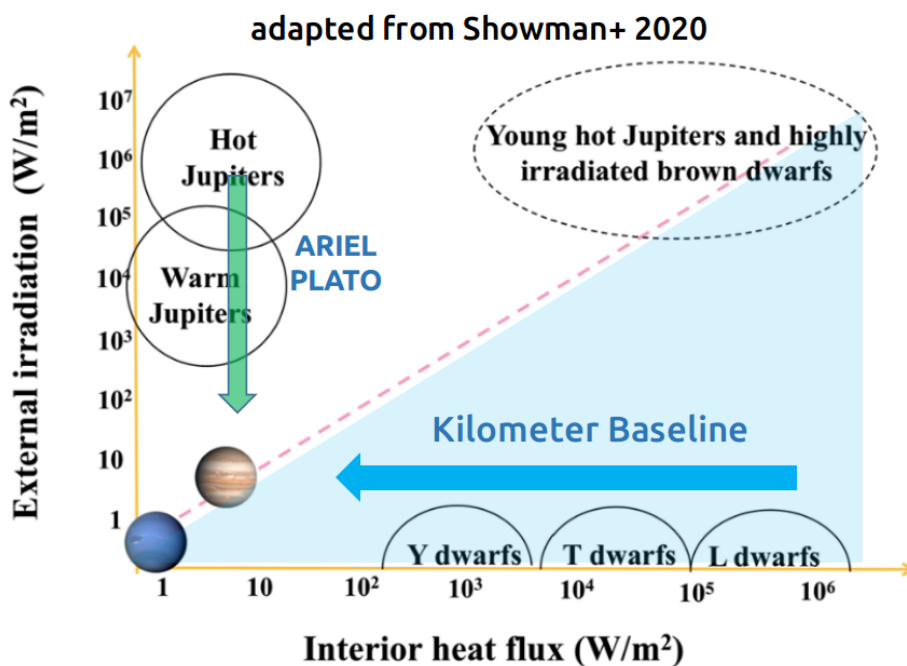
## Introduction

Since the discovery of the first exoplanet (Mayor & Queloz, 1995), ground-based and space-based observations have provided a wealth of observations which allows us to characterize the fundamental parameters of exoplanets (mass, radius, temperature, composition), and among the most valuable information, the composition of their atmosphere. Combined with numerical modeling, those observations provides an insight on the physical conditions and the formation pathways of these planets. Transits, optical and infrared light curves provide information on the composition of hot/warm Jupiters, and in some conditions information on the spatial distribution and atmospheric circulation on their surfaces, which is dominated by the irradiation of the host star. On the other hand, direct imaging focus on brown-dwarf and young giants, which radiative balance is dominated by strong interior flux of the planet, are probing a different regime of atmosphere dynamic (Showman et al. 2020, Figure 1). Finally, planetology and space probes in our own Solar System allow to observe mature planets in extreme details, but is limited to only a very limited sample. Using a future angular resolution of  $100\mu\text{as}$  angular resolution would allow to resolve directly the surface of planets, opening up the ability of truly comparative exoplanetology at the horizon 2040s.

## Cloud coverage and surface imaging

From existing models, brown-dwarf and giant planets are expected to show large atmospheric circulation (Tan et al. 2020, Charnay et al. 2024). For nearby brown-dwarfs, doppler imaging observations have shown the presence of large clouds (Crossfield et al. 2014), although those observations are intrinsically degenerated in latitude. For giant planets, clouds and dynamic circulation is already taken into account in the atmosphere modeling (Molliere et al. 2020), although they are not resolved and little is known about their spatial distribution.

Ultimately, the spectral characterization of nearby planets in reflected light - which is the goal of third generation of VLT/I and ELT instruments - should be available by 2040. Beyond the ELT, kilometer baseline interferometry (KBI) will allow to directly resolve the surface and cloud coverage of exoplanets.



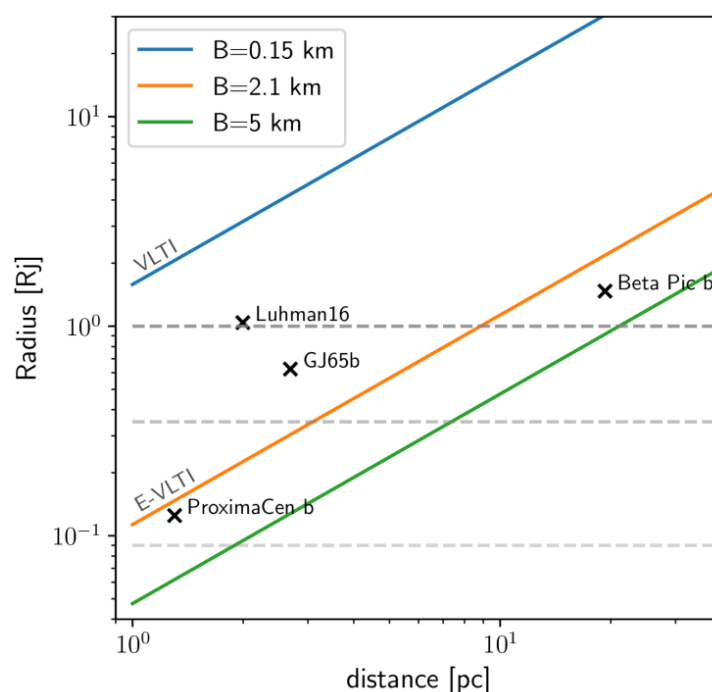
**Figure 1:** Parameter space of planet populations, adapted from Showman+2020, as a function of Interior heat flux (horizontal axis) and flux received from the star (vertical axis).

## Sub-milliarcsecond imaging in the infrared

Sensitivity is a fundamental parameter for an improvement of angular resolution: this is the equivalent of brightness temperature for large configurations on radio-arrays. With the existing sensitivity achieved by GRAVITY+ (GRAVITY+ Collab. 2022), the extension of infrared interferometer arrays is possible up to several 10km baseline (Bourdarot & Eisenhauer 2024). The improvement of sensitivity in GRAVITY+ relied on the use of large telescopes (VLT's Unitary Telescope, 8m class) and key technologies: dual-field combiner, fringe-tracking, noiseless infrared detectors, and the combination of interferometry with extreme Adaptive Optics and Laser Guide stars (Eisenhauer et al. 2023). Sensitivity is therefore a key parameter of an extended interferometric array, which should be carried on an array of telescopes of at least 4m to 8m diameter.

## Resolving exoplanet surfaces

The development of an extension of VLTI with outrigger telescopes located a few kilometers from the VLTI platform would already allow us to resolve the surface of nearby planets (Figure 3). For a 5km baseline array, the surfaces of Proxima Cen b (1.3 pc), Neptune size planets around M-dwarfs at 2-3 pc (e.g GJ65) or Young Giant planets like e.g. Beta Pic b (20 pc) are all resolved. Snapshot imaging requires a minimum of 6 telescopes (see Figure 2), an important parameter given that these objects are usually fast rotators (Snellen et al. 2014). In addition, a  $100 \mu\text{as}$  imaging capability and  $1 \mu\text{as}$  astrometry capability would be sensitive to exomoons orbiting these planets (Winterhalder et al. 2026), and the circumplanetary disks around protoplanets (Benisty et al. 2021, Marleau et al. 2026).



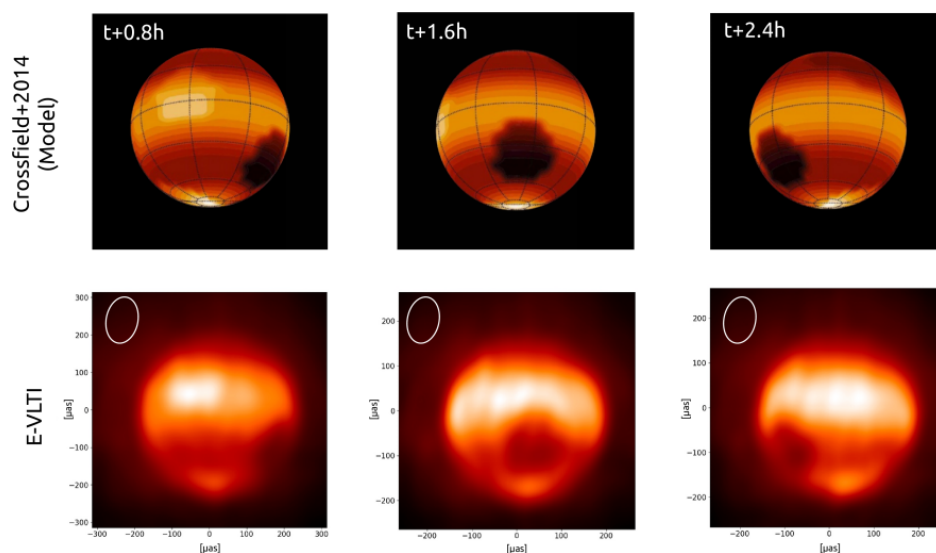
**Figure 2:** Planetary radius versus distance. Nearby planets which are resolved with an extended VLTI (E-VLTI) array for a 5km (green) array at  $2 \mu\text{m}$  wavelength.

In the 2040s landscape:

- Hot/Warm Jupiters: ARIEL / PLATO will characterize hundreds to thousands of planets, focusing on hot and warm planets (strongly irradiated planets, weak interior flux), down to warm super-Earths (Ariel Definition Study Report 2020, Rauer et al. 2025)
- Directly Imaged Giants and Brown Dwarfs: ELT will be able to perform high-spectral resolution characterization of young giant planets at large separation their star (negligible stellar irradiation, strong planet interior flux, rapid rotator), and nearby rocky planets with ELT/PCS (Kasper et al. 2021).

The uniqueness of a Kilometer Baseline Interferometry (KBI) compared to:

- Doppler imaging: KBI will provide non-degenerate spatial observations compared to doppler imaging reconstruction.
- Transit: KBI will sample a complementary population of weakly irradiated planets, at larger separation from their host star, probing different atmospheric circulation regime.
- ELT/Direct imaging: the angular resolution of KBI will provide spatially resolved observations of their surface, and a direct measurement of planetary radius of directly imaged planets.



**Figure 3:** Simulation of the surface imaging of the brown-dwarf Luhman 16 with a 6 telescopes, 4km baseline interferometer at  $2\mu\text{m}$  wavelength.

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