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The Future of Rocky Worlds Exploration

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Abstract
This article reviews the short-, medium-, and long-term prospects for characterizing rocky exoplanets, a central goal of contemporary astrophysics. The primary objectives are to determine whether these planets host atmospheres; if so, to constrain their molecular composition and search for potential biosignatures; if not, to infer their surface composition and thereby enabling a form of exo-geology. In the near term, the *James Webb Space Telescope* (*JWST*) will continue to lead this effort through photometric and spectroscopic observations of transits, eclipses, and phase curves, primarily targeting rocky exoplanets orbiting M dwarfs, including a limited number within their habitable zones. By the early 2030s, Giant Segmented-Mirror Telescopes (GSMTs) will provide the combination of high angular resolution, high contrast, and high spectral resolution needed to characterize rocky exoplanets around nearby M dwarfs via direct imaging, significantly broadening the accessible target sample and enabling detailed atmospheric and surface studies. Extending these investigations to rocky exoplanets orbiting solar-type stars, particularly those within habitable zones, will require the launch of next-generation space observatories in the 2040s, such as the *Habitable Worlds Observatory* (*HWO*), optimized for ultraviolet-to-near-infrared observations, and the *Large Interferometer For Exoplanets* (*LIFE*), designed for mid-infrared interferometry. In parallel, characterizing the broader planetary environment — including host stars and additional companions — will provide essential context. Missions such as *Gaia* (astrometric detection of companions), *PLATO*, *Earth 2.0* (stellar characterization via asteroseismology), and *Ariel* (population-level atmospheric studies) will offer critical complementary insights into the architectures and habitability of nearby planetary systems.

Keywords Rocky exoplanets · Atmospheres · Geoscience · Space missions · Extremely large telescopes · Biosignatures

1 Introduction

The quest to determine whether life exists beyond Earth is ancient. Philosophers and theologians have argued in one way or another without definitive conclusions. The science has never been closer to providing an answer. The first discovery of an exoplanet is relatively recent. The surprising detection of a hot Jupiter orbiting close to its Sun-like stellar host was announced in 1995 (Mayor and Queloz 1995). This giant exoplanet, 51 Pegasi b, orbits extremely close to its host star at 0.053 astronomical units (AU); for comparison, Mercury

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orbits the Sun at 0.39 AU. Since then, more than 6000 exoplanets have been detected, including rocky planets in the habitable zone of their host star — see the Exoplanet Encyclopedia (Schneider et al. 2011) or the NASA Exoplanet Archive (Akeson et al. 2013). The first rocky exoplanet was detected in 2009 thanks to transit observations with the *CoRoT* space mission (Léger et al. 2009), complemented by radial velocity measurements to determine the exoplanet mass (Queloz et al. 2009). The exoplanet, CoRoT-7 b, has a radius of $\sim 1.58\ R_\oplus$ and a mass of $\sim 4.8\ M_\oplus$. With a radius of $1.02\ R_\oplus$, Kepler-186 f was the first Earth size exoplanet detected in the habitable zone of its host star (Quintana et al. 2014). The observations were transit observations obtained with the *Kepler* space mission (Borucki et al. 2010). The *Kepler* mission has been very successful with the confirmed detection of ~ 2800 exoplanets, including about 30% with a radius lower than $1.6\ R_\oplus$ (NASA Exoplanet Archive 2026), and thus likely rocky (Rogers 2015).

The vast majority of the exoplanets discovered during the prime *Kepler* mission are too far away for detailed follow-up observations in terms of studying their atmosphere. The *TESS* mission (Ricker et al. 2015) was deployed in 2018 with a key goal of identifying many new promising rocky exoplanets for detailed follow-up by the *James Webb Space Telescope* (*JWST*) (Gardner et al. 2023), which was launched on the 25th of December 2021. *TESS* surveys nearby stars across the sky, with a strong yield of planets around M dwarfs. *TESS* is currently in its third extended mission (EM3) and should continue to operate at least until September 2028, utilizing repeated visits and extended dwell time on each observed sector to search for exoplanets with longer orbital periods.

Planets around M dwarfs represent an exciting opportunity for investigating potential habitable planets. These stars are the most abundant in our vicinity (Henry and Jao 2024 and references therein) and present multiple advantages. First, their smaller radii compared to Sun-like stars make transits easier to detect. Second, they often host more than one short-period rocky planets (e.g., Mignon et al. 2025). Third, their cooler effective temperatures lower the ratio between the star and planet emissions, facilitating atmospheric characterization through eclipse observations. Fourth, their habitable zones lie close to the star, resulting in shorter orbital periods and higher transit probabilities. Consequently, habitable-zone planets around M dwarfs are currently the only potentially habitable exoplanets whose atmospheres can be probed, making them a primary focus of ongoing observational and theoretical studies.

The hunt for transiting rocky planets around M dwarfs began well before *TESS*, through ground-based programs such as *MEarth* (Irwin et al. 2009) or *TRAPPIST* (Gillon et al. 2011), the latter leading to the discovery of the exceptional seven-planets TRAPPIST-1 system. Observational strategies have progressively shifted toward the near-infrared, the wavelength range in which late-type M dwarfs emit most of their flux. For example, using deep-depletion CCD detectors, the *Tierras* Observatory operates with a custom narrow-band filter (40.2 nm Full Width Half Maximum) centered at 863.5 nm (Garcia-Mejia et al. 2020). The use of InGaAs detectors enables observations at longer wavelengths than CCDs. The *SPIRIT* (SPeculoos InfraRed Imager for Transits) instrument (Pedersen et al. 2024), mounted on one of the telescopes of the *SPECULOOS* Southern Observatory (Delrez et al. 2018), provides coverage over the 0.81–1.33 μm wavelength range. A comparable spectral range ($\sim$0.8–1.55 μm) is probed by the *ExTrA* facility (Exoplanets in Transit and their Atmospheres). In general, transit observations do not provide the mass of the exoplanet, except in systems with multiple planets in near mean-motion resonances; indeed, transit timing variations (TTVs) offer a powerful method for mass determination, as demonstrated in the TRAPPIST-1 system (Agol et al. 2021).

Radial velocity (RV) observations of nearby M dwarf systems have also ramped up over the last decade, both to discover new non-transiting exoplanets and to help determine,

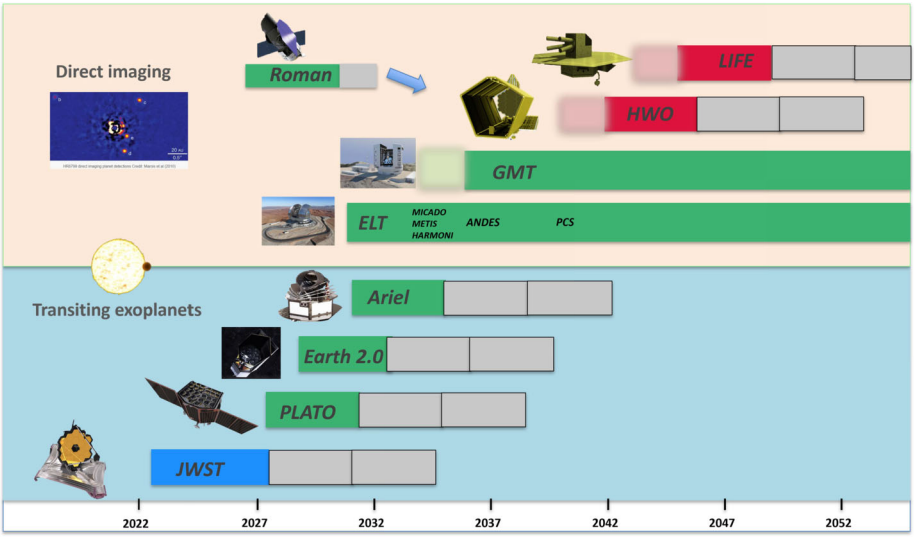


Fig. 1 Roadmap of future observatories relevant to the study of rocky exoplanets. The large rectangle in light blue encompasses facilities primarily observing transiting rocky exoplanets, while the rectangle in color sand indicates facilities using direct imaging but capable of observing transiting planets as well. Bar colors represent operational status: blue for in operation, green for in development, red for under study, and grey for possible extensions beyond the nominal operational phase. For the *ELT*, first-generation instruments (*MICADO, METIS, HARMONI*), as well as second-generation instruments under study (*ANDES, PCS*), are shown. Fuzzy rectangles preceding the bars for *GMT*, *HWO*, and *LIFE* indicate that the operational start date is uncertain. The *Roman* telescope is highlighted with an arrow to show its technological contributions to prepare *HWO*. Using microlensing, *Roman* will also provide exoplanet demographics in regions not yet explored (Wilson et al. 2023); same is true for *Earth 2.0*

through accurate mass measurements, the density of the planets detected by transit surveys. RV facilities include *HARPS* (Mayor et al. 2003), *HARPS-N* (Cosentino et al. 2012), *ESPRESSO* (Pepe et al. 2021), *CARMENES* (Quirrenbach et al. 2016), *SPIRou* (Donati et al. 2020), *NIRPS* (Bouchy et al. 2017), *GIANO-B* (Claudi et al. 2018), *IRD* (Kotani et al. 2018), and *MAROON-X* (Seifahrt et al. 2020). RV surveys are discovering an increasing number of non-transiting and potentially rocky planets around the nearest ultracool dwarfs, such as Proxima Centauri b (Anglada-Escudé et al. 2016) and Barnard's Star b (Ribas et al. 2018).

Owing to the combined capabilities of current facilities, we now possess a growing sample of rocky exoplanets ready for detailed characterization. In the following sections, we outline the future of rocky temperate exoplanet observations in three temporal stages: near term, medium term, and long term. Section 2 deals with the near term; the *James Webb Space Telescope* (*JWST*) will remain the key facility for studying rocky planets orbiting M dwarfs. Section 3 is devoted to the medium term, early 2030s; next-generation Giant Segmented-Mirror Telescopes (GSMTs) will advance the study of rocky exoplanets, while space missions such as *Gaia*, *PLATO*, *Earth 2.0* and *Ariel* will provide essential context, including the characterization of stellar and circumstellar environments. The long term (2040s) is discussed in Sect. 4; *the Habitable Worlds Observatory* (*HWO*) and the *Large Interferometer for Exoplanets* (*LIFE*) will offer complementary approaches to the ultimate goal of detecting and characterizing temperate, Earth-sized planets orbiting Sun-like stars. The projected timeline of these facilities is summarized in Fig. 1.

2 What Is Possible Now and in the Near Term: Characterization of Rocky Exoplanets Around M Dwarfs with *JWST*

The *JWST* has opened a transformative chapter in exoplanetary science, particularly in the study of rocky exoplanets. With its large diameter aperture (primary mirror of 6.5 m size) and its wide wavelength coverage (from 0.6 to 28 μm), *JWST* is uniquely positioned to characterize small, temperate exoplanets orbiting nearby M dwarfs. The *JWST* observations can probe whether the rocky exoplanets have an atmosphere or not, and if yes, what is the composition of the atmosphere. Indeed in the *JWST* wavelength range, there are signatures of key molecular species expected in the atmosphere of an exoplanet, such as H_2O, CO, CO_2, CH_4, SO_2, NH_3... *JWST* is an observatory which is of interest for many astronomers in various themes. More than 6000 astrophysicists have participated in answering to the cycle 4 proposal call; there is about 9 times more observing time requested than available, so that the telescope pressure is high. About 27% of the observing time is devoted to exoplanet science (Espinoza and Perrin 2025). Another large fraction of time ($\sim$ 30%) is devoted to the observation of galaxies.

JWST began searching for atmospheres around rocky exoplanets shortly after scientific operations commenced in July 2022. As listed in the TrExoLiSTS database (https://www.stsci.edu/~nnikolov/TrExoLiSTS/JWST/trexolists.html), which compiles all *JWST* observations of transiting exoplanets, out of the 173 exoplanets observed or scheduled to be observed with *JWST* during cycles 1 to 4, about 25% are rocky; (37 based on the density and 6 with no density measurement but with a radius R $< 1.6\ R_\oplus$; Rogers 2015). About 30% of the observing time allocated to exoplanet characterization is devoted to rocky planets.

2.1 Methods to Study Rocky Exoplanet Atmospheres

The observations are limited to those exoplanets which are transiting. The observations employ two main approaches: (i) transit spectroscopy, observing the exoplanet before, during, and after a transit, and (ii) eclipse observations, conducted photometrically or spectroscopically before, during, and after an eclipse. Combining transit and eclipse data helps constrain atmospheric models more tightly, as demonstrated in the study of GJ 1132 b (Bennett et al. 2025b). A small subset of exoplanets with ultra-short orbital periods — typically less than one day — have been monitored throughout a full orbit (phase curve).

Transit spectroscopy probes the absorption of starlight at the exoplanet's limbs, most often in the near-infrared using the NIRSpec instrument. Eclipse observations are of special interest to search for atmosphere around rocky exoplanets which are tidally locked. Indeed, for such exoplanets, there is a side always receiving photons from the star (dayside) and a side which does not receive light from the star (nightside). If there were an atmosphere, energy would be transported from the dayside to the nightside, so that the luminosity of the dayside would be lower than if there were no atmosphere. The thermal emission from the exoplanet's permanent dayside is typically probed in the mid-infrared with *JWST/MIRI*, using either photometry or slitless low-resolution spectroscopy. In photometry, the F1500W filter is often used (Greene et al. 2023; Zieba et al. 2023; Gillon et al. 2025; Redfield et al. 2024; Diamond-Lowe et al. 2023) because of the strong detectable CO_2 absorption feature around 15 μm (e.g. Deming et al. 2009).

2.2 The Search of Atmosphere: First Results and Perspectives

A comprehensive review of early results is presented in (Kreidberg and Stevenson 2025). To date, no rocky temperate exoplanet atmosphere has been definitively detected at a confidence level of 5σ or higher. Nevertheless, there are hints of the presence of atmosphere

for several exoplanets. For example, the spectrum of the sub-Earth-sized planet L 98-59 b (planet radius of 0.85 $R_\oplus$) is so far the one which deviates the most from a flat line (at the level 3.6 σ), showing hint of a SO_2 rich atmosphere, which is interpreted as replenishment of the atmosphere by volcanism (Bello-Arufe et al. 2025). Hints of a non-flat spectrum have also been found for the super-Earth L 98-59 d (1.58 $R_\oplus$ and 2.31 $M_\oplus$) (Gressier et al. 2024); but the nature of the object (rocky or not) is questioned (Demangeon et al. 2021). In terms of eclipses, achievements have been obtained with the measurement of the brightness temperature of temperate rocky exoplanets starting with Trappist-1 b (500 K) (Greene et al. 2023; Ducrot et al. 2025); a temperature as low as 340 K has been measured when observing Trappist-1 c (Zieba et al. 2023). Thick CO_2 atmosphere has been ruled out, but the precision of the observations is not yet sufficient to distinguish between a bare rock and an exoplanet with a thin atmosphere made mostly of heavy elements; thick meaning a surface pressure greater than 10 bars (Kreidberg and Stevenson 2025). Indications, at the 2 σ level, in favor of an atmosphere have been found for LHS 1478 b, a rocky exoplanet with a radius of 1.24 $R_\oplus$ and a mass of 2.33 $M_\oplus$ (August et al. 2025a); follow-up observations have been granted in Cycle 4 (August et al. 2025b). Eclipse observations of 55 Cancri e with *JWST/MIRI* (LRS slitless mode) and *JWST/NIRCam* suggest the possible presence of a substantial atmosphere, potentially with significant variability in both composition and temperature (Hu et al. 2024; Patel et al. 2024). 55 Cancri e is a very intriguing object. It has a radius of 1.9 $R_\oplus$, a mass of 8 $M_\oplus$ (Bourrier et al. 2018) and orbits a solar-type star. It is very hot, with an equilibrium temperature of 1958 K (Demory et al. 2011). The mean density of 5.5 g cm^{-3} is lower than the one of a planet of that size made of rocks. The exact nature of the exoplanet is under debate, (e.g. Ross et al. 2025). Another intriguing ultrahot super earth, TOI-561, has a measured temperature between 1800^{+120}_{-60} K and 2150 $\pm$ 80 K, according to the data reduction in use (Teske et al. 2025). In any case, it is much lower than the maximum temperature of 2950 K (calculated with zero albedo and no energy distribution between the dayside and the nightside), suggesting the presence of a thick volatile envelope that is cooling the dayside (Teske et al. 2025).

The study of the thermal emission of rocky planets will keep on being a major subject for *JWST*. For example, following the recommendations from the Working Group on Strategic Exoplanet Initiatives with HST and *JWST* (Redfield et al. 2024), 500 hours over 3 years from the STScI Director's Discretionary Time (DDT) has been awarded to a program, whose main objective is to search for atmospheres on rocky exoplanets orbiting M dwarfs. As explained in Sect. 2.1, the way to get hints about the presence or not of an atmosphere consists in measuring the dayside luminosity of the exoplanet, via *MIRI* observations with the F1500W filter. The list of 80 potential targets can be found at https://rockyworlds.stsci.edu/rw-website-targets.html. The first target of the program, GJ-3929 b, has been observed and its measured temperature of 782$\pm$79 K makes it compatible with a bare rock (Xue et al. 2025). Eight other targets have been selected: LTT 1445 A c, LTT 1445 A b, LHS 1140 b, TOI-198 b, TOI-406 c, TOI-771 b, HD 260655 c, and TOI-244 b. Note that, rocky exoplanet transit observations are also well represented, with a 245-hours General Observing program accepted for Cycle 4 (Lustig-Yaeger et al. 2025).

Given the possible JWST life time of more than 20 years, at least from the point of view of propellant reserve (Rigby et al. 2023), we can expect a lot of key results from *JWST* on the knowledge of atmosphere of rocky exoplanets around M stars. The Trappist-1 system should keep on generating a lot of interest. Stellar contamination, throughout the so-called Transit Light Source effect (Rackham et al. 2018), has so far limited the transit observations. But ways to mitigate the effect, such as observing first with Trappist-1 b (assumed to be bare rock) to monitor the star behavior and right after observing the Trappist-1 e exoplanet

(Allen et al. 2025). The exoplanet is in the habitable zone of Trappist-1 and the holy grail would be to find biosignatures. It is done by finding pairs of molecules which would not be both present if the atmosphere were in a thermodynamically equilibrium state. Krissansen-Totton et al. (2018) have shown that a high abundance of CH_4, CO_2 and low abundance of CO would be probably a candidate biosignature that could be detectable by the *JWST* if Trappist-1 e had an anoxic atmosphere analogous to that which has likely existed on the early Earth.

2.3 Studying the Surface of Rocky Planets

For exoplanets that lack a substantial atmosphere, it becomes possible to peer directly at their surface composition and inaugurate a form of exogeology, framing our Solar System's rocky worlds in a broader exoplanetary context. In their foundational work, Hu et al. (2012) developed a model combining reflected starlight and thermal emission to show that silicate surfaces imprint broad Si–O absorption features in the mid-infrared (e.g. $\sim$ 7–13 μm). They also proposed that the wavelength location of the so-called Christiansen feature could distinguish mafic versus felsis surfaces, thereby offering a spectral probe of surface mineralogy on bare rock exoplanets.

Building on the theoretical foundations, two recent laboratory-driven studies have greatly advanced the prospects for detecting exoplanet surfaces with *JWST*. First et al. (2025) obtained mid-infrared emissivity spectra of basaltic, altered, and hydrous rocks across 2–25 μm and demonstrated, through synthetic exoplanet emission models, that *JWST* could feasibly identify bulk mineralogical differences even with low-resolution data. Their results show that stacking on the order of 5–20 eclipses may allow observers to distinguish hydrated phases such as amphibole or serpentine, or to constrain broad compositional metrics like Al_2O_3 content, thus identifying geochemical diversity across exoplanets. Complementing this, Paragas et al. (2025b) developed an expanded spectral library that significantly extends earlier archetypes by including a wide range of silicate compositions, multiple surface textures (slabs, coarse powders, fine powders), and, importantly, high-temperature (500–800 K) emissivity measurements. They show that texture exerts a strong influence on albedo and spectral slopes — making broadband albedo alone an incomplete diagnostic of surface composition — and identify several key mid-infrared features, including the 5.6 μm olivine absorption, the transparency feature, and the classic Si–O stretching mode and Christiansen feature. Together, these studies demonstrate that realistic laboratory spectra, accounting for mineralogy, texture, and temperature, are essential for interpreting *JWST* observations.

For a practical *JWST* strategy, one selects transiting rocky planets with high planet-to-star flux ratio, (preferably around M dwarfs), and schedules repeated secondary-eclipse observations, especially with *MIRI* low-resolution spectroscopy across 5–12 μm. For example, an intensive campaign targeting LHS 3844 b in cycle 4 (Paragas et al. 2025a) proposes eight MIRI LRS eclipses plus one NIRSpec G395H eclipse to isolate surface signatures (e.g. basalt, ultramafic, or granitoid fractions) while constraining residual atmosphere or volcanic outgassing (e.g. trace SO_2). The strategy hinges on stacking many eclipses, rigorous calibration of systematics (such as the brighter-fatter effect (Argyriou et al. 2023) or time-dependent persistence ramps (Dicken et al. 2024), especially for *MIRI*), and fitting emission continua plus candidate mineral absorption features.

Despite challenges — *JWST*'s moderate spectral resolution, the faintness of planet thermal signals, degeneracies in temperature– emissivity profiles, and effects of surface mixture or space weathering—theoretical, laboratory, and simulation studies together suggest that *JWST* offers the first real chance to spectroscopically characterize rocky exoplanet surfaces.

Success will likely be limited to the most favorable cases, but even non-detections will refine the limits on bare-rock occurrence and guide the exploration of rocky exoplanets in general.

2.4 New Observing Modes

The observations of transiting exoplanets need special requirements in terms of temporal stability and detector saturation. Indeed, there is a huge dynamical range in flux between observing the first galaxies at the end of the dark age and the bright nearby stars surrounded by exoplanets. During the development of the instruments, several modes have been optimized to observe exoplanets (for example subarrays, slitless spectroscopy). But there is still room for improvement.

On the *NIRCam side*, a new mode, *NIRCam* Short-Wavelength Grism Time Series has been opened for cycle 4 observations. This mode takes advantage of *NIRCam*'s Dispersed Hartmann Sensor (DHS), which, producing eight spatially separated spectra per source at $R \approx 300$, makes possible the observation of brighter targets. Such a mode allowed to observe, without risk of saturation, the closest rocky exoplanet transiting a M dwarf: LTT 1445 Ab (Bennett et al. 2025a), a 1.3 $R_\oplus$ and 2.9 $M_\oplus$ exoplanet located 6.9 pc away.

On the *NIRISS* side, the *NIRISS SOSS* multistripe mode has been introduced to observe very bright stars in exoplanet time-series spectroscopy without saturating the detector. By changing how the detector is read out, observations can reach stars as bright as J magnitude of about 3.5, compared to about J magnitude of 7–8 with traditional SOSS subarrays.

On the *MIRI* side, the telescope jitter is so low that a mode with slit LRS Time Series Observations has been proposed (Dyrek et al. 2024). Such a mode should allow a reduction of the background by almost two orders of magnitude and then allowing to gain in signal over noise, improving the performances of LRS observations of rocky exoplanets. The potential gain in Signal over Noise ratio, depends on the flux of the star compared to the background flux. Gain in signal over noise starts to be significant for stars with a Ks magnitude of 11.

3 Mid Term Facilities to Characterize Rocky Exoplanets and Their Environment

3.1 Characterization of Rocky Exoplanets Around M Dwarfs with Ground-Based Giant Segmented-Mirror Telescopes

Three ground-based very large telescopes are under development: the Extremely Large Telescope (*ELT*) (Tamai et al. 2024), the Giant Magellan Telescope (*GMT*) (Johns et al. 2012) and the Thirty Meter Telescope (*TMT*) (Sanders 2013). With a primary mirror of 39 m, the ESO's *ELT*, is the largest one. It is also the most advanced one; its first test observations are planned in 2029 (https://elt.eso.org/about/timeline/).

3.1.1 High Spatial Resolution

These Giant Segmented-Mirror Telescopes (GSMTs) bring a huge increase in the photon collecting area: almost 1000 m^2 (for the *ELT*) to be compared to 25 m^2 for *JWST*. This large collecting area alone provides a substantial improvement in the characterization of exoplanets compared to what is currently achievable with 8 m-class ground-based telescopes.

GSMTs also offer very high angular resolution, up to six times better than JWST. Table 1 lists the approximate Full Width at Half Maximum (FWHM) of the diffraction Point

Table 1 Full Width at Half Maximum ($1.03\ \lambda/D$) for the Point Spread Function of a 39 m telescope at different wavelengths

Wavelength λ (μm)	PSF FWHM (mas)
0.6	3.3
1.0	5.5
2.0	10.9
3.0	16.4
4.0	21.8
5.0	27.2

Table 2 Angular size of the habitable zone for stars of different spectral types located at 10 pc. Following Kopparapu et al. (2014), two cases are considered: runaway and maximum greenhouse (GH)

Spectral type	$L/L_\odot$	Runaway GH (AU)	Max GH (AU)	HZ angular size at 10 pc (mas)
F5 V	3.0	1.57	2.72	157 / 372
G2 V	1.0	0.96	1.68	96 / 168
K5 V	0.17	0.42	0.77	42 / 77
M0 V	0.08	0.29	0.55	29 / 55
M5 V	0.008	0.09	0.18	9 / 18
M8 V	0.0005	0.02	0.04	2 / 4

Spread Function (PSF). While the classic diffraction formula is strictly valid only for continuous circular apertures, it remains a good approximation (within 10%) for segmented mirrors. The gaps between segments have little impact on the width of the PSF core but redistribute energy into secondary diffraction features. Simulated PSFs for the *ELT* are shown in Leschinski and Gendron (2020).

In order to achieve the potential image quality, "extreme" adaptive optics is needed to correct from atmospheric turbulence. GSMTs will be equipped with a first generation of advanced adaptive optics. R&D programs are going on to further improve performances of adaptive optics (e.g. Kasper et al. 2021).

Such a high angular resolution opens the possibility to observe rocky exoplanets in the habitable zone of nearby stars by direct imaging. Indeed as can be seen in Table 2, the spatial resolution allows to probe the habitable zone of stars located at 10 pc with a luminosity down to the one of M5 stars. However, the habitable zone around M8 stars remains inaccessible. This is the case for the Trappist-1 system, located 12.4 pc away, which hosts three exoplanets (Trappist-1 e, f, g) within the habitable zone of its M8V host star. Their orbital angular sizes are only 2–3 mas, making them unreachable even with the *ELT*.

In addition to spatial resolution, another key parameter has to be considered: the planet/star flux ratio.

3.1.2 High Contrast with Both Coronagraphy and Spectroscopy at High Spectral Resolution

The ratio between the exoplanet flux and the host star flux is tiny. It is of the order of 10^{-10} in the visible for an Earth-sized planet around a Sun-like star but "only" 10^{-7} for an Earth-size planet around a M star.

At the position of the exoplanet, the signal from the diffraction pattern of the star is often much higher than the exoplanet signal. Coronagraphs are therefore needed to decrease the

Table 3 Transit probability for an exoplanet orbiting stars of various types at a distance where the insolation is equivalent to that received by Earth

Spectral type	$M/M_\odot$	$R/R_\odot$	$L/L_\odot$	R_p ($R_\oplus$)	a_{HZ} (AU)	P_{HZ} (days)	P_{tr} (%)
F5 V	1.40	1.30	3.20	1.00	1.79	833.60	0.34
G2 V	1.00	1.00	1.00	1.00	1.00	365.25	0.47
K5 V	0.67	0.70	0.17	1.00	0.41	228.70	0.79
M3 V	0.35	0.37	0.02	1.00	0.12	85.50	1.46
M5 V	0.21	0.27	0.01	1.00	0.08	47.40	1.49
M8 V	0.10	0.12	0.001	1.00	0.03	20.00	1.86

star signal. Coronagraphs will be installed in the various instruments under development for GSMTs. But this is not enough. To further remove the star contribution, the method consists in separating spectroscopically the signal from the planet and the star thanks to the Doppler shift induced by the orbital motion of the exoplanet. On the ground, a high enough spectral resolution (typically $>$ 50,000) is also needed to separate the planet signal from telluric lines. In order to get the signal over noise ratio, the individual lines have to be co-added using the cross correlation technique, which requires precise models of the lines. The technique of associating High Contrast imaging and High Spectral Resolution is referred as the HCHR technique. A thorough discussion of ground-based exoplanet observations at high spectral resolution can be found in the review by Snellen (2025).

The HCHR technique has many advantages over transit spectroscopy:

- Most of the nearby planets are non-transiting. As the HCHR method does not require the planet to transit, this increases significantly the pool of planets which can be probed by this technique (see Table 3);
- Observing a planet in reflected light allows to probe deeper in the atmosphere than transit spectroscopy. In fact, in visible, it can even probe down to the surface (providing no clouds are blocking the view);
- Probing down to the surface of a planet means that this method could be potentially used to determine the presence of an ocean or bodies of liquid water at the surface of the planet by capturing the glint (Palle et al. 2025), and also to probe the vegetation red edge (e.g. Roccetti et al. 2025);
- Contrary to transit spectroscopy which is impacted by stellar contamination (for instance, for the TRAPPIST-1 system, observed with *JWST*, Lim et al. 2023), for the reflected light at HCHR this is less the case (Palle et al. 2025; Fauchez et al. 2025).

3.1.3 The GSMTs Instruments and Simulated Performances

Two ESO's *ELT* instruments (see Table 4) combine high contrast imaging and high spectral resolution (R = 100,000): *ANDES* (ArmazoNes high Dispersion Echelle Spectrograph) at short wavelengths (0.4–1.8 μm) (Marconi et al. 2024) and *METIS* in the 3–4.5 μm range (Brandl et al. 2021). *ANDES* is a second generation instrument. Two first generation instruments will cover the short wavelength range: *MICADO* (Multi-AO Imaging Camera for Deep Observations) (Sturm et al. 2024) and *HARMONI* (High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph) (Thatte et al. 2021), whose maximal spectral resolution is of 17,000. In front of *MICADO* will be installed *MORFEO*, a Multiconjugate adaptive Optics Relay for *ELT* Observations, to correct the blurring effect

Table 4 *ELT* instruments

Instrument	Field of view / pixel scale	Spectral resolution	Wavelength coverage (μm)
MICADO	Imager (with coronagraph) 50.5"×50.5" at 4 mas/pix 19"×19" at 1.5 mas/pix	I, Z, Y, J, H, K + narrow bands	0.8–2.45
	Single slit	$R \sim 20{,}000$	
HARMONI	Integral Field Unit, 4 spaxel scales from: 0.8"×0.6" at 4 mas/pix to 6.1"×9.1" at 30 × 60 mas/pix (with coronagraph)	$R \sim 3200$ $R \sim 7100$ $R \sim 17{,}000$	0.47–2.45
METIS	Imager (with coronagraph) 10.5"×10.5" at 5 mas/pix in L, M 13.5"×13.5" at 7 mas/pix in N	L, M, N + narrow bands	3-13
	Single slit	$R \sim 1400$ in L $R \sim 1900$ in M $R \sim 400$ in N	
	Integral Field Unit 0.6"×0.9" at 8 mas/pix (with coronagraph)	L, M bands $R \sim 100{,}000$	
ANDES	Single object	$R \sim 100{,}000$	0.4–1.8 simultaneously
	Integral Field Unit	$R \sim 100{,}000$	
	Multi object (To be confirmed)	$R \sim 10{,}000$	
MOSAIC	~7-arcminute FoV ~200 objects (To be confirmed)	$R \sim 5000$–$20{,}000$	0.45–1.8 (To be confirmed)
	~8 Integral Field Units (To be confirmed)	$R \sim 5000$–$20{,}000$	0.8–1.8 (To be confirmed)
PCS	Extreme Adaptive Optics camera and spectrograph	To be determined	To be determined

of the atmosphere (Ciliegi et al. 2022). Instruments providing high contrast high dispersion are also in development for the *GMT* (Millan-Gabet et al. 2022).

The burning question about GSMTs is their capacity to characterize Earth-like exoplanets in their habitable zones and to detect biosignatures in the atmosphere of those exoplanets. An overview of potential biosignatures is given in Schwieterman and Leung (2024).

Pioneering studies of the detection of O_2 with GSMTs have started in the 2010's for example Snellen et al. (2013), Rodler and López-Morales (2014), López-Morales et al. (2019). Zhang et al. (2024) have recently studied what could be achieved with the first generation of *ELT* instruments: *HARMONI* and *METIS*. They assume a spectral resolution of 1000 and a coronagraph contrast of 10^{-3} for *HARMONI* and 10^{-4} for *METIS*. Assuming a modern Earth-like atmosphere, they found that the best target is GJ 887 b. Indeed it will be possible to detect relatively easily the CH_4 feature with *METIS* at a Signal over Noise level of 5 in about 1 hour of observation. It would be interesting to also detect the O_2 feature. The O_2 feature is not accessible in the wavelength range of *METIS* but in the one of *HARMONI*, but the Signal over Noise in 10 h is only of 1.

Another study (Hardegree-Ullman et al. 2025), assuming a higher spectral resolution (100 000) which helps to disentangle planet lines from star lines and telluric lines, reaches the more optimistic conclusion that the O_2 line could be probed in the atmospheres of several nearby habitable-zone exo-Earths. Such a spectral resolution in the visible and near Infrared

will be provided with ANDES. The science team of *ANDES* has identified 5 golden targets, (nearby Earth-sized planets in the habitable zone of their host M star), which could be detected within a few tens of nights (Palle et al. 2025). This list includes Proxima-b (Anglada-Escudé et al. 2016), which could be detected in just 7 h at 5σ for a planet-to-star contrast ratio of 10^{-7}. To summarize, ANDES will be able to detect the reflected light atmospheric signal from a carefully selected set of nearby, non-transiting, Earth-sized planets in or near the habitable zone within just a few tens of nights. This could start around 2033. On a longer timescale, *PCS* (Planetary Camera and Spectrograph) will have even better capabilities than *ANDES* and will further improve our capacity to probe small rocky planets around nearby dwarf stars (Kasper et al. 2021). In particular, *PCS*, with its extreme adaptive optics, should reach much lower angular separation than *ANDES* (10 mas for *PCS* vs 20 mas for *ANDES*) and much lower contrast (10^{-9} for *PCS* vs 10^{-8} for *ANDES*). These improved capabilities will expand the number of rocky planets available for characterization quite significantly and allow new science compared to *ANDES*.

The observations are very challenging, so that years will be probably needed to optimize the performances. Gaining experience on sky for the HCHR technique is in preparation, for example with the *RISTRETTO* instrument which will combine high spatial contrast (5×10^{-5}) and high spectral contrast of 10^{-3} to arrive to the contrast of 10^{-7} needed to detect the reflected star light from the Proxima b exoplanet in the visible from the ESO Very Large Telescopes (*VLT*) (Blind et al. 2024; Bugatti et al. 2025).

3.2 Space Missions and the Environment of the Rocky Planets

For the understanding of the structure and evolution of rocky planets it is essential, not only to have a precise determination of their mass and radius, and thus their mean density, but also their radiation and gravitational environment. To this end, it is mandatory to characterize the properties and the behavior of the host star, its interactions with the planet, and explore the presence of other bodies in the system.

3.2.1 Better Knowledge of the Star 'Hosting' Rocky Planets

The ESA mission *PLATO* (PLAnetary Transits and Oscillations of stars), to be launched beginning of 2027, will provide an excellent tool for the study of rocky planets (Rauer et al. 2025).

Selected as ESA's M3 mission in the Cosmic Vision 2015-2025 Program in 2014, *PLATO* is designed to conduct a wide-field transit survey of up to a million stars, with the precision to detect and characterize Earth-sized planets around Sun-like stars, as well as conducting asteroseismic monitoring to determine stellar characteristics (Rauer et al. 2014). The observatory consists of 24 cameras monitoring a wide field of view in white light and obtaining high-precision photometric light curves of thousands of stars, with 2 additional cameras to follow up these fields to obtain color information on the stars by observing in the blue (505-700 nm) and in the red (665-1000 nm) wavelength ranges respectively.

Among its driving objectives, *PLATO* will determine the bulk properties (radius, mass, and mean density) of terrestrial planets in the habitable zone of solar-like stars. For this purpose, an accurate characterization of the host star is necessary since the transits only provide relative values. Precise distances, leading to stellar luminosities and radii, are being provided by the mission *Gaia* since some years ago, allowing a better determination of the radius of the star and thus of the planet (Johns et al. 2018).

For high-density planets, their derived mean densities will allow the identification of interior structures and the study of their composition leading to the test of formation theories. The interior composition of small rocky exoplanets cannot be observed directly but are expected to relate to the composition of the host star, which can be derived from high-resolution spectroscopy (Hinkel et al. 2024). Then interior structure and composition models of the planet, including their refractory content (e.g. Fe or Si) can be linked to the host star and the geophysical evolution information derived.

A key contribution of *PLATO* to the study of Sun-like stars is the measurement of their asteroseismology behaviour. Oscillation frequencies can be linked to the internal structure and the age of the star with the use of appropriate stellar models, thus constraining the geophysical evolution of the planet. Gyrochronology, magneto-gyrochronology and age-activity relationships will be used to provide estimates for the ages of targets where p-modes cannot be detected.

3.2.2 Star-Planet Interactions

Study of star-planet interactions are needed to evaluate planetary formation, evolution, and habitability, particularly in close-in exoplanetary systems where complex magnetic, gravitational and atmospheric effects are found. Indeed, interactions can influence both stellar activity and planetary evolution (see Strugarek 2024 for a general introduction of star-planet interactions and the references therein). Moreover, exoplanetary environments do largely influence habitability and observational signatures across different wavelengths, while stellar contamination affects the transit measurements and must be properly characterized. Small missions like *Pandora* (Barclay et al. 2025), in NASA Pioneers Program, will monitor stars hosting planets in the visible and near IR, facilitating the study of stellar contamination.

The behaviour of the host stars in the UV and X-ray domains provides key information about stellar chromospheric and coronal activity, mass ejection, as well as high-energy radiation. Current and future facilities in the UV and X-ray domains permit the acquisition of the necessary information. In this context, small missions are currently planned to monitor high energy UV flares that significantly affect the atmospheres of exoplanets, driving atmospheric loss and altering conditions for habitability. This is the idea of the planned small mission *SPARCS* which eventually could facilitate detailed analysis with the Habitable Worlds Observatory (Ardila et al. 2022).

PLATO will also allow detailed studies of stellar rotation which can then be analyzed in detail and correlated with tidal interactions. Of course, there is always the possibility to detect orbital variations in eccentric systems, leading to the measurement of apsidal motions. This is the best way to measure internal structure density concentrations and therefore the test of internal structure planetary models.

3.2.3 *Gaia* and the Detection of Other Planets in the System

With precise astrometry, it is possible to observe the change in the on-sky position of a star due to the gravitational interaction between the star and a planetary mass companion. The ESA mission *Gaia* provides precise information for relatively massive planets and the prospects for the detection of exoplanets has been discussed in the early stages of the mission development (Bernstein and Bastian 1995) and later expanded upon in Perryman et al. (2014). The full analysis of the latest data releases by the Gaia consortium will permit the discovery of other stellar companions in addition of already known transiting rocky planets. In addition, ESA is already discussing a successor to Gaia, the so-called *GaiaNIR*, to expand the astrometric survey to objects in the infrared.

3.2.4 The Yield of Earth-Size Planets Around 'Nearby' Sun-Like Stars

One of the key parameters for accurately predicting the discovery yield of Earth-like planets around the nearest stars with future direct imaging missions is $\eta_\oplus$, the occurrence rate of Earth-like exoplanets in the habitable zone of Sun-like stars. The *Kepler* mission provided the first opportunity to statistically constrain the frequency of Earth-sized planets in the HZ of Sun-like stars (Borucki et al. 2011); however, the lack of robust detections of Earth-sized planets in the HZ, resulted in the need for extrapolations of the trends in shorter-period planets (Bryson et al. 2021). The resulting large uncertainty in $\eta_\oplus$ is actually the dominant challenge in constraining the required target sample for future direct imaging missions, and is therefore a key science driver of the *PLATO* mission.

Based on updates to the *PLATO* Input Catalog (PIC) and statistics from previous surveys, *PLATO* is expected to discover around 1200 planets around stars of $V < 11$, and 4600 planets around stars brighter than $V = 13$ (Rauer et al. 2025). This is similar to the total planet yield for the *Kepler* mission, but most *Kepler* planets orbit stars of $V > 14$ and are therefore much more difficult to characterize. Current planet yields predict the detection of a few up to a bit more than a hundred small planets in the Habitable Zone of Sun-like stars (see Fig. 5 of Rauer et al. 2025), depending on the value of $\eta_\oplus$ — therefore significantly improving statistics on the frequency of these planets and aiding in improved discovery yield predictions for direct imaging missions such as *HWO* and *LIFE*.

Another mission, the *Earth 2.0 (ET)* China space mission, has also for objective to understand how frequently habitable Earth-like planets orbit solar-type stars. It is in phase C study. The final design of *ET* includes six 28 cm diameter transit telescope systems, each with a field of view of 550 square degrees, and one 35 cm diameter microlensing telescope with a field of view of 4 square degrees (Ge et al. 2024).

3.2.5 *Ariel* and the Statistical Studies of Exoplanet Atmospheres

The ESA-led *Ariel* mission (Atmospheric Remote-sensing Infrared Exoplanet Large-survey) is the first space mission specifically designed to perform a large-scale, homogeneous survey of exoplanet atmospheres, enabling a transformative step in our understanding of planetary system formation and evolution (Tinetti et al. 2021). *Ariel* will perform transit spectroscopy of ∼1000 exoplanet atmospheres spanning a wide range of sizes, masses, and orbital distances around diverse host stars, from which the atmosphere chemical compositions, thermal structures, and cloud properties will be retrieved. By observing a statistically significant number of planets, Ariel enables the first comparative exoplanetology study at population scale, allowing identification of trends and correlations between planetary atmospheres and their host star properties.

Ariel is equipped with 2 instruments, *FGS* (Skup et al. 2024) and *AIRS* (Martignac et al. 2024), which provide **simultaneous** observations over the 0.5 – 7.8 μm wavelength range. Although *FGS* stands for Fine Guidance System, it not only delivers precise pointing and guiding towards the observed target, but also scientific data over the 0.5 – 1.95 μm range (3 photometric channels over the 0.5 – 1.1 μm wavelength range and a low resolution spectrometer in the 1.1 – 1.95 μm range). The detector focal plane and associated electronics is provided by NASA (project CASE, Contribution to Ariel Spectroscopy of Exoplanets). *AIRS* stands for Ariel InfraRed Spectrometer; it comprises two channels covering 1.95–3.90 μm (CH0) and 3.90–7.80 μm (CH1) using prism dispersers, with spectral resolution of 100 and 30, respectively. Operating at 60 K, AIRS delivers Nyquist-sampled spectra on two HgCdTe detectors cooled below 42 K.

Ariel is a relatively small telescope compared to JWST (0.64 m^2 compared to 25 m^2). Because *Ariel* covers simultaneously the whole 0.5–7.8 μm range and can get the needed signal over noise ratio after a single transit observation for many exoplanets, *Ariel* can be more efficient than *JWST* for those targets (Changeat et al. 2025). But *Ariel* will not compete with *JWST* for temperate rocky exoplanets. However, it will be able to monitor exoplanets such as 55 Cancri e, studying their variability and more generally studying the transition regime between warm super-Earths and sub-Neptune. The target list of *Ariel* is flexible and can be adjusted taken into account the new discoveries, for example with *JWST*.

The launch by an Ariane 6 toward an L2 orbit for a 4-year survey is expected in 2031. Given the possible life time of the *JWST* of more than 20 years, we can expect simultaneous and complementary observations between *Ariel* and *JWST*, for example to have simultaneous observations over the 0.5 – 12 μm range.

4 Long Term: Search and Characterizing Rocky Planets in the Habitability Zone of Sun Like Stars

Though we are currently only able to examine habitable-zone planets around M dwarfs, the ultimate goal of exoplanet atmosphere studies is to characterize Earth-like planets around G dwarfs and establish whether they could be habitable and show signs of life. Habitable planets around M dwarfs and G dwarfs offer different opportunities and challenges for discovery. M dwarf planets in the HZ are detectable today due to their relatively high transit probability and larger radial velocity signal; HZ planets around G dwarfs have very low transit probabilities and radial velocity signals but have larger orbital separations. Transit survey missions such as *Kepler* and *PLATO* can provide statistics on the frequency of Earth-like planets in the HZs of G stars, but the likelihood of a transiting Earth-like planet around a nearby star is vanishingly low; therefore we must use high-contrast direct imaging techniques to detect and characterize these worlds.

4.1 Habitable Worlds Observatory

As specified in the National Academies of Sciences, Engineering, and Medicine (2023), the characterization of habitable rocky exoplanets is one of the primary goals for the next Ultra Violet (UV) /Optical/Near InfraRed (NIR) flagship observatory that will succeed the Hubble Space Telescope. In order to achieve this goal, NASA recently initiated the preliminary design and development of the Habitable Worlds Observatory (*HWO*). One of the primary driving scientific goals for *HWO* is to directly image Earth-like planets around a large number of Sun-like stars and analyze their atmospheres for signs of habitability or life. By using ultra-high-contrast starlight suppression technologies, *HWO* will be able to block the light of the host star to contrast levels of $\sim 10^{-10}$, enabling the detection of the faint light reflected from Earth-like planets in the HZ. *HWO* is currently in the pre-formulation phase, with a Mission Concept Review (MCR) expected in 2029 and a nominal launch date in the late 2030s. A technological demonstrator of high contrast imaging will fly with the *Roman* space telescope (Perkins et al. 2024), to be launched end of 2026 or beginning of 2027. Candidate instruments on *HWO* include: a VIS/NIR coronagraph, a UV multi-object spectrograph, a VIS/NIR camera with high-precision astrometry capability, a UV integral field spectrograph, a NUV coronagraph, and a UV spectropolarimeter.

A main exoplanet-related objective for an *HWO*-like mission is to observe 25 - 50 terrestrial planets around nearby FGK stars over the span of 5 mission years, though the potential

of a serviceable observatory is also discussed and would extend and enhance the nominal mission. Through spectroscopy, *HWO* will be able to identify the chemical composition of their atmospheres. This will enable the detection of key biosignature gases present in the atmosphere of Earth through different geologic eras, such as oxygen (O_2), ozone (O_3), methane (CH_4), and carbon dioxide (CO_2), each of which would provide complementary context for constraining the absence or presence of biological activity. In addition, the observatory will analyze climate indicators such as water vapor, cloud coverage, and surface reflectance which provide insights into surface conditions. These data will help determine whether a planet's environment could support life as we know it and whether it may harbor living organisms, while also ruling out known "false positive" scenarios which may have some characteristics of habitable or inhabited planets but are in fact not habitable.

HWO will also be capable of conducting transit spectroscopy from UV to near infrared. Beyond characterizing potentially habitable planets around M stars, *HWO* will also be able to examine the atmospheres of the population of extremely irradiated rocky planets on ultra-short-period (USP) orbits. The intense irradiation on these planets leads to dayside temperatures reaching over 2500 K, and they are expected to have dayside surfaces that are partially or completely molten (Kite et al. 2016). Models predict that these planets should partially vaporize their rocky mantles and out-gas significant but highly refractory atmospheres dominated by silicates and heavy metals, potentially allowing us to directly probe the bulk mantle compositions (Miguel et al. 2011). In the Near Ultra Violet (NUV) and visible (VIS) wavelength regions, there are major spectral features for key metal species predicted by outgassing models, such as sodium, calcium, potassium, and TiO. Well-known USPs such as 55 Cancri e, CoRoT-7 b, and Kepler-10 b would be a high priority, as well as additional planets found by *PLATO*.

4.2 LIFE

The Large Interferometer For Exoplanets (*LIFE*, (Quanz et al. 2022)) project aims to develop a space-based mid-infrared (MIR) nulling interferometer to detect and characterize the atmospheres of terrestrial exoplanets.

Nulling interferometry combines light from multiple apertures to cancel out the usually orders of magnitude brighter stars while preserving the extremely faint thermal emission signals from the orbiting exoplanets. This is achieved through destructive interference of the starlight, allowing the mid-infrared light directly emitted by the planets to be isolated and analyzed for atmospheric properties and potential biosignatures. *LIFE*'s current baseline design involves four collector telescopes in a formation flying configuration with a central beam-combiner spacecraft, enabling high spatial resolution and sensitivity to detect and characterize terrestrial exoplanets (Dannert et al. 2022; Alei et al. 2022; Hansen et al. 2023).

4.2.1 *LIFE* and the Characterization of Rocky Planets in the Habitability Zone of Sun Like Star

LIFE will be great for observing rocky planets orbiting earlier type stars. *LIFE* is expected to detect and subsequently characterize several dozens of "Earth twins" (Kammerer et al. 2022), temperate, rocky planets orbiting FGK type stars. Various biosignatures are accessible in the MIR, some even exclusively (see e.g., Angerhausen et al. 2023, 2024).

Konrad et al. (2022) and Alei et al. (2022) explored the potential of *LIFE* for characterizing emission spectra of an Earth twin at 10 pc at various stages of its evolution. The

study shows that *LIFE* can identify key spectral features (e.g., CO_2, H_2O, O_3, CH_4) and distinguish between inhabited and lifeless scenarios.

Konrad et al. (2023) investigated the impact of clouds on atmospheric retrievals for a Venus-twin exoplanet. The study shows that *LIFE* is able to characterize the structure and composition of a Venus-like atmosphere above the cloud deck if an adequate model is chosen.

Carrión-González et al. (2023) computed the list of currently known exoplanets detectable with *LIFE* in thermal emission. LIFE's reference configuration can detect 212 known planets within 20 pc, including 38 in the habitable zone.

Alei et al. (2024) explored the benefits of combining data from *HWO* and *LIFE*. The study simulates observations of an Earth-like planet 10 pc away and finds that combining both missions' data significantly improves constraints on atmospheric components like carbon dioxide, water, and oxygen, as well as surface temperature. This synergy enhances the search for biosignatures and life indicators.

4.2.2 *LIFE* and the Characterization of Rocky Planets in the Habitability Zone of M Stars

Due to its very large baselines between the collecting telescopes of up to several hundreds of meters, *LIFE* allows spatial resolutions that are very well suited for the study of terrestrial, temperate exoplanets around M dwarfs as their habitable zones are usually too close in (i.e. within the inner working angle) for observations with single aperture telescopes at shorter wavelengths (Quanz et al. 2022; Dannert et al. 2022; Carrión-González et al. 2023). Some exemplary science cases for M star systems discussed for *LIFE* are the detection of phosphine (PH_3) in exoplanetary atmospheres of temperate super-Earths (Angerhausen et al. 2023) or nitrous oxide N_2O, or methylated halogens (CH_3Cl and CH_3Br) in Earth-like planets orbiting later type stars, potential capstone biosignatures (Angerhausen et al. 2024) in exoplanet atmospheres with *LIFE*.

5 Conclusion

The characterization of rocky exoplanets represents a major and exciting challenge for contemporary astronomy. The coming decades promise significant discoveries, driven by the complementarity of current and upcoming instruments and missions. In the short term, *JWST* will keep on studying the atmospheres and surfaces of rocky exoplanets, mainly around M type stars. The advent of ground-based Giant Segmented-Mirror Telescopes in the 2030s will provide unprecedented access to a broader range of targets through direct imaging, while future missions such as the Habitable Worlds Observatory and *LIFE* will pave the way for exploring potentially habitable planets around Sun-like stars. The projected timeline of these facilities is summarized in Fig. 1.

At the same time, understanding planetary environments — including host stars and complete planetary systems — will be essential to interpret exoplanetary properties. Missions like *Gaia*, *PLATO*, *Earth 2.0* and *Ariel* will contribute by delivering precise data on stellar and planetary atmospheric characteristics.

Overall, the study of rocky exoplanets, their atmospheres, and surfaces is entering a new era, where the detection of biosignatures and the investigation of conditions conducive to life are becoming realistic and scientifically attainable goals.

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Declarations

Competing Interests The authors declare that they have no competing interests.

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