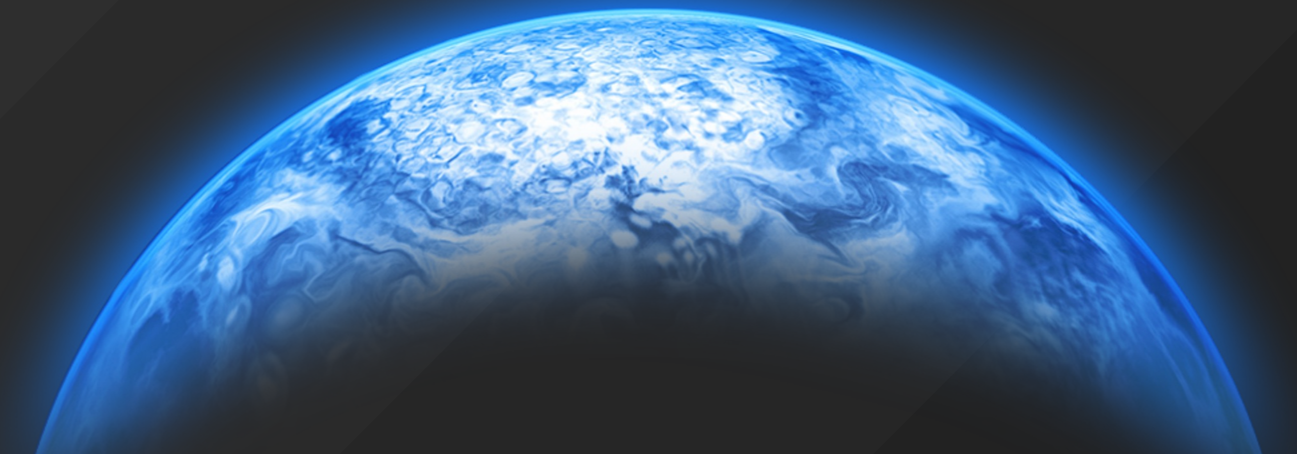
LIFE
LARGE INTERFEROMETER FOR EXOPLANETS



The Large Interferometer For Exoplanets (LIFE)

A space-based mid-infrared nulling interferometer to characterise terrestrial exoplanets and find life beyond the Solar System

2-4 of April 2025, Leiden, The Netherlands

Future Role of FIR-Submm Space Observations
Defining Urgent Science and Instrumentation

In honor of Thijs de Graauw and his collaborators

Authors:

Tim Lichtenberg
University of Groningen

for the LIFE mission

ETH zürich
PlanetS National Centre of Competence in Research
ETH zürich | SPACE
Rensselaer
university of groningen
NOVA
SRON Netherlands Institute for Space Research
u^b UNIVERSITÄT BERN CSH CENTER FOR SPACE AND HABITABILITY
M ASTRONOMY

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

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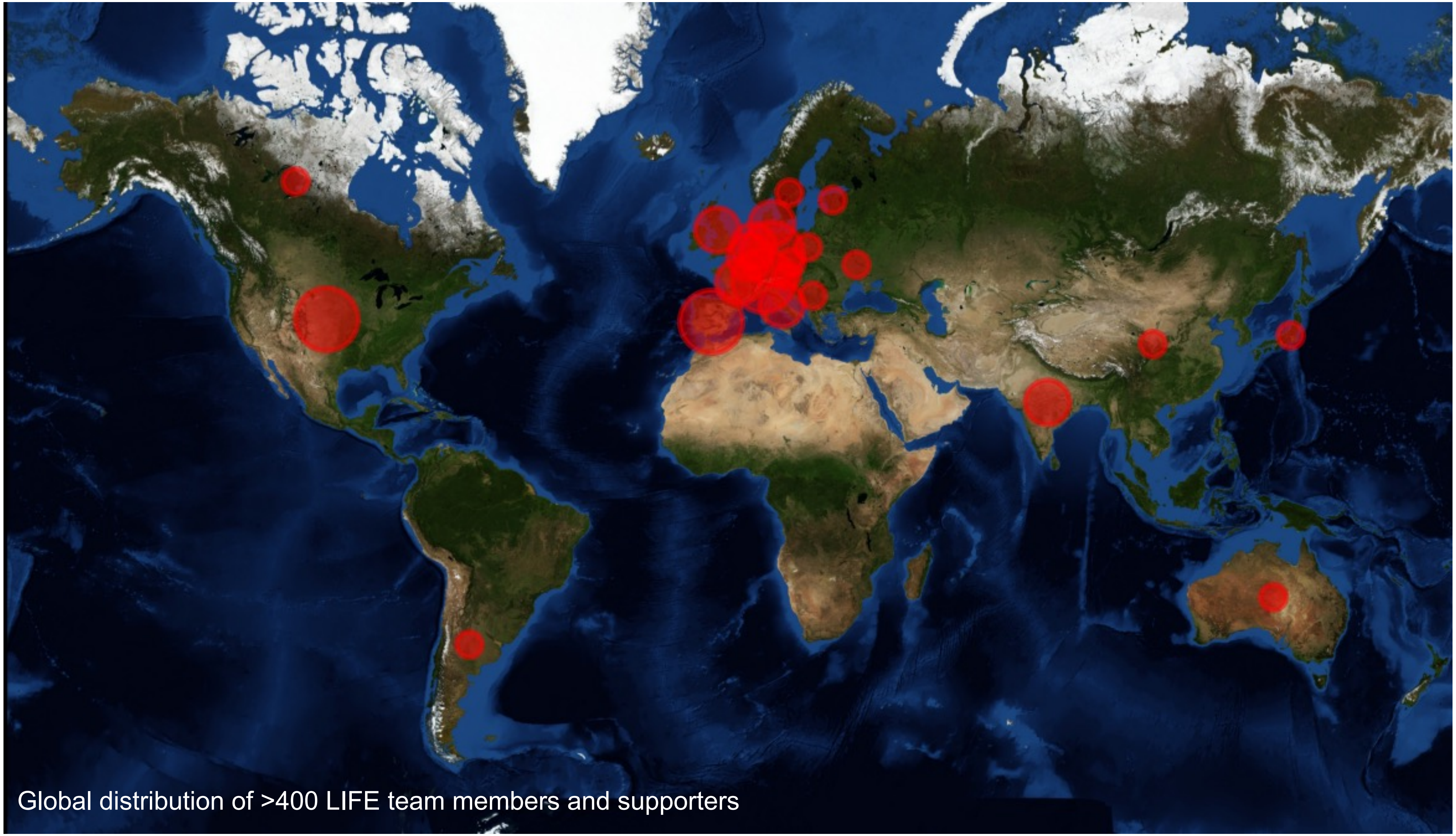
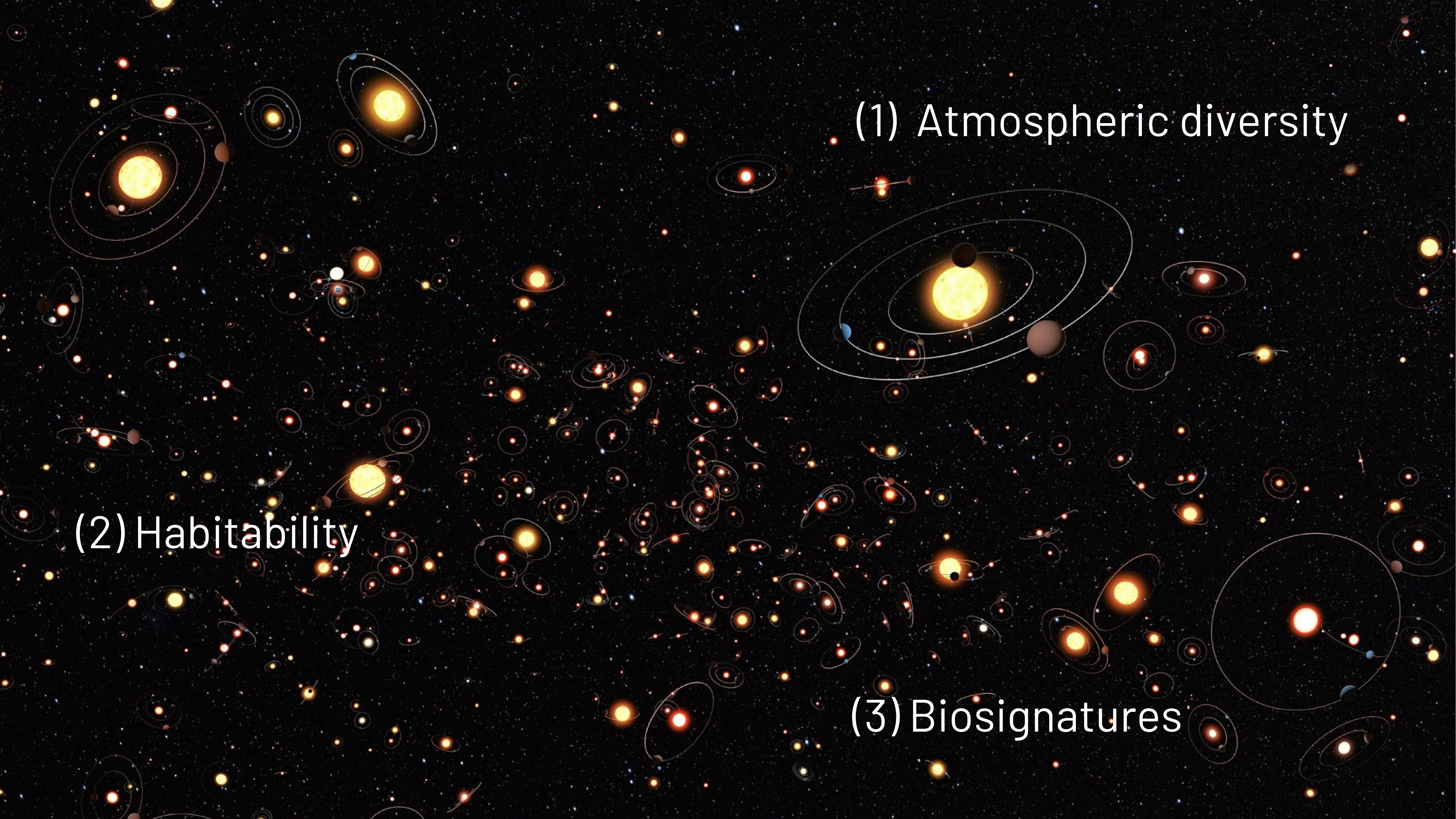
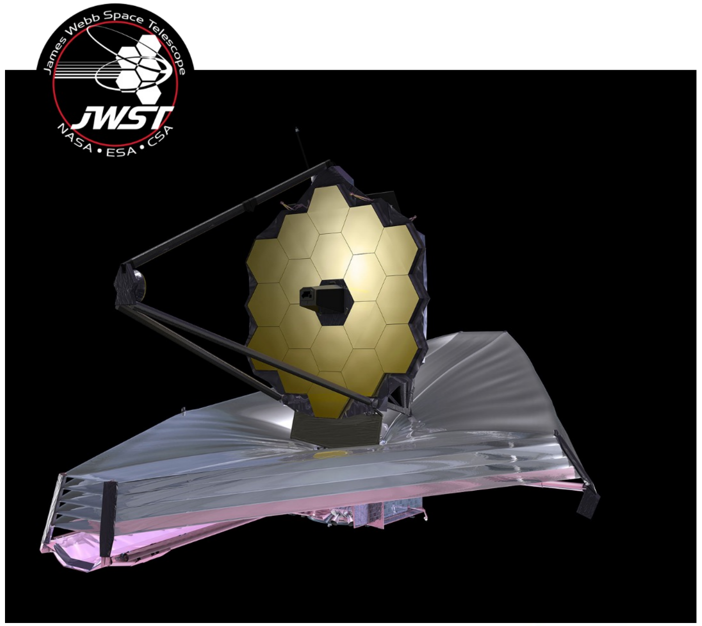
LIFE is European-led, but has a global footprint

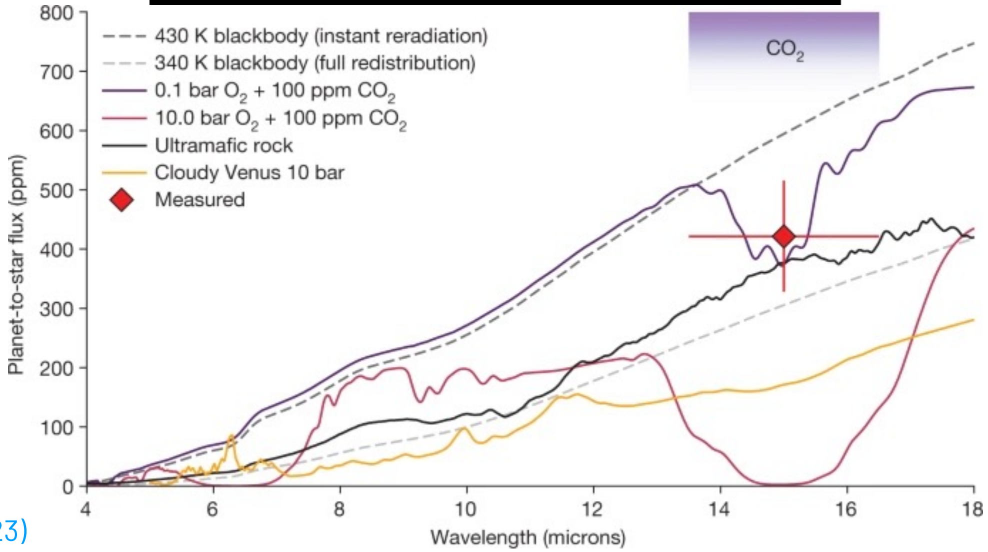


Why is LIFE needed?


(1) Atmospheric diversity
(2) Habitability
(3) Biosignatures

First steps are taken by JWST and Ariel





Zieba et al. (2023)

“A long term scientific objective is to characterize the whole range of exoplanets, including, of course, potentially habitable ones. ARIEL would act as a pathfinder **for future, even more ambitious campaigns**.”

ARIEL Assessment Study Report (Yellow Book)

A candidate theme for a future ESA L-class missions

ESA Voyage 2050 - European roadmap for future space exploration

"Therefore, launching a Large mission enabling the **characterisation of the atmosphere of temperate exoplanets *in the mid-infrared* should be a top priority** for ESA within the Voyage 2050 timeframe."

"This would give ESA and the **European community** the opportunity to **solidify its leadership** in the field of exoplanets, [...]"

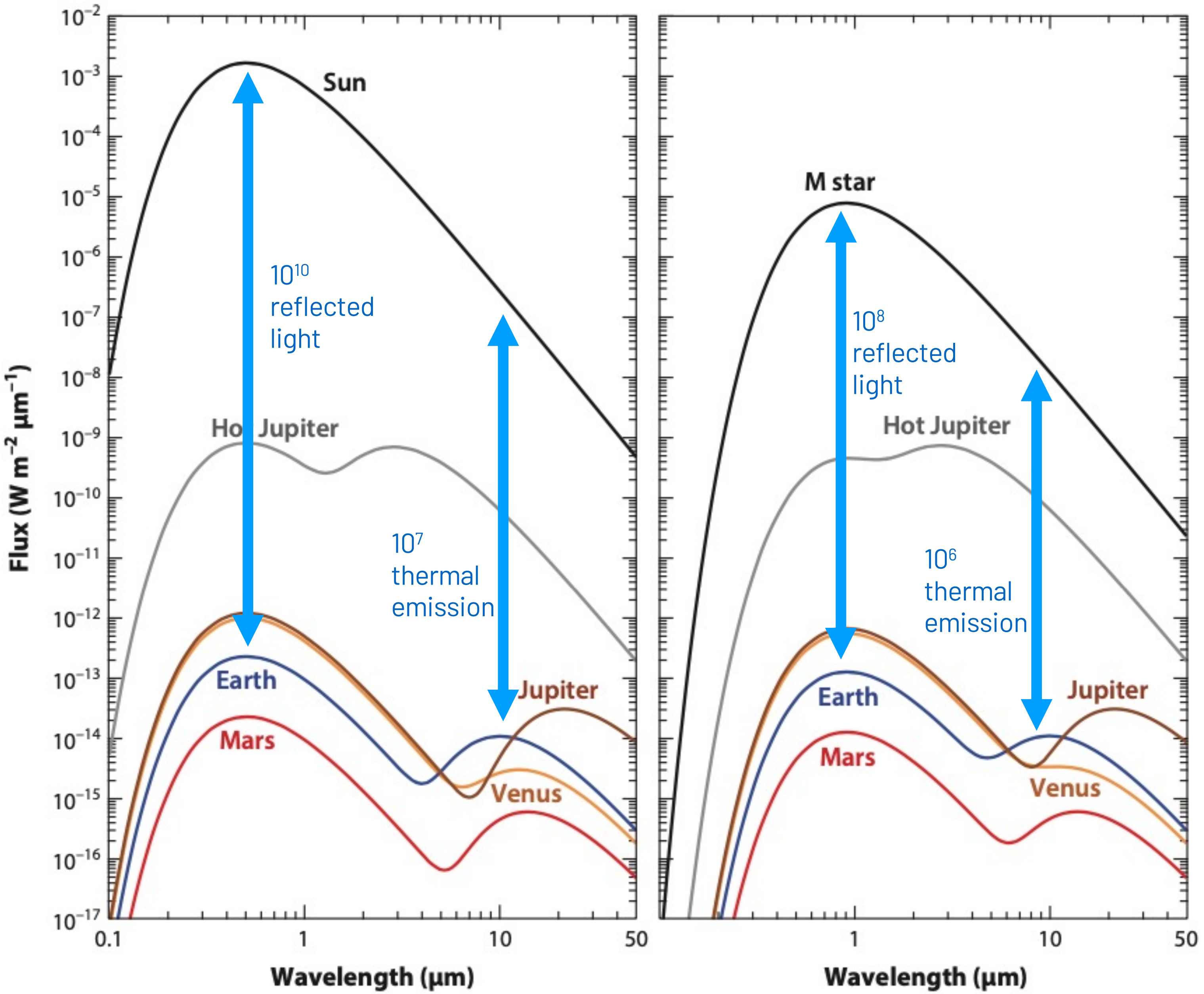
"Being the first to **measure** a spectrum of the direct **thermal emission of a temperate exoplanet** in the mid infrared **would be an outstanding breakthrough** that could lead to yet again another paradigm-shifting discovery."

ESA Senior Committee Report; June 2021

https://www.cosmos.esa.int/web/voyage-2050

Challenges for the direct detection of terrestrial exoplanets

1. **...high spatial resolution:** the planet-star separation is extremely small
2. **...high contrast performance:** the planet is orders of magnitude fainter than the star
3. **...high sensitivity:** terrestrial planets are intrinsically extremely faint



cf. Kaltenegger 2017

Large facilities are needed to directly detect rocky exoplanets

Synergies between different upcoming missions and ground-based telescopes

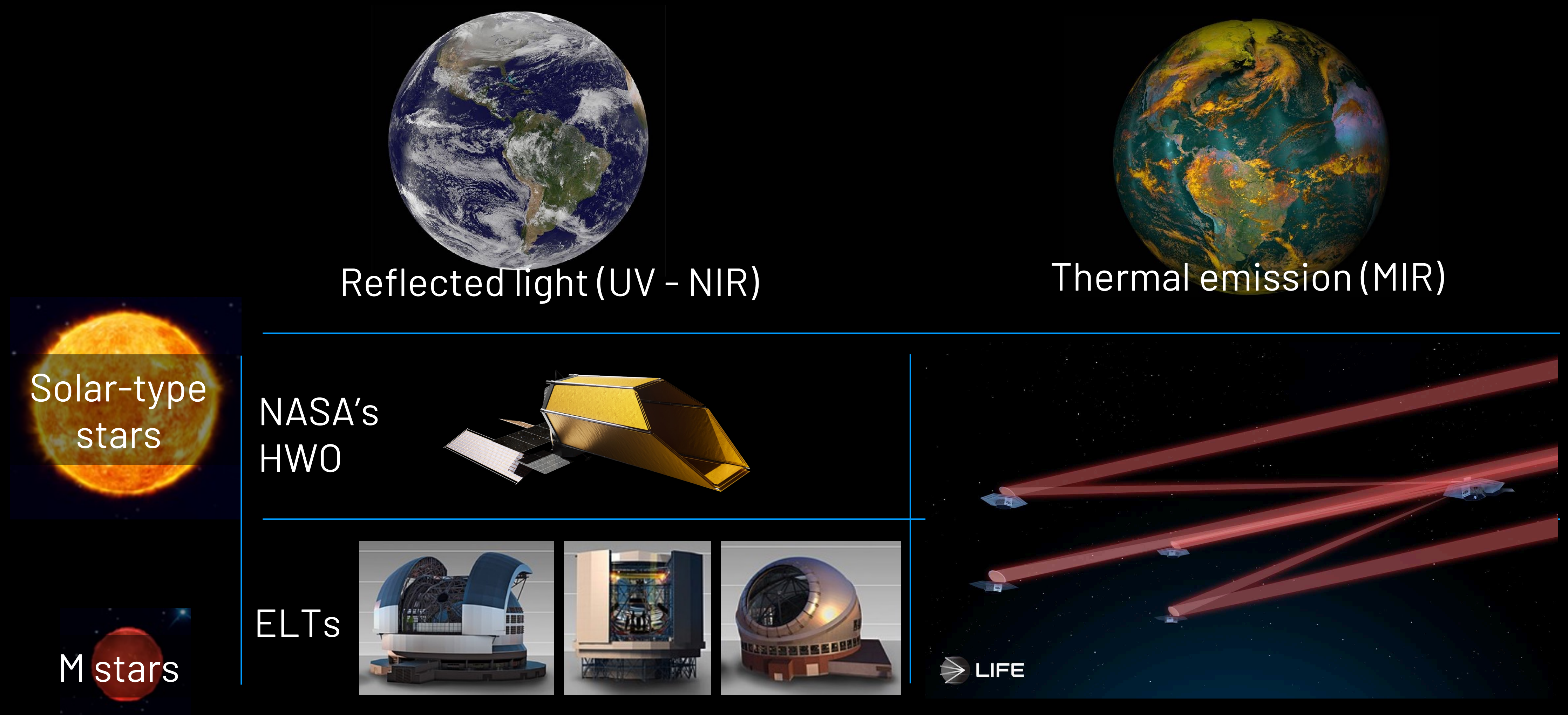
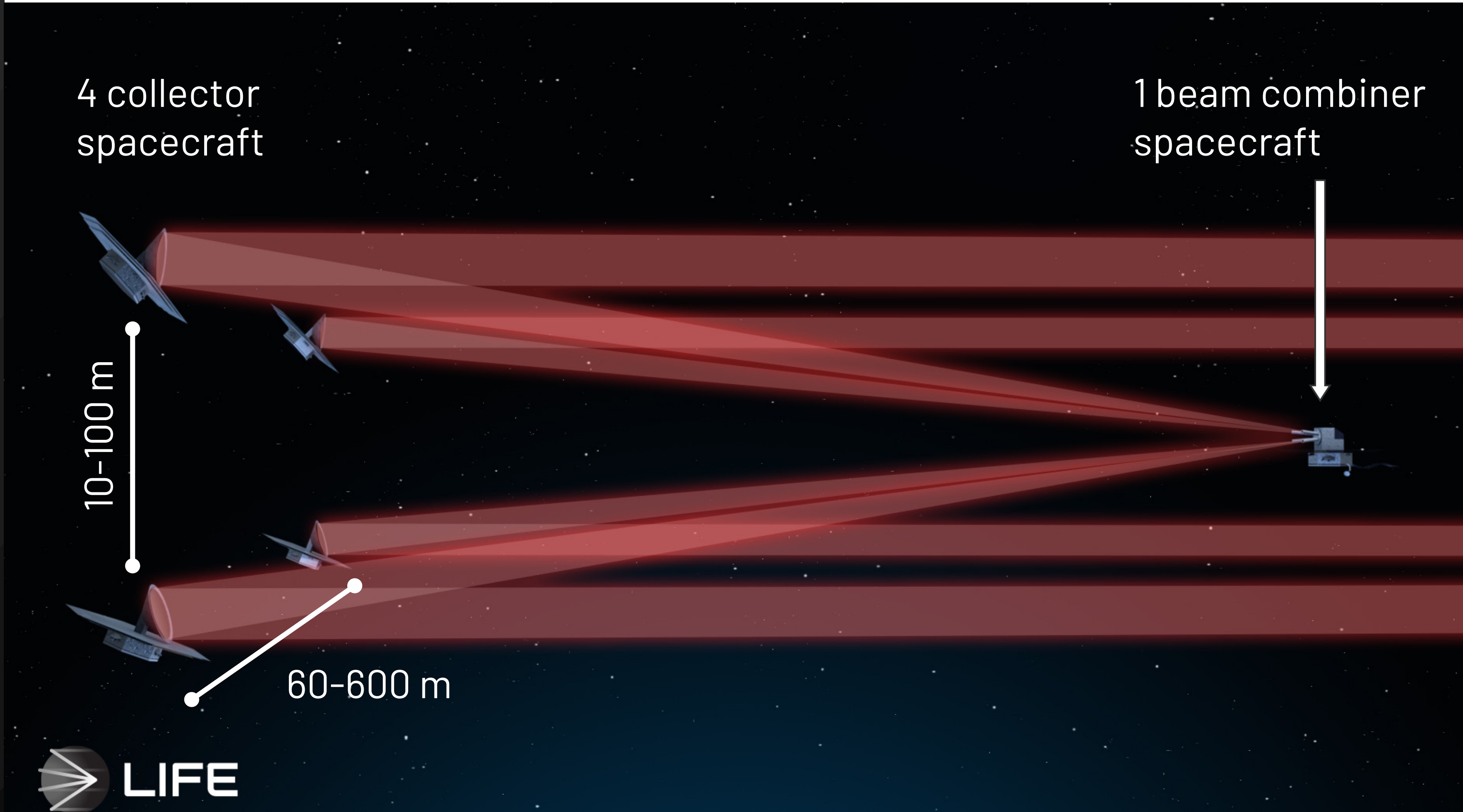


Image credit: NASA's Goddard Space Flight Center Conceptual Image Lab, LIFE Initiative, ESO, TMT, GMT

The LIFE mission

- LIFE is a space-based formation-flying nulling interferometer
- It consists of 4 collector spacecraft in a rectangular array and a central beam combiner spacecraft above the array
- The separation between the collectors can be freely adjusted to optimize the performance for each nearby star
- Like the James Webb Space Telescope, LIFE will orbit around Lagrange Point 2
- The mission lifetime will be 5-6 years
- LIFE covers the mid-infrared wavelength range between ~6-16 μm (requirement) / ~4-18.5 μm (goal) with a spectral resolution of $R = \lambda/\delta\lambda \sim 100$

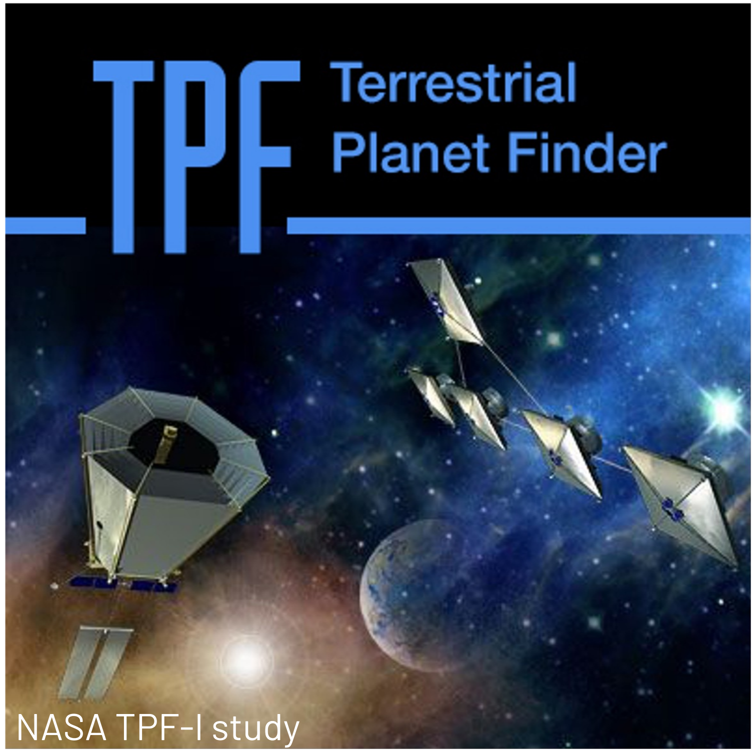


Artist impression of LIFE concept (credit: LIFE mission)

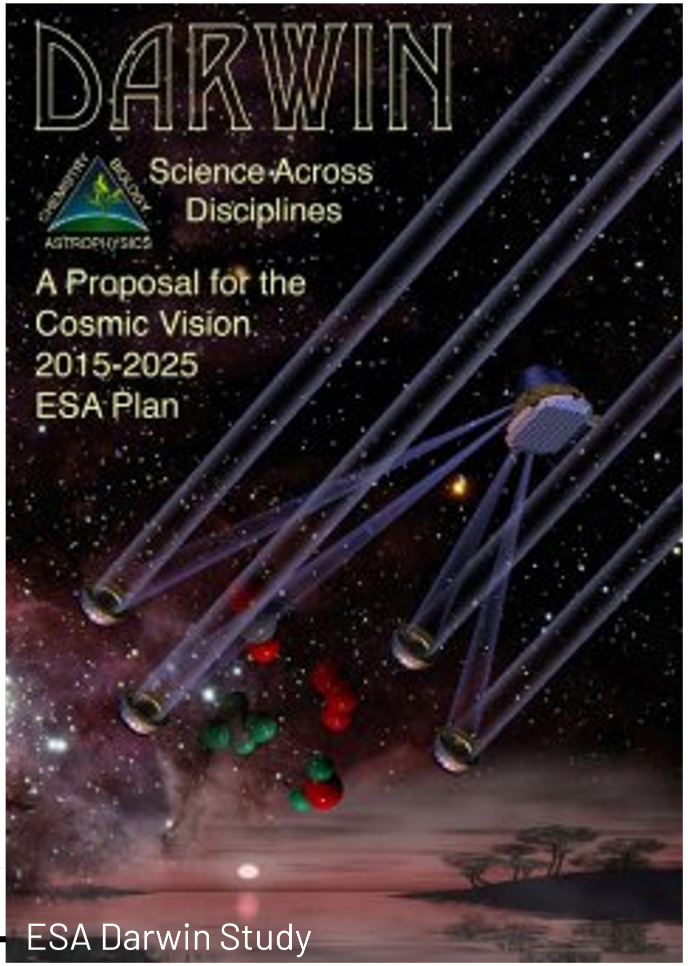
Heritage

Space based nulling-interferometry for exoplanet science is not a new idea. However,

- Our knowledge about exoplanets has significantly increased with hundreds of terrestrial planets waiting to be discovered
- Tremendous progress was made in several key technologies



NASA TPF-I study



ESA Darwin Study

nature

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nature › letters › article

Published: 24 August 1978

Detecting nonsolar planets by spinning infrared interferometer

R. N. BRACEWELL

Nature **274**, 780–781 (1978) | Cite this article

702 Accesses | **257** Citations | **48** Altmetric | Metrics

Investigating other worlds

- LIFE's wavelength range is chosen to cover the peak of the thermal emission of temperate terrestrial planets

- This wavelength range features absorption bands of major atmospheric constituents including molecules that are only present because biological activity such as ozone (O_3), methane (CH_4) and nitrous oxide (N_2O)

Emission spectra of terrestrial planets in our Solar System

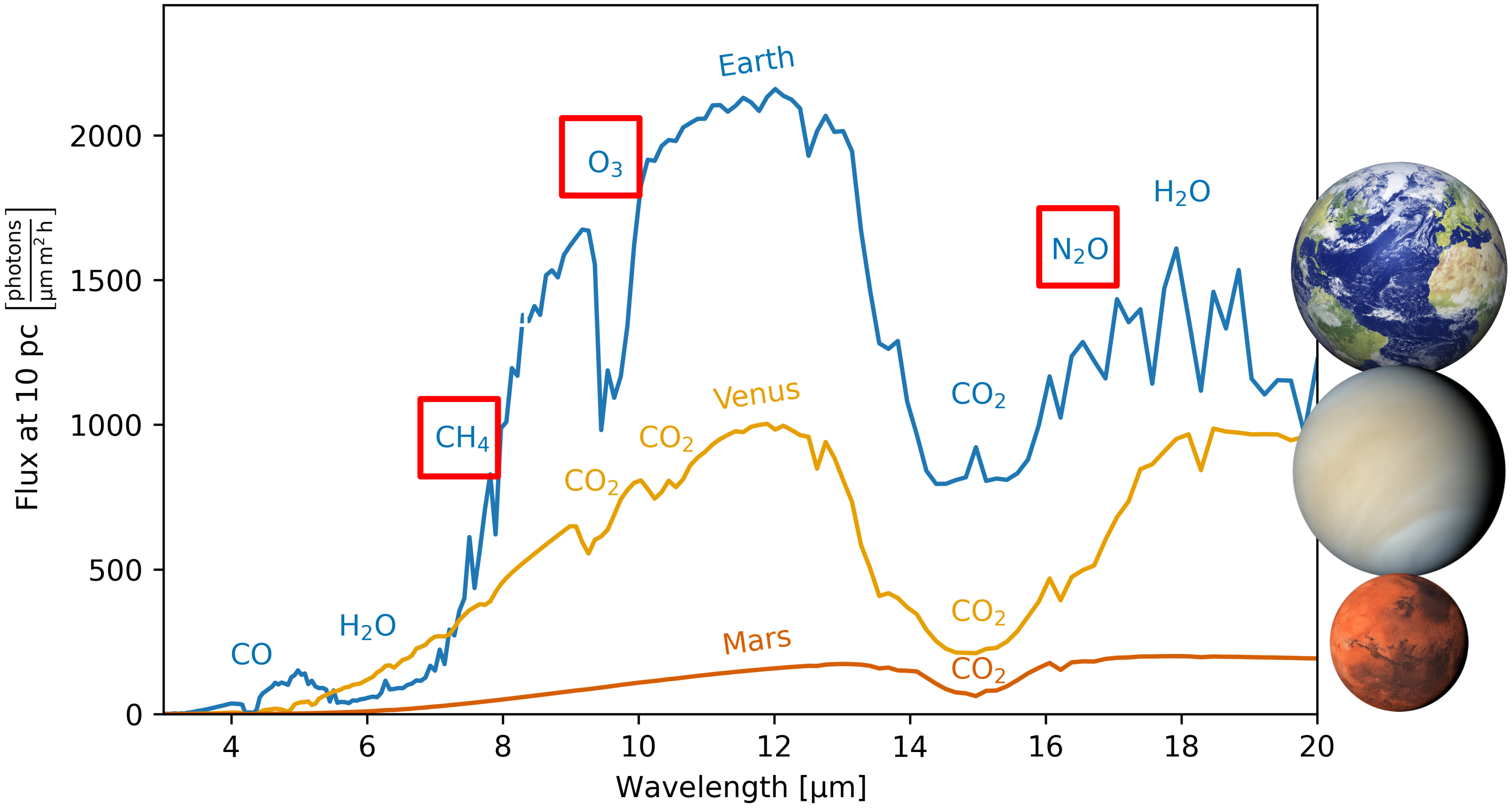

Figure credit: B. Konrad

Investigating other worlds

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Our Solar System as seen with LIFE from 10 pc distance

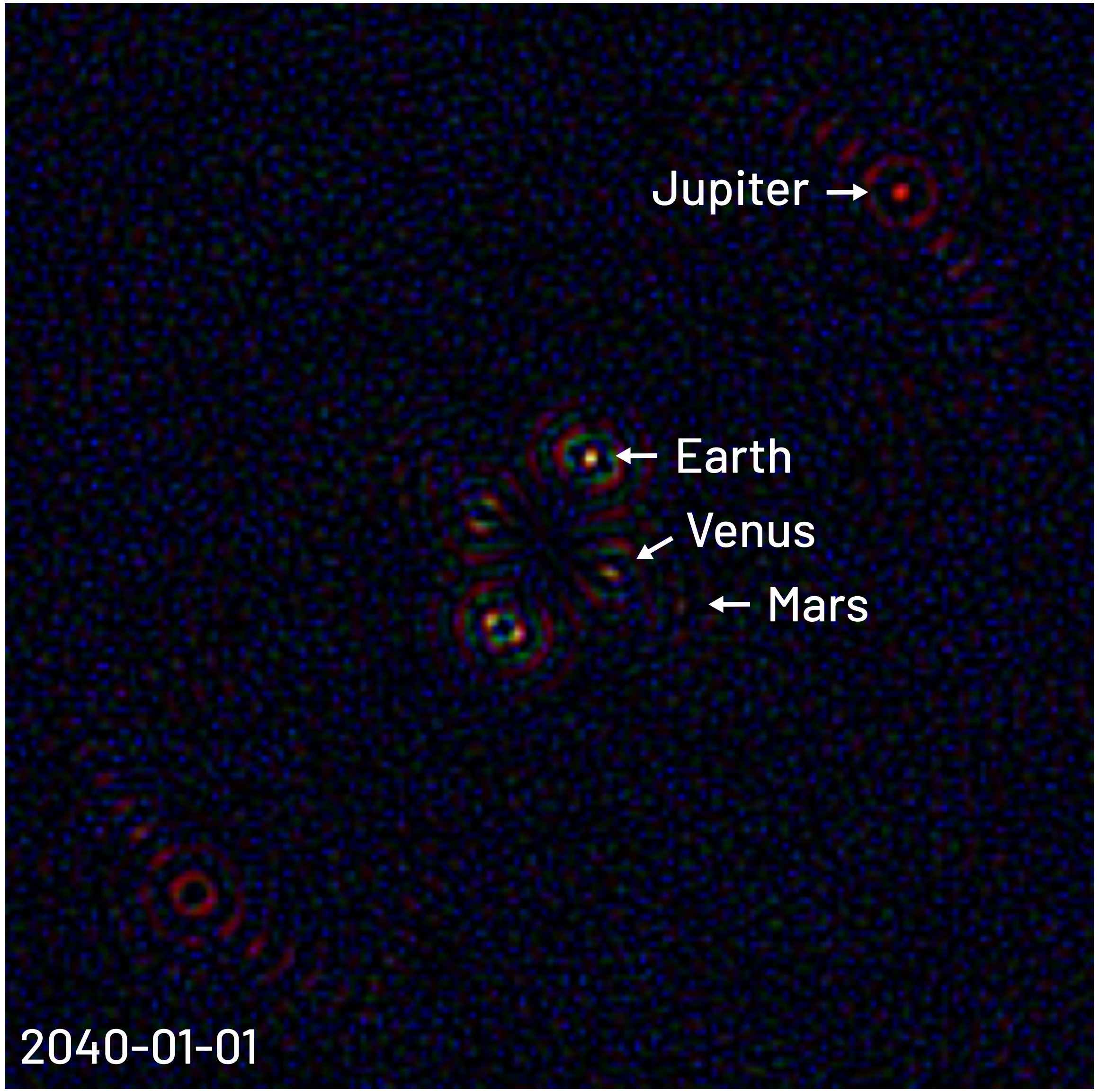
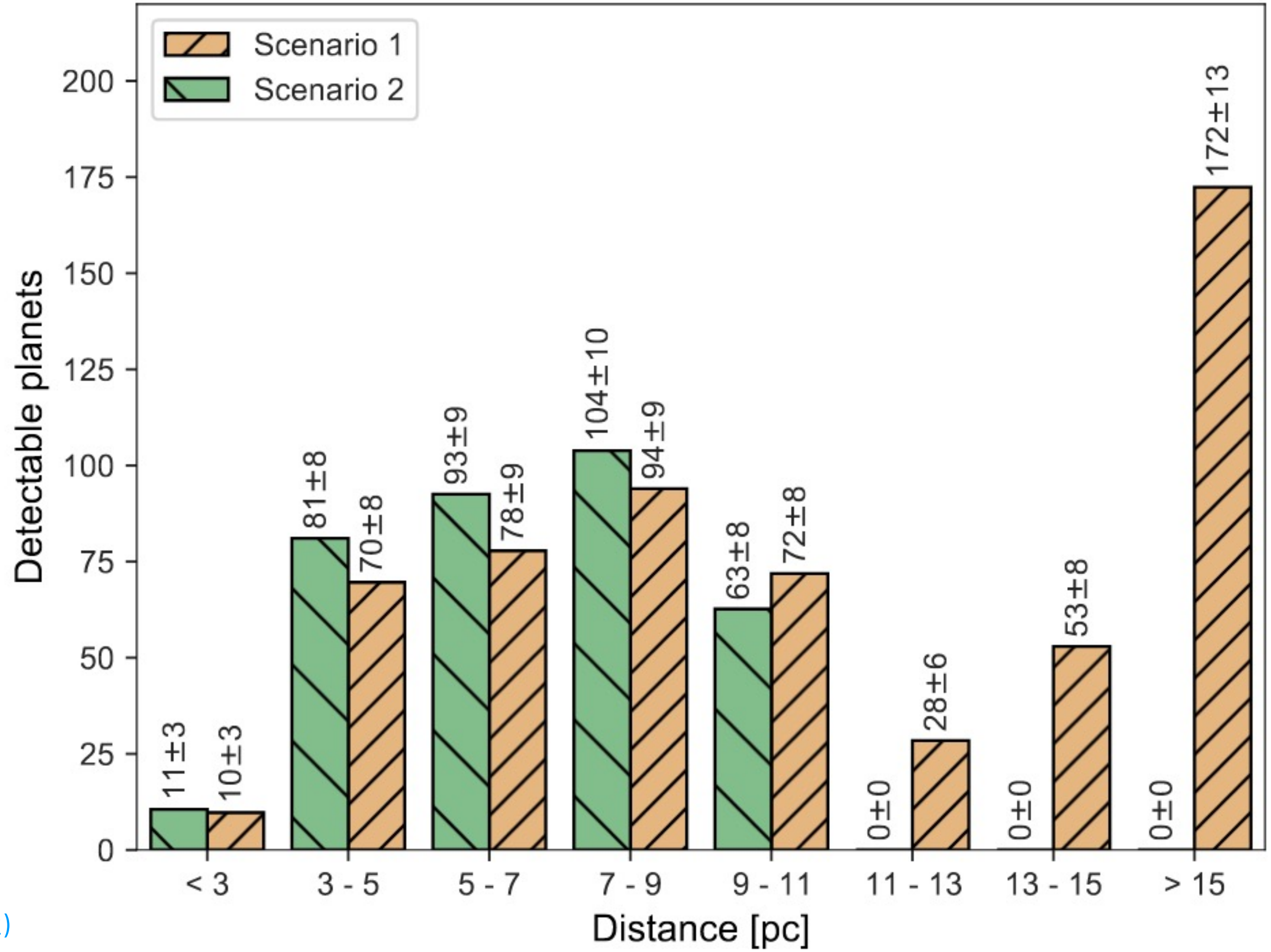


Figure credit: Ph. Huber

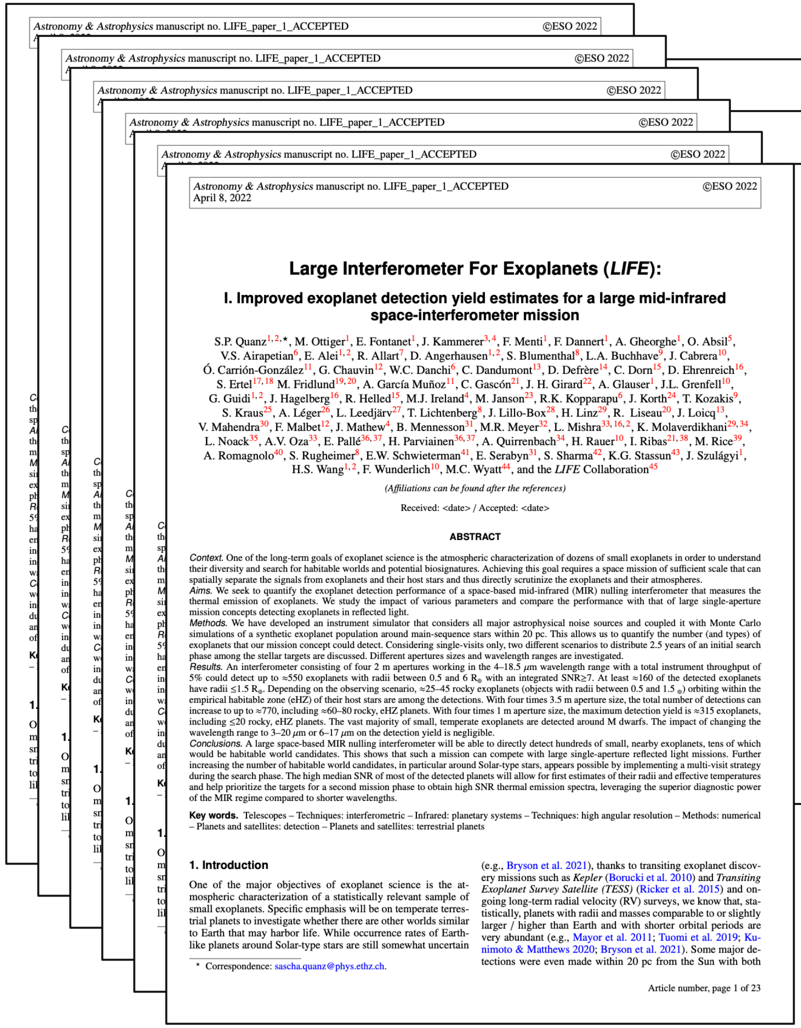
Exoplanet detection yield estimates – providing context

Assuming an initial search phase of the mission of 2.5 years



Quanz et al. A&A 664, A21 (2022)
cf. Kammerer et al. (2022)

Check-out LIFE-related paper series!



Astronomy & Astrophysics manuscript no. LIFE_paper_1_ACCEPTED ©ESO 2022
April 8, 2022

Large Interferometer For Exoplanets (*LIFE*):

I. Improved exoplanet detection yield estimates for a large mid-infrared space-interferometer mission

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Received: <date> / Accepted: <date>

ABSTRACT

Context. One of the long-term goals of exoplanet science is the atmospheric characterization of dozens of small exoplanets in order to understand their diversity and search for habitable worlds and potential biosignatures. Achieving this goal requires a space mission of sufficient scale that can spatially separate the signals from exoplanets and their host stars and thus directly scrutinize the exoplanets and their atmospheres.
Aims. We seek to quantify the exoplanet detection performance of a space-based mid-infrared (MIR) nulling interferometer that measures the thermal emission of exoplanets. We study the impact of various parameters and compare the performance with that of large single-aperture mission concepts detecting exoplanets in reflected light.
Methods. We have developed an instrument simulator that considers all major astrophysical noise sources and coupled it with Monte Carlo simulations of a synthetic exoplanet population around main-sequence stars within 20 pc. This allows us to quantify the number (and types) of exoplanets that our mission concept could detect. Considering single-visits only, two different scenarios to distribute 2.5 years of an initial search phase among the stellar targets are discussed. Different apertures sizes and wavelength ranges are investigated.
Results. An interferometer consisting of four 2 m apertures working in the 4–18.5 μm wavelength range with a total instrument throughput of 5% could detect up to ≈550 exoplanets with radii between 0.5 and 6 $R_\oplus$ with an integrated SNR≥7. At least ≈160 of the detected exoplanets have radii ≤1.5 $R_\oplus$. Depending on the observing scenario, ≈25–45 rocky exoplanets (objects with radii between 0.5 and 1.5 $_\oplus$) orbiting within the empirical habitable zone (eHZ) of their host stars are among the detections. With four times 3.5 m aperture size, the total number of detections can increase to up to ≈770, including ≈60–80 rocky, eHZ planets. With four times 1 m aperture size, the maximum detection yield is ≈315 exoplanets, including ≤20 rocky, eHZ planets. The vast majority of small, temperate exoplanets are detected around M dwarfs. The impact of changing the wavelength range to 3–20 μm or 6–17 μm on the detection yield is negligible.
Conclusions. A large space-based MIR nulling interferometer will be able to directly detect hundreds of small, nearby exoplanets, tens of which would be habitable world candidates. This shows that such a mission can compete with large single-aperture reflected light missions. Further increasing the number of habitable world candidates, in particular around Solar-type stars, appears possible by implementing a multi-visit strategy during the search phase. The high median SNR of most of the detected planets will allow for first estimates of their radii and effective temperatures and help prioritize the targets for a second mission phase to obtain high SNR thermal emission spectra, leveraging the superior diagnostic power of the MIR regime compared to shorter wavelengths.

Key words. Telescopes – Techniques: interferometric – Infrared: planetary systems – Techniques: high angular resolution – Methods: numerical – Planets and satellites: detection – Planets and satellites: terrestrial planets

1. Introduction

One of the major objectives of exoplanet science is the atmospheric characterization of a statistically relevant sample of small exoplanets. Specific emphasis will be on temperate terrestrial planets to investigate whether there are other worlds similar to Earth that may harbor life. While occurrence rates of Earth-like planets around Solar-type stars are still somewhat uncertain (e.g., Bryson et al. 2021), thanks to transiting exoplanet discovery missions such as *Kepler* (Borucki et al. 2010) and *Transiting Exoplanet Survey Satellite (TESS)* (Ricker et al. 2015) and ongoing long-term radial velocity (RV) surveys, we know that, statistically, planets with radii and masses comparable to or slightly larger / higher than Earth and with shorter orbital periods are very abundant (e.g., Mayor et al. 2011; Tuomi et al. 2019; Kunimoto & Matthews 2020; Bryson et al. 2021). Some major detections were even made within 20 pc from the Sun with both

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Exoplanet science with a space-based mid-infrared nulling interferometer

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ABSTRACT

One of the long-term goals of exoplanet science is the (atmospheric) characterization of a large sample (>100) of terrestrial planets to assess their potential habitability and overall diversity. Hence, it is crucial to quantitatively evaluate and compare the scientific return of various mission concepts. Here we discuss the exoplanet yield of a space-based mid-infrared (MIR) nulling interferometer. We use Monte-Carlo simulations, based on the observed planet population statistics from the Kepler mission, to quantify the number and properties of detectable exoplanets (incl. potentially habitable planets) and we compare the results to those for a large aperture optical/NIR space telescope. We investigate how changes in the underlying technical assumptions (sensitivity and spatial resolution) impact the results and discuss scientific aspects that influence the choice for the wavelength coverage and spectral resolution. Finally, we discuss the advantages of detecting exoplanets at MIR wavelengths, summarize the current status of some key technologies, and describe what is needed in terms of further technology development to pave the road for a space-based MIR nulling interferometer for exoplanet science.

Keywords: exoplanets, interferometry, space, high-spatial resolution, infrared, habitability

1. INTRODUCTION

Since the first detection of a planet orbiting a main sequence star other than our Sun in 1995[1] the field of exoplanet science has been growing at a breathtaking speed: to date we know more than 5000 exoplanets and exoplanet candidates*. The overwhelming majority of these objects were detected via dedicated long-term surveys using indirect techniques – the radial velocity (RV) or the transit technique – from both the ground (e.g., the HARPS survey or the California Planet Survey) and from space (e.g., NASA's Kepler mission). Thanks to the statistics derived from these surveys, we have a first quantitative understanding of the occurrence rate of different planet types as a function of their radius / mass, orbital period and also spectral type of the host star.[2–4] For some planets, transit spectroscopy and/or secondary eclipse spectroscopy measurements (primarily done from space with the Hubble Space Telescope and the Spitzer Space Telescope) provide empirical constraints on the atmospheric composition of these objects.[5,6] With a few exceptions,[7,8] up to now these investigations targeted so-called hot Jupiters, gas-giant planets on orbits with periods of a few days only, but with the upcoming launch of the James Webb Space Telescope (JWST) in 2020 some smaller planets, i.e., the low-hanging fruits with sizes possibly down to those of super-Earths or Earth-like planets, might come within reach of atmospheric detection or even characterization studies.[9]

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CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2312051

Exoplanet characterization: the mid-infrared advantage

In contrast to exoplanet observations in reflected light in the optical/near-infrared, LIFE will...

- ...directly constrain the **pressure-temperature structure** of exoplanet atmospheres
- ...access (multiple) absorption bands of **major atmospheric molecules** such as H_2O and CO_2 as well as collision induced absorption from N_2 and O_2
- ...search for numerous **atmospheric biosignatures** in the context of terrestrial exoplanets and gas dominated Super-Earths (e.g., O_3 and CH_4, but also N_2O, PH_3, NH_3, and C_5H_8)
- ...constrain directly **the effective temperature** of exoplanets and provide access to their **radii**
- ...deliver a **higher detection yield** during search phase as it is less affected by the orbital phase function of the exoplanets' emission compared to reflected light missions
- ...immediately **start observing already known small, temperate exoplanets** around nearby M-stars

cf. Line, Quanz et al. (2019; decadal White Paper), Quanz et al. 2022, Dannert et al. 2022, Alei et al. 2022, Konrad et al. 2022

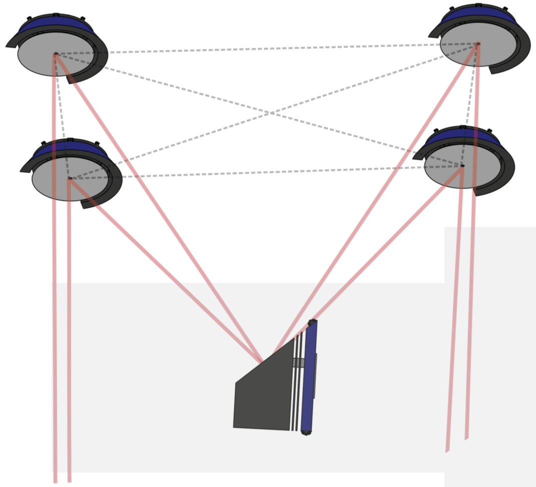
Ongoing technology developments

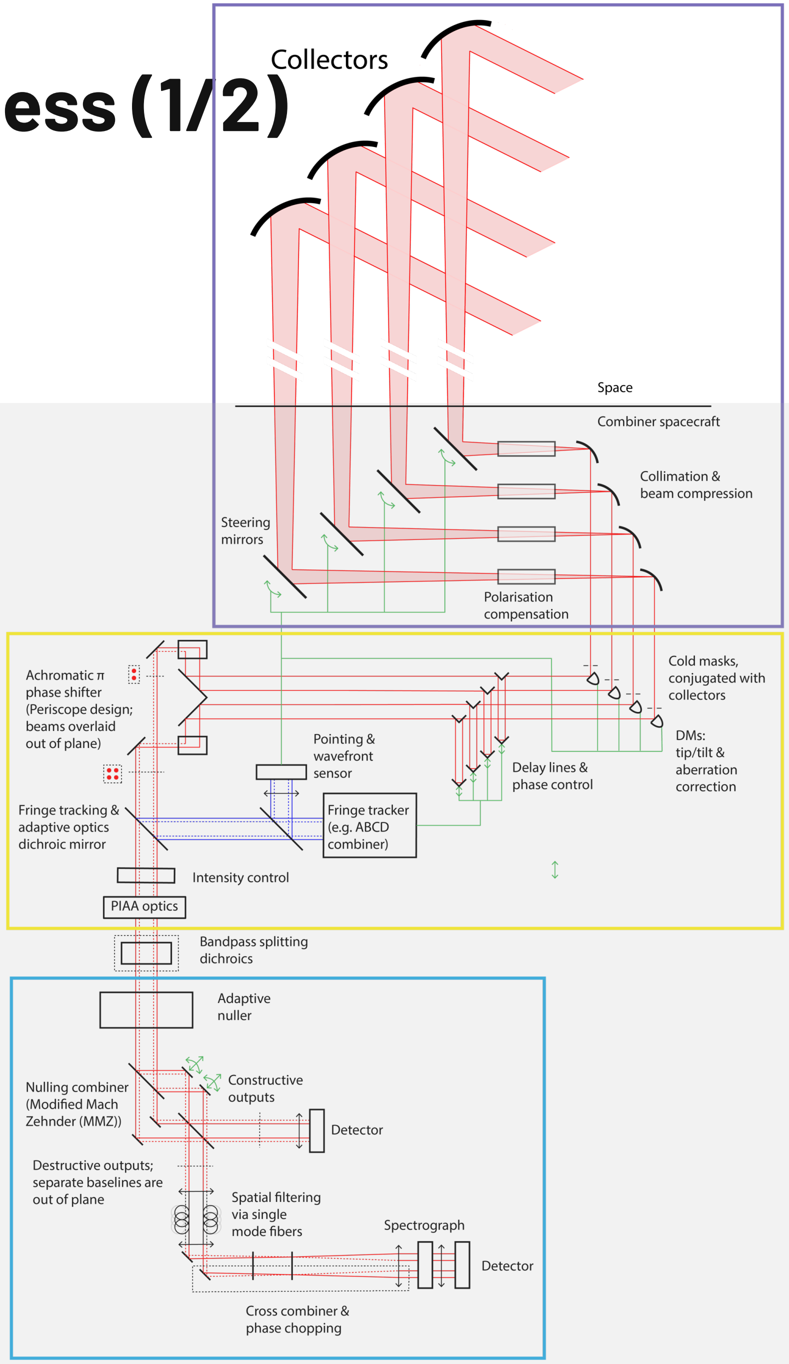
Ongoing efforts increase technological readiness (1/2)

1. Mission requirements are being finalized
2. Preliminary optical concept is defined

Check out Glauser et al. 2024 (SPIE) for description of current mission baseline;

NOVA funding to look at optical design and cryogenic deformable mirrors (PI: van der Tak)





Legend
- Science wavelengths
- Fringe tracking & adaptive optics wavelengths (< 4 μm)
- Control signal
- Receiving optics
- Correcting optics
- Nulling stages (x number of bandpasses)

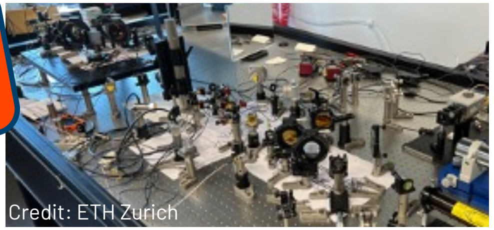
Ongoing efforts increase technological readiness (2/2)

NOT EXHAUSTIVE

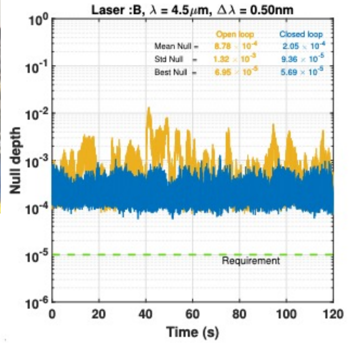
3 Nulling interferometry cryogenic experiment

New mid-infrared testbench under construction at ETH Zurich to demonstrate interferometric nulling under realistic conditions (NICE)

Check out SPIE papers Ranganathan et al. (2024) Birbacher et al. (2024)



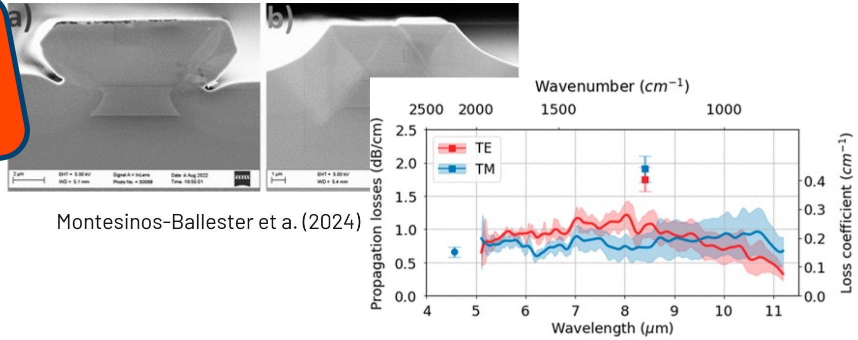
Credit: ETH Zurich



4 Photonics

Major breakthroughs in astro-photonics for interferometric nulling at near-infrared wavelengths motivate mid-infrared applications as next step

Grant at ETH to investigate materials and designs for fringe tracker, spatial filter, nulling chip

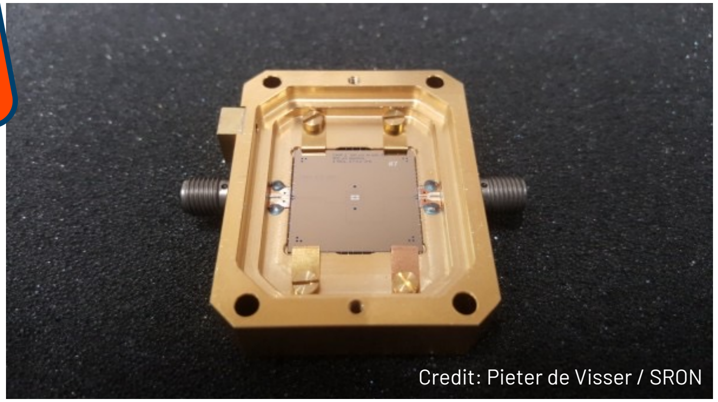


Montesinos-Ballester et a. (2024)

5 Low-noise detectors

KIDs (Kinetic Inductance Detectors) show excellent performance at sub-mm and near-infrared wavelengths and close-in on mid-infrared regime

SRON (PI: de Visser) colleagues received grant to continue development

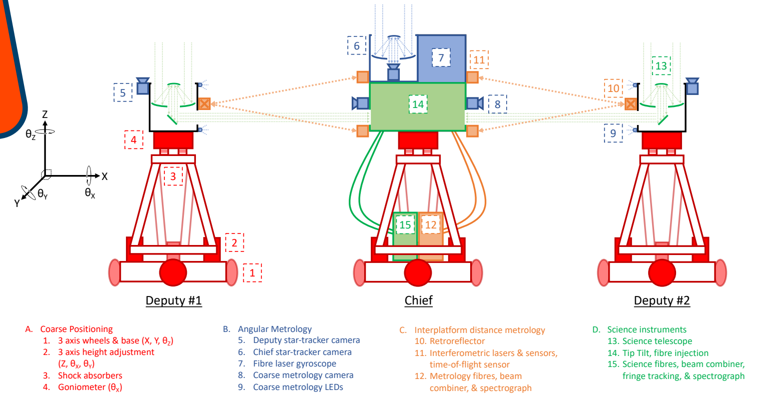


Credit: Pieter de Visser / SRON

6 Autonomous formation flying

Various experiments and missions aim to demonstrate high-precision formation flying performance in the coming years

Proba-3 launched; ongoing efforts in Japan and Australia (SEIRIOS / SILVIA missions); grant for cubesat mission in US



LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

Outlook

Aiming at a launch in 2040 we consider 3 development and funding stages

Stage 1: Preparation
Today - 2028

- Conclude mission concept study and development plan
- Demonstrate LIFE measuring principle in the lab
- Mature key technologies and investigate commercialization potential

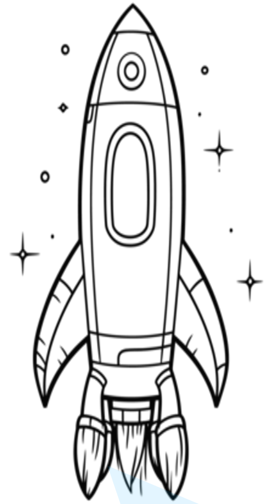
Stage 2: Maturation
2029 - 2033

- Conclusion of mission design
- Maturation and demonstration of sub-system performance, in particular formation flying, interferometric nulling

Stage 3: Implementation
2034-2040

- Manufacturing / Integration of spacecraft
- Securing of launch opportunity
- Setting up of ground-segment, mission operations, and data center

Launch



Establish mission consortium

Develop fundraising strategy

Develop communication strategy

Aiming at a launch in 2040 we consider 3 development and funding stages

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Today - 2028

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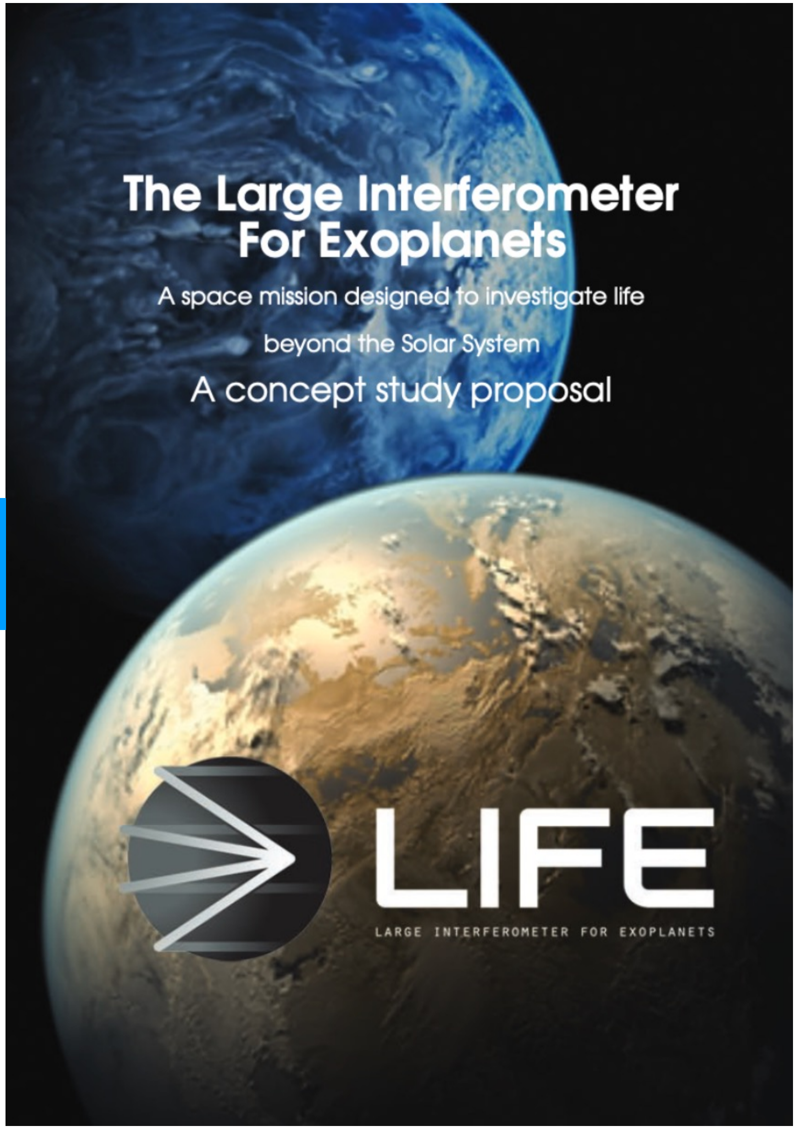

Study proposal will include:
- Refocused science case / objectives
- Mission requirements
- Summary of current mission baseline architecture
- Work-packages to engage partners

Next steps:
- Finish study proposal and define scope study
- Continue discussion with potential industry partners

Goal:
- Kick-off study in 2025
- Understand final mission
- Identify technology gaps
- Develop implementation plan