The LIFE Initiative
Scientific Prospects and Challenges

Authors:

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Characterization of exoplanet atmospheres
in the mid-infrared -
diversity, habitability, biosignatures

ETH zürich

PlanetS
National Centre of Competence in Research

The vision of the LIFE initiative

Understanding our place in the cosmos in the context of exoplanet and planetary science

The LIFE initiative seeks to develop the scientific context, the technology, and a roadmap for an ambitious mid-infrared space mission that investigates the atmospheric properties of a large sample of terrestrial exoplanets–including 30-50 orbiting within the habitable zone of their host stars.

The LIFE mission will

- Investigate the diversity of planetary bodies
- Assess the habitability of terrestrial exoplanets
- Search for potential biosignatures in exoplanet atmospheres

Quanz et al. 2021 (Experimental Astronomy; 10.1007/s10686-021-09791-z)

Detecting and characterizing rocky exoplanets from space

Scientific synergies between different missions and ground-based instruments

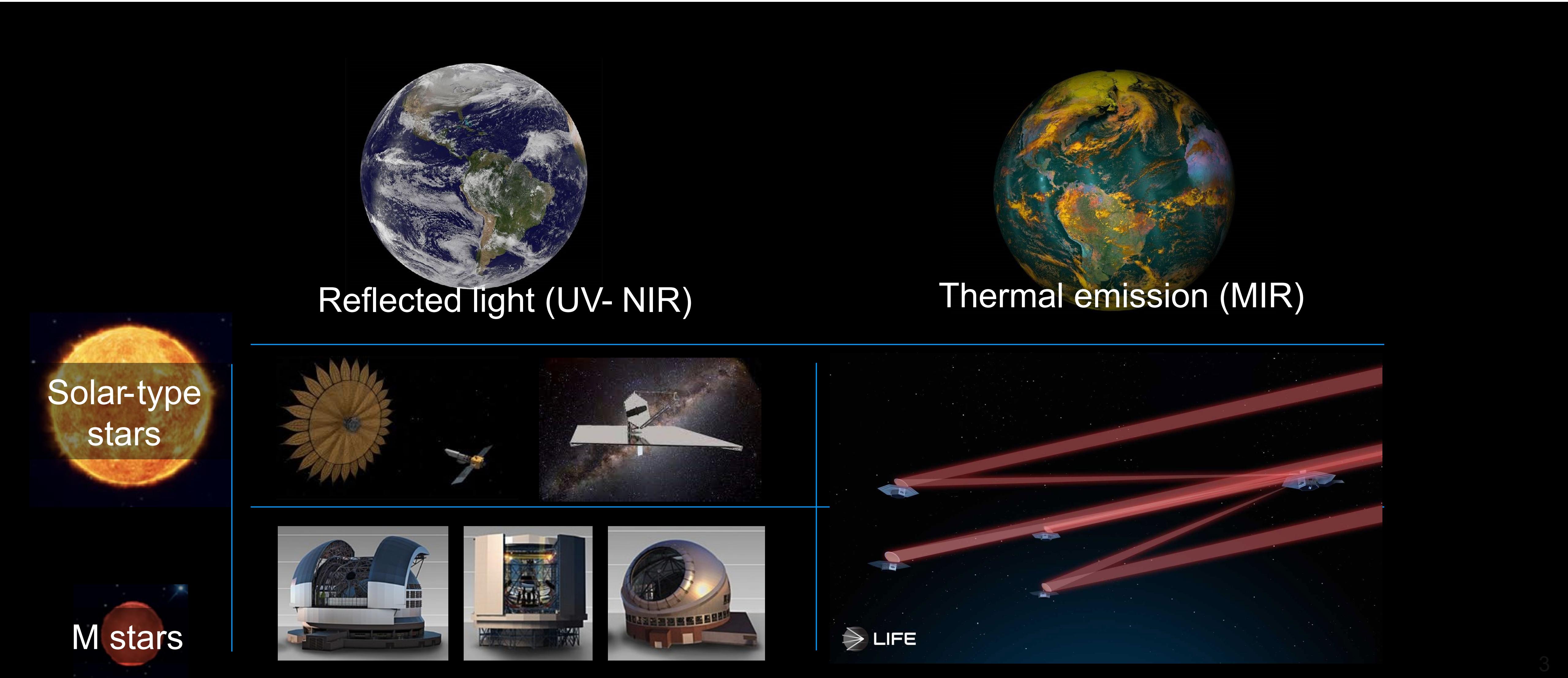
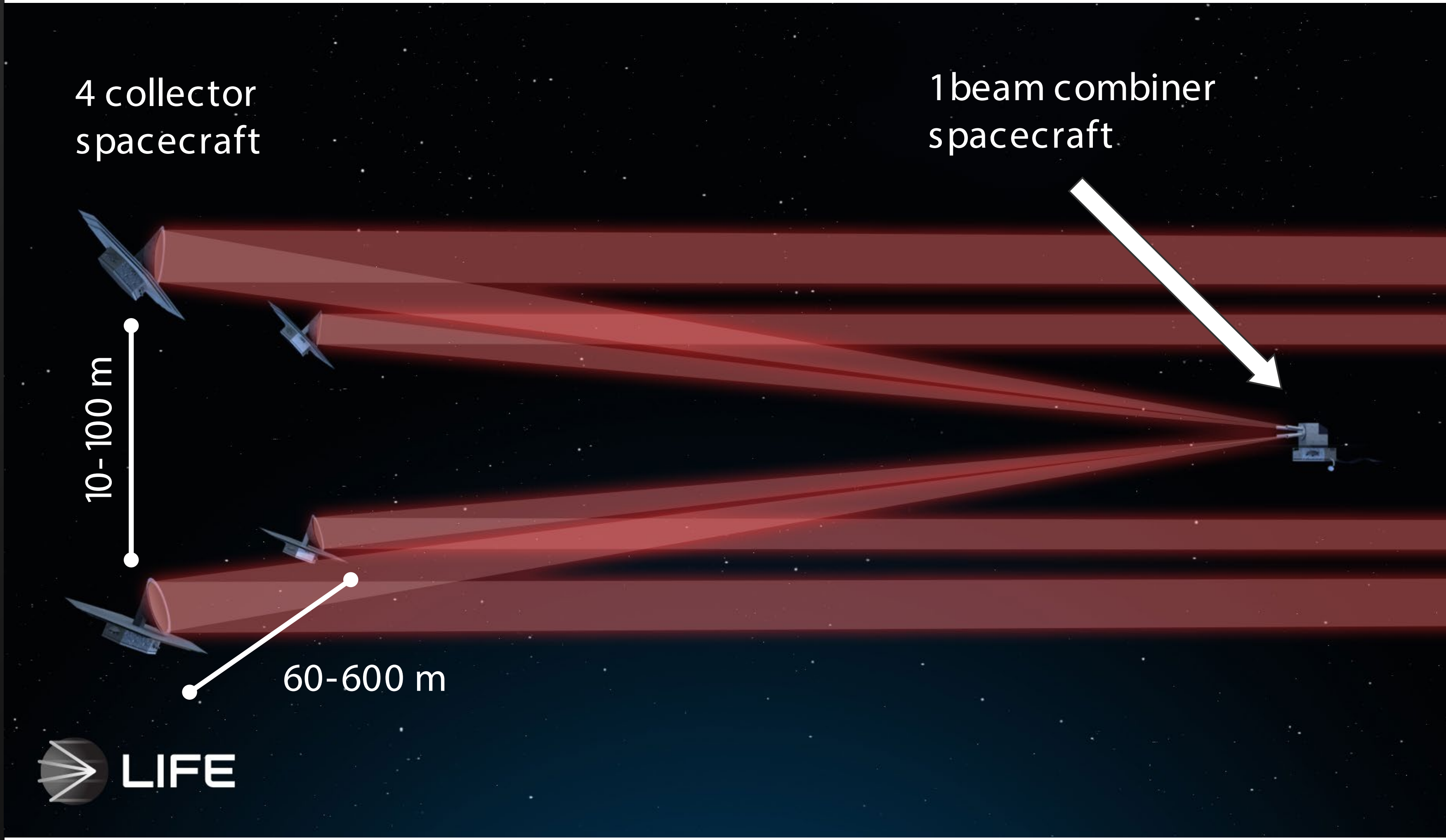


Image credit: NASA, LIFE Initiative, ESO, TMT, GMT

The LIFE mission

- …is a spacebased formation-flying mid-infrared (nulling) interferometer
- …consists of 4 collector spacecraft (tbc) separated by tens to hundreds of meters and a beam combiner
- …covers the mid-infrared wavelength range between ~4-18.5µm with a spectral resolution of R ~ 50 (tbc)



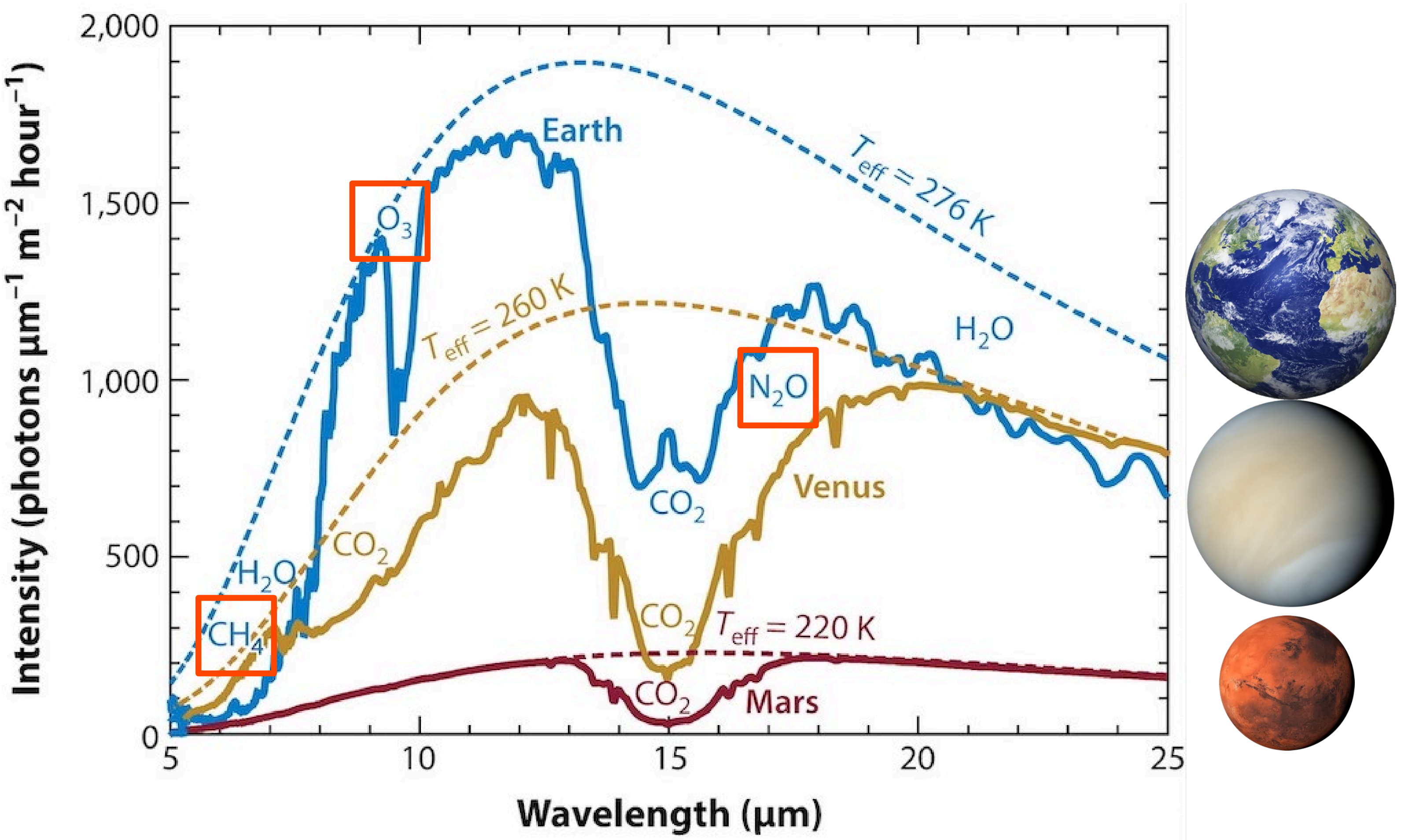
Artist impression of LIFE concept (credit: LIFE initiative)

Quanz et al. 2022 (arXiv2101075000)

The LIFE mission

- The wavelength range is chosen to cover the peak of the thermal emission of temperate terrestrial planets
- This wavelength range features absorption bands of major molecular constituents including biosignatures such as ozone (O_3), methane (CH_4) and nitrous oxide (N_2O)

MIR spectra of terrestrial planets in our Solar System



Kaltenegger2017

Exoplanet characterization: the mid -infrared advantage

A mission like LIFE can…

…directly constrain the **pressure-temperature structure** of exoplanet atmospheres

…access (multiple) atmospheric absorption bands of **major molecules** such as H_2O, CO_2, and CO 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**

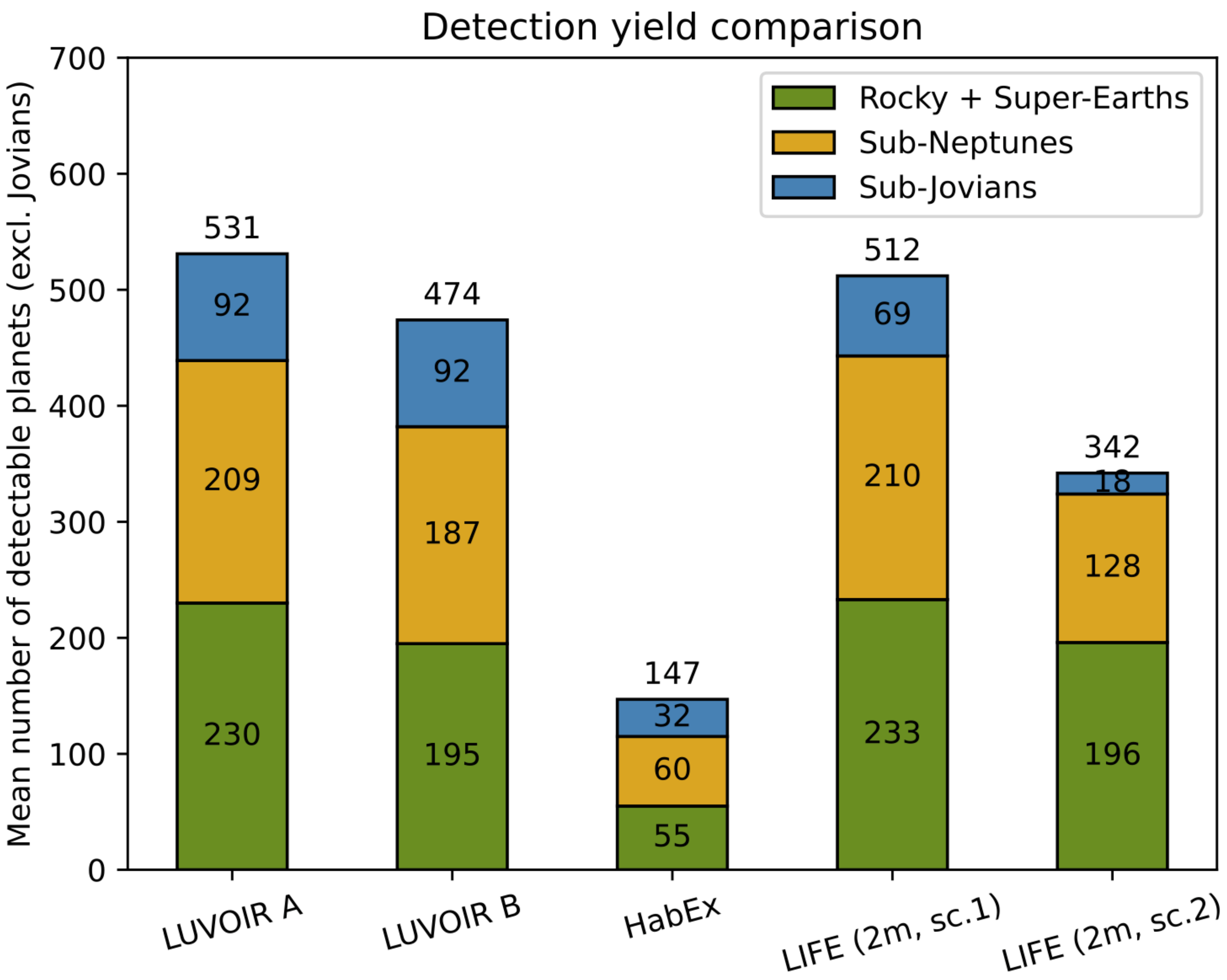
…secure a higher detection yield during search phase as it is **less affected by the orbital phase function** of the exoplanets' emission compared to reflected light missions

…immediately **start observing already known small, temperate exoplanets** around nearby M-stars and include those in the final target list

cf. Line, Quanz et al. (2019; decadal White Paper)

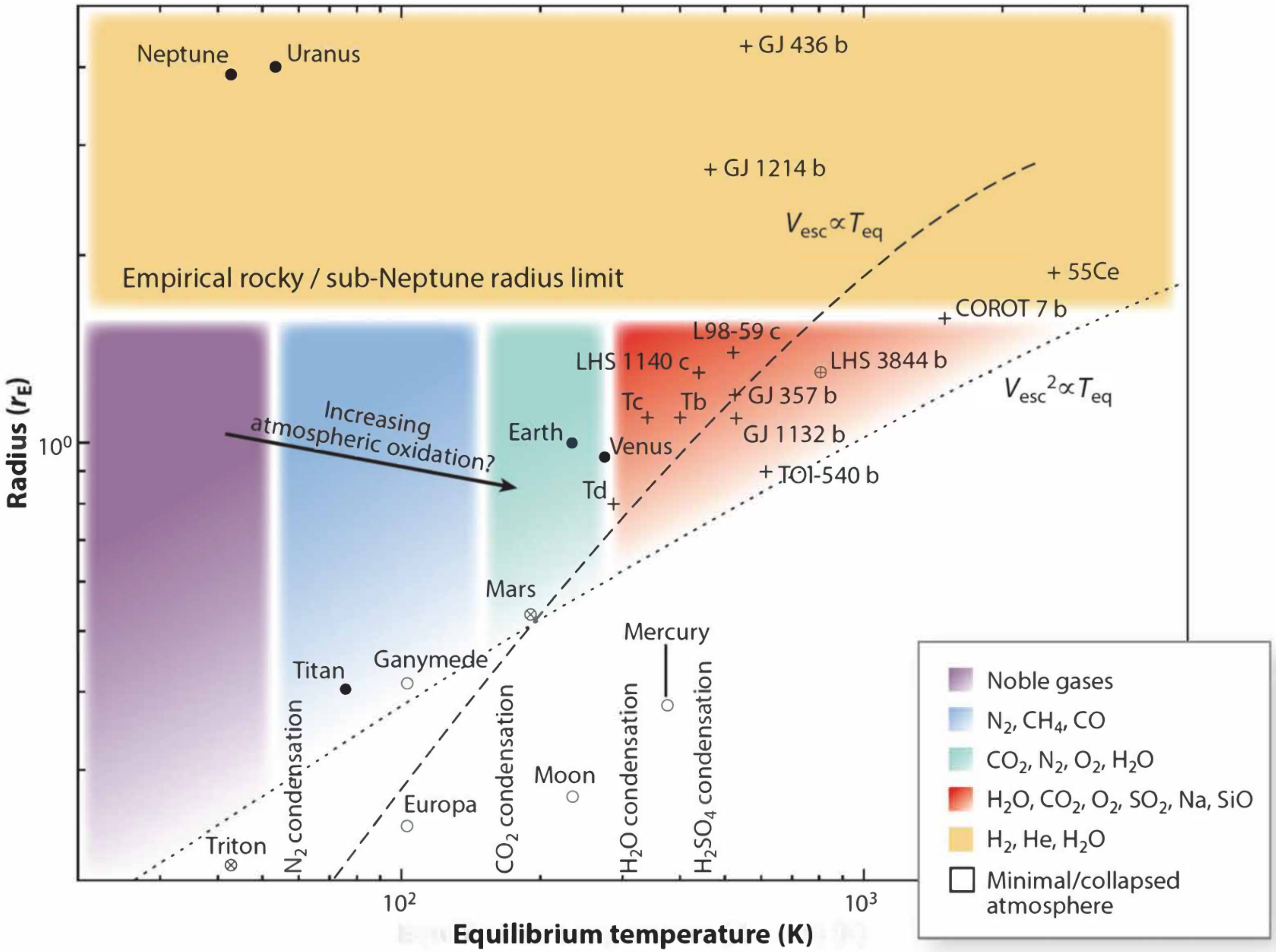
LIFE: Exoplanet Detection Yield Estimates

- Expected detection yields are similar to large future NASA flagship concepts
- Monte Carlo simulations based on Kepler statistics (SAG13) and stars within ~20 pc
- Assuming
  - 2.5 years total search phase
  - 4 x 2m apertures
  - 5% total instrument throughput
  - 10 h slew between targets
  - 20% general overhead



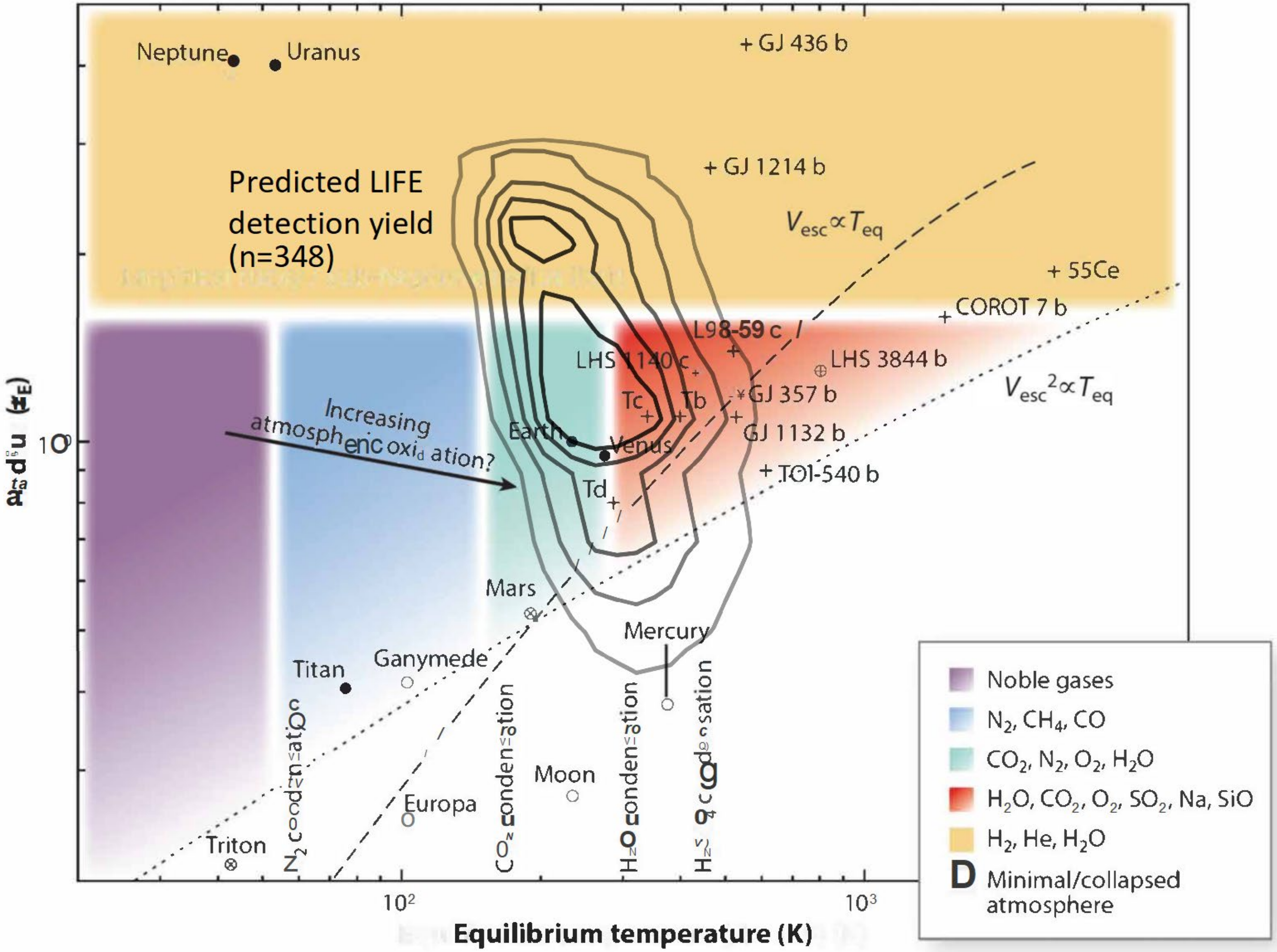
Quanz et al. 2022 (arXiv2101075000)

LIFE discovery space vs. JWST



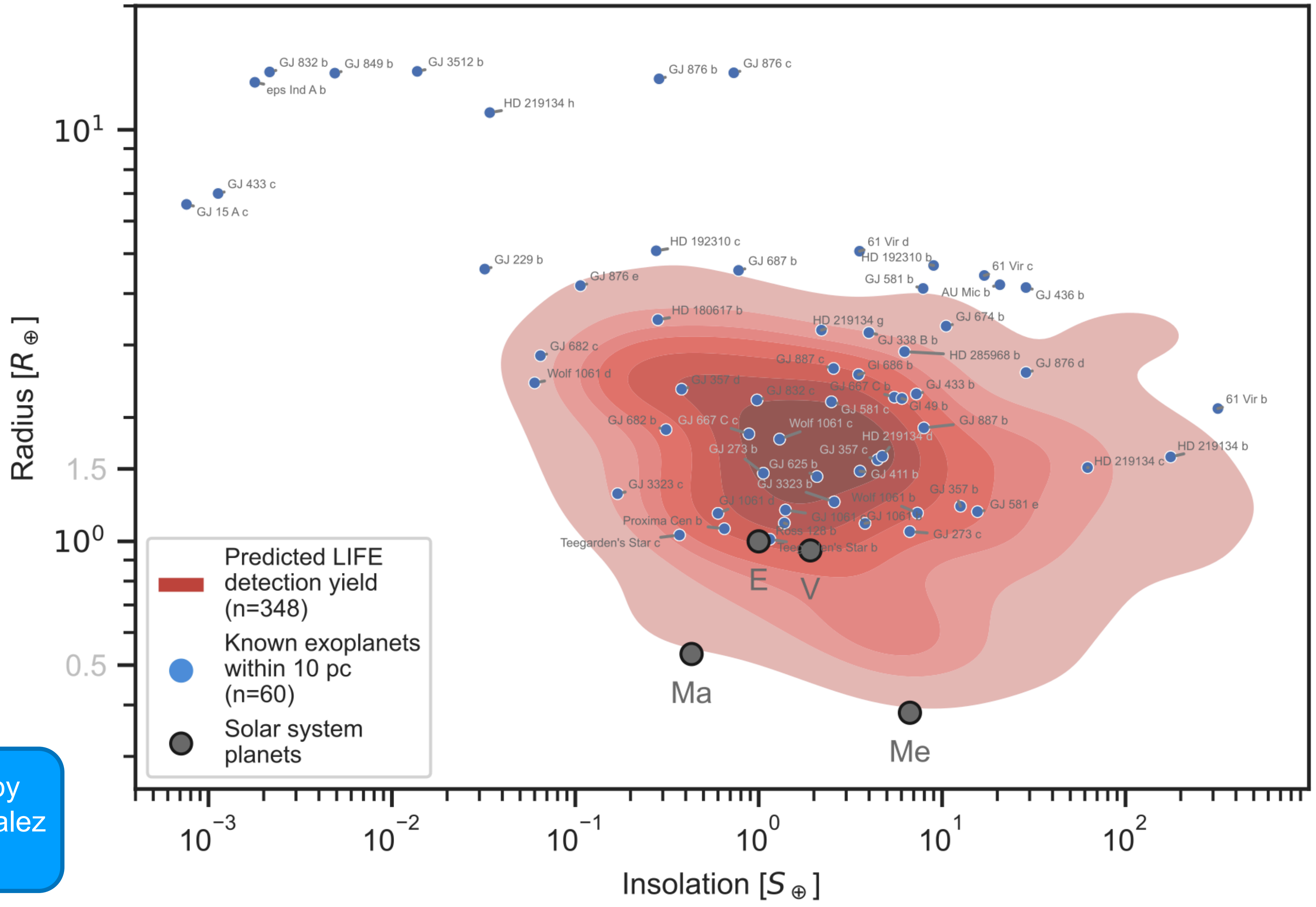
Wordsworth & Kreidberg 2022

LIFE discovery space vs. JWST



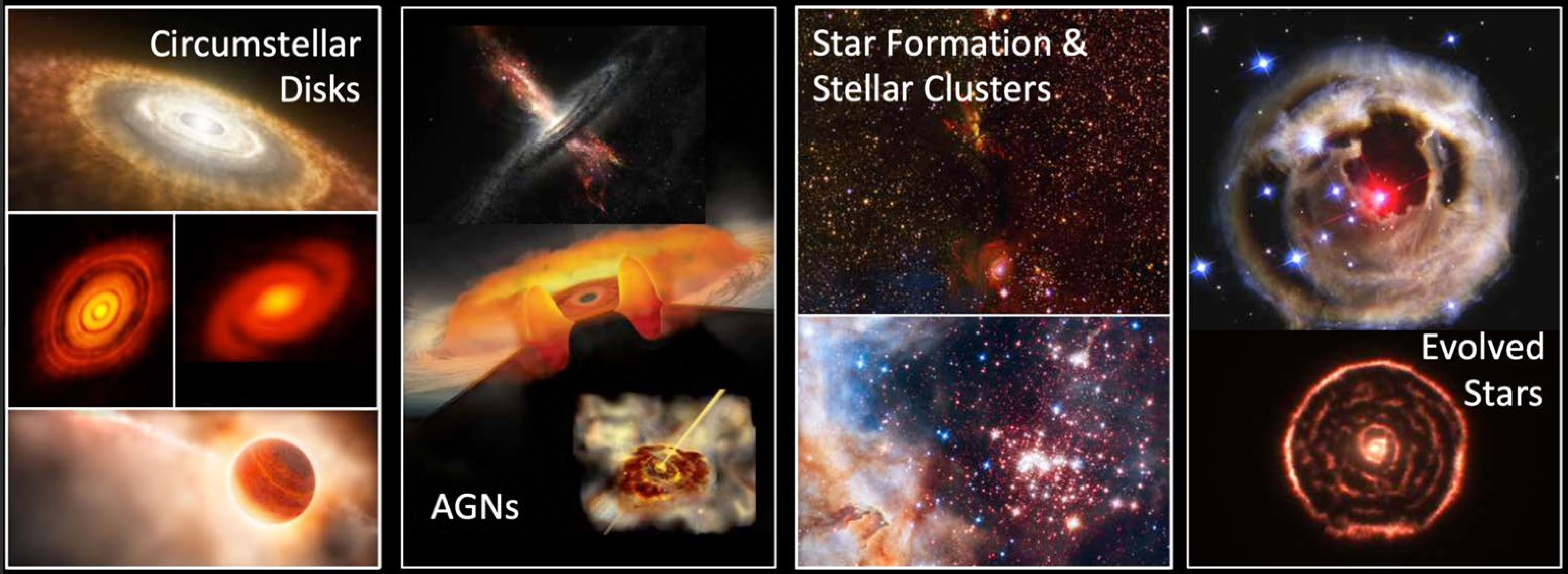
Wordsworth & Kreidberg 2022

LIFE discovery space vs. known exoplanets within 10 pc



Quanz et al. 2022

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS



…probing the terrestrial planet formation region

…resolving the dusty torus

…probing the innermost regions of dense clouds and cores

…revealing dust properties and distribution within their shells

The science of LIFE: challenges ahead

- LIFE's impact on non-exoplanet science not quantified yet
- Different beam combination and/or signal modulation schemes are being looked at, but quantifying the impact on growing number of science cases remains to be done
- Implementation of instrumental noise terms and their impact on detection yield and other science cases is ongoing
- Quantitative science cases leveraging larger sub-sets of the population of detectable planets still missing
- Uncertainties in exoplanet statistics (Bryson et al. 2021) leads to large uncertainties in expected detection yield and hence science return
- How do we manage to find more (all?) good targets prior to launch ?

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

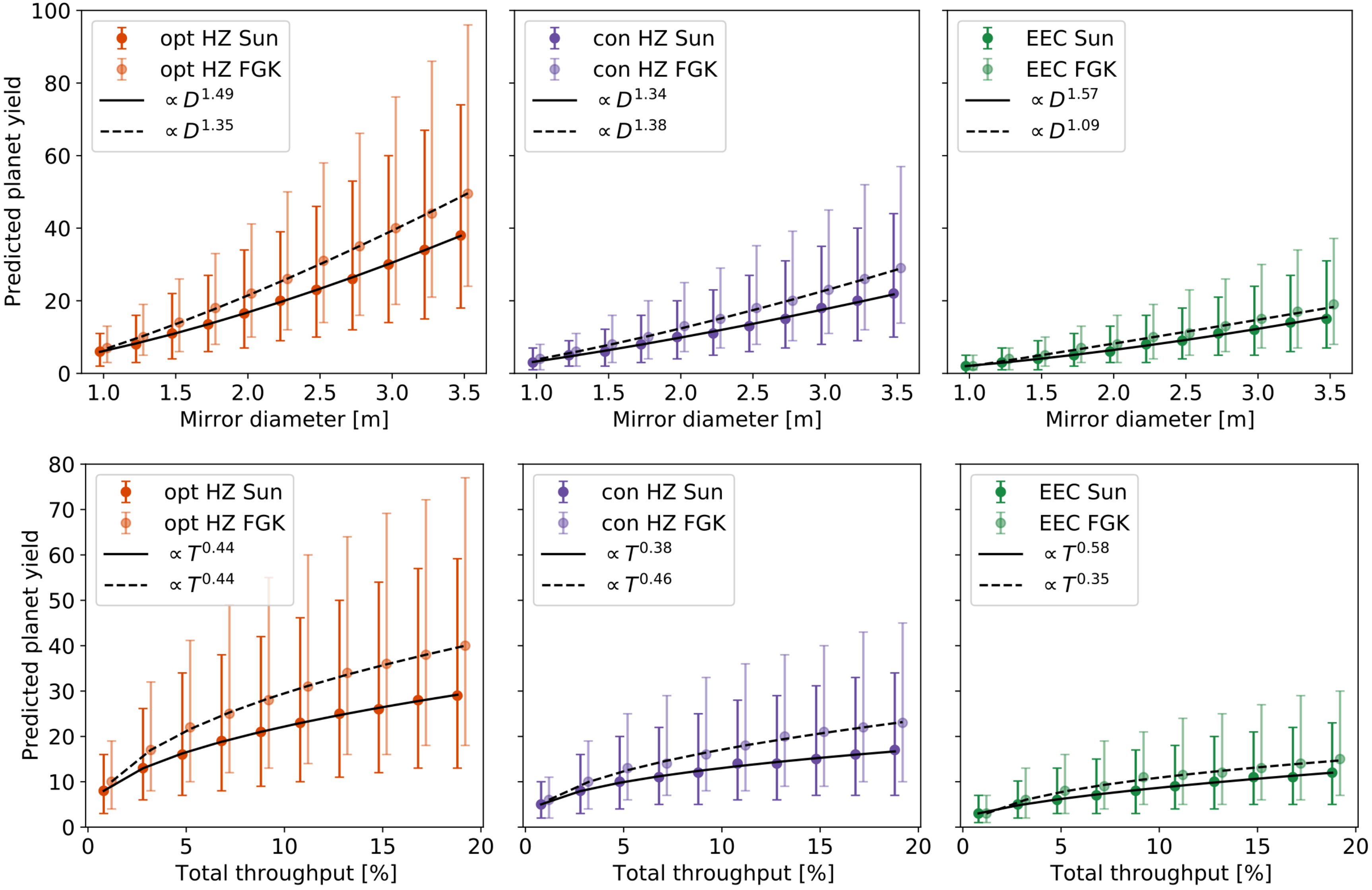
Thank you

Detection yield of rocky planets around Sun-like stars

Revising the detection yield of the search phase based on Bryson et al. 2021

Assumption:
5% throughput

Assumption:
2-m aperture size

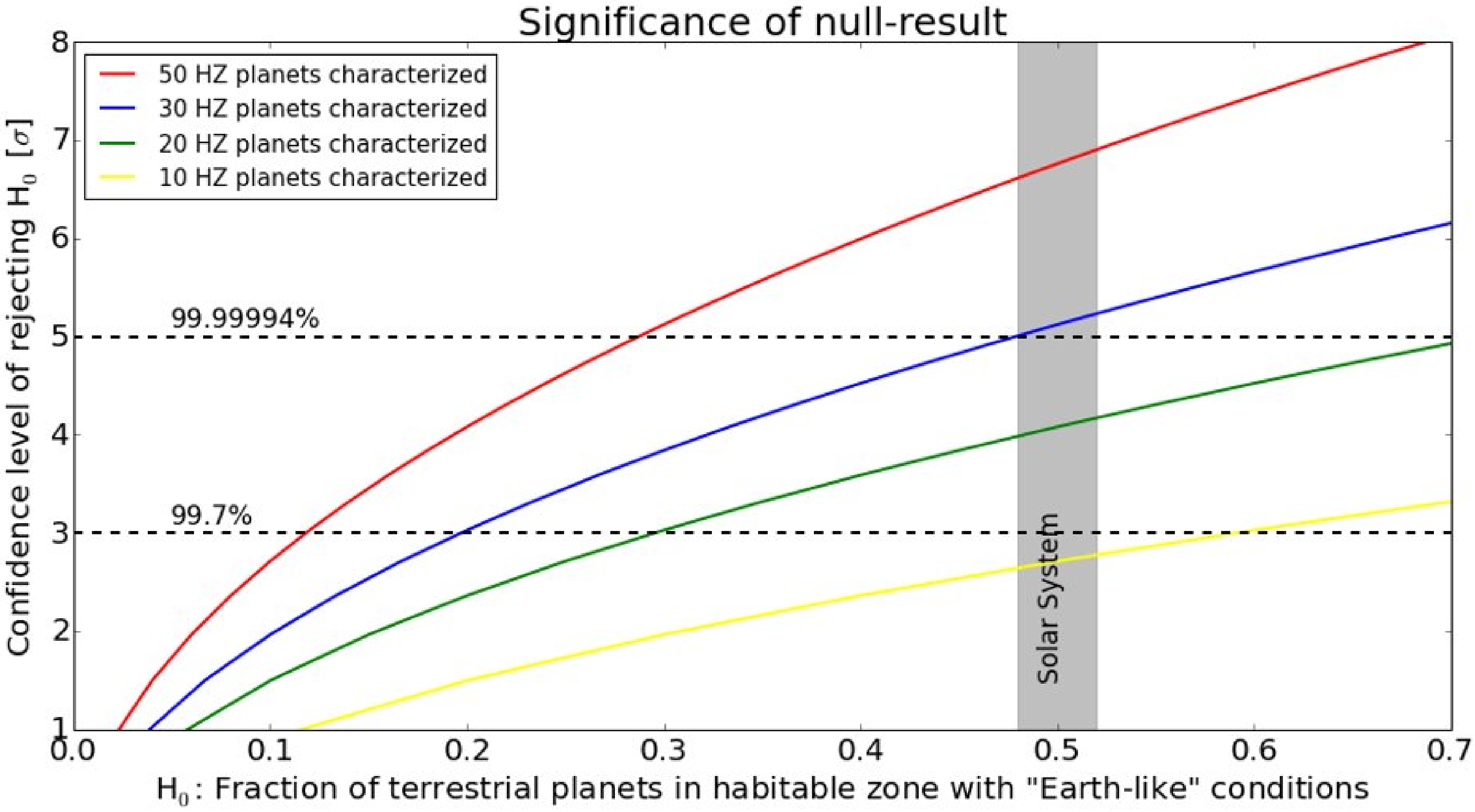


Kammerer et al. 2022

Comprehensive Habitability Studies

LIFE will enable **comparative studies** of potentially habitable environments.

Sample size needs to be large enough for **null result to be significant and scientifically interesting.**



Quanz et al. 2021 (Experimental Astronomy 10.1007/s10686-021-09791-z)

The LIFE initiative in an international context

ESA Voyage 2050 Senior Committee report emphasizes importance of LIFE science case in the context of ESA Science Programm

"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."

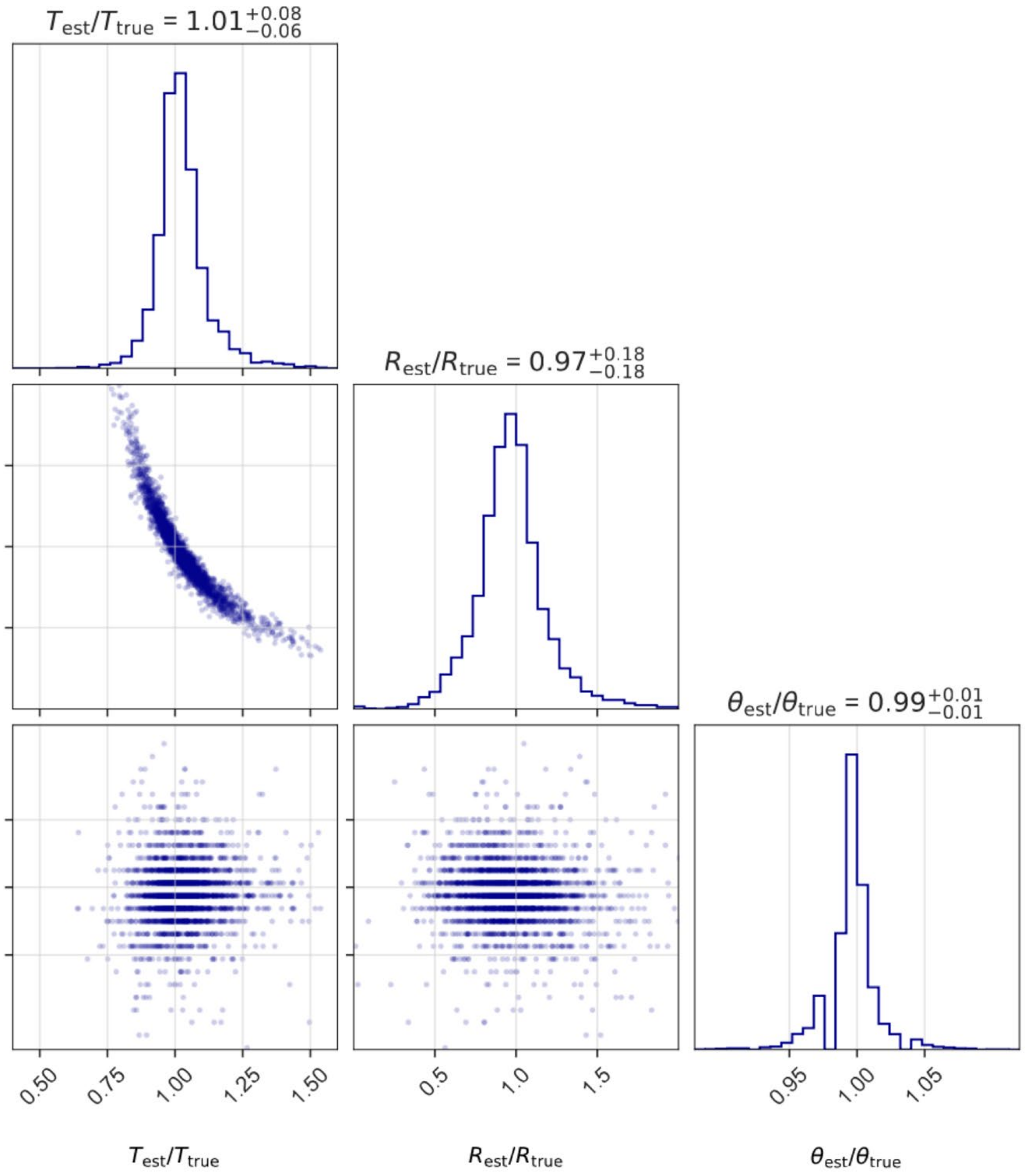
"This would give ESA and the European community the opportunity to **solidify its leadership** in the field of exoplanets, […]"

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

Fundamental planet parameter from single epoch

- Investigating rocky, HZ planets detected during search phase
- Signal is extracted from noisy time series and data is fitted with black-body
- Average error on
  - Temperature: ~10%
  - Radius: ~20%
  - Separation: ~12%

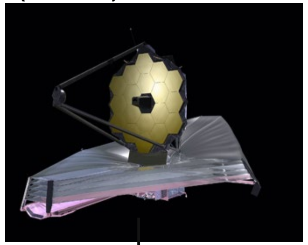


Dannertet al. 2022

LIFE: a unique opportunity for rocky exoplanet science

ESA Voyage 2050 – European roadmap for future space exploration

JWST
(2021)



Ariel
(2029)

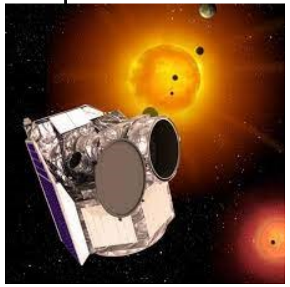
- No call for proposals anytime soon
- We already had 3 F/M-class missions

F3–mission
(~2037-2039)

F4–mission
(~2040-2043)

M8–mission
(~2045-2048)

2020 2030 2040 2050



CHEOPS
(2019)

Plato
(2026)

F2–mission
(~2030-2031)

M7–mission
(~2037)

- Calls are already closed
- No exoplanet mission candidate

LIFE
L5
(2043?)

The LIFE paper series is a growing success

Astronomy & Astrophysics manuscript no. LIFE_paper_1_FINAL_EDITED ©ESO 2022
April 20, 2022

Accepted

Large Interferometer For Exoplanets (*LIFE*):

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

S.P. Quanz[1,2,⋆], M. Ottiger[1], E. Fontanet[1], J. Kammerer[3,4,22], F. Menti[1], F. Dannert[1], A. Gheorghe[1], O. Absil[5], V.S. Airapetian[6], E. Alei[1,2], R. Allart[7], D. Angerhausen[1,2], S. Blumenthal[8], L.A. Buchhave[9], J. Cabrera[10], Ó. Carrión-González[11], G. Chauvin[12], W.C. Danchi[6], C. Dandumont[13], D. Defrère[14], C. Dorn[15], D. Ehrenreich[16], S. Ertel[17,18] M. Fridlund[19,20], A. García Muñoz[11], C. Gascón[21], J. H. Girard[22], A. Glauser[1], J.L. Grenfell[10], G. Guidi[1,2], J. Hagelberg[16], R. Helled[15], M.J. Ireland[4], M. Janson[23], R.K. Kopparapu[6], J. Korth[24], T. Kozakis[9], S. Kraus[25], A. Léger[26], L. Leedjärv[27], T. Lichtenberg[8], J. Lillo-Box[28], H. Linz[29], R. Liseau[20], J. Loicq[13], V. Mahendra[30], F. Malbet[12], J. Mathew[4], B. Mennesson[31], M.R. Meyer[32], L. Mishra[33,16,2], K. Molaverdikhani[29,34], L. Noack[35], A.V. Oza[31,33], E. Pallé[36,37], H. Parviainen[36,37], A. Quirrenbach[34], H. Rauer[10], I. Ribas[21,38], M. Rice[39], A. Romagnolo[40], S. Rugheimer[8], E.W. Schwieterman[41], E. Serabyn[31], S. Sharma[42], K.G. Stassun[43], J. Szulágyi[1], H.S. Wang[1,2], F. Wunderlich[10], M.C. Wyatt[44], and the *LIFE* Collaboration[45]

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March 3, 2022

Accepted

Large Interferometer For Exoplanets (*LIFE*):

II. Signal simulation, signal extraction and fundamental exoplanet parameters from single epoch observations

Felix Dannert[1,2⋆], Maurice Ottiger[1⋆⋆], Sascha P. Quanz[1,2], Romain Laugier[3], Emile Fontanet[1], Adrian Gheorghe[1], Olivier Absil[4⋆⋆⋆], Colin Dandumont[5], Denis Defrère[3], Carlos Gascón[6], Adrian M. Glauser[1], Jens Kammerer[7], Tim Lichtenberg[8], Hendrik Linz[9], Jerôme Loicq[5,10], and the *LIFE* collaboration[11]

Astronomy & Astrophysics manuscript no. aanda ©ESO 2022
March 4, 2022

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Large Interferometer For Exoplanets (LIFE):

III. Spectral resolution, wavelength range and sensitivity requirements based on atmospheric retrieval analyses of an exo-Earth

B.S. Konrad[1,2,⋆], E. Alei[1,2], D. Angerhausen[1,2,3], Ó. Carrión-González[4], J.J. Fortney[5], J.L. Grenfell[6], D. Kitzmann[7], P. Mollière[8], S. Rugheimer[9], F. Wunderlich[6], S.P. Quanz[1,2,⋆⋆], and the *LIFE* Collaboration ⋆⋆⋆

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April 20, 2022

Accepted

Large Interferometer For Exoplanets (*LIFE*):

IV. Where is the phosphine? Observing exoplanetary PH_3 with a space based MIR nulling interferometer

D. Angerhausen[1,2,3,⋆], M. Ottiger[1], F. Dannert[1], Y. Miguel[4,5], C. Sousa-Silva[6], J. Kammerer[7], F. Menti[1], E. Alei[1,2], B.S. Konrad[1,2], H. S. Wang[1,2], S.P. Quanz[1,2], and the *LIFE* collaboration[8]

Astronomy & Astrophysics manuscript no. output ©ESO 2022
April 20, 2022

Accepted

Large Interferometer For Exoplanets (LIFE):

V: Diagnostic potential of a mid-infrared space-interferometer for studying Earth analogs

Eleonora Alei[1,2,⋆], Björn S. Konrad[1,2], Daniel Angerhausen[1,2], John Lee Grenfell[3], Paul Mollière[4], Sascha P. Quanz[1,2], Sarah Rugheimer[5], Fabian Wunderlich[3], and the *LIFE* collaboration[6]

Astronomy & Astrophysics manuscript no. main ©ESO 2022
January 14, 2022

Accepted

Large Interferometer For Exoplanets (*LIFE*):

VI. Ideal kernel-nulling array architectures for a space-based mid-infrared nulling interferometer

Jonah T. Hansen[1⋆], Michael J. Ireland[1] and the *LIFE* Collaboration[2]

Astronomy & Astrophysics manuscript no. main ©ESO 2022
April 27, 2022

Under review

Large Interferometer For Exoplanets (*LIFE*):

VII. Practical implementation of a kernel-nulling beam combiner with a discussion on instrumental uncertainties and redundancy benefits

Jonah T. Hansen[1⋆], Michael J. Ireland[1], Romain Laugier[2], and the *LIFE* Collaboration[3]

Astronomy & Astrophysics manuscript no. output ©ESO 2022
April 20, 2022

Accepted

Large Interferometer For Exoplanets (*LIFE*):

VIII. Detecting terrestrial exoplanets in the habitable zones of Sun-like stars

Jens Kammerer[1,⋆], Sascha P. Quanz[2,3], Felix Dannert[2], Christopher C. Stark[4], and the *LIFE* Collaboration[5]

Astronomy & Astrophysics manuscript no. output ©ESO 2022
April 20, 2022

Close to submission

Large Interferometer For Exoplanets (LIFE):

IX. Assessing the Impact of Clouds on Observations of Venus-Twin Exoplanets

B.S. Konrad[1,2,⋆], E. Alei[1,2], S.P. Quanz[1,2,⋆⋆], P. Mollière[3], D. Angerhausen[1,2,4], More Colleagues, and the *LIFE* Collaboration[3]

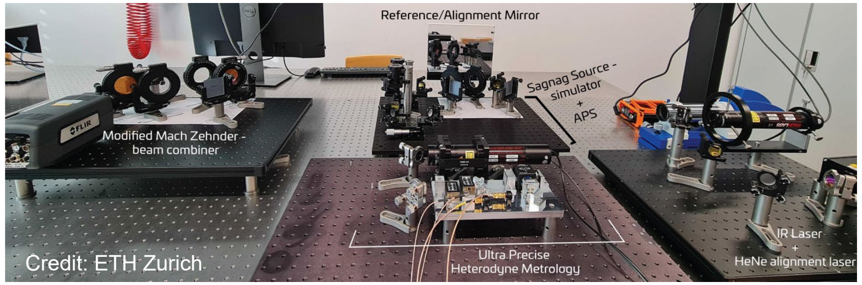
arXiv:2101.07500 arXiv:2203.00471 arXiv:2112.02054 arXiv:2201.04891

Recent progress and ongoing efforts increase technological readiness

Major technological challenges for mid-infrared space-based interferometry are being tackled by various groups

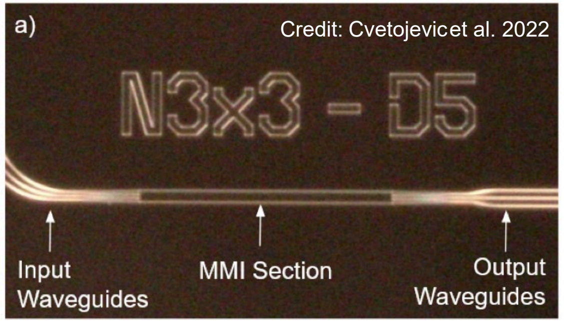
Cryogenic nulling

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



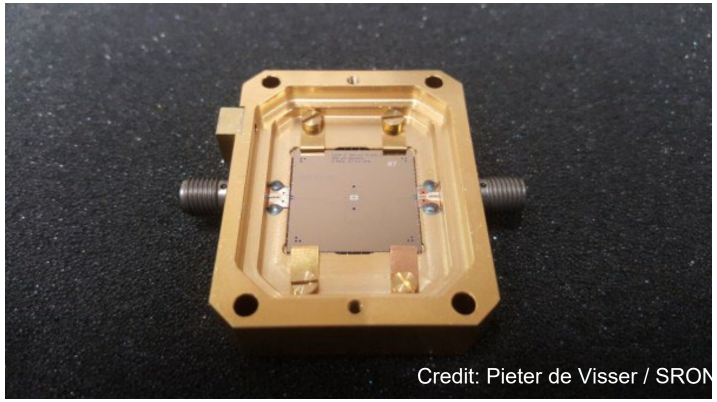
Photonics

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



Low-noise detectors

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



Autonamous formation flying

Various space missions aim to demonstrate high-precision formation flying performance in the coming years including ESA's Proba-3