



The LIFE Initiative Scientific Prospects and Challenges

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

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](https://doi.org/10.1007/s10686-021-09791-z))



Detecting and characterizing rocky exoplanets from space

Scientific synergies between different missions and ground-based instruments

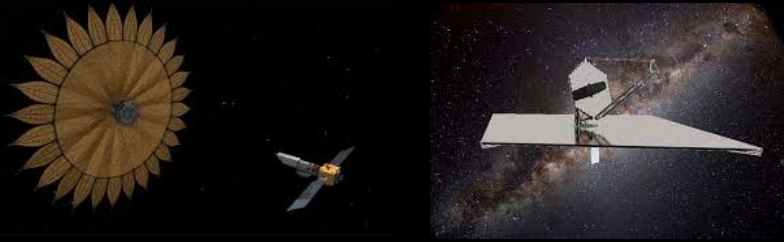


Reflected light (UV- NIR)

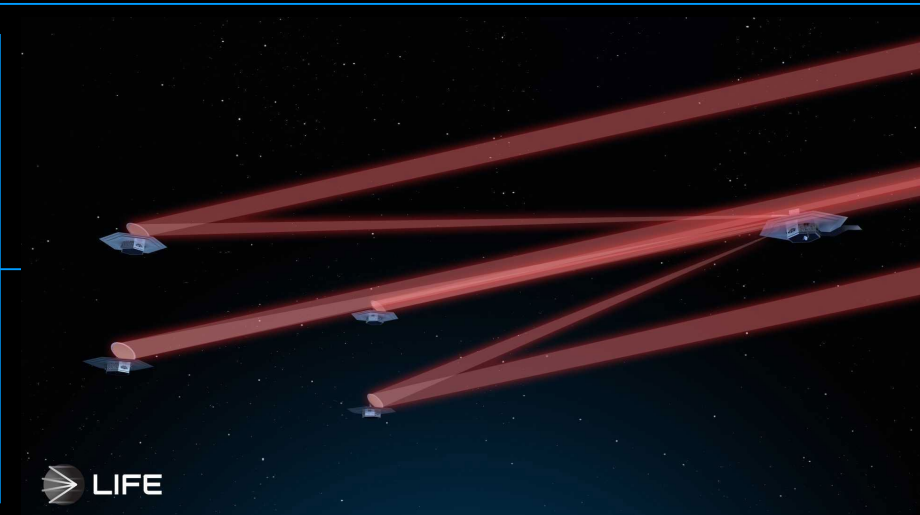


Thermal emission (MIR)

Solar-type stars

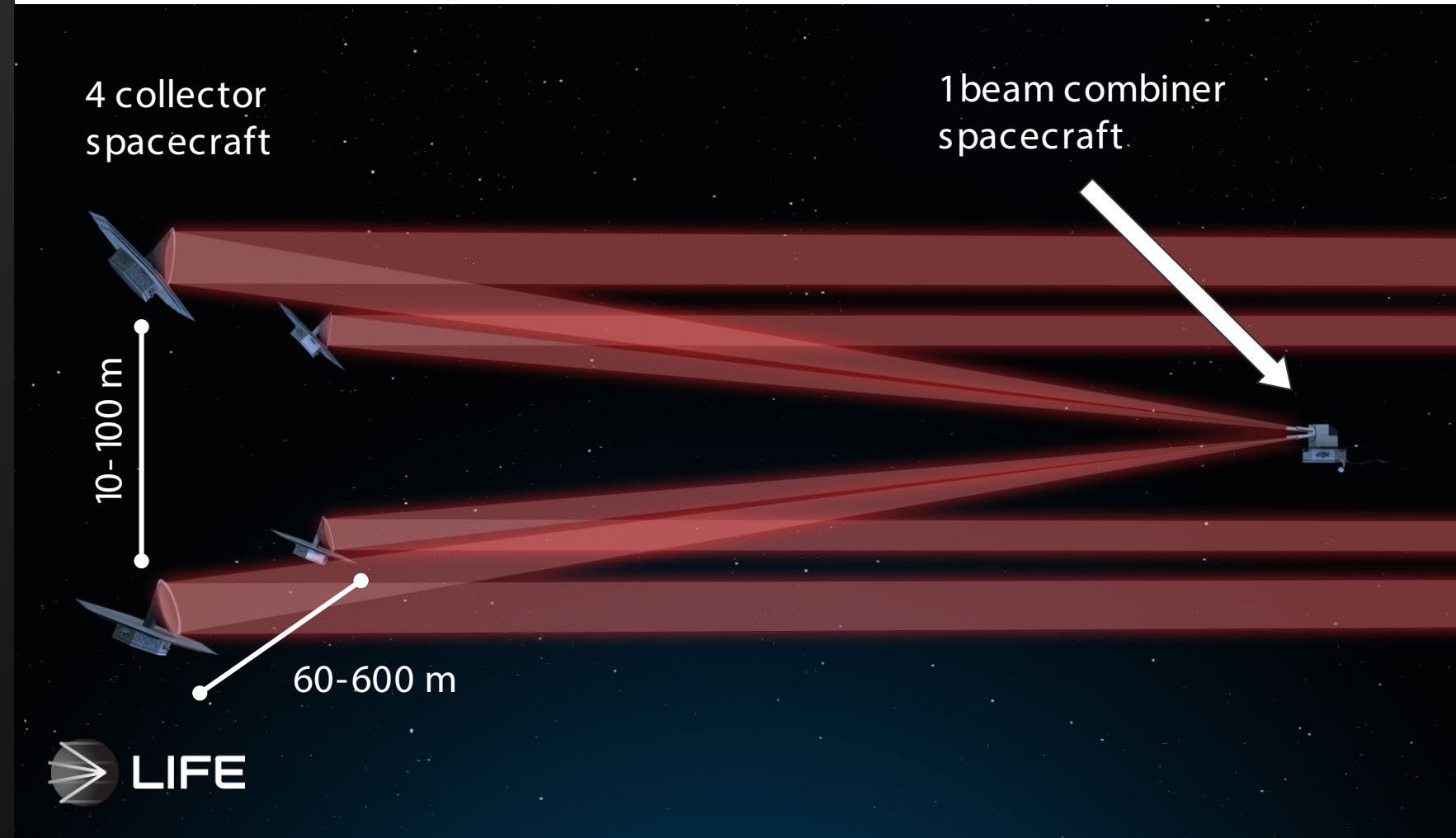


M stars



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 midinfrared wavelength range between $\sim 4\text{-}18.5\mu\text{m}$ with a spectral resolution of $R \sim 50$ (tbc)

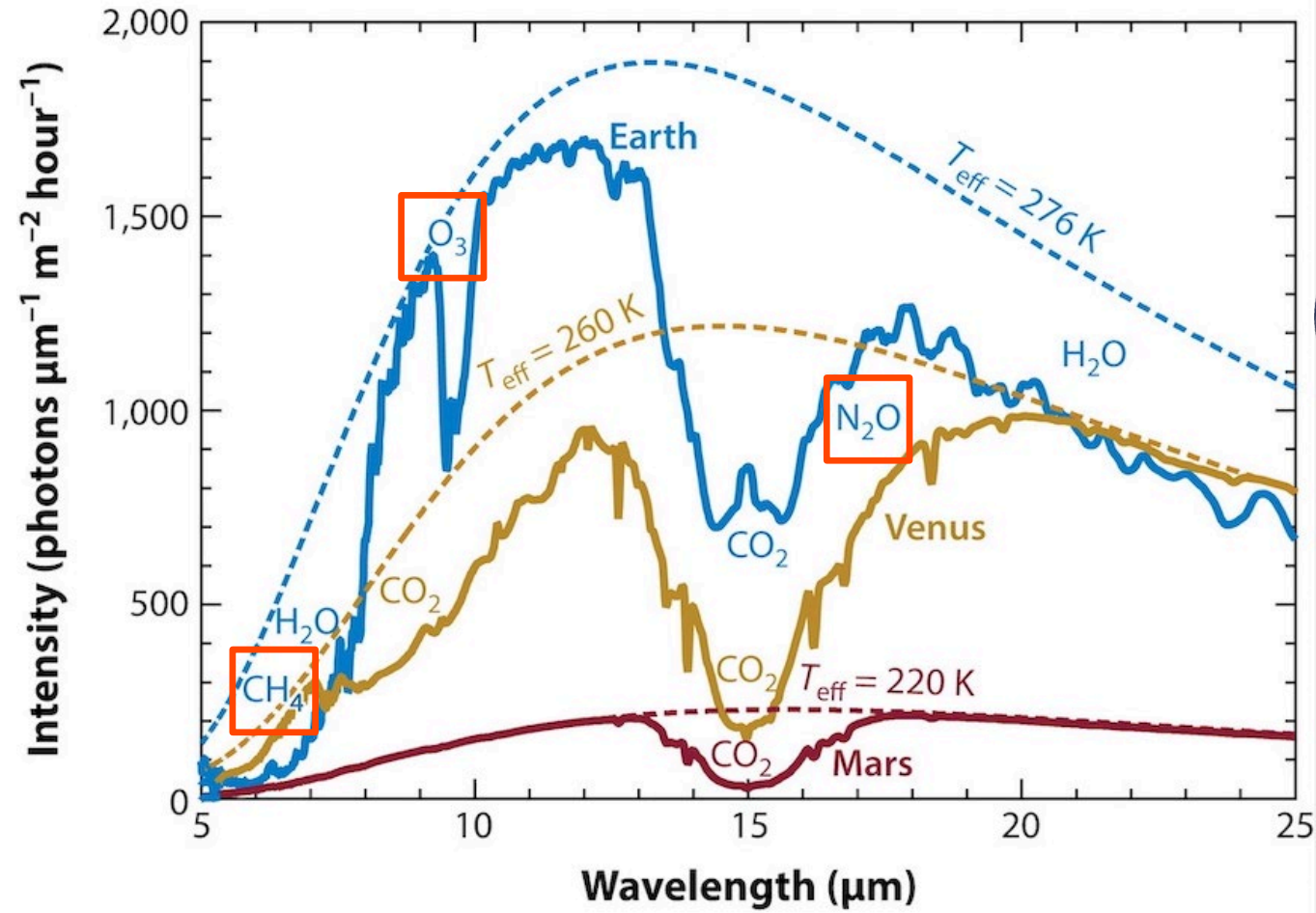


Artist impression of LIFE concept (credit: LIFE initiative)

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



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 H₂O, CO₂, and CO as well as collision induced absorption from N₂ and O₂



..search for numerous **atmospheric biosignatures** in the context of terrestrial exoplanets and gas dominated Super-Earths (e.g., O₃ and CH₄, but also N₂O, PH₃, NH₃, and C₅H₈)



..constrain directly **the effective temperature** of exoplanets and provide access to their **radii**



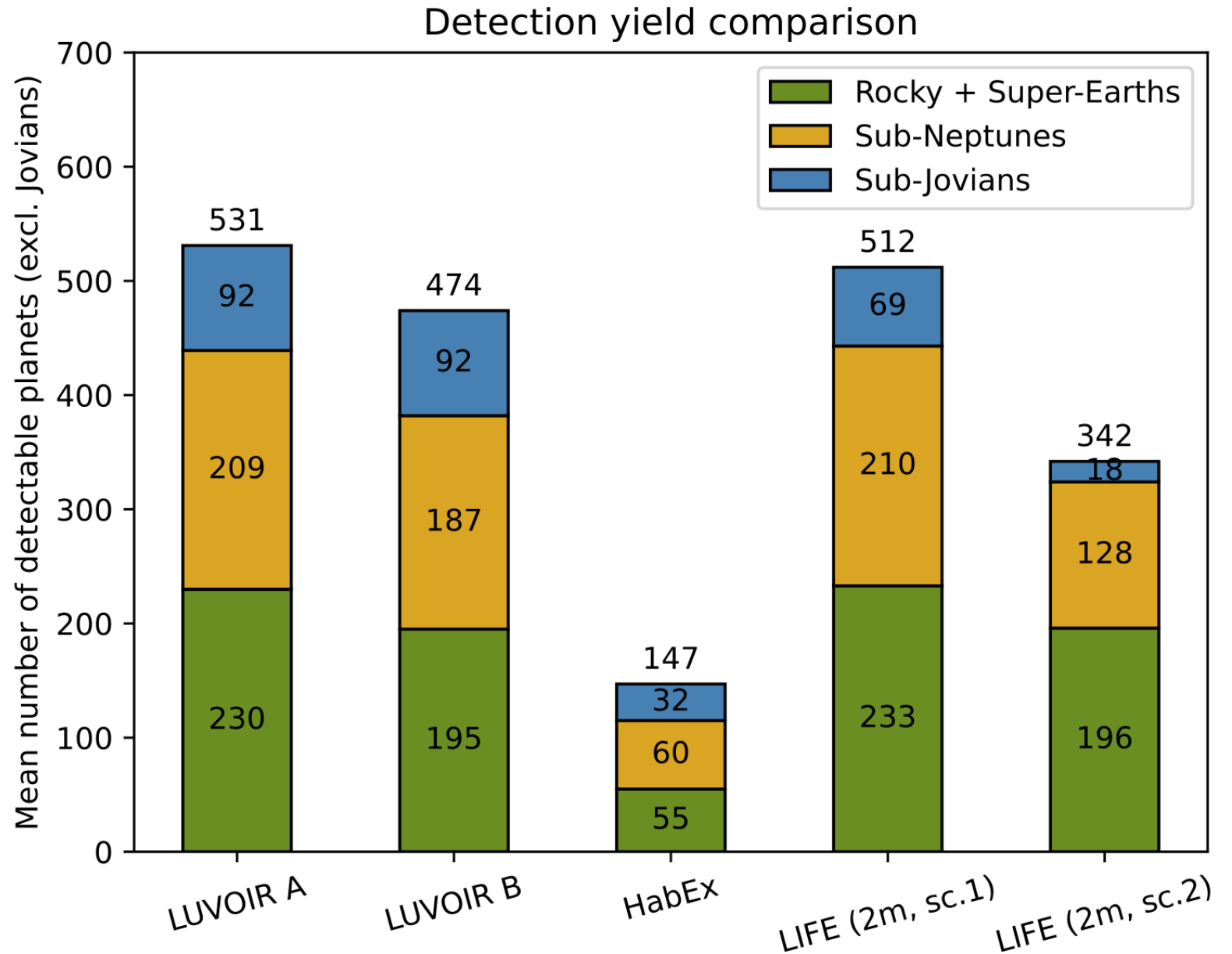
..secure a higher detection yield during search phase as it is **less affected by the orbital phase function** of the exoplanets' emission compared to reflected light missions



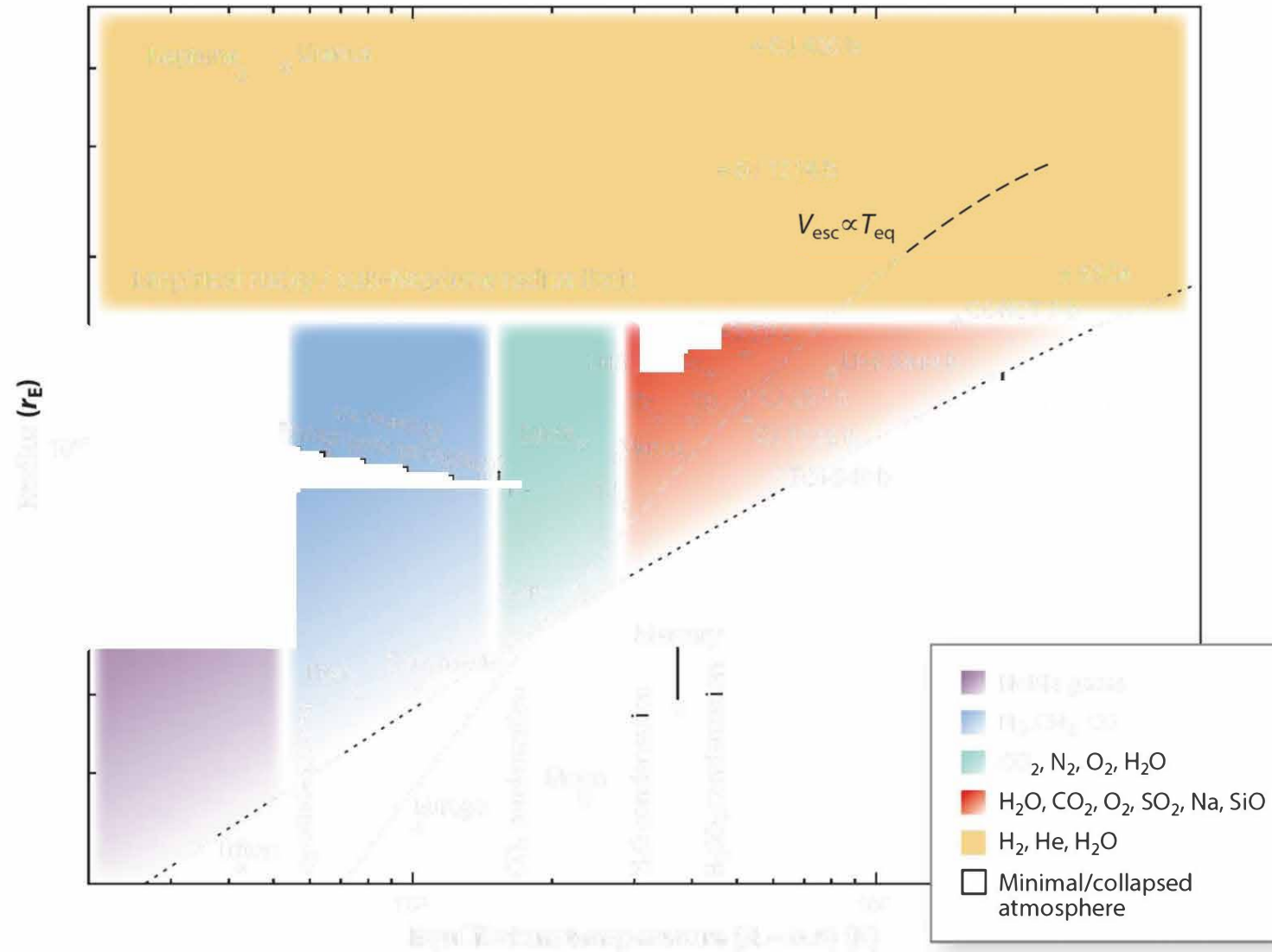
..immediately **start observing already known small, temperate exoplanets** around nearby M-stars and include those in the final target list

LIFE: Exoplanet Detection Yield Estimates

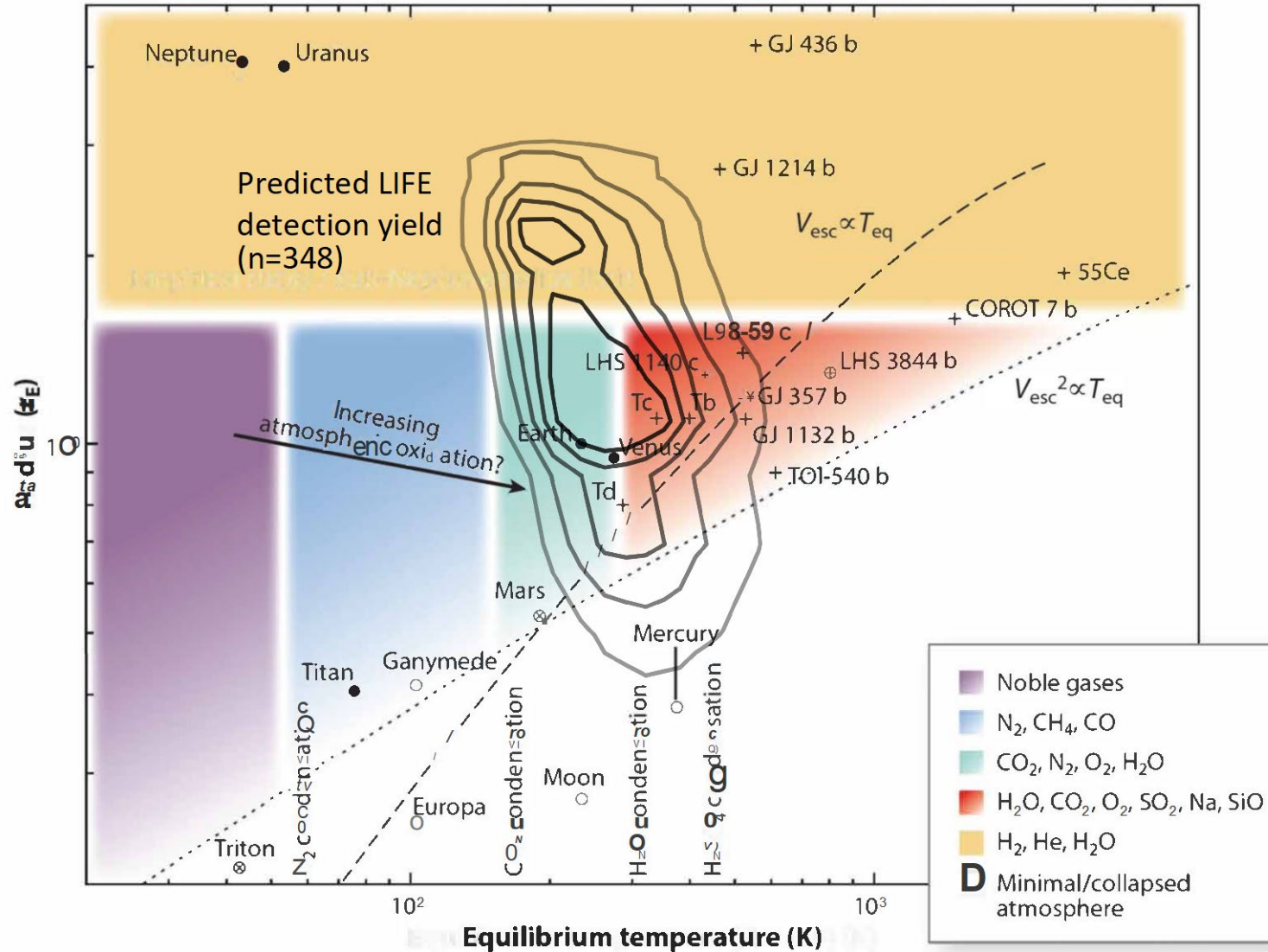
- Expected detection yields are similar to large future NASA flagship concepts
- Monte Carlo simulations based on Kepler statistics (SAG13) and stars within ~20 pc
- Assuming
 - 2.5 years total search phase
 - 4 x 2m apertures
 - 5% total instrument throughput
 - 10 h slew between targets
 - 20% general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



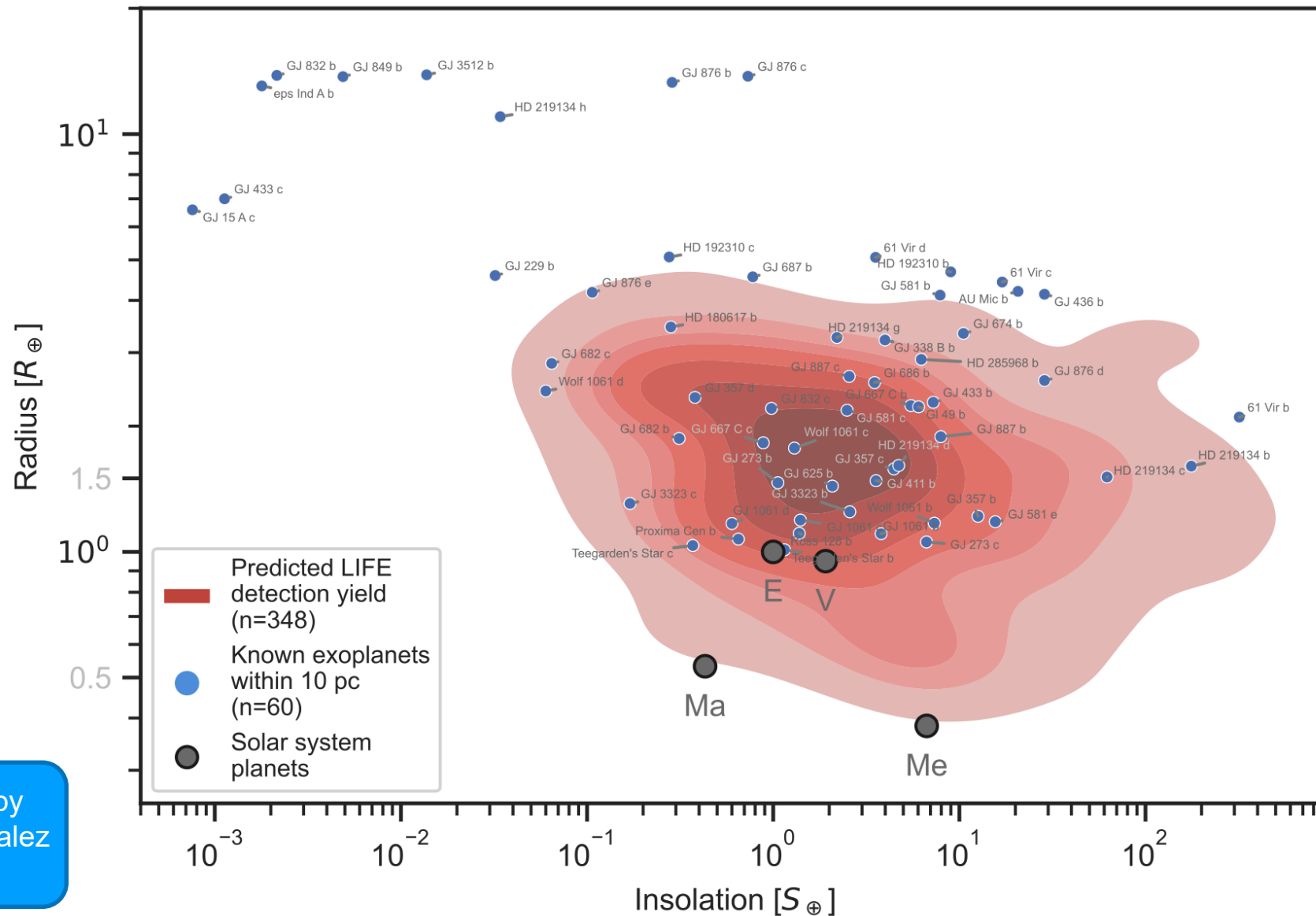
LIFE discovery space vs. JWST



LIFE discovery space vs. JWST



LIFE discovery space vs. known exoplanets within 10 pc

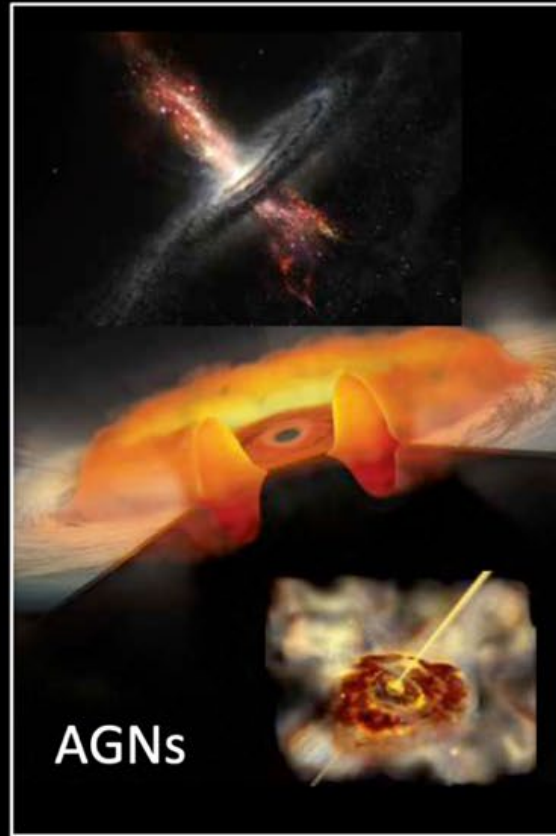


New LIFE paper by Oscar CarrionGonzalez in preparation



Circumstellar Disks

...probing the terrestrial
planet formation region



AGNs

...resolving the dusty torus



Star Formation & Stellar Clusters

...probing the innermost
regions of dense clouds and
cores



Evolved Stars

...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 subsets 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 ?

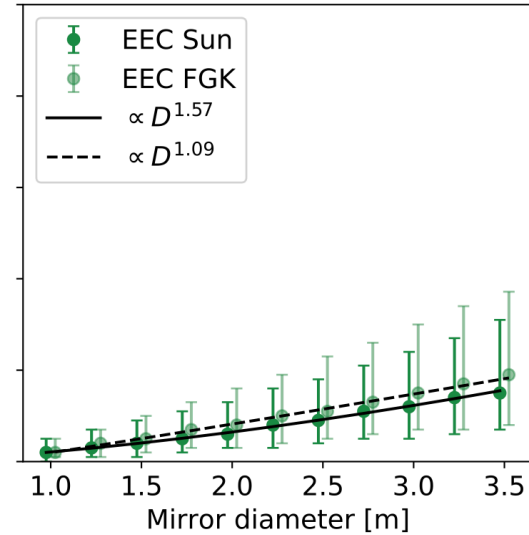
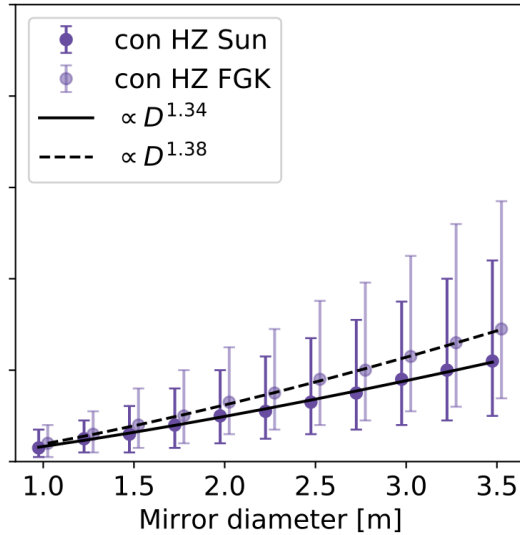
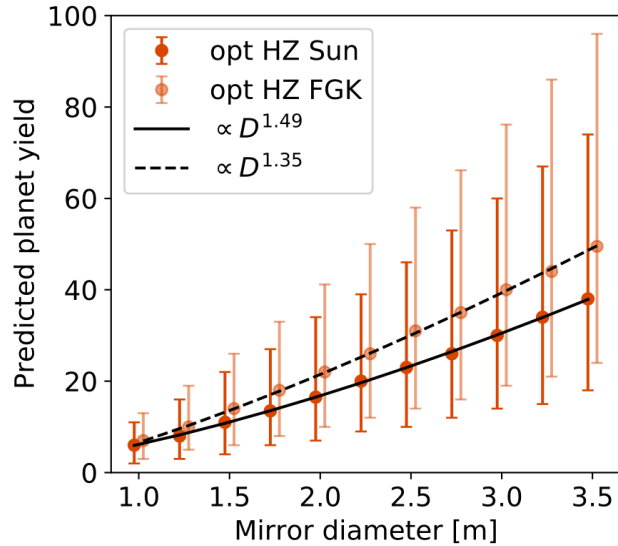


Thank you

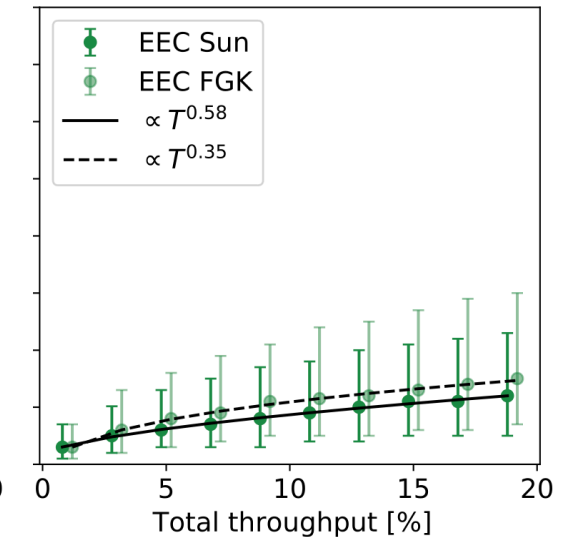
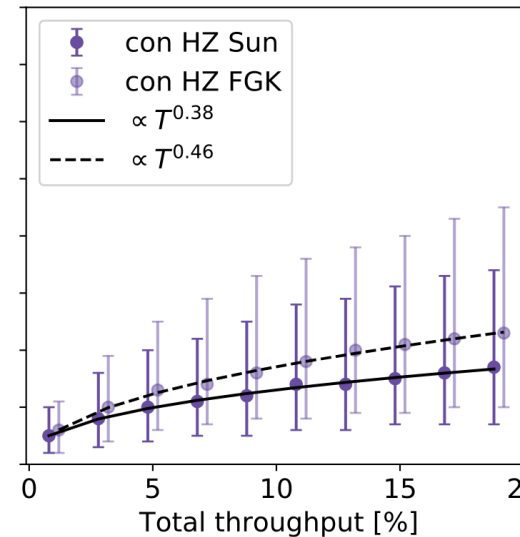
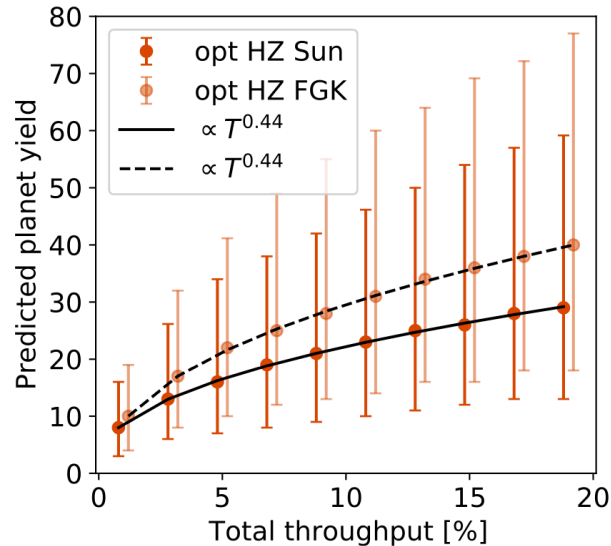
Detection yield of rocky planets around Sun-like stars

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

Assumption:
5% throughput



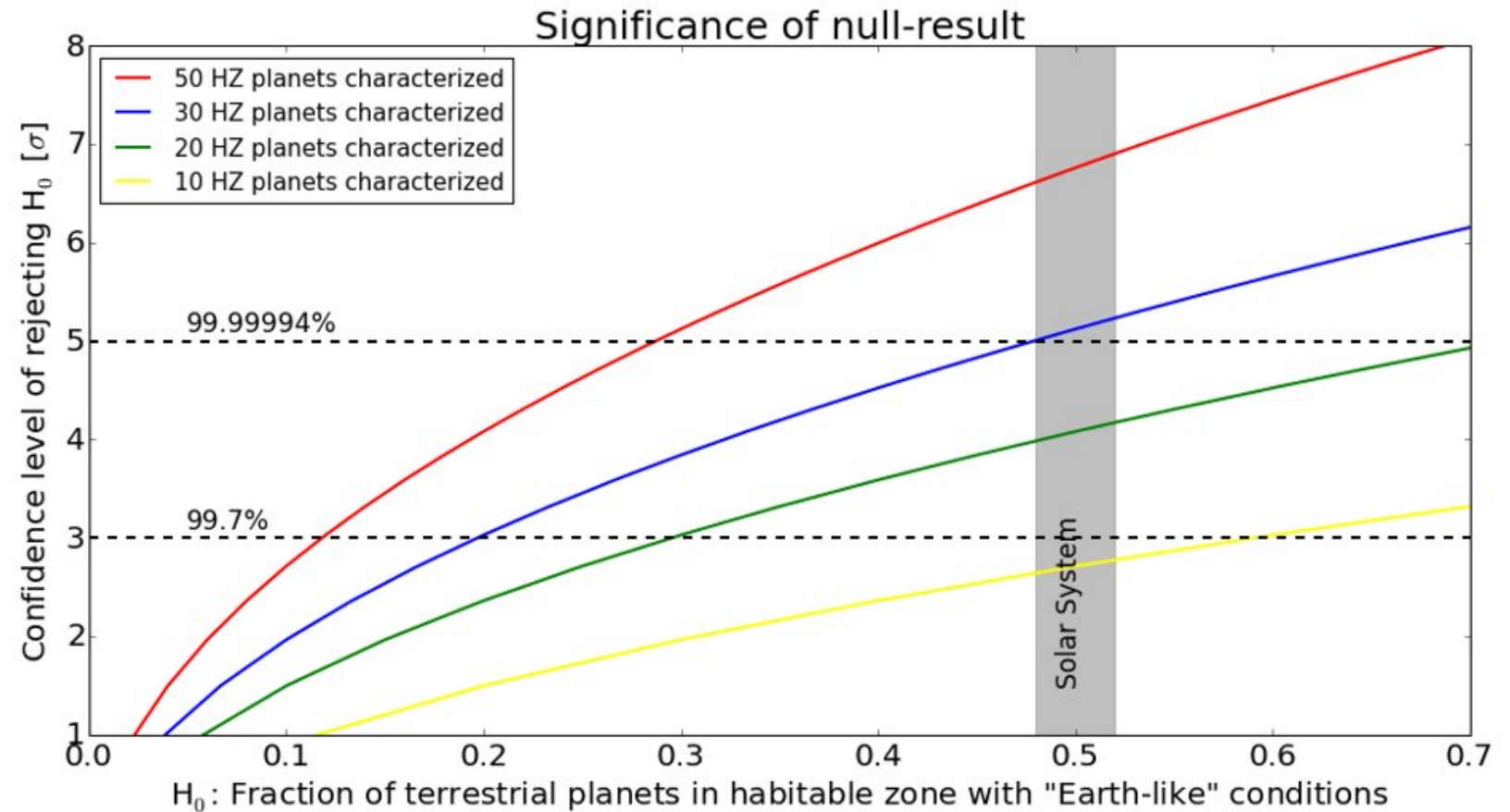
Assumption:
2-m aperture size



Comprehensive Habitability Studies

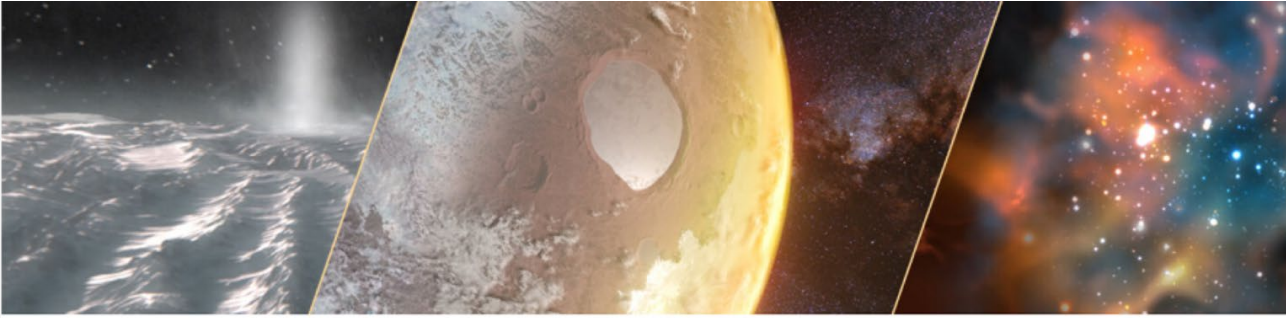
LIFE will enable comparative studies of potentially habitable environments.

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



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 Program



SCIENCE & EXPLORATION

Voyage 2050 sets sail: ESA chooses future science mission themes

“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.”

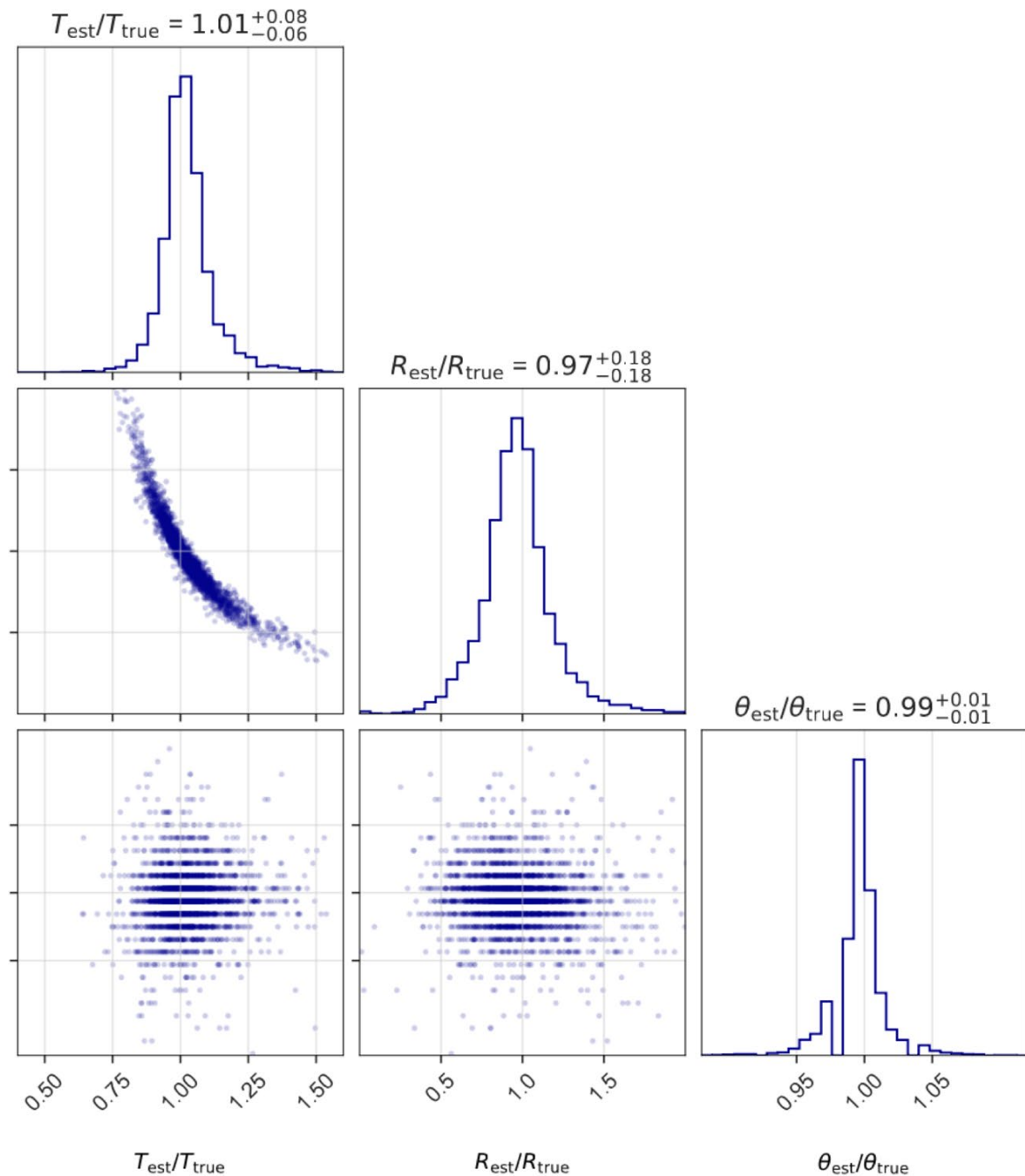
“This would give ESA and the European community the opportunity to **solidify its leadership** in the field of exoplanets, [...]”

“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

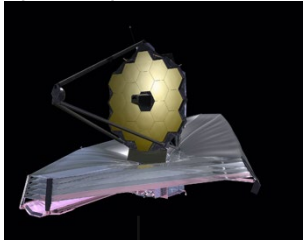
- Investigating rocky, HZ planets detected during search phase
- Signal is extracted from noisy time series and data is fitted with black-body
- Average error on
 - Temperature: ~10%
 - Radius: ~20%
 - Separation: ~12%



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

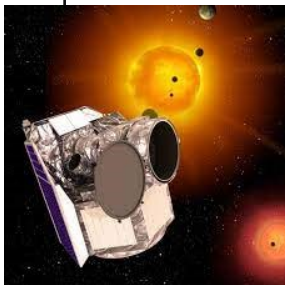
F3-mission (~2037-2039) F4-mission (~2040-2043) M8-mission (~2045-2048)

2020

2030

2040

2050



CHEOPS
(2019)

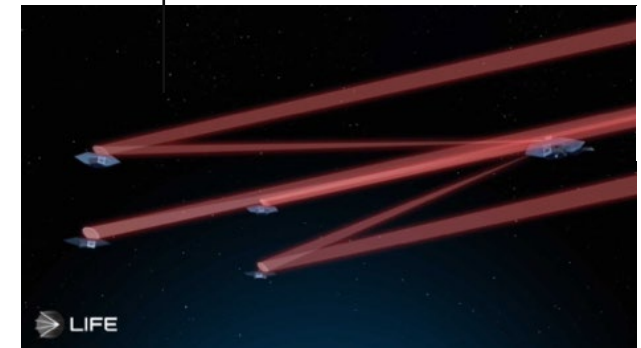


Plato
(2026)

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
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. Ottiger¹, E. Fontanet¹, J. Kammerer^{3,4,22}, F. Menti¹, F. Dannert¹, A. Gheorghe¹, O. Absil⁵, V.S. Airapetian⁶, E. Alei^{1,2}, R. Allart⁷, D. Angerhausen^{1,2}, S. Blumenthal⁸, L.A. Buchhave⁹, J. Cabrera¹⁰, Ó. Carrión-González¹¹, G. Chauvin¹², W.C. Danchi¹³, C. Dandumont¹³, D. Defrère¹⁴, C. Dorn¹⁵, D. Ehrenreich¹⁶, S. Ertel^{17,18}, M. Fridlund^{19,20}, A. García Muñoz¹¹, C. Gascón²¹, J. H. Girard²², A. Glauser¹, J.L. Grenfell¹⁰, G. Guidi^{1,2}, J. Hagelberg¹⁶, R. Helled¹⁵, M.J. Ireland⁴, M. Janson²³, R.K. Kopparapu⁶, J. Korth²⁴, T. Kozakis⁹, S. Kraus²⁵, A. Léger²⁶, L. Leedjävär²⁷, T. Lichtenberg⁸, J. Lillo-Box²⁸, H. Linz²⁹, R. Liseau³⁰, J. Loicq¹³, V. Mahendra³⁰, F. Malbet¹², J. Mathew⁴, B. Mennesson³¹, M.R. Meyer³², L. Mishra^{33,16,2}, K. Molaverdikhani^{29,34}, L. Noack³⁵, A.V. Oza^{31,33}, E. Pallé^{36,37}, H. Parviainen^{36,37}, A. Quirrenbach³⁴, H. Rauer¹⁰, I. Ribas^{21,38}, M. Rice³⁹, A. Romagnolo⁴⁰, S. Rugheimer⁹, E.W. Schwieterman⁴¹, E. Serabyn³¹, S. Sharma⁴², K.G. Stassun⁴³, J. Szulágyi¹, H.S. Wang^{1,2}, F. Wunderlich¹⁰, M.C. Wyatt⁴⁴, and the LIFE Collaboration⁴⁵

Astronomy & Astrophysics manuscript no. main
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 Laugier³, Emile Fontanet¹, Adrian Gheorghe¹, Olivier Absil^{4***}, Colin Dandumont⁵, Denis Defrère⁶, Carlos Gascón⁶, Adrian M. Glauser¹, Jens Kammerer⁷, Tim Lichtenberg⁸, Hendrik Linz⁹, Jérôme Loicq^{5,10}, and the LIFE collaboration¹¹

Astronomy & Astrophysics manuscript no. aanda
March 4, 2022

Accepted

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-González¹, J.J. Fortney⁵, J.L. Grenfell⁶, D. Kitzmann⁷, P. Mollière⁸, S. Rugheimer⁹, F. Wunderlich⁶, S.P. Quanz^{1,2,***}, and the LIFE Collaboration^{***}

Astronomy & Astrophysics manuscript no. output
April 20, 2022

Accepted

Large Interferometer For Exoplanets (LIFE):

IV. Where is the phosphine? Observing exoplanetary PH₃ with a space based MIR nulling interferometer

D. Angerhausen^{1,2,3,*}, M. Ottiger¹, F. Dannert¹, Y. Miguel^{4,5}, C. Sousa-Silva⁶, J. Kammerer⁷, F. Menti¹, E. Alei^{1,2}, B.S. Konrad^{1,2}, H. S. Wang^{1,2}, S.P. Quanz^{1,2}, and the LIFE collaboration⁸

Astronomy & Astrophysics manuscript no. output
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 Grenfell³, Paul Mollière⁴, Sascha P. Quanz^{1,2}, Sarah Rugheimer⁵, Fabian Wunderlich³, and the LIFE collaboration⁶

Astronomy & Astrophysics manuscript no. main
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. Ireland¹ and the LIFE Collaboration²

Astronomy & Astrophysics manuscript no. main
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. Ireland¹, Romain Laugier², and the LIFE Collaboration³

Astronomy & Astrophysics manuscript no. output
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 Dannert², Christopher C. Stark⁴, and the LIFE Collaboration⁵

Astronomy & Astrophysics manuscript no. output
April 20, 2022

Close to submission

Large Interferometer For Exoplanets (LIFE):

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

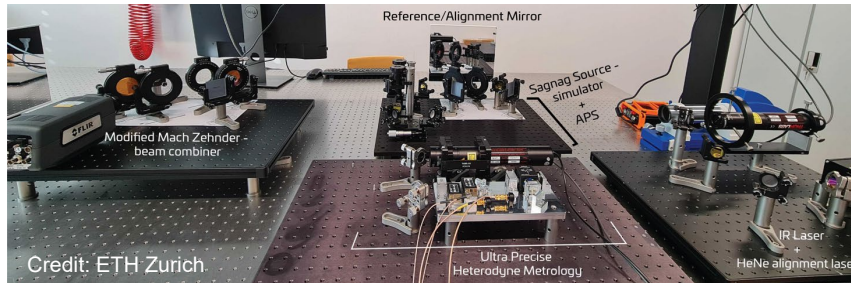
B.S. Konrad^{1,2,*}, E. Alei^{1,2}, S.P. Quanz^{1,2,***}, P. Mollière³, D. Angerhausen^{1,2,4}, More Colleagues, and the LIFE Collaboration³

Recent progress and ongoing efforts increase technological readiness

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

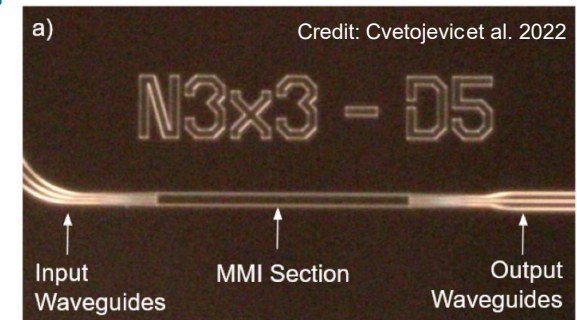
Cryogenic nulling

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



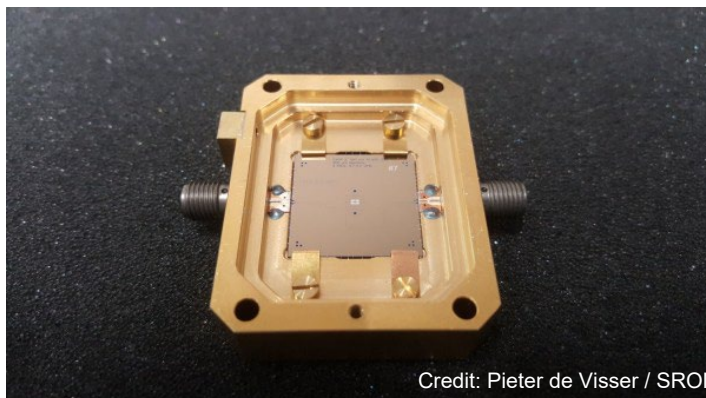
Photonics

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 nearinfrared wavelengths and closein on mid-infrared regime



Autonomous formation flying

Various space missions aim to demonstrate high precision formation flying performance in the coming years including ESA's Proba3

