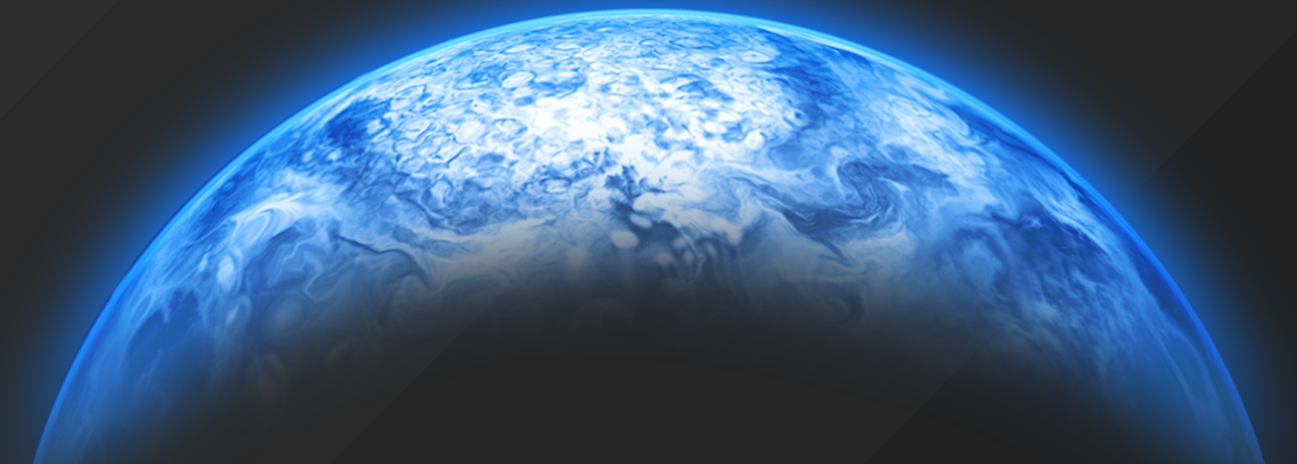
LIFE
LARGE INTERFEROMETER FOR EXOPLANETS



The LIFE initiative – atmospheric characterization of terrestrial exoplanets in the mid-infrared with a large space-based nulling interferometer

Authors:

Sascha P. Quanz
ETH Zurich

SF2A workshop - S12
20/21 June, 2023
Strasbourg

ETH zürich

CENTRE FOR ORIGIN & PREVALENCE OF LIFE

PlanetS
National Centre of Competence in Research

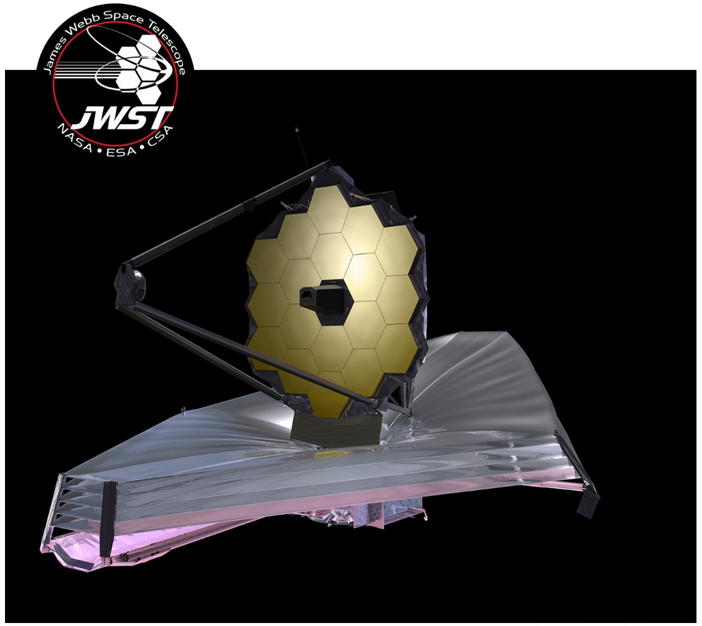
ETH zürich | SPACE

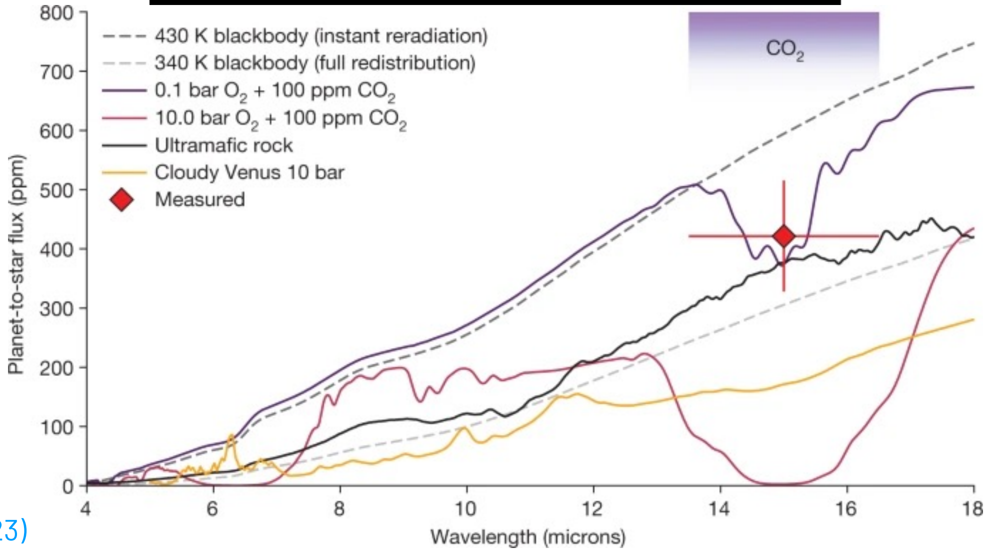
The LIFE initiative seeks to develop the scientific context, the technology, and a roadmap for an ambitious mid-infrared space mission that investigates the atmospheric properties of a large sample of terrestrial exoplanets.

LIFE’s primary mission objective:

Determining the occurrence rate of life – as we now it - on nearby exoplanets

First steps are taken by JWST and Ariel





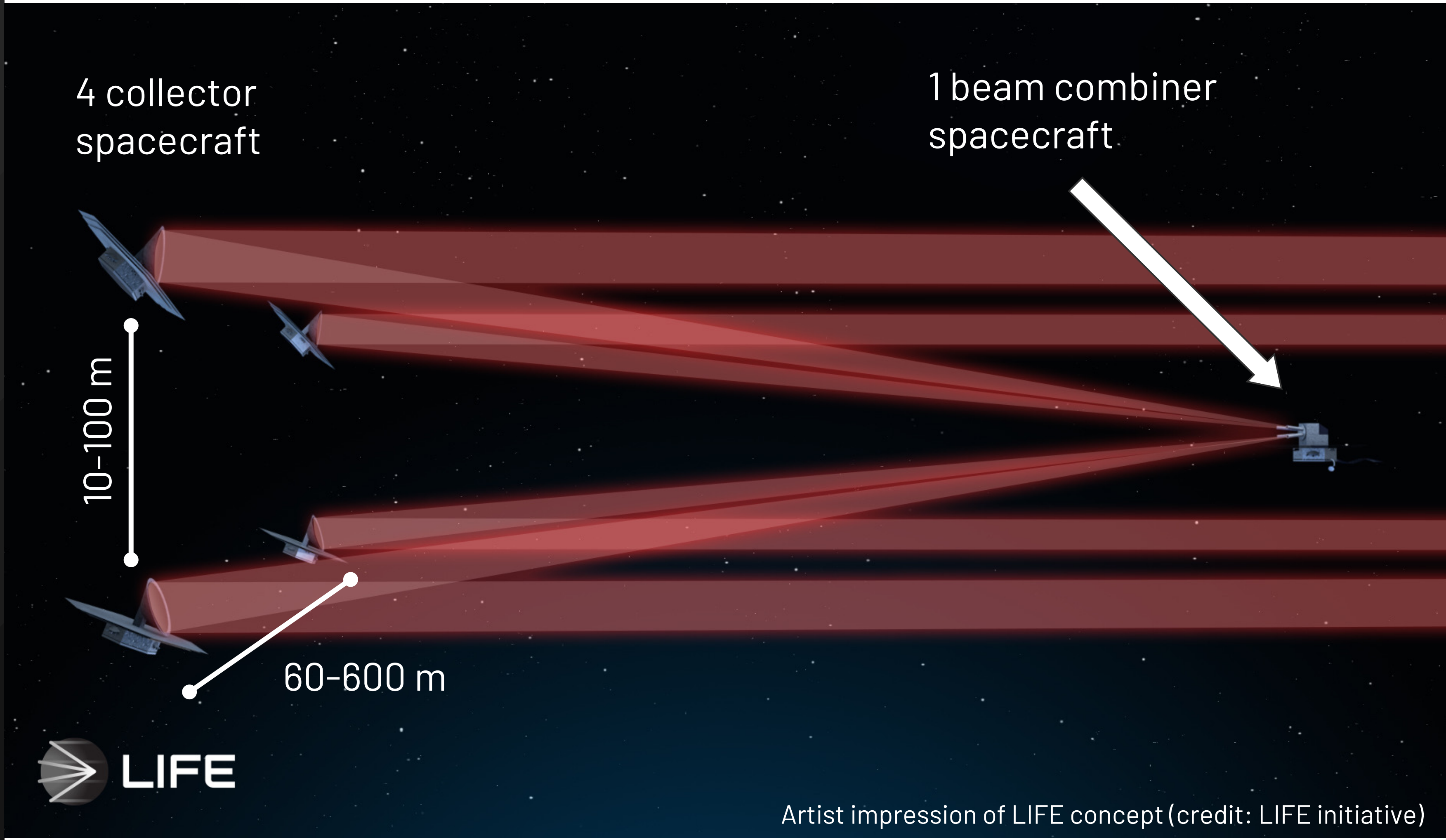
Zieba et al. (2023)

"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)

The LIFE mission

- ...is a space-based formation-flying mid-infrared (nulling) interferometer in L2 with a nominal mission lifetime of at least 5 years
- ...consists of 4 collector spacecraft separated by tens to hundreds of meters and a beam combiner spacecraft
- ...will survey hundreds of nearby stars within 25 parsec, discover hundreds of new exoplanets, and investigate the atmospheres of dozens of them



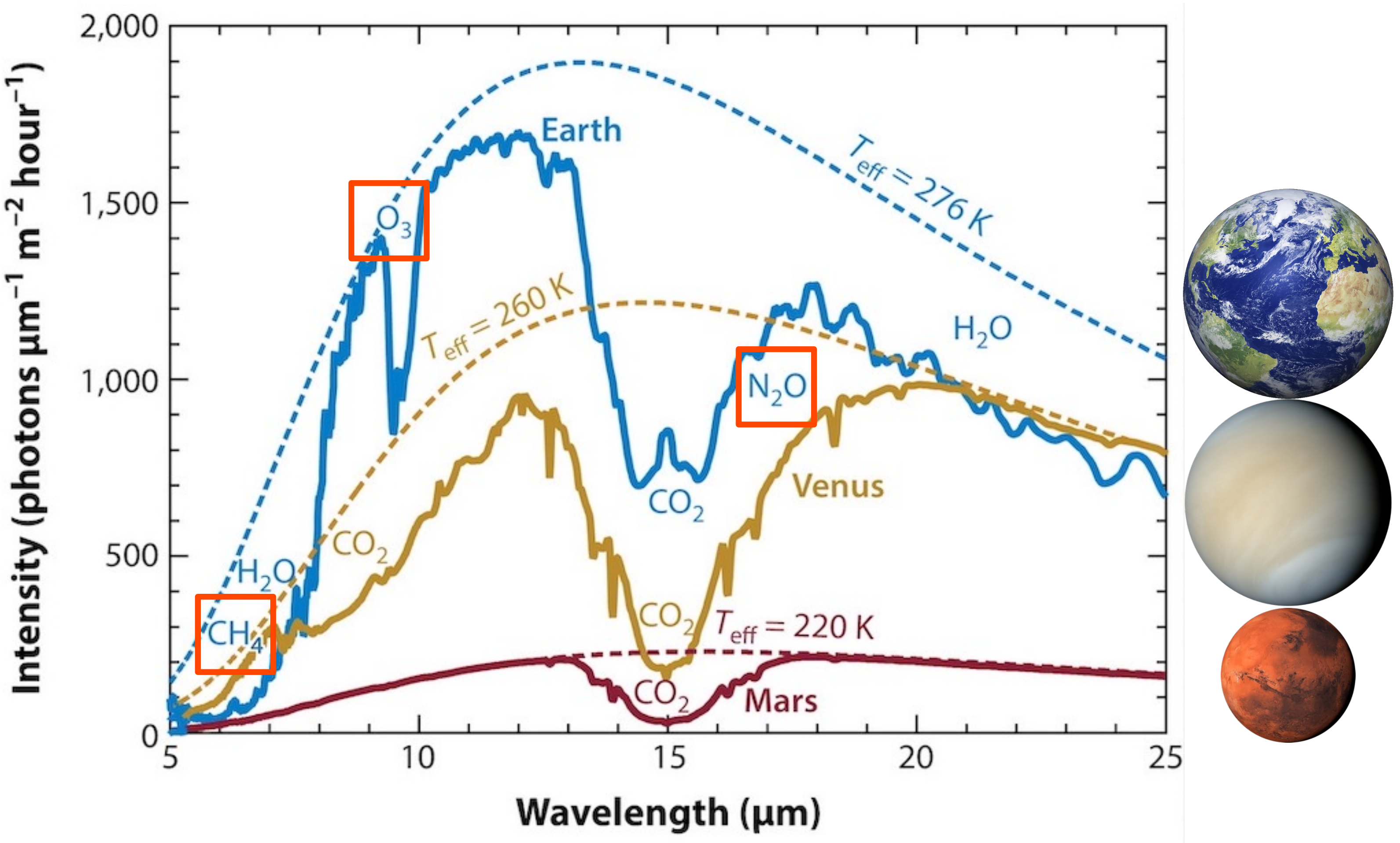
Artist impression of LIFE concept (credit: LIFE initiative)

Quanz et al. 2022 (arXiv2101075000)

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 biosignatures such as ozone (O_3), methane (CH_4) and nitrous oxide (N_2O)

Emission spectra of terrestrial planets in our Solar System

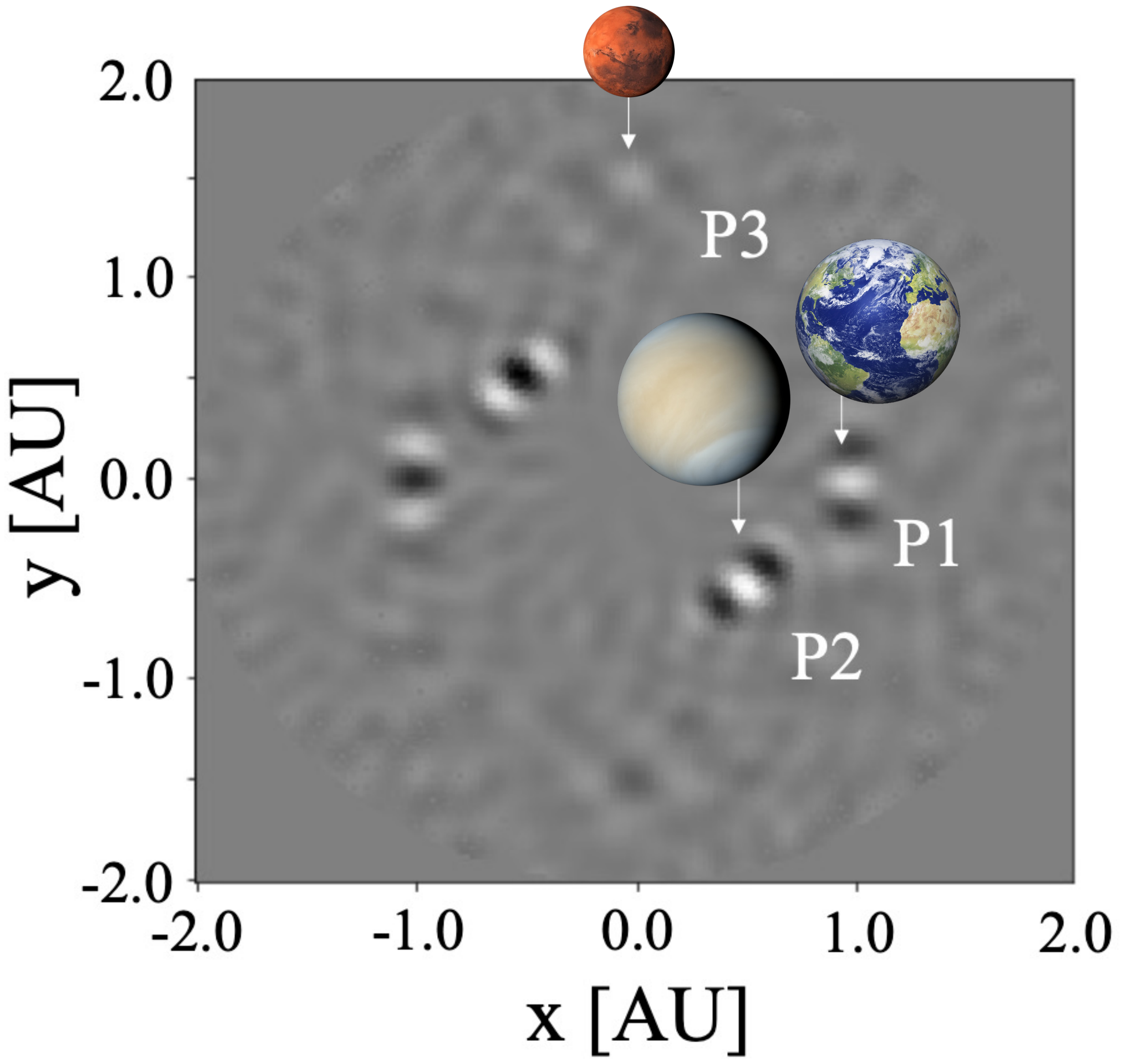


Kaltenegger 2017

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 biosignatures such as ozone (O_3), methane (CH_4) and nitrous oxide (N_2O)

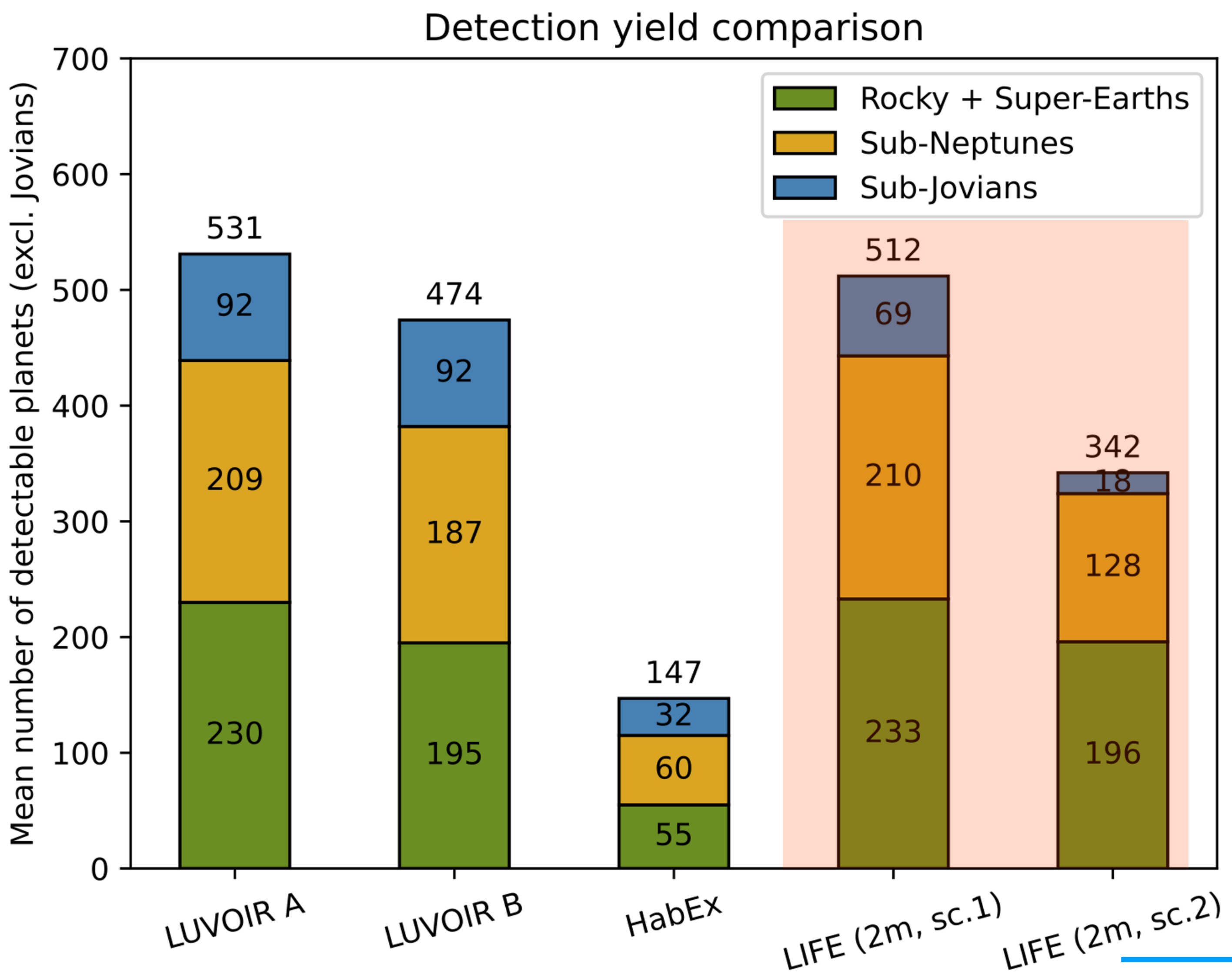
Reconstructed LIFE image of Solar System analog at 10 pc



Kaltenegger 2017, Matsuo et al. (submitted)

LIFE: Exoplanet Detection Yield Estimates

Assuming an initial search phase of the mission of 2.5 years



- Expected detection yields are similar to large future NASA flagship concepts
- Monte Carlo simulations based on Kepler statistics (SAG13) and stars within ~20 pc

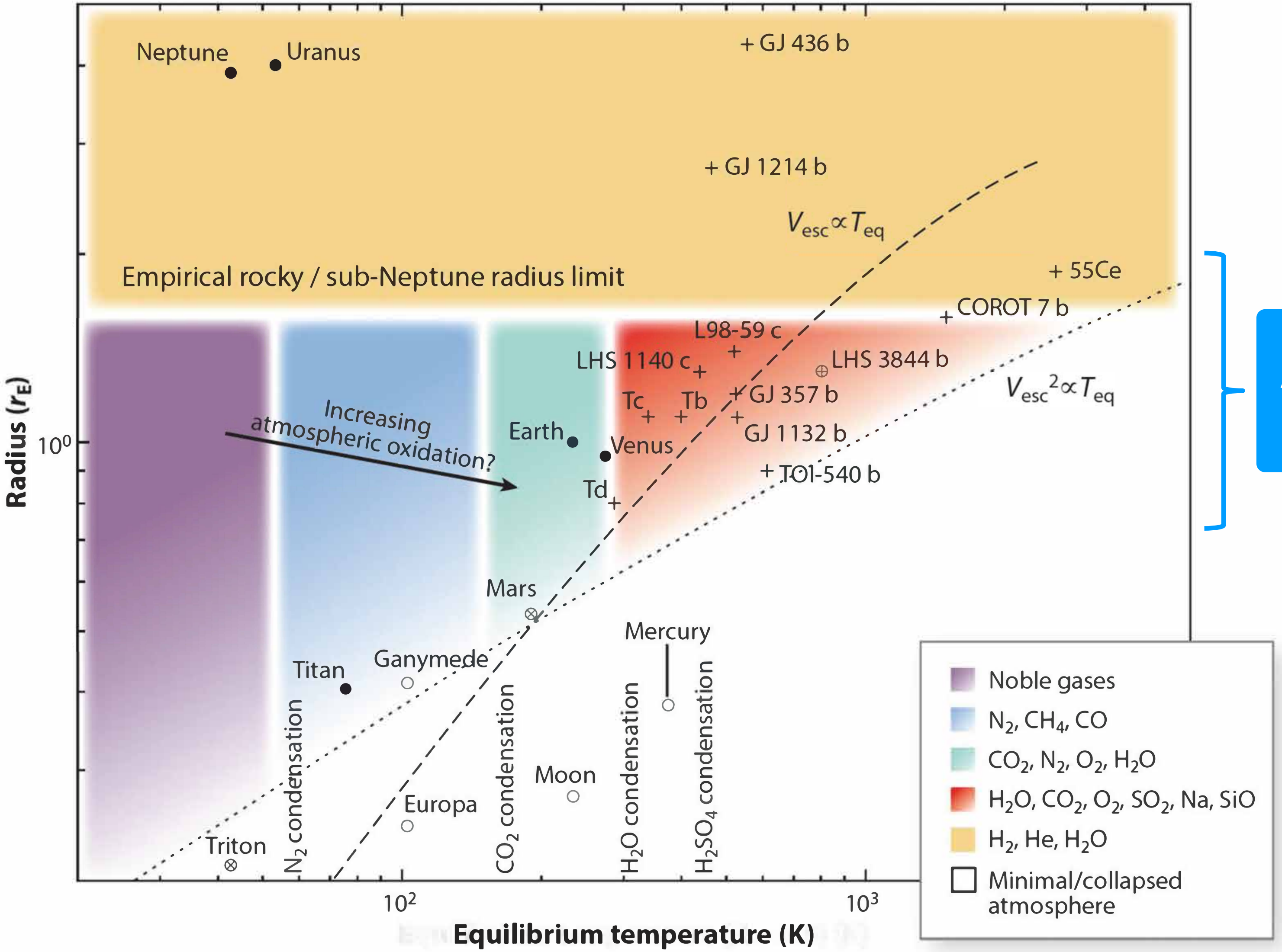
2 scenarios:

Maximizing **total number** of planets vs. maximizing **rocky planets in habitable zone**

Quanz et al. 2022 (arXiv2101075000)

LIFE provides unprecedented discovery potential

LIFE discovery space vs. rocky exoplanets with JWST



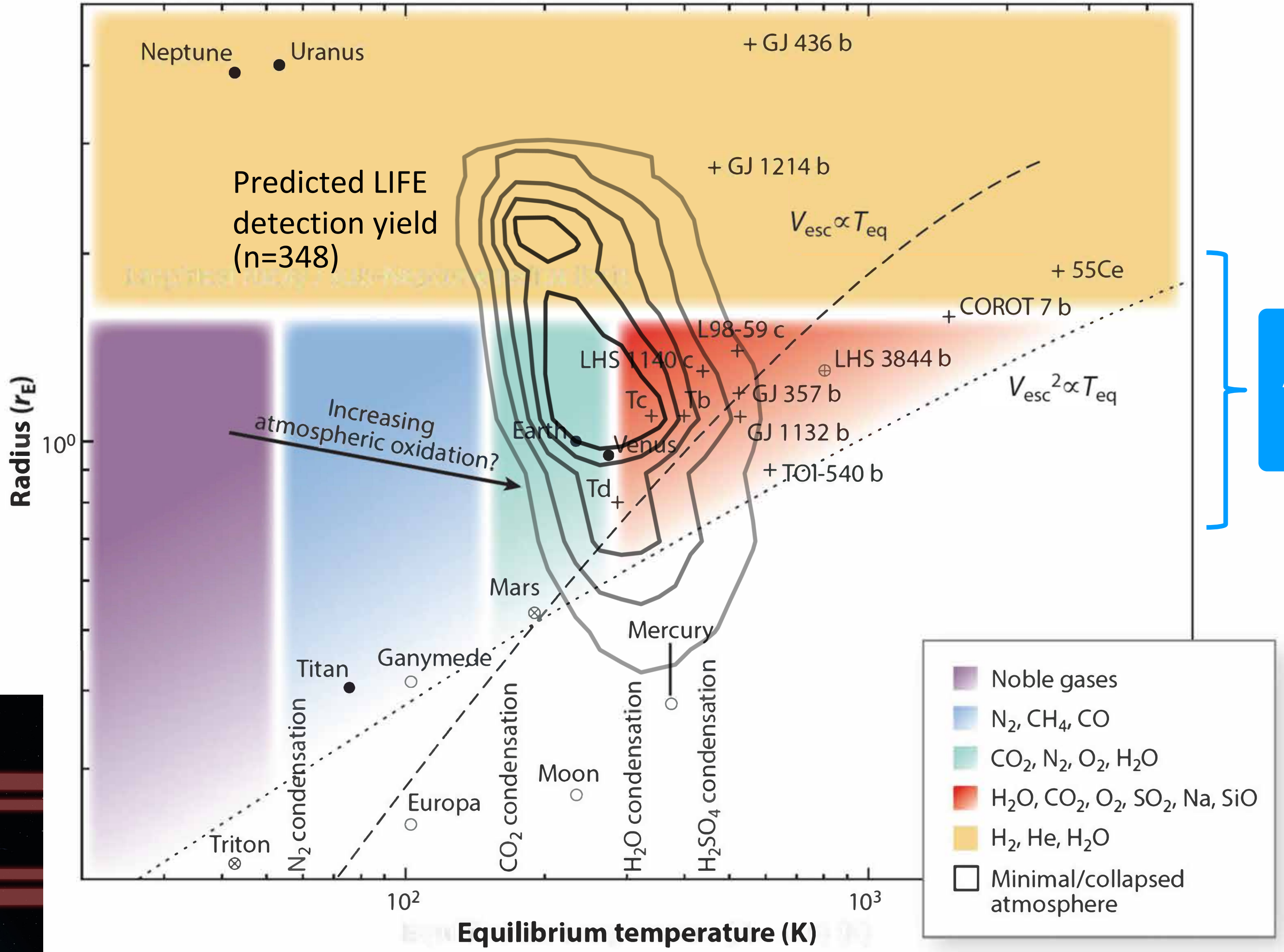
Crosses: All known "rocky-ish" exoplanets to be observed with JWST

Wordsworth & Kreidberg 2022

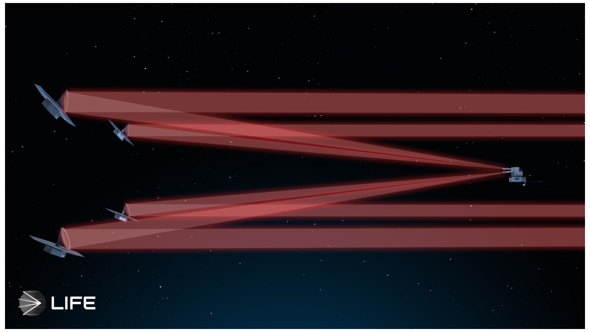
LIFE provides unprecedented discovery potential

LIFE discovery space vs. rocky exoplanets with JWST

Primary discovery space of LIFE mission



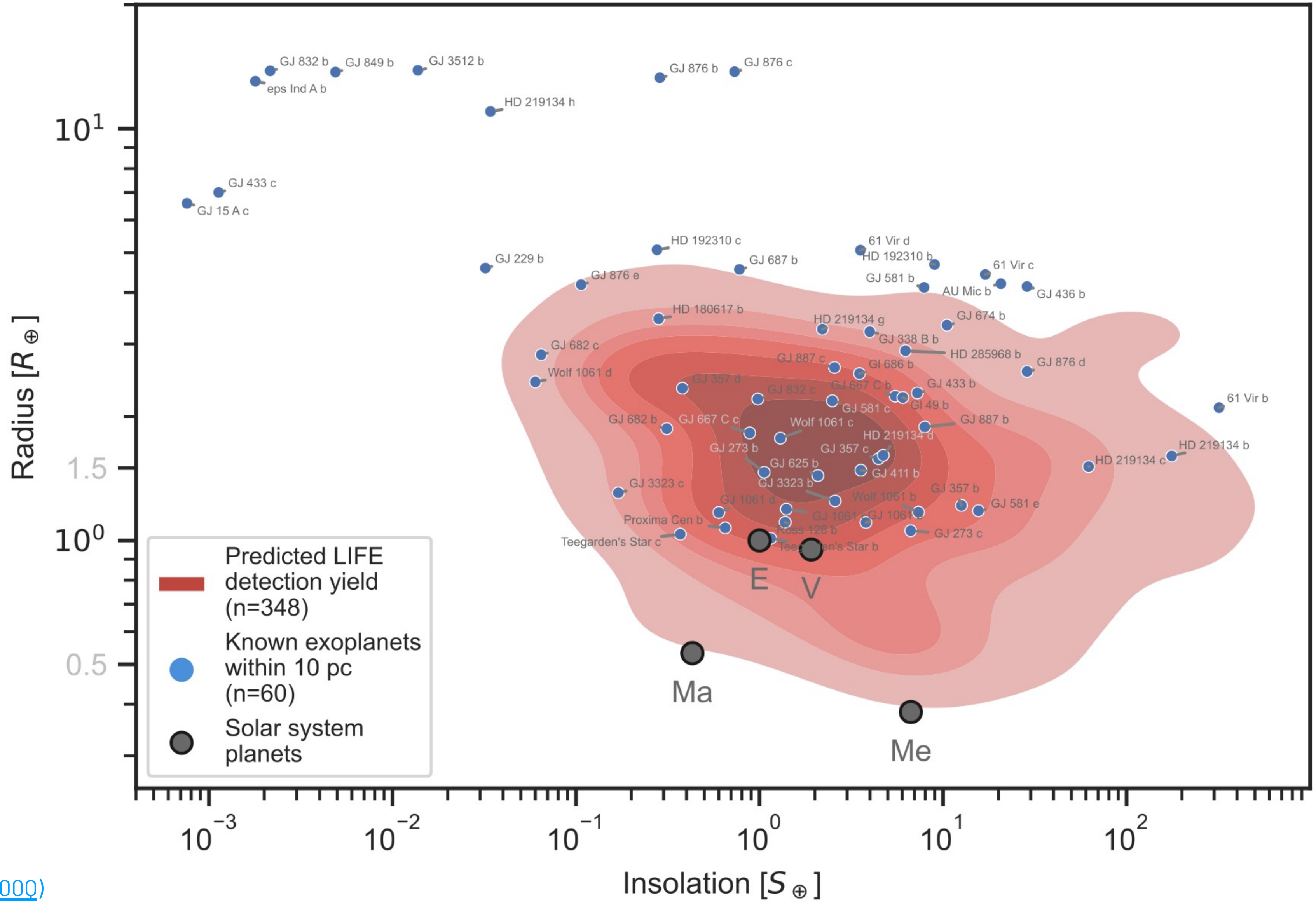
Crosses: All known "rocky-ish" exoplanets to be observed with JWST



Wordsworth & Kreidberg 2022

LIFE is a characterization mission from day 1

LIFE discovery space vs. known exoplanets within 10 pc



Quanz et al. 2022 (arXiv2101075000)

Exoplanet characterization: the mid-infrared advantage

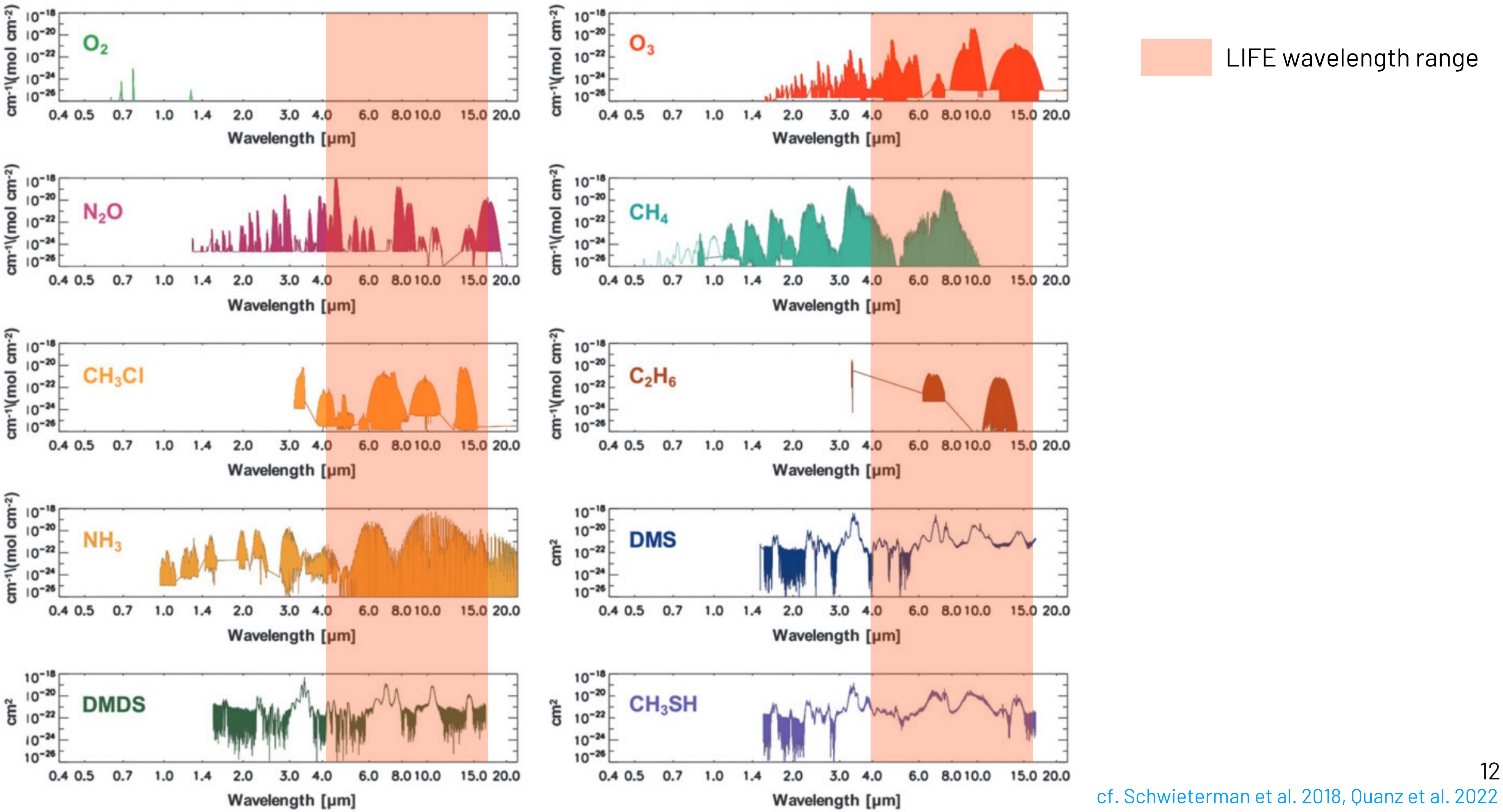
In contrast to a reflected light mission, LIFE will...

- ...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**
- ...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

Biosignature detection: the mid-infrared advantage

Many atmospheric biosignatures have absorption bands in the LIFE wavelength range



cf. Schwieterman et al. 2018, Quanz et al. 2022

LIFE-related paper series is a growing success

A&A 664, A21 (2022)
https://doi.org/10.1051/0004-6361/202140366

Astronomy & Astrophysics

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]

A&A 664, A22 (2022)
https://doi.org/10.1051/0004-6361/202141958

Astronomy & Astrophysics

Large Interferometer For Exoplanets (LIFE)

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

Felix A. 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***

A&A 664, A23 (2022)
https://doi.org/10.1051/0004-6361/202141964

Astronomy & Astrophysics

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], S. P. Quanz[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], and the LIFE Collaboration*

A&A 664, A52 (2022)
https://doi.org/10.1051/0004-6361/202243107

Astronomy & Astrophysics

Large Interferometer For Exoplanets (LIFE)

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

Jonah T. Hansen, Michael J. Ireland, and the LIFE Collaboration*

A&A 665, A106 (2022)
https://doi.org/10.1051/0004-6361/202243760

Astronomy & Astrophysics

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[1,2,3], John Lee Grenfell[4], Paul Mollière[5], Sascha P. Quanz[1,2], Sarah Rugheimer[6], Fabian Wunderlich[4], and the LIFE Collaboration*

A&A 668, A52 (2022)
https://doi.org/10.1051/0004-6361/202243846

Astronomy & Astrophysics

Large Interferometer For Exoplanets (LIFE)

VI. Detecting rocky exoplanets in the habitable zones of Sun-like stars

Jens Kammerer[1], Sascha P. Quanz[2,3], Felix Dannert[2], and the LIFE Collaboration[4]

A&A 670, A57 (2023)
https://doi.org/10.1051/0004-6361/202243863

Astronomy & Astrophysics

Large Interferometer For Exoplanets (LIFE)

VII. Practical implementation of a five-telescope 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*

A&A 671, A114 (2023)
https://doi.org/10.1051/0004-6361/202245402

Astronomy & Astrophysics

Imaging of exocomets with infrared interferometry

Markus Janson[1], Jayshil Patel[1], Simon C. Ringqvist[1], Cicero Lu[2], Isabel Rebollido[3], Tim Lichtenberg[4,5], Alexis Brandeker[1], Daniel Angerhausen[6,7,8], and Lena Noack[9]

A&A 673, A94 (2023)
https://doi.org/10.1051/0004-6361/202245655

Astronomy & Astrophysics

Large Interferometer For Exoplanets (LIFE)

IX. Assessing the impact of clouds on atmospheric retrievals at mid-infrared wavelengths with a Venus-twin exoplanet*

ASTROBIOLOGY
Volume 23, Number 2, 2023

DOI: 10.1089/ast.2022.0010

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Large Interferometer for Exoplanets: VIII. Where Is the Phosphine? Observing Exoplanetary PH_3 with a Space-Based Mid-Infrared Nulling Interferometer

Daniel Angerhausen,[1–3] Maurice Ottiger,[1] Felix Dannert,[1] Yamila Miguel,[4,5] Clara Sousa-Silva,[6,7] Jens Kammerer,[8] Franziska Menti,[1] Eleonora Alei,[1,2] Björn S. Konrad,[1,2] Haiyang S. Wang,[1,2] Sascha P. Quanz[1,2]; and The LIFE Collaboration[9]

PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

The Nulling Interferometer Cryogenic Experiment: I

Mohanakrishna Ranganathan, Adrian Glauser, Thomas Birbacher, Adrian Gheorghe, Sascha Quanz

Mohanakrishna Ranganathan, Adrian M. Glauser, Thomas Birbacher, Adrian A. Gheorghe, Sascha P. Quanz, "The Nulling Interferometer Cryogenic Experiment: I," Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121830L (26 August 2022); doi: 10.1117/12.2629514

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

PROCEEDINGS OF SPIE

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A sub-nanometer long-term stable heterodyne laser metrology system for the Nulling Interferometry Cryogenic Experiment

Thomas Birbacher, Adrian Glauser, Mohanakrishna Ranganathan, Sascha Quanz

Thomas Birbacher, Adrian M. Glauser, Mohanakrishna Ranganathan, Sascha P. Quanz, "A sub-nanometer long-term stable heterodyne laser metrology system for the Nulling Interferometry Cryogenic Experiment," Proc. SPIE 12183, Optical and Infrared Interferometry and Imaging VIII, 121831A (29 August 2022); doi: 10.1117/12.2631654

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

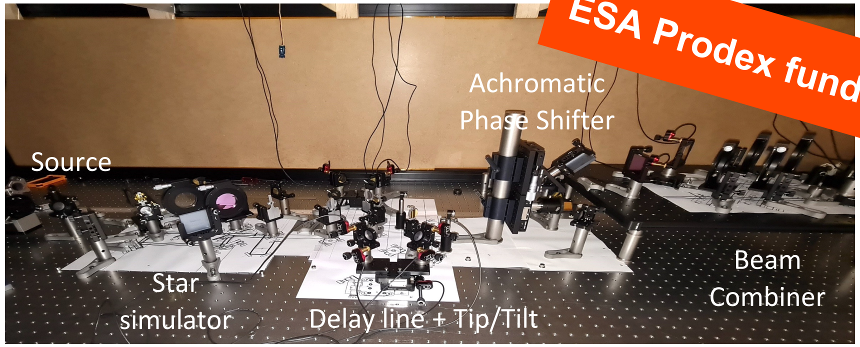
Recent progress and ongoing efforts increase technological readiness

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

1 Cryogenic nulling

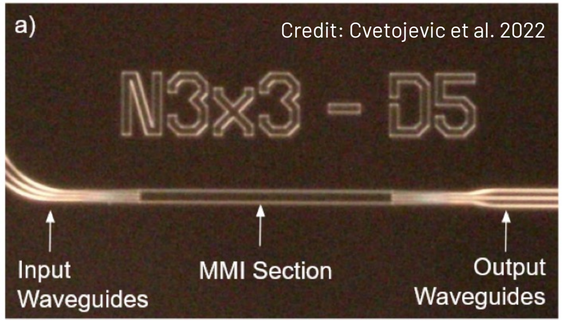
New mid-infrared testbench under construction at ETH Zurich to demonstrate interferometric nulling under realistic conditions

ESA Prodex funded



2 Photonics

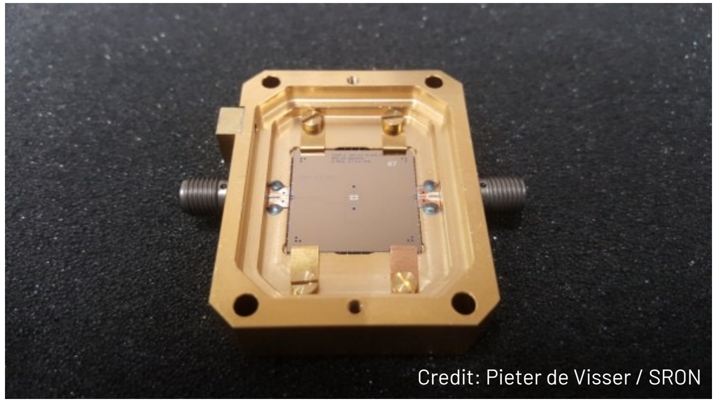
Major breakthroughs in astro-photonics for interferometric nulling at near-infrared wavelengths motivate mid-infrared applications as next step



Credit: Cvetojevic et al. 2022

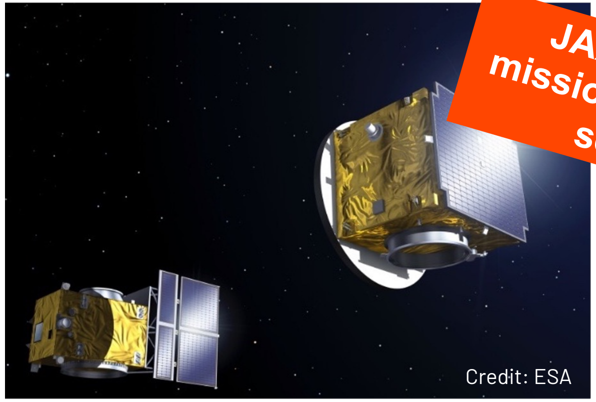
3 Low-noise detectors

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


Credit: Pieter de Visser / SRON

4 Autonamous formation flying

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


Credit: ESA

JAXA's SILVIA mission up for down selection

LIFE: 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.”

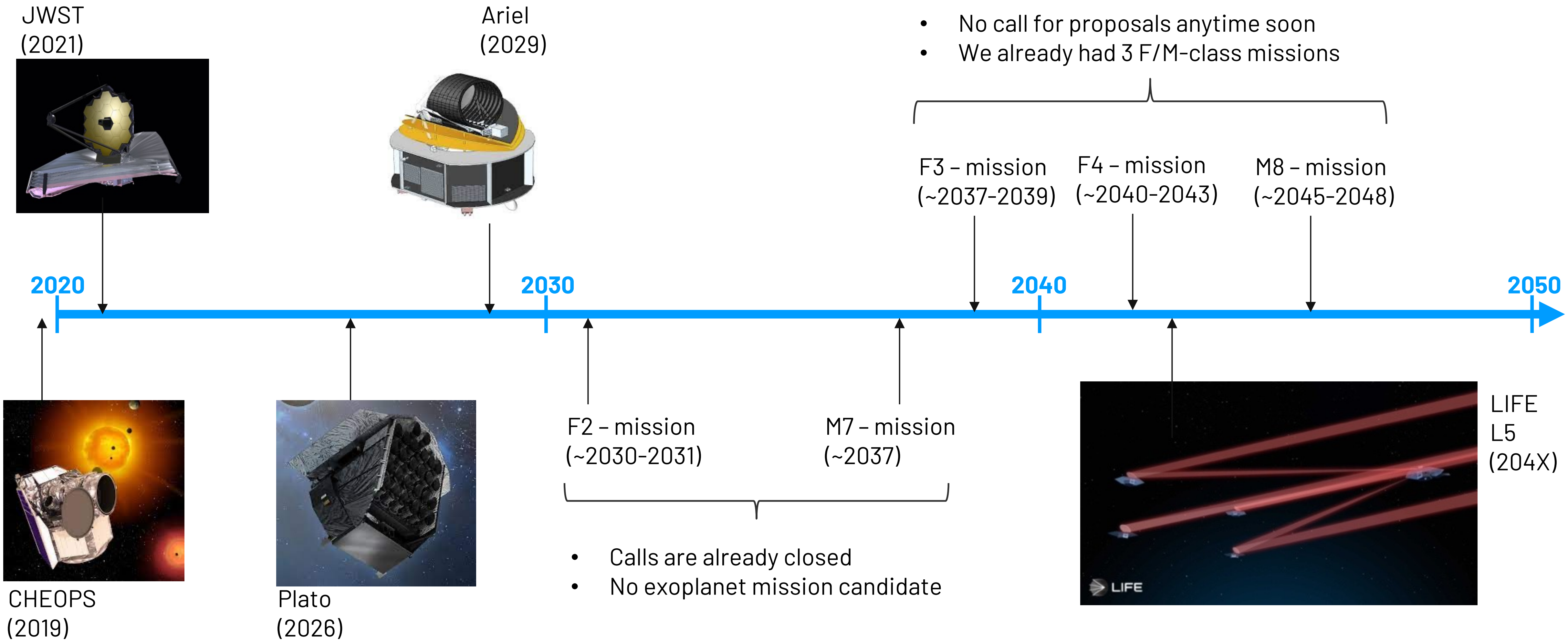
“This would give ESA and the European community the opportunity to **solidify its leadership** in the field of exoplanets, [...]”

“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.”

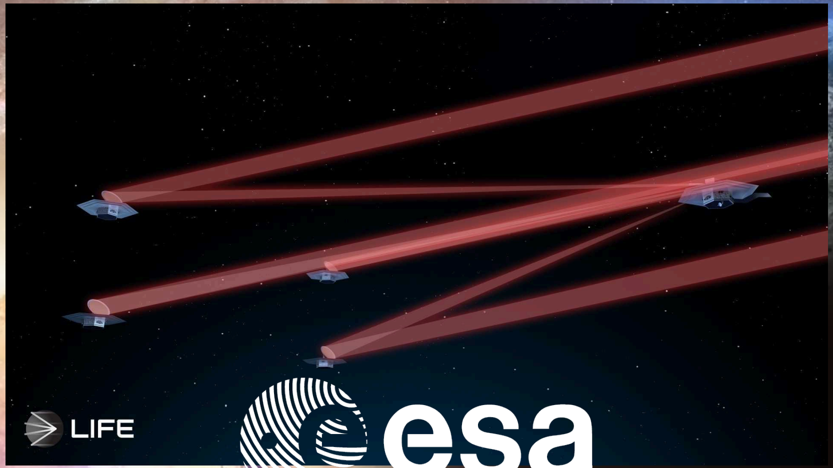
ESA Senior Committee Report; June 2021

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

LIFE: a unique opportunity for Europe to lead the way...



...for the next Copernican revolution with established partners



Lead

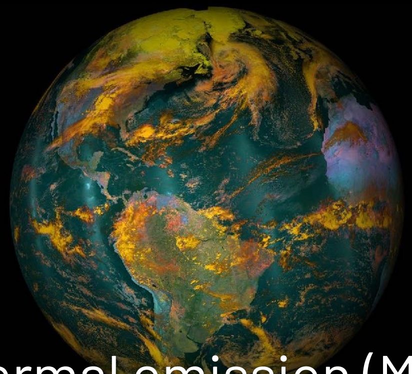
Potential partners

Image Creator: Guillaume Preat / EyeEm | Credit: Getty Images/EyeEm

Coordinated efforts will provide a holistic view of Earth-analogs

Synergies between different missions and ground-based telescopes

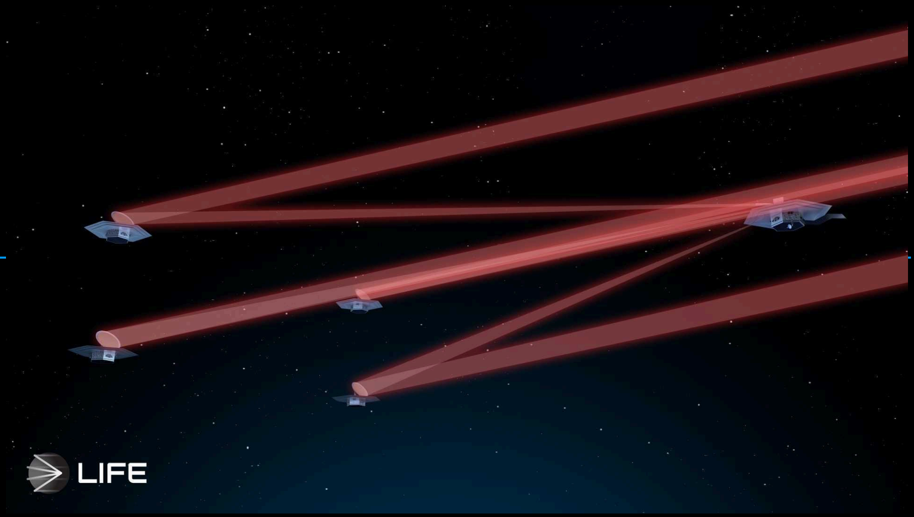
Reflected light (UV - NIR)

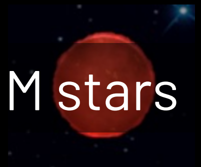


Thermal emission (MIR)

Solar-type stars

NASA's HWO





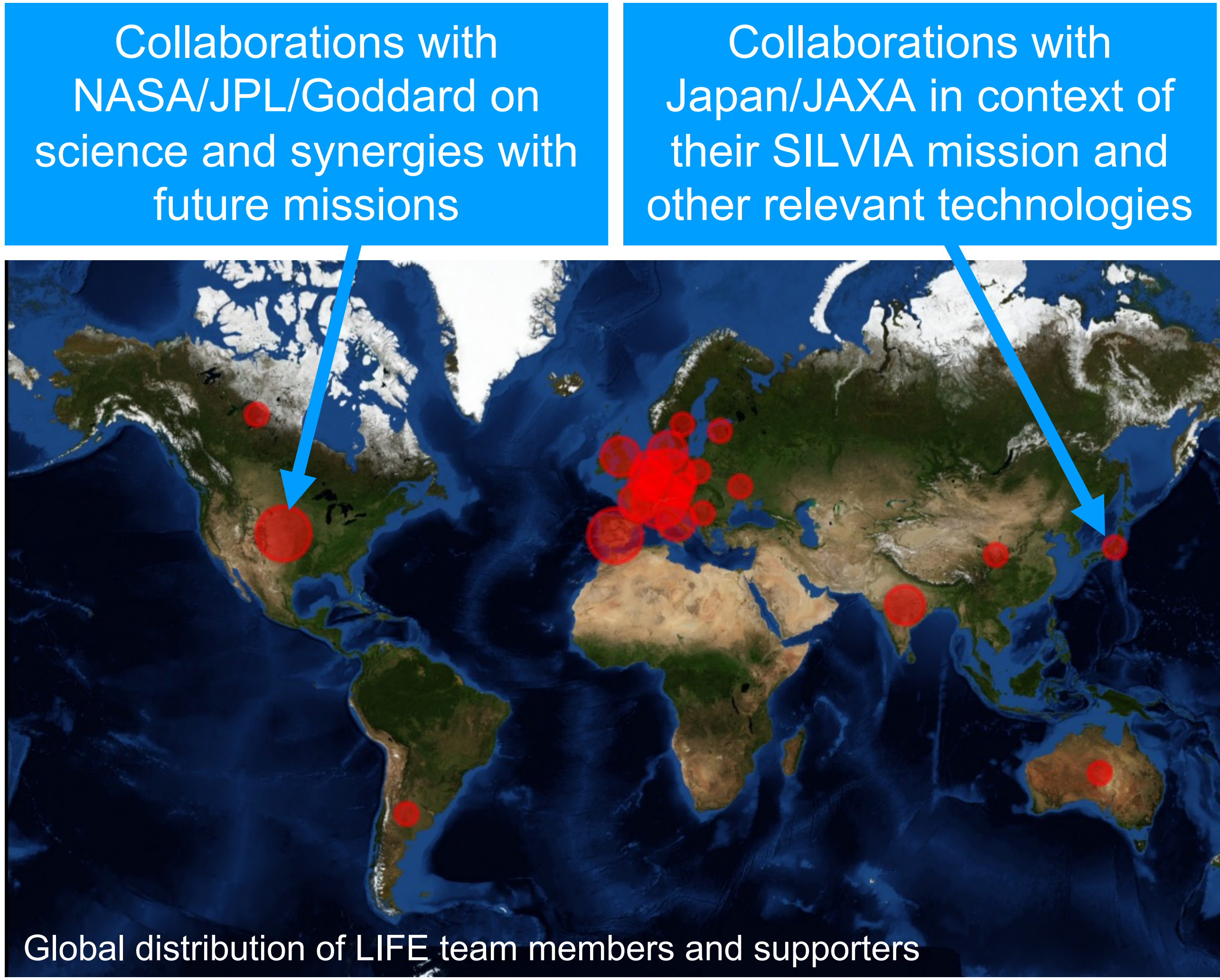
M stars

ELTs

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

Join the global LIFE initiative!

- LIFE is a European-led but global initiative for a large future exoplanet mission!
- The science theme has been recognized as a potential candidate for an L-class mission within ESA's Science Programme
- R&D for critical components / sub-systems is starting to ramp up, **and we are working towards a mission concept study with our academic and industry partners (kick-off 2024)**
- LIFE is not a closed-club; collaborations / contributions / partnerships at various levels are more than welcome!
- More information:
  - www.life-space-mission.com
  - Sign up for newsletter: life@phys.ethz.ch
  - Follow us: @LIFE_telescope



Global distribution of LIFE team members and supporters

LIFE

LARGE INTERFEROMETER FOR EXOPLANETS

Thank you

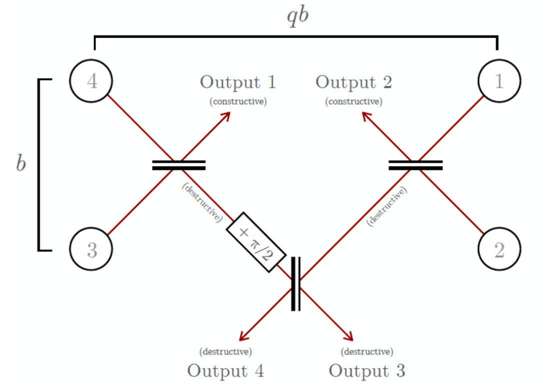
LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

BACKUP

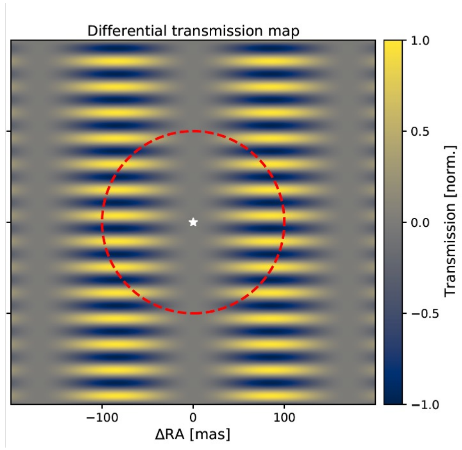
From Source to Detection

Summary Slide

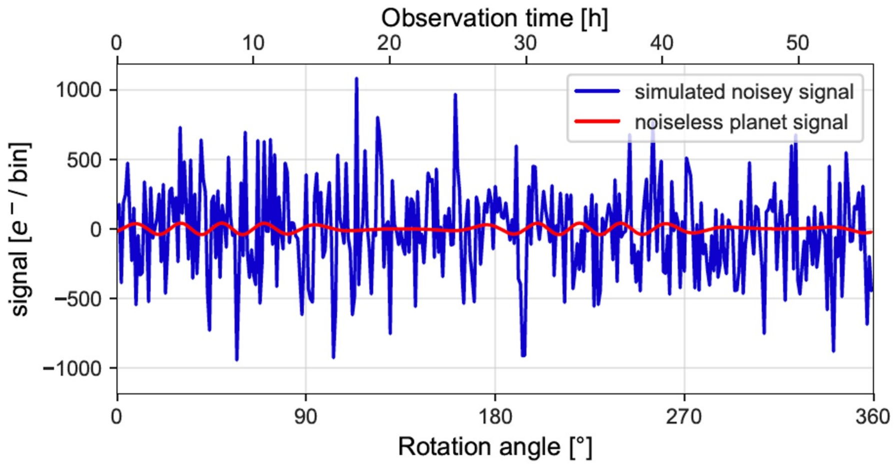
Instrument Model



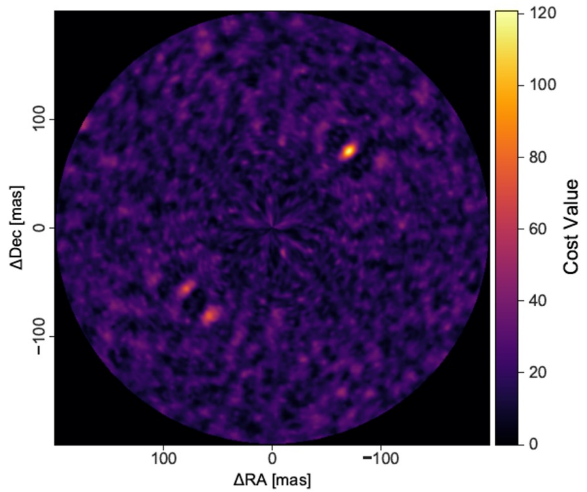
Transmission Map



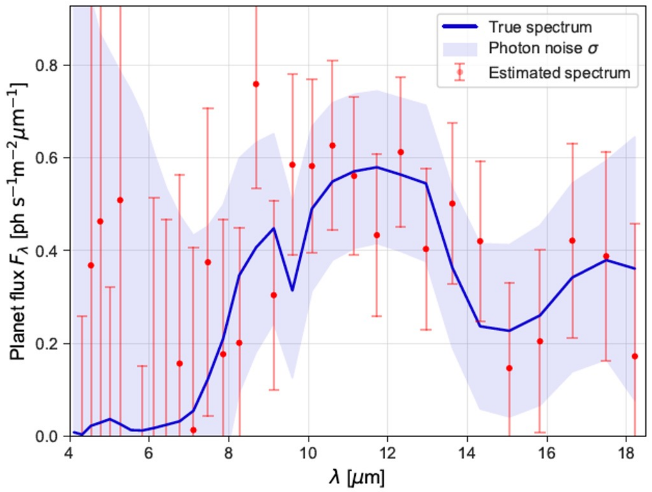
Noisy Time Series



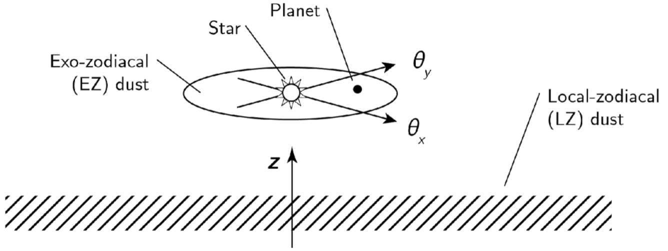
Detection Map



Spectrum



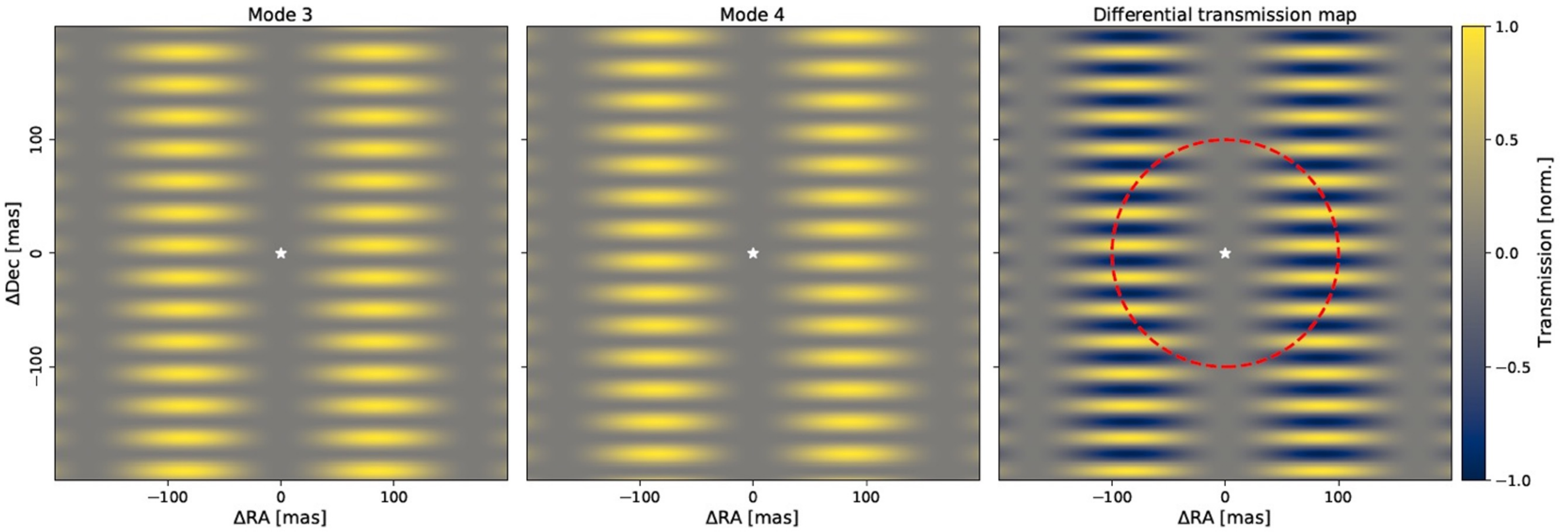
Source Simulation



Lay 2004

Signal Simulation

- Double Bracewell nulling interferometer; there are 2 constructive and 2 destructive outputs
- In one branch, a p/2 phase shift is introduced to enable the difference map
- Phase Chopping between Outputs 3 & 4 makes instrument less susceptible to perturbation
- Assume fundamental noise limit (ideal instrument)

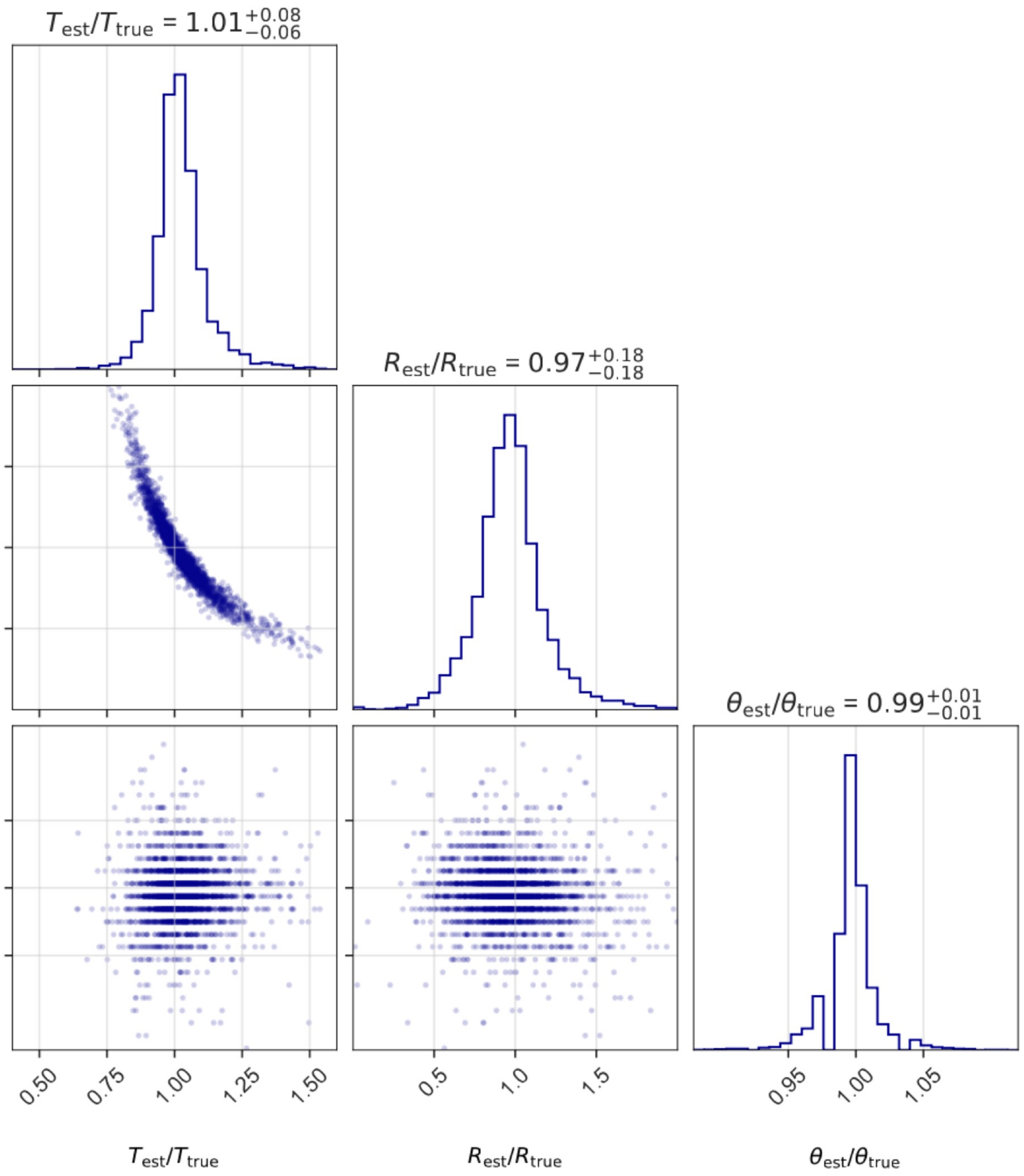


Difference map is antisymmetric wrt central point and filters out point-symmetric emission, but offset planet signal remains

Array rotation (on timescales of 16 – 20 h) will lead to a virtual path of the exoplanet emission through the difference map

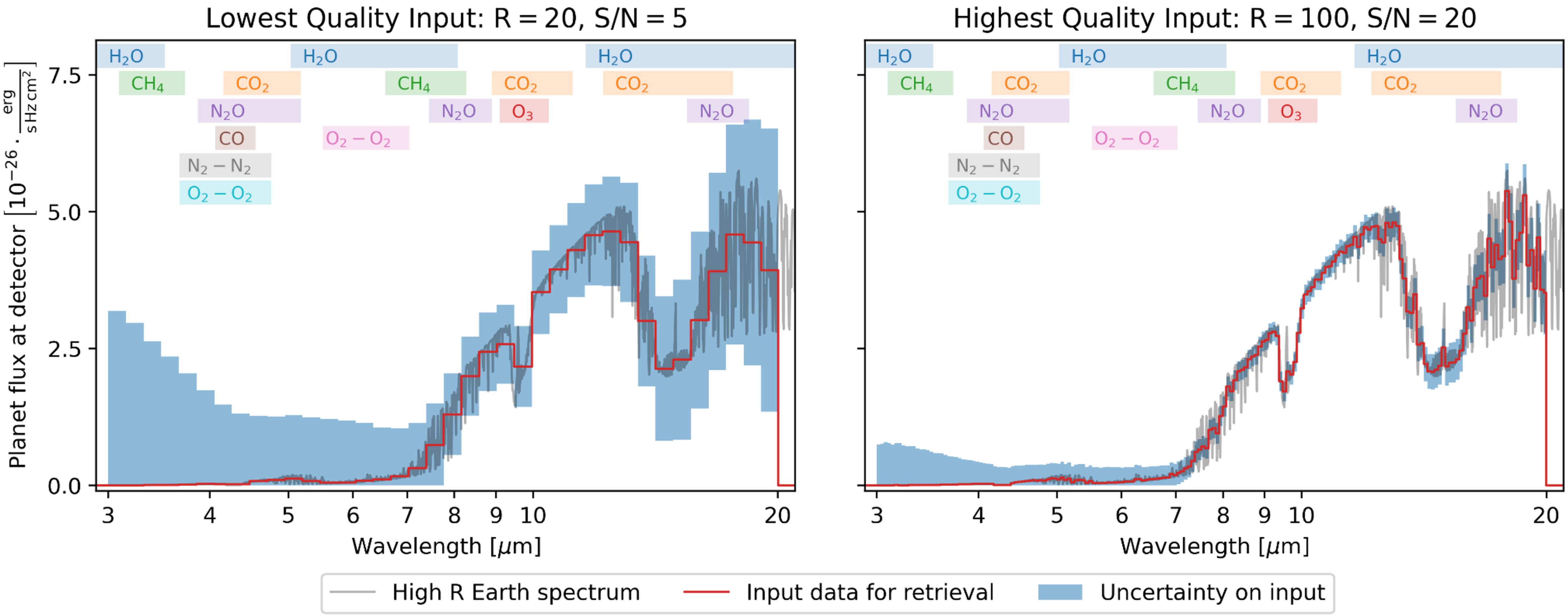
Fundamental planet parameter from single epoch

- 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: ~1-2%



Dannert et al. 2022 (arXiv220300471D)

Earth-twin retrieval studies to determine characterization potential

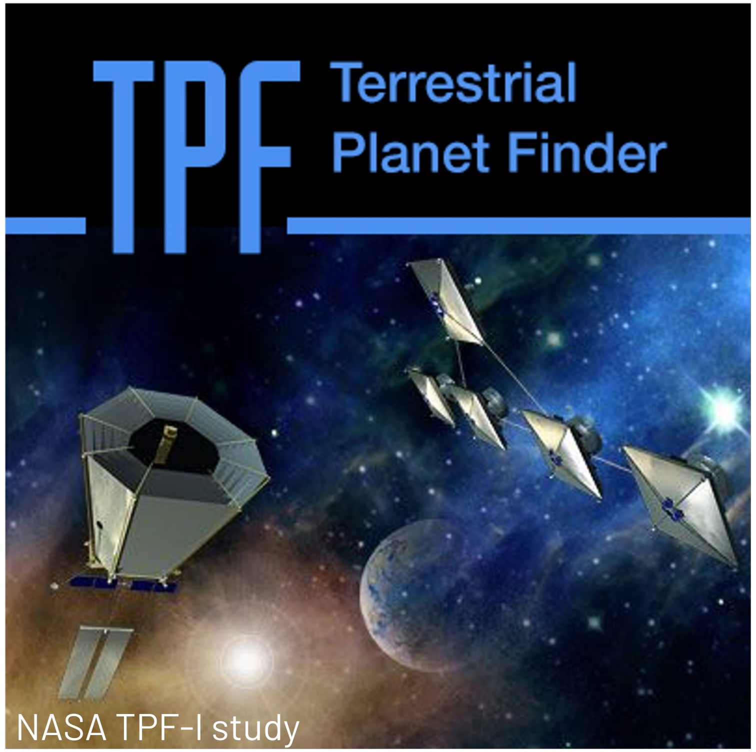


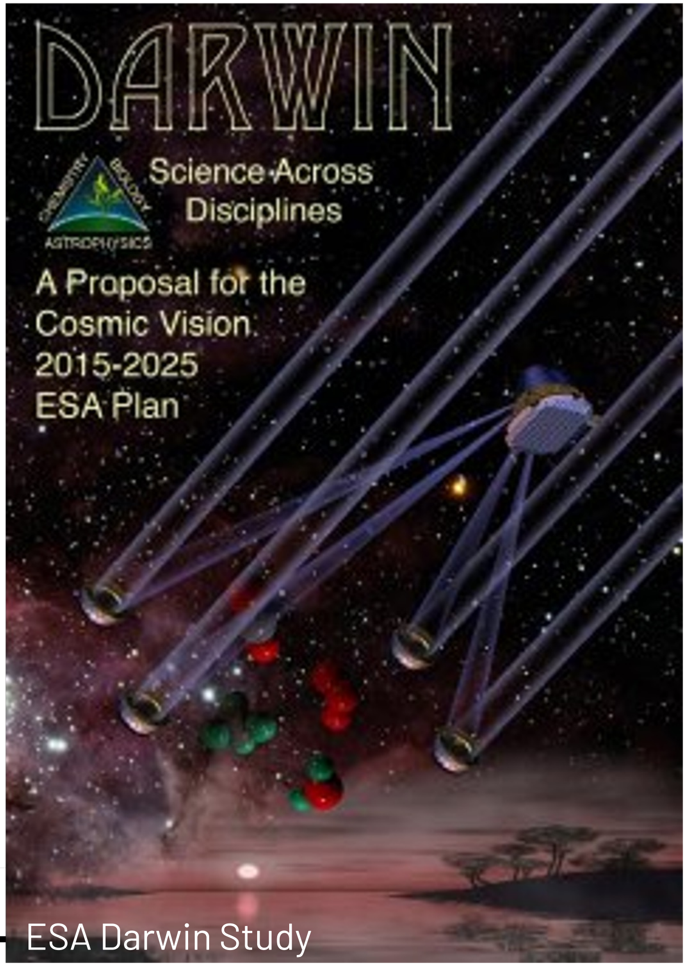
Konrad et al. 2022

Heritage

Space based (MIR, nulling) interferometry 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





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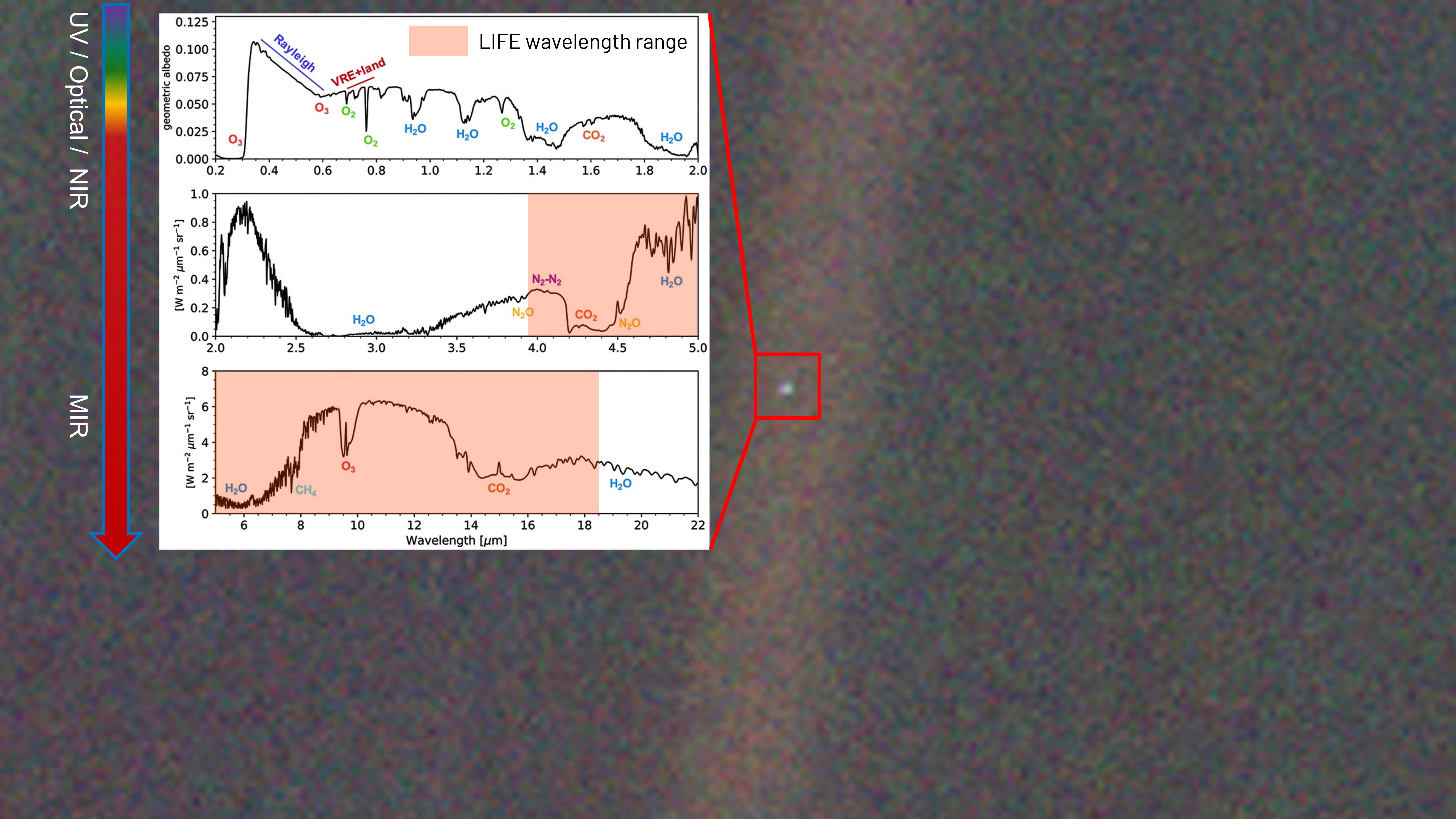

UV / Optical / NIR
MIR
LIFE wavelength range
geometric albedo
Rayleigh
VRE+land
O3
O2
H2O
CO2
N2-N2
N2O
CH4
[W m−2 μm−1 sr−1]
Wavelength [μm]