The LIFE initiative

Authors:

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Adrian Glauser
(ETH)

for the
LIFE initiative

Atmospheric characterization of terrestrial exoplanets in the mid-infrared with a large space-based nulling interferometer

ETH zürich

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

Overview

- Towards the direct detection of terrestrial exoplanets
- The LIFE mission – a short introduction
- Exemplary science cases for LIFE
- Relevant technologies for LIFE

Overview

- **Towards the direct detection of terrestrial exoplanets**
- The LIFE mission – a short introduction
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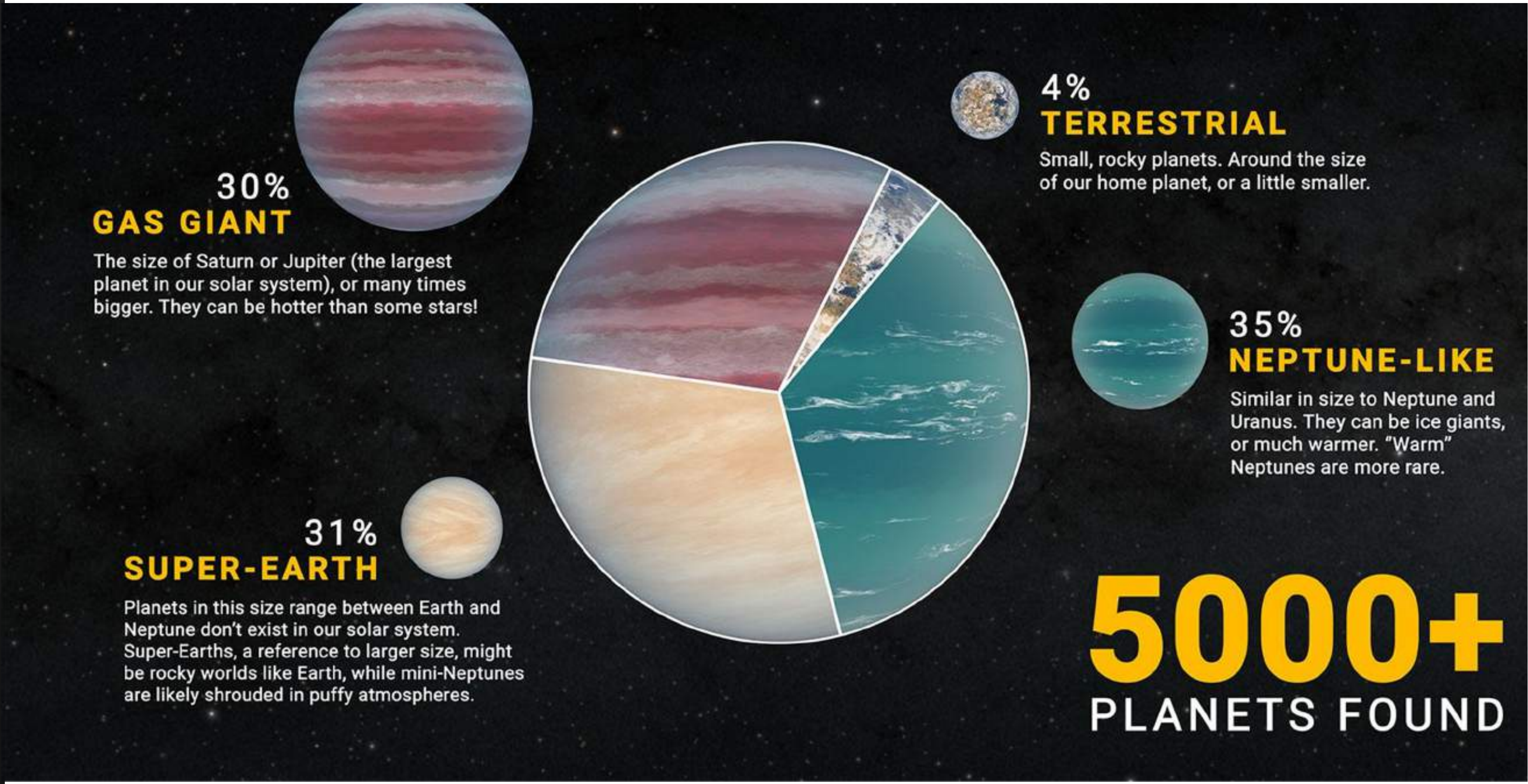
Exoplanets are everywhere

- First detection of an exoplanet around a Sun-like star was in 1995
- Today more than 5000 exoplanets have been detected
- Various detection techniques probe different parts of parameters space



Credits: NASA/JPL-Caltech

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- First detection of an exoplanet around a Sun-like star was in 1995
- Today more than 5000 exoplanets have been detected
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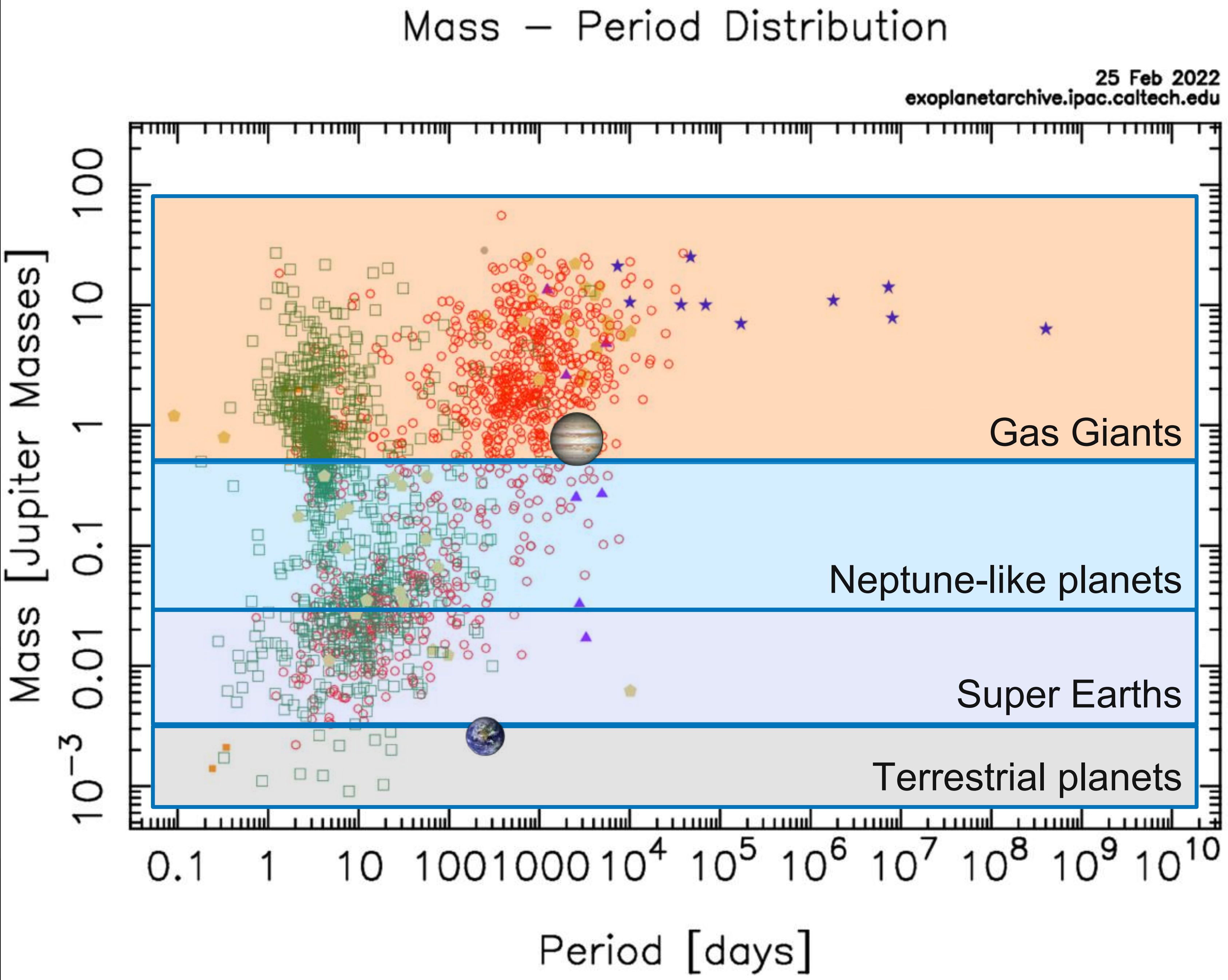
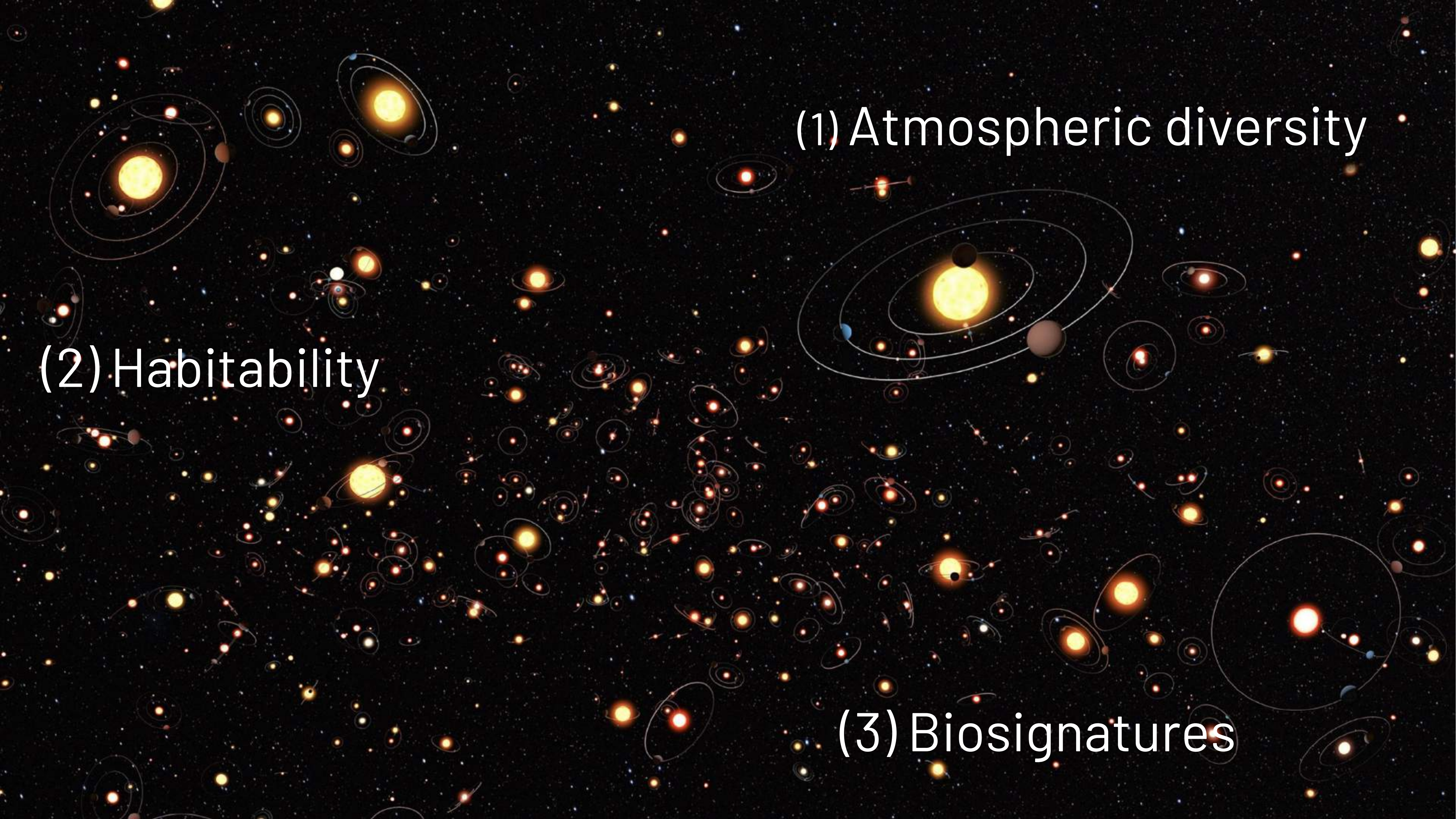
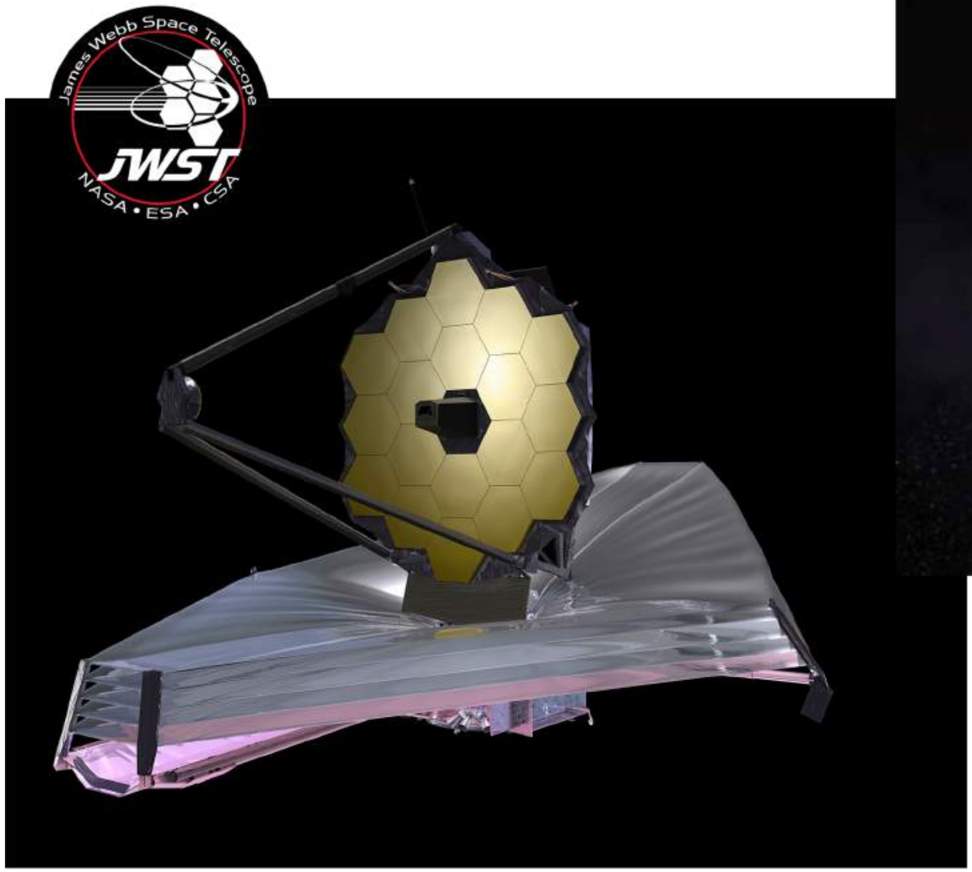



(1) Atmospheric diversity
(2) Habitability
(3) Biosignatures

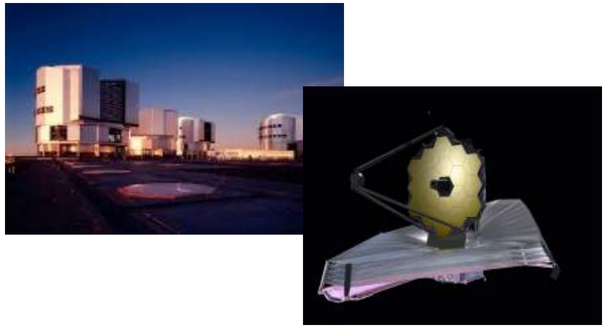
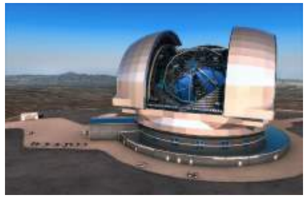
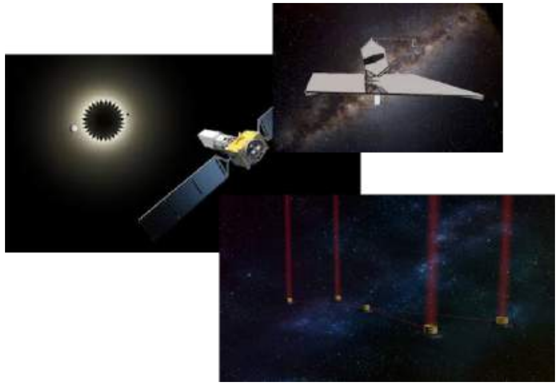
Upcoming MIR missions will focus on hot/warm transiting exoplanets

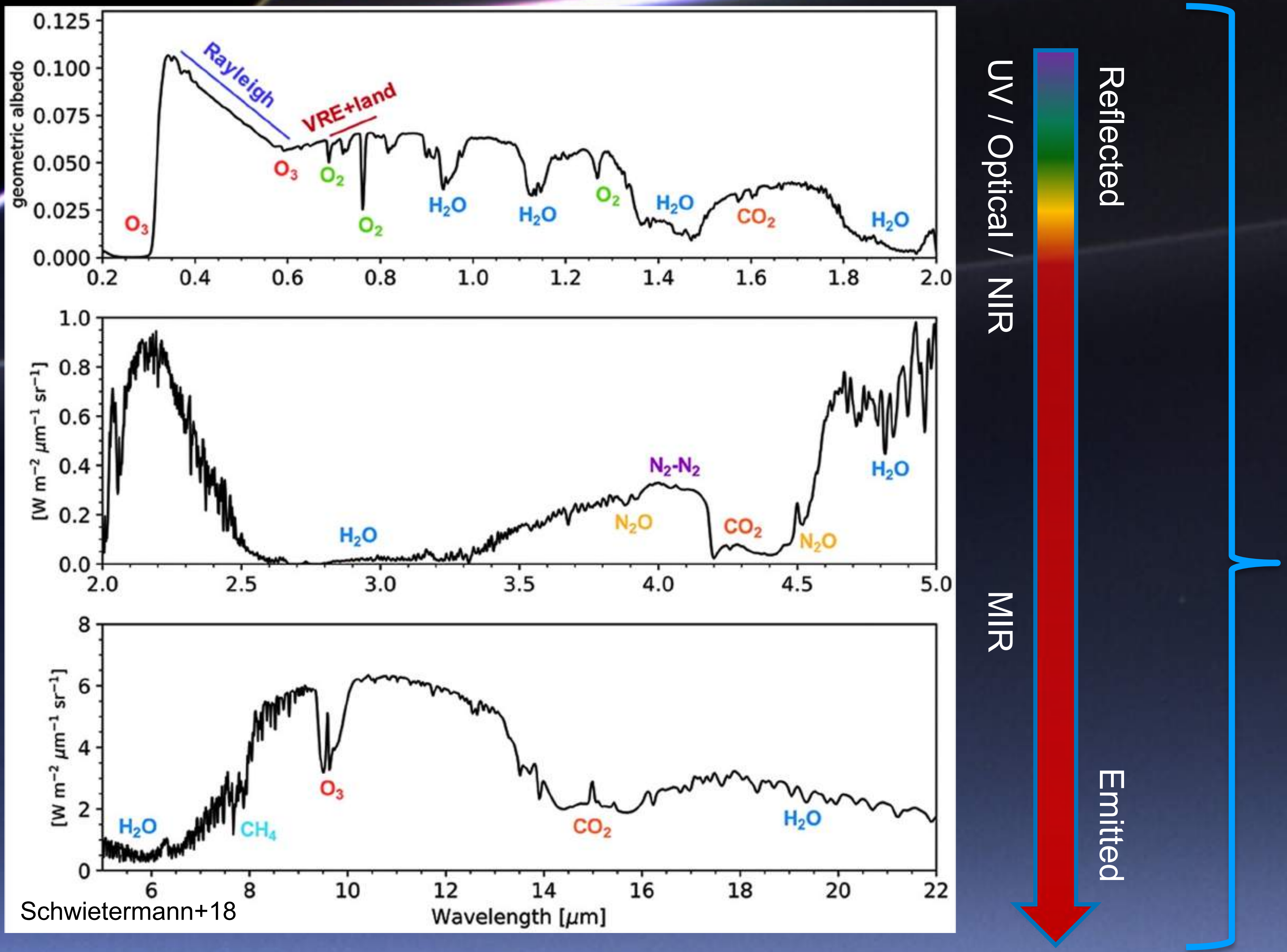


"A long term scientific objective is to characterize the whole range of exoplanets, including, of course, potentially habitable ones. ARIEL would act as a pathfinder for future, even more ambitious campaigns."

ARIEL Assessment Study Report (Yellow Book)

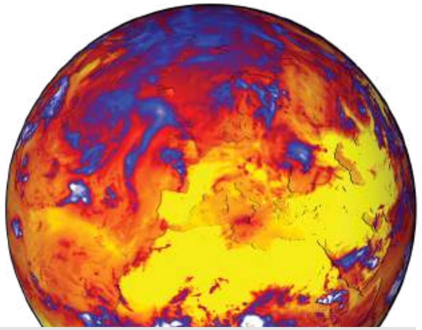
Direct detection of terrestrial exoplanets requires large space missions

			Direct detection and atmospheric characterization of terrestrial exoplanets
Today	8-10 m telescopes JWST		None
10+ years	30-40 m telescopes		Some Earth-sized exoplanets
20-30+ years	Next flagship missions		Dozens of Earth-sized exoplanets

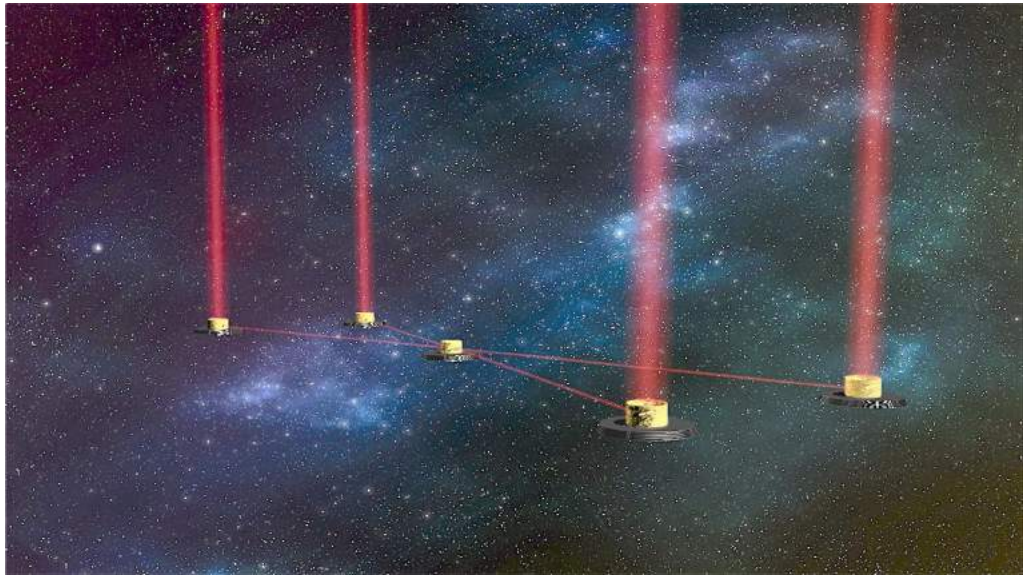

geometric albedo
0.125
0.100
0.075
0.050
0.025
0.000
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Rayleigh
VRE+land
O_3
O_2
H_2O
CO_2
[W m^{-2} μm^{-1} sr^{-1}]
1.0
0.8
0.6
0.4
0.2
0.0
2.0
2.5
3.0
3.5
4.0
4.5
5.0
N_2-N_2
N_2O
8
6
4
2
0
6
8
10
12
14
16
18
20
22
CH_4
Wavelength [μm]
Schwietermann+18
UV / Optical / NIR
MIR
Reflected
Emitted

The LIFE initiative in an international context

Reflected light
UV & Optical & NIR

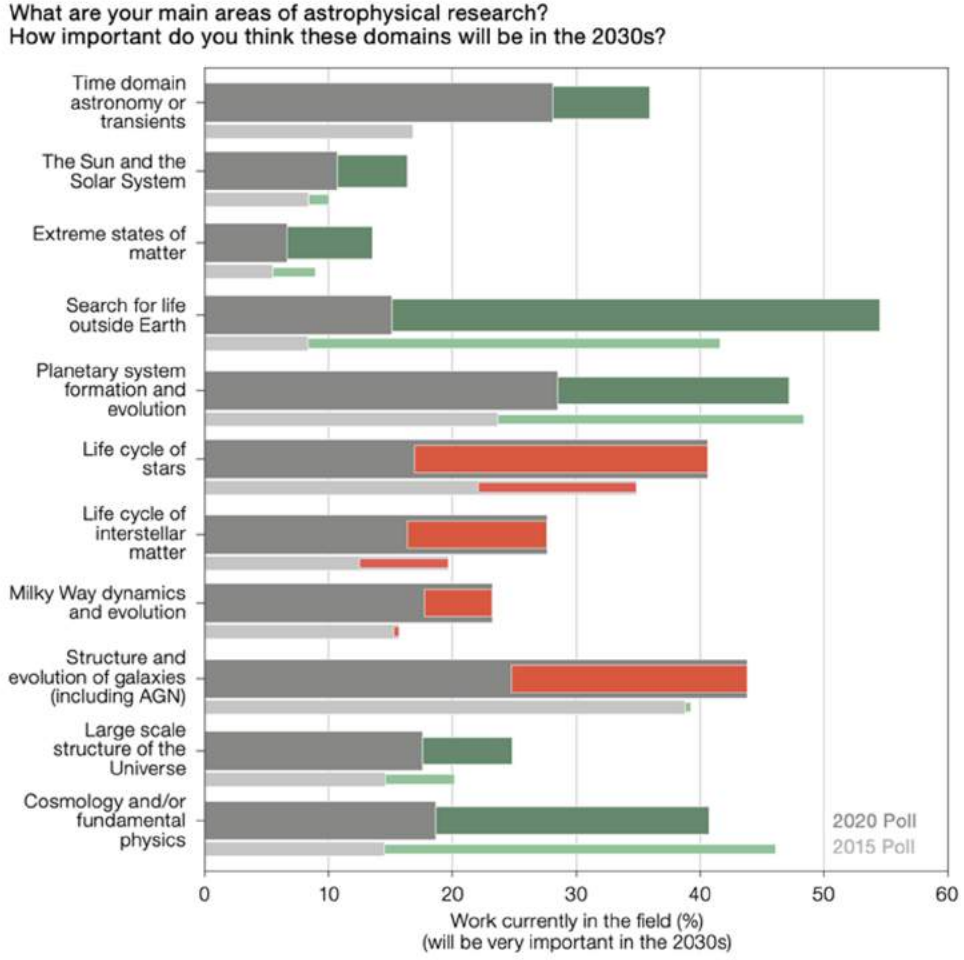


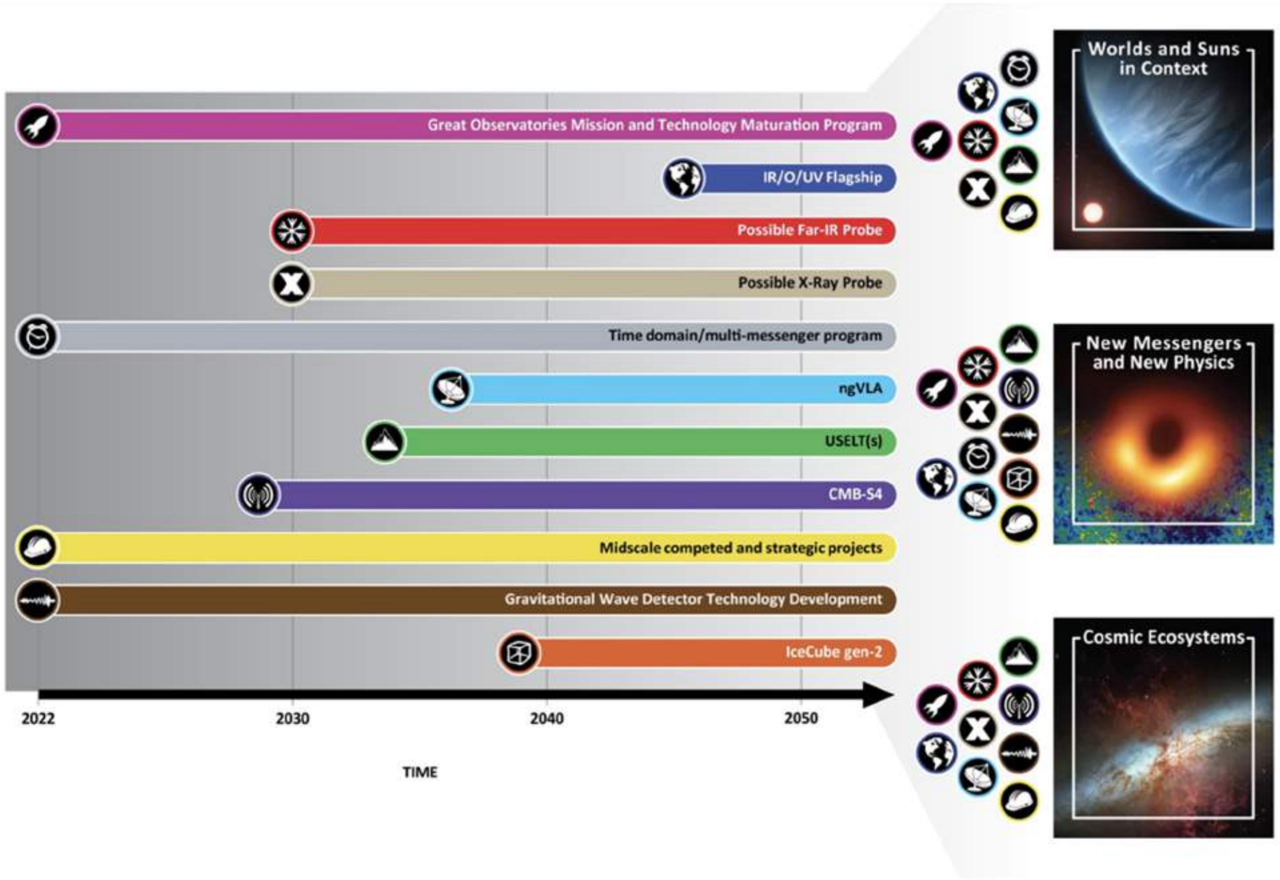
Thermal emission
MIR



Community agreement: temperate, terrestrial exoplanets as next focus

European Southern Observatory poll – NASA decadal survey

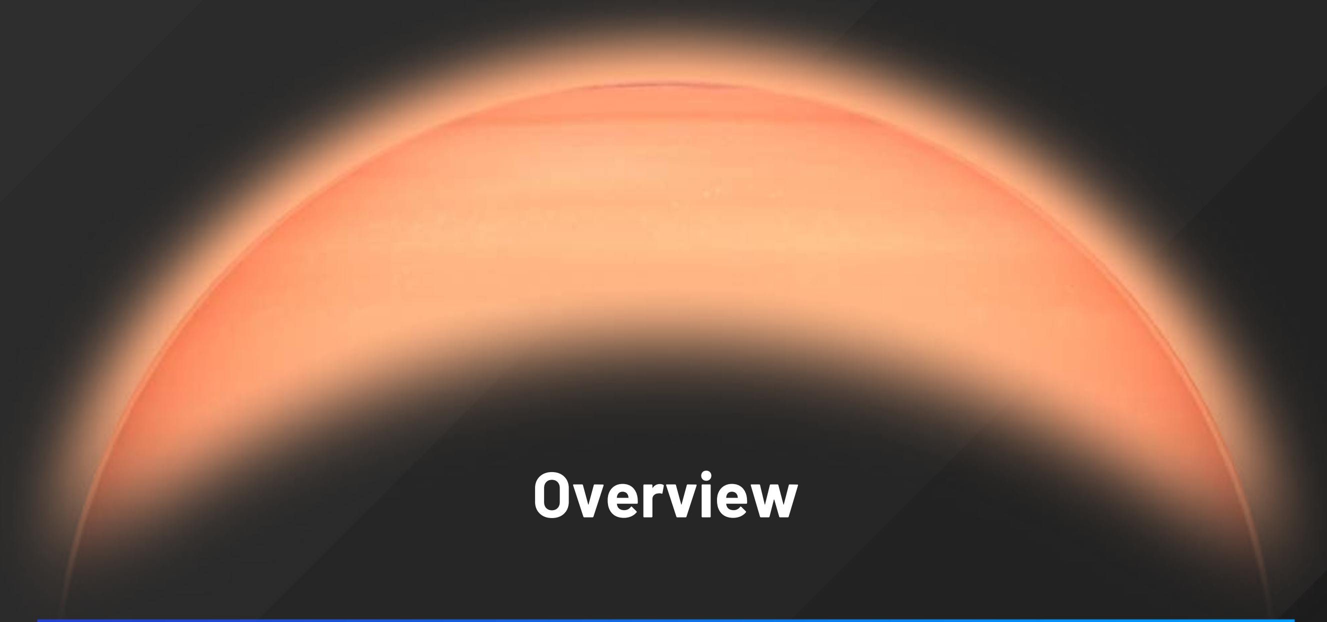




https://www.eso.org/sci/publications/messenger/archive/no.184-sep21/messenger-no184.pdf

National Academies of Sciences, Engineering, and Medicine. 2021. Pathways to Discovery in Astronomy and Astrophysics for the 2020s. Washington, DC: The National Academies Press.https://doi.org/10.17226/26141.

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS



Overview

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- **The LIFE mission – a short introduction**
- Exemplary science cases for LIFE
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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 space mission that investigates the atmospheric properties of ~100 terrestrial exoplanets (~30-50 within the HZ) to

- Understand the diversity of planetary bodies
- Assess the habitability of terrestrial exoplanets
- Search for potential biosignatures (such as oxygen and methane) in exoplanet atmospheres

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

LIFE: a candidate for 1 out of 3 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."

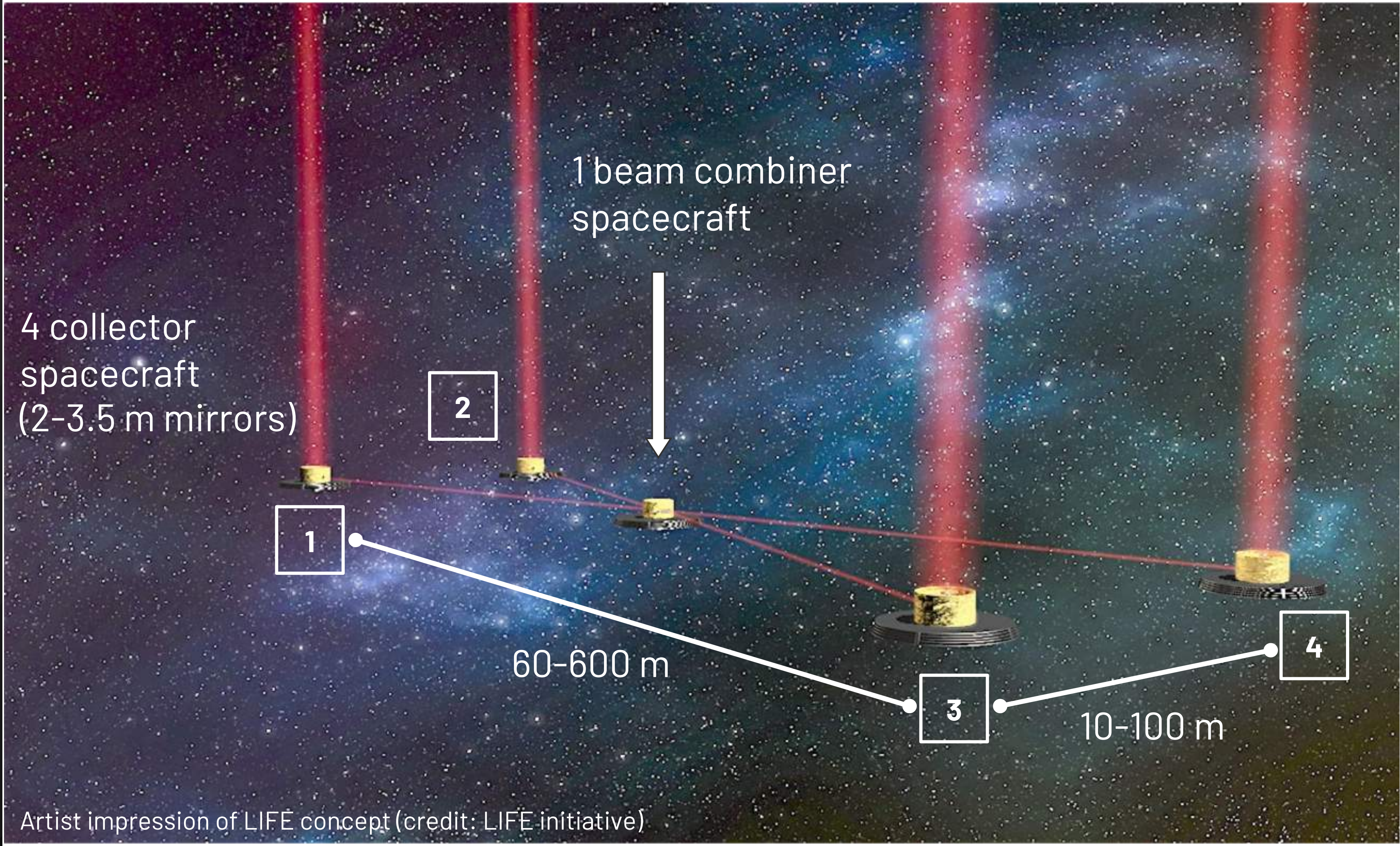
"This would give ESA and the European community the opportunity to **solidify its leadership** in the field of exoplanets, [...]"

"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

The LIFE mission

- ...is a space-based formation-flying mid-infrared (nulling) interferometer
- ...consists of 4 collector spacecraft and a beam combiner spacecraft
- ...covers the mid-infrared wavelength range between ~4-18.5 μm

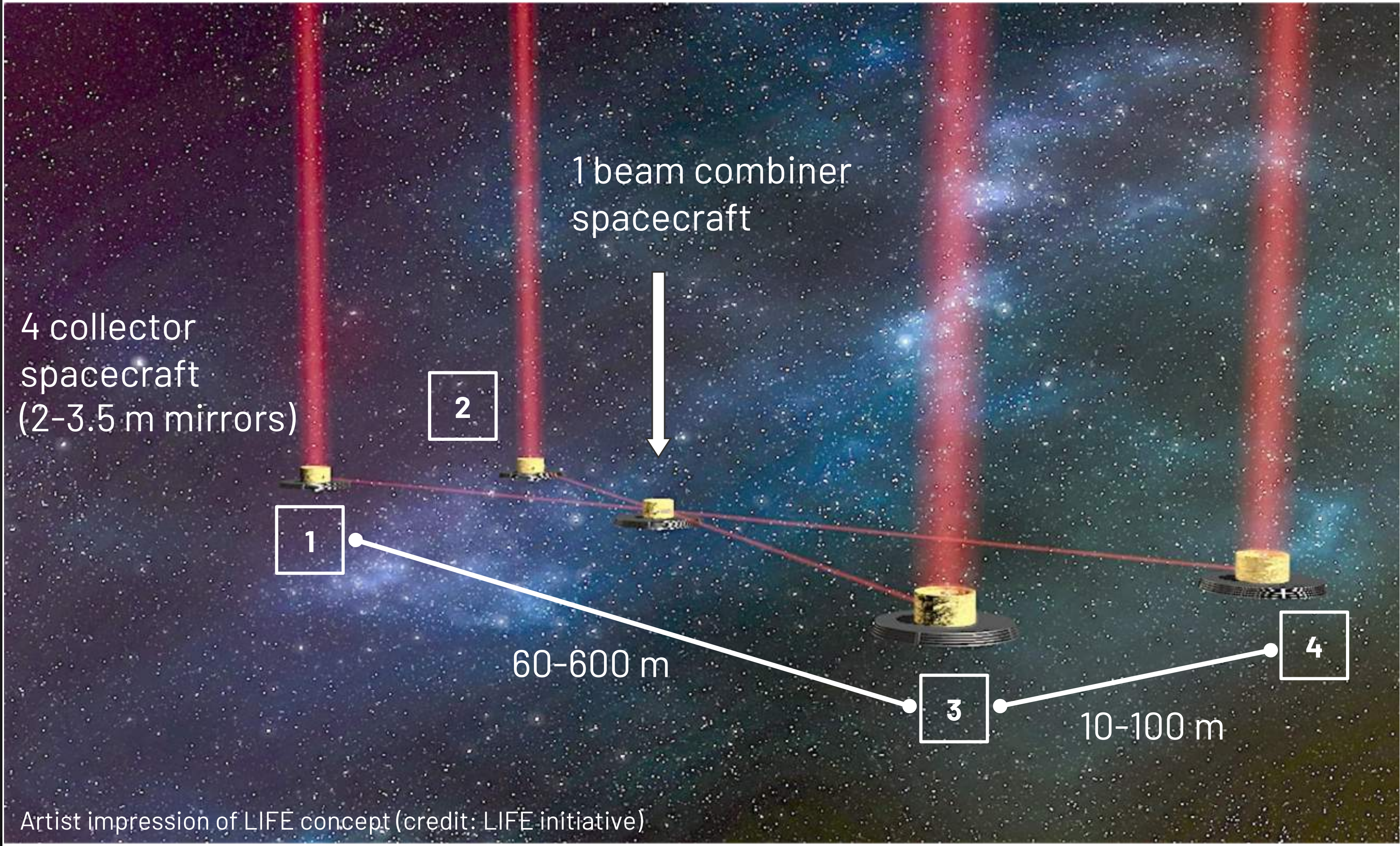


Artist impression of LIFE concept (credit: LIFE initiative)

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

The LIFE mission

- Why do you need to go to space?

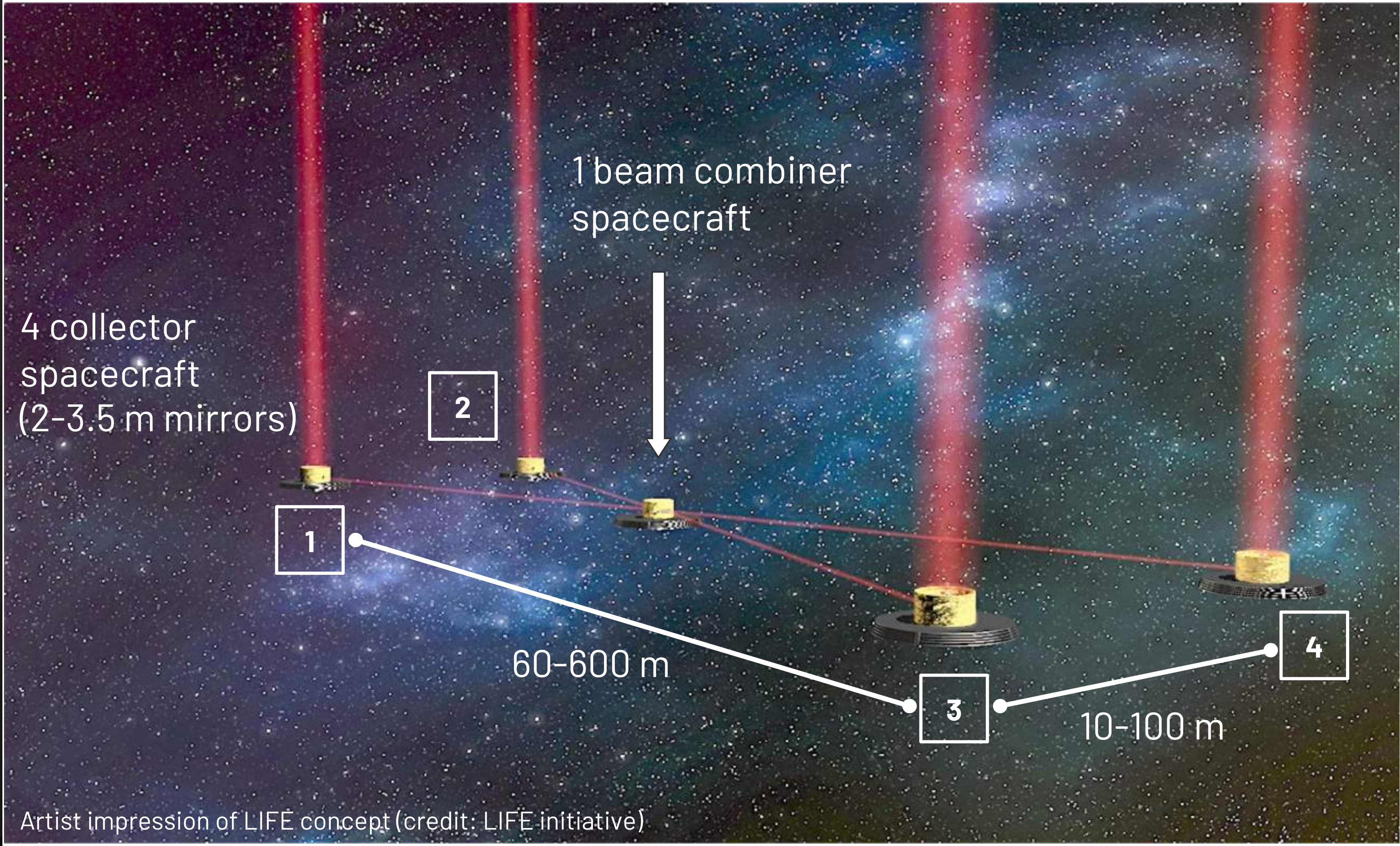


Artist impression of LIFE concept (credit: LIFE initiative)

Quanz et al. 2021 (Experimental Astronomy; [10.1007/s10686-021-09791-z](https://doi.org/10.1007/s10686-021-09791-z))

The LIFE mission

- Why do you need to go to space?
- Why do you need to build an interferometer?

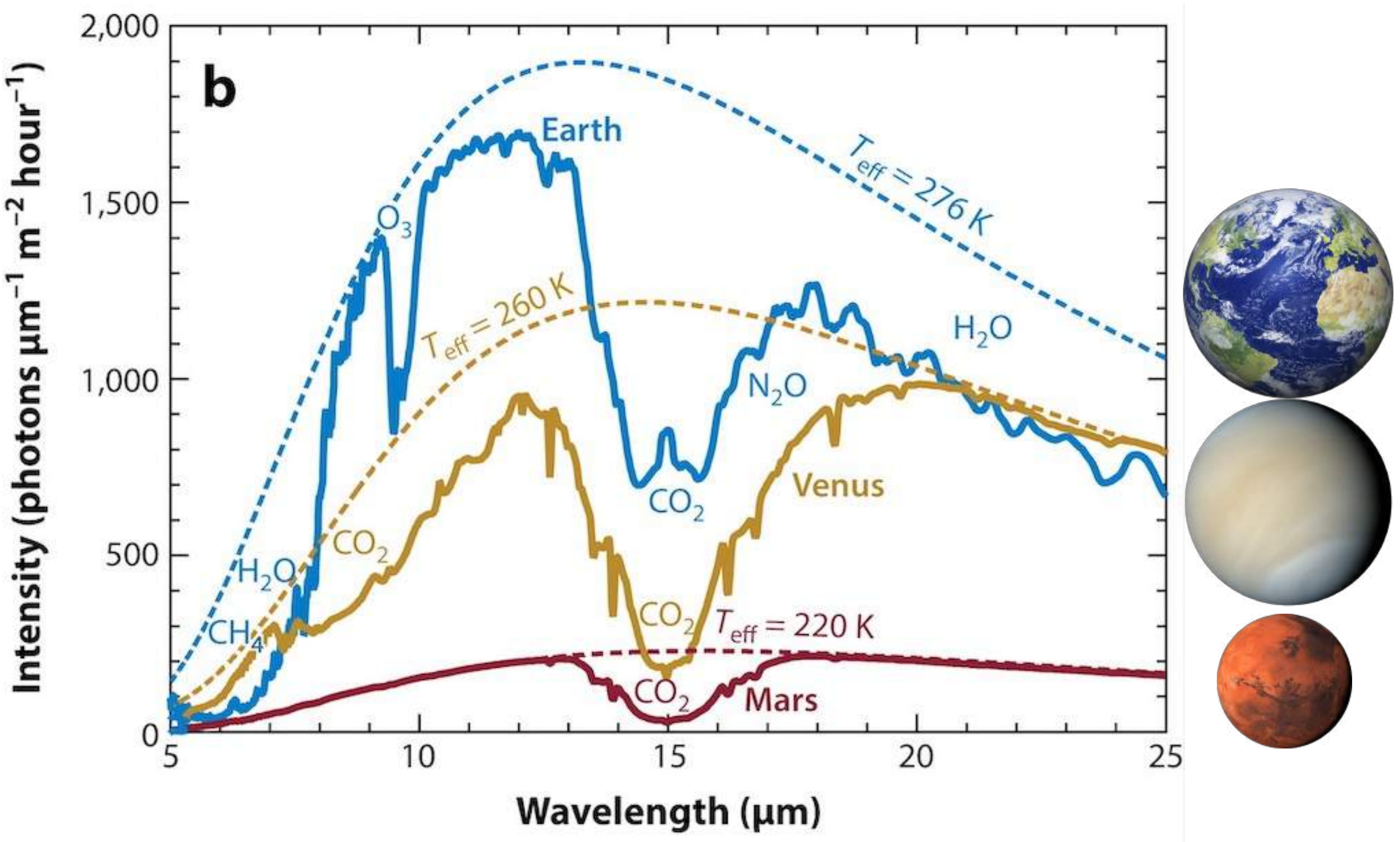


Quanz et al. 2021 (Experimental Astronomy; 10.1007/s10686-021-09791-z)

The LIFE mission

- Why do you need to go to space?
- Why do you need to build an interferometer?
- Why did you chose this wavelength range?

MIR spectra of terrestrial planets in our Solar System



Kaltenegger 2017

The LIFE mission

- Why do you need to go to space?
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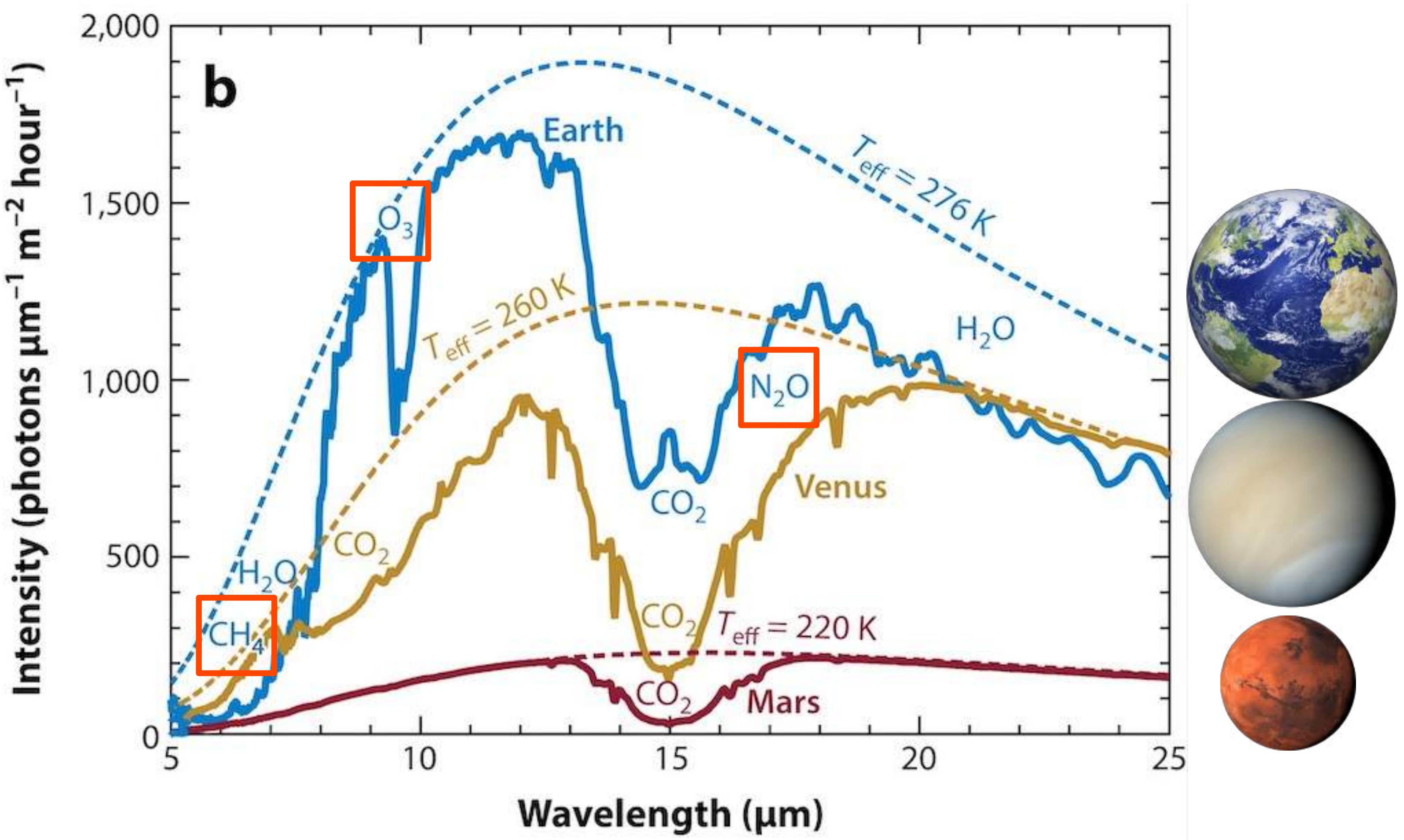
MIR spectra of terrestrial planets in our Solar System

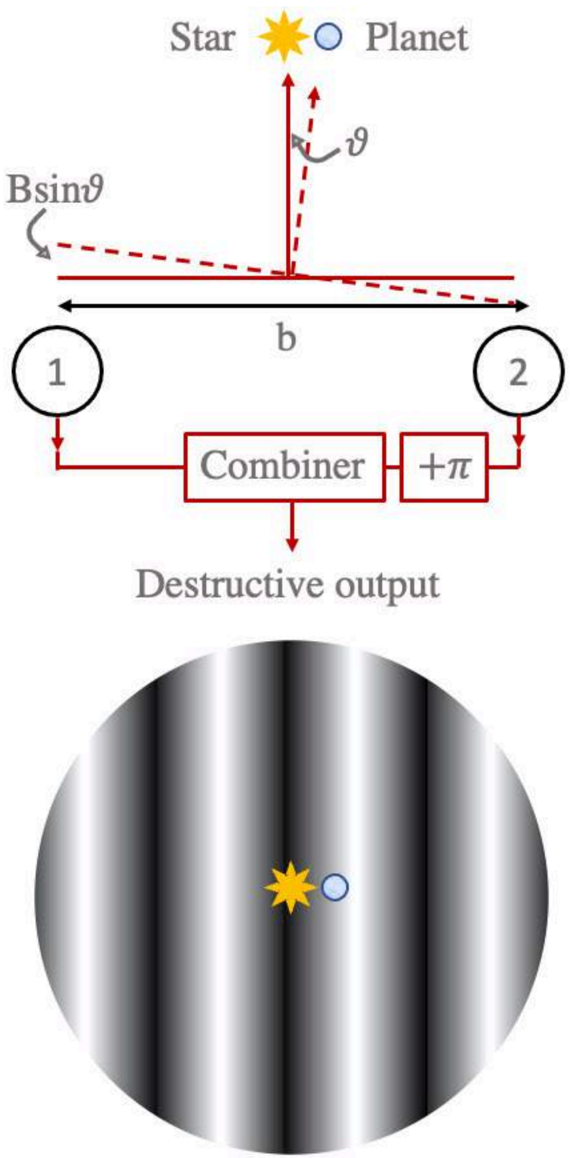


Kaltenegger 2017

The LIFE mission

- Why do you need to go to space?
- Why do you need to build an interferometer?
- Why did you chose this wavelength range?
- Why does it have to be a *nulling interferometer?*

Nulling principle



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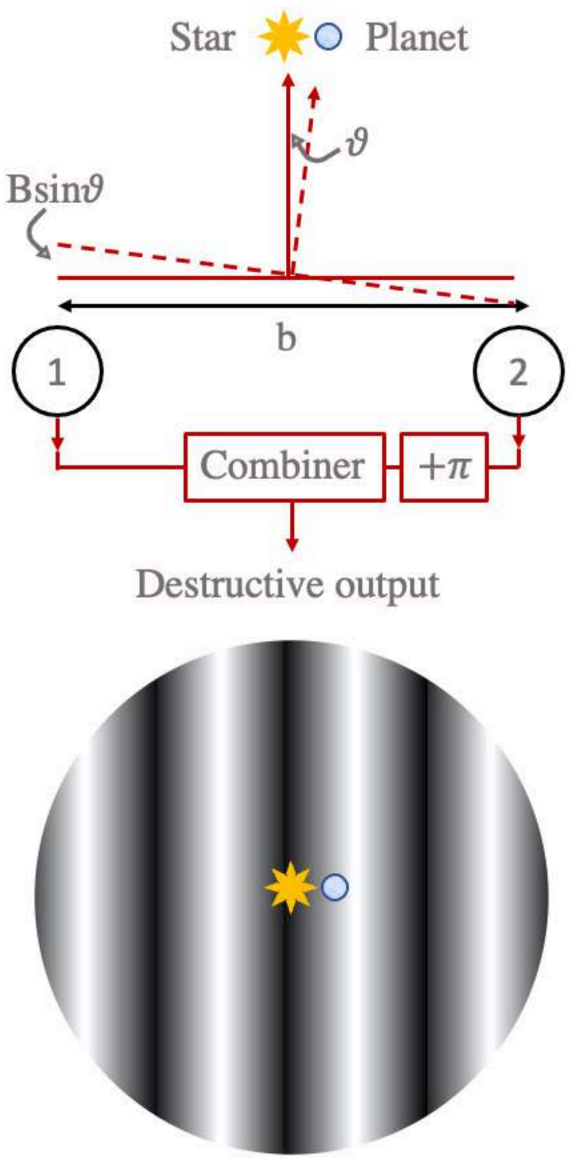
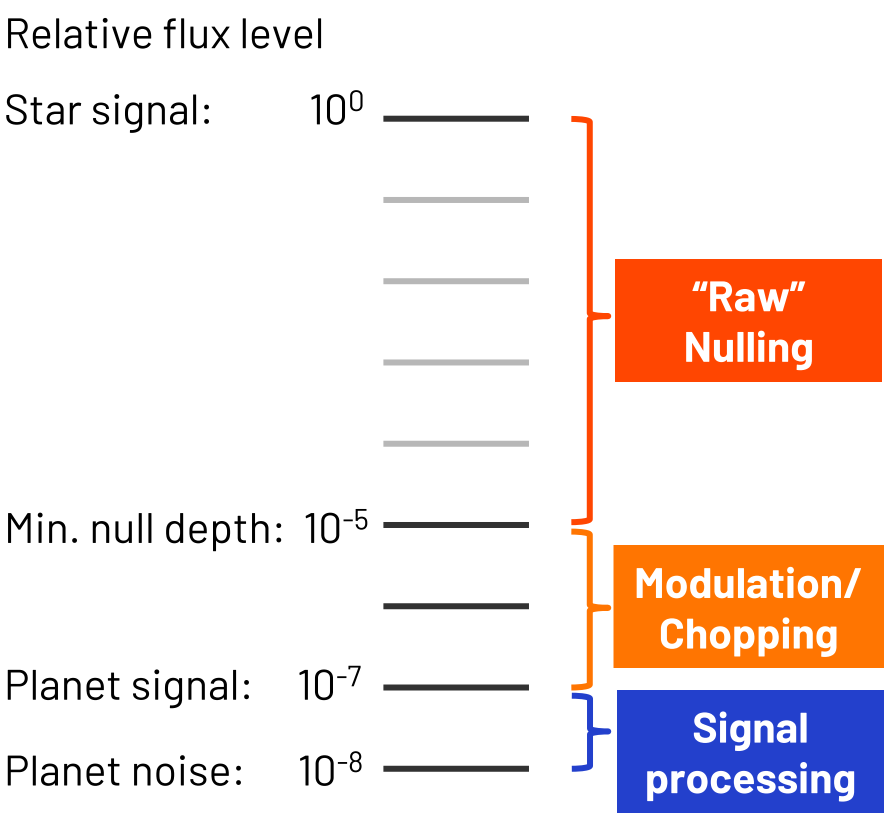


Nulling requirement



Heritage

Space-based (MIR, nulling) interferometry is not a new idea, but

- We know exoplanet statistics much better with hundreds of terrestrial planets waiting to be discovered
- Progress was made in several key technologies

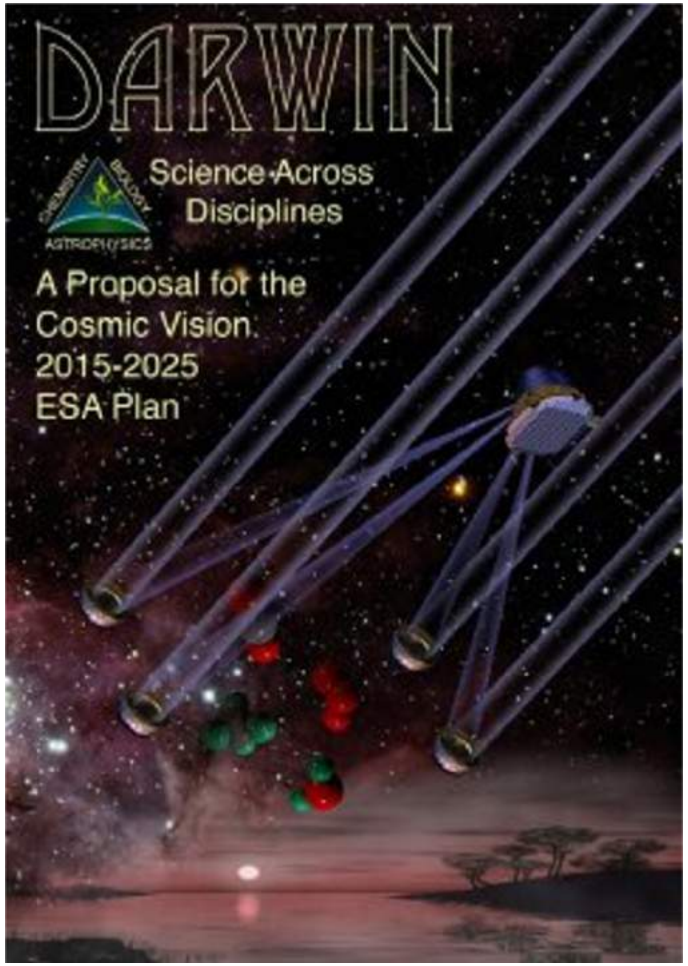
letters to nature

Detecting nonsolar planets by spinning infrared interferometer

R. N. Bracewell

Nature Vol. 274 24 August 1978

NASA TPF-I study



ESA Darwin Study

Overview

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- **Exemplary science cases for LIFE**
- Relevant technologies for LIFE

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]

Astronomy & Astrophysics manuscript no. main ©ESO 2022
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

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-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 ***

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

Under review

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

Under review

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

Under review

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

Under review

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

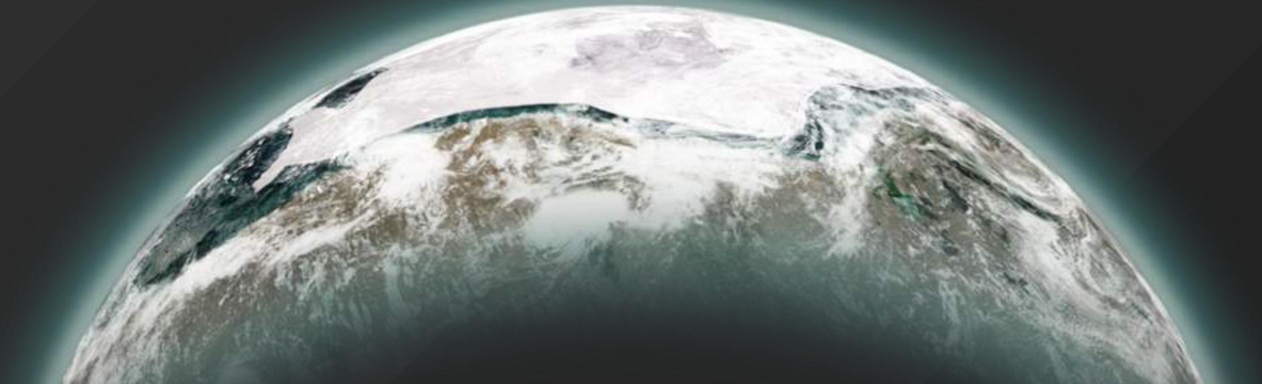
Close to submission

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



LIFE paper I

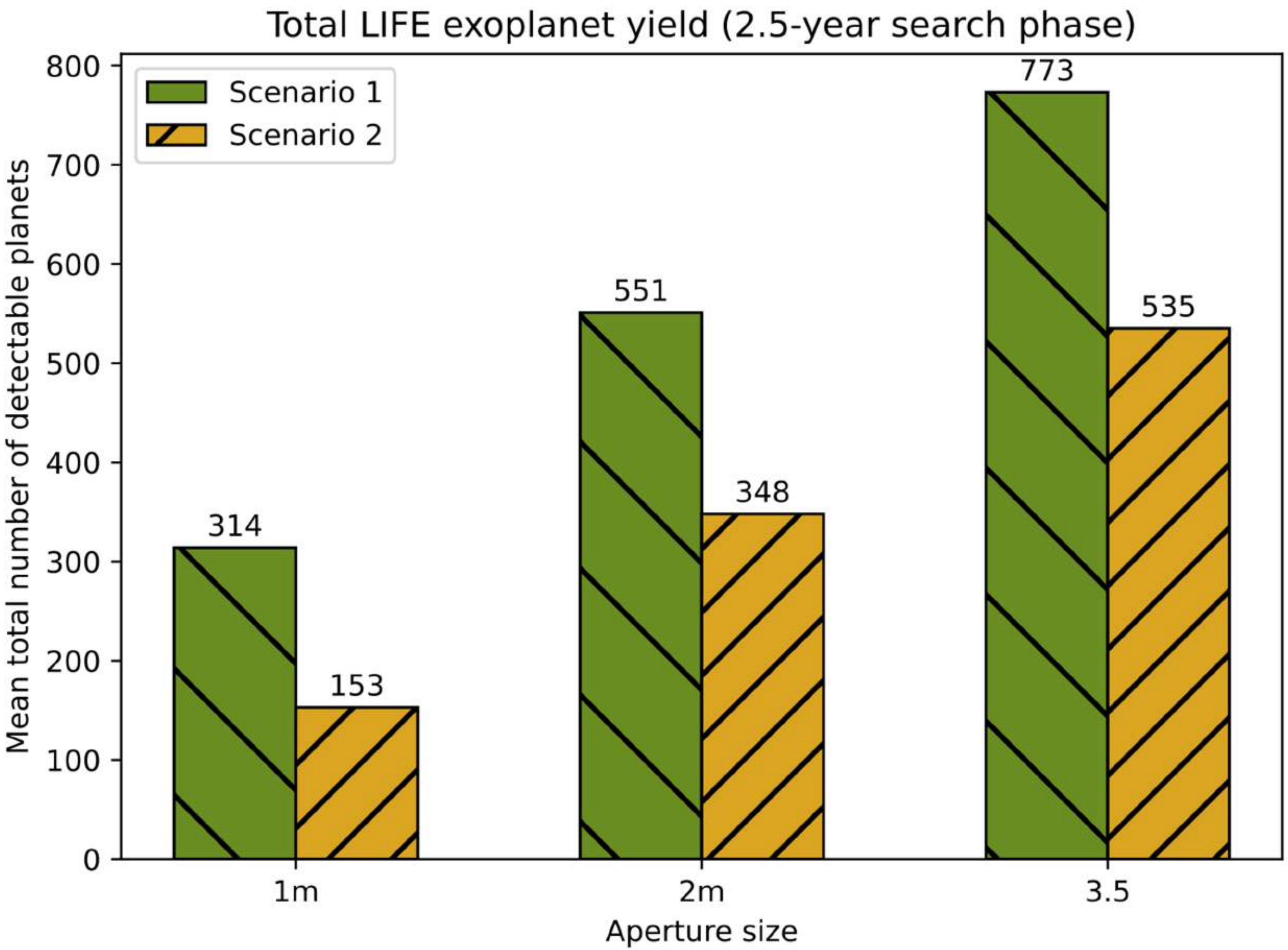
Large Interferometer For Exoplanets (LIFE):
I. Improved exoplanet detection yield estimates for a large mid-infrared space-interferometer mission

Quanz et al., A&A, accepted

Exoplanet Detection Yield

- Monte Carlo simulations based on Kepler statistics (SAG13) and stars within ~20 pc

- Assuming
  - 4 x 2m apertures
  - 2.5 years total search phase
  - 5% total instrument throughput
  - 10 h slew between targets
  - 20% general overhead



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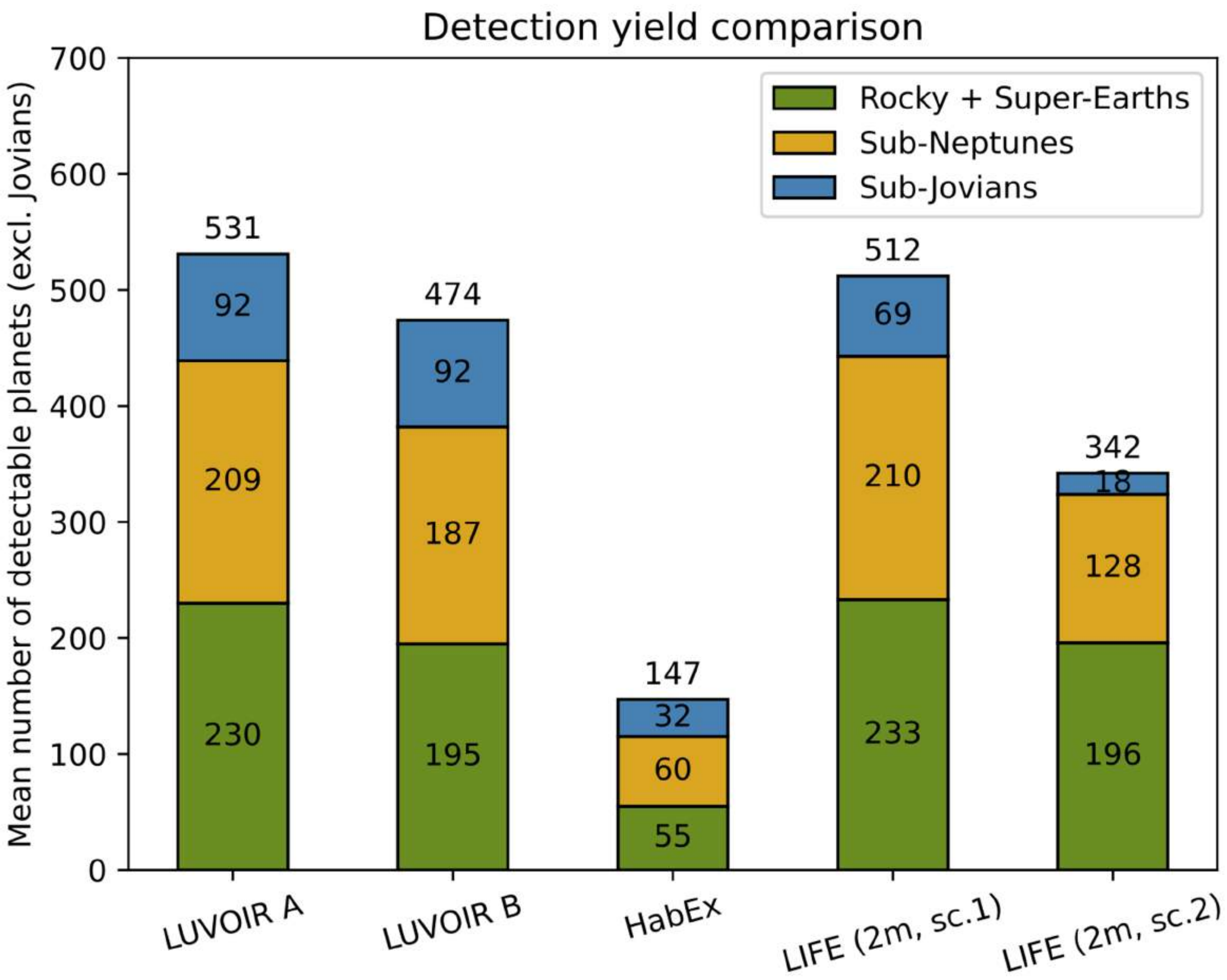

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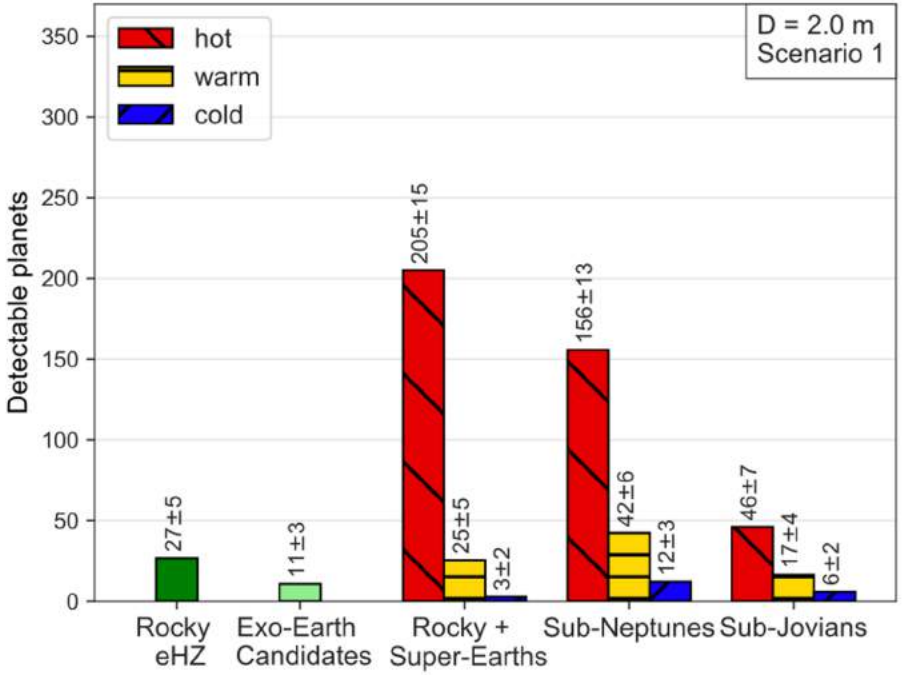
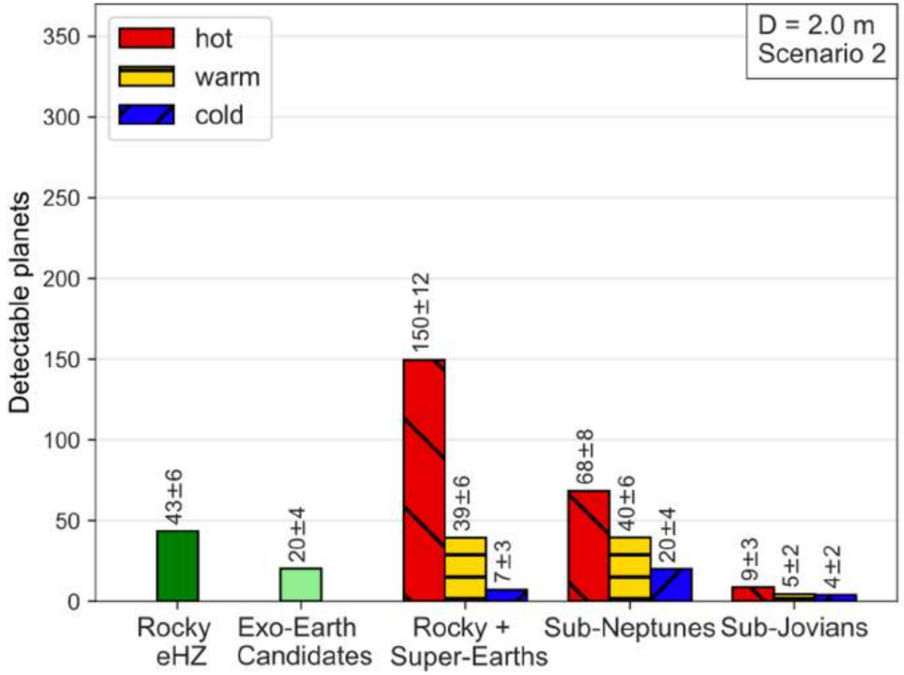
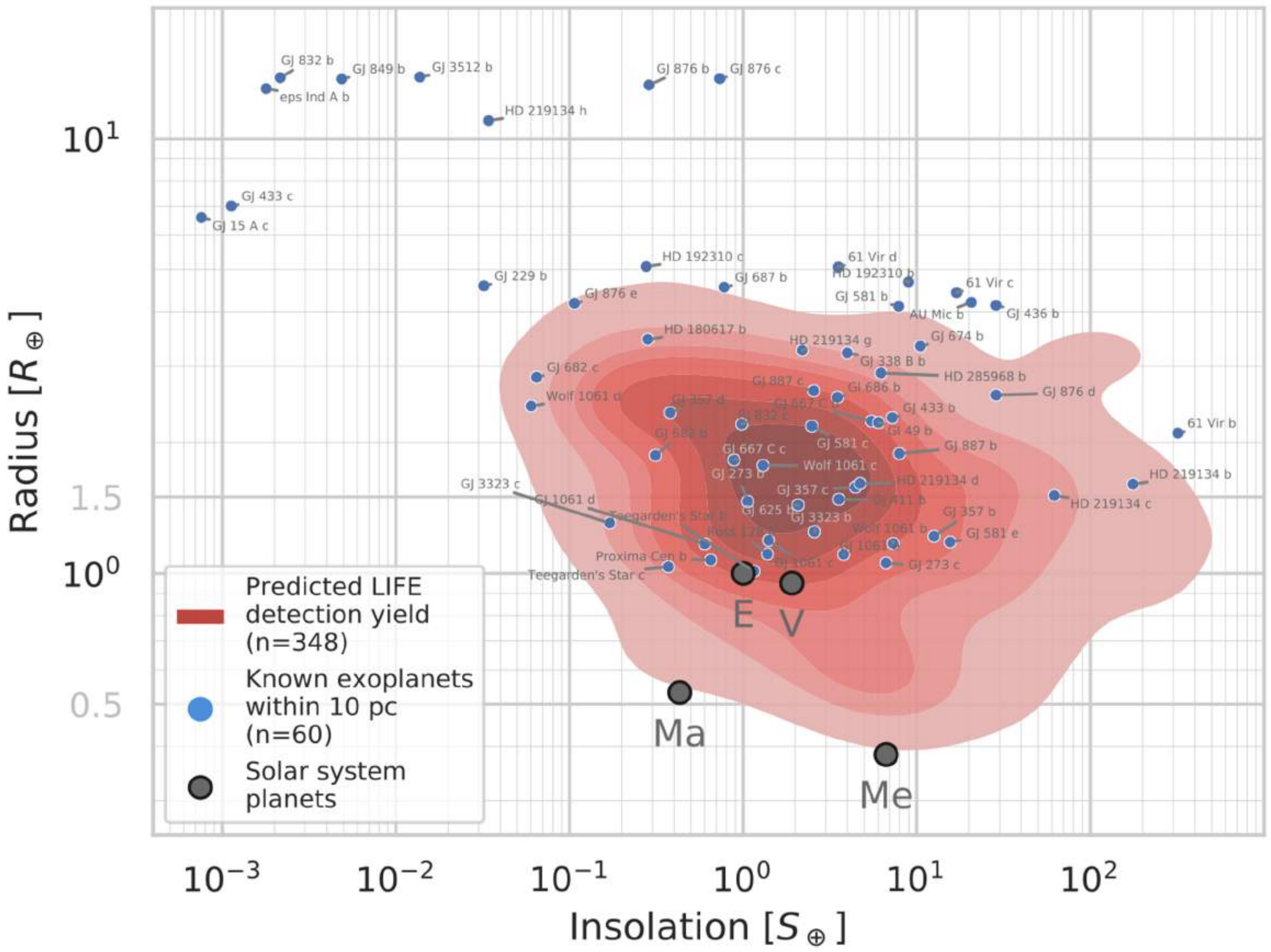


Maximizing total number of detected exoplanets



Maximizing number of rocky, HZ exoplanets

Discovery space vs. known nearby exoplanets



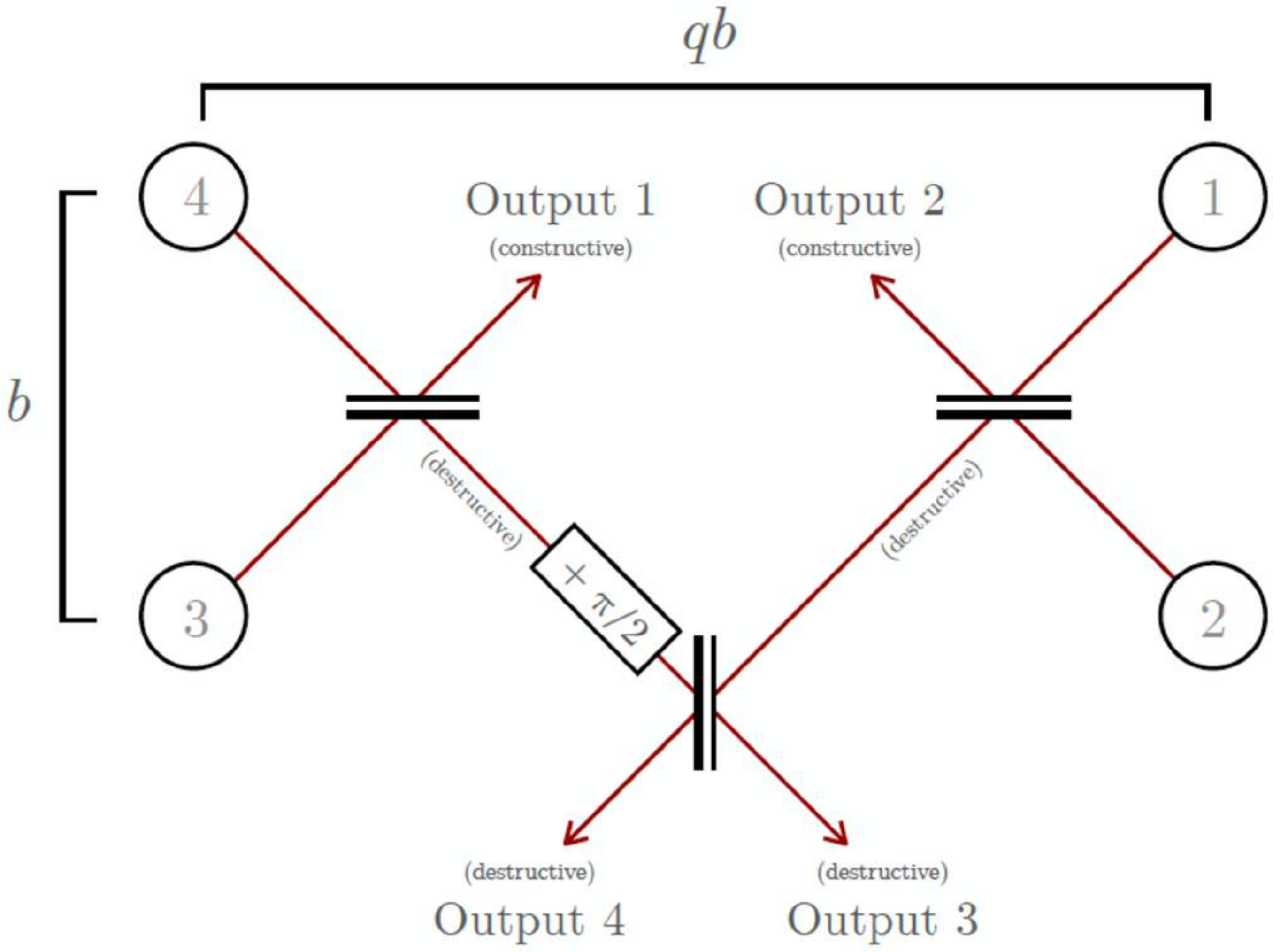
LIFE paper II

Large Interferometer For Exoplanets (LIFE):
II. Signal simulation, signal extraction and fundamental exoplanet parameters from single epoch observations

Dannert et al. 2022, A&A, accepted

Signal Simulation

- Double Bracewell nulling interferometer
- In one branch, a pi/2 phase shift is introduced to enable the difference map
- Phase chopping between Outputs 3 & 4 makes instrument less susceptible to perturbation
- Planet and astrophysical noise sources propagated through difference map
- Noise sources:
  - Stellar geometric leakage
  - Exo-zodiacal thermal emission
  - Local-zodiacal thermal emission



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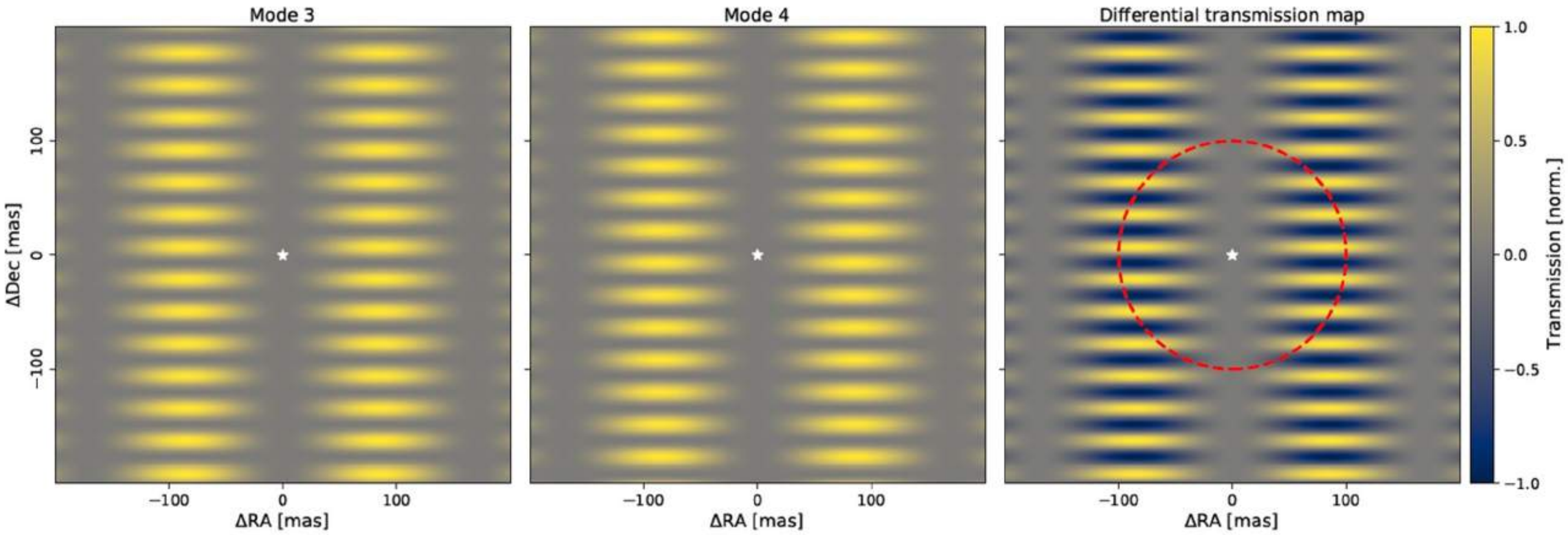


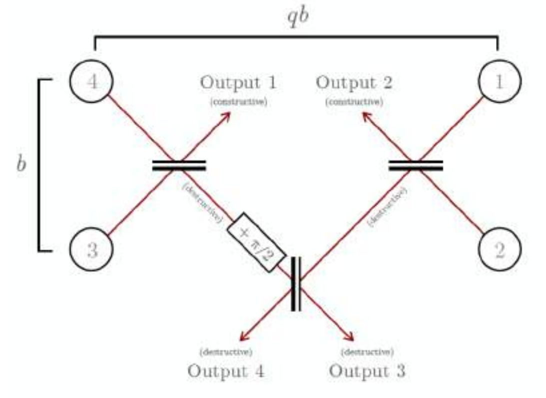
Difference map is antisymmetric wrt central point and filters out point-symmetric emission, but offset planet signal remains

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

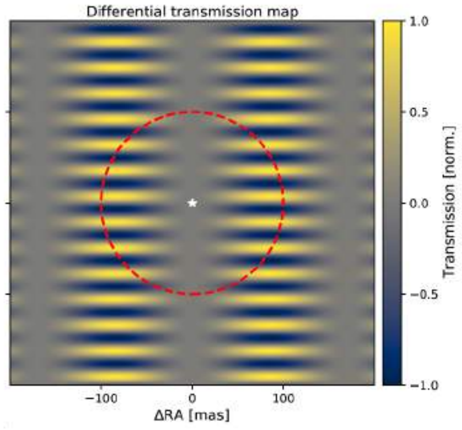
From Source to Detection

Summary Slide

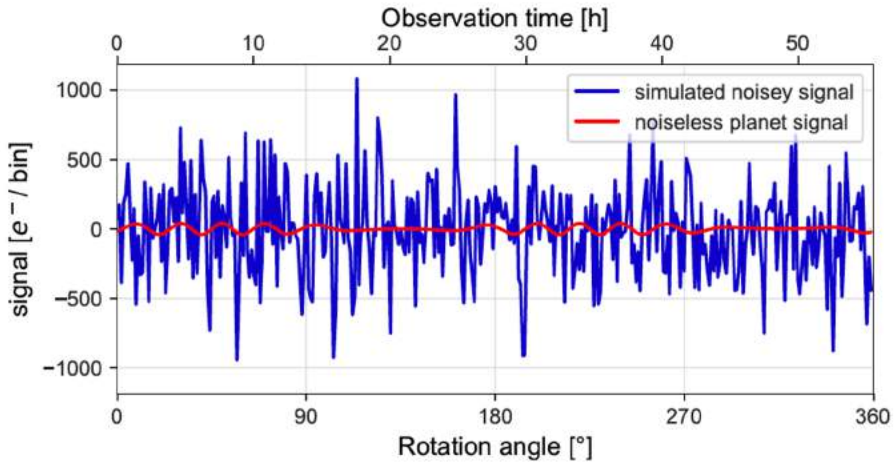
Instrument Model



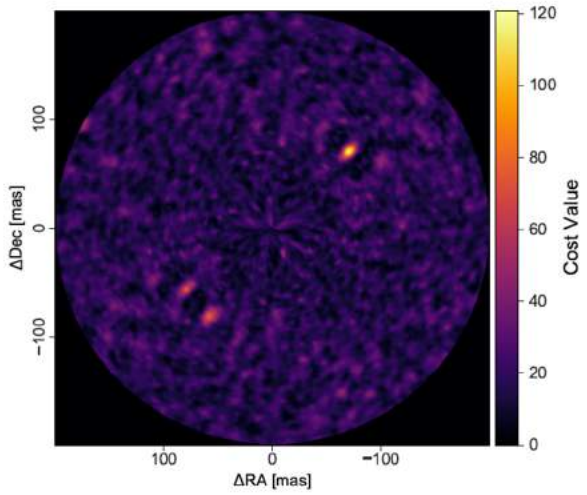
Transmission Map



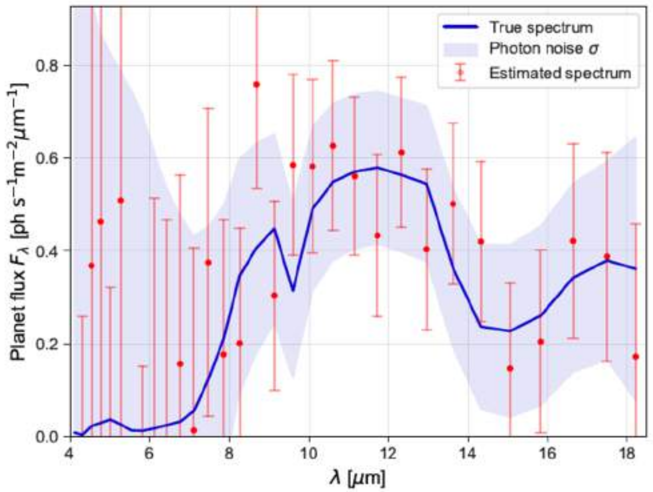
Noisy Time Series



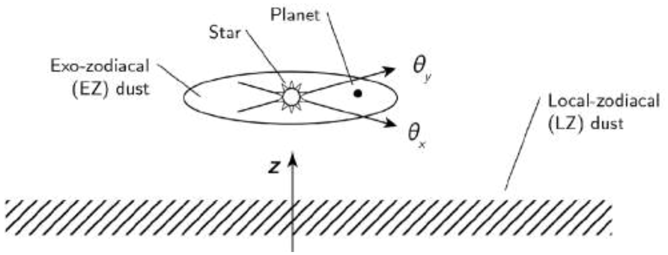
Detection Map



Spectrum



Source Simulation



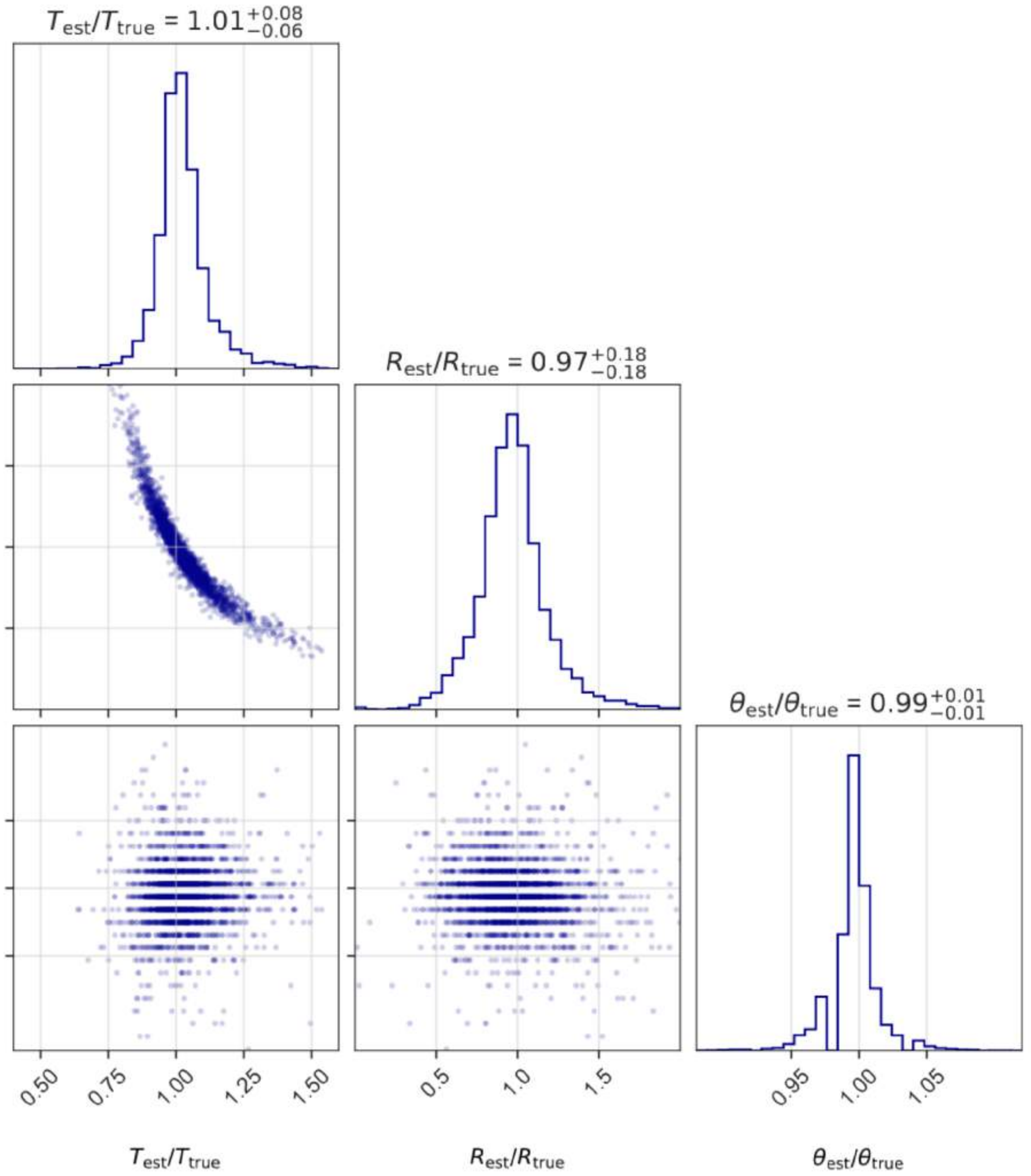
Lay 2004

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

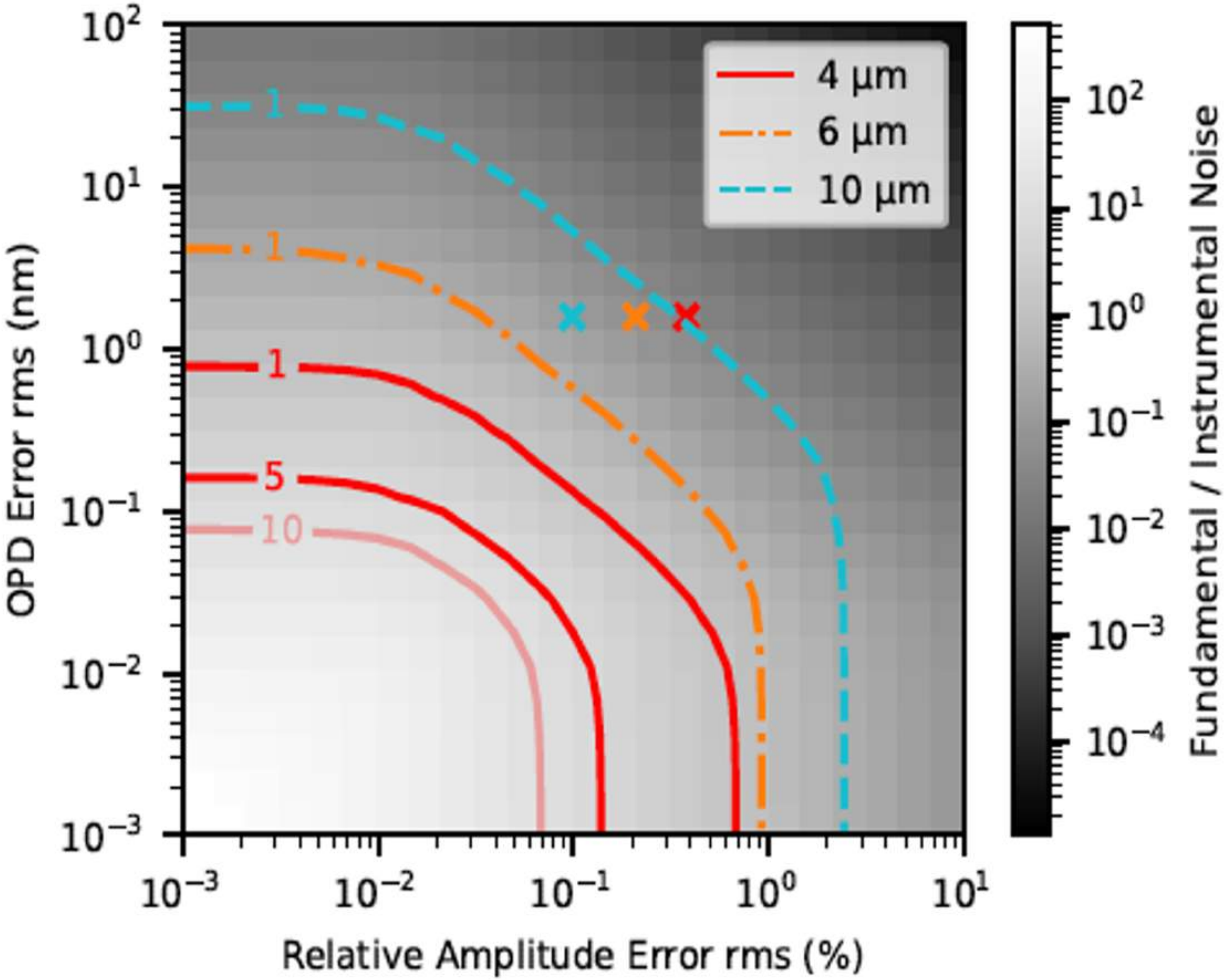
- Average error on
  - Temperature: ~10%
  - Radius: ~20%
  - Separation: ~1-2%



Instrumental Noise

How to stay fundamental noise dominated

- Simulate perturbations to amplitude, phase, polarization and position
- Pink noise perturbation spectra
- Stability requirements for fundamental noise to dominate instrumental noise



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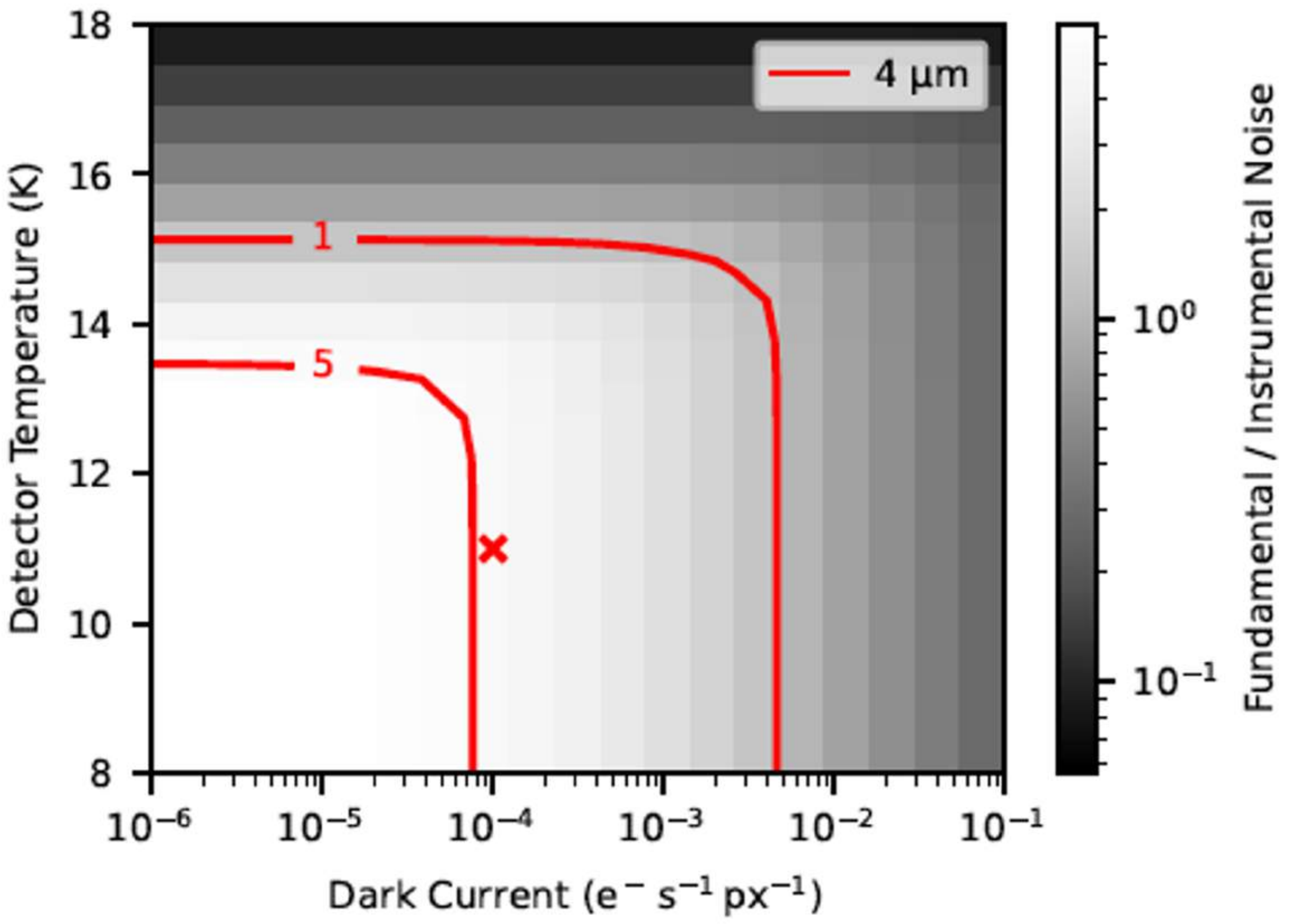


LIFE paper III

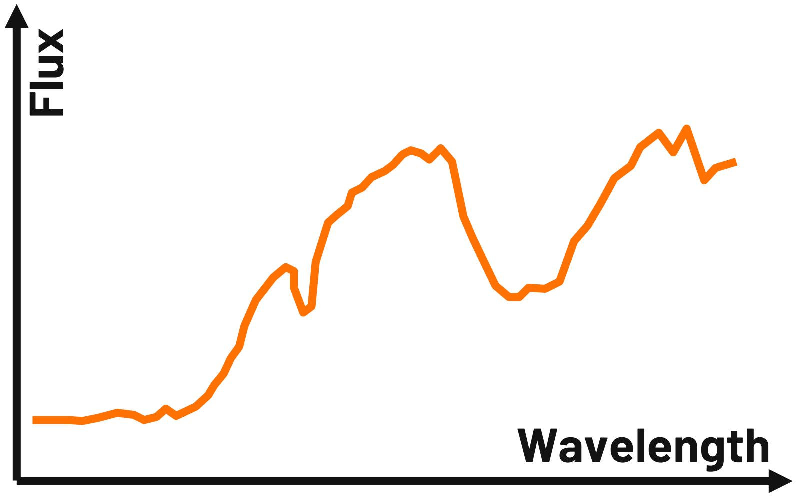
Large Interferometer For Exoplanets (LIFE):
III. Spectral resolution, wavelength range and sensitivity requirements based on atmospheric retrieval analyses of an exo-Earth

Konrad et al. 2022, A&A, accepted

From spectra to planet properties: Earth-twin retrieval grid

Konrad+ (2021)

Input Spectrum



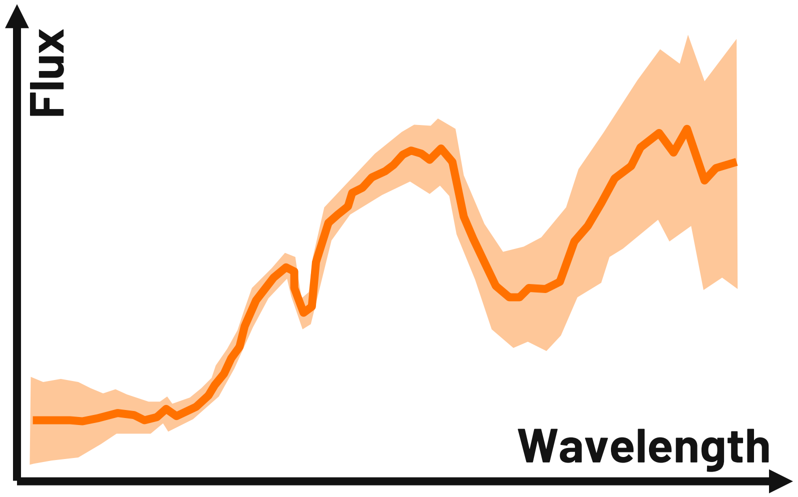
petitRADTRANS (Mollière+ 2019):

- Earth around G2V Star at 10 pc
- Atmosphere containing N_2, O_2, CO_2, H_2O, O_3, CH_4, CO, and N_2O

Grid:

- R: 20, 35, 50, 100
- Range: 3-20, 4-18.5, 6-17 micron

LIFESIM Noise



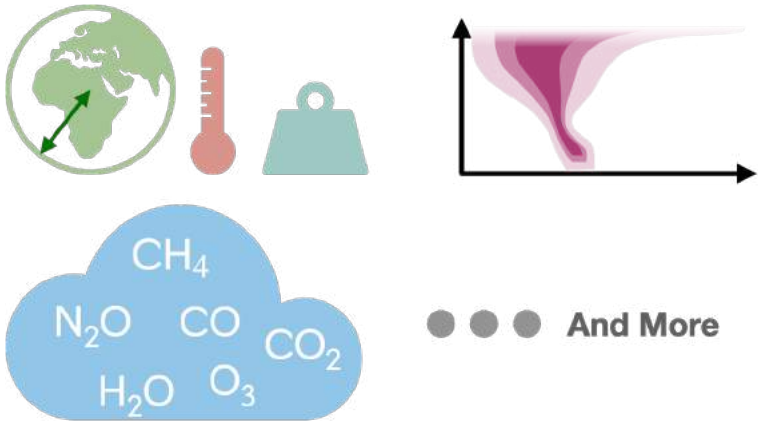
LIFEsim (Dannert et al. 2022)

- Photon noise
- Stellar leakage
- Local & Exo-zodiacal dust emission

Grid:

- R: 20, 35, 50, 100
- Range: 3-20, 4-18.5, 6-17 micron
- S/N: 5, 10 15, and 20 at 10 micron

Retrieval Framework

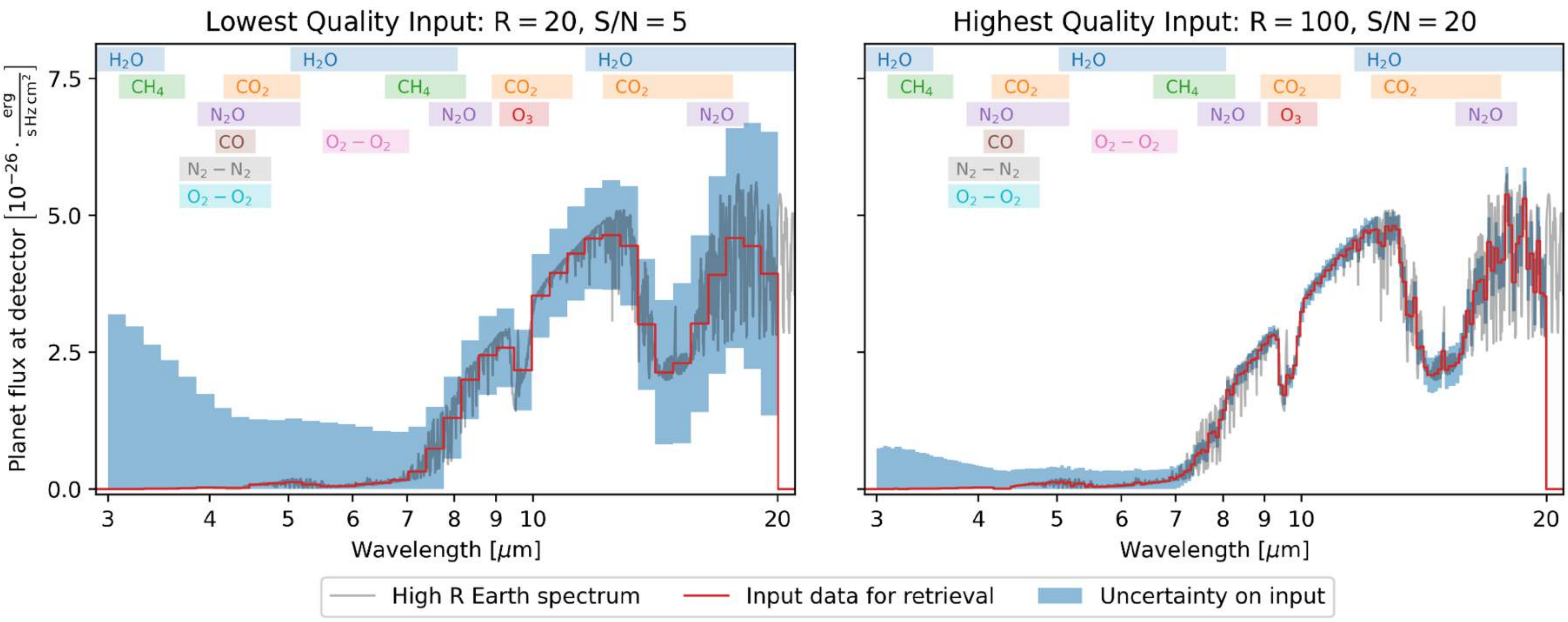


Relies on routines:

- 1D radiative tansfer model – petitRADTRANS (Mollière+ 2019)
- Bayesian param. estimation – MultiNest (Feroz+ 2009)

From spectra to planet properties: Earth-twin retrieval grid

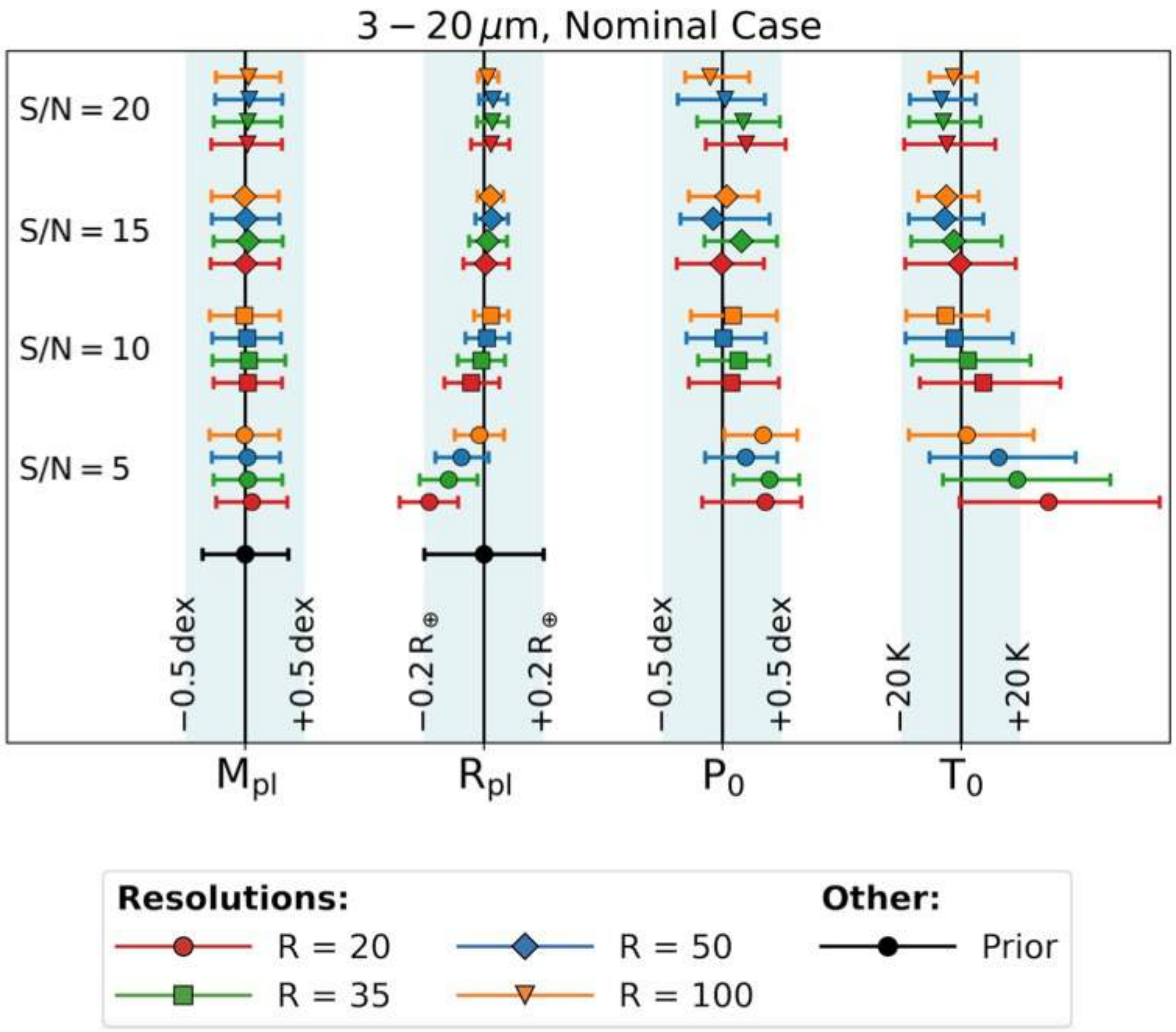
Konrad+ (2021)



Earth-twin retrieval results

Planetary parameters

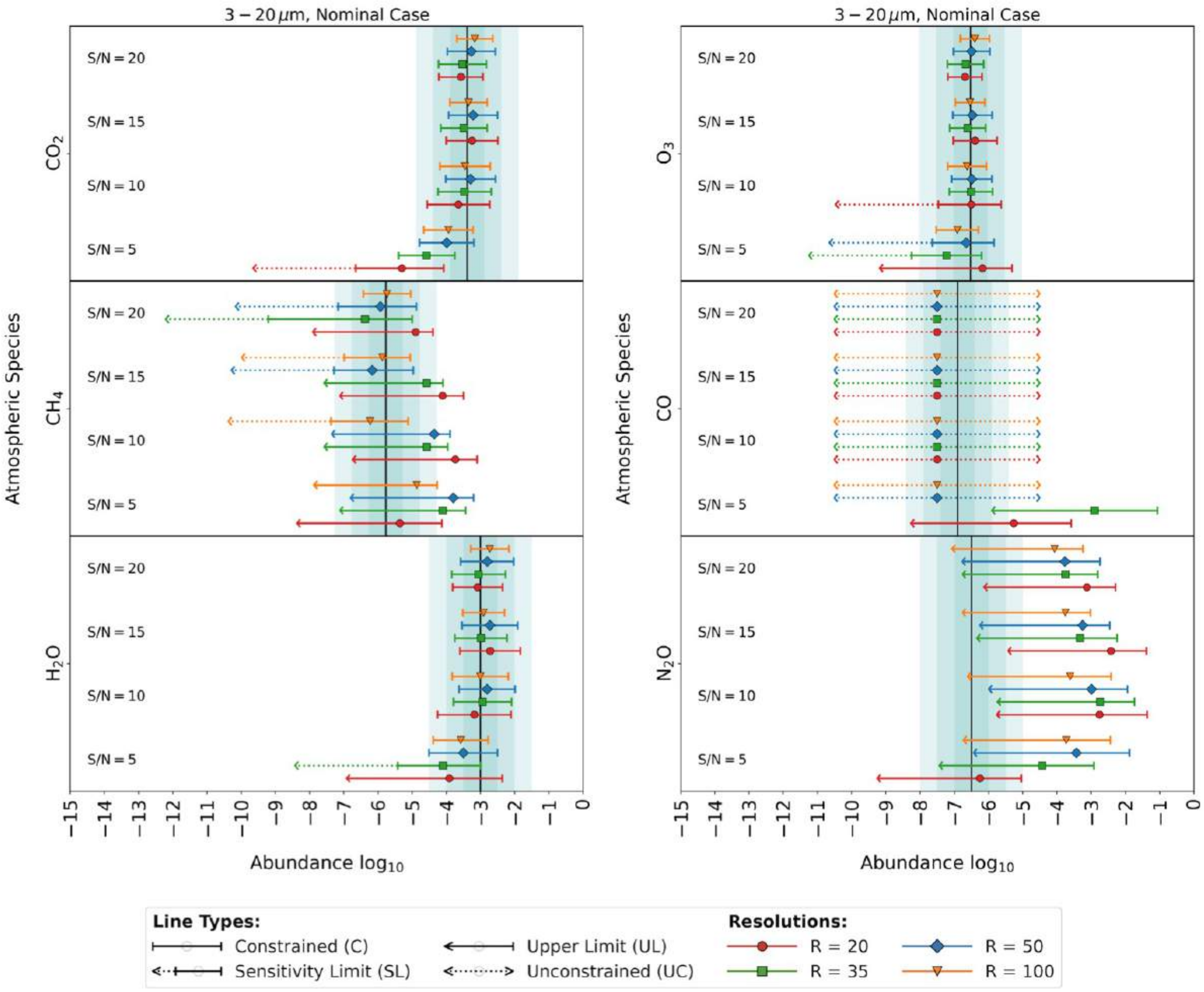
Konrad et al. (2022); A&A accepted



Earth-twin retrieval results

Atmospheric composition

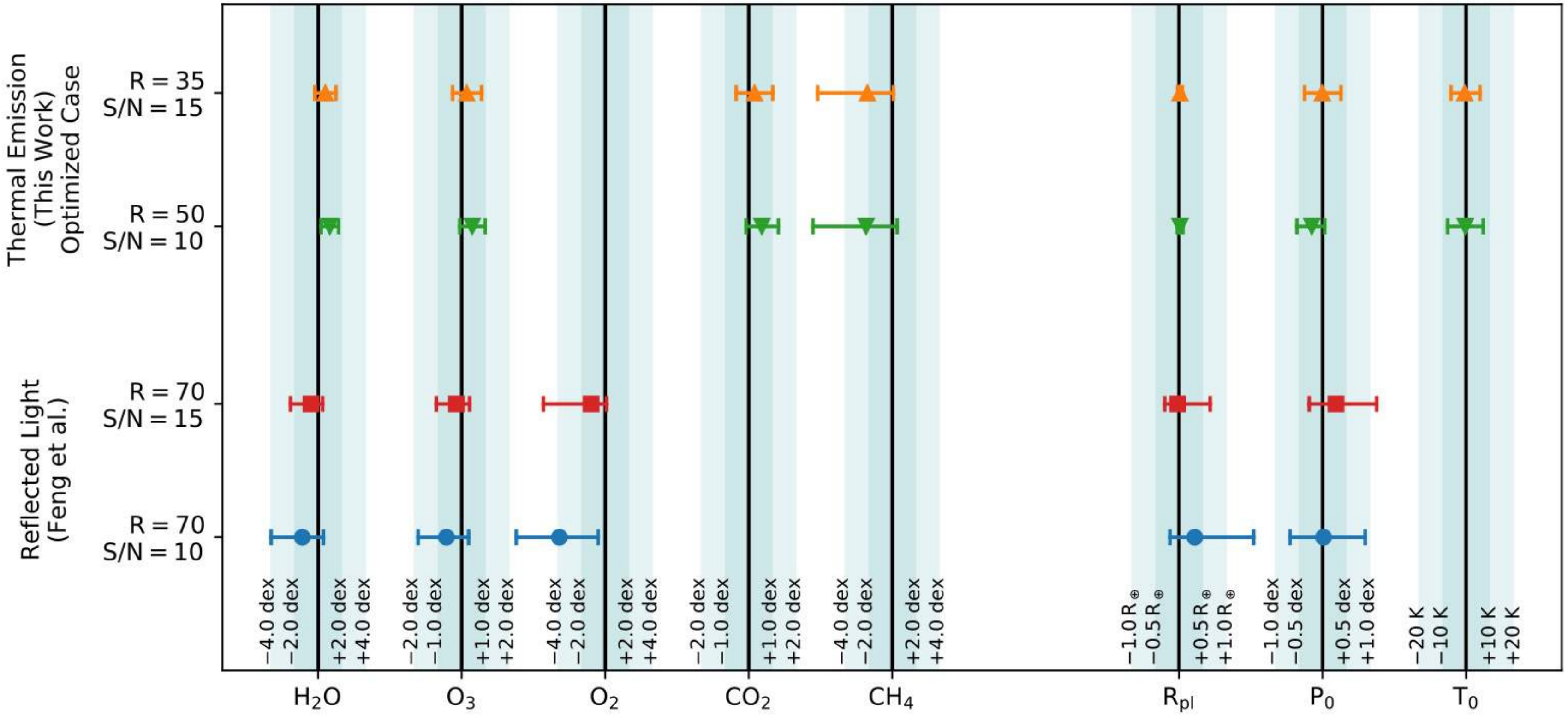
Konrad et al. (2022); A&A accepted



Earth-twin retrieval results

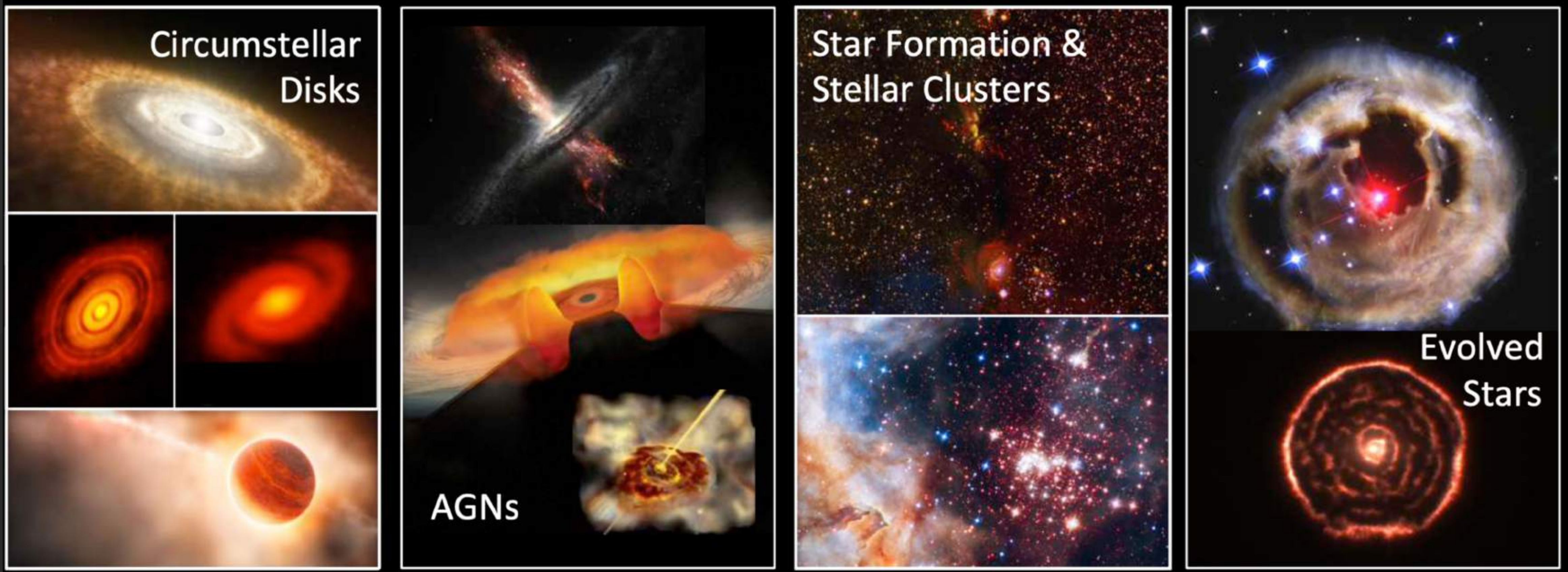
Comparison w/ reflected light

Konrad et al. (2022); A&A accepted



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

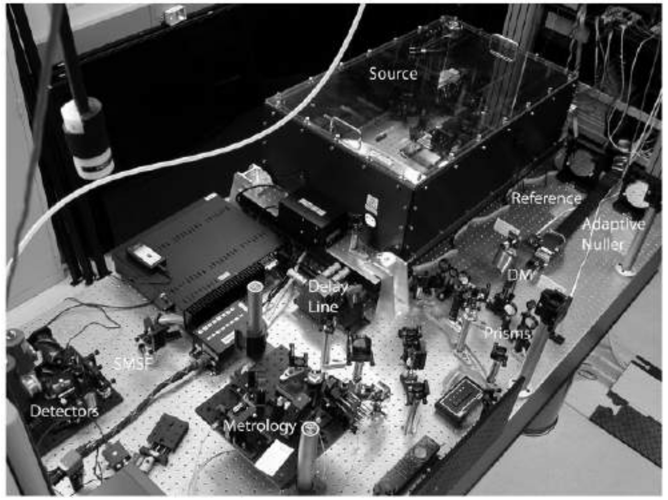
Overview

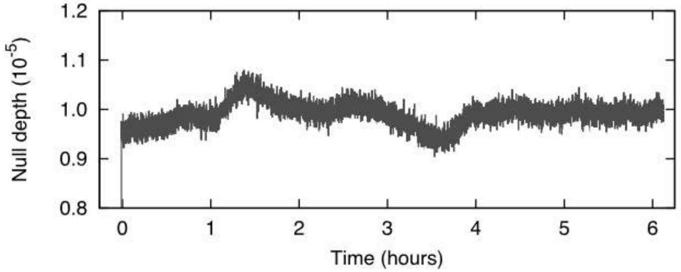
- Towards the direct detection of terrestrial exoplanets
- The LIFE mission – a short introduction
- Exemplary science cases for LIFE
- **Relevant technologies for LIFE**

Previous nulling test benches did not focus on sensitivity

Examples from earlier NASA-funded efforts in the context of the TPF-I mission concept

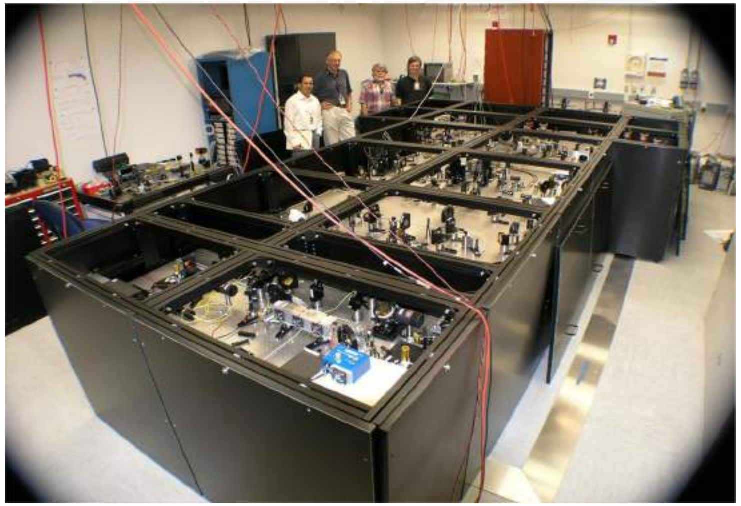
Adaptive Nuller Testbed
at JPL (~2008)





Demonstrated starlight suppression of 10^{-5}
(10 μm with 34% bandwidth)

The Planet Detection Testbed
at JPL (~2008)



Demonstrated final starlight suppression of 10^{-8} after post-processing
(10 μm; mono-chromatic)

All earlier test benches focused on starlight suppression **but ignored sensitivity requirements**

They **did not demonstrate the feasibility** of the final space-based measurement

Peters et al. (2008, 2010); Martin et al. (2012)

NICE: Nulling Interferometry Cryogenic Experiment

Objectives and top-level requirements

Objective

Develop and integrate cryogenic laboratory hardware to demonstrate

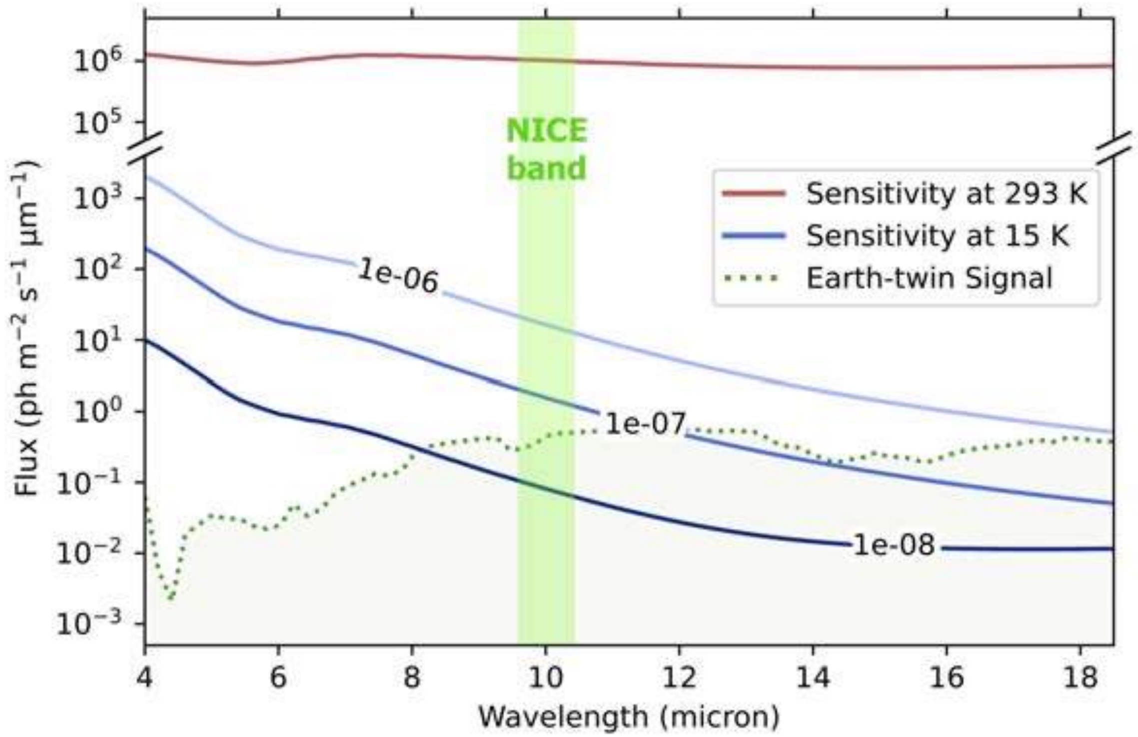
with realistic flux levels

that a 2-beam MIR nulling interferometer at 10 µm wavelength and with ~10% spectral bandwidth can

achieve a sensitivity that would imply the detectability of Earth-like planets

around Sun-like stars at 10 pc distance

Requirements for NICE



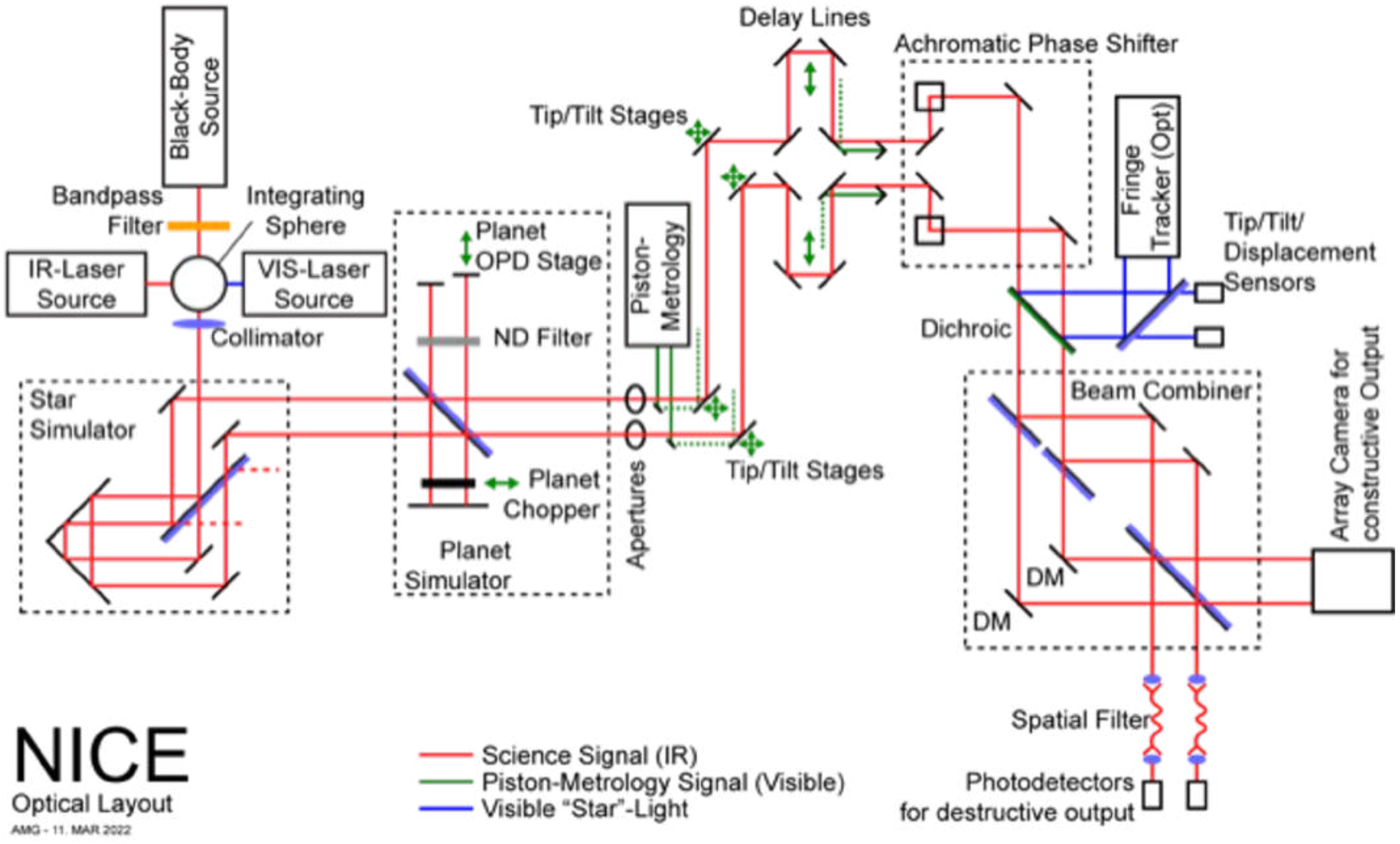
- Detection of very low photon fluxes
- Sub-nanometer wavefront and optical path control

-> Highly optimized cryogenic system needed

NICE: Nulling Interferometry Cryogenic Experiment

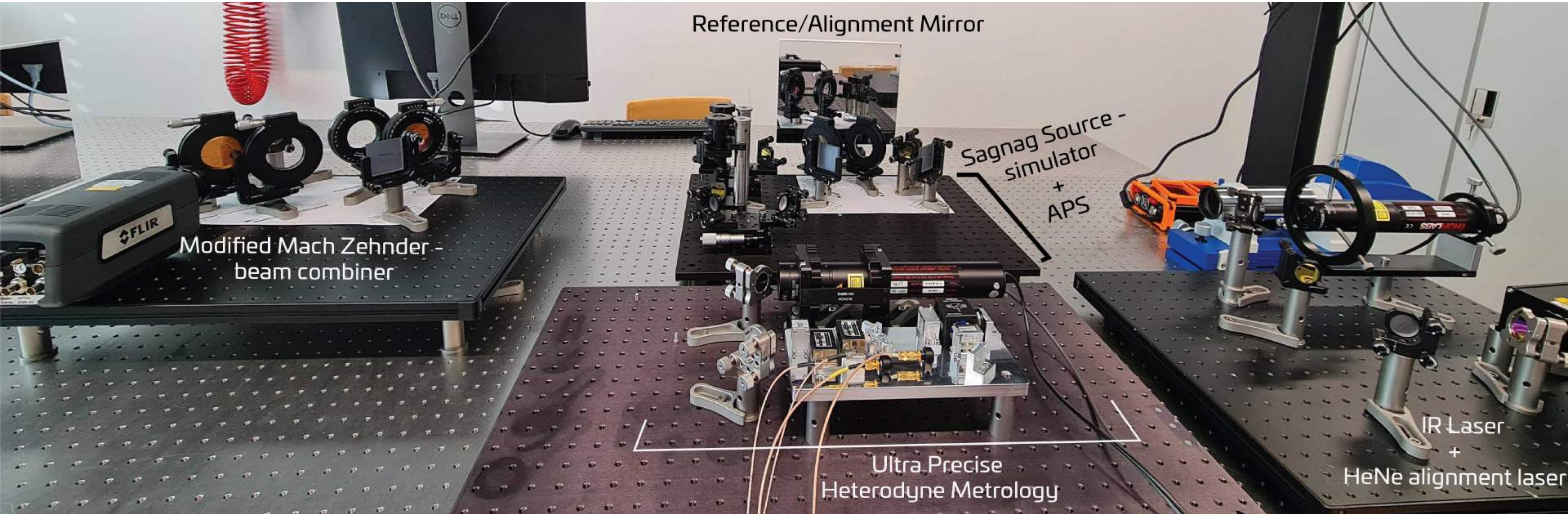
First concept for the NICE cryostat

Updated optical layout for NICE (March 2022)



Ongoing preparatory work

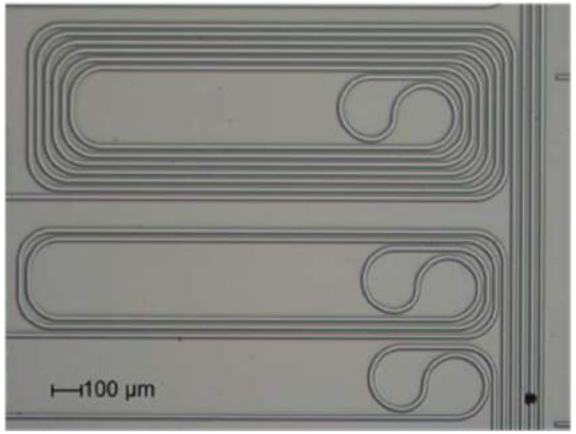
Status of warm precursor as of April 2022

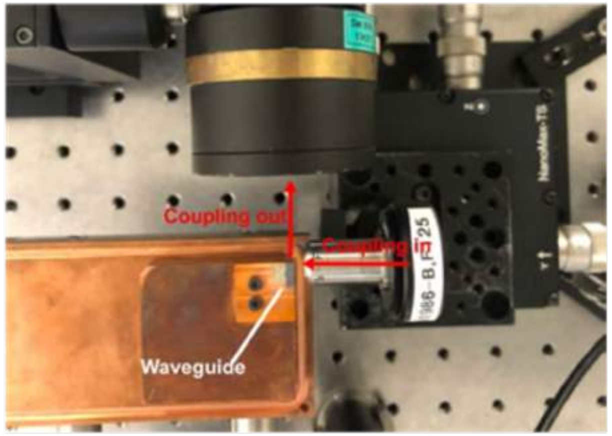


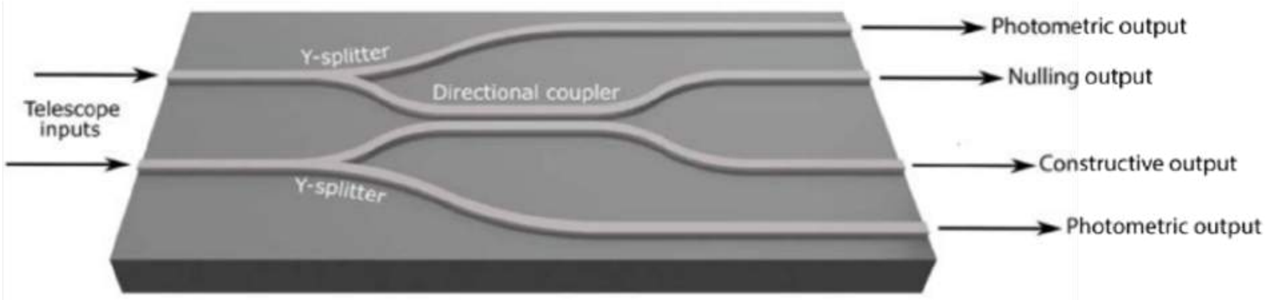
- Integration of 2-beam warm precursor experiment (at 4 µm) is ongoing
- Final alignment of all sub-components and incl. active beam and wavefront control is main current task
- New measurements of null-depth and system stability planned for later this summer

NICE component development

MIR waveguides / integrated optics

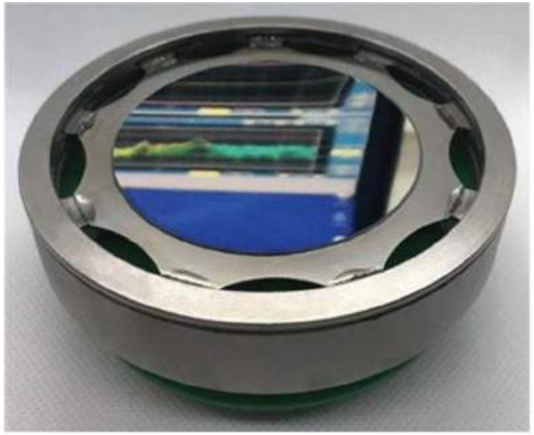






ETH, Institute for Quantum Electronics (Prof. J. Faist)

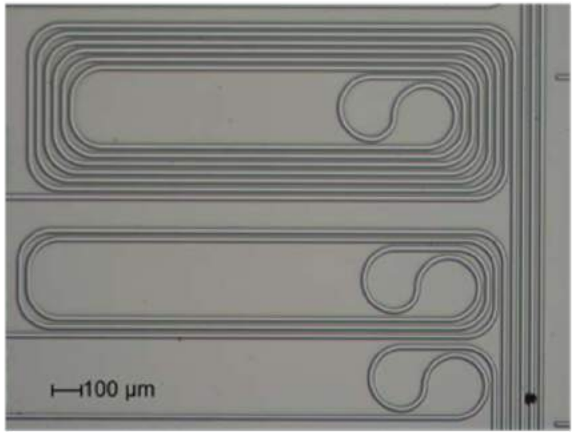
Cryogenic DMs

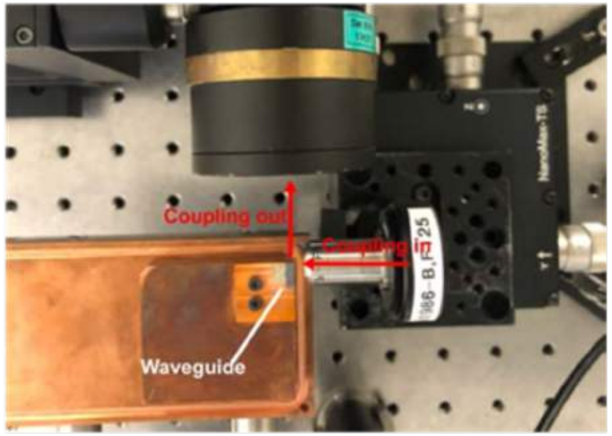


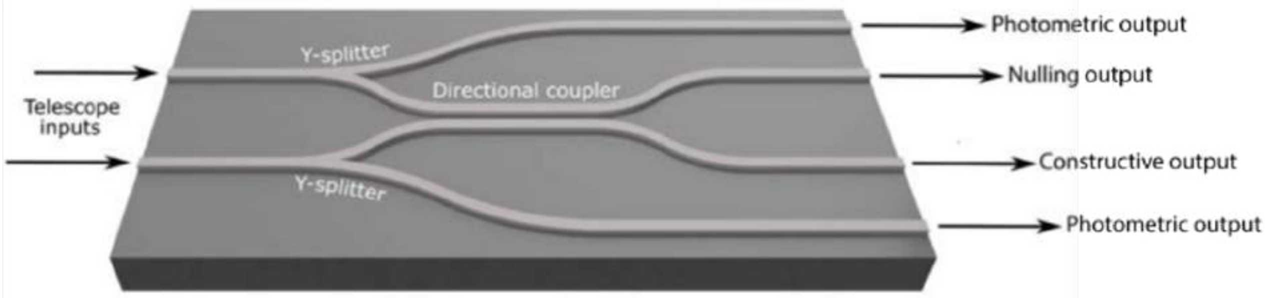
FH Muenster, Germany (Prof. U. Wittrock)

NICE component development

MIR waveguides / integrated optics

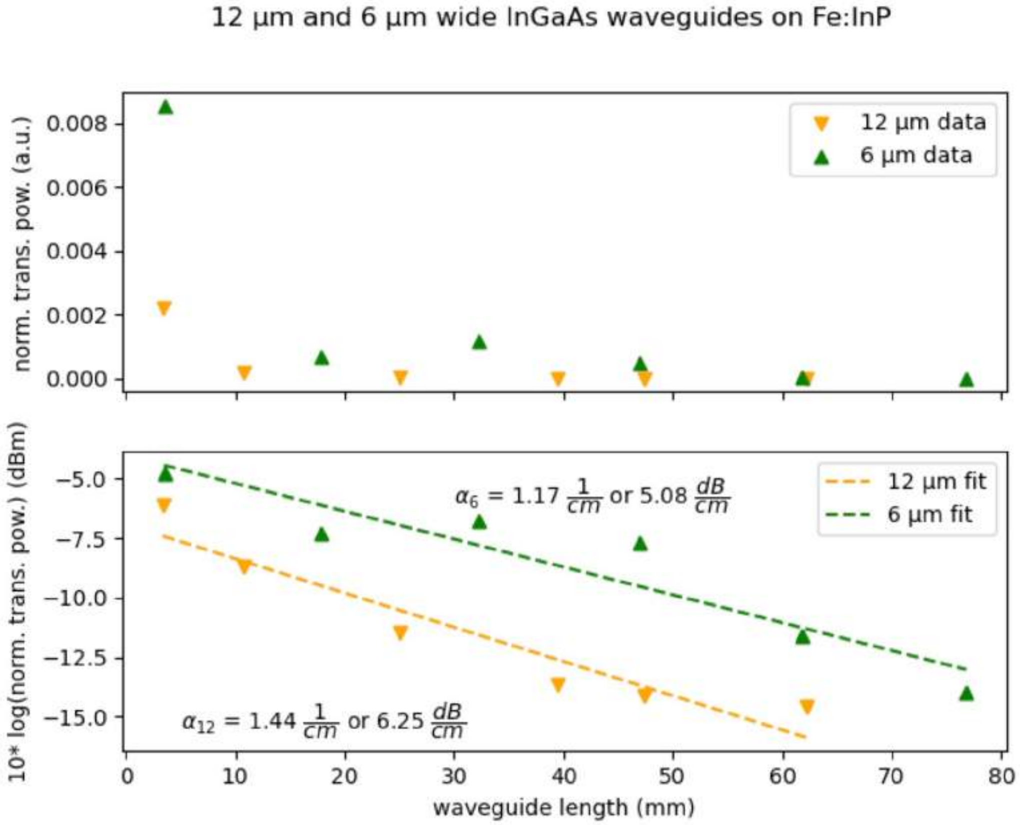






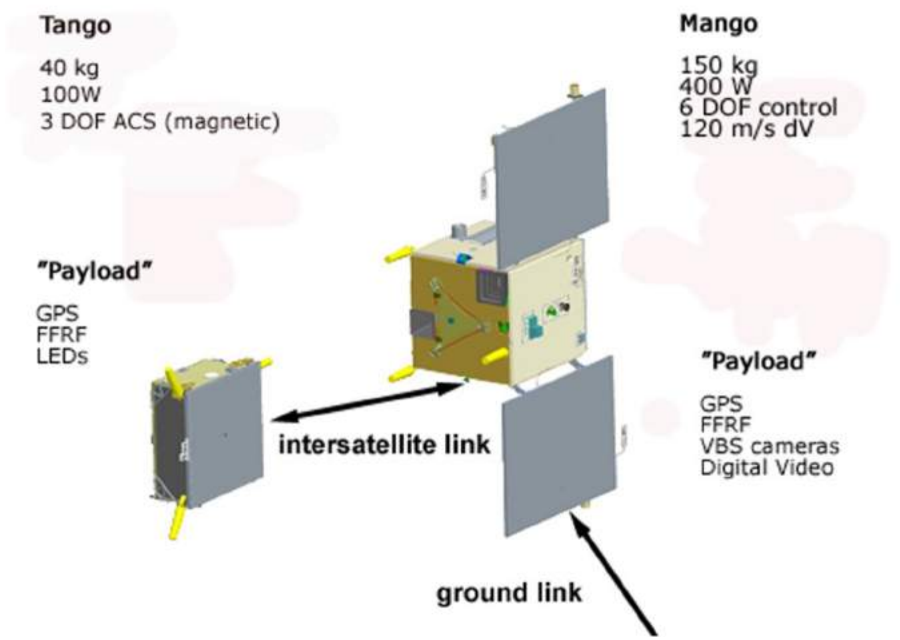
ETH, Institute for Quantum Electronics (Prof. J. Faist)

First loss measurements (March 2022)



Autonomous Formation Flying (1/2)

PRISMA Mission (2010)



Small satellite mission under leadership of Sweden

- Test formation flying using GPS, RF, and optical sensors
- Test several types of (micro-)thrusters
- Position and velocity knowledge via GPS: 10 cm and 1mm/s, resp.

(D'Amico et al. 2012, JGCD 353, 834)

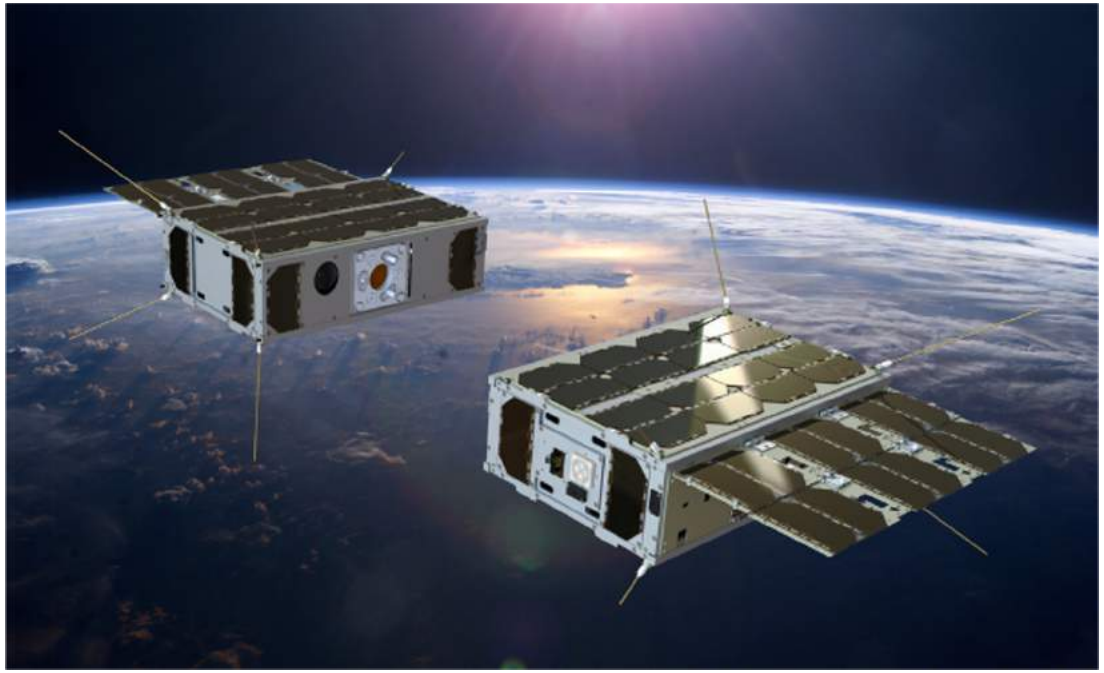
ESA's Proba-3 Mission (2023)

New benchmark for formation-flying control

- Test formation flying to mm and arcsec precision
- Operate and manoeuvre autonomously w/o ground control
- Cold-gas micro-thrusters for fine manoeuvering

Autonomous Formation Flying (2/2): cubesat missions

RACE (launch 2022 / 2023 tbc)



European consortium + ESA's General Support & Technology Programme

In-orbit testbed for advanced guidance, navigation and control software and autonomous system behaviour

NASA's Starling (launch 2022 tbc)

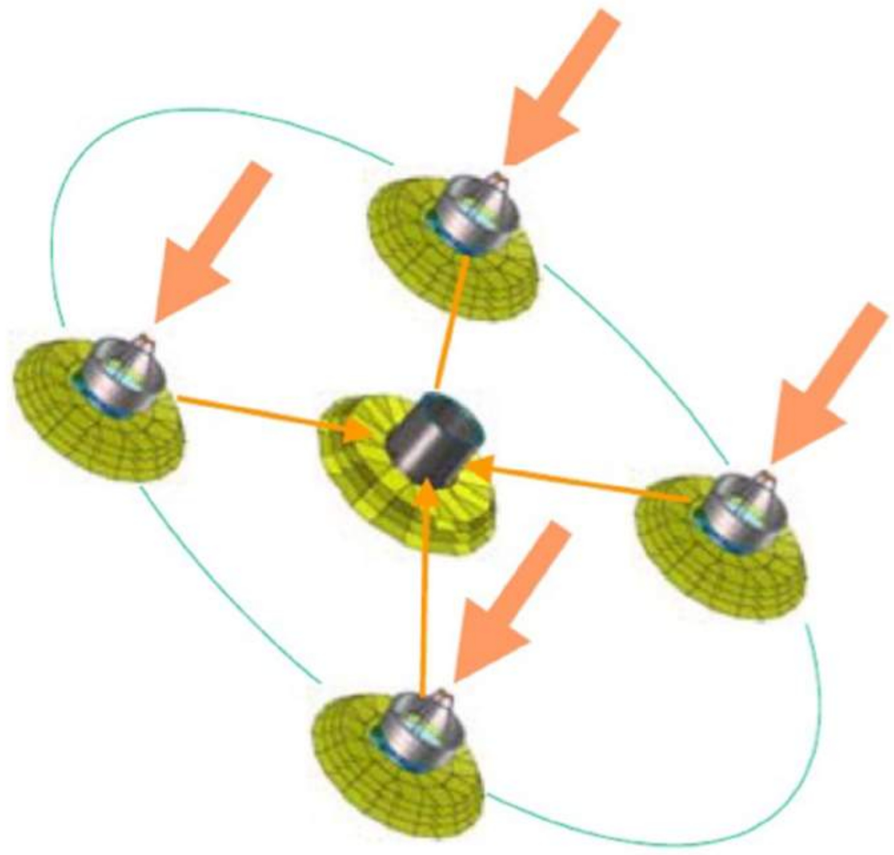
4 cubesats at wider separation establishing a local communication network

Testing swarm dynamics and different levels of autonomy

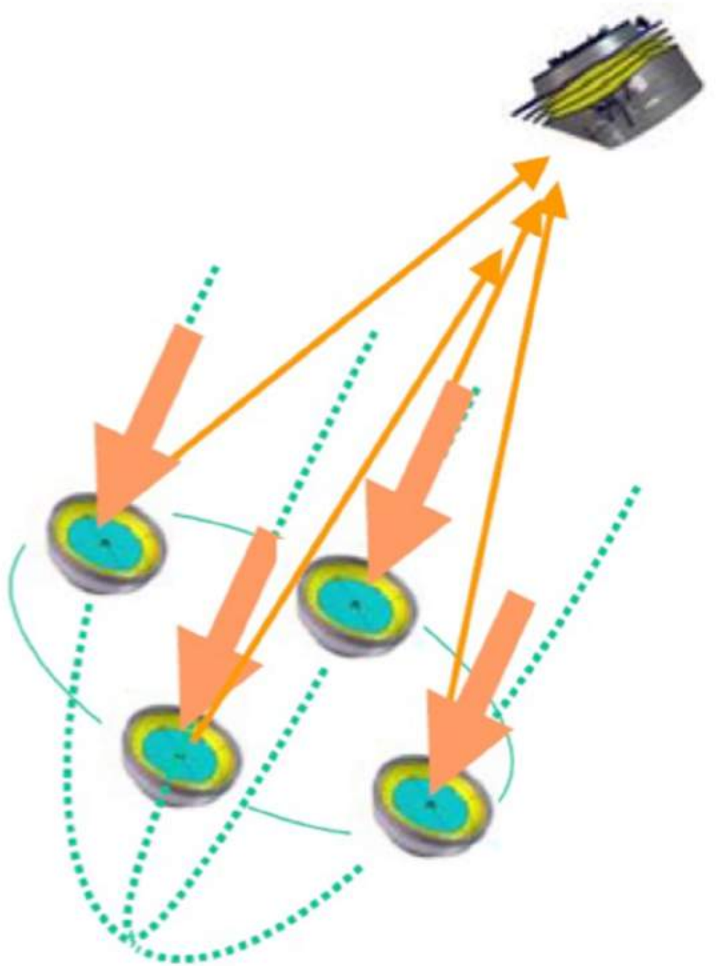
Array architecture - heritage from Darwin / TPF-I

New trade-off required

Co-planar "X-array" with relay optics in the collector spacecraft



Out-of-plane "Emma-X-array" with with siderostats



Take home message

LIFE take home message

- LIFE is a European-led initiative for a large future exoplanet mission

- A space-based MIR nulling interferometer like LIFE will allow us to
  - directly detect the thermal emission of hundreds of nearby planets
  - investigate their atmospheric diversity, probe for habitable conditions and investigate atmospheric bio-signatures in a significant sub-set

- The science theme LIFE 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, but a more systematic and broader approach with more partners actively contributing is needed (-> Study Phase)

- 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

Europe is in a strong position to lead a space-based MIR interferometer

Ground-based optical interferometry

Formation Flying

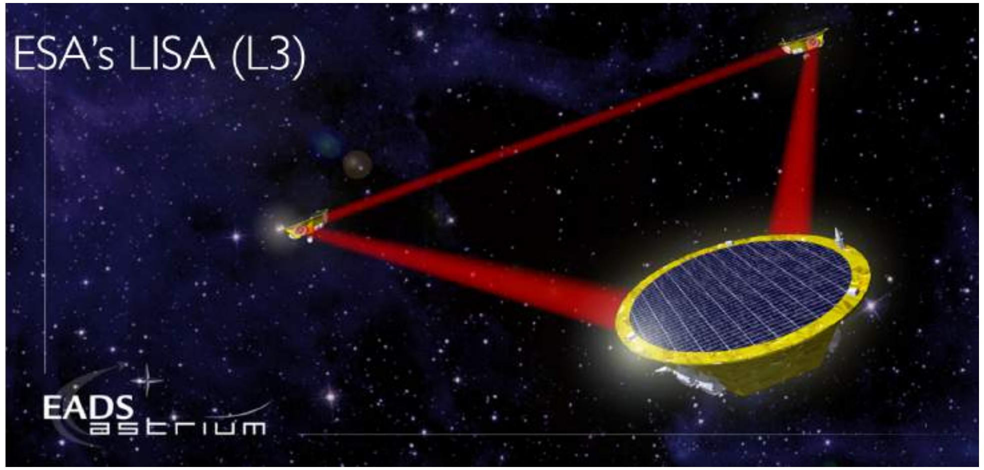
MIR space instrumentation

ARIEL

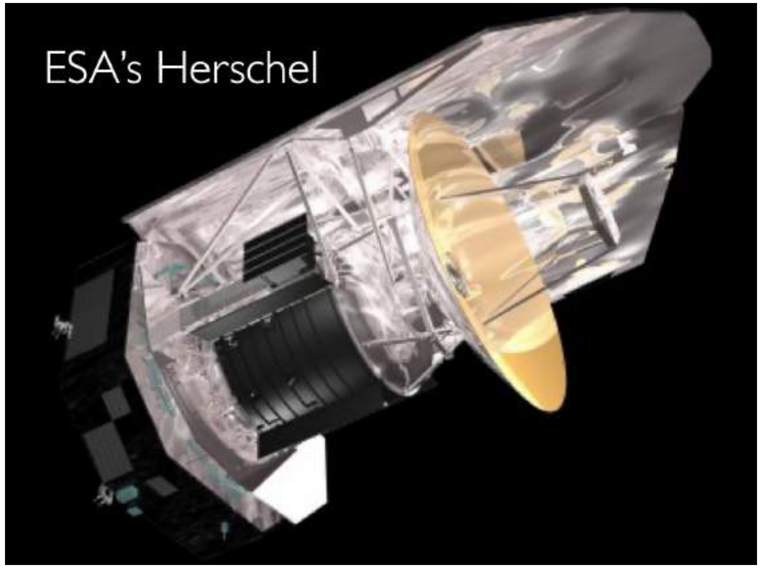
James Webb Space Telescope
JWST
NASA • ESA • CSA

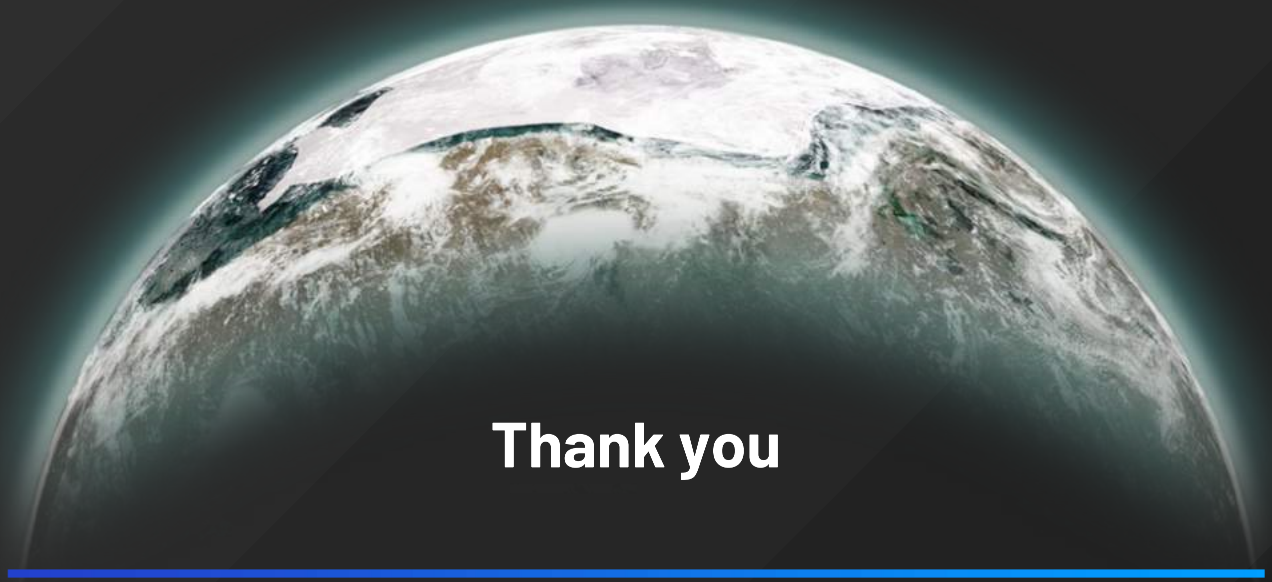
MIRI

Space-based interferometry



Cryogenic space telescopes





Thank you