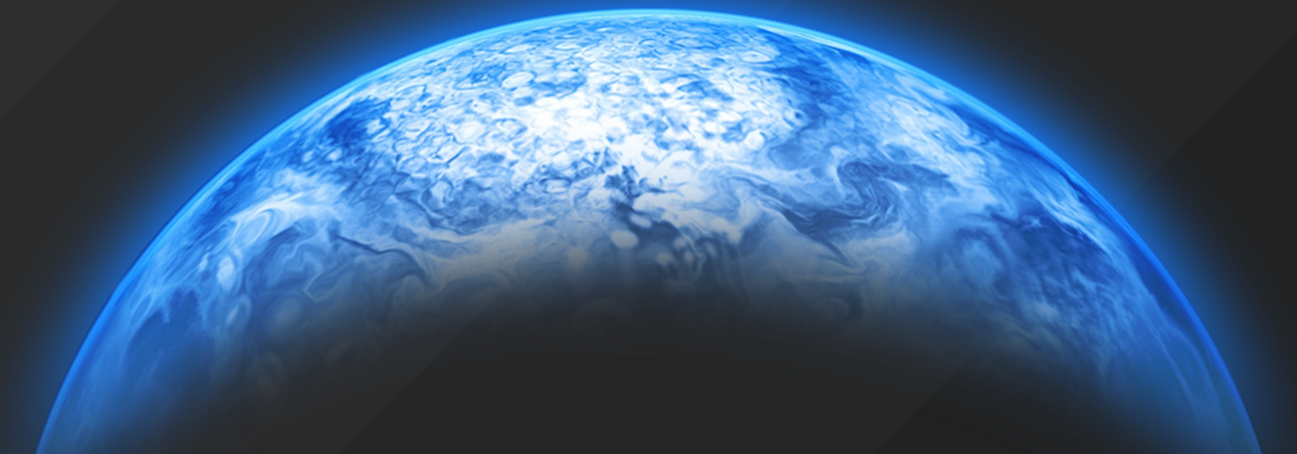

Interferometry for Exoplanets

Authors:

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ETH Zurich

2023 Sagan Summer Workshop
July 25, 2023
Caltech

CENTRE FOR ORIGIN & PREVALENCE OF LIFE

PlanetS
National Centre of Competence in Research

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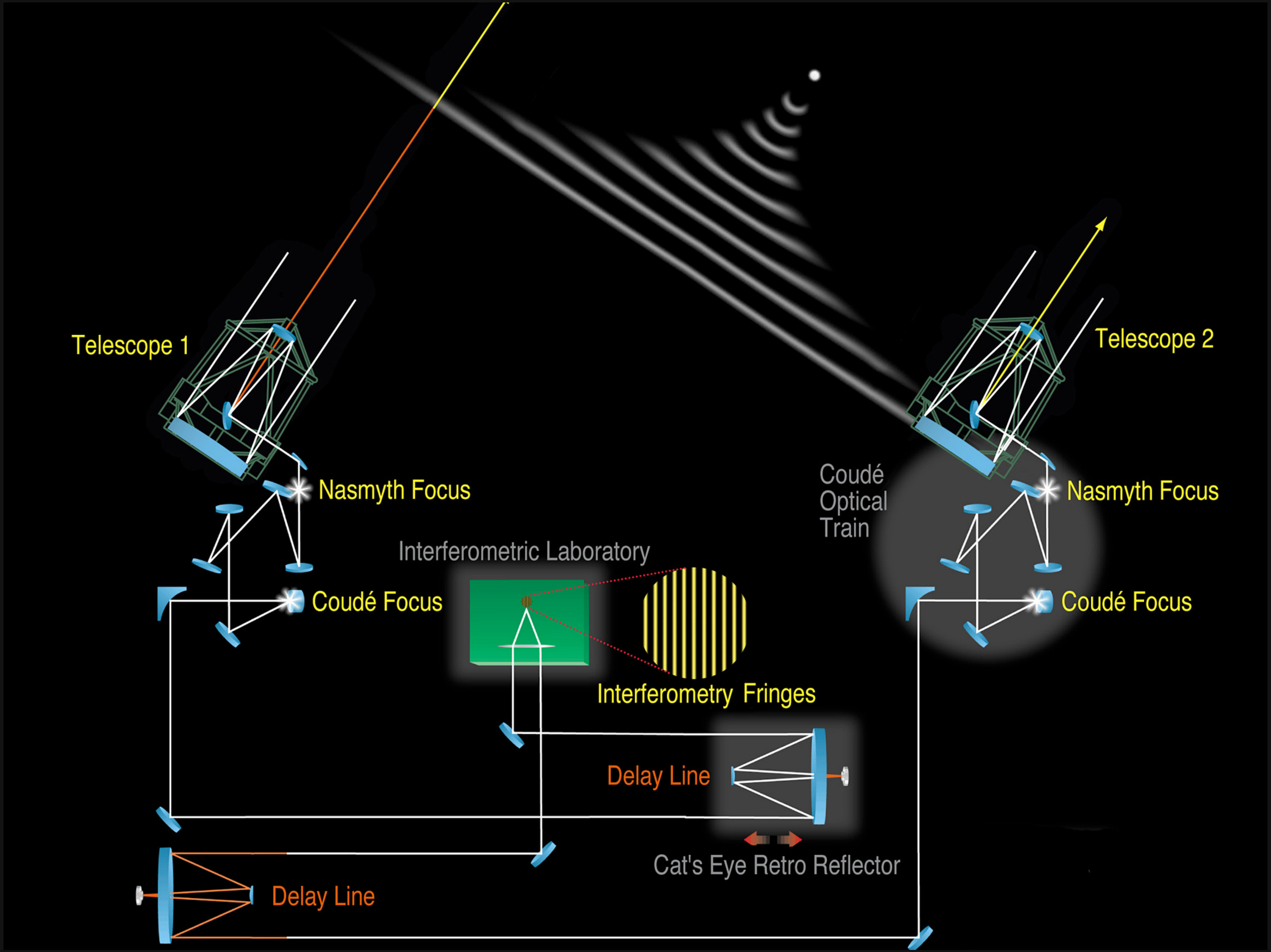
What is interferometry?

What is interferometry?

“Interferometry is a technique which uses the interference of superimposed waves to extract information”
(Wikipedia)


Telescope 1
Telescope 2
Nasmyth Focus
Nasmyth Focus
Coudé Optical Train
Interferometric Laboratory
Coudé Focus
Coudé Focus
Interferometry Fringes
Delay Line
Cat's Eye Retro Reflector
Delay Line

Credit: ESO

What is the motivation to use **optical, nulling interferometry** in exoplanet science?

Directly detect photons from exoplanets - in particular non-transiting ones - to study their atmospheres

Three requirements for the direct detection of 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:** the planet signal is intrinsically very faint

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$\vartheta \sim 1.22\ \lambda/D$

0.34″ (or 3.4 AU @ 10 pc) for D=8.2 m and $\lambda = 11\ \mu$m
0.07″ (or 0.7 AU @ 10 pc) for D=39 m and $\lambda = 11\ \mu$m
0.0003″ (or 0.003 AU @ 10 pc) for D=39 m and $\lambda = 0.5\ \mu$m

Three requirements for the direct detection of exoplanets

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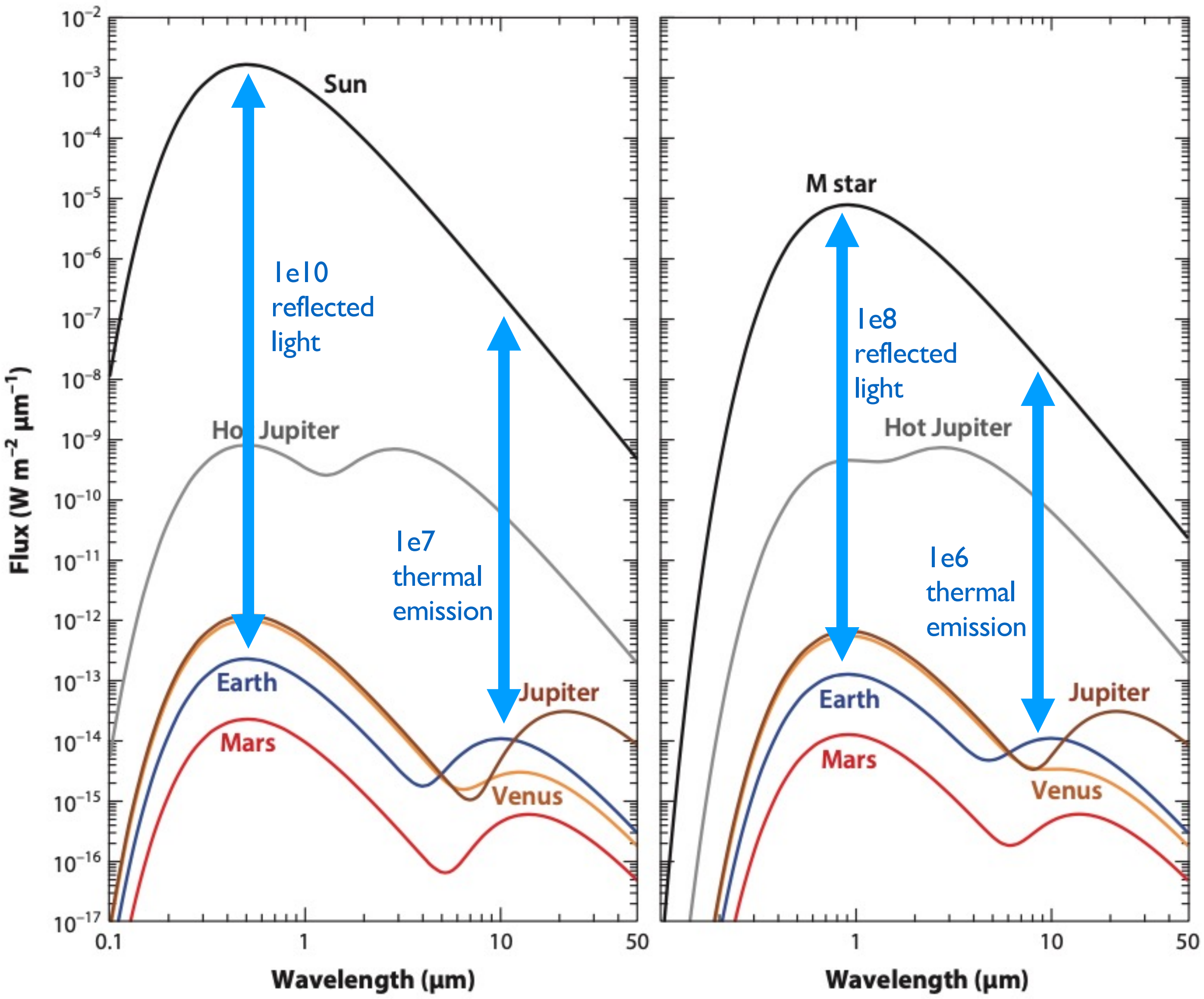

Based on Kaltenegger 2017

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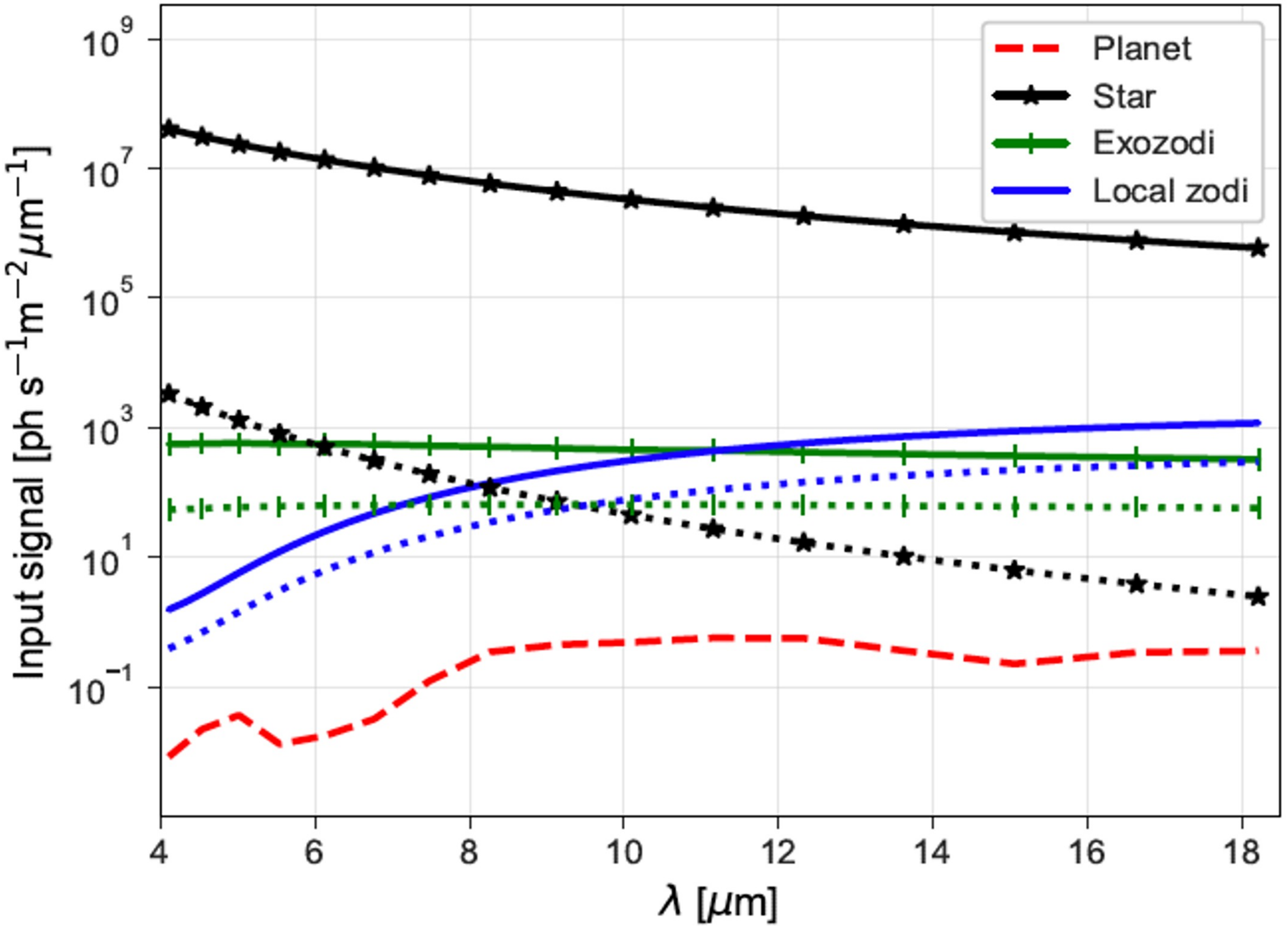
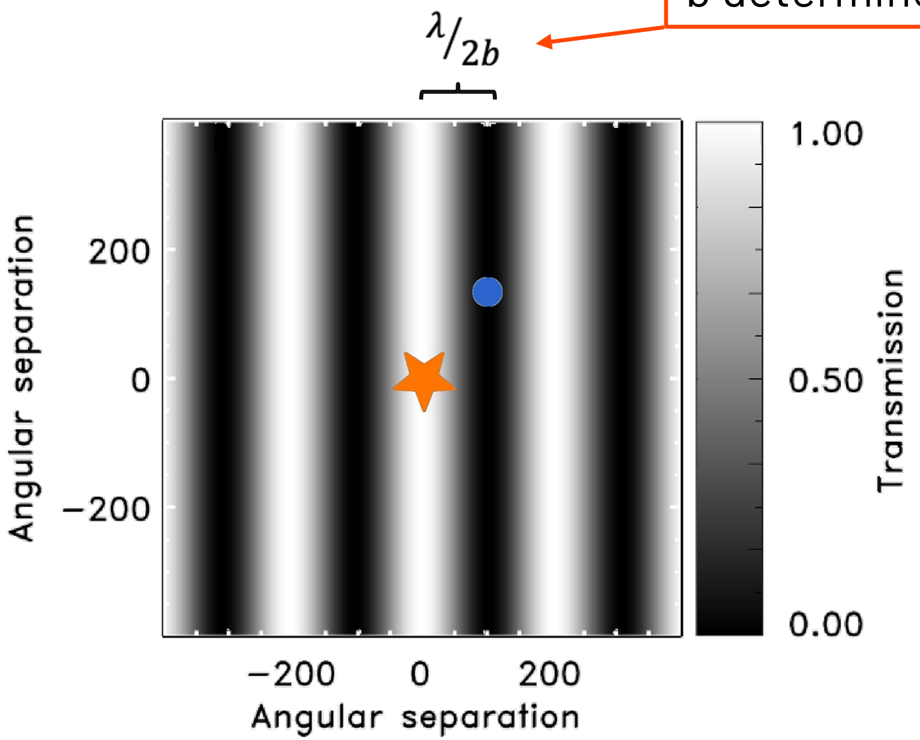


Dannert et al. 2022

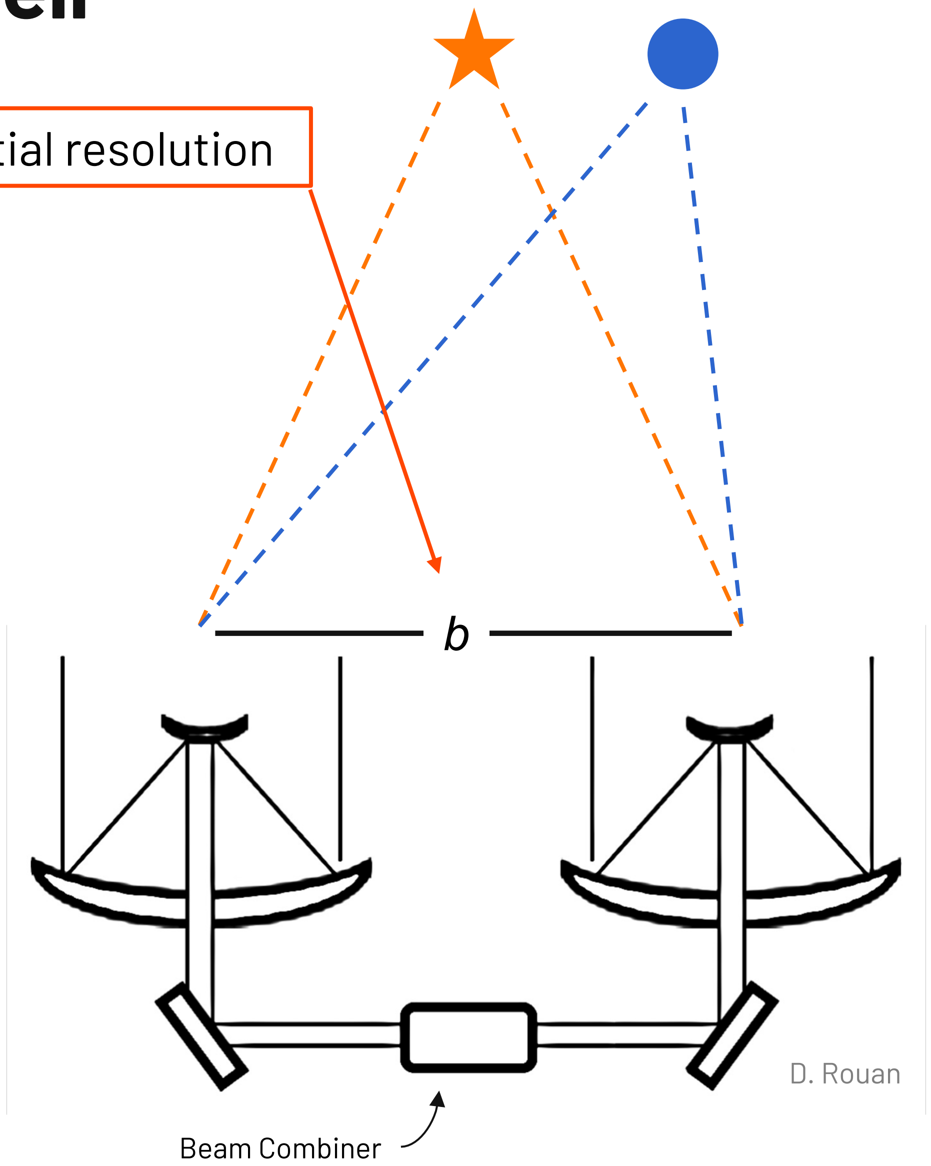
How does **optical nulling interferometry** work?

Nulling Interferometry in a nutshell

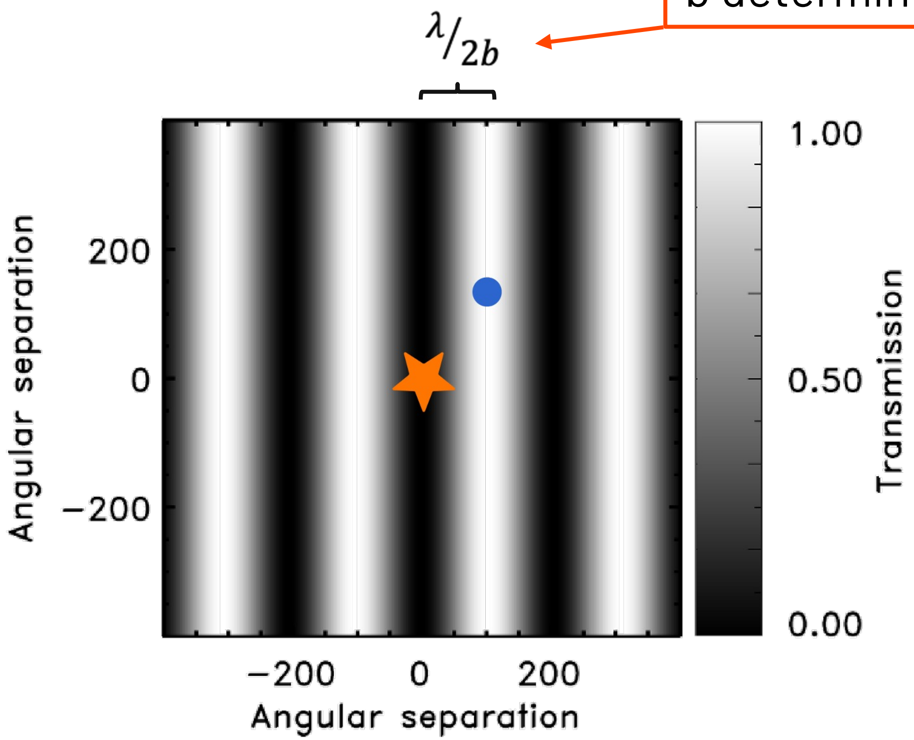
b determines the spatial resolution



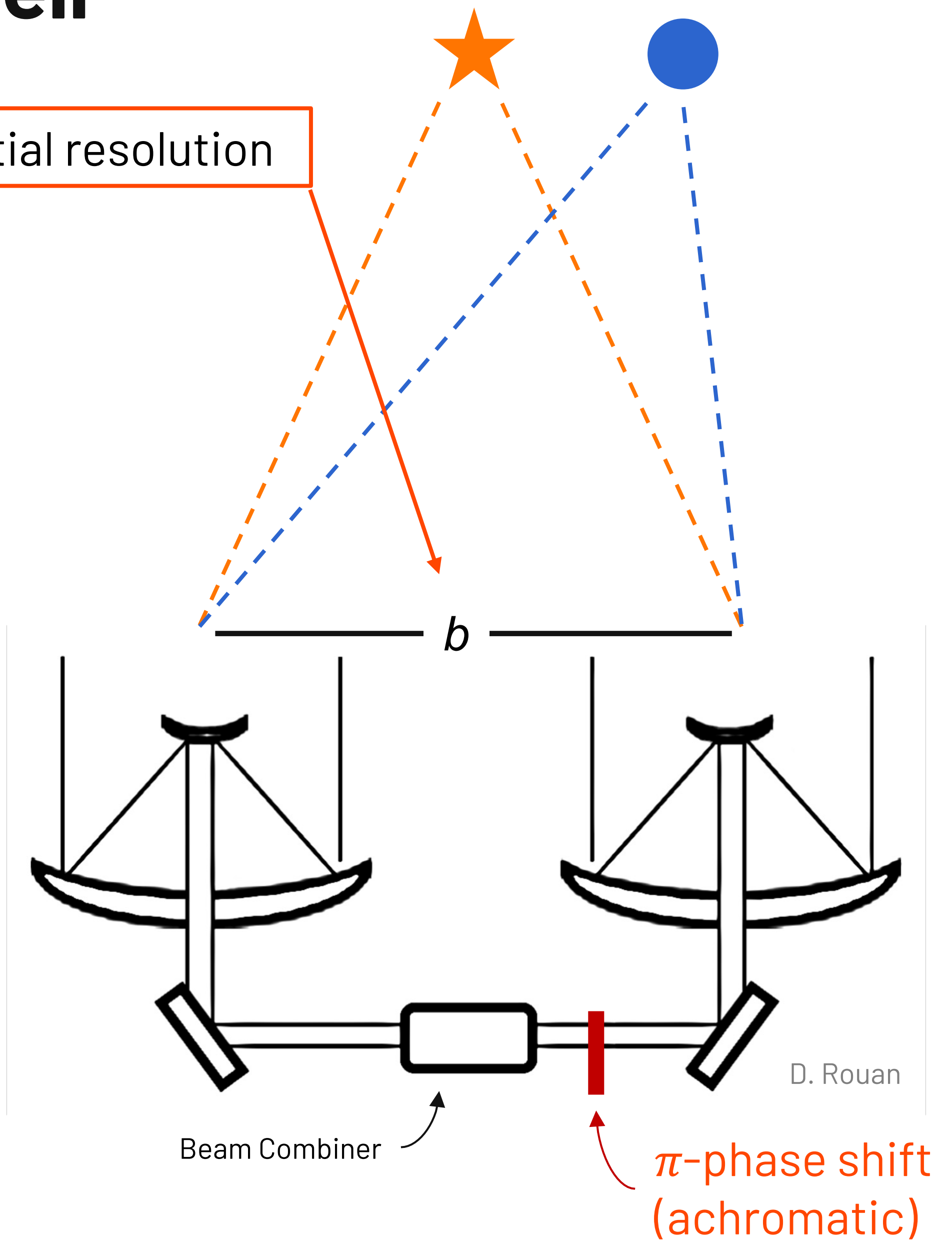
Interferometer



Nulling Interferometry in a nutshell

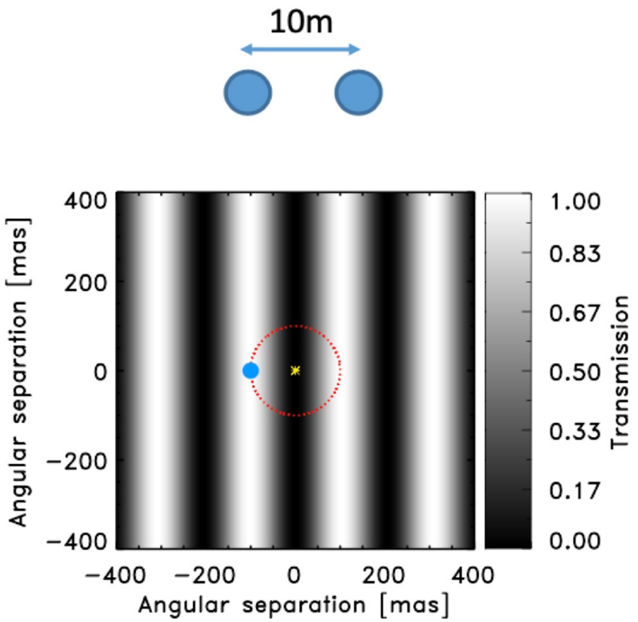


Nulling Interferometer



Nulling Interferometry in a nutshell

Example: Earth-Sun system seen from 10 pc at 10 micron wavelength



Based on Defrère et al. 2018b

Nulling Interferometry in a nutshell

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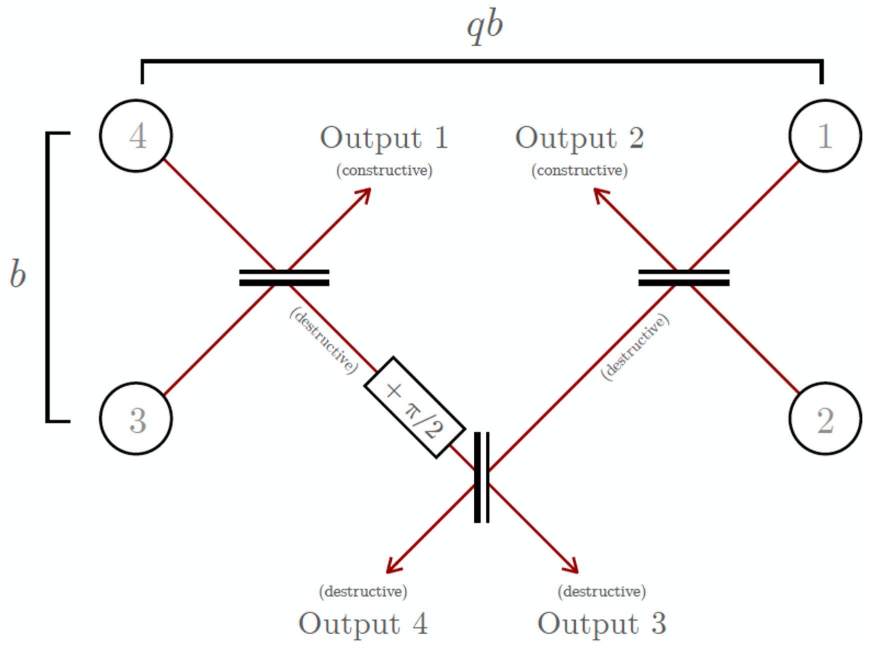
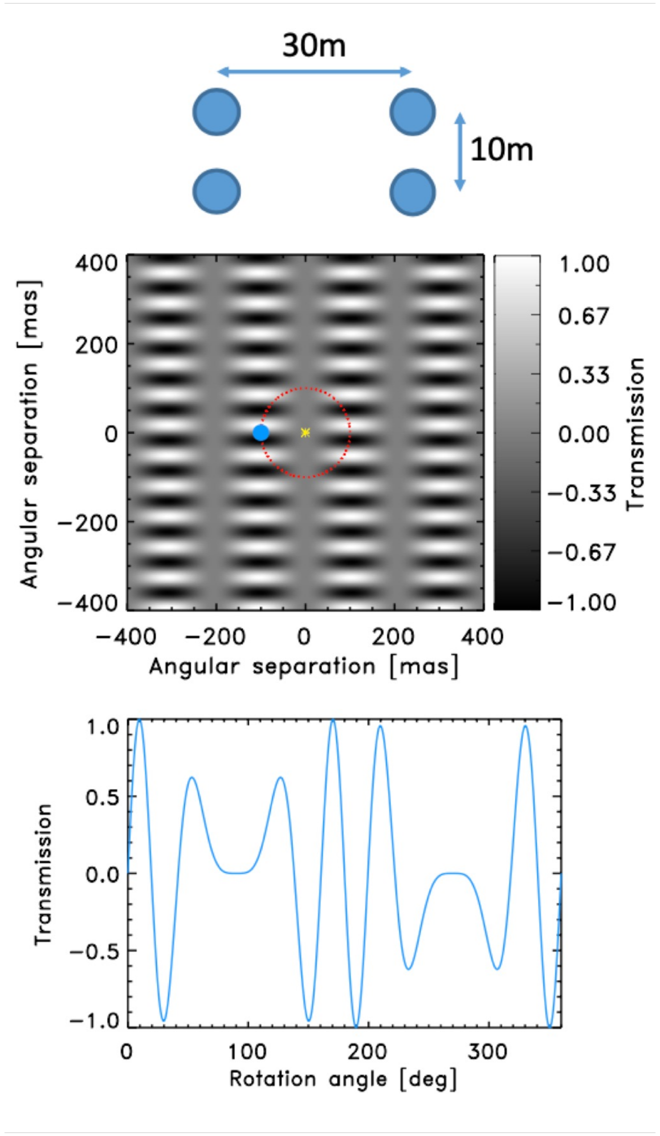


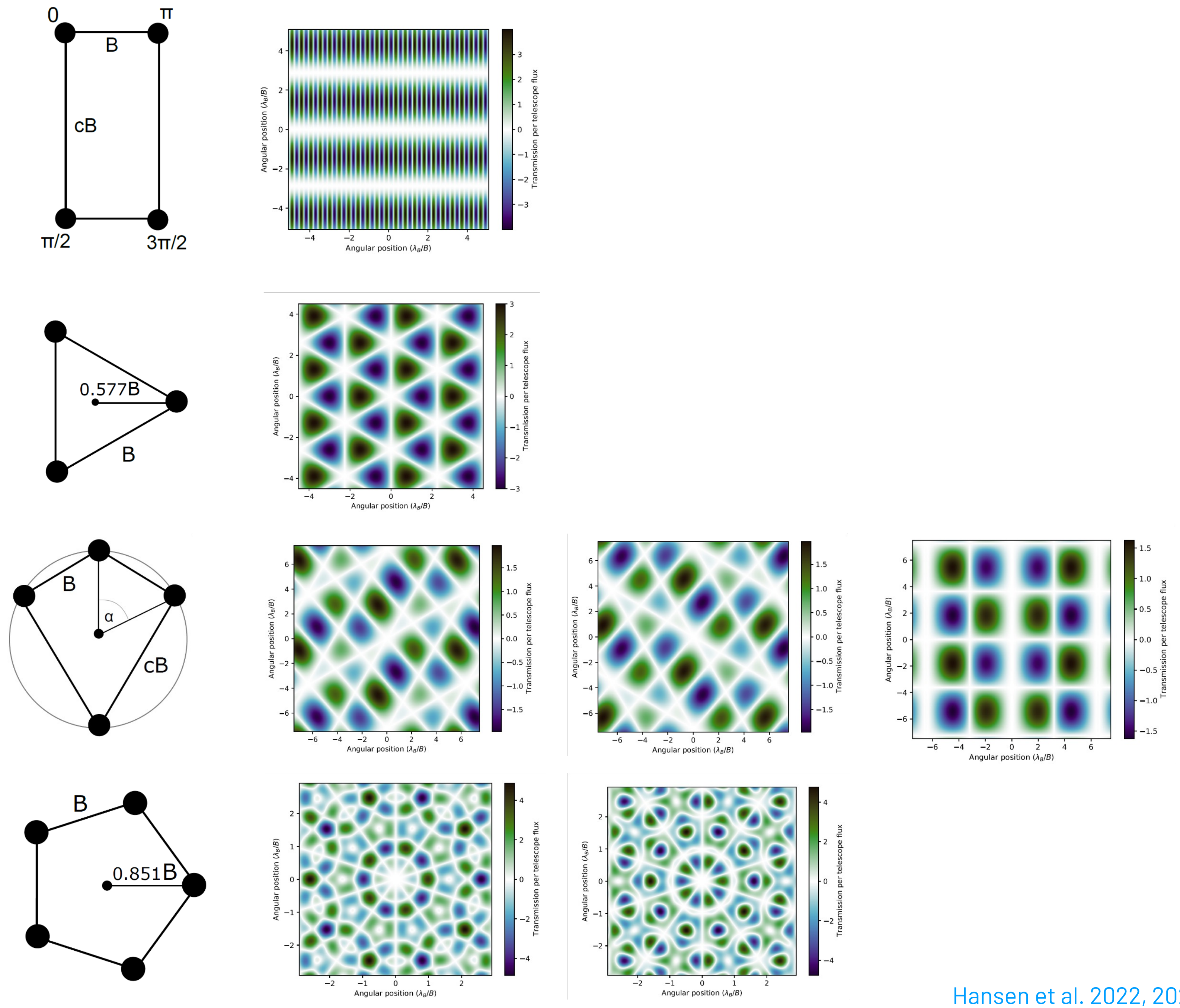


- In one branch, a $\pi/2$ phase shift is introduced to enable the difference map
- Phase chopping between Outputs 3 & 4 makes instrument less susceptible to perturbation

Based on Defrère et al. 2018b

Investigating different architectures

- Double Bracewell vs. various Kernel Nulling approaches



Hansen et al. 2022, 2023

Where was this technique successfully used?

The Hunt for Observable Signatures of Terrestrial Systems (HOSTS) at the Large Binocular Telescope Interferometer (LBTI)

...was a NASA-funded survey of mid-infrared emission from exozodiacal dust in the habitable zones of nearby main sequence stars, using the LBTI's N-band (10 micron) **nulling mode**.

The goal was to inform the design of future space missions to directly detect and characterize exo-Earths.

THE ASTRONOMICAL JOURNAL, 159:177 (18pp), 2020 April
https://doi.org/10.3847/1538-3881/ab7817

CrossMark

The HOSTS Survey for Exozodiacal Dust: Observational Results from the Complete Survey

Image Credit: NASA/JPL-Caltech

Where will this technique be applied in the future?

On the ground:
VLT/NOTT

L-band nulling interferometry at the VLTI with Asgard/NOTT

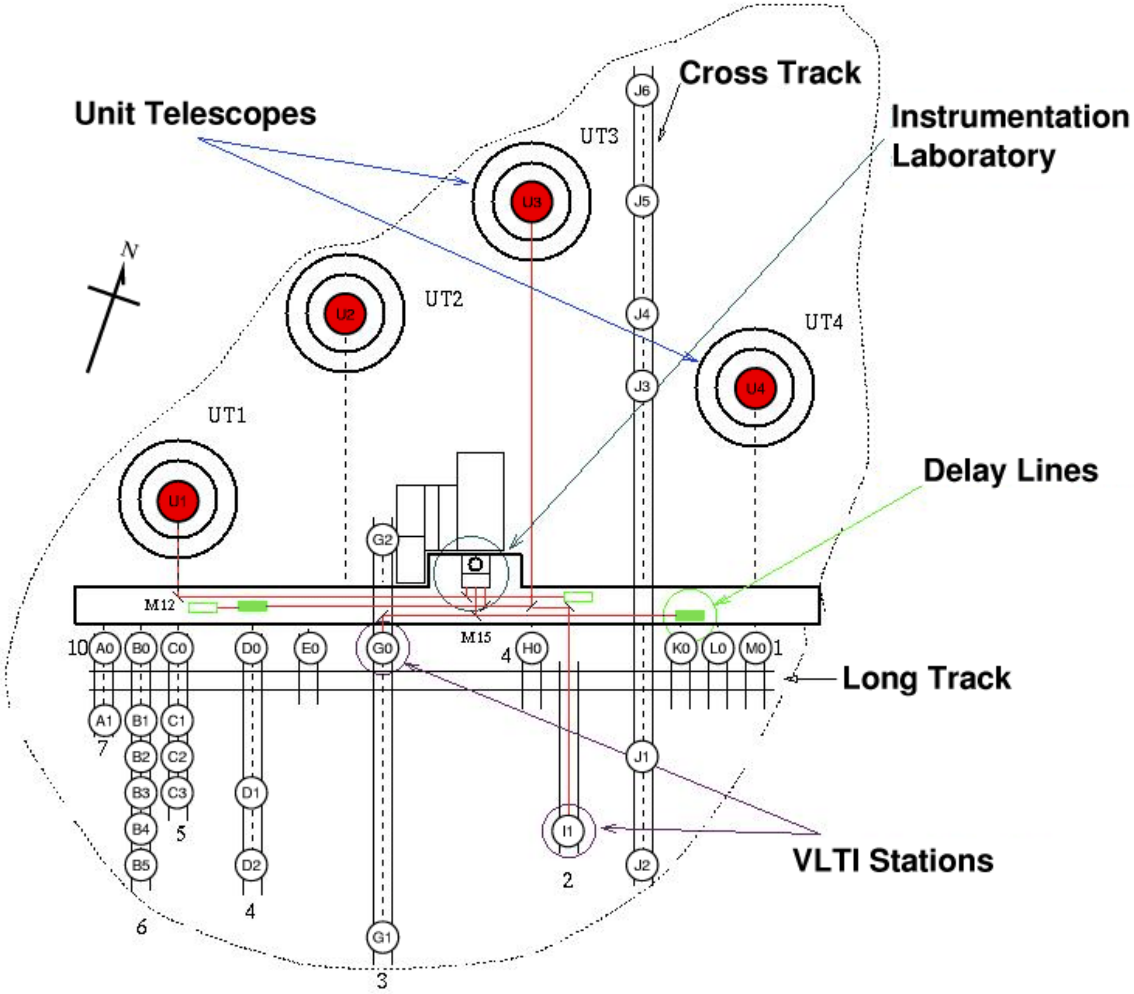


Image Credit: ESO

L-band nulling interferometry at the VLTI with Asgard/NOTT

A&A 671, A110 (2023)
https://doi.org/10.1051/0004-6361/202244351

Astronomy & Astrophysics

ASGARD
HEIMDALLR | Baldr | BIFROST | NOTT

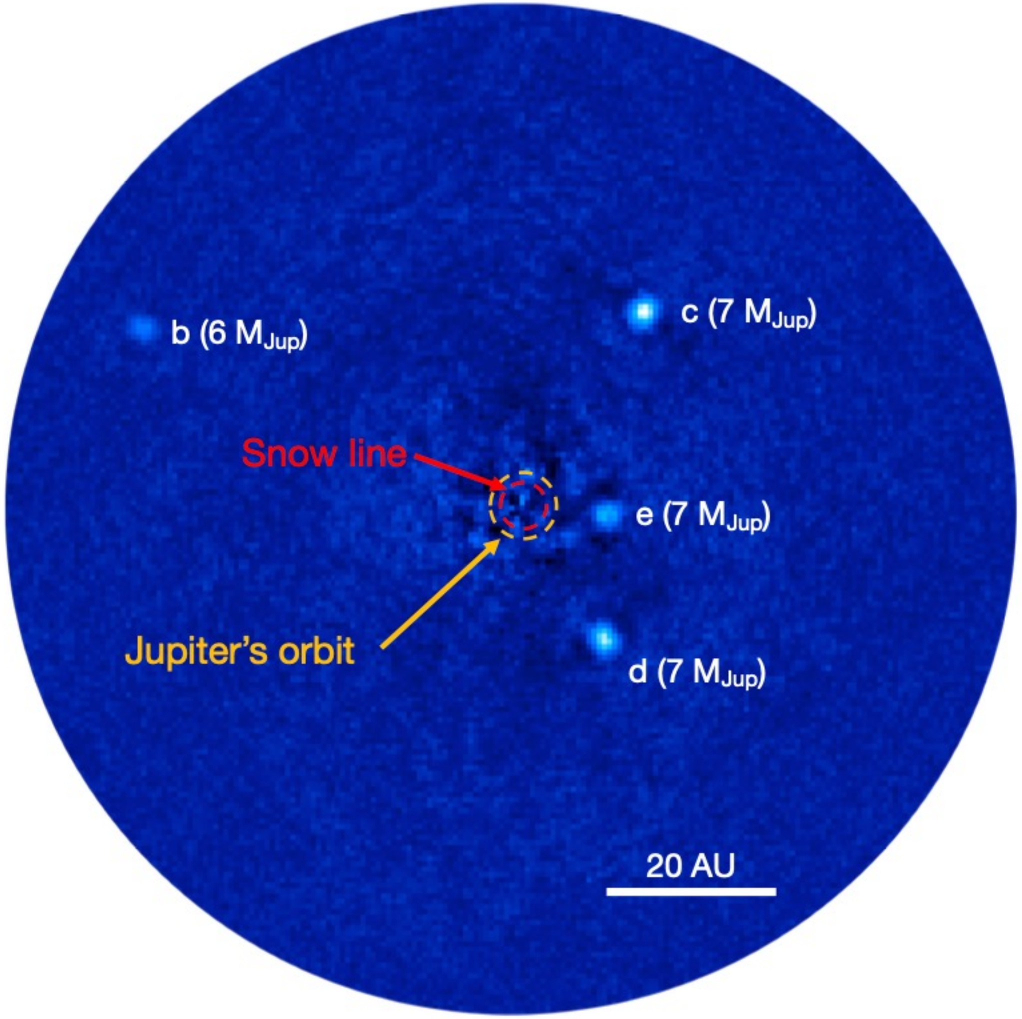
Asgard/NOTT: *L*-band nulling interferometry at the VLTI

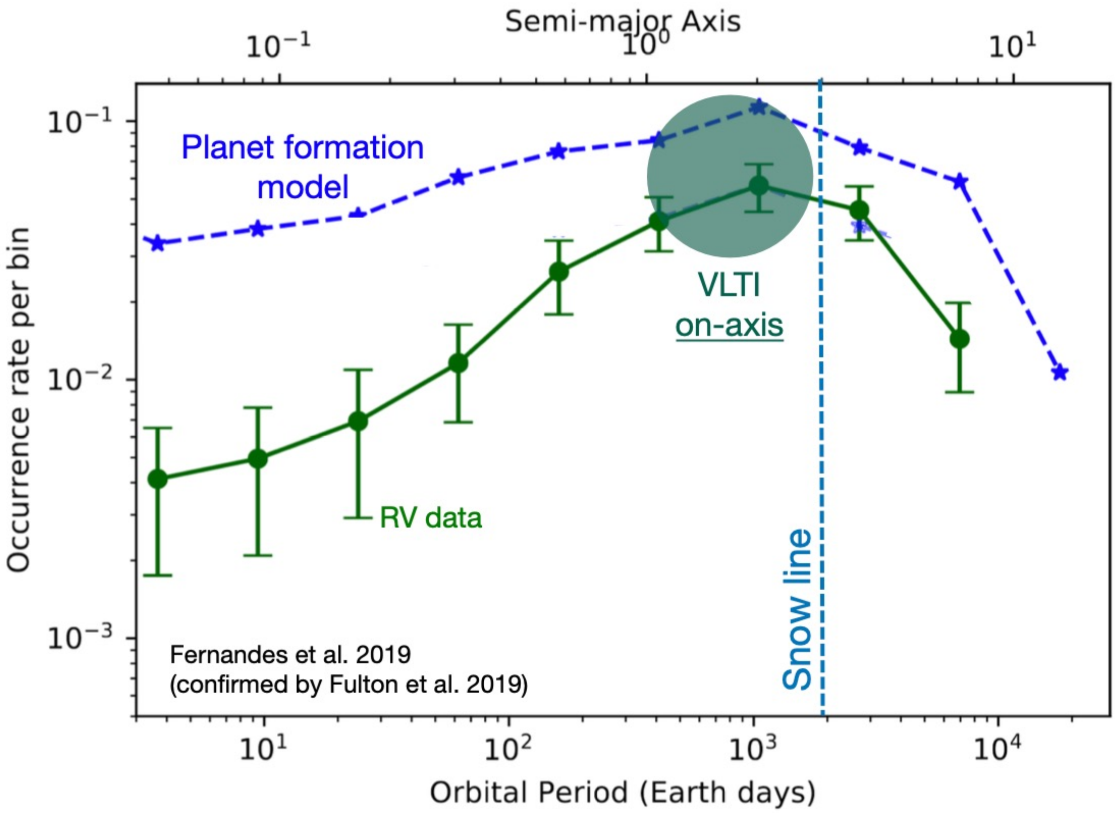
I. Simulating the expected high-contrast performance

Romain Laugier[1], Denis Defrère[1], Julien Woillez[2], Benjamin Courtney-Barrer[2,10], Felix A. Dannert[3,4], Alexis Matter[5], Colin Dandumont[6], Simon Gross[7], Olivier Absil[6], Azzurra Bigioli[1], Germain Garreau[1], Lucas Labadie[9], Jérôme Loicq[6,8], Marc-Antoine Martinod[1], Alexandra Mazzoli[6],

KU LEUVEN | LIÈGE université | CSL | Australian National University | University of Cologne | ETH Zürich | The University of Arizona | IPAG | ESO | TU Delft | University of Exeter | IAS Orsay | Konkoly

L-band nulling interferometry at the VLTI with Asgard/NOTT





Search for young gas giant planets

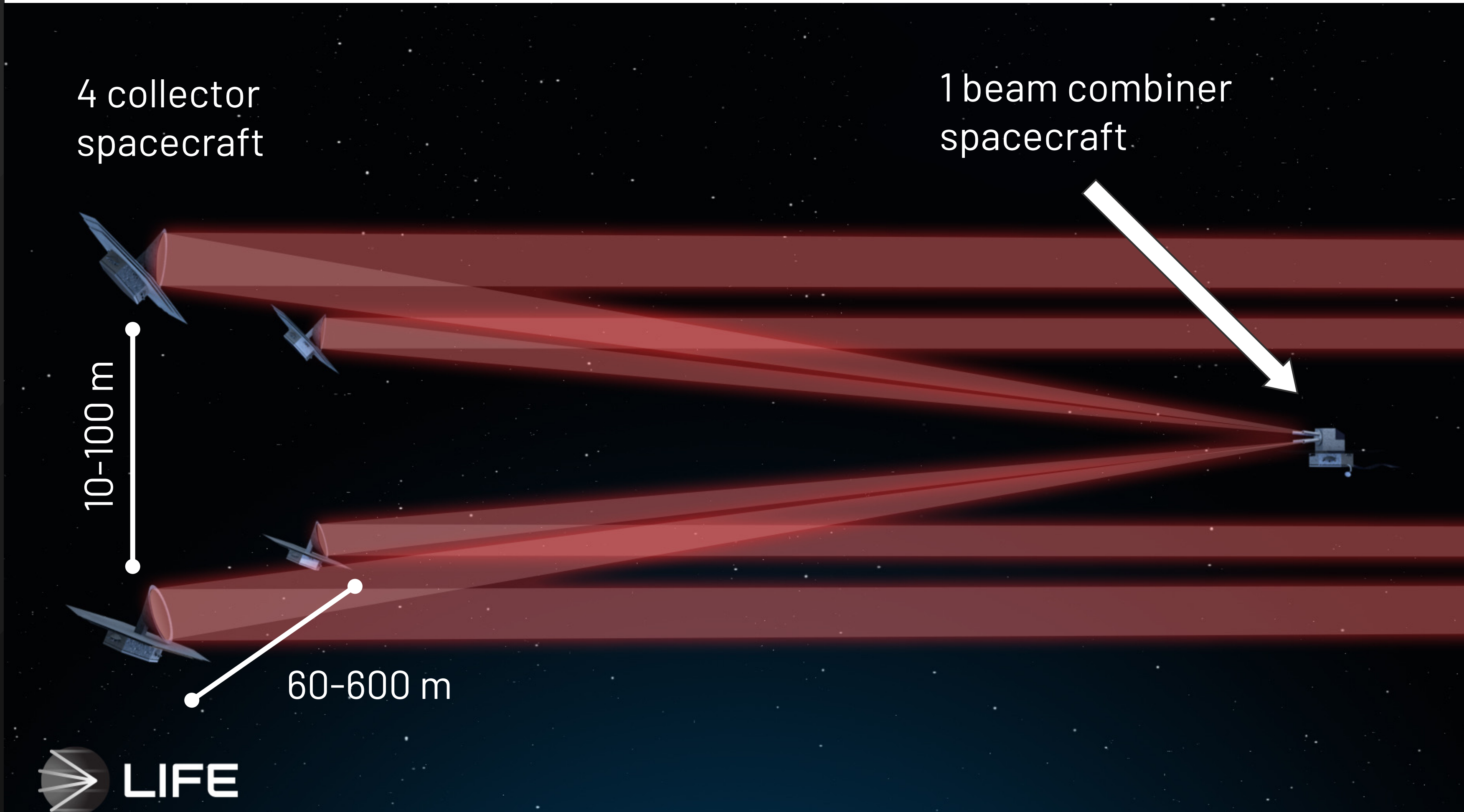
- in gaps of transition disks
- around the nearest youngest stars

Credit: Denis Defrere

In space:
Large Interferometer For Exoplanets (LIFE)

The LIFE mission

- ...is a space-based formation-flying mid-infrared (nulling) interferometer
- ...consists of 4 collector spacecraft separated by tens to hundreds of meters and a beam combiner
- ...covers the mid-infrared wavelength range between ~4-18.5 μm with a spectral resolution of R ~ 50-100 (tbc)



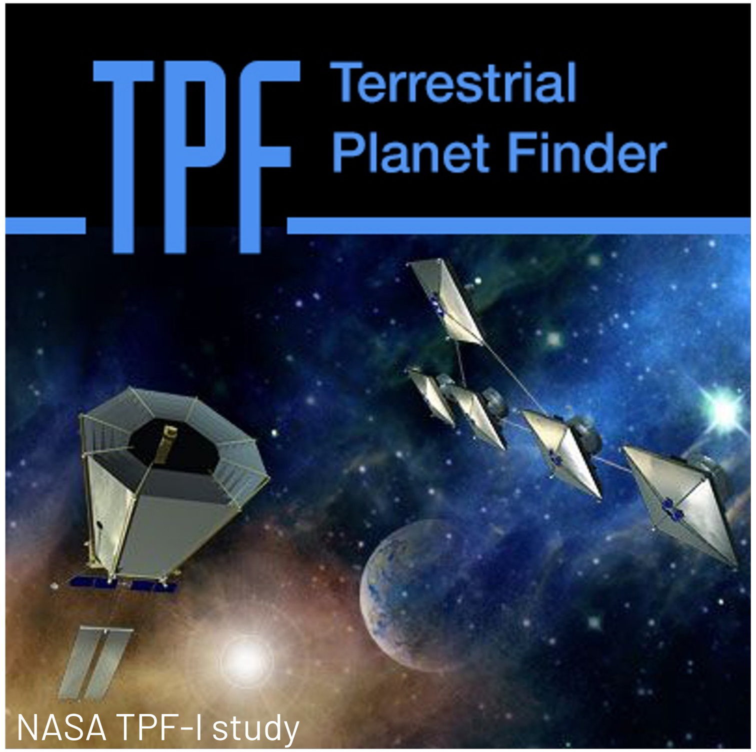
Artist impression of LIFE concept (credit: LIFE initiative)

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

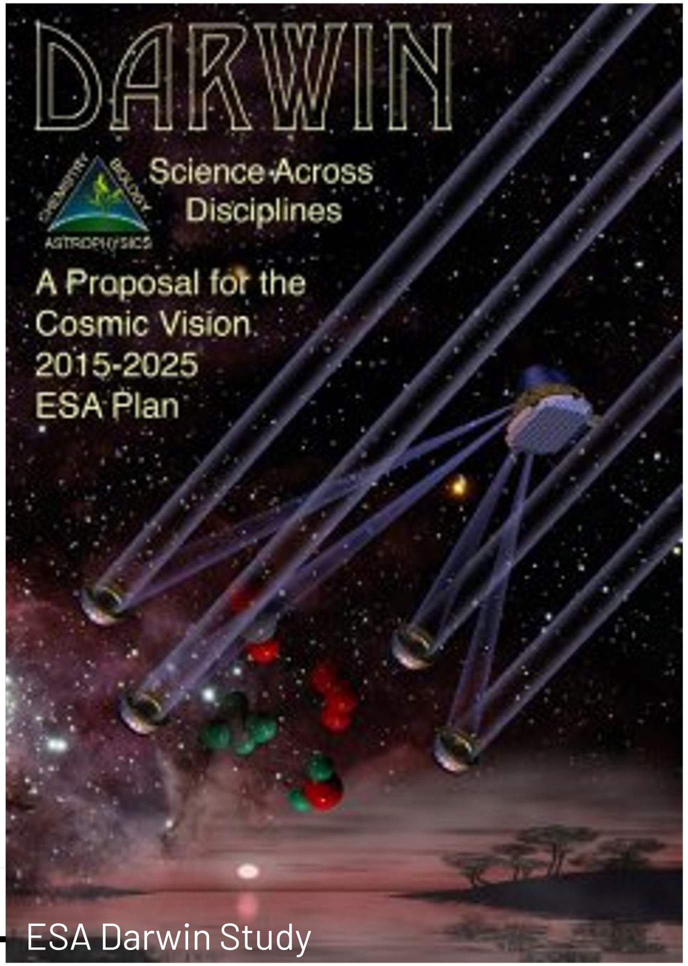
Heritage

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

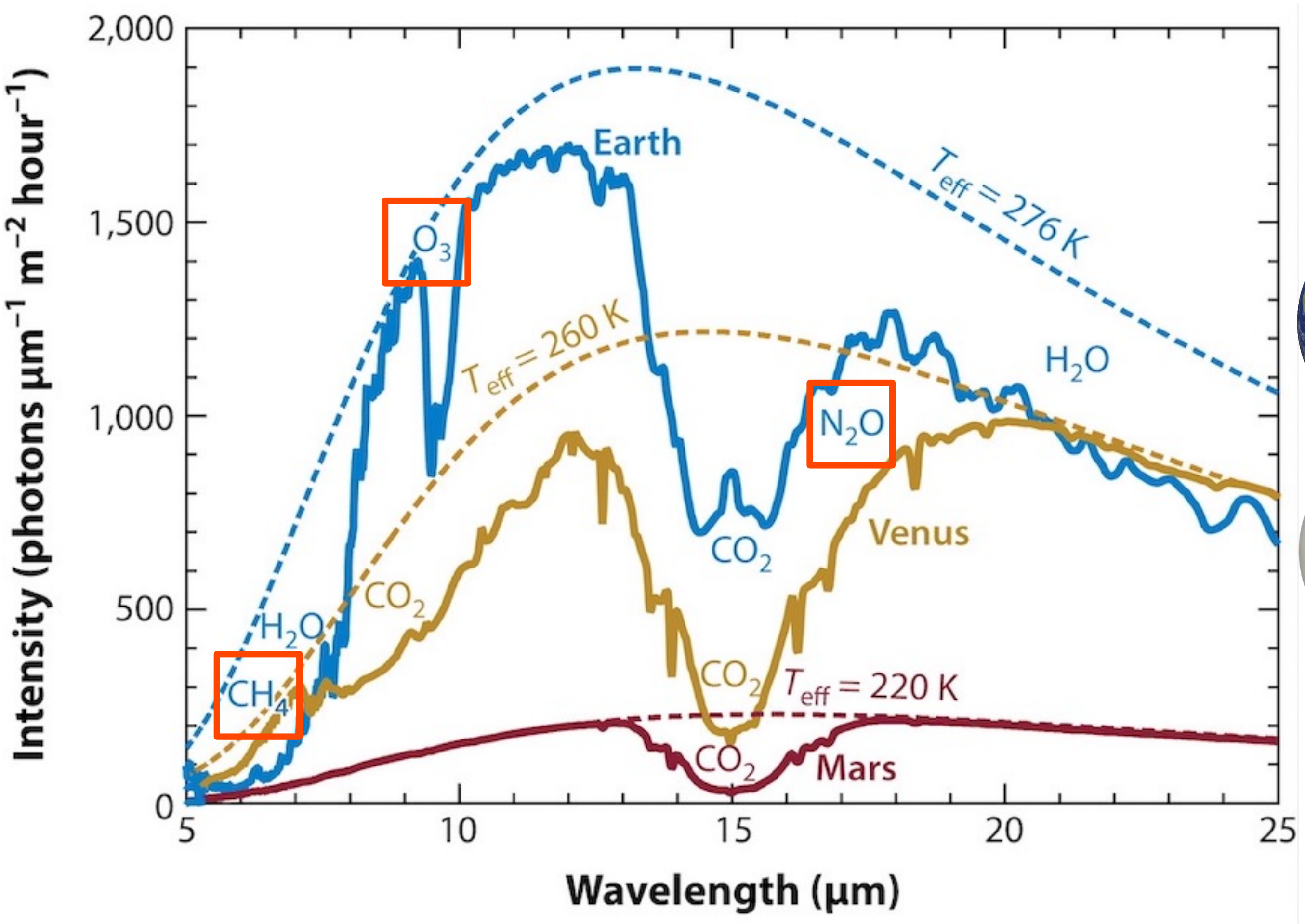
Nature **274**, 780–781 (1978) | Cite this article

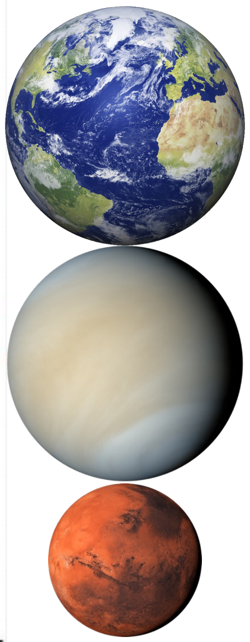
702 Accesses | **257** Citations | **48** Altmetric | Metrics

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

Emission spectra of terrestrial planets in our Solar System





Based on Kaltenegger 2017

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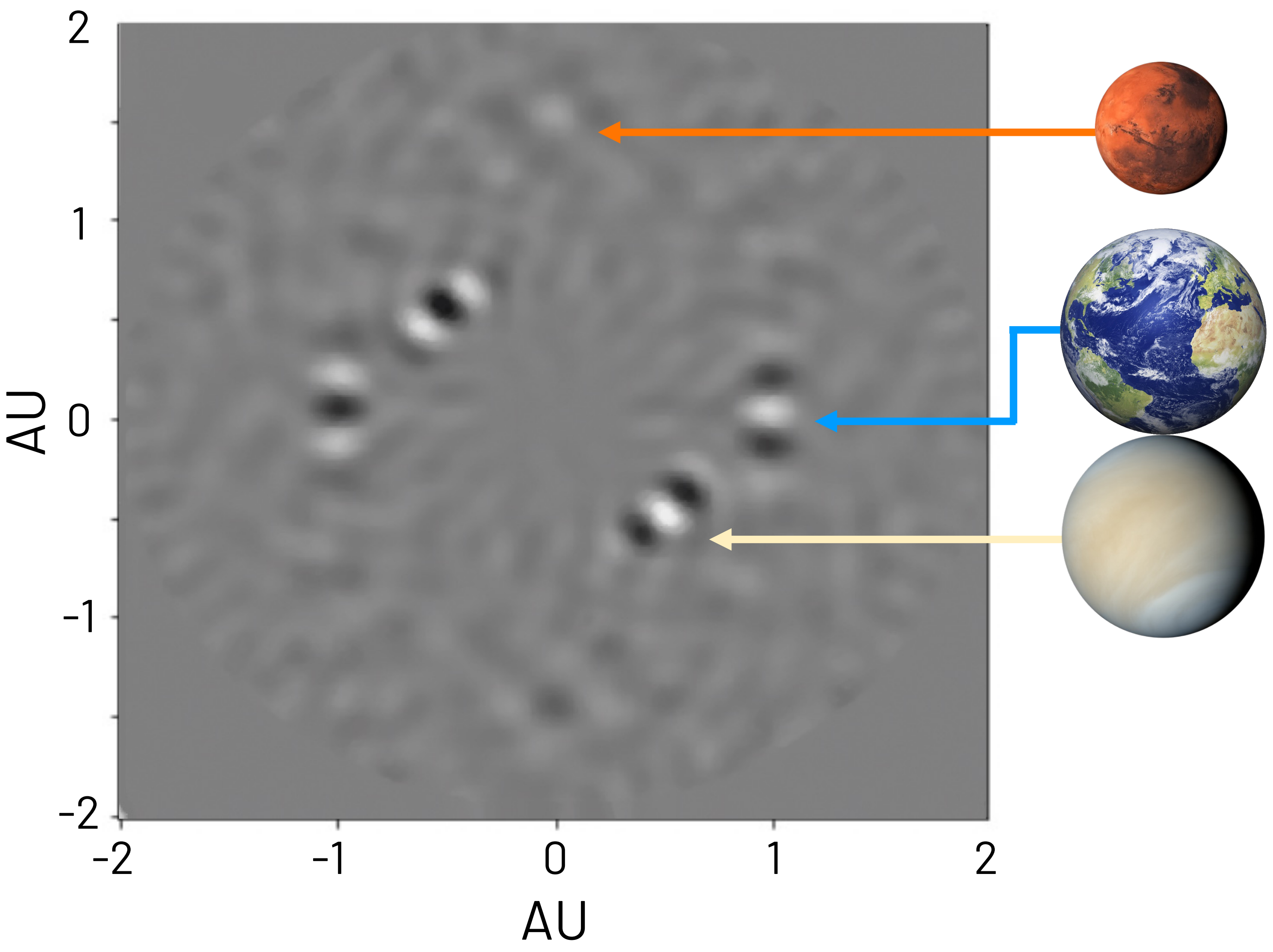
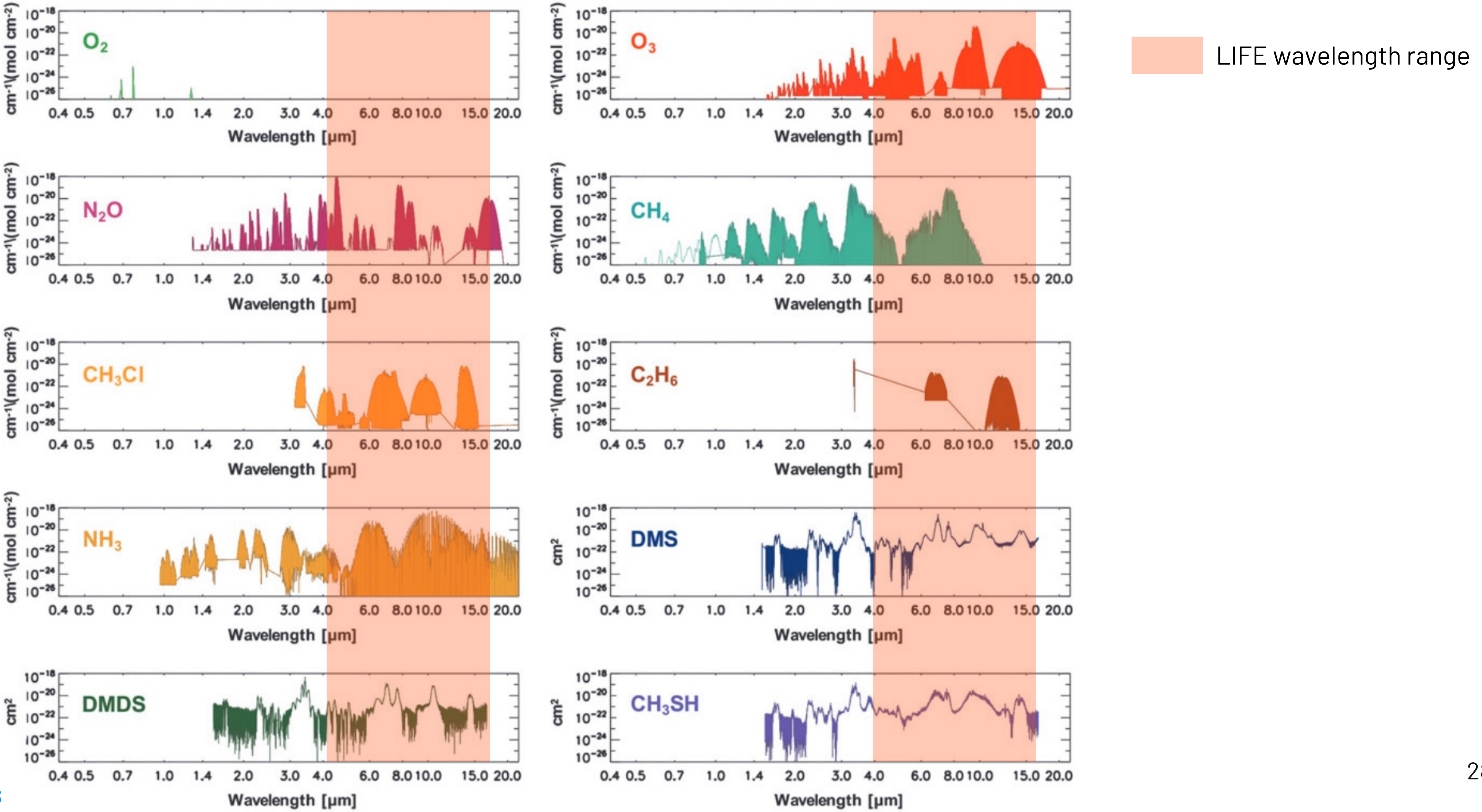
Reconstructed LIFE image of Solar System analog at 10 pc



Matsuo et al. (2023, accepted for publication in A&A)

Biosignature detection: the mid-infrared advantage

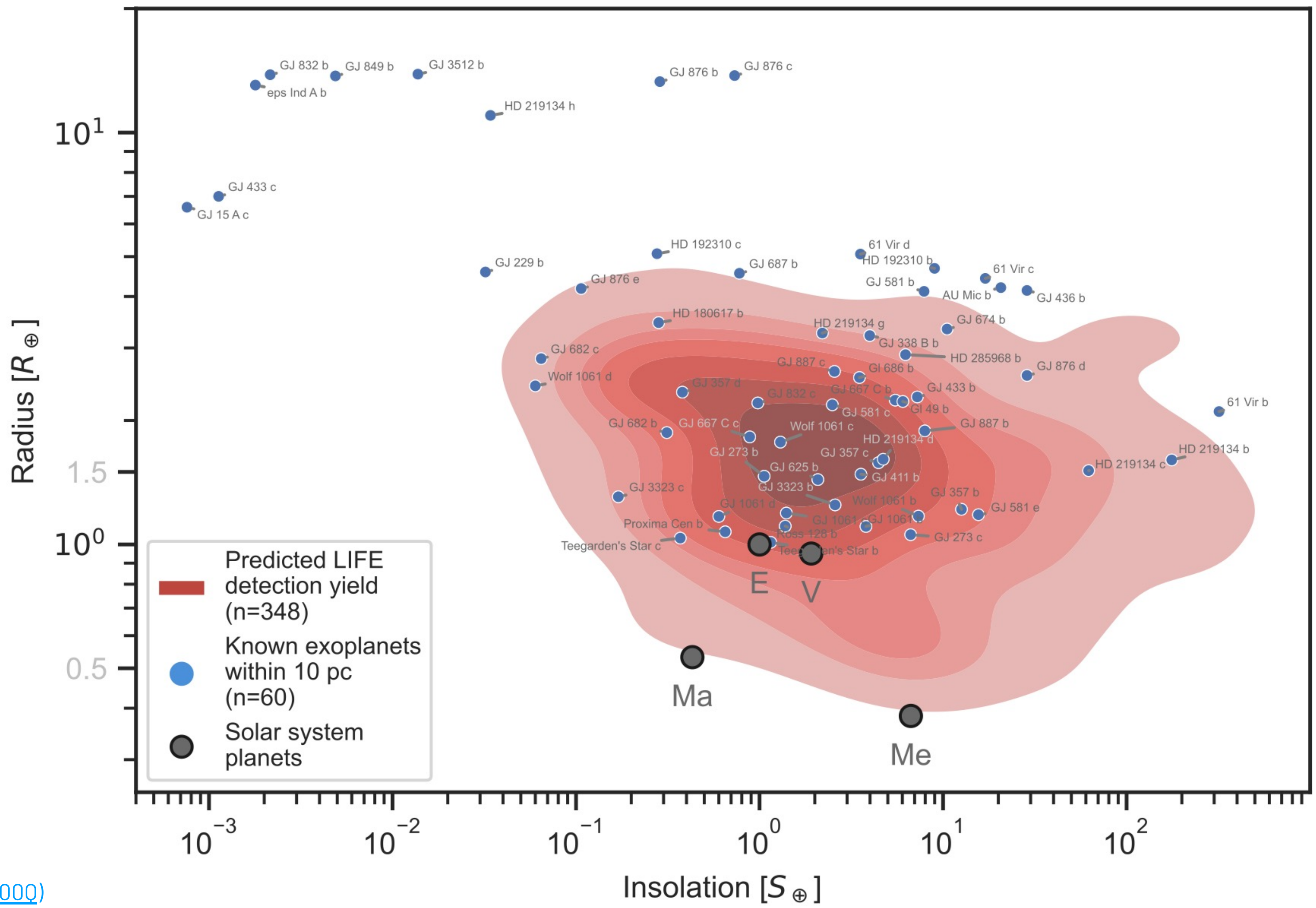
Many atmospheric biosignatures have absorption bands in the LIFE wavelength range



Schwieterman et al. 2018

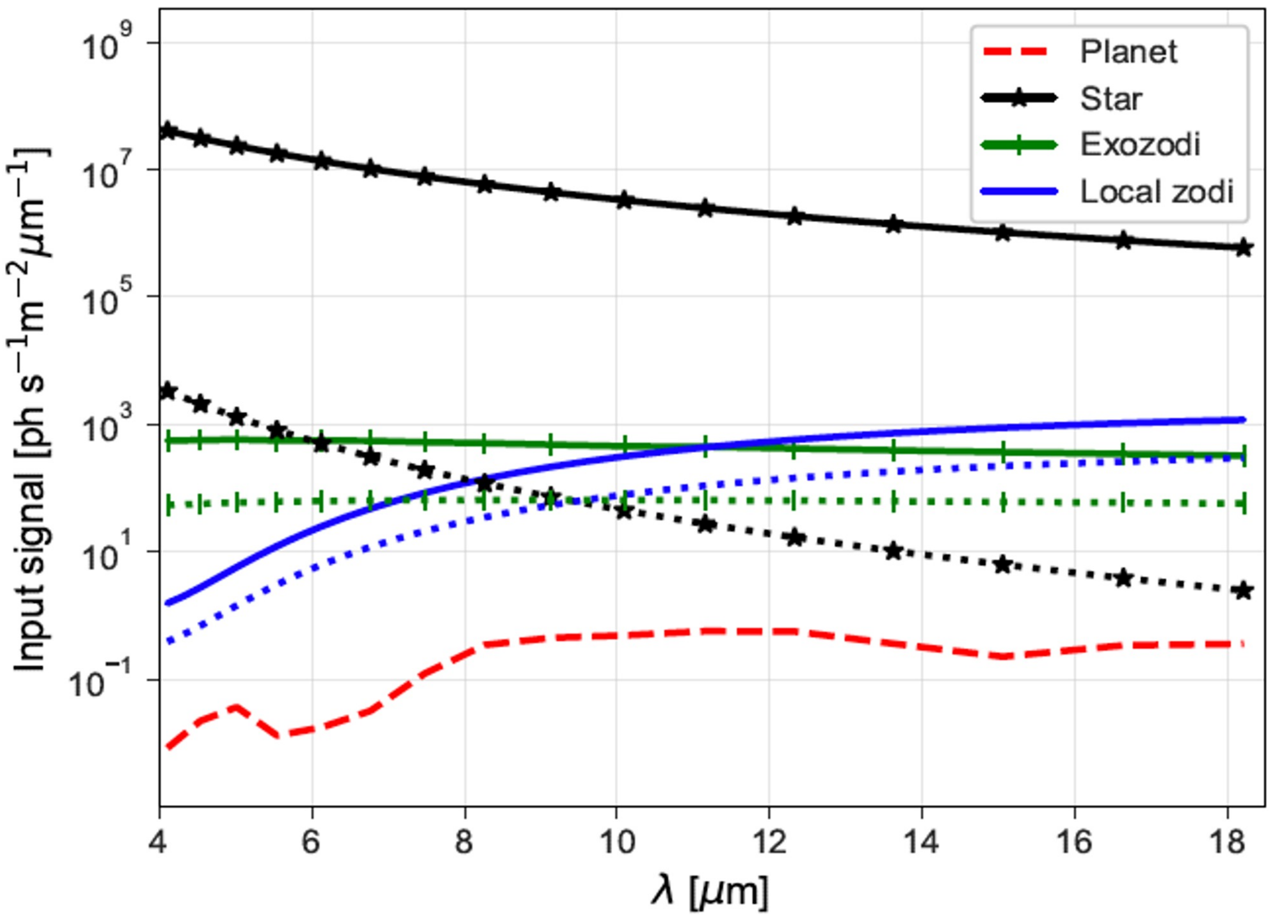
LIFE discovery and characterization potential

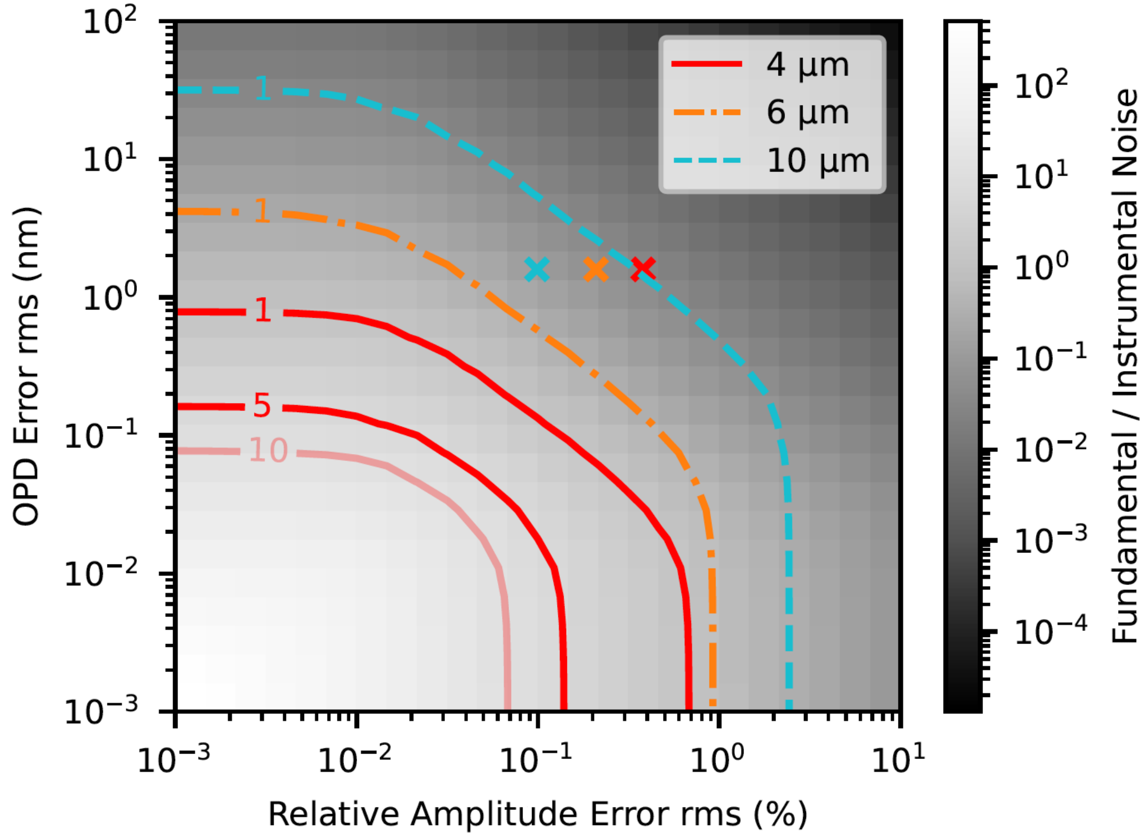
LIFE discovery space vs. known exoplanets within 10 pc



Quanz et al. 2022 (arXiv2101075000)

Challenges for detecting Earth-like planets with LIFE





Dannert et al. 2022

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."

"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

A holistic understanding of exo-Earths requires global efforts

Synergies between different missions and ground-based telescopes

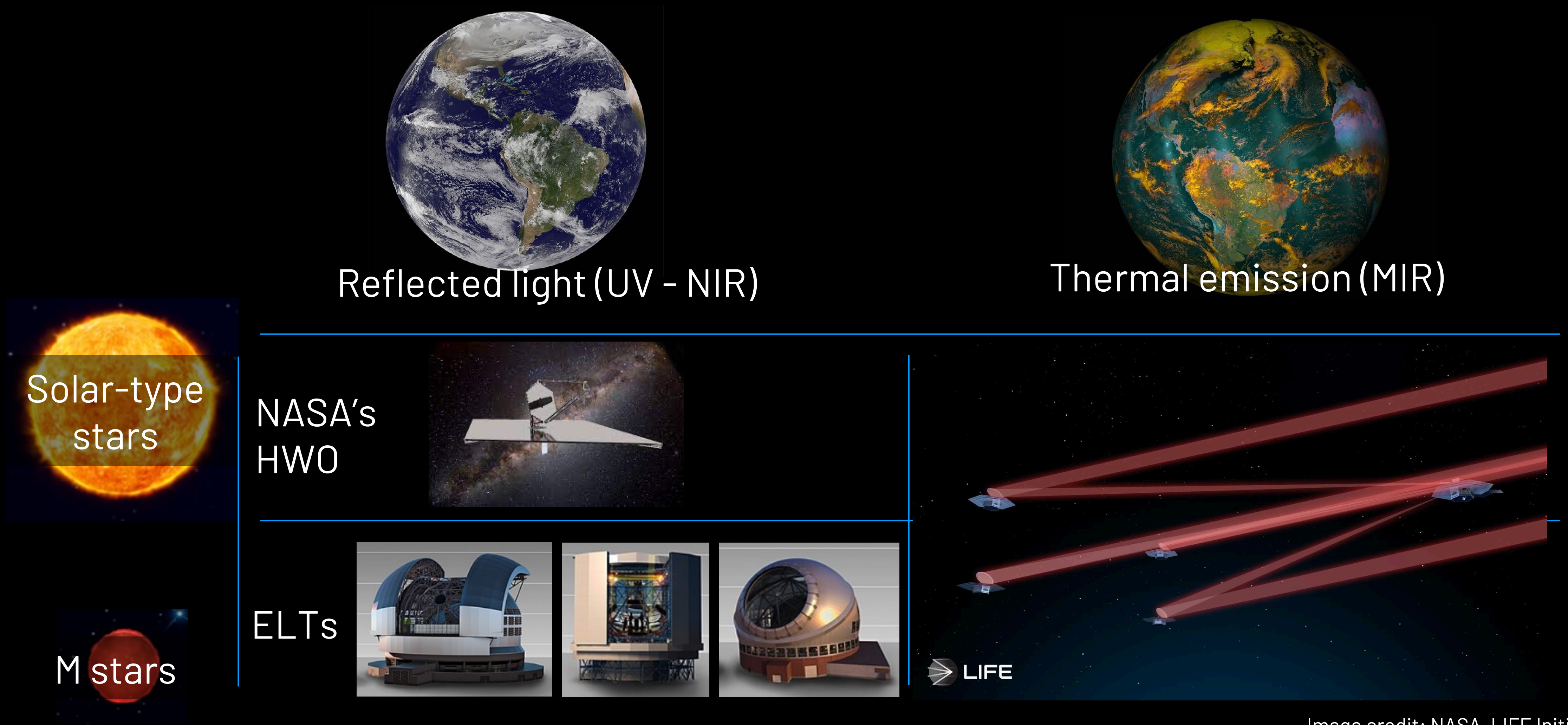


Image credit: NASA, LIFE Initiative, ESO, TMT, GMT

Take home messages

- Nulling interferometry is a high-spatial resolution, high-contrast observing technique that allows for the direct detection of extrasolar planets

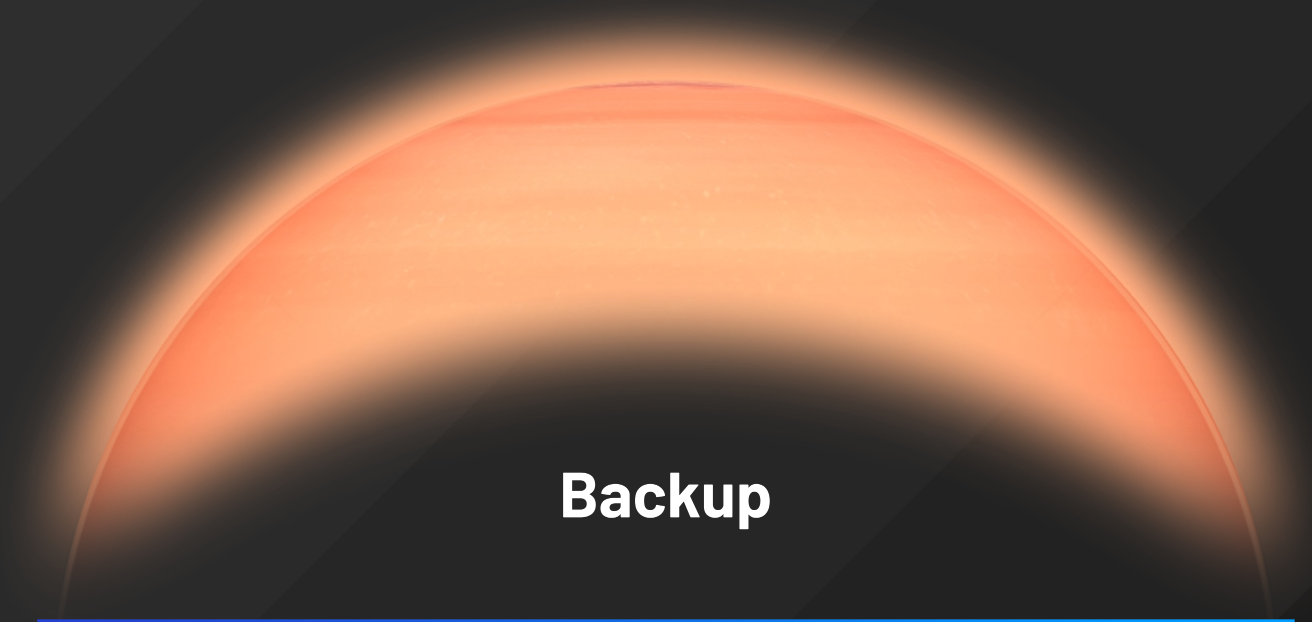
- It is particularly suited for observations at mid-infrared wavelength, where single-aperture telescopes lack spatial resolution and where requirements on phase and amplitude control – despite still being stringent - are more relaxed

- Recent successes of nulling interferometry include the HOSTS survey at the VLTI determining the occurrence rate of (massive) exozodiacal dust disks

- Future applications include the NOTT instrument at the VLTI and the LIFE space mission; as of today, a space-based nulling interferometer is the most promising approach to directly characterize the atmospheres of dozens of temperate, terrestrial exoplanets in the mid-infrared

Thank you

LIFE
LARGE INTERFEROMETER FOR EXOPLANETS

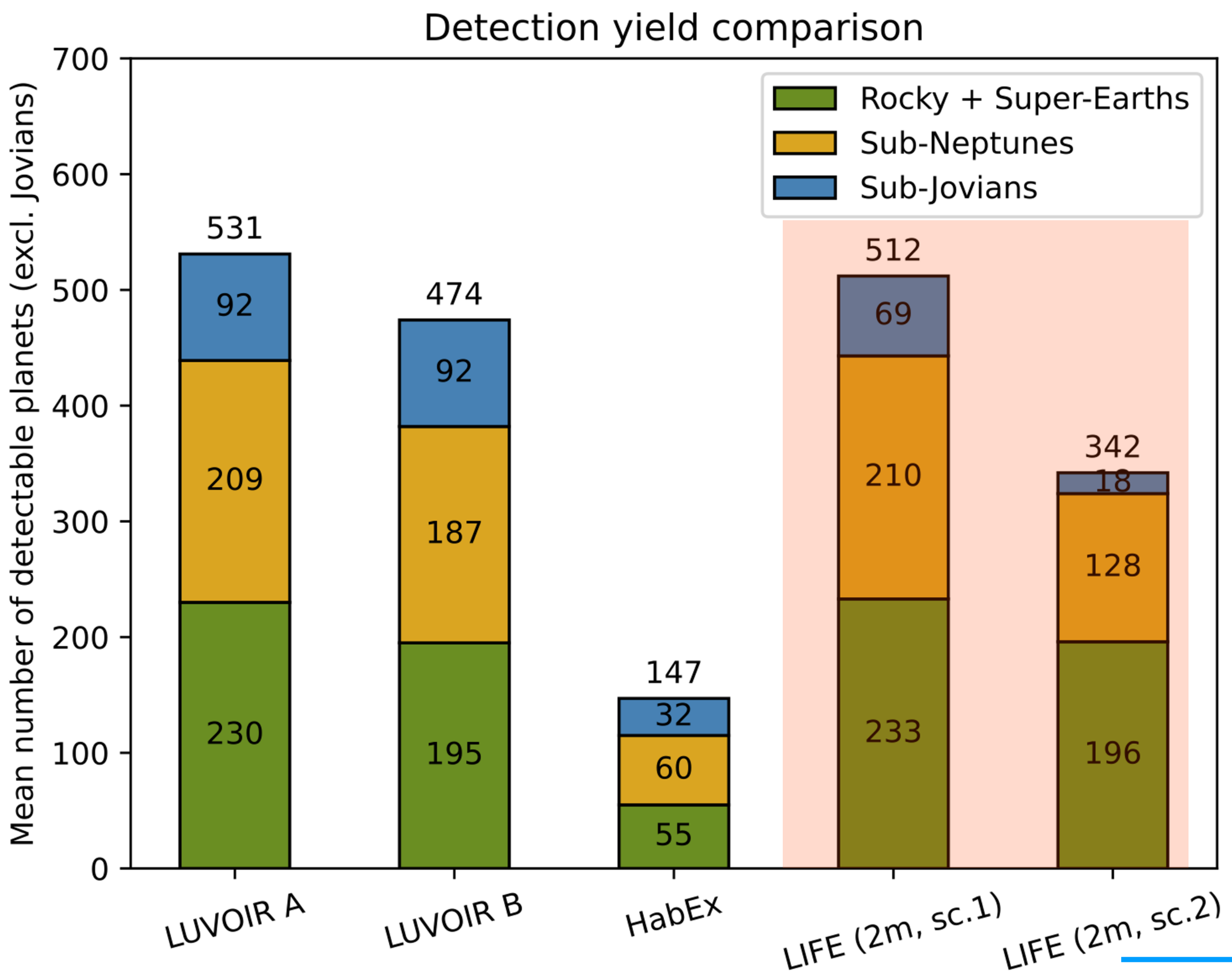


Backup

Everything else

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. A&A 664, A21 (2022)

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)

LIFE: Exoplanet Detection Yield Estimates

Assuming an initial search phase of the mission of 2.5 years

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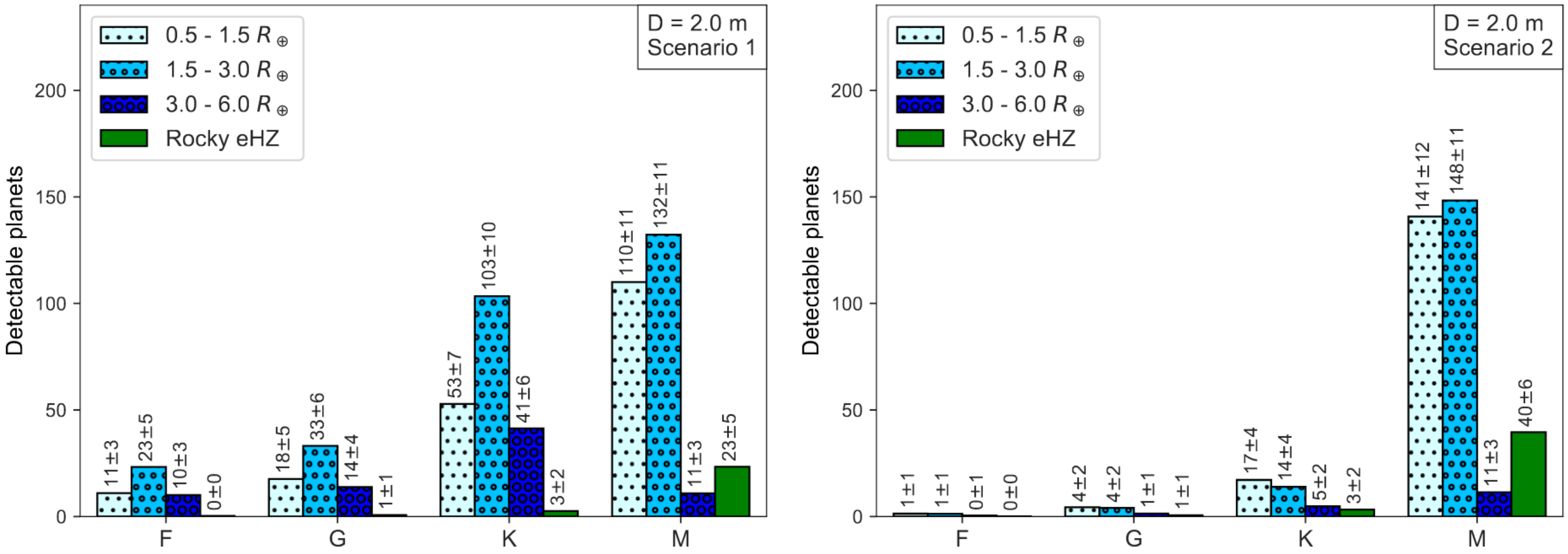
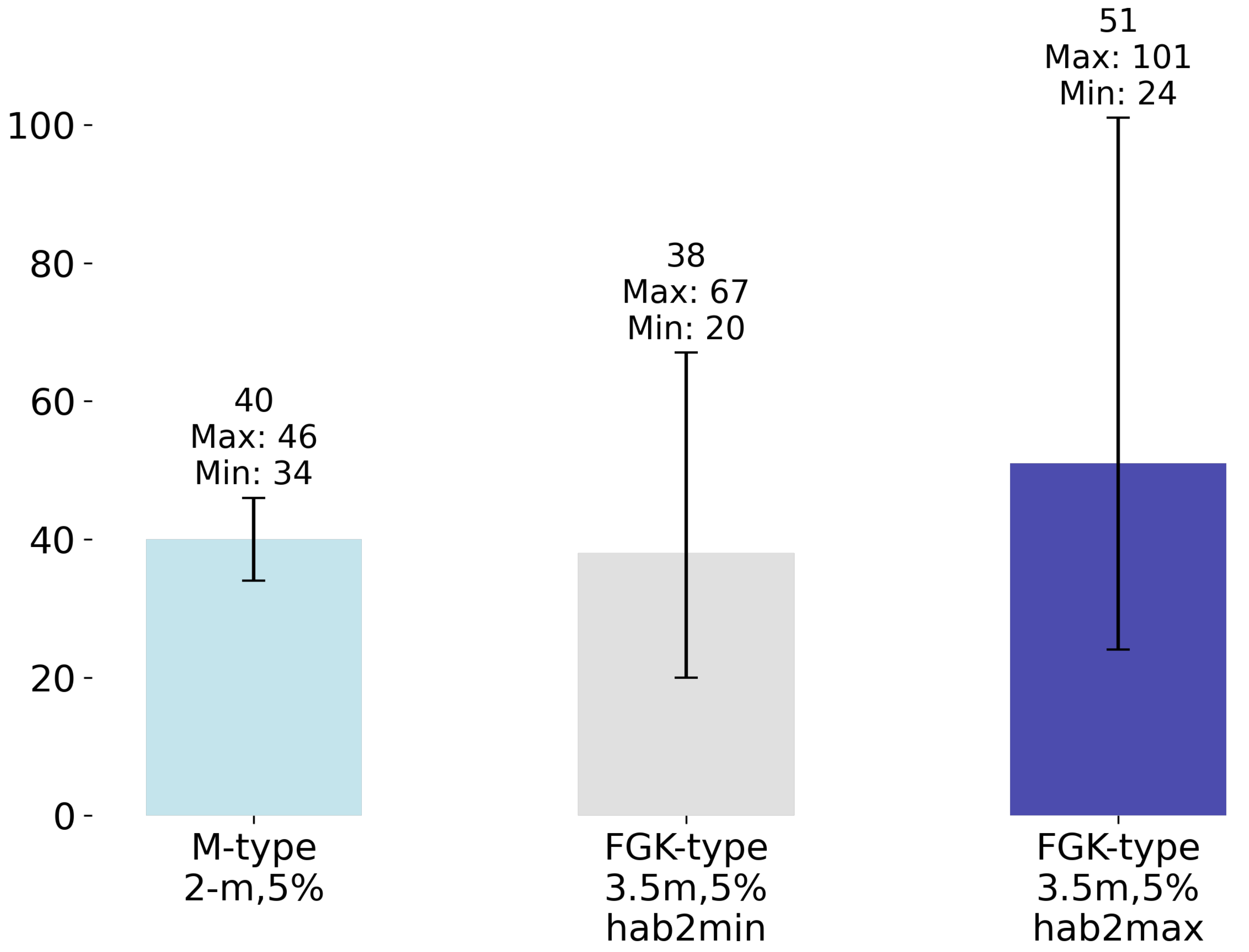
Maximizing **total number** of planets vs. maximizing **rocky planets in habitable zone**



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

LIFE: Detection Yield Estimates for Rocky Planets in HZ

Dominated by large uncertainties and the need for sensitivity

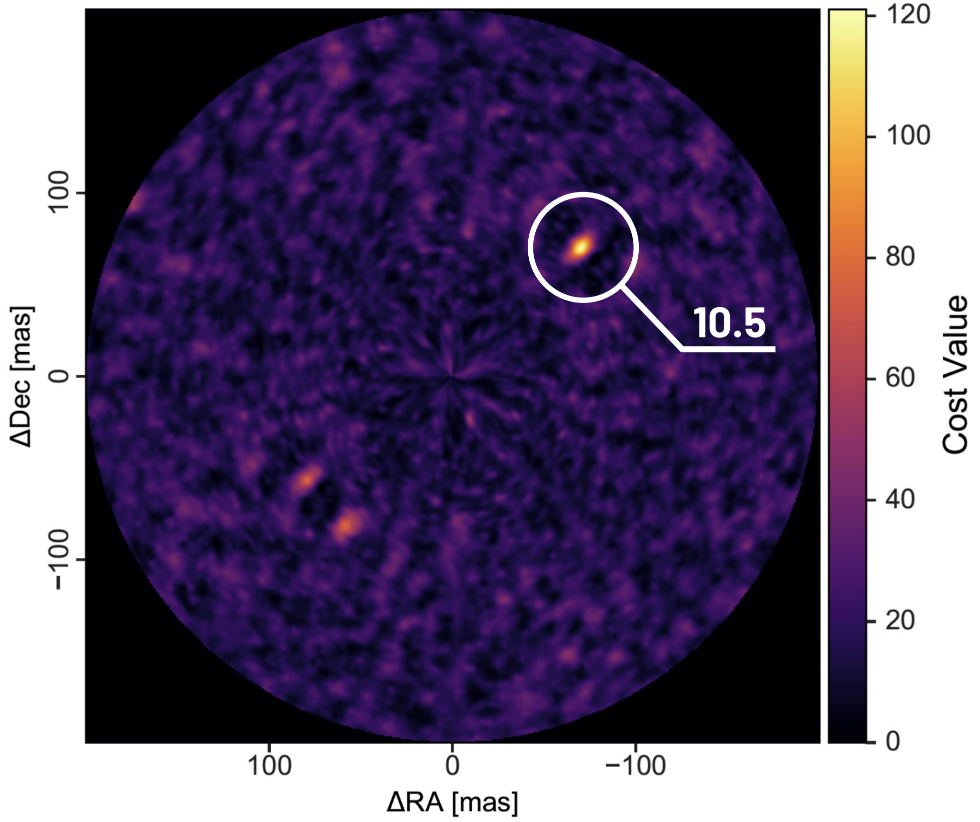


- M-star planet statistic from SAG13
- FGK-star planet statistic from Bryson et al. 2021
- Throughput assumed to be 5%
- Mirror size:
  2m for M-stars
  3.5 m for FGK-stars

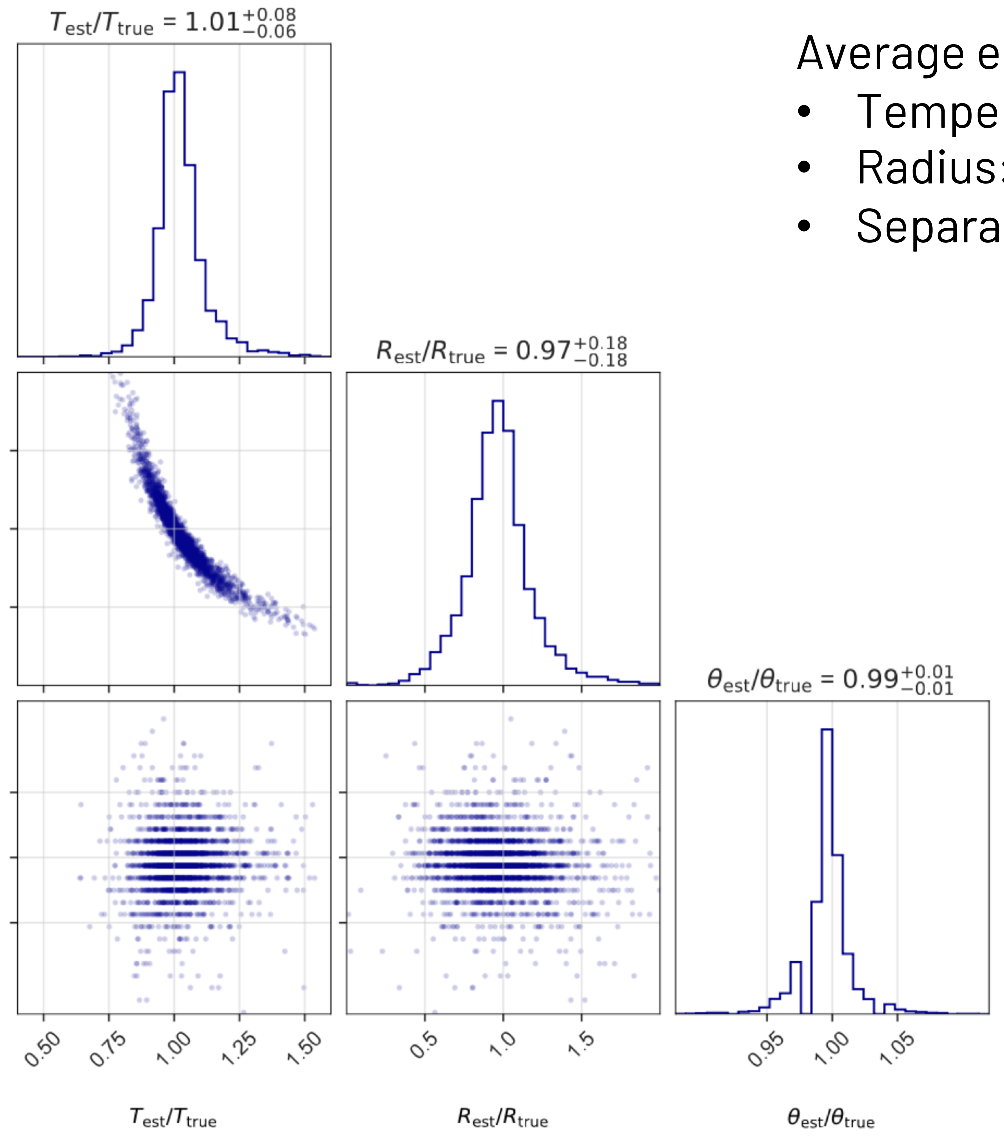
Quanz et al. A&A 664, A21 (2022); Kammerer et al. A&A 668, A52 (2022)

Obtaining critical planet parameters from single epoch data

Rocky planets in habitable zone can be readily identified during search phase



For Earth-analogue at 10 pc,
56 h integration time

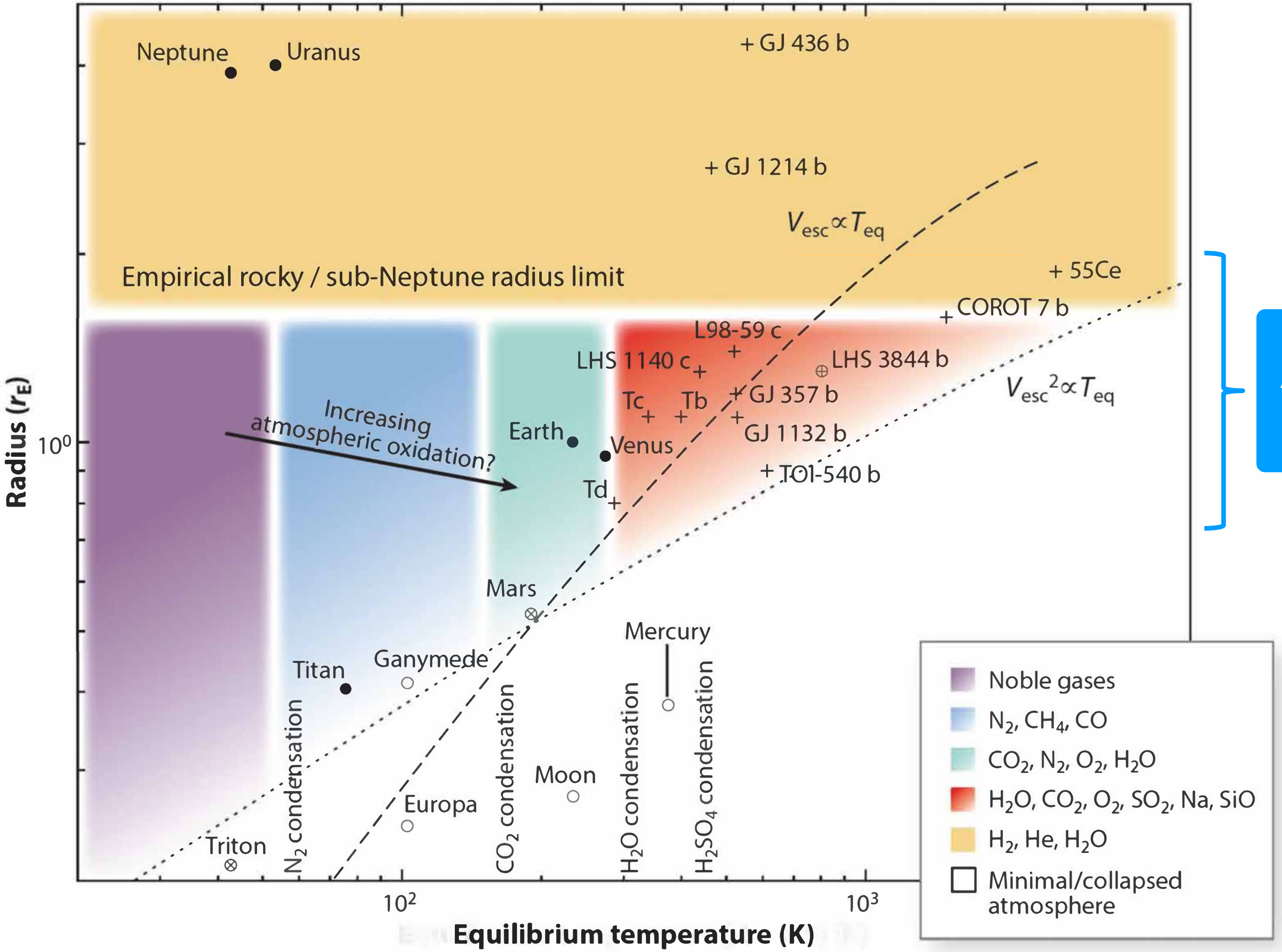


Average error on

- Temperature: ~10%
- Radius: ~20%
- Separation: ~1-2%

Dannert et al. A&A 664, A22 (2022)

LIFE discovery space vs. JWST

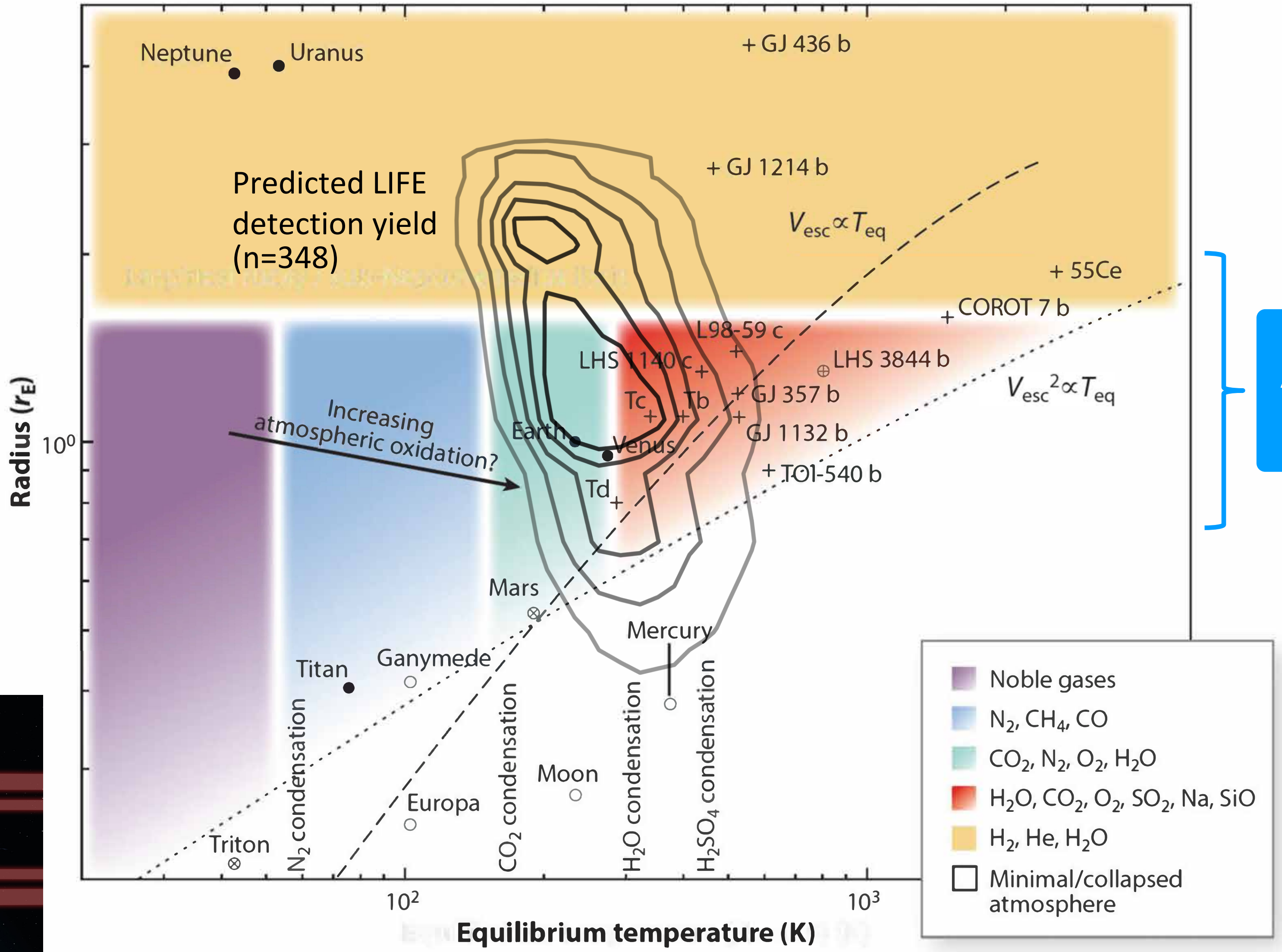


Crosses: All known "rocky-ish" exoplanets to be observed with JWST

Based on Wordsworth & Kreidberg 2022

LIFE discovery space vs. JWST

Primary discovery space of LIFE mission



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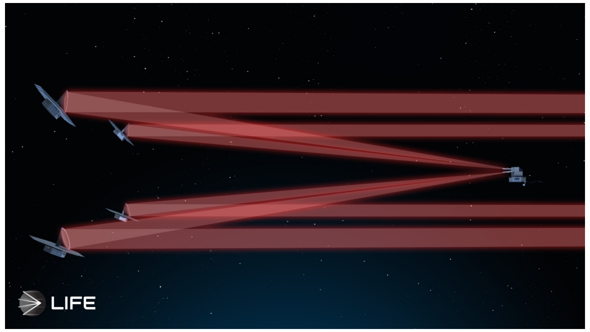

Based on Wordsworth & Kreidberg 2022