INVESTIGATING OTHER WORLDS

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Credits: SPP 1992/Patricia Klein

Towards atmospheric biosignature detection

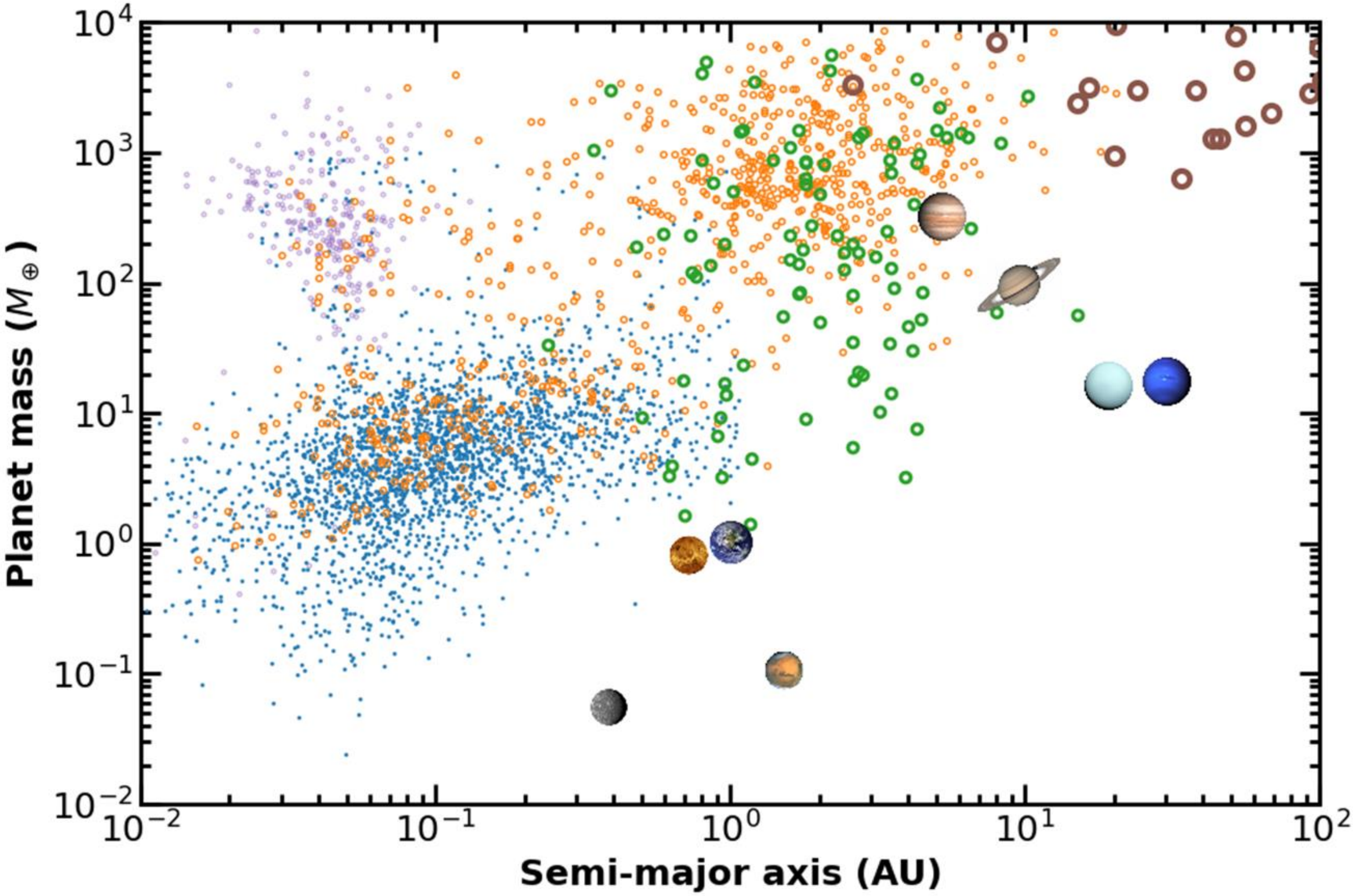
Content

- Exoplanet detection status today
- Where to go from here? - The next steps (space missions)
  - Detection and bulk parameter characterization missions (TESS, CHEOPS, PLATO)
  - Atmosphere characterization missions (JWST, ARIEL)
  - Biosignatures and prospects for their detection (HWO, LIFE)
- Summary

The main science questions for ongoing and upcoming space missions

- How do planets and planetary systems form and evolve?
- Is our solar system unique and are there other systems like ours?
- Are there potentially habitable planets?
- What are planets made of?
- What are the physical processes shaping planetary atmospheres?

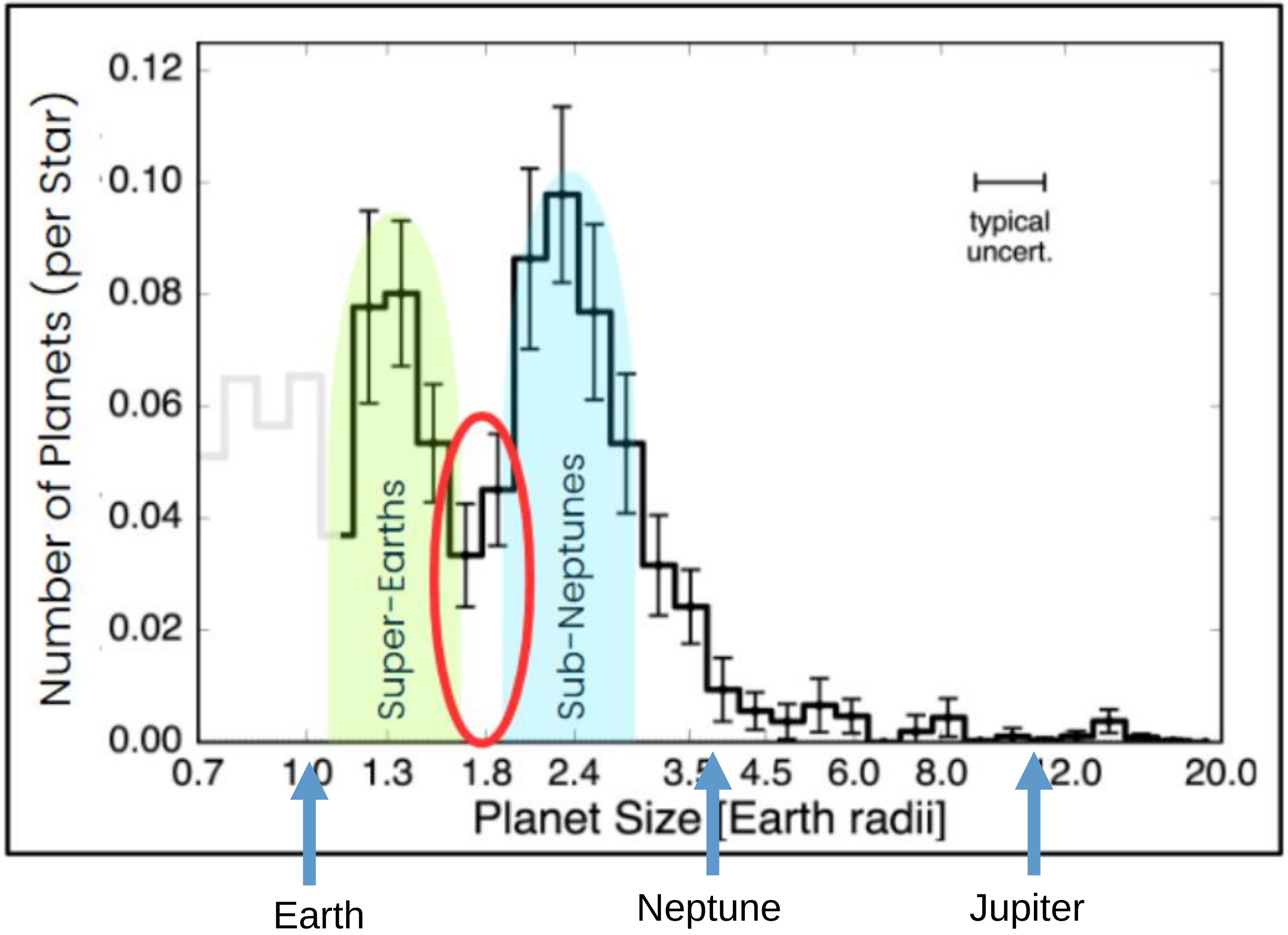
Exoplanet detection status today



- >5200 planets in exoplanet.eu
- >1100 planets with m + r
- ~170 with m<10 M_earth and with r<2 R_earth

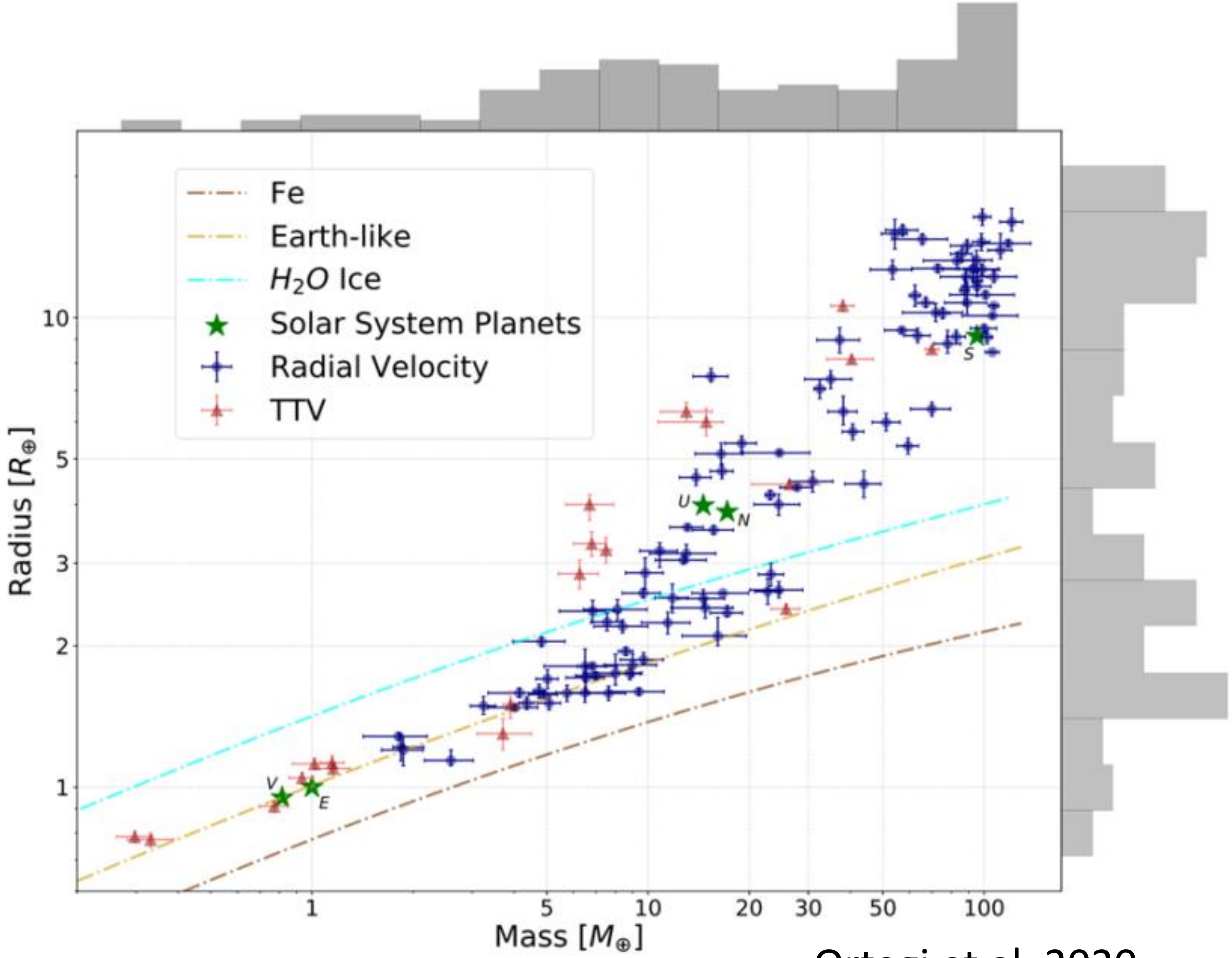
Many more „planet candidates“.

Super-Earths and Mini-Neptunes



Fulton et al. 2017, Fulton & Petigura 2018, van Eylen et al. 2018

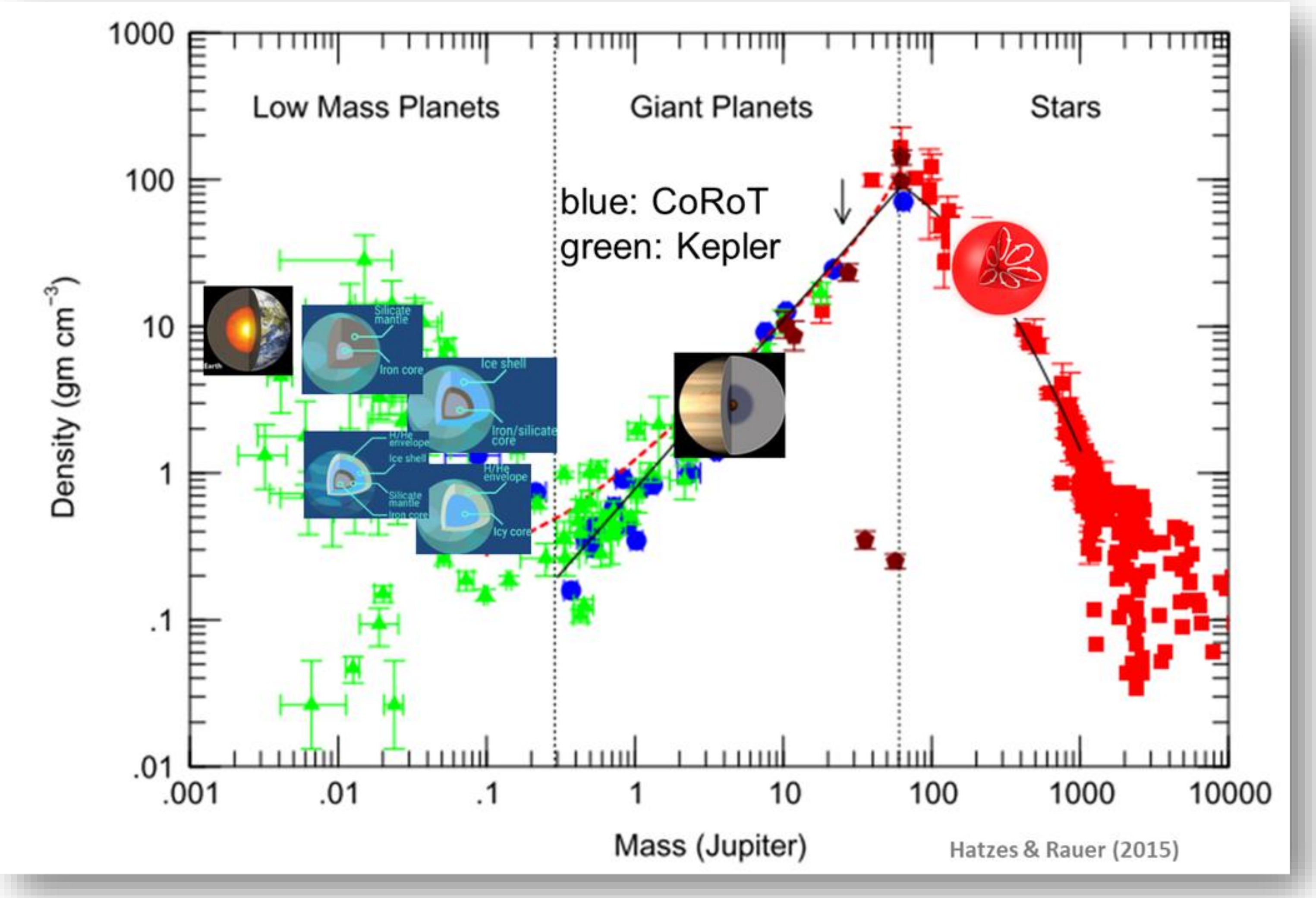
Mass-Radius



Ortegi et al. 2020

Mass-radius provide a rough indication on the nature of a planet: terrestrial – gas giant – brown dwarf

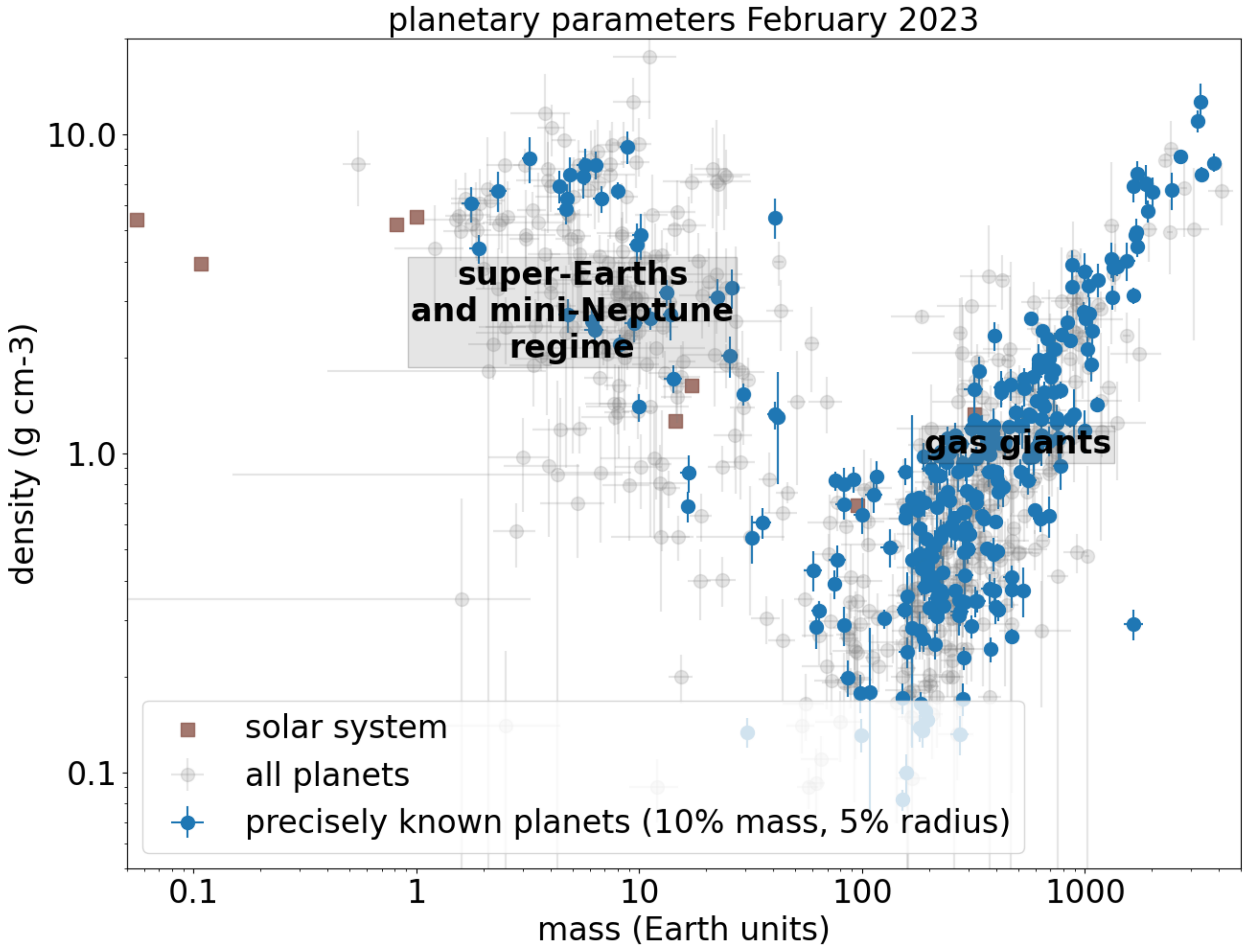
Mean density



Hatzes & Rauer (2015)

Mean density

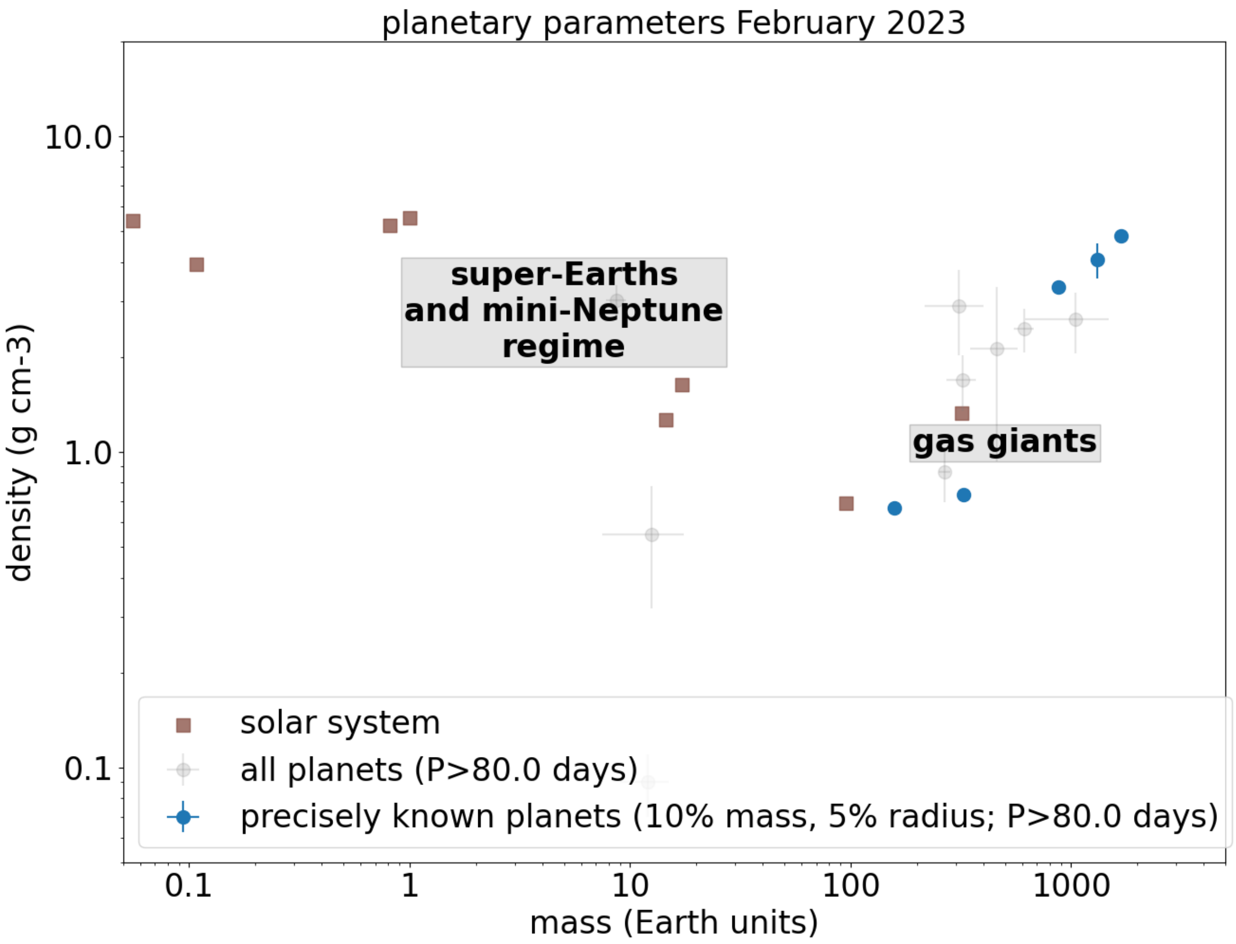
All orbital periods



Rauer et al., 2024

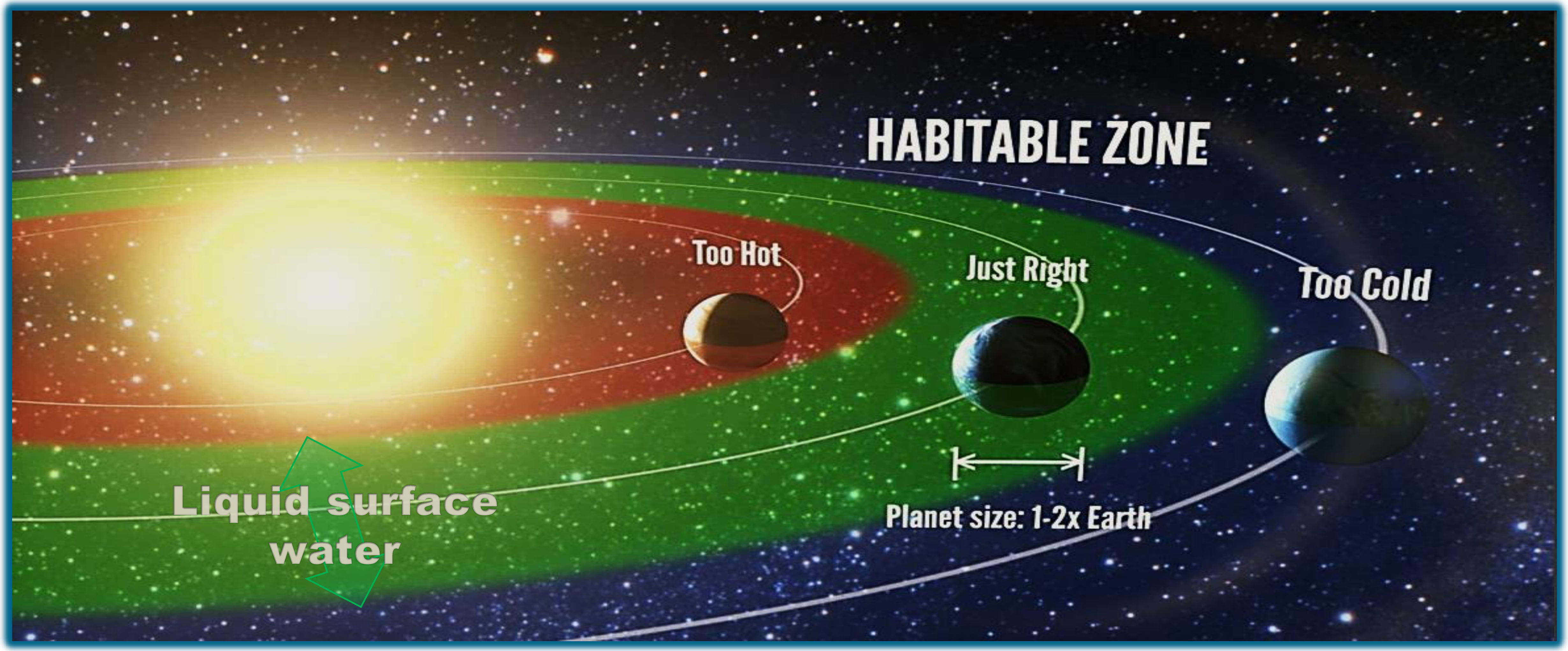
Mean density

Orbital Periods >80 days



Rauer et al., 2024

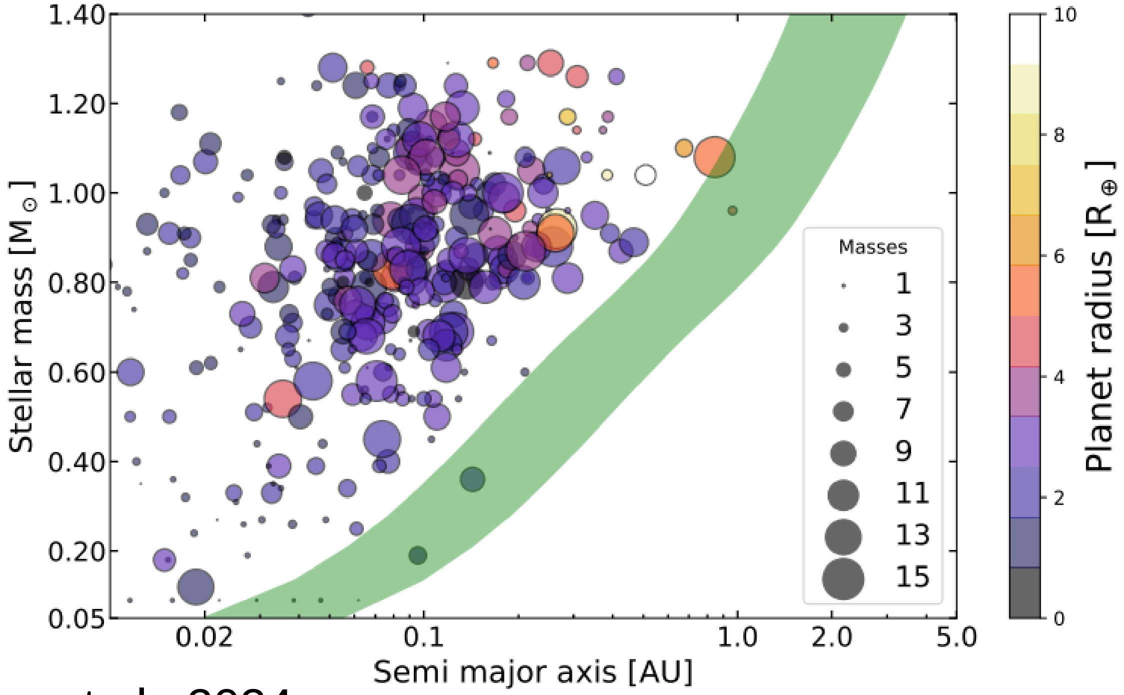
How about planets in the habitable zone?



Planets in the habitable zone

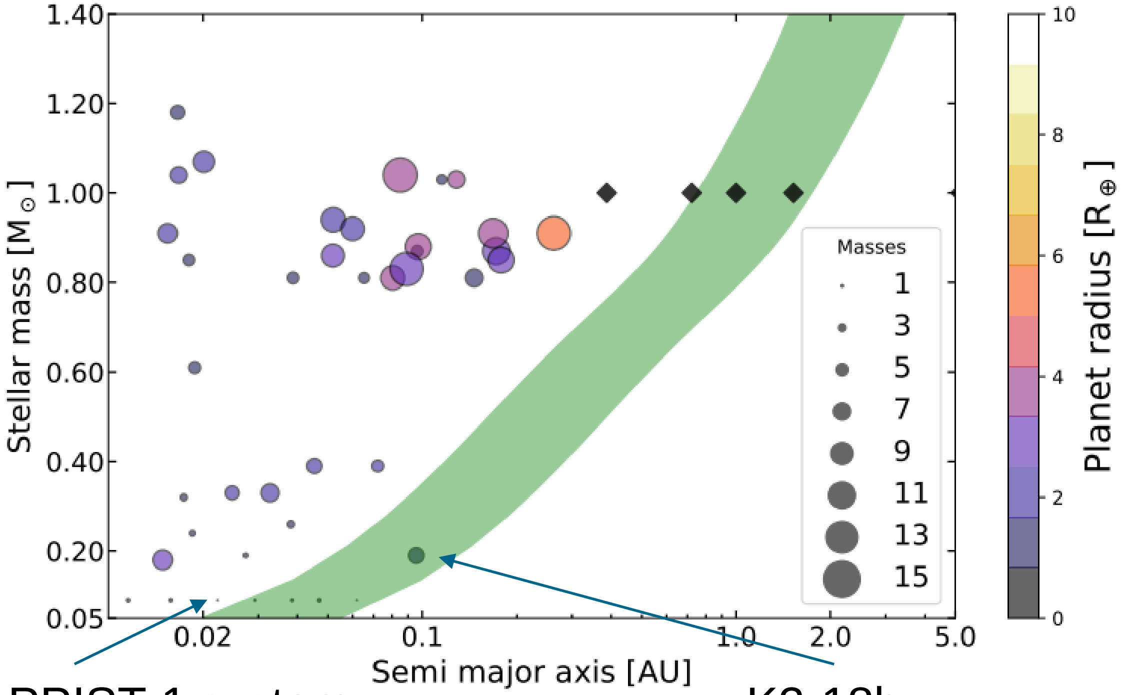
Few small planets in the habitable zone known today.

Mass <15 Mearth, radius <10Rearth



Rauer et al., 2024

With <10% mass and <5% radius precisions



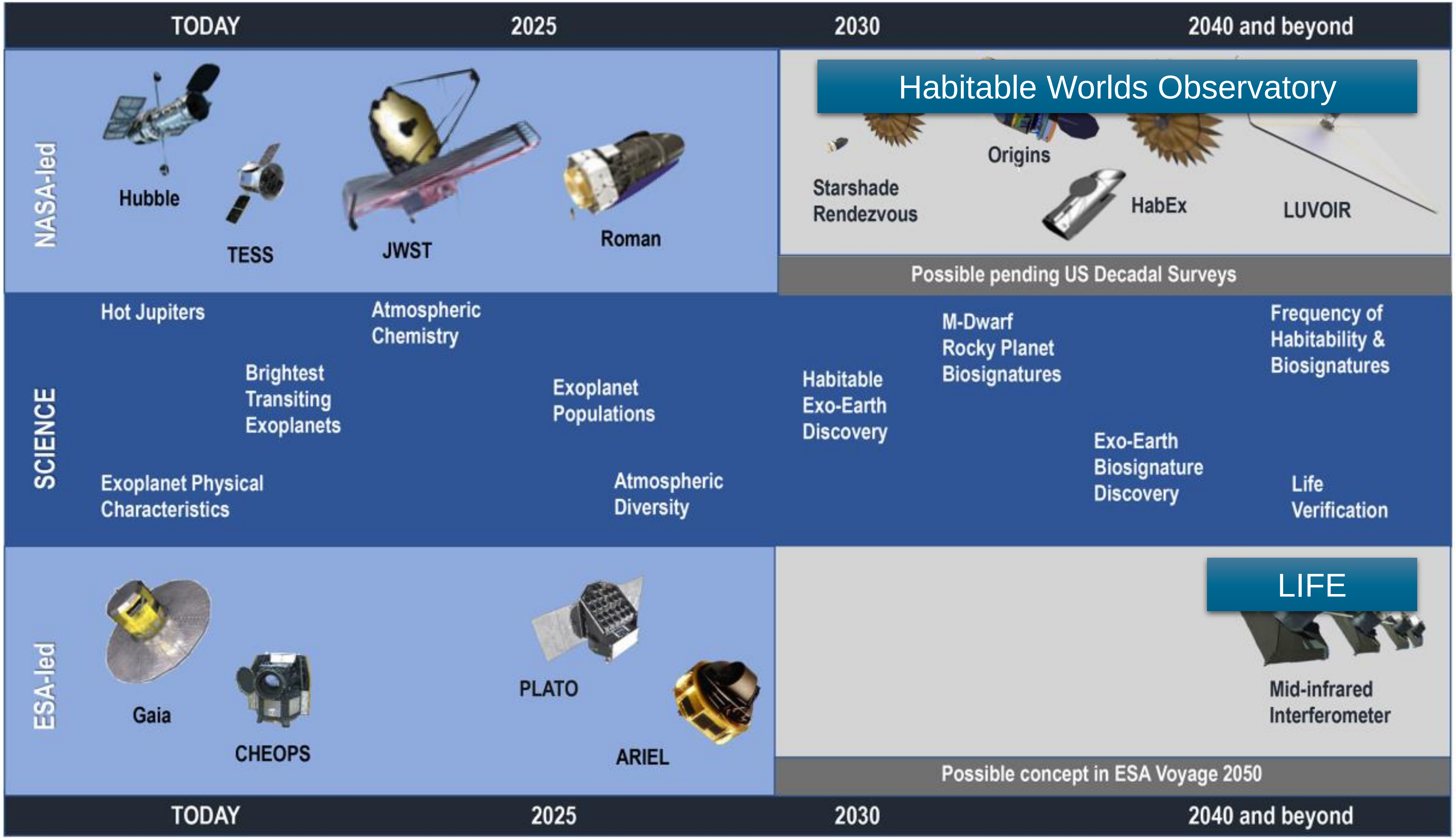
TRAPPIST-1 system

K2-18b

Where to go from here?

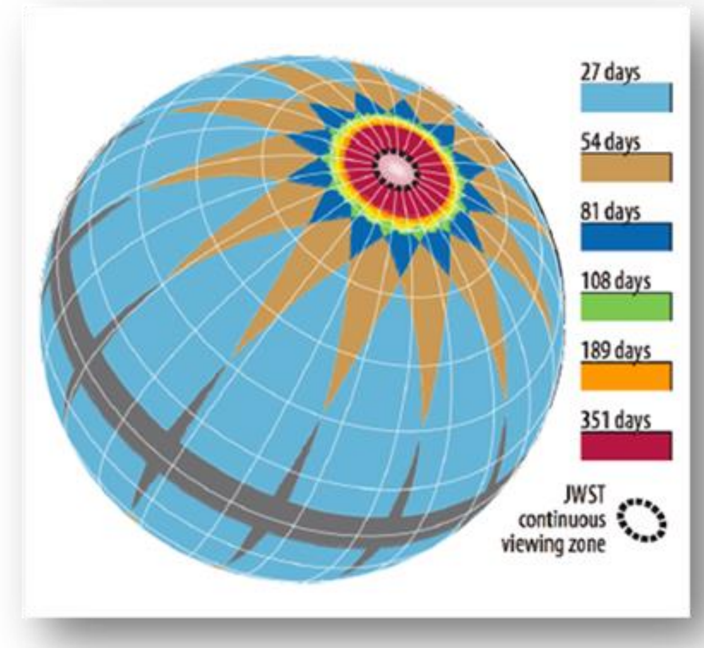
The next basic steps…:

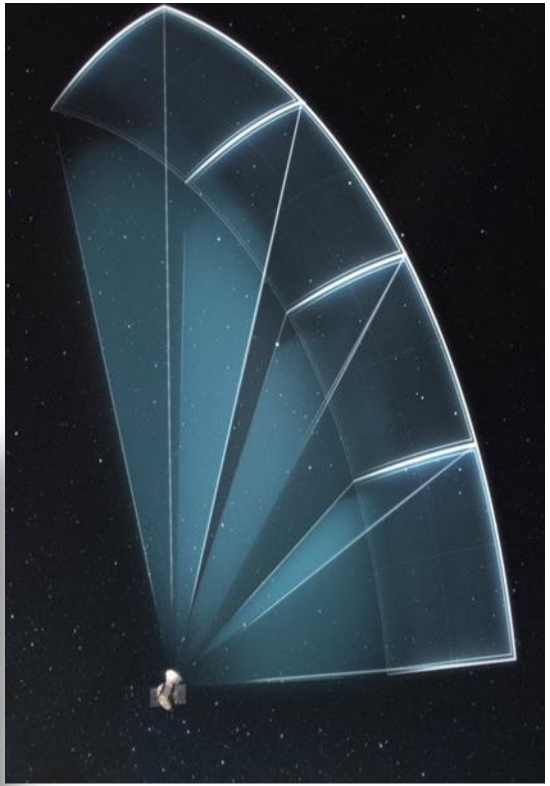
- Detect and characterize exoplanets and determine bulk (main) properties
- Detect atmospheres and link to interiors
- Detect habitable planets and biosignatures



Stapelfeldt et al. 2021

TESS Mission (NASA)

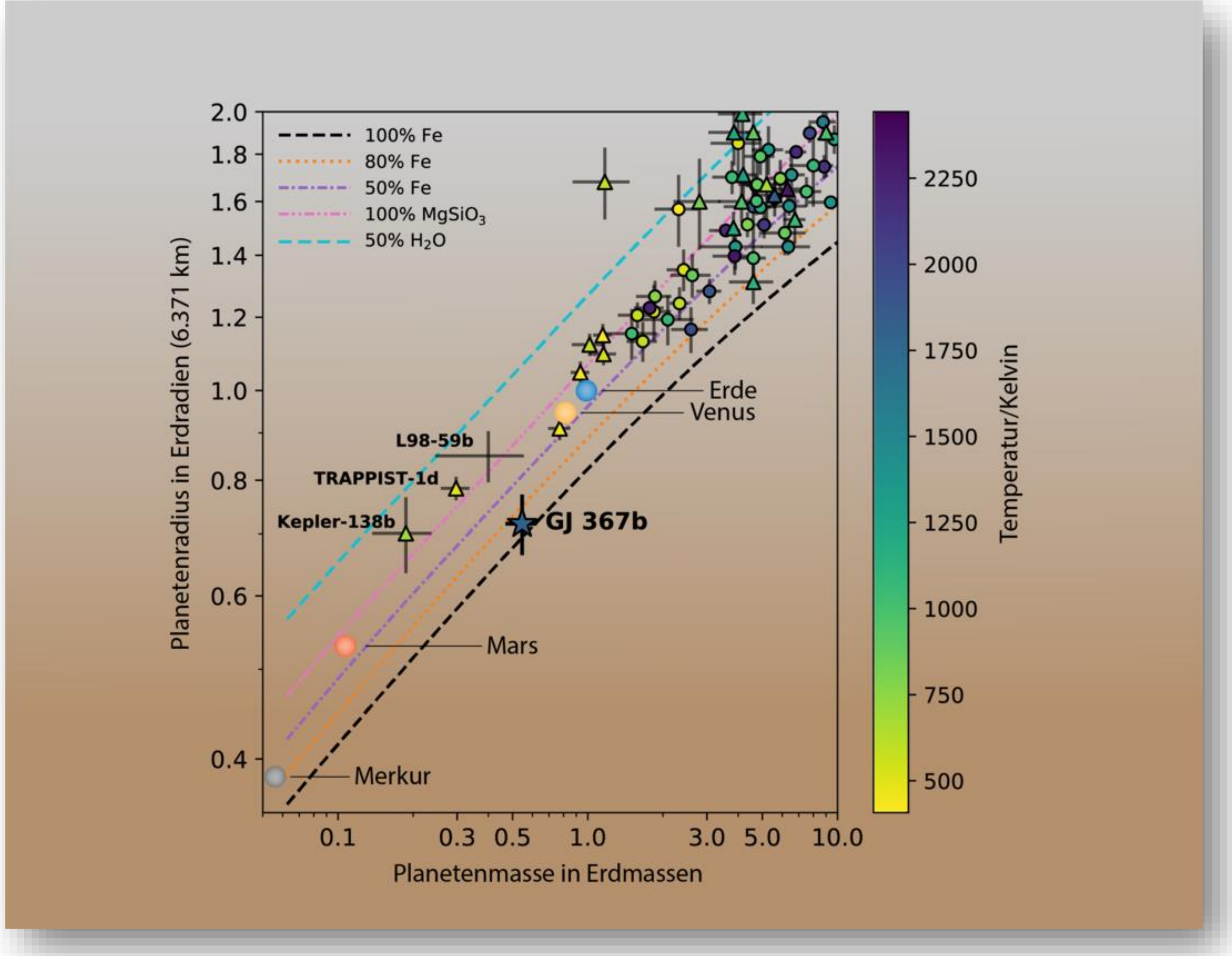




Figures: NASA

- Launched April 2018
- 4 telescopes with 10cm aperture
- All-sky survey
- Goal: short-period transiting planets around bright stars

Ultra-light and super-fast: GJ 367b

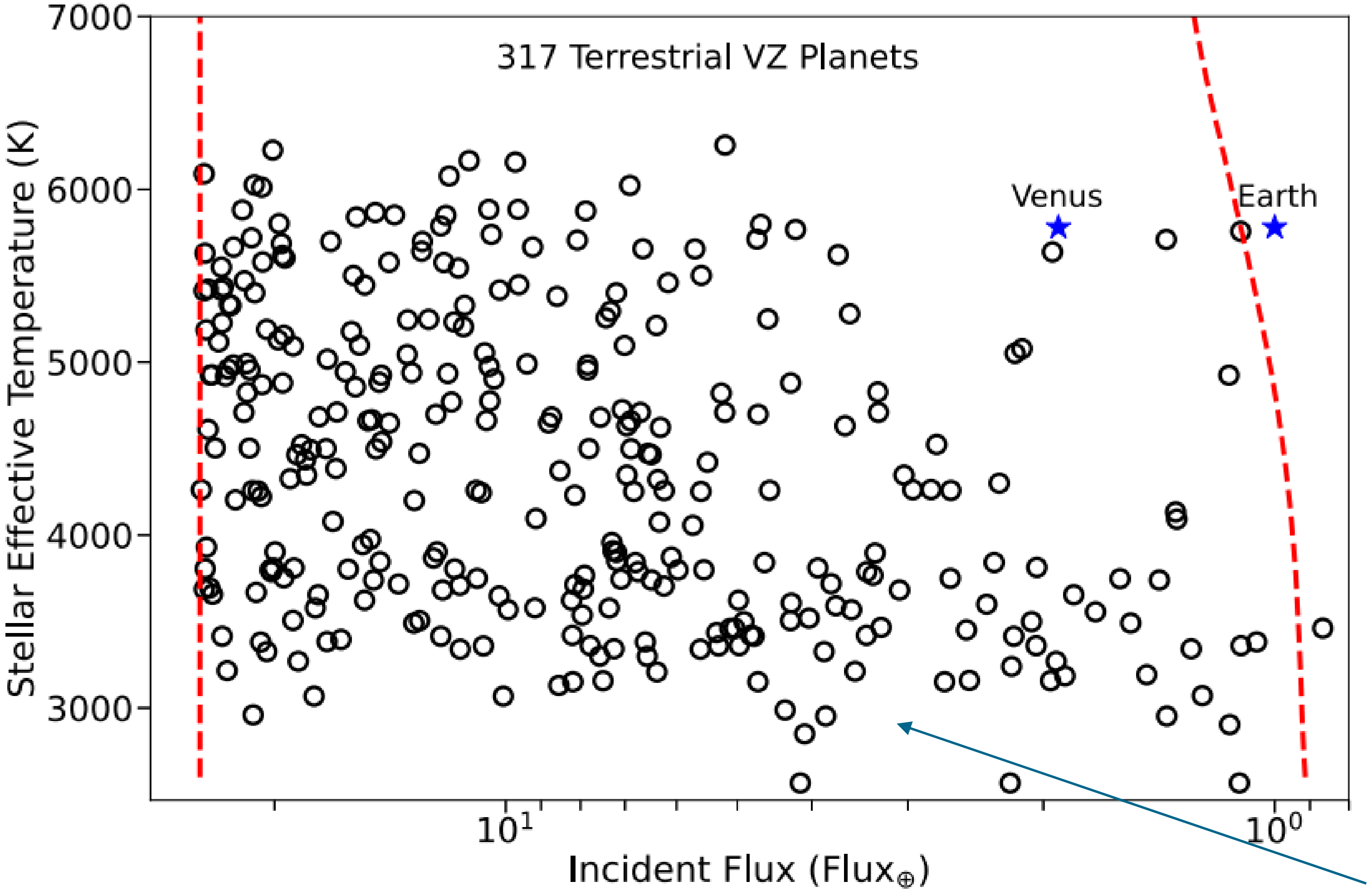


(Lam et al. 2021).

Radius: 0.72 R_earth
Mass: 0.55 M_earth
Density: 8.1 g/cm^3
Obital Period: 7.7 hours

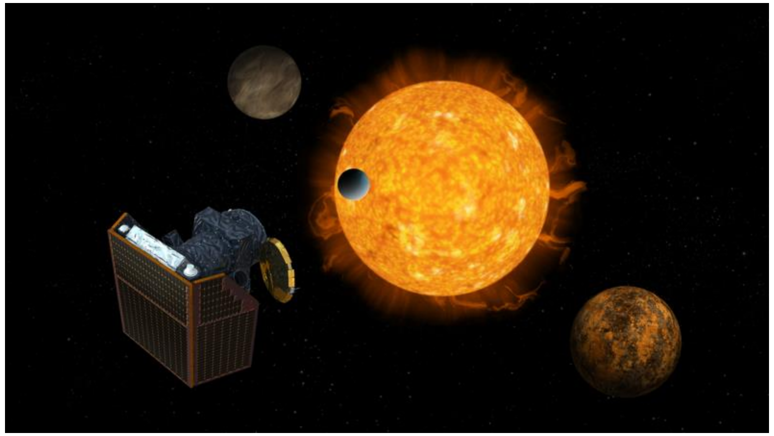
→ GJ 367b: a super-Mercury?

Hundreds of known <2R_earth exoplanets in the Venus Zone discovered by TESS (Ostberg et al., 2023)



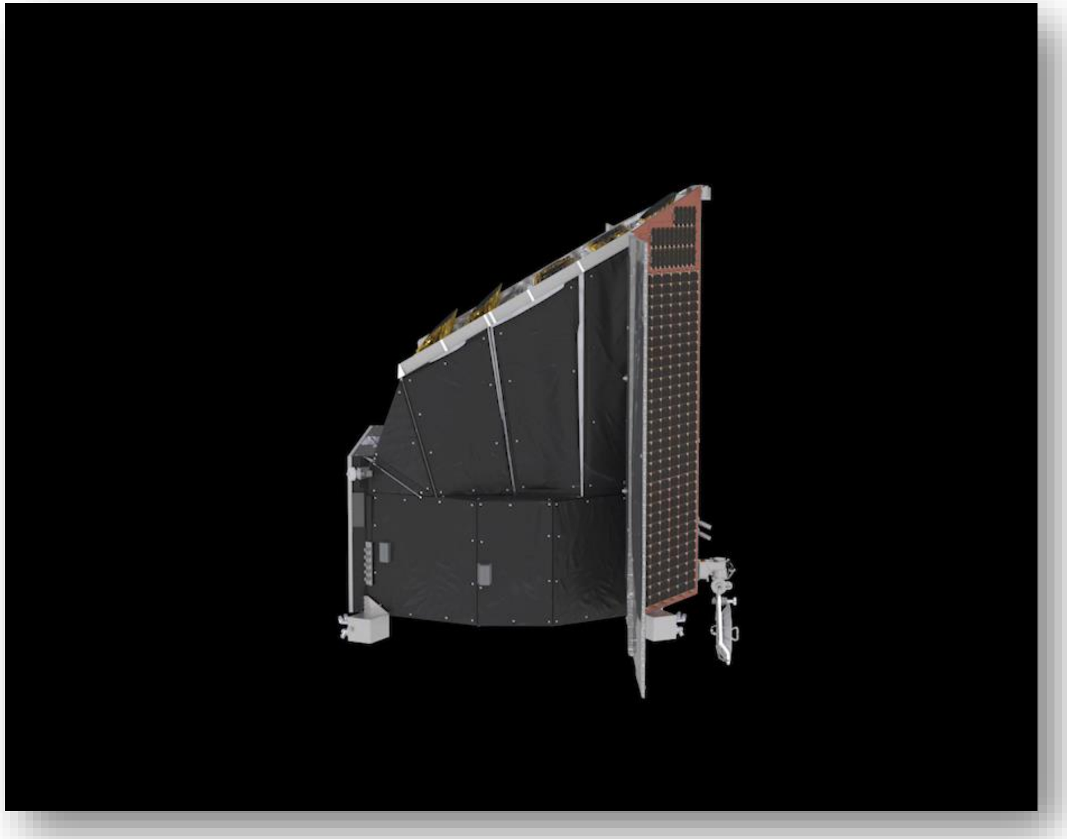
potentially Venus-type planets

CHEOPS Mission (ESA)



- First ESA S-class mission
- Launched December 2019
- Telescope with 30cm aperture
- 19x19 square degrees field-of-view
- Goal: determine precise radii of known exoplanets

PLATO Mission (ESA)
(PLAnetary Transits and Oscillations of stars)

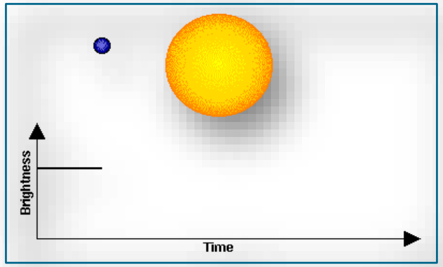


ESA/ATG medialab

- ESA M3 mission
- Launch December 2026
- 26 telescopes with 12cm aperture each
- First 10 flight model cameras completed
- ~49°x 49° field-of-view
- High precision photometry : $4 \leq m_V \leq 11$ (13)
- 4 years mission operations (8.5 yrs consumables)
- Goal: Detect and characterize (radius, mass, age) exoplanets, including small planets in the habitable zone of solar-like stars.

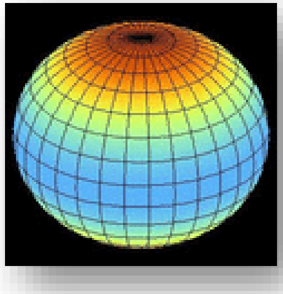
The PLATO Mission

Methods:



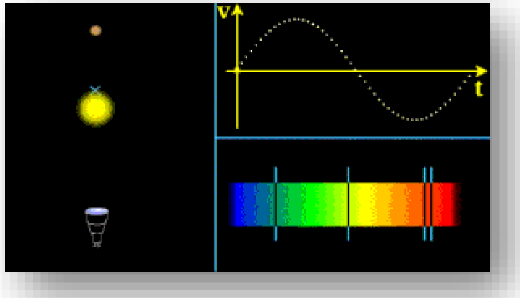
Transit detection

→ Planet/star radius ratio
→ Inclination



Asteroseismology

→ Stellar radius, mass
→ Stellar age



Ground-based observations

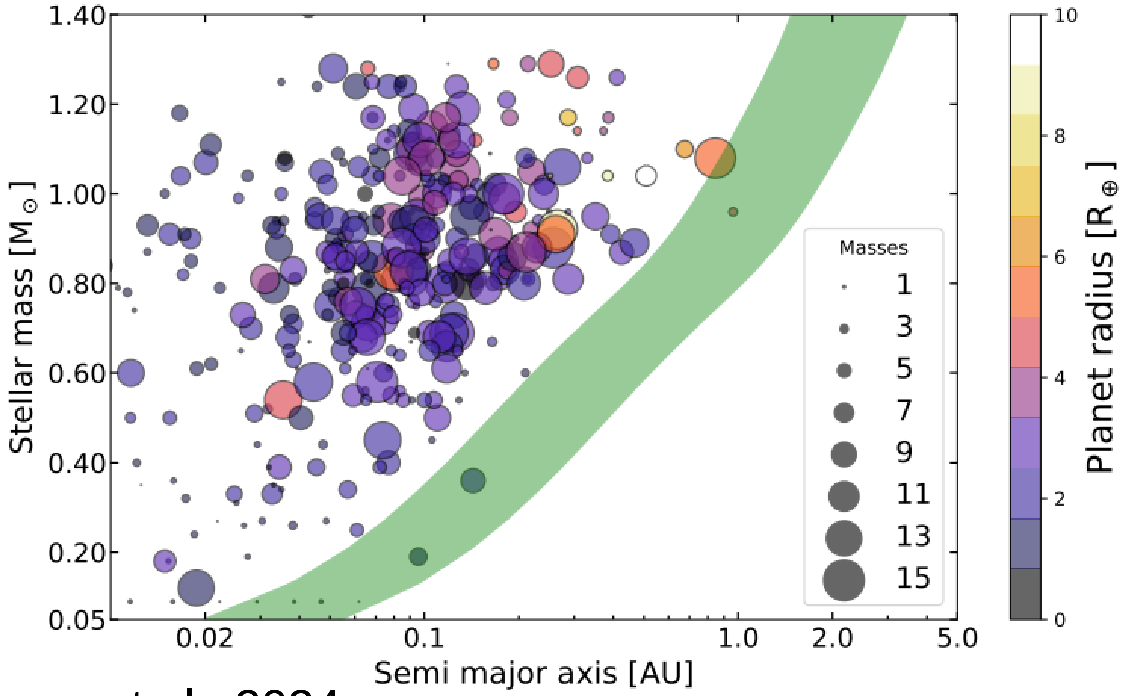
→ Planet mass

- **Mean density**
- **Age**

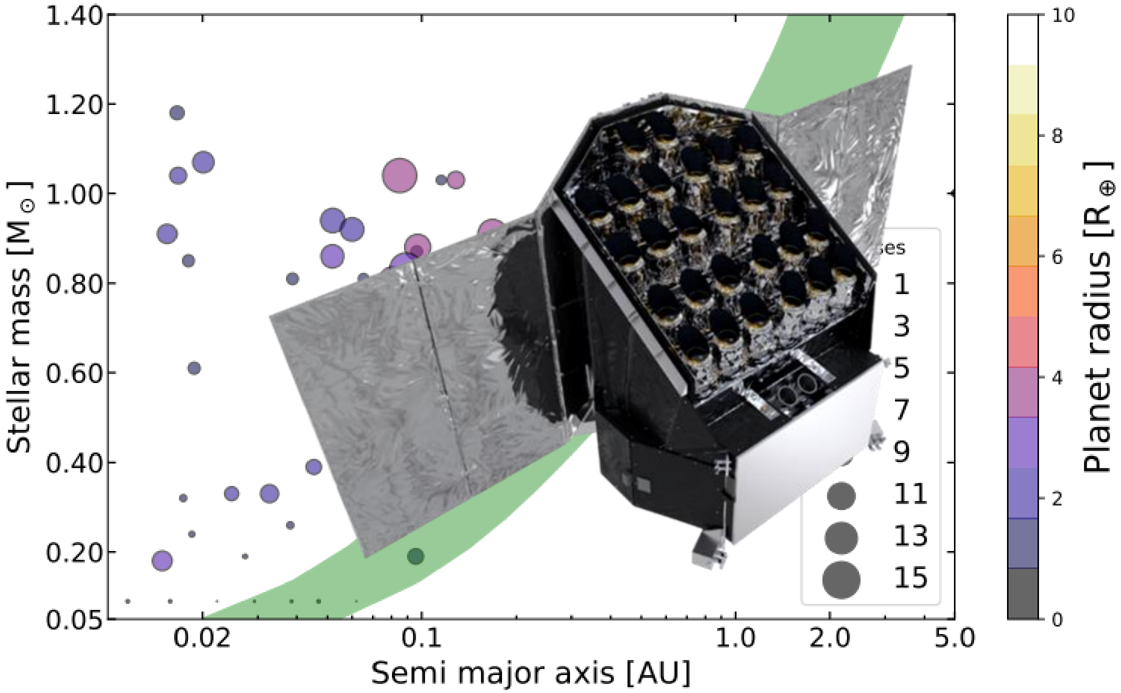
Small planets in the habitable zone

Mass <15 M_earth, radius <10R_earth

With <10% mass and <5% radius precisions



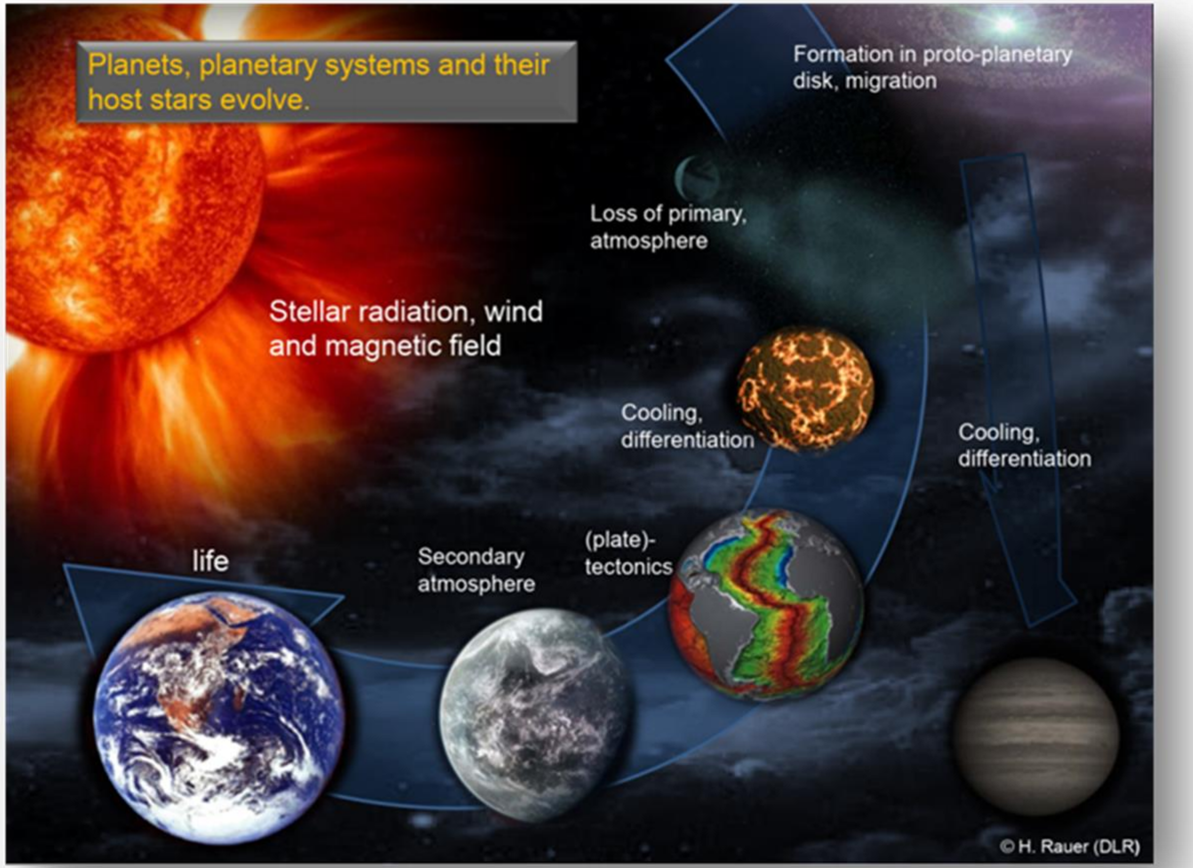
Rauer et al., 2024



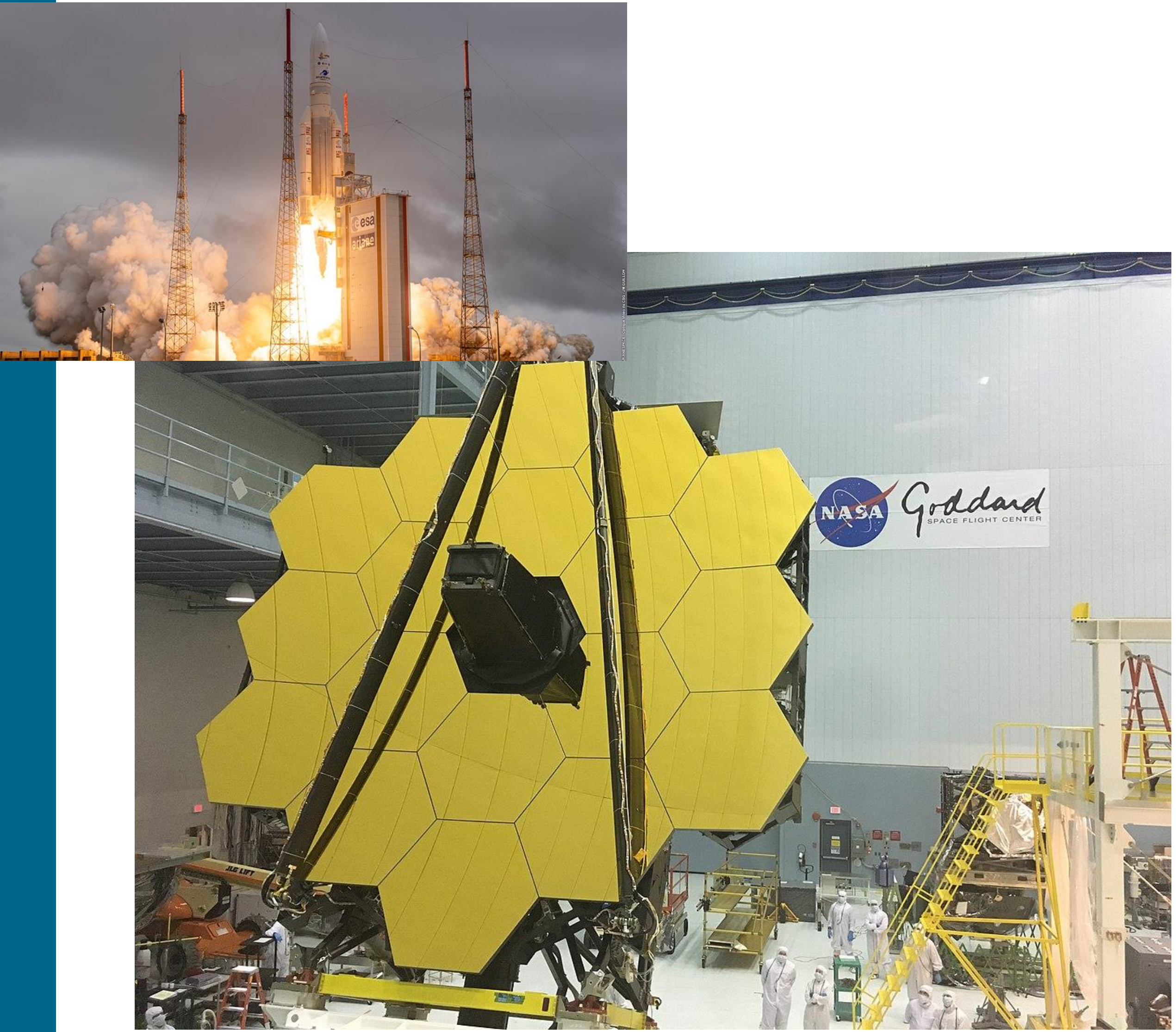
Studying habitability – it is a big puzzle to solve..

Combine well-known ages and spectroscopic observations (JWST, ARIEL, HWO, LIFE):

- When does the magma ocean phase for terrestrial planets end?
- At which ages can we identify habitable conditions?
- How does atmosphere composition vary with age and stellar environment?
- Are our model time scales for the evolution of gaseous planets correct?

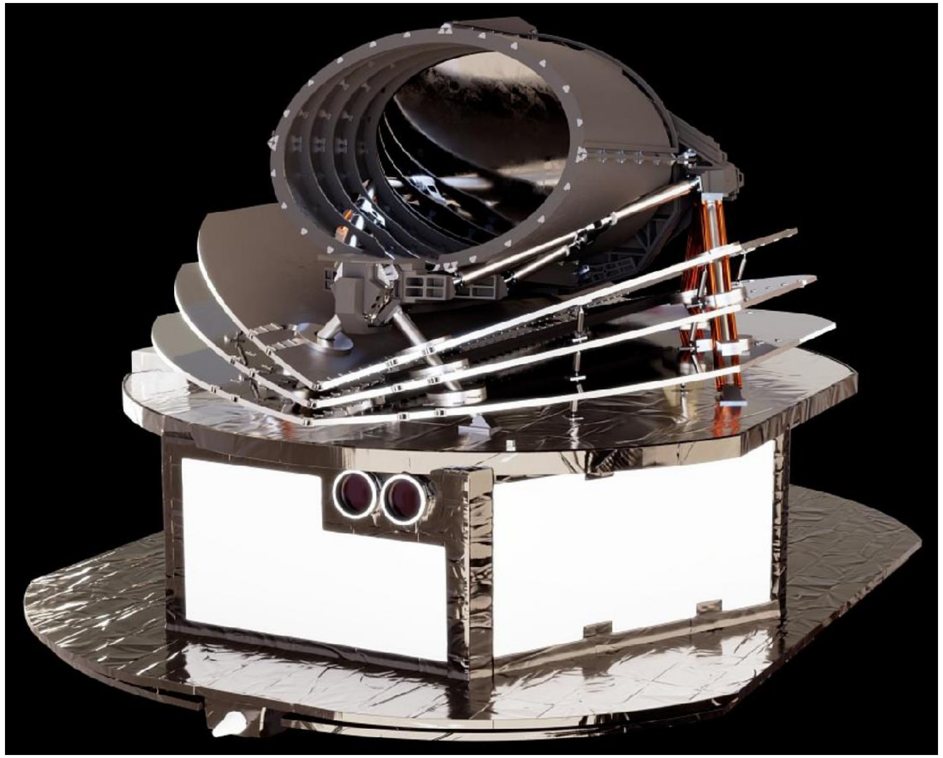


James-Webb-Telescope (NASA/ESA)



- Launch: December 2021
- Segmented mirror: 6.5 m aperture
- Instruments: Cameras and spectrometers from 0.6 to 28.8 micron
- Orbit: L2
- Goals: Astronomy, Exoplanets

ARIEL (Atmospheric Remote-Sensing Infrared Exoplanet Large-survey)



Credit: Airbus

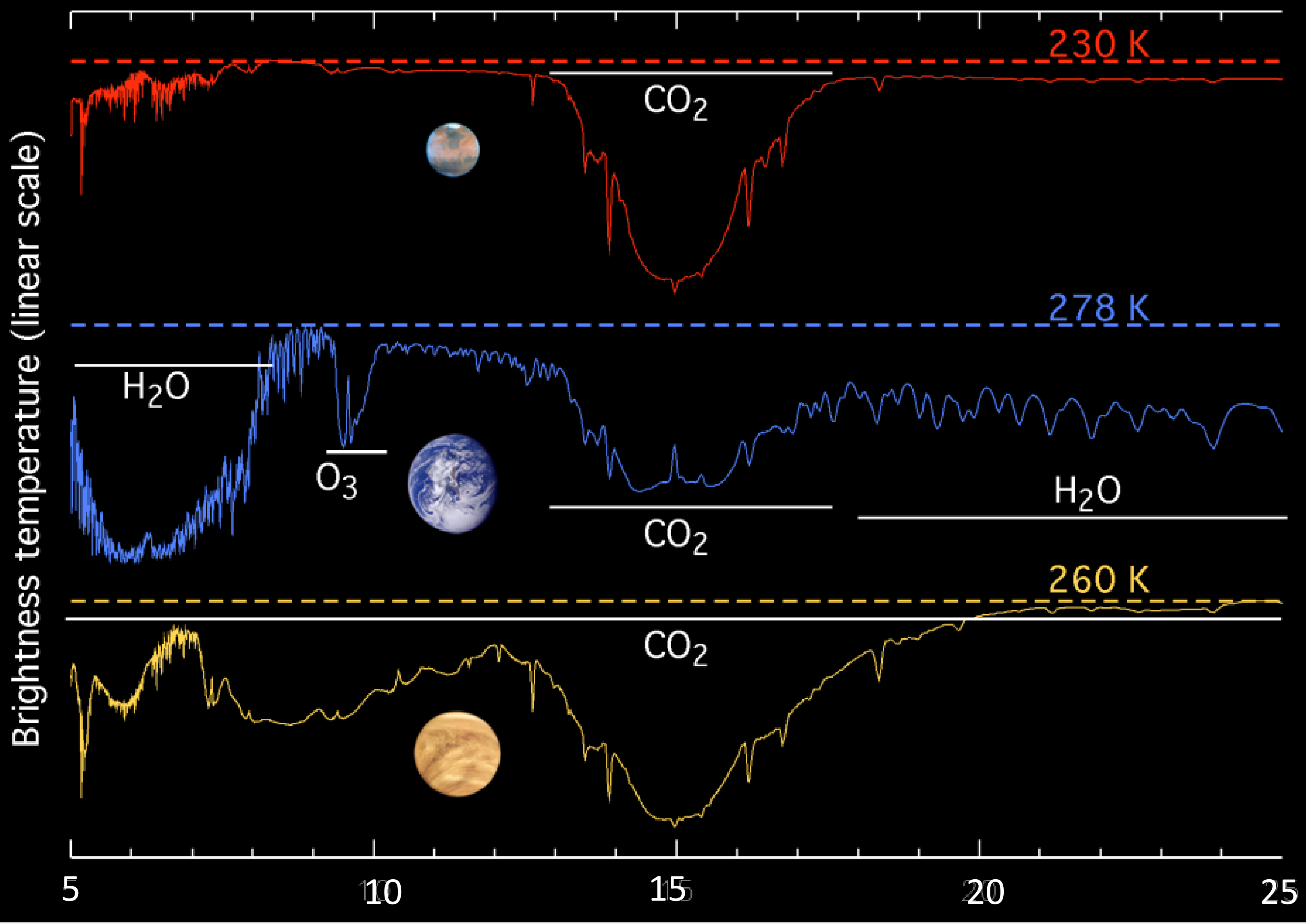
- ESA M4 mission
- > 0.6m2 collecting area telescope
- Definition study phase (B1) completed
- Launch planned in 2029
- 4 year mission lifetime
- Dedicated survey mission for transit and eclipse spectroscopy as well as phase-curves
- Infrared spectrometer from 0.5 to 7.8 µm
- Spectral resolution ~100
- Transit of ~1000 planets (Gas giants, Neptunes, super-Earths and Earth-size)

Biosignatures: Diversity of Life on Earth

(Some) Atmospheric Biosignatures

Species	Biotic Source	Abiotic Source
Oxygen (Ozone)	**Cyanobacteria**	CO_2+hv H_2O+hv H escape
Nitrous Oxide	**(De)nitrifying Bacteria**	Photochemistry Energetic Particles
Methane	**Methanogens**	geology
Chloromethane	**Phytoplankton**	photochemistry

Atmospheric Spectra: Mars Earth Venus

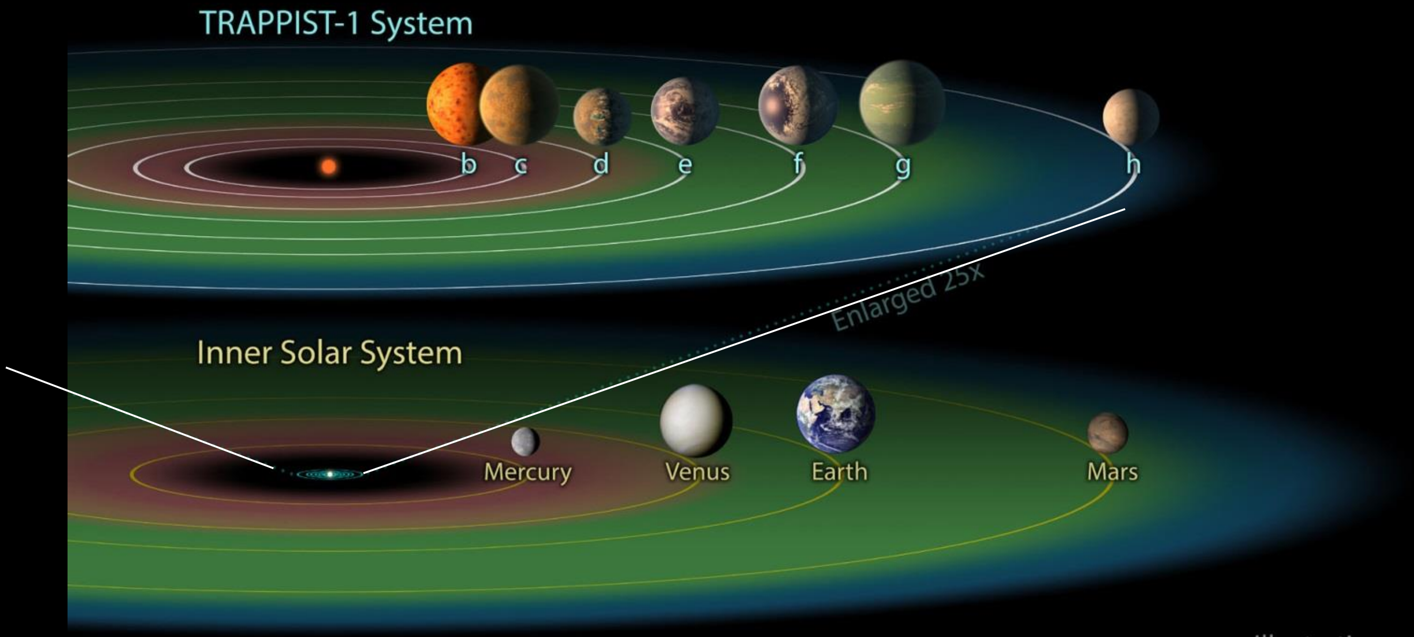


Wavelength (microns)

See Cockell et al. (2009) and references therein

TRAPPIST-1 – a second solar system?

A system with rocky planets in the habitable zone: TRAPPIST -1

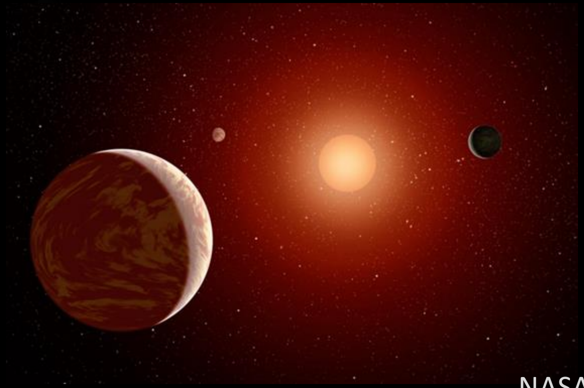


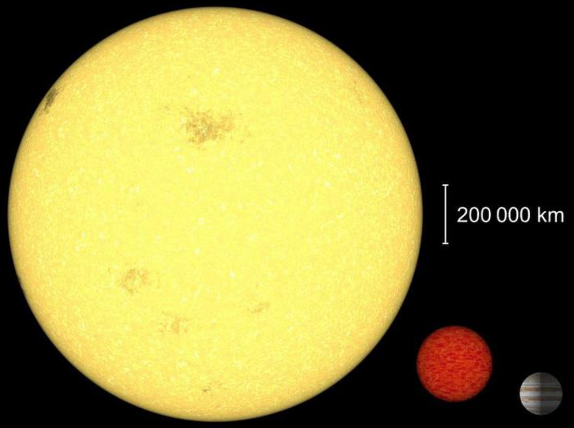
Illustration

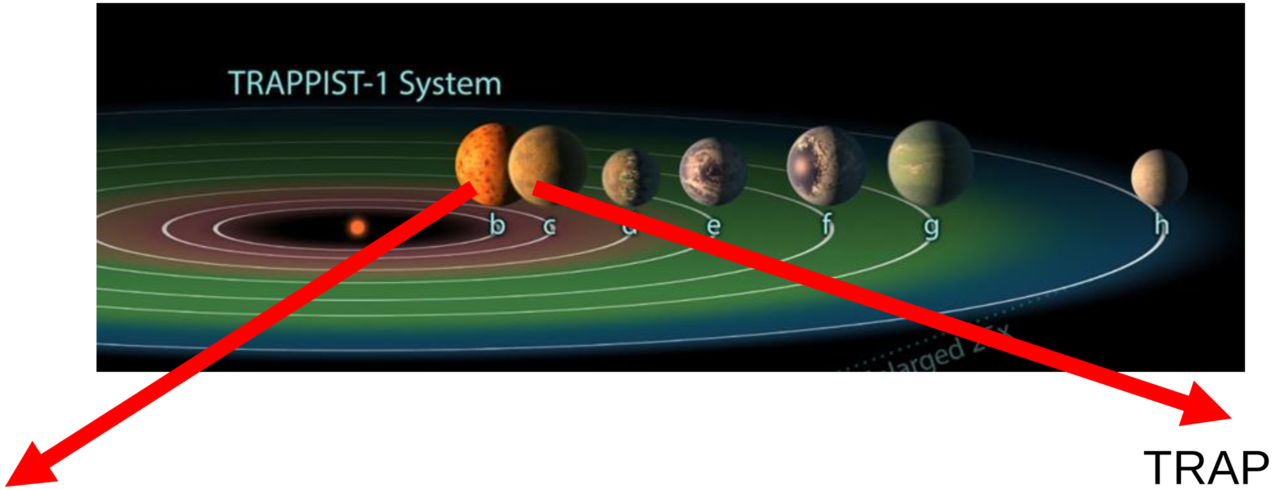
- 7 planets orbiting an M dwarf star

M. Gillon et al. 2017

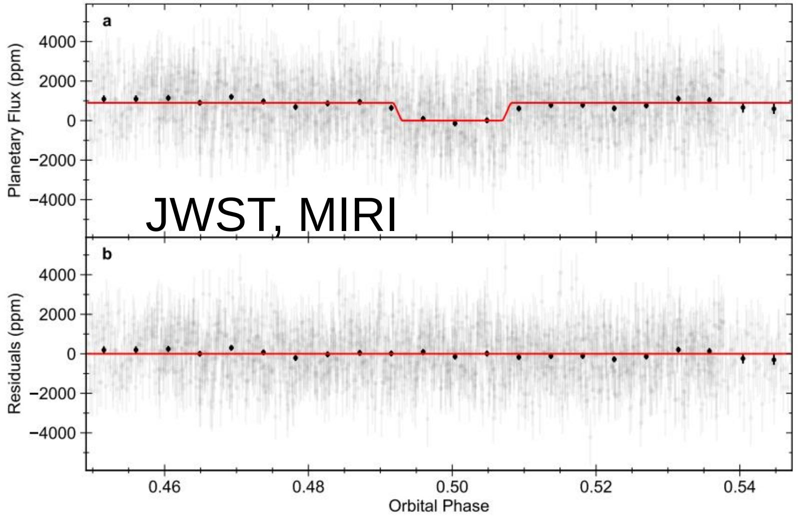

TRAPPIST


NASA





TRAPPIST-1 b

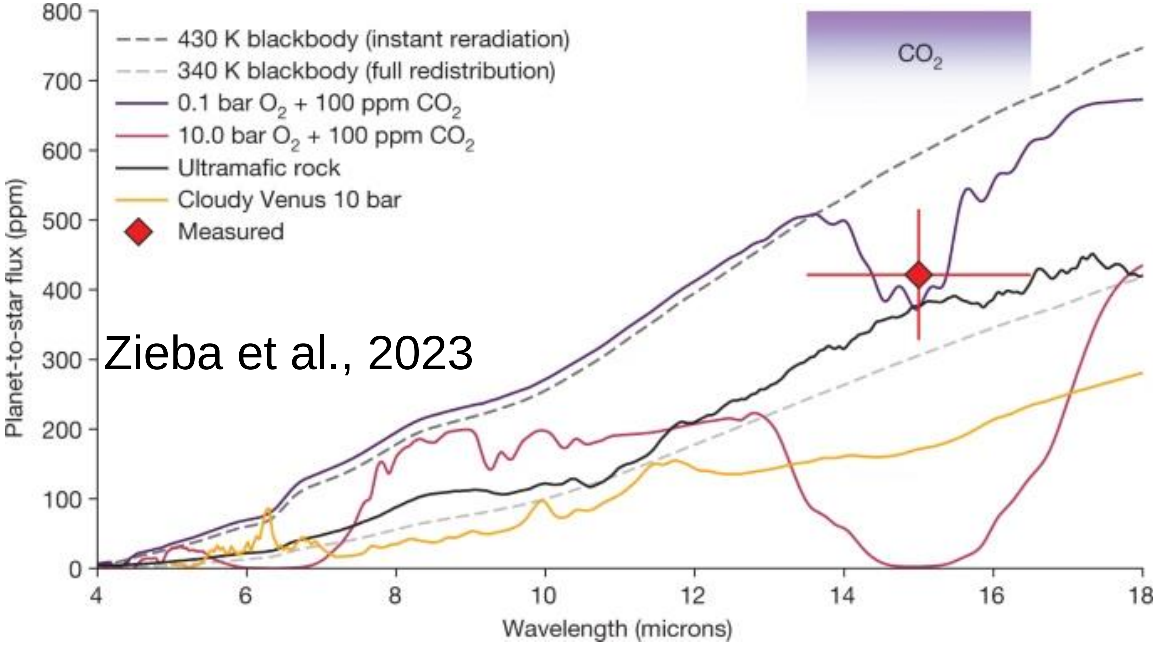


JWST, MIRI

Observations consistent with bare rock planet.

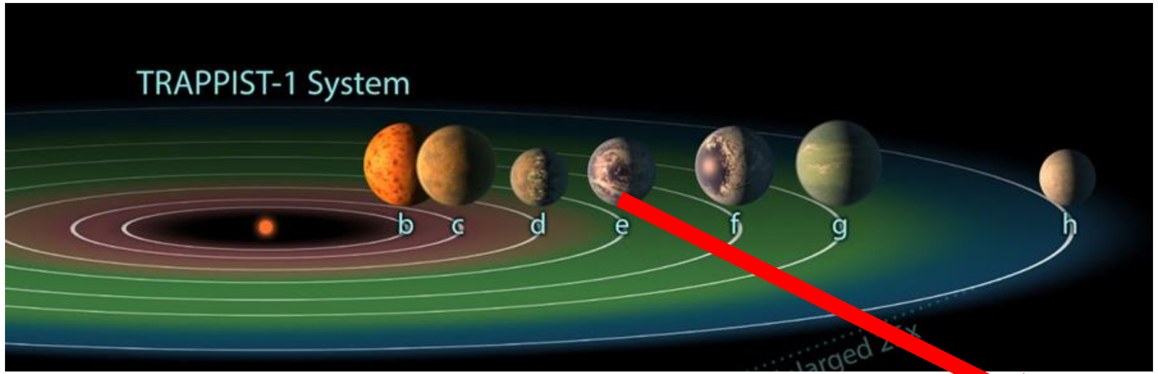
Greene et al. 2023, Jegug et al. 2023

TRAPPIST-1 c

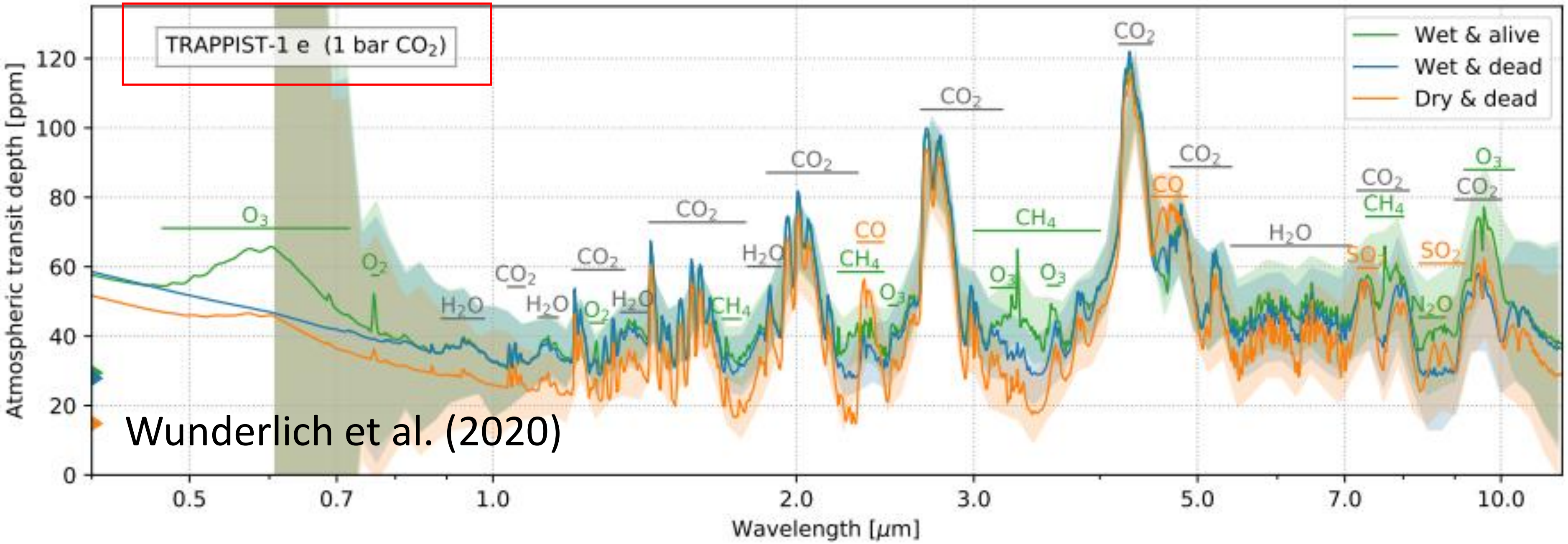


Zieba et al., 2023

No thick carbon dioxide atmosphere. Consistent with a bare rock surface or a thin, O_2-dominated, low-CO_2 atmosphere



Prediction: Detectability of Spectral Features on TRAPPIST-1e

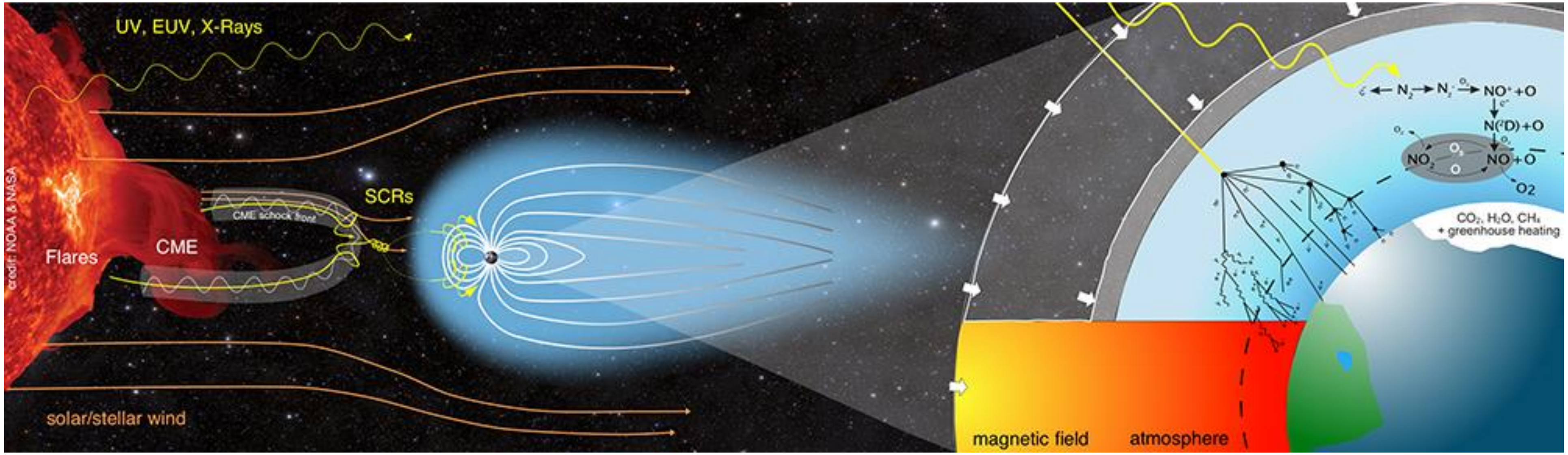


Wunderlich et al. (2020)

Shading = one sigma S/N for 30 transits with JWST

→ Detection of biosignatures, e.g. ozone, with JWST is very challenging …

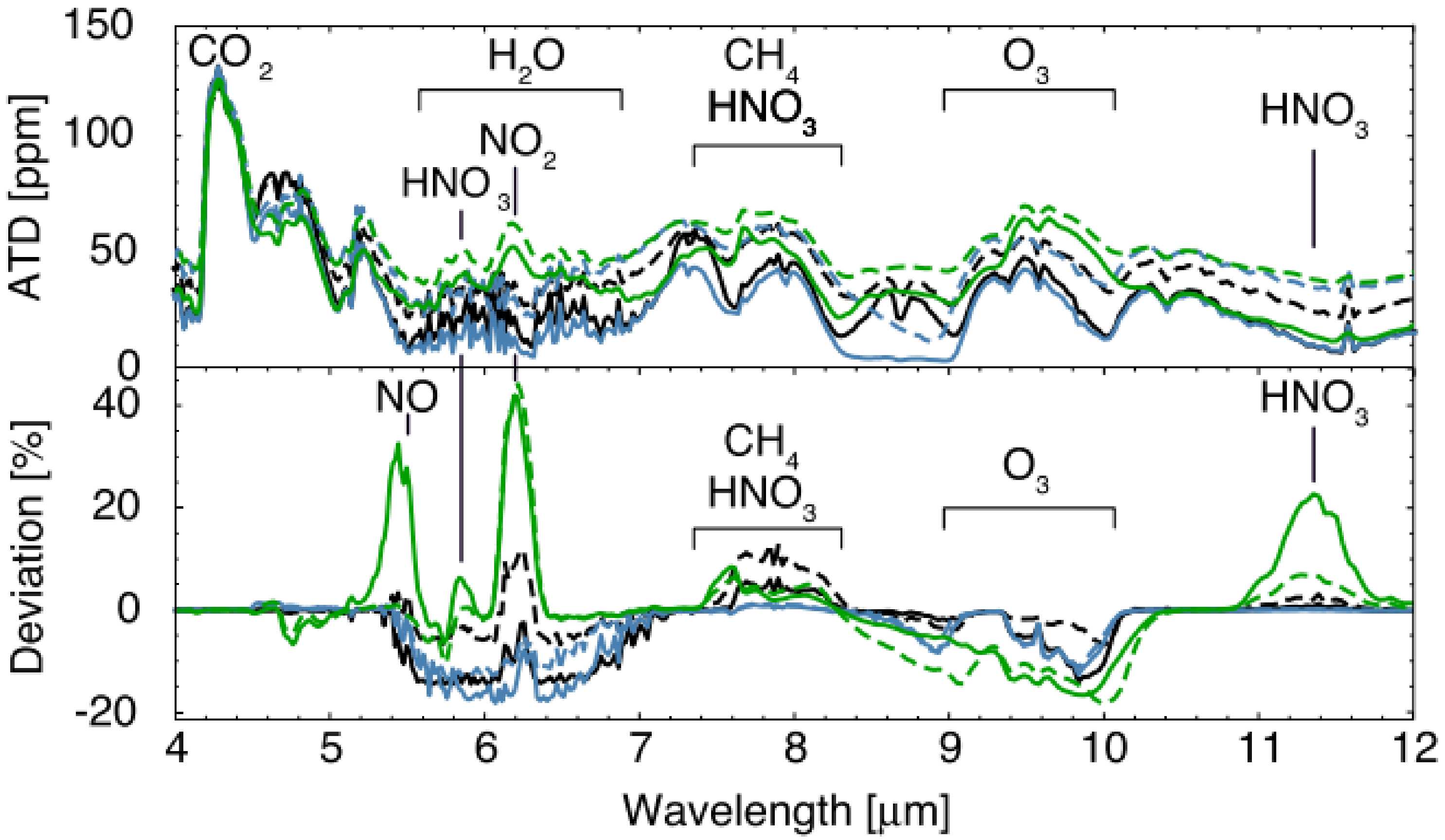
Effect of High Energy Particles on Earth-like Atmospheres in the Habitable Zone of M-dwarf Stars



New Model Suite investigating High Energy Particles in exoplanetary atmospheres et (Herbst al., 2019)
Effect of High Energy Particles in the atmosphere of Proxima Centauri b (Scheucher et al.,2020)

Slide adapted from: Konstantin Herbst (ISSI Team 464)

Effect of High Energy Particles (HEPs) on modelled Atmospheric Transit Depth (ATD) for Trappist-1e



%(with HEPs minus without HEPs)

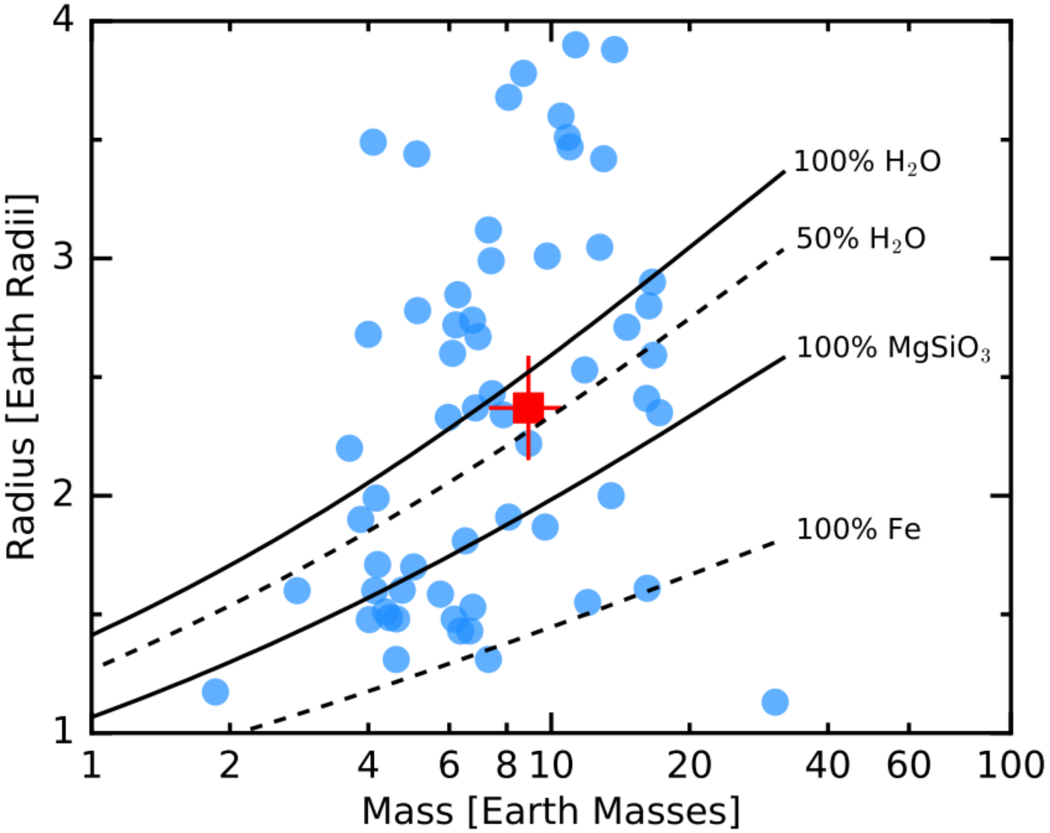
Herbst et al. 2024

Scenarios as before, but now also including HEP impacts.

Lower panel shows that HEPs lead to more HNO_3 (HEP breaks up N_2, N reacts with Ox to form NOx, which produces HNO_3); and less O_3 (NOx removes O_3 in stratosphere)

→ HEPs destroy ozone significantly
→ HNO_3 is a spectral signature of HEPs

The case K2-18 b

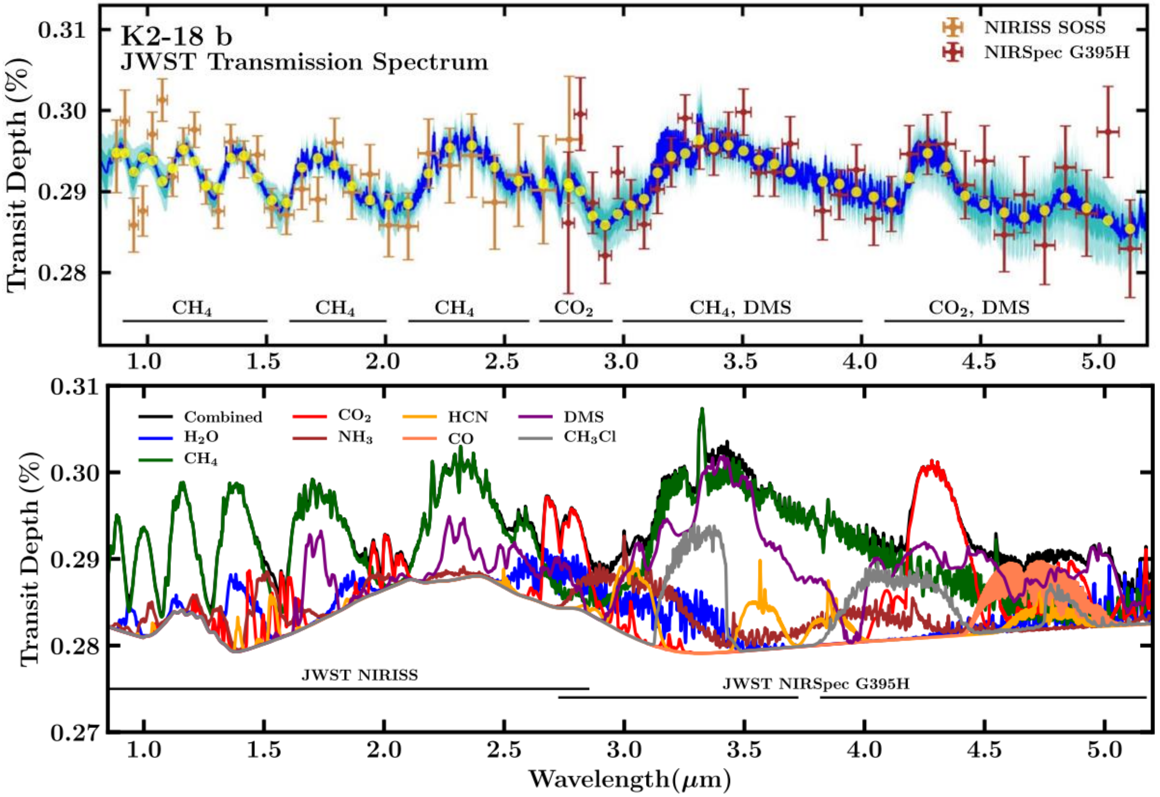


Sarkis et al. 2015

Mass:	8.92 M_earth
Radius:	2.37 R_earth
Orbital distance:	0.1429 au
Orbital period:	32.939 d
Host star:	M2.5 dwarf

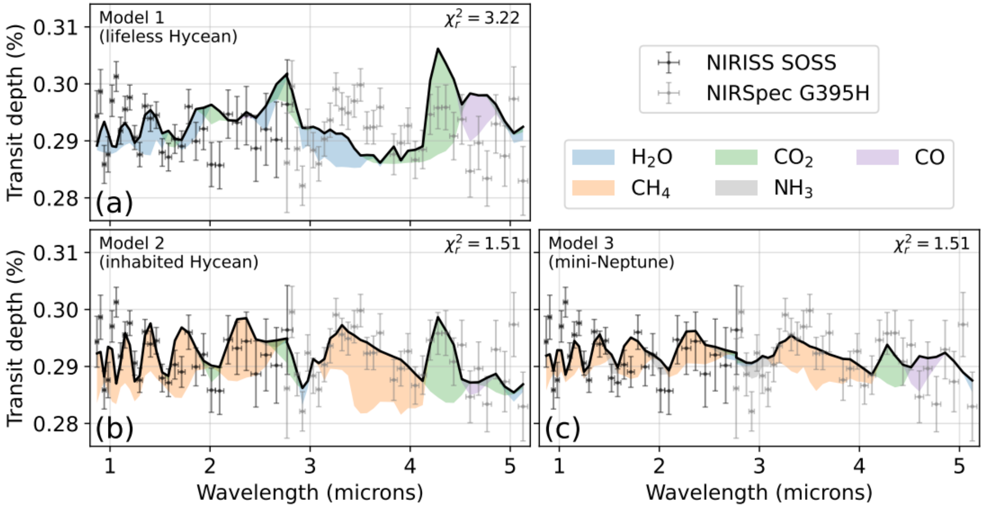
The case K2-18 b – JWST Observations

Tentative detection (~2σ) of potential biosignature Dimethyl Sulphide (DMS)



Adapted from Madhusudhan et al. (2023)

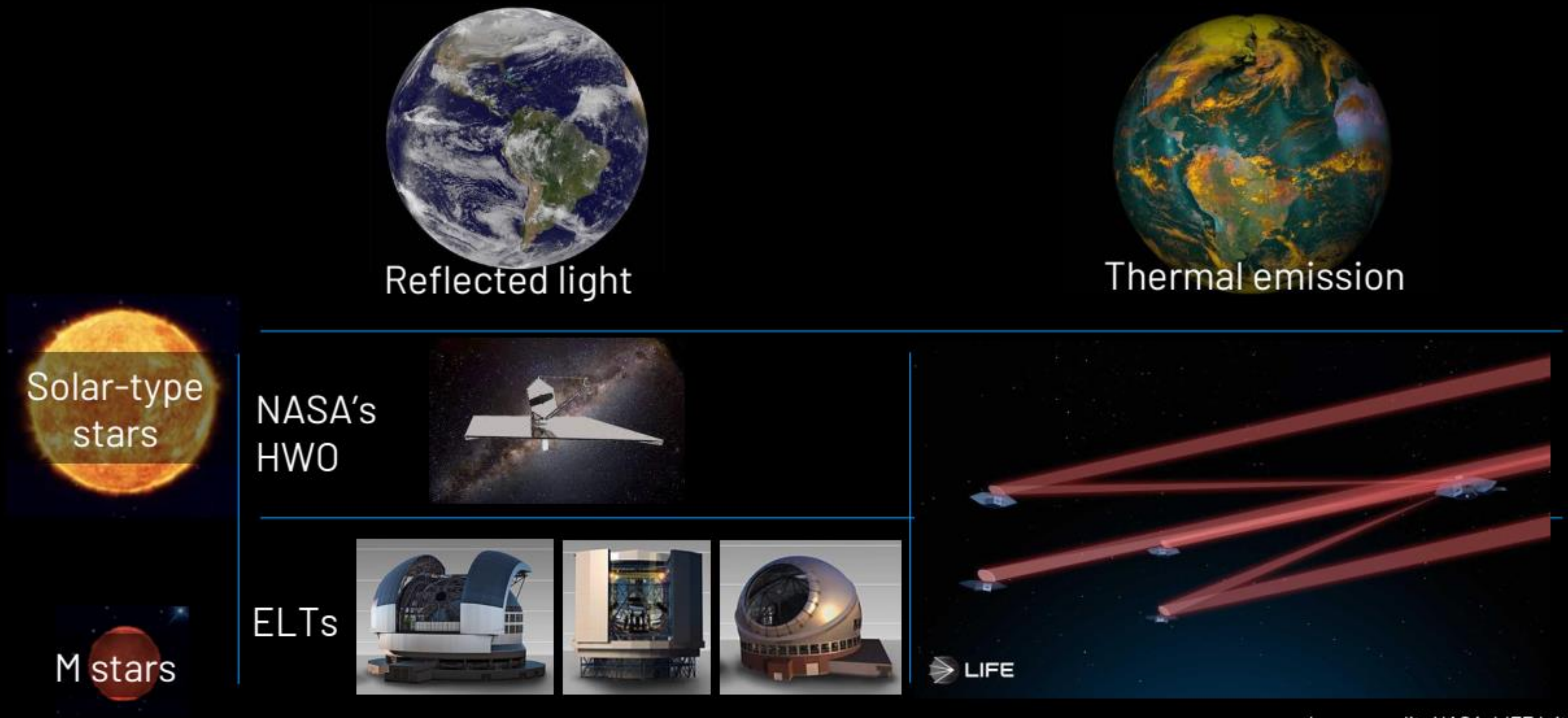
Life-less mini-neptune



Wogan et al. (2024)

Direct detection of terrestrial exoplanets from ground and space

Synergies between different missions and ground-based telescopes for the direct detection of terrestrial exoplanets



Reflected light

Thermal emission

Solar-type stars

M stars

NASA's HWO

ELTs

LIFE

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

Habitable Worlds Observatory (NASA)
a concept for NASA Flagship mission

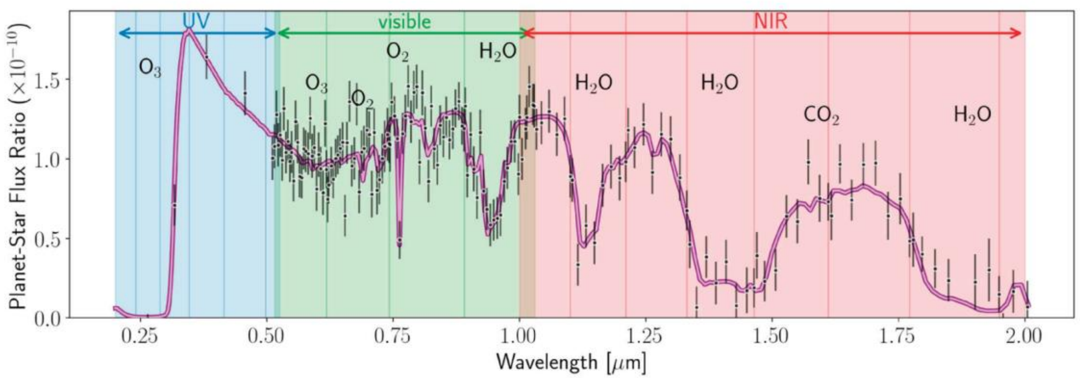
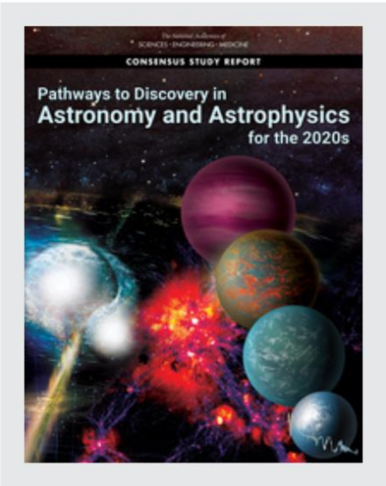


FIGURE I.1 Simulated UV-near-IR exoearth spectrum that highlights absorption from several key molecules for biosignature detection such as ozone, molecular oxygen, water, and carbon dioxide. SOURCE: LUVOIR and HabEx final reports. Courtesy of J. Lustig-Yaeger (University of Washington).


Habitable Worlds Observatory
Simulated Solar System Time-lapse
Observed from 33 light-years away
Time = 10 years, 1 second = 72 days

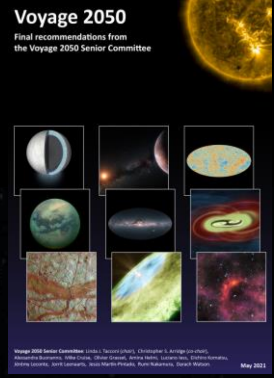

The National Academies of SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
Pathways to Discovery in
Astronomy and Astrophysics
for the 2020s

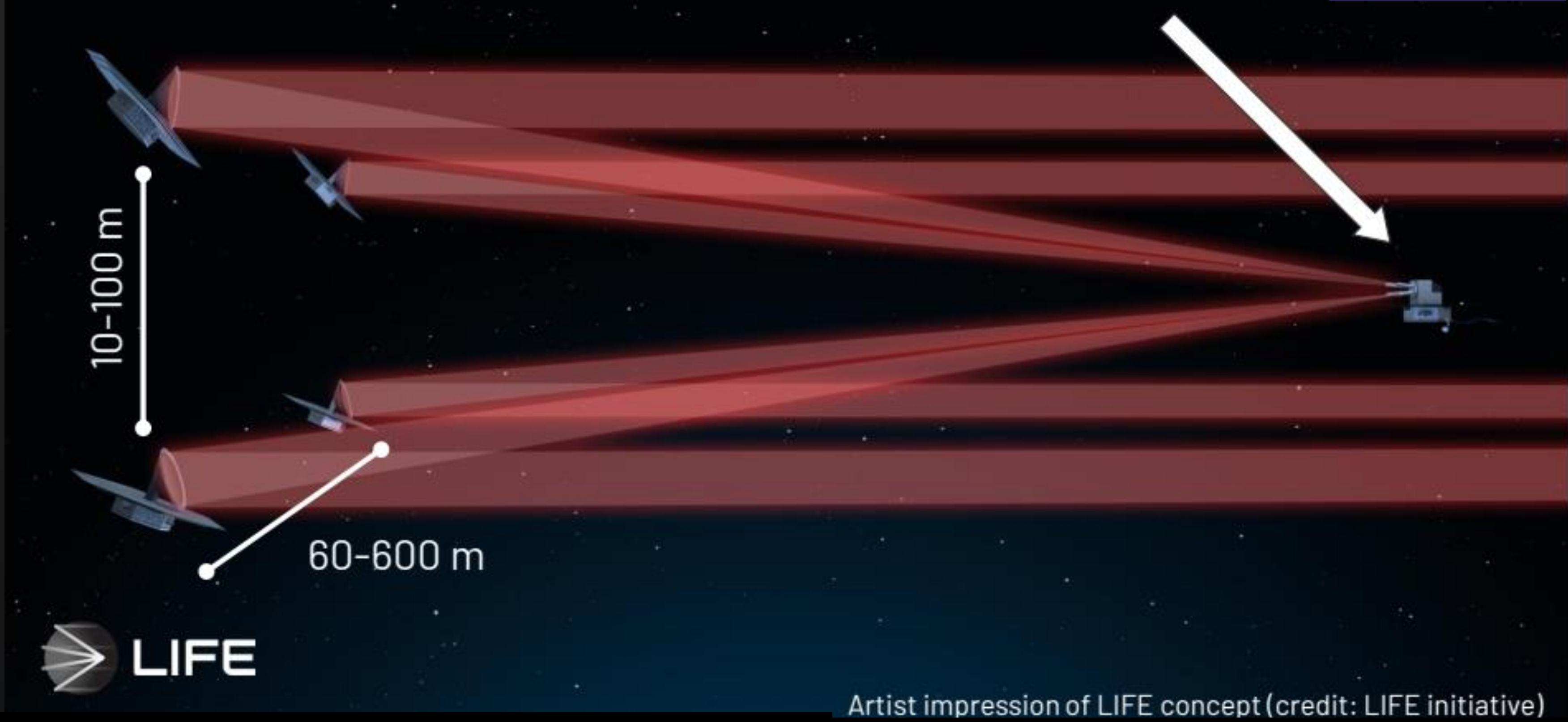
(Image credits: NASA)

- Coronographic concept
- Optical to near-IR wavelengths ranges

J J

- LIFE = Large Interferometer For Exoplanets
- ...is a space-based formation-flying mid-infrared (nulling) interferometer based on the heritage of Darwin and TPF-I
- ...consists of 4 collector spacecraft separated by tens to hundreds of meters and a beam combiner spacecraft
- ...covers the mid-infrared wavelength range between ~4-18.5 μm with a spectral resolution of R ~ 100 (tbc)

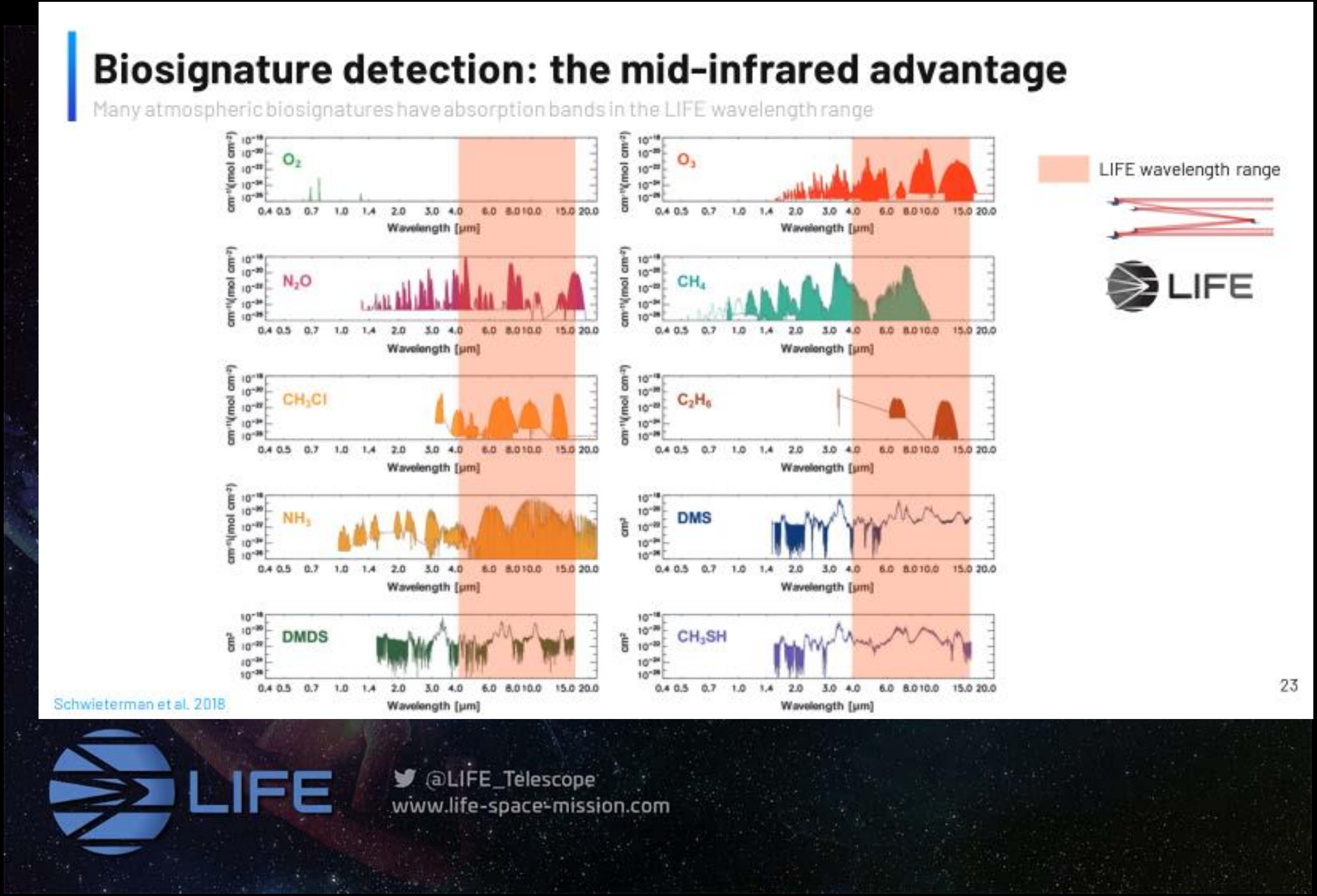

Voyage 2050
Final recommendations from the Voyage 2050 Senior Committee



Artist impression of LIFE concept (credit: LIFE initiative)

Sascha Quanz et al., A&A 2021

Concept LIFE: Large Interferometer For Exoplanets (Europe)



Biosignature detection: the mid-infrared advantage

Many atmospheric biosignatures have absorption bands in the LIFE wavelength range

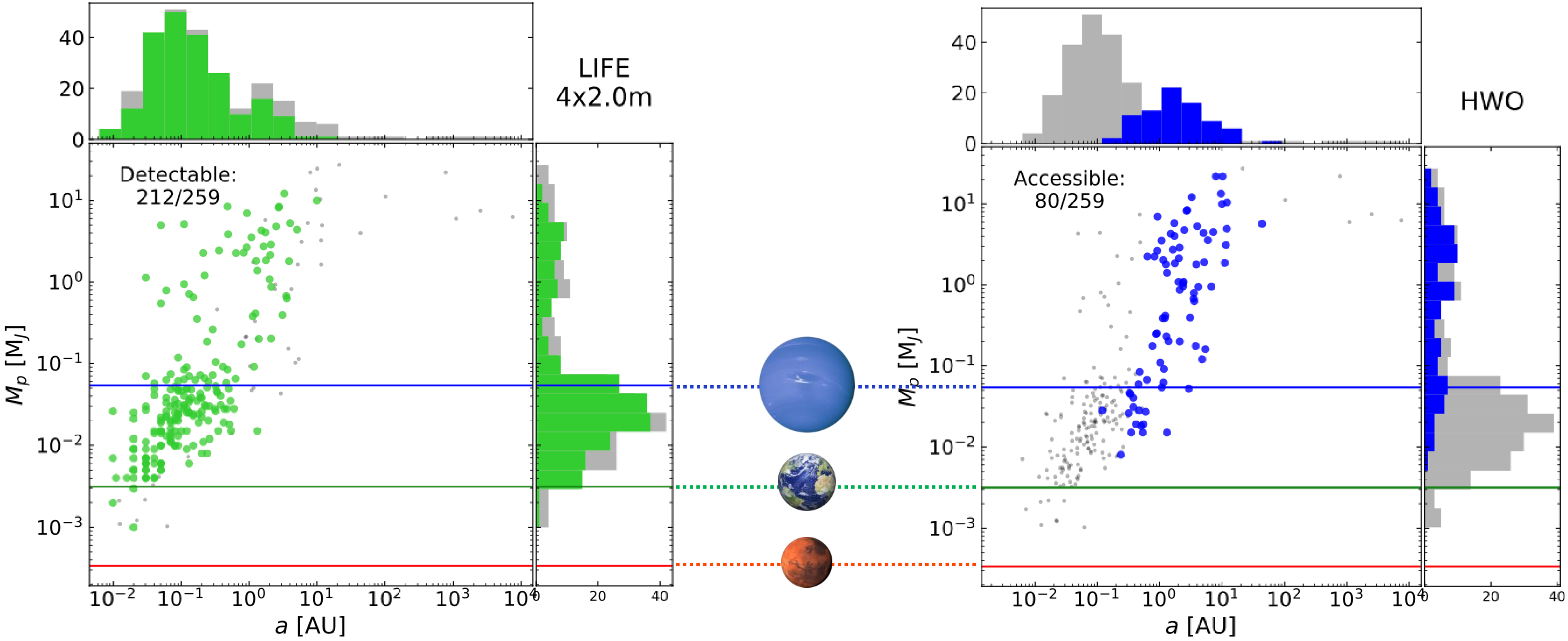
Schwieterman et al. 2018

23

@LIFE_Telescope
www.life-space-mission.com

Characterizing known nearby planets from mission day 1

Detectability of known exoplanets within 20 pc for LIFE and HWO



Carrión-González et al. (2023)

Courtesy S. Quanz

Summary

- Exoplanet research enters an area of planet characterization: different types, different environments, ages, formation conditions, interiors, atmospheres,…
- Biosignature detection is challenging with currently available instrumentation – large missions under study.
- Comprehensive understanding of conditions for habitability as well as biogenic and abiotic processes imprinting biosignatures is key for detection of life.

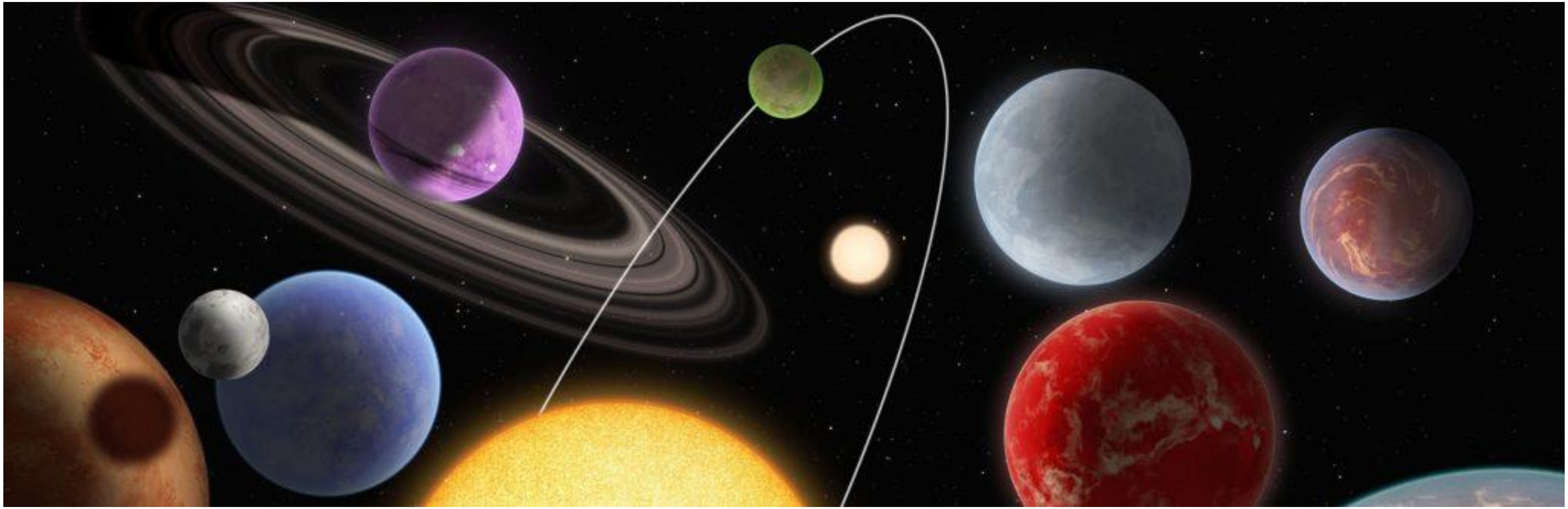


Image credit: SPP 1992 Exoplanet Diversity / Nico Bartmann