Characterizing cold giant exoplanets and their systems in direct imaging

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Hence, there may be many objects of planet-like character in the galaxy.

But how should we proceed to detect them? The method of direct photography used by Strand is, of course, excellent for nearby binary systems, but it is quite limited in scope. There seems to be at present no way to discover objects of the mass and size of Jupiter; nor is there much hope that we could discover objects ten times as large in mass as Jupiter, if they are at distances of one or more astronomical units from their parent stars.

O. Struve, The Observatory, Vol. 72 (1952)

Roman, Nancy Grace. *Planets of other suns.*

As seen from the distance of Alpha Centauri, Jupiter, at its maximum apparent separation from the sun, $3''.94$, would be a star of $23^{m}.4$ (assuming that its phase function is that of Venus); it would brighten to a maximum of $22^{m}.0$ at exterior conjunction. For Venus, Earth, Saturn, the maximum brightnesses and separations are, respectively: $22^{m}.5$ and $0''.55$, $23^{m}.4$ and $0''.76$, and $22^{m}.7$ and $7''.23$ (with the rings at moderate inclination).

Thus, a similar planetary system around Alpha Centauri would be within the reach of our largest telescopes and our current photoelectric techniques if our terrestrial atmosphere did not limit our resolution. At a separation of more than $2''$, it does not seem to be a serious problem to get rid of the light of the primary in the absence of an atmosphere.

N. G. Roman, Astronomical Journal, Vol. 64 (1959)

The 90s set the stage

TOPS: Towards Other Planetary Systems report (1991)

The 90s set the stage

TOPS: Towards Other Planetary Systems report (1991)

– *The observational techniques to detect evidence of other planetary systems are developed sufficiently to begin a promising search now, using indirect methods at first, and progressing to direct detection.*

– Three phases of the proposed program:

→ TOPS-0: building Keck-II

→ TOPS-1: imaging instrument on an orbiting telescope

→ TOPS-2: imaging interferometer in space or in the Moon to *study "Earths" around other stars.*

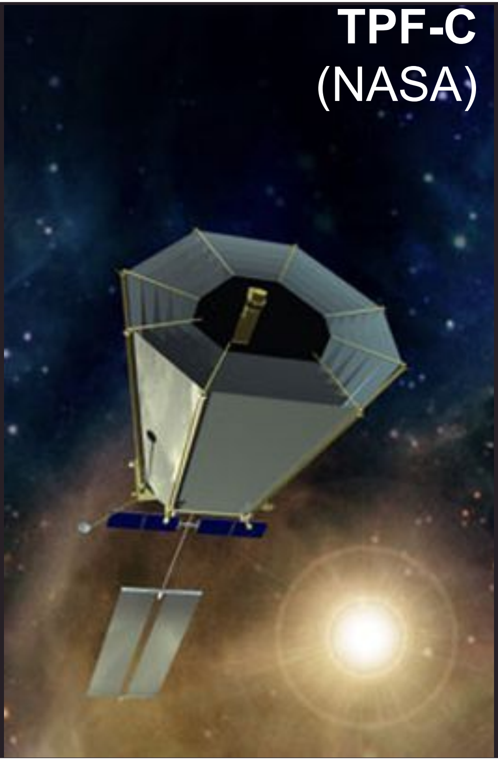
The 90s set the stage

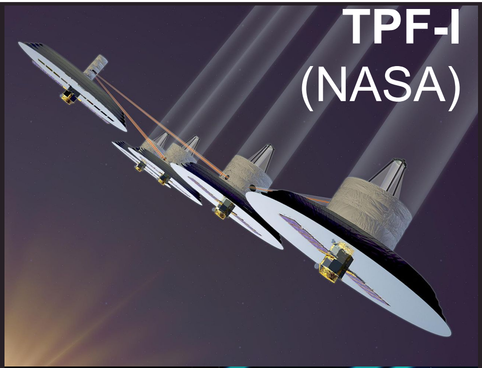
Visible & near-IR

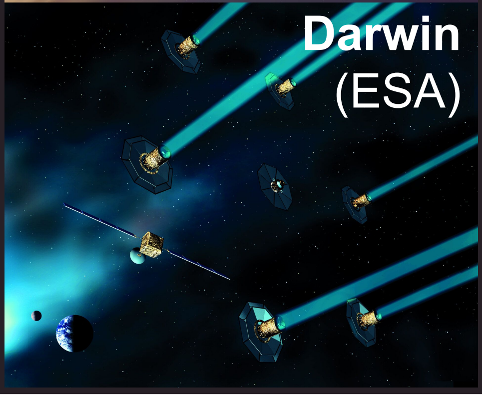
Mid-IR

How unique is our Earth?

(A lingering question)



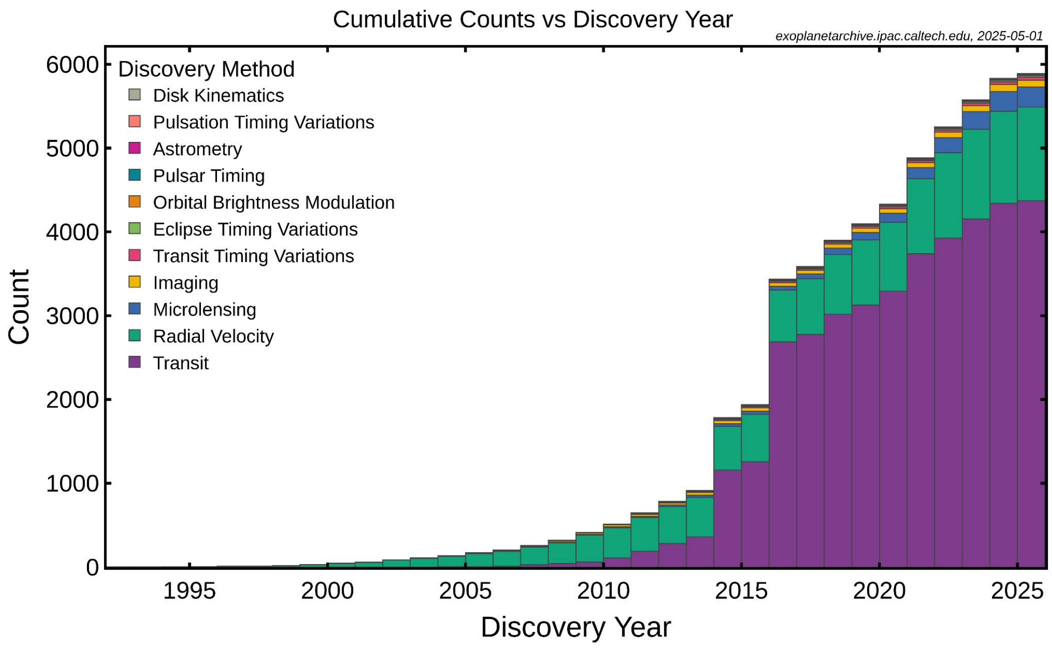




30 years of exoplanet discoveries

~6000 confirmed exoplanets so far.

~4400 of them transit
~1100 discovered in RV



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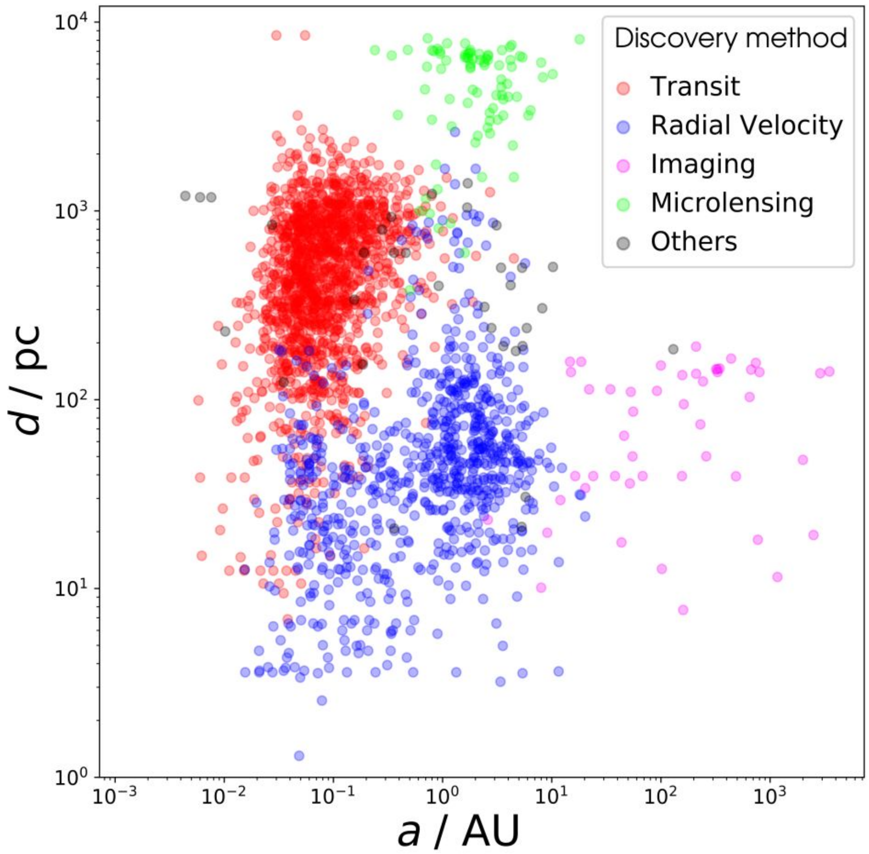
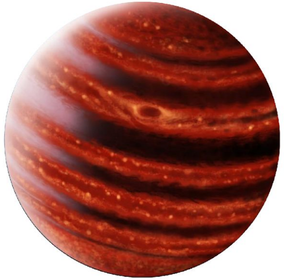
Many not yet accessible for atmospheric characterization.

→ Need for direct imaging



Direct imaging timeline

Currently



Young giants very far out observed in **emitted light**

Roman
(NASA-led + ESA)

mid-2020s

Jupiter analogs + some super-Earths/ mini-Neptunes

ELT
HWO
LIFE

2040s

Earth-like planets around Sun-like stars

Looking ahead

Which planets will future missions probe?

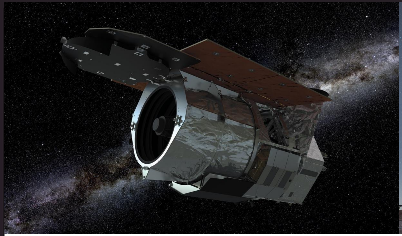
What is their overlap?

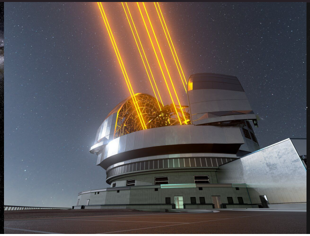
NANCY GRACE ROMAN SPACE TELESCOPE

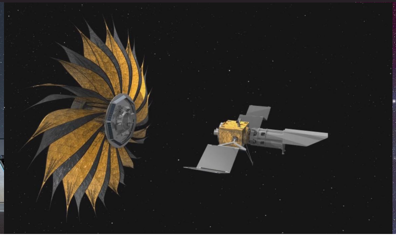
ESO ELT

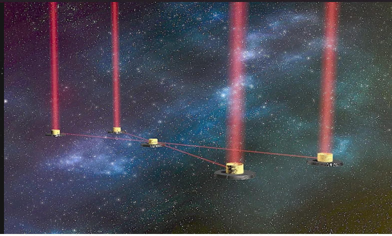
HABITABLE WORLDS OBSERVATORY

LIFE Large Interferometer For Exoplanets









Credit images:
NASA GSFC, ESO, JPL, LIFE

Statistical method

Statistical method

Planet & star parameters
(± uncertainties)

1000s of orbits

Instrument performance

Detectability predictions

Carrión-González et al. (2021a)

Statistical method

Planet & star parameters
(± uncertainties)

1000s of orbits

Detectability predictions

Instrument performance

LOCATIS

Carrión-González et al. (2021a)

LOCATIS

Currently
Private code

Upcoming
Online interactive tool

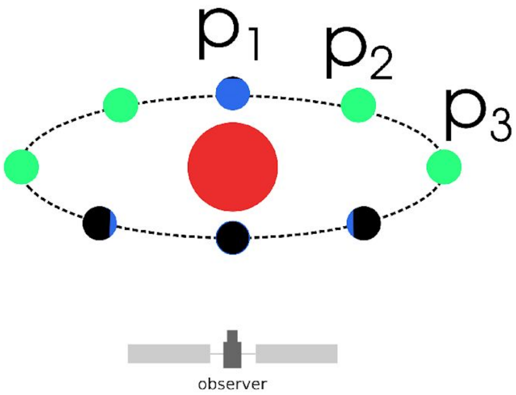
Paulina Palma-Bifani
Postdoc at Obs. de Paris

Currently
Only reflected light

Upcoming
Thermal emission

Sebastian Schwaiger
ETH Zurich, MSc at MPIA

Statistical method



Brightness

Angular separation

Accessible planet

p_1: $\Delta\theta_1$; $(F_p/F_*)_1$

p_2: $\Delta\theta_2$; $(F_p/F_*)_2$

p_3: $\Delta\theta_3$; $(F_p/F_*)_3$

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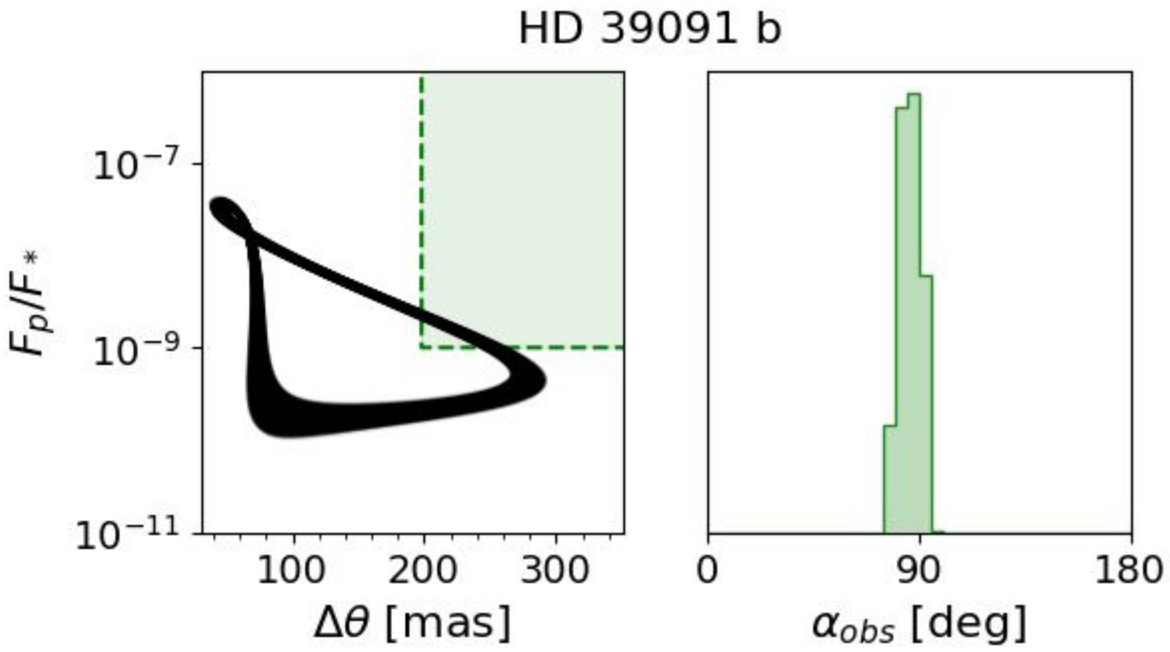
360 positions,

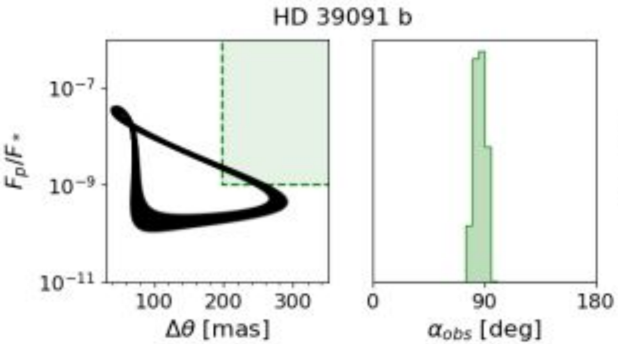
Nancy Grace Roman Space Telescope

Launch in 2026/27

Equipped with an optical coronagraph as a technology demonstrator for HWO.

Carrión-González et al. (2021a)


HD 39091 b
10^{-7}
10^{-9}
10^{-11}
F_p/F_*
100
200
300
$\Delta\theta$ [mas]
0
90
180
α_{obs} [deg]



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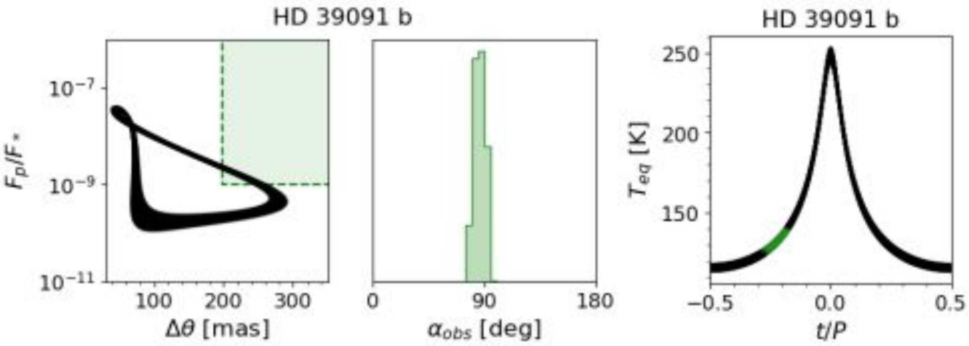
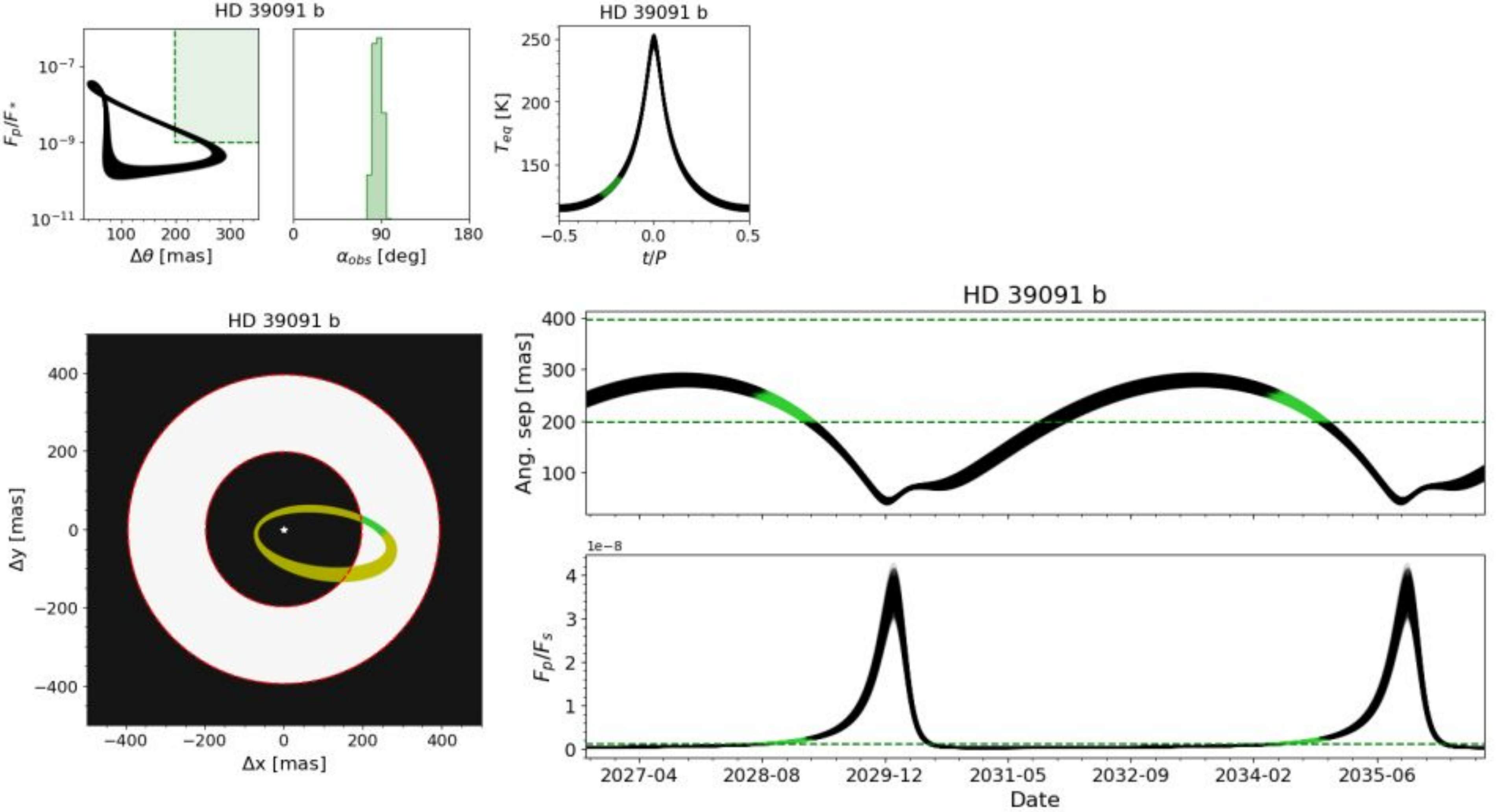

HD 39091 b
10^{-7}
10^{-9}
10^{-11}
F_p/F_*
100
200
300
$\Delta\theta$ [mas]
0
90
180
α_{obs} [deg]
HD 39091 b
250
200
150
T_{eq} [K]
−0.5
0.0
0.5
t/P



HD 39091 b
F_p/F_*
$\Delta\theta$ [mas]
α_{obs} [deg]
HD 39091 b
T_{eq} [K]
t/P
HD 39091 b
Δy [mas]
Δx [mas]
HD 39091 b
Ang. sep [mas]
F_p/F_s
1e−8
Date
2027-04
2028-08
2029-12
2031-05
2032-09
2034-02
2035-06

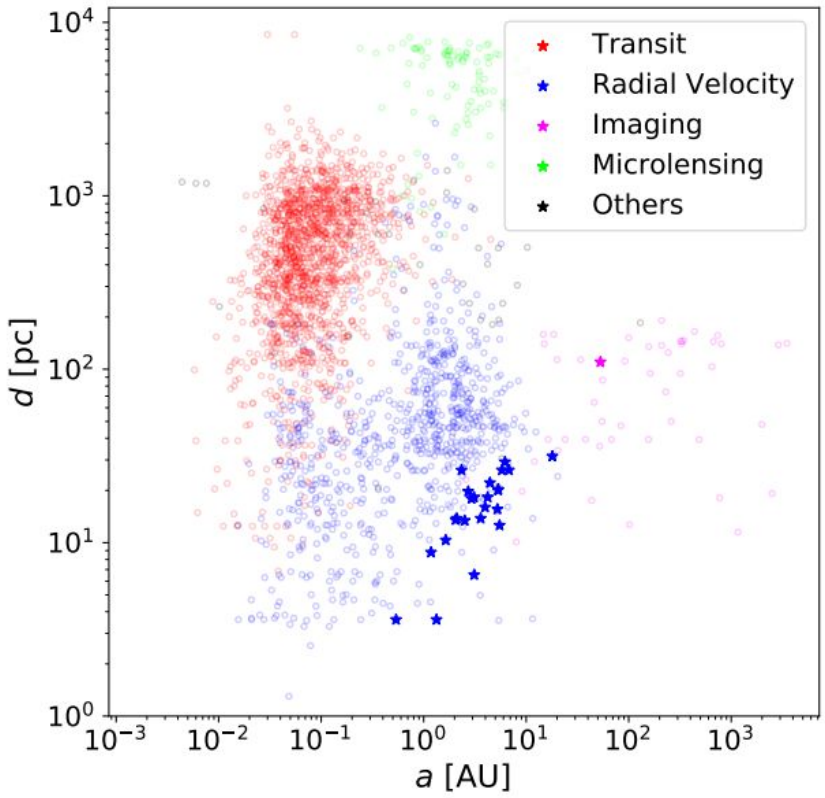
Up to 26 Roman-accessible exoplanets

Optimistic 3-9λ/D, $C_{min}=10^{-9}$ case:
26 accessible planets

Intermediate 3.5-8.5λ/D, $3\cdot10^{-9}$:
11 accessible planets

Pessimistic 4-8λ/D, $5\cdot10^{-9}$:
3 accessible planets

Carrión-González et al. (2021a)



Exoplanets with P_{access}>25% in the optimistic scenario, around stars brigther than V=7 mag

Ground-based

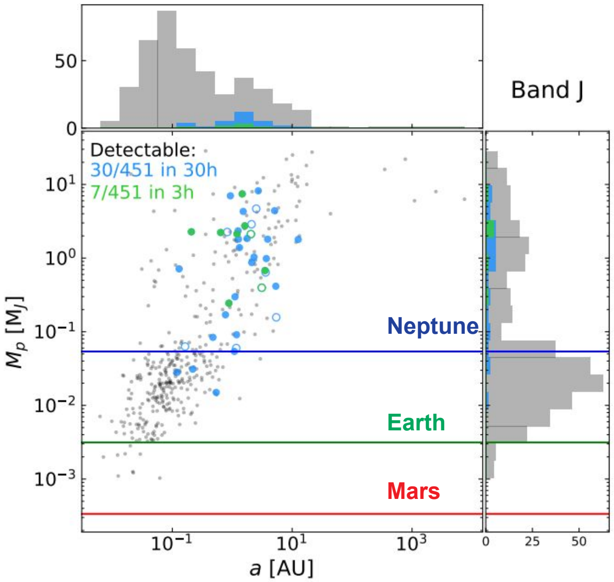
Proposed VLTI extension

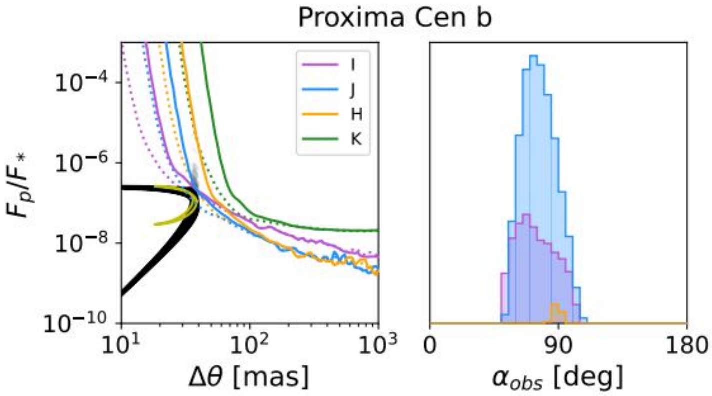
Ground-based

Proposed VLTI extension

Lacour et al. (2025)

VLTI + J band





- Known exoplanets within 30 pc
- Detectable in 30h of integration
- Detectable in 3h of integration

Several targets potentially within Roman's reach

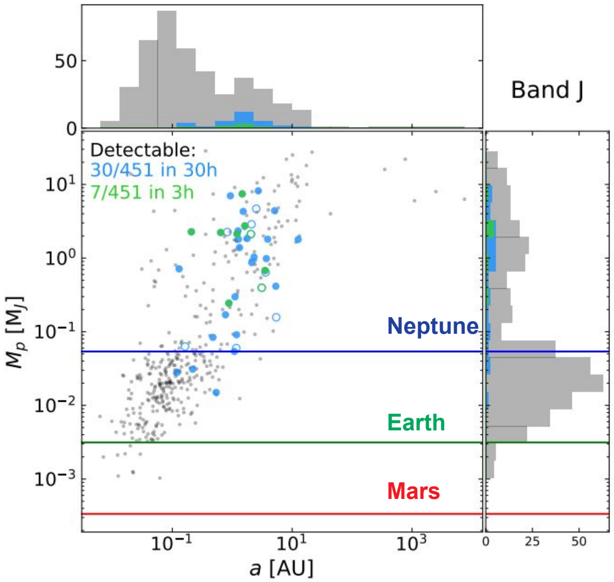
Ground-based

Proposed VLTI extension

Funded: reflected-light wavs. in the J (1.2 μm) band

Lacour et al. (2025)

VLTI + J band



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Several targets potentially within Roman's reach

Funded by the European Union

European Research Council
Established by the European Commission

ERC Advanced ***PLANETES*** (PI: Lacour)

LIFE & HWO

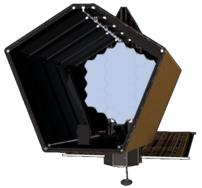
LIFE & HWO

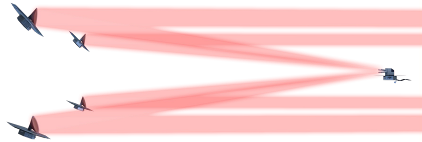
Potential targets

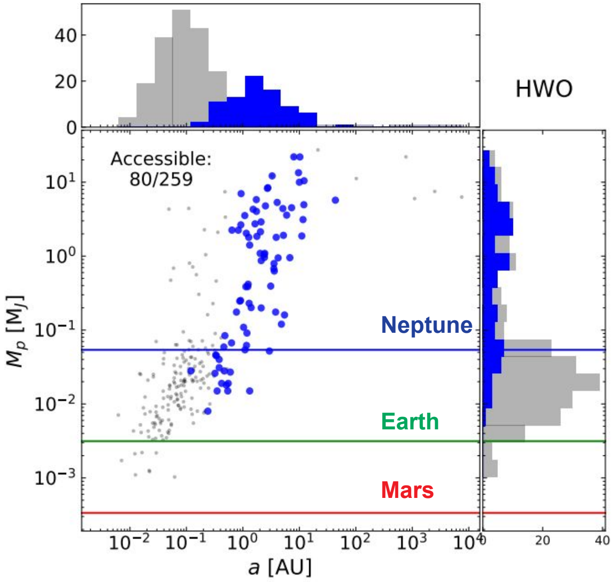
38 LIFE-detectable HZ planets

13 of them also accessible to HWO

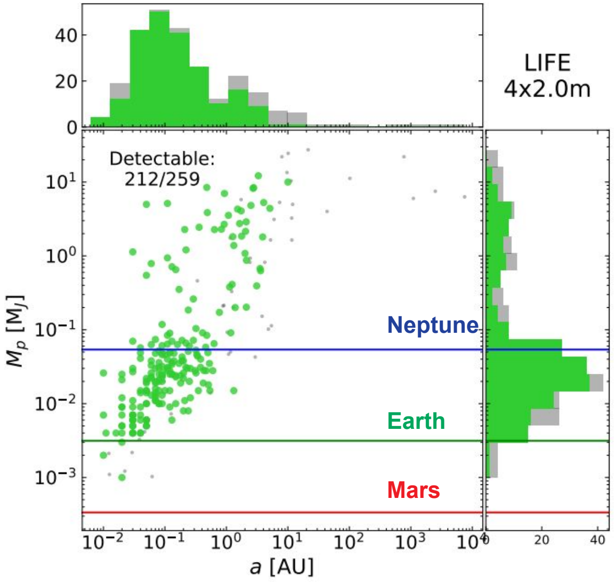
Carrión-González et al. (2023)







- Known exoplanets within 20 pc
- Accessible to HWO
  in reflected starlight



- Known exoplanets within 20 pc
- Detectable with **LIFE** (4x2m)

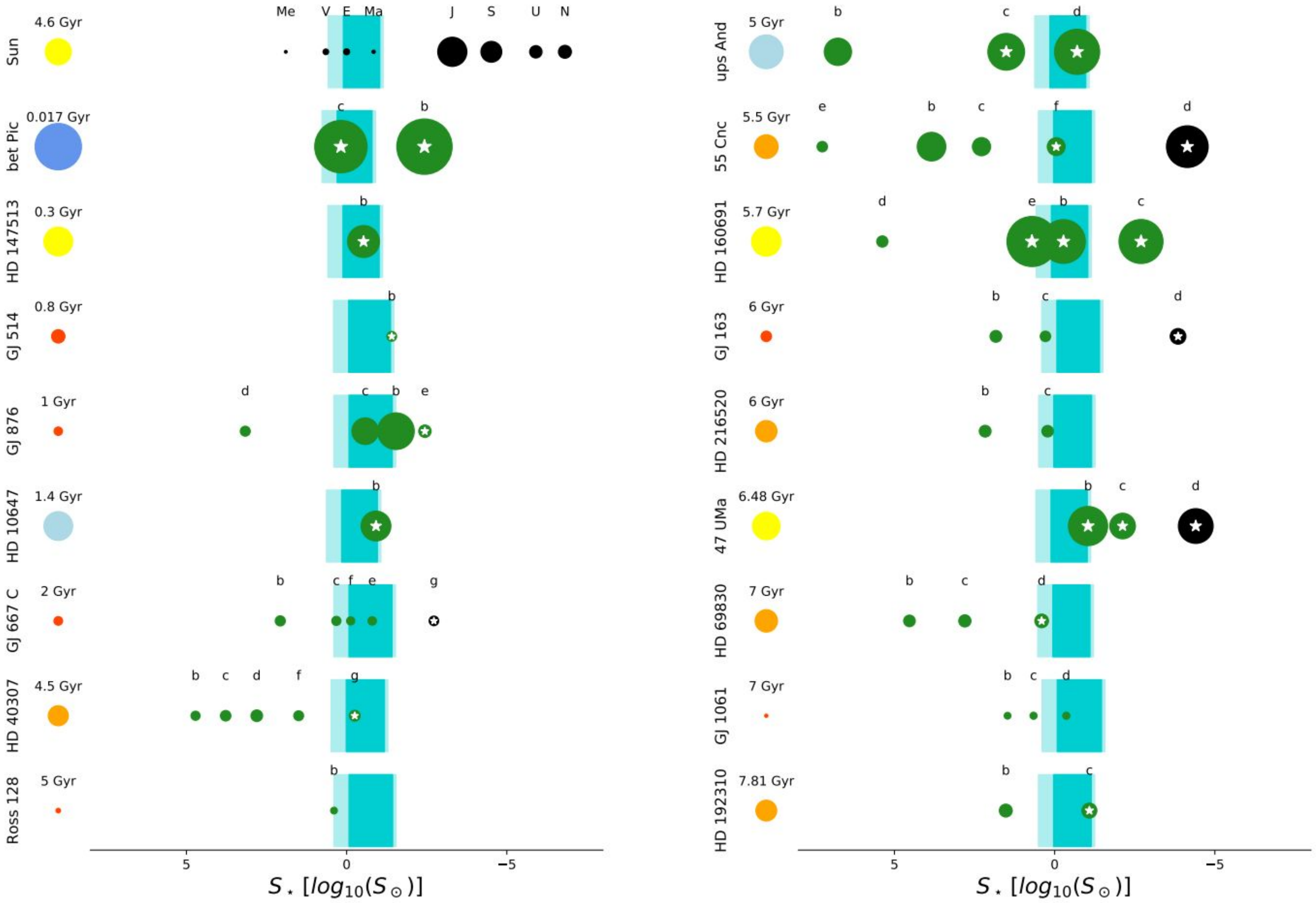
LIFE & HWO

Detectable HZ planets

38 LIFE-detectable HZ planets (●)

13 of them also accessible to HWO (★)

Carrión-González et al. (2023)



LIFE & HWO

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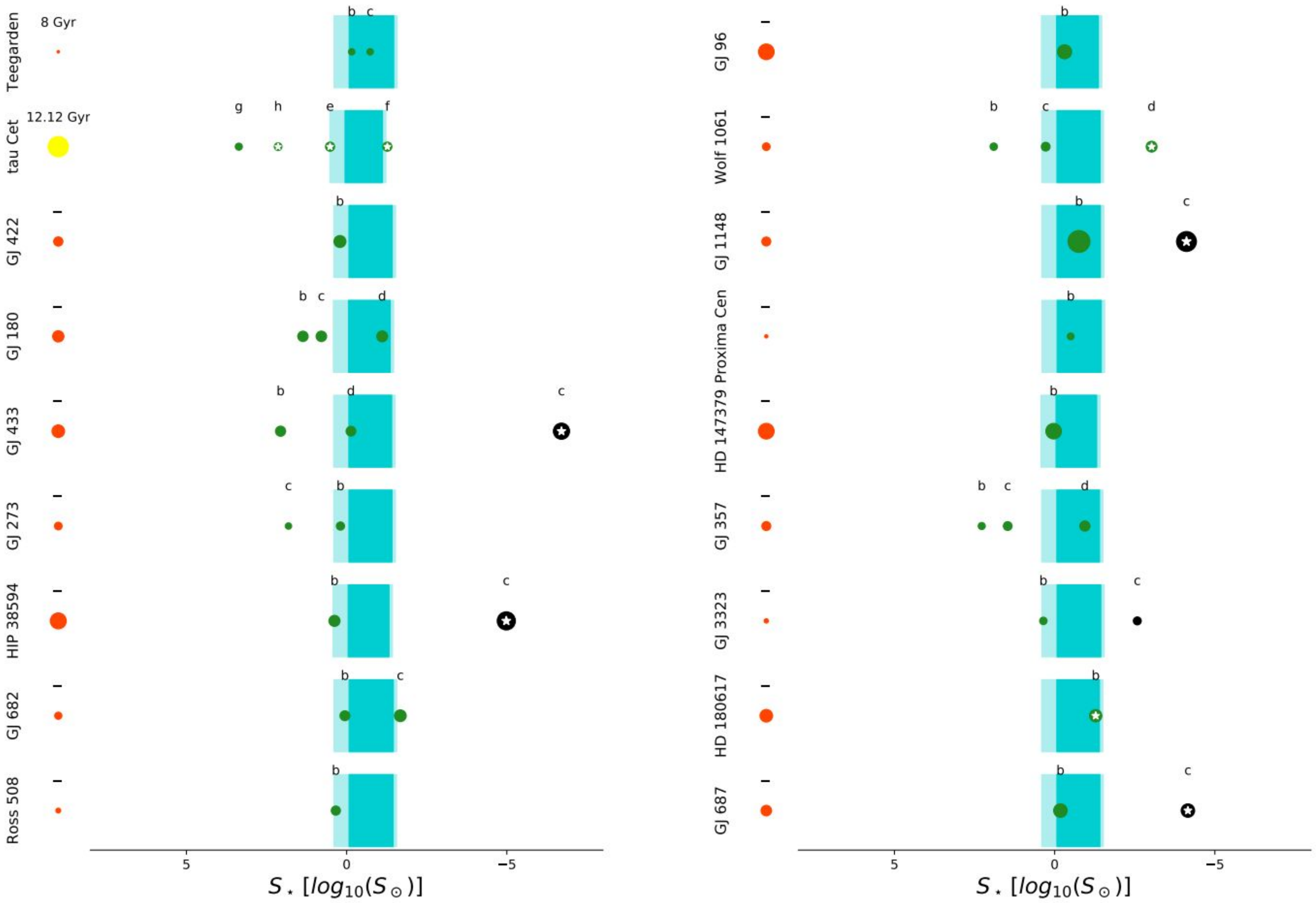
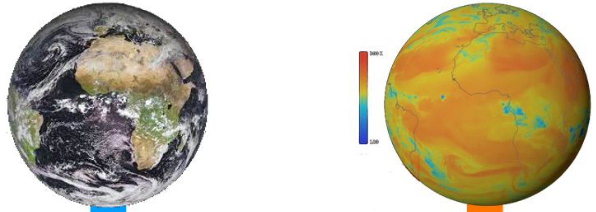


Visible & mid-IR science outlook

The total is greater than the sum of the parts

HWO
IR/O/UV

LIFE
mid-IR



– Cloud properties [1,2,3]
– Ocean glint [4]
– Vegetation red edge [5,6]

– Planet radius [7]
– P-T profile [8]
– H_2O, CO_2, CH_4, O_3 [7,9]

– Breaking the radius-albedo degeneracy [10]
– Deriving the wavelength-dependent albedo and the planet's full energy budget
– Detecting eventual greenhouse effect

[1] Lupu et al. 2016
[2] Damiano & Hu 2020
[3] Carrión-González et al. 2021b
[4] Lustig-Yaeger et al. 2018
[5] Sagan et al. 1993
[6] Seager et al. 2005
[7] Konrad et al. 2022
[8] Konrad et al. 2023
[9] Alei et al. 2022
[10] Carrión-González et al. 2020

Visible & mid-IR science outlook

The total is greater than the sum of the parts

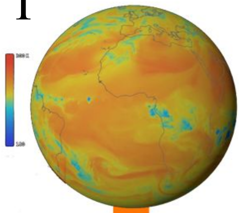
Applicable to HWO & LIFE but also to ELT

PCS@ELT

IR/O/UV

METIS@ELT

mid-IR



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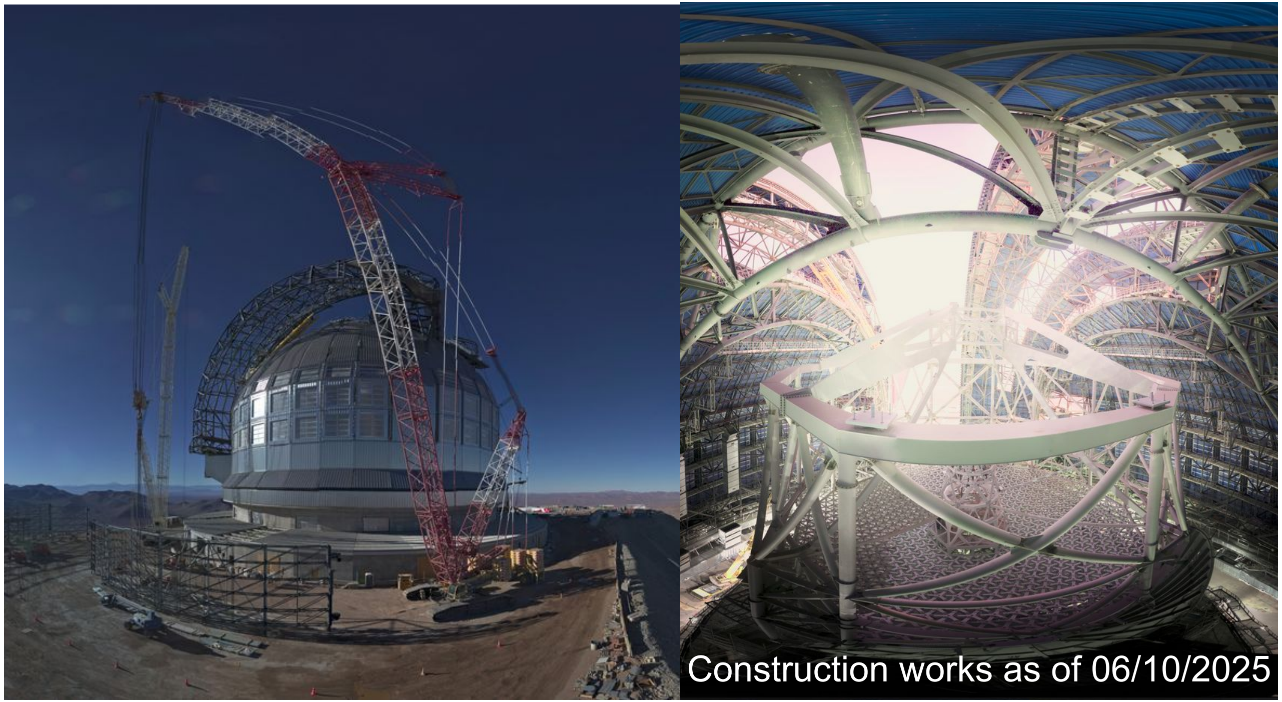
[7] Konrad et al. 2022
[8] Konrad et al. 2023
[9] Alei et al. 2022
[10] Carrión-González et al. 2020

ELT

1st light
planned for 2029



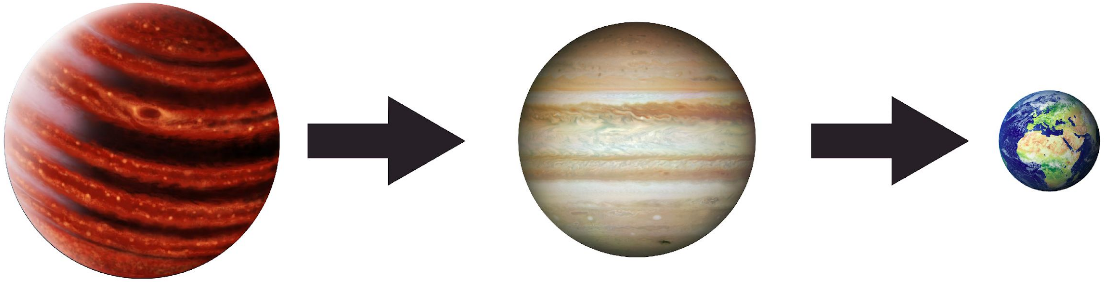
Construction works as of 06/10/2025

Several instruments capable of directly imaging exoplanets:

- METIS (mid-IR)
- PCS (visible – near-IR)
- ANDES, HARMONI (visible – near-IR)

Outlook

Currently | **mid-2020s** | **2040s**



We are moving from detection to atmospheric characterization

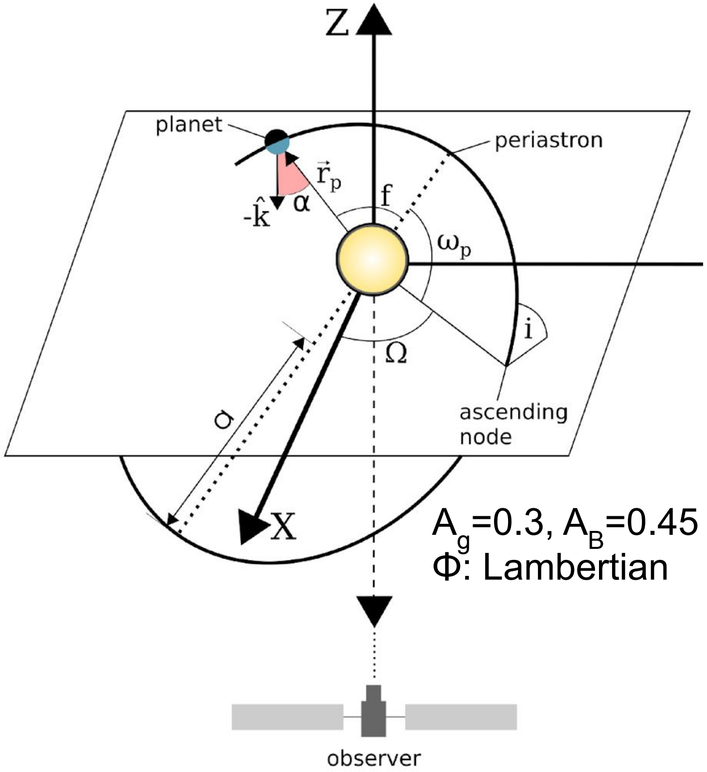
Contact: oscarrion@mpia.de

Instrument	Main specifications			Schedule				
	Field of view/slit length/ pixel scale	Spectral resolution	Wavelength coverage (μm)	Phase A	Project start	PDR	FDR	First light
MICADO	Imager (with coronagraph) 50.5″ × 50.5″ at 4 mas/pix 19″ × 19″ at 1.5 mas/pix	*I*, *Z*, *Y*, *J*, *H*, *K* + narrowbands	0.8–2.45	2010	2015	2019		
	Single slit	*R* ~ 20 000						
MORFEO	AO Module SCAO – MCAO		0.8–2.45	2010	2015	2023		
HARMONI + LTAO	IFU 4 spaxel scales from: 0.8″ × 0.6″ at 4 mas/pix to 6.1″ × 9.1″ at 30 × 60 mas/pix (with coronagraph)	*R* ~ 3 200 *R* ~ 7 100 *R* ~ 17 000	0.47–2.45	2010	2015	2018		
METIS	Imager (with coronagraph) 10.5″ × 10.5″ at 5 mas/pix in *L*, *M* 13.5″ × 13.5″ at 7 mas/pix in *N*	*L*, *M*, *N* + narrowbands	3–13	2010	2015	2019		
	Single slit	*R* ~ 1400 in *L* *R* ~ 1900 in *M* *R* ~ 400 in *N*						
	IFU 0.6″ × 0.9″ at 8 mas/pix (with coronagraph)	*L*, *M* bands *R* ~ 100 000						
ANDES	Single object	*R* ~ 100 000	0.4–1.8 simultaneously	2018				
	IFU (SCAO)							
	Multi object (TBC)	*R* ~ 10 000						
MOSAIC	~ 7-arcminute FoV ~ 200 objects (TBC)	*R* ~ 5 000–20 000	0.45–1.8 (TBC)	2018				
	~ 8 IFUs (TBC)	*R* ~ 5 000–20 000	0.8–1.8 (TBC)					
PCS	Extreme AO camera and spectrograph	TBC	TBC					

1 milliarcsecond (mas) = 0.001″

Statistical method

Theoretical setting



A_g=0.3, A_B=0.45
Φ: Lambertian

Compatible with missing parameters

$e \in [0,1)$

$\cos(i) \in [-1,1]$

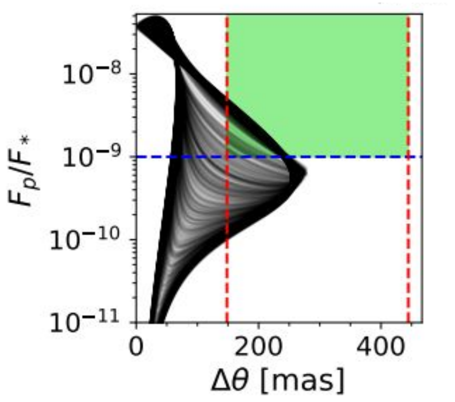
$\omega_p \in [0,2\pi]$

R_p: Hatzes & Rauer 2015
Otegi et al. 2020

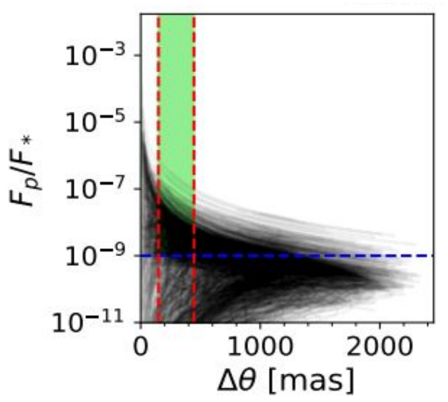
The importance of knowing the orbital inclination

Jones et al. (2002)
Damasso et al. (2020)

π Men b



Proxima c

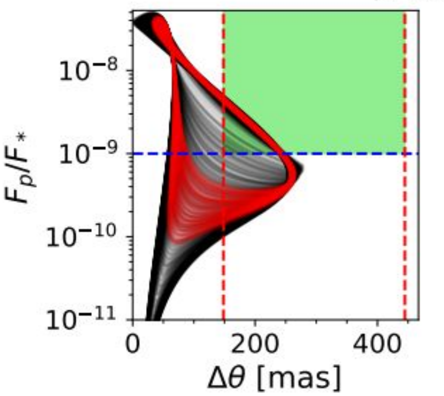


For π Men b and Proxima Cen c, astrometric measurements are available.

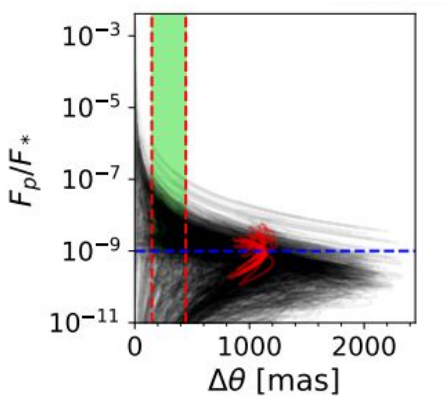
- $i_{(\pi \text{ Men b})}$~130º (Xuan & Wyatt 2020; De Rosa et al. 2020; Damasso et al. 2020)
- $i_{(\text{Proxima c})}$~30º (Benedict & McArthur 2020; Kervella et al. 2020)

The importance of knowing the orbital inclination

π Men b



Proxima c



- The main results for π Men b do not change if *i* is known (α_{obs}=[70°,95°]) or unknown (α_{obs}=[69°,95°]).
- With current estimates of *i* and *e*, the orbit of Proxima c is not accessible with Roman.
  - Gaia will provide astrometry of many more planets.

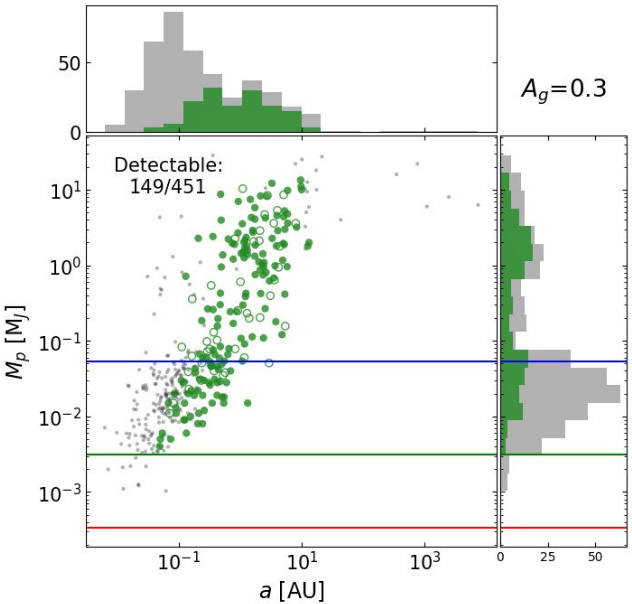
PCS

PCS

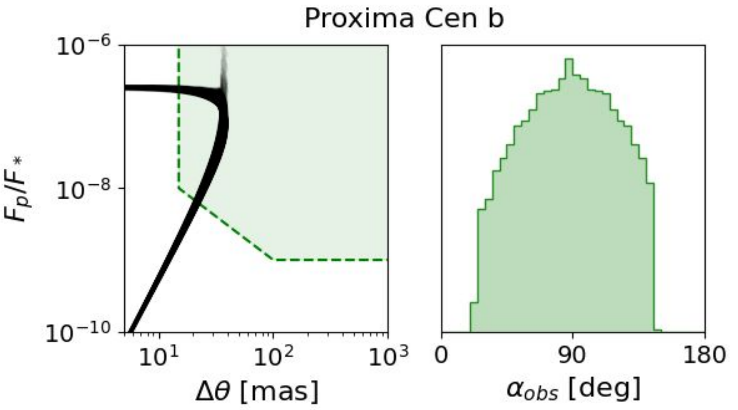
(preliminary)

Orbital simulations from Carrión-González et al. (2021)

Contrast curve from Kasper et al. (2021)



Considering only planets within 30 pc



PCS (preliminary)

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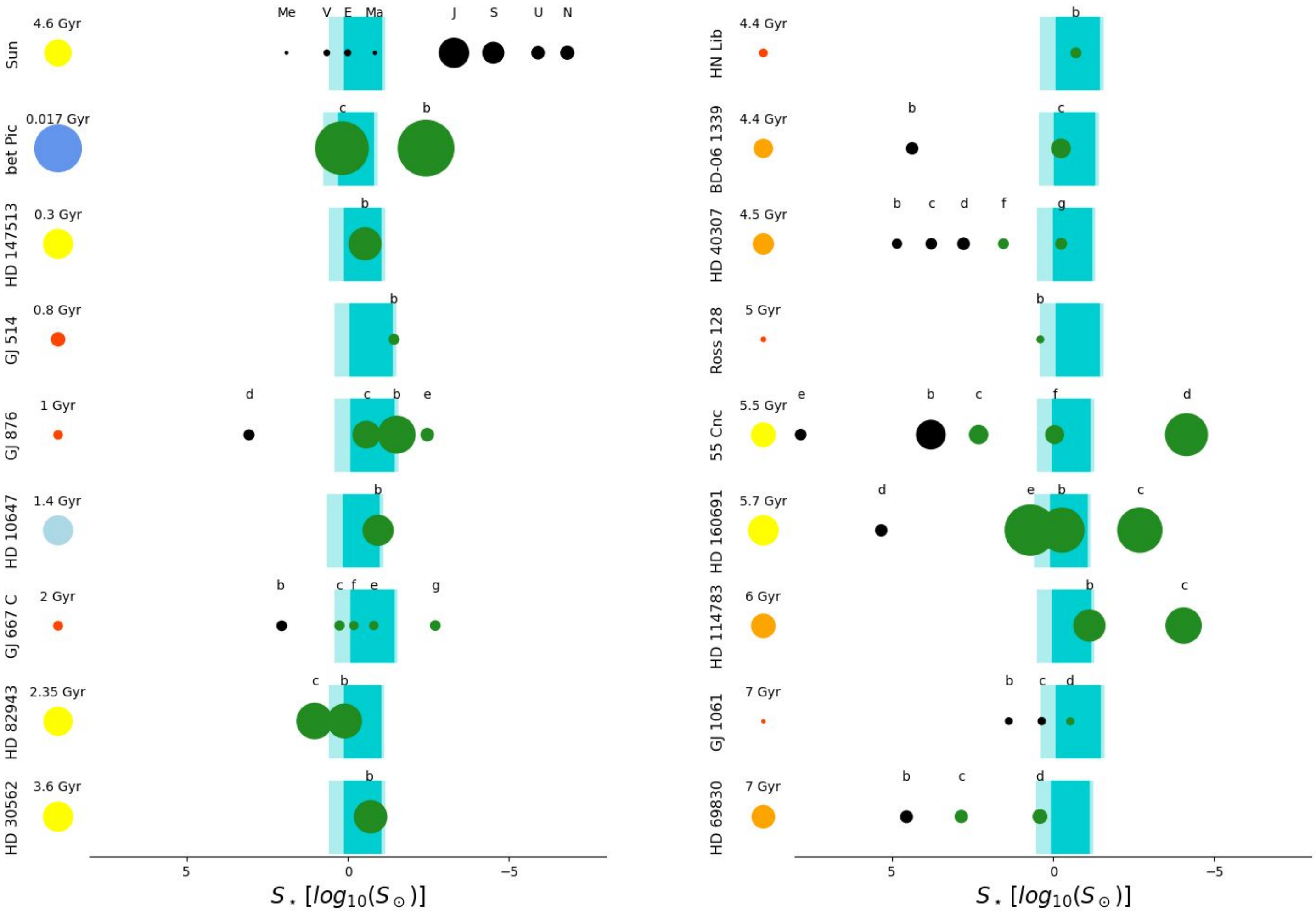

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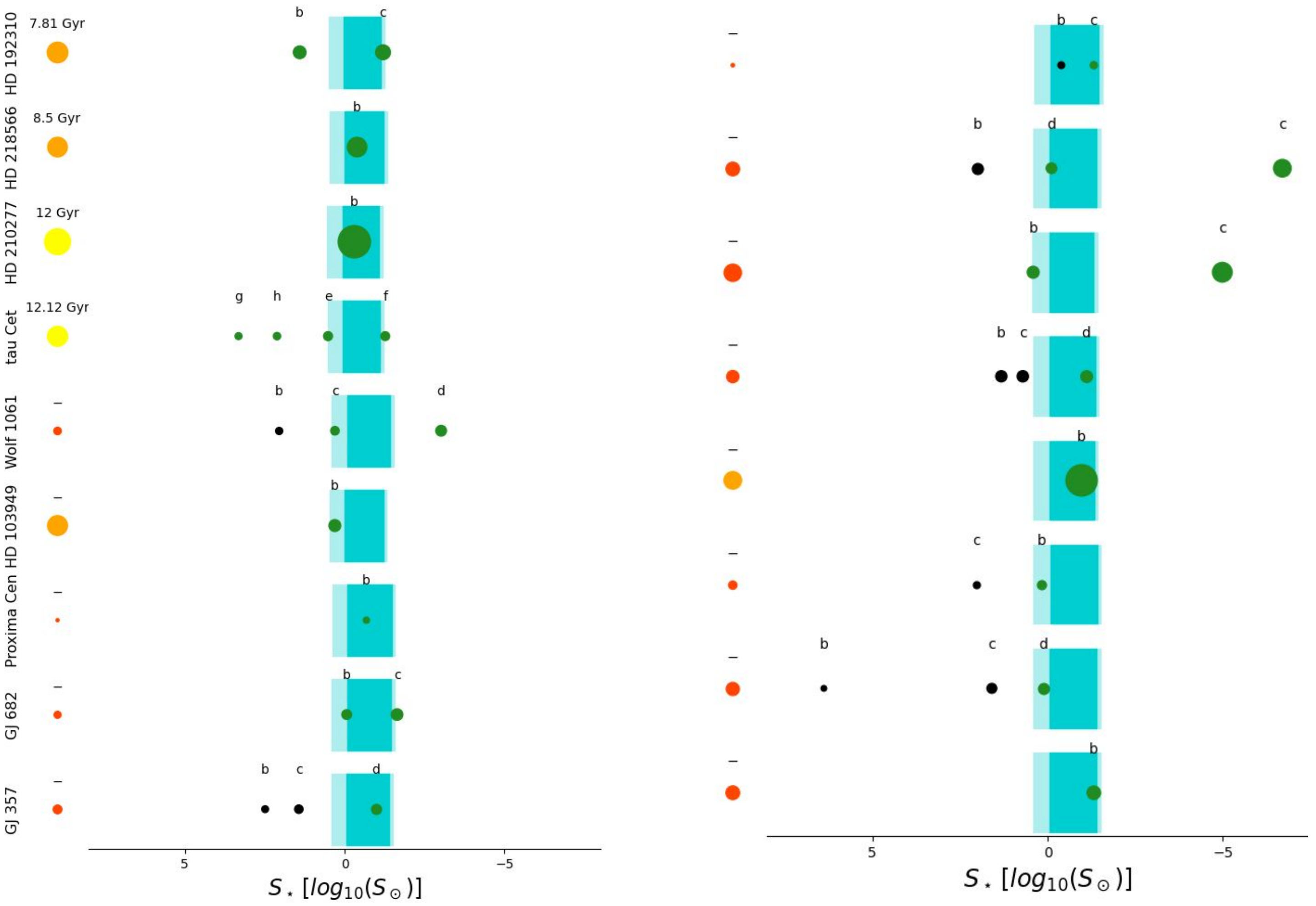


METIS

Mid-infrared
ELT Imager and
Spectrograph

Mid-infrared
ELT Imager and
Spectrograph

METIS Direct Imaging of Old, Cold Jupiters Identified by Radial Velocity Surveys

References:

- METIS Science Case September 2022 (FdR document)
- METIS System Design & Analysis Report (FdR document)
- METIS User manual draft

METIS REFERENCE PROGRAMMES

Mid-infrared
ELT Imager and
Spectrograph

A search for nearby temperate rocky planets

Important references:

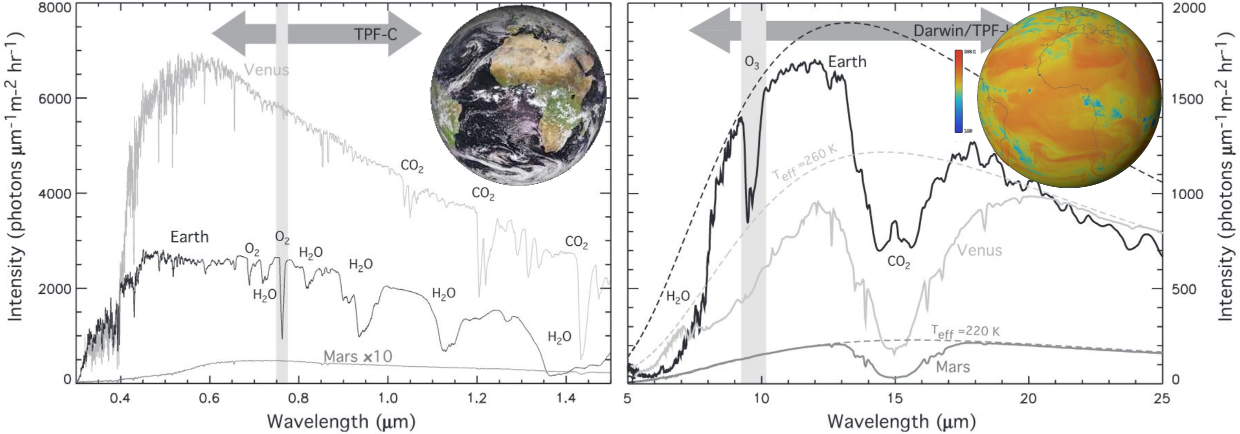
- Bowens et al. 2021, A&A 653, A8
- Alpha Centauri 2023 workshop
- Wagner et al.,2021, NatCo, 12, 922
- E-REP-ULG-MET-1024 v1-0 (HCI performance analysis)
- E-REP-ULG-MET-1019 v1-0 (Influence of water vapor on HCI performance)

Complementary methods, same science goals

How unique is our Earth?

Visible & near-IR

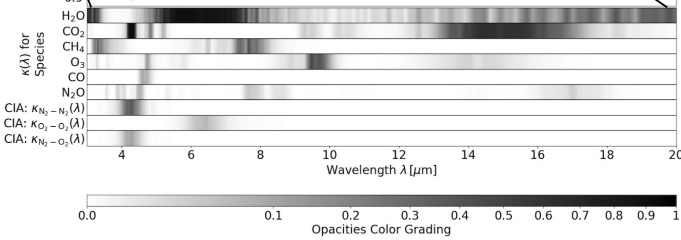
Mid-IR



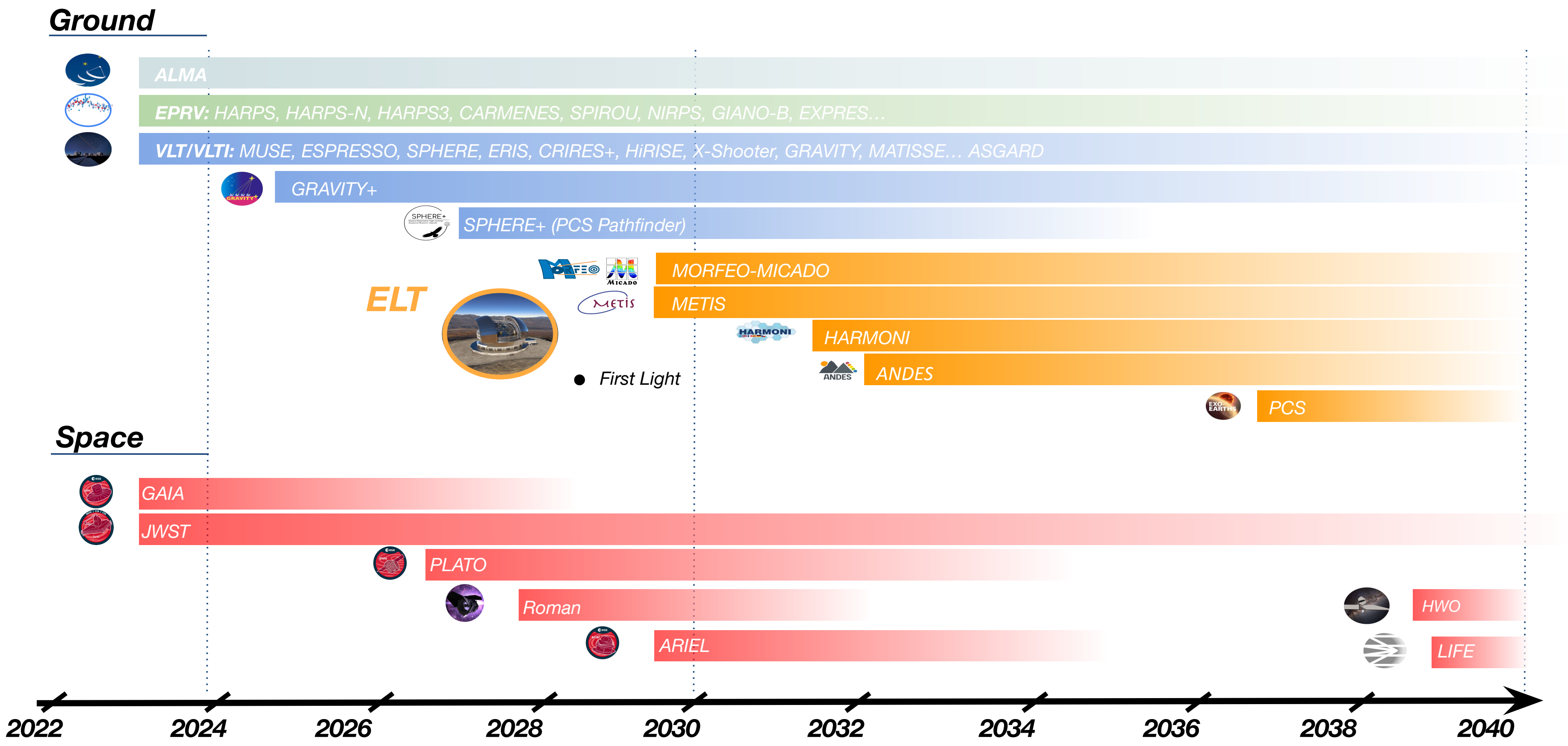
Roman: 0.5-0.8 µm

LIFE: 4-20 µm

HWO: 0.2-2.0 µm



Selsis et al. (2008)
Konrad et al. (2022)
Credit images: ESA


Ground
ALMA
EPRV: HARPS, HARPS-N, HARPS3, CARMENES, SPIROU, NIRPS, GIANO-B, EXPRES…
VLT/VLTI: MUSE, ESPRESSO, SPHERE, ERIS, CRIRES+, HiRISE, X-Shooter, GRAVITY, MATISSE… ASGARD
GRAVITY+
SPHERE+ (PCS Pathfinder)
ELT
MORFEO-MICADO
METIS
HARMONI
ANDES
First Light
PCS
Space
GAIA
JWST
PLATO
Roman
ARIEL
HWO
LIFE
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040

Ground-based

Next step: new 5th UT & I band

Lacour et al. (2025)

Direct imaging timeline

Astro2020 Decadal Survey (Nov. 2021)

The decadal survey recommends a large (~6m diameter) IR/O/UV space telescope with high-contrast imaging and spectroscopy (...) This is an ambitious mission with the goal of searching for biosignatures from habitable zone exoplanets and providing a powerful new facility for general astrophysics.

ESA Voyage 2050 (June 2021)

The "Characterisation of Temperate Exoplanets" [in thermal emission] is considered as having the highest scientific priority (…). The committee recommends that ESA launch a detailed study involving the scientific community for the exoplanet theme to assess its likelihood of success of feasibility within the Large mission cost-cap. (…) If it is found that at least 10 temperate exoplanets (within some reasonable bound of uncertainty) can be characterised and thus a scientific breakthrough can be achieved in a feasible and affordable mission, then the committee recommends such a theme to be selected for the third Large mission in the Voyage 2050 timeframe.

(…) we thus need to observe a sample of temperate planets with varying size and insolation, including planets that are bigger and receive more insolation that what we think is theoretically possible [to develop a habitable climate]

Statistical method

Input catalogue

d (pc)

a (AU)

P (days)

e

i (deg)

ω_p (deg)

M_p (M_{Jup})

R_p (R_{Jup})

M_* (M_{Sun})

R_* (R_{Sun})

T_* (K)

NASA Exoplanet Archive

+ upper & lower uncertainties

10000 simulations

10000 orbits

Output catalogue

Carrión-González et al. (2021a)