The exoplanet landscape in the 2040s

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Thanks to E. Alei, A. Sozzetti

Two fundamental questions, many science goals

Is our solar system common / rare?

Is our Earth common / rare?

Two fundamental questions, many science goals

Frequency of planets
vs size / host properties

Pathways of
planet formation

Is our solar system common / rare?

Early evolution

Diversity of exoplanet
composition

Is our Earth common / rare?

The gaseous-rocky
dichotomy / transition

Likelihood to host life
including false positives

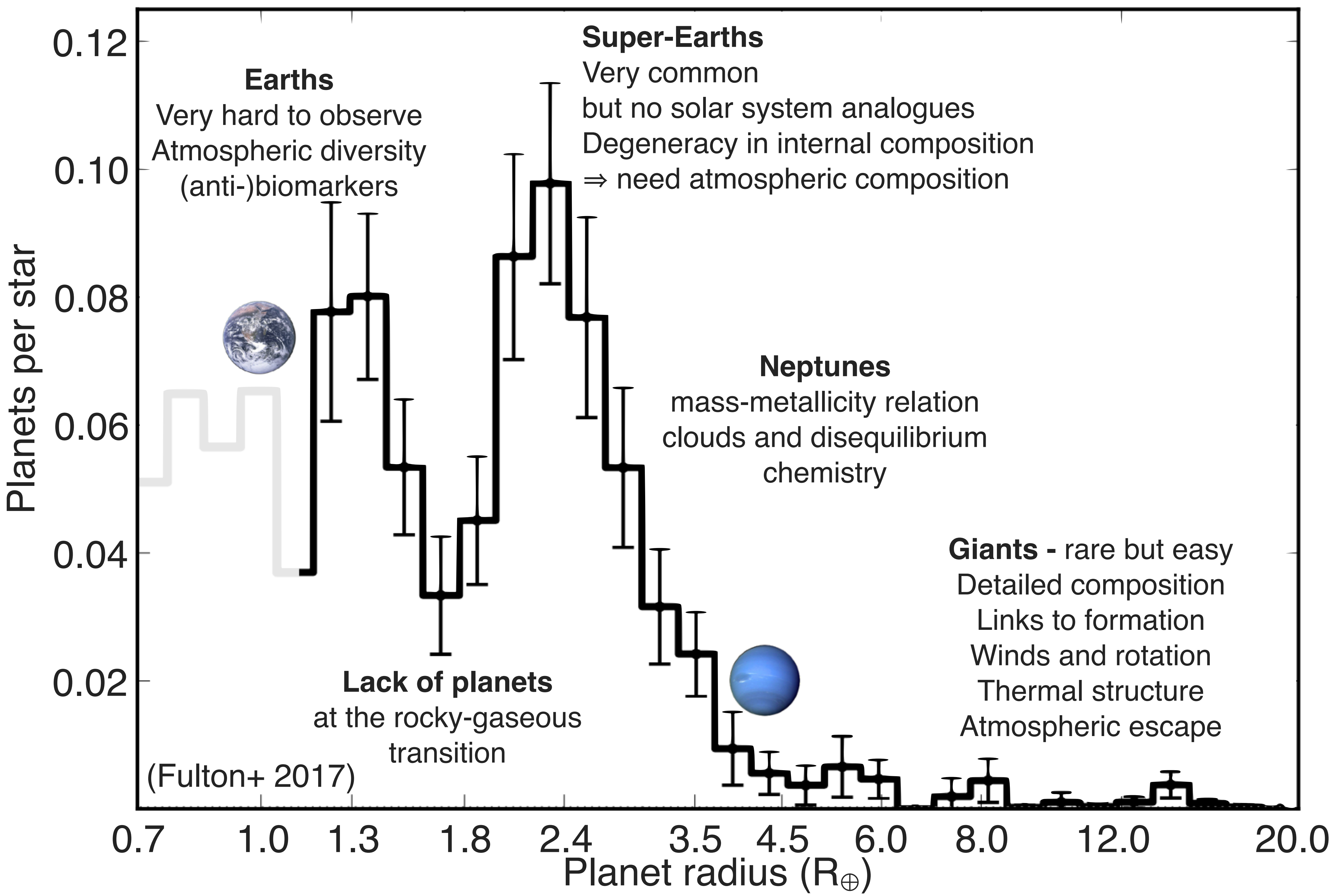
Two fundamental questions, many science goals

	Frequency of planets vs size / host properties	**2010s**
	Pathways of planet formation	**2010-202x**
Is our solar system common / rare?		
	Early evolution	**2010-20xx**
	Diversity of exoplanet composition	**2015-203x**
Is our Earth common / rare?		
	The gaseous-rocky dichotomy / transition	**2020-203x**
	Likelihood to host life including false positives	**2025-204x**

The science is different according to the sample

Statistics from *Kepler* detections of transiting planets around FGK stars (P < 100 days)

Nearly 1 planet per solar-type star; more than 2 planets per M-dwarf star



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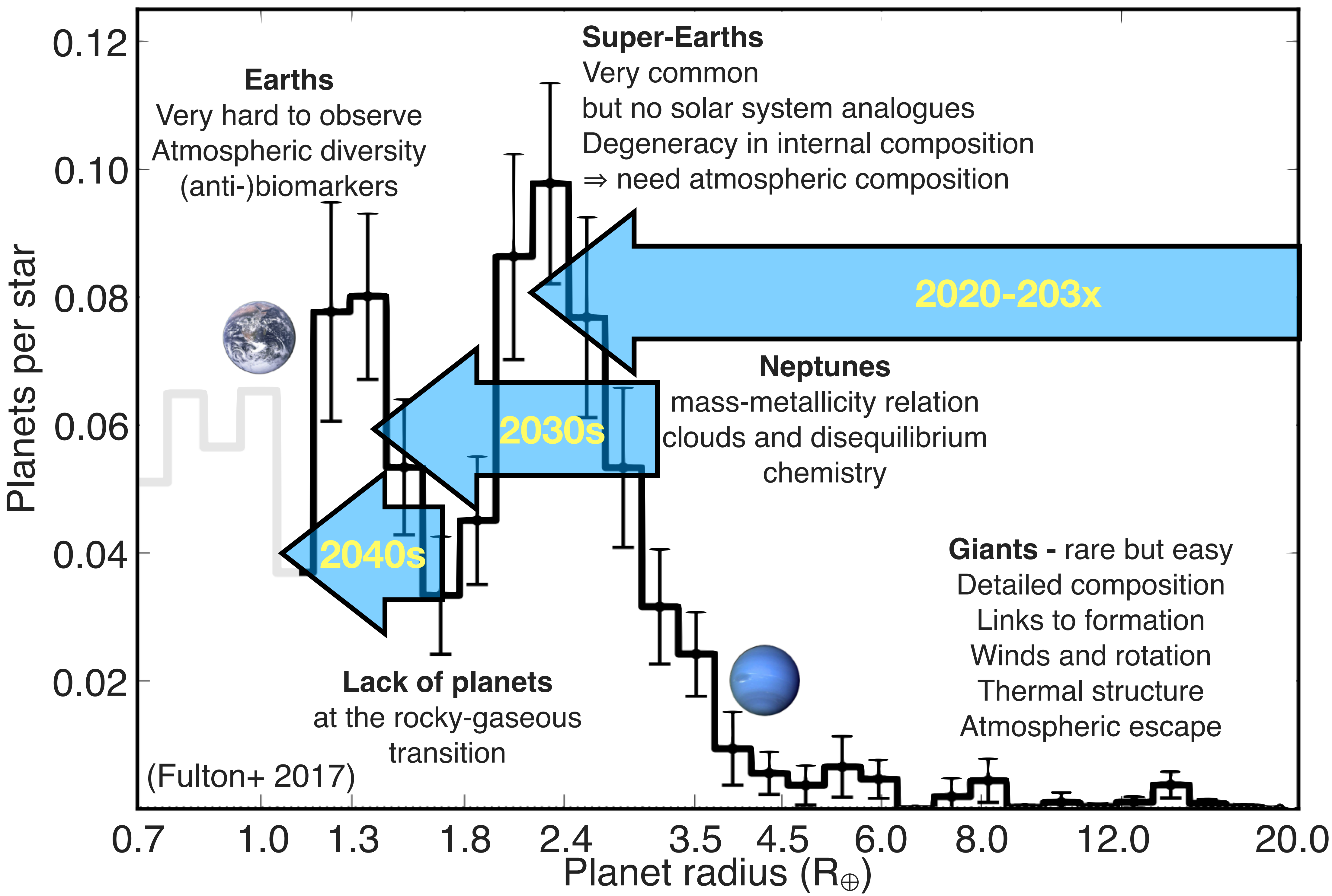

A challenging landscape to imagine and exploit

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(targeted exoplanets are completely unexplored or not even found yet!)

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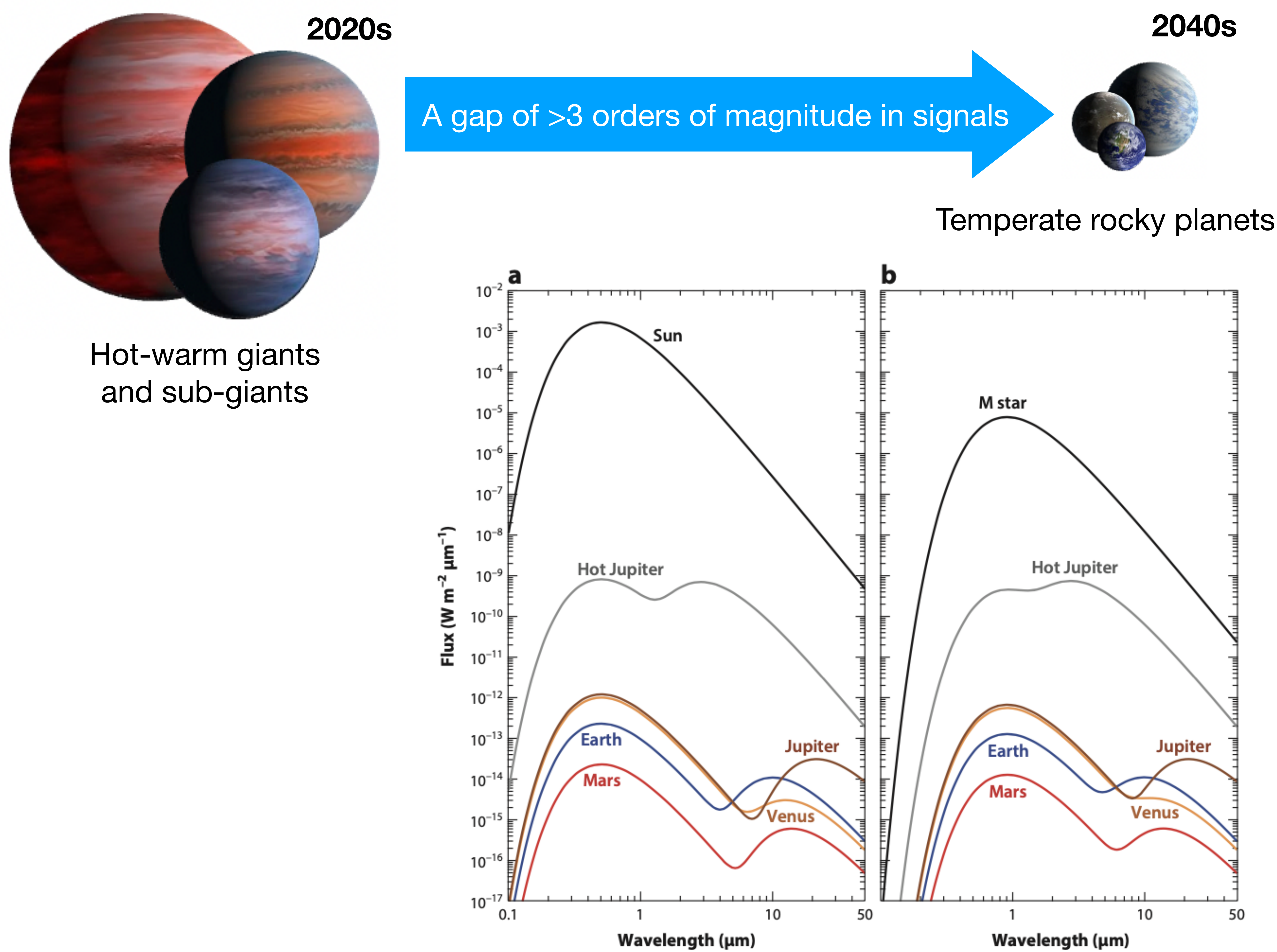
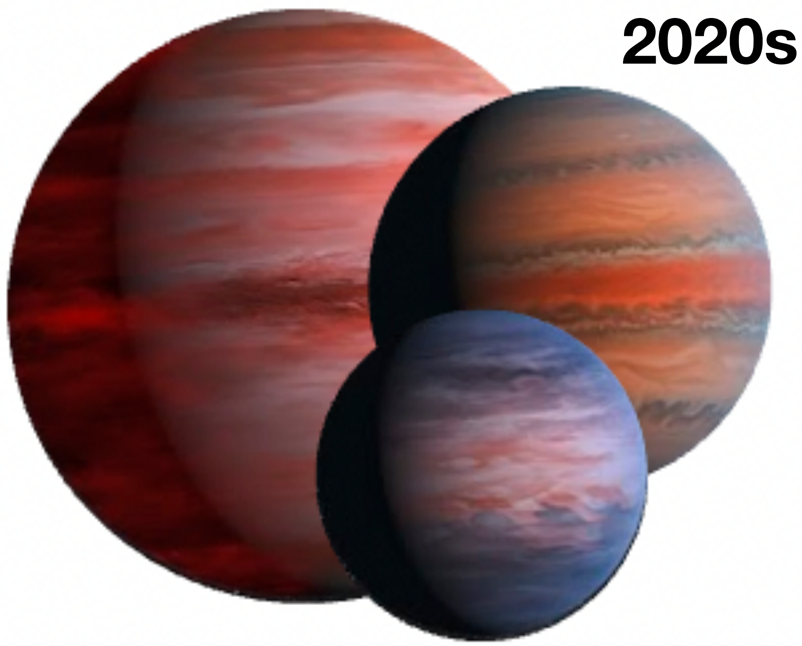
Main opportunities for ESO
The ELT will have superior collective area and spectral resolution
ESO will enter the decade at the forefront of exoplanet research
(ANDES and PCS ⇒ generational leap from gaseous to rocky planets)


2020s
A gap of >3 orders of magnitude in signals
2040s
Temperate rocky planets
Hot-warm giants
and sub-giants
a
b
Sun
M star
Hot Jupiter
Hot Jupiter
Earth
Mars
Jupiter
Venus
Earth
Mars
Jupiter
Venus
Flux (W m⁻² μm⁻¹)
Wavelength (μm)
Wavelength (μm)

2020s



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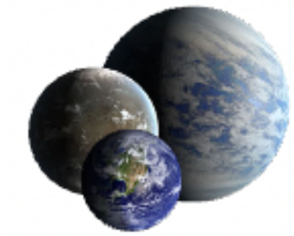
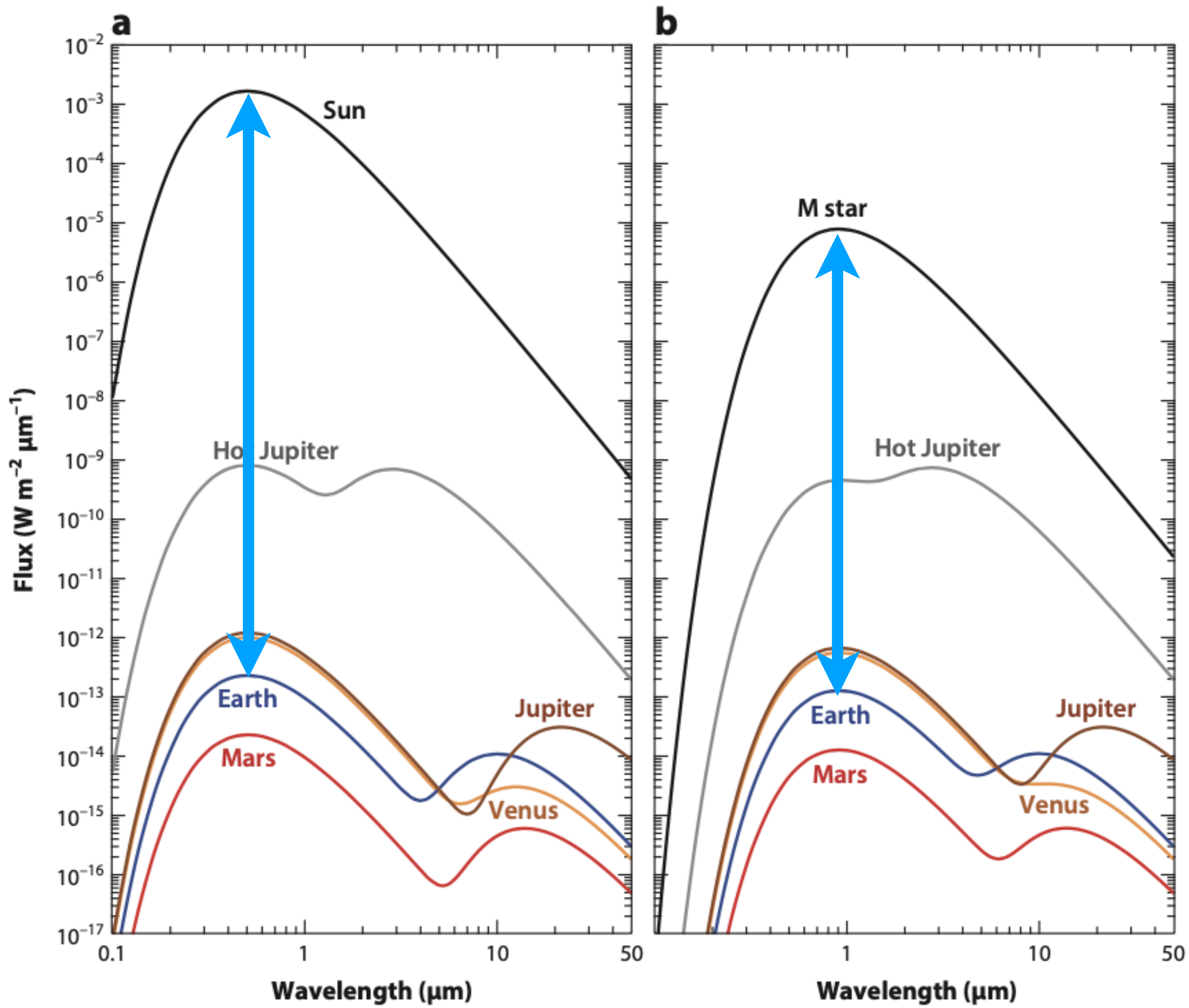


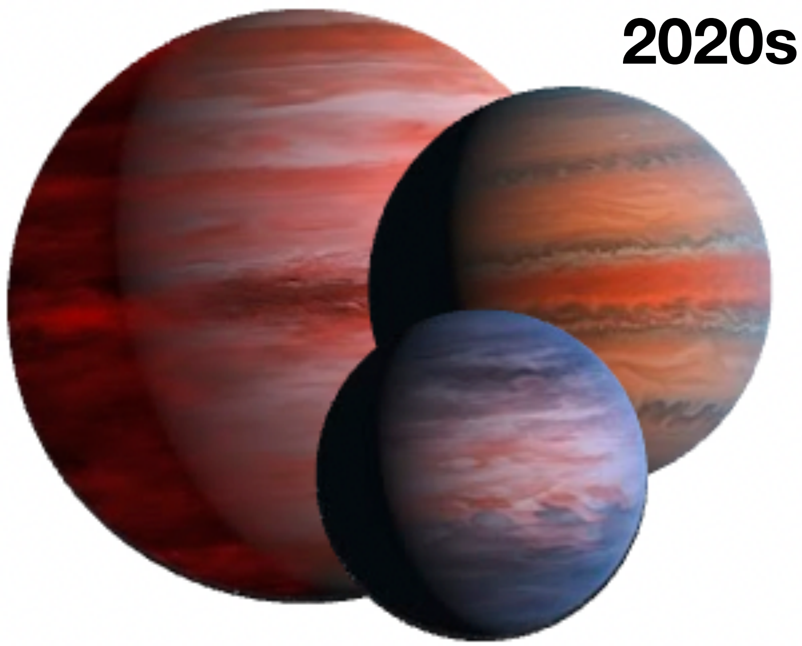
Temperate rocky planets

Planet/star contrast in reflected light

10^{-10} (G stars)

10^{-8} (M stars)





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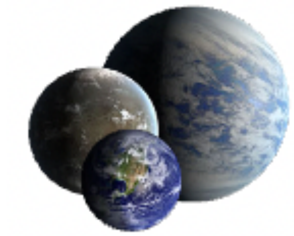

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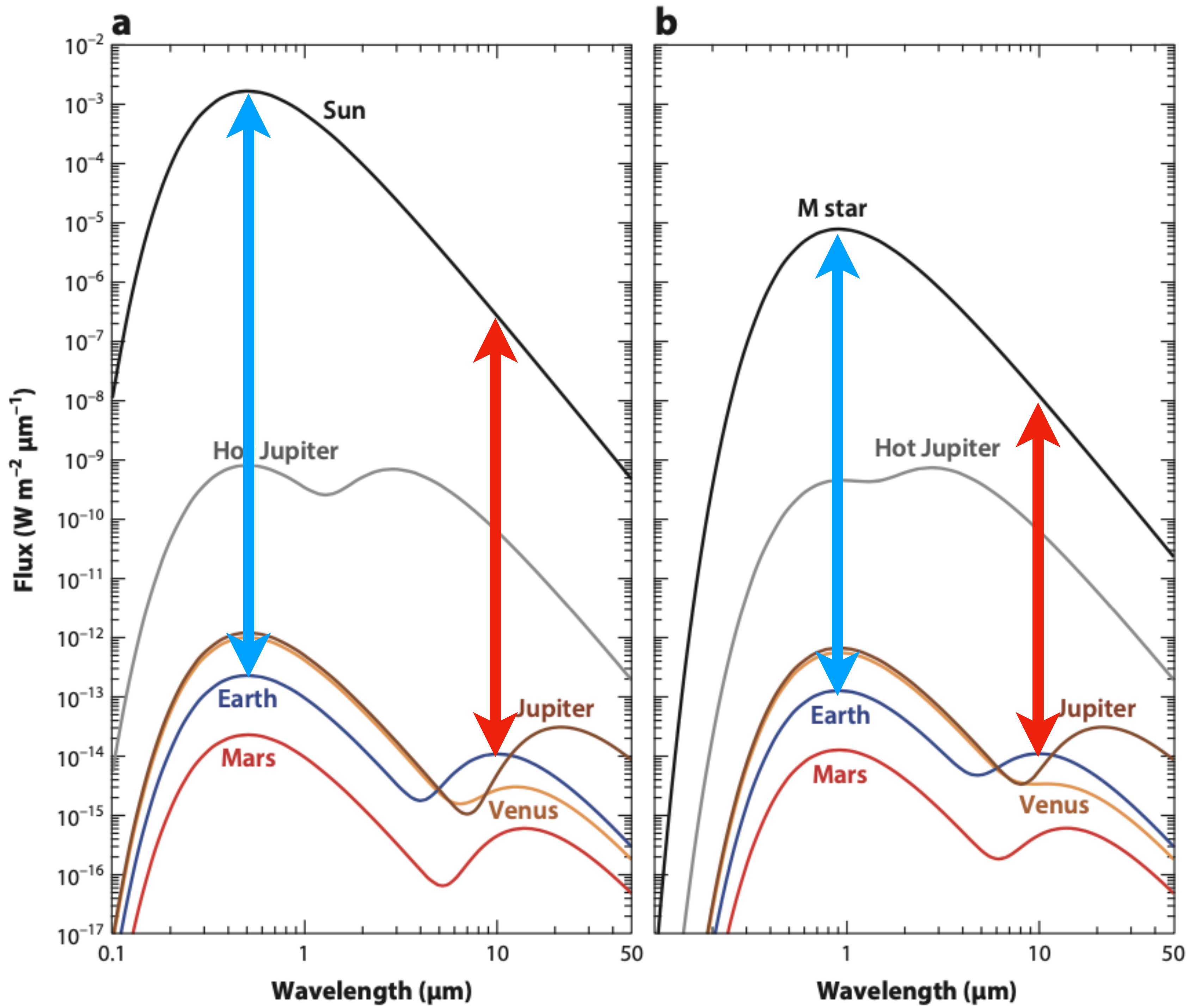
Planet/star contrast in thermal emission

10^{-7} (G stars)

10^{-6} (M stars)



Where we start from: facilities and sensitivity

From space

(HST, JWST)
(Ariel - 2029)

From the ground

ESO facilities
(SPHERE, CRIRES+)
(HARPS, Espresso)

Other 4-8m class
(IGRINS, GIARPS,
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0.8–24 μm at R~10-50 (native: up to ~3500)

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0.35-2.45 μm at R=45k-140k **+ cross correlation**
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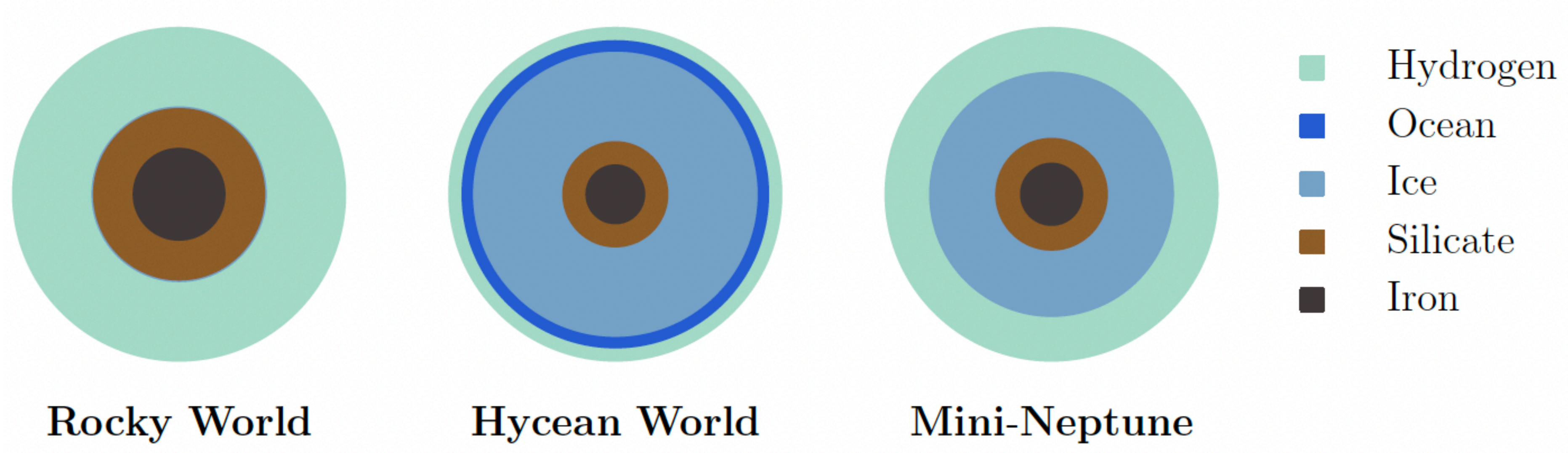
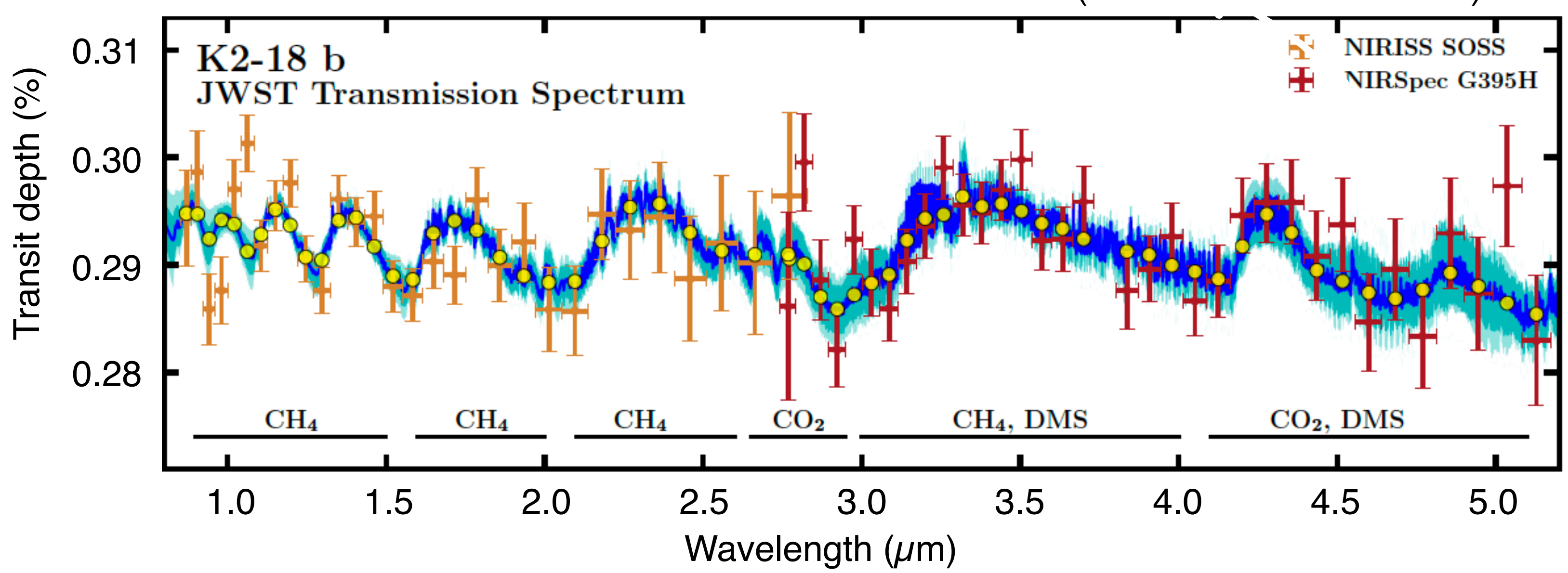
High spatial and spectral resolution
R=5k-100k via IFUs or long-slits
down to planet/star contrasts $\sim 10^{-6}$

Expect the unexpected: Hycean worlds

One possible model solution to the interior-envelope degeneracy (~1.5-2.5 Earth radii)



(Madhusudhan+23)



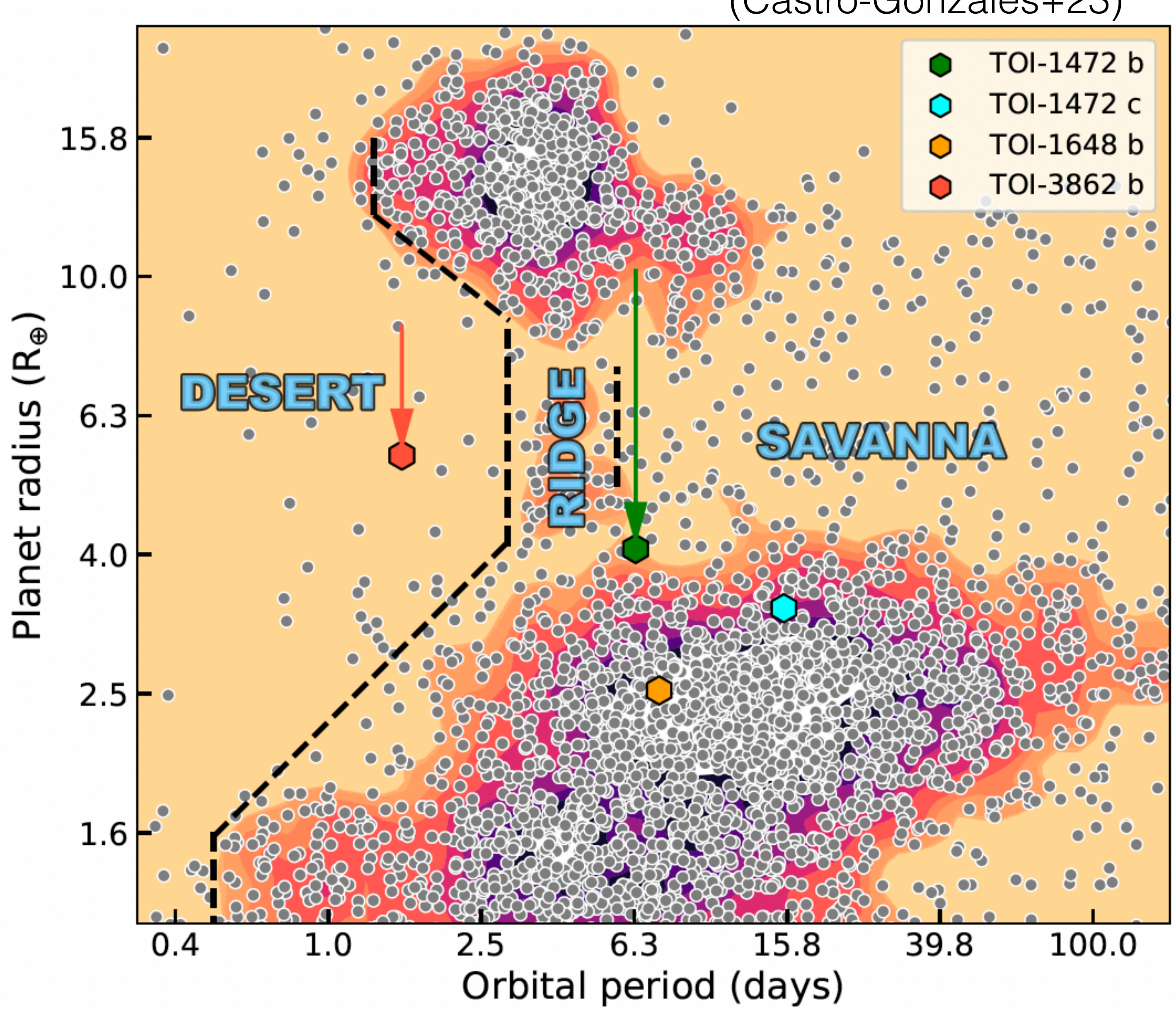
Highly-contested claim of DMS in K2-18b as indicators of biological activity

Potential Hycean planet already within reach of current-gen (space & ground)
Interpretation likely degenerate at very low S/N or spectral resolution

Might need the whole JWST lifetime and some help from ELT/ANDES (2030s)

Desert, ridge and savanna: the rocky-gaseous transition

(Castro-Gonzáles+23)



Planets > 1.5 R_{Earth} are mostly gaseous (Rogers, 2015)

The rocky-gaseous transition can be a consequence of **formation** pathways or **atmospheric loss**

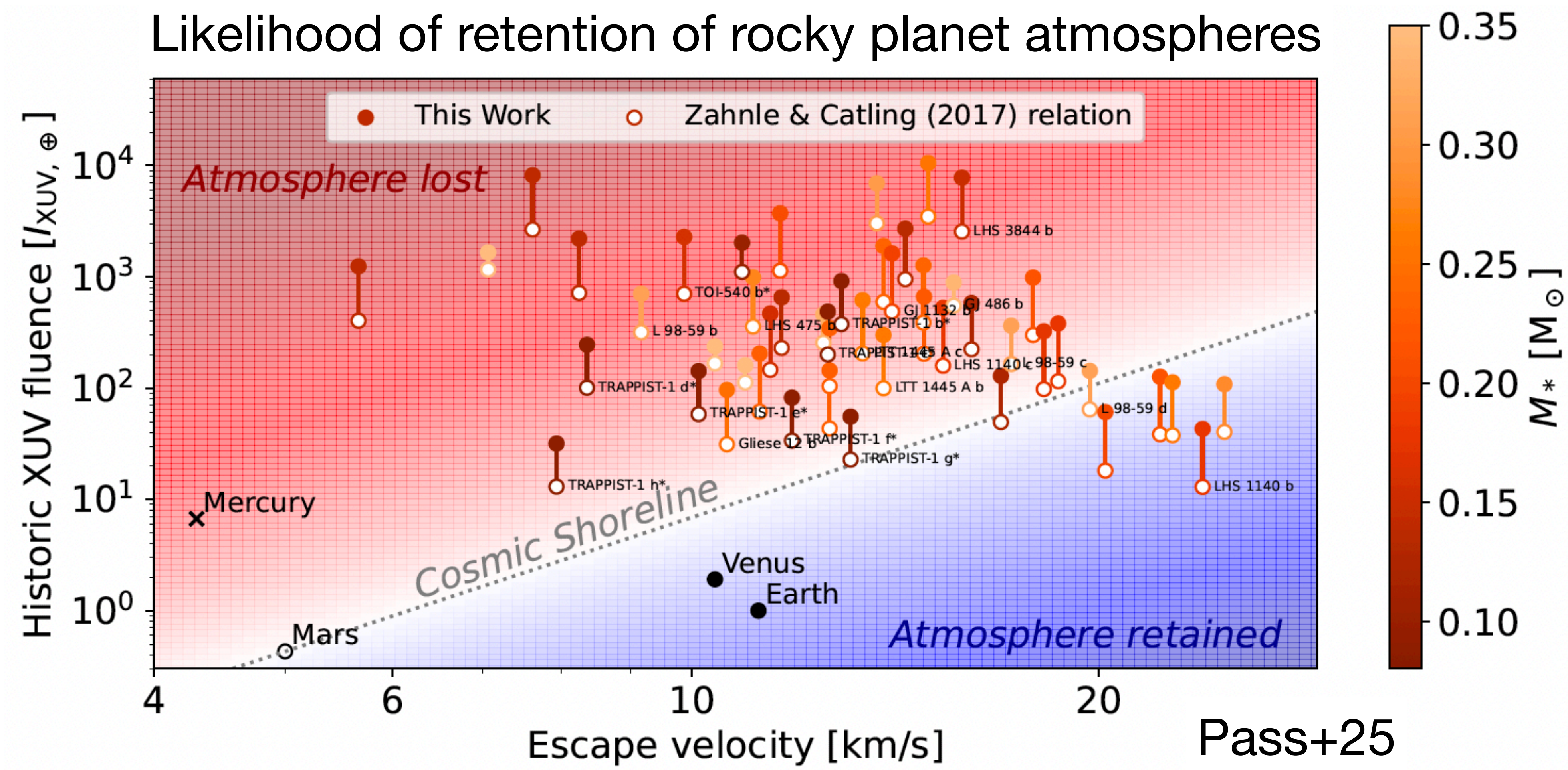
Transmission signals decrease by 8-32× at the transition

Gaseous exoplanets: targeted with current instruments both from space (JWST) and via high spectral resolution from the ground

Rocky exoplanets: only lower limits on mean molecular weight with current instruments ⇒ ELT science for the 2030s

The "cosmic shoreline": a science case for the 2030s

Rocky planets around M-dwarfs can lose their atmospheres entirely



Pass+25

Combination of super-luminous pre main sequence, XUV fluxes, flaring

2 planets (LHS 1140b, L98-59d) already selected for JWST DDT
⇒ measurement <u>limited</u> to secondary eclipse brightness at 15 μm

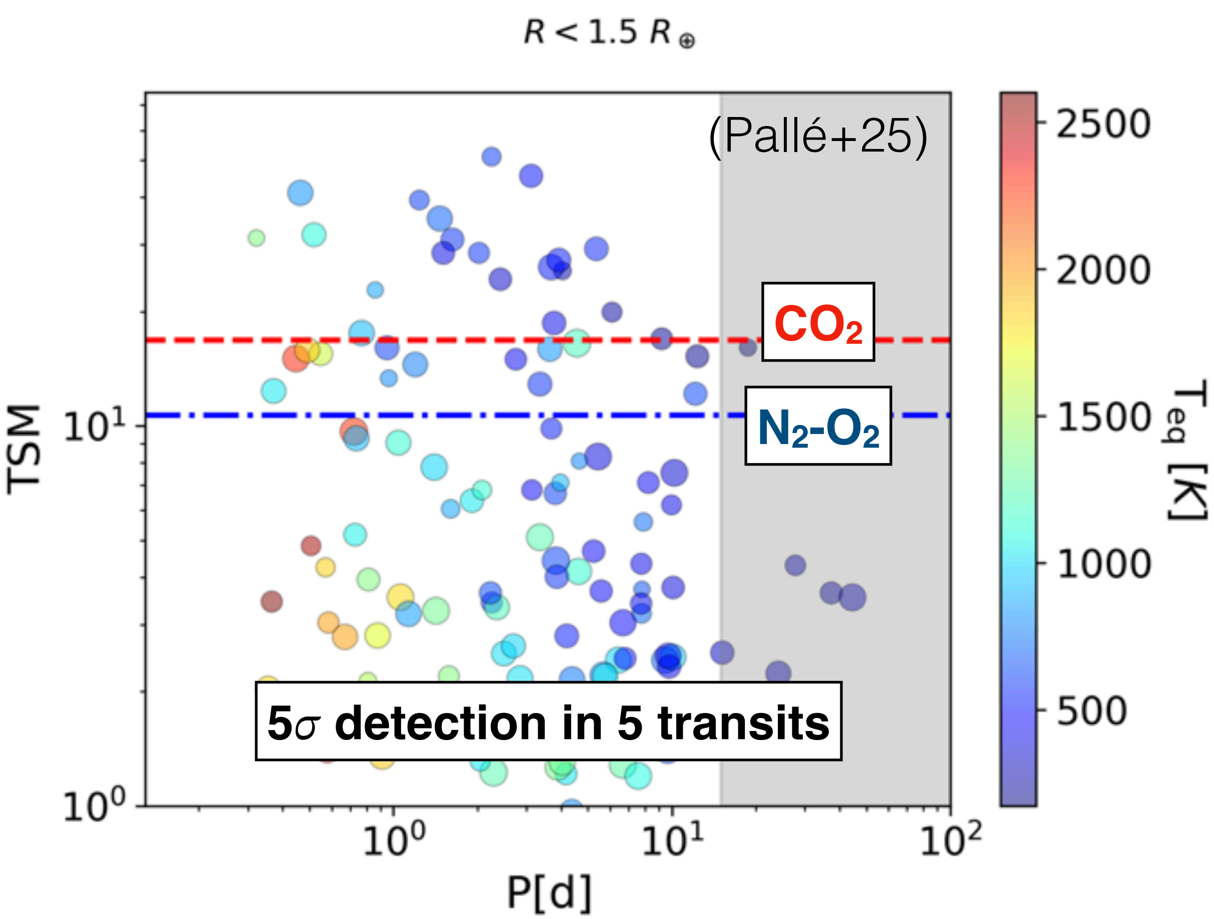
This is science for the (late) 2030s, probably needs ELT-PCS and might need HWO/LIFE to be fully addressed

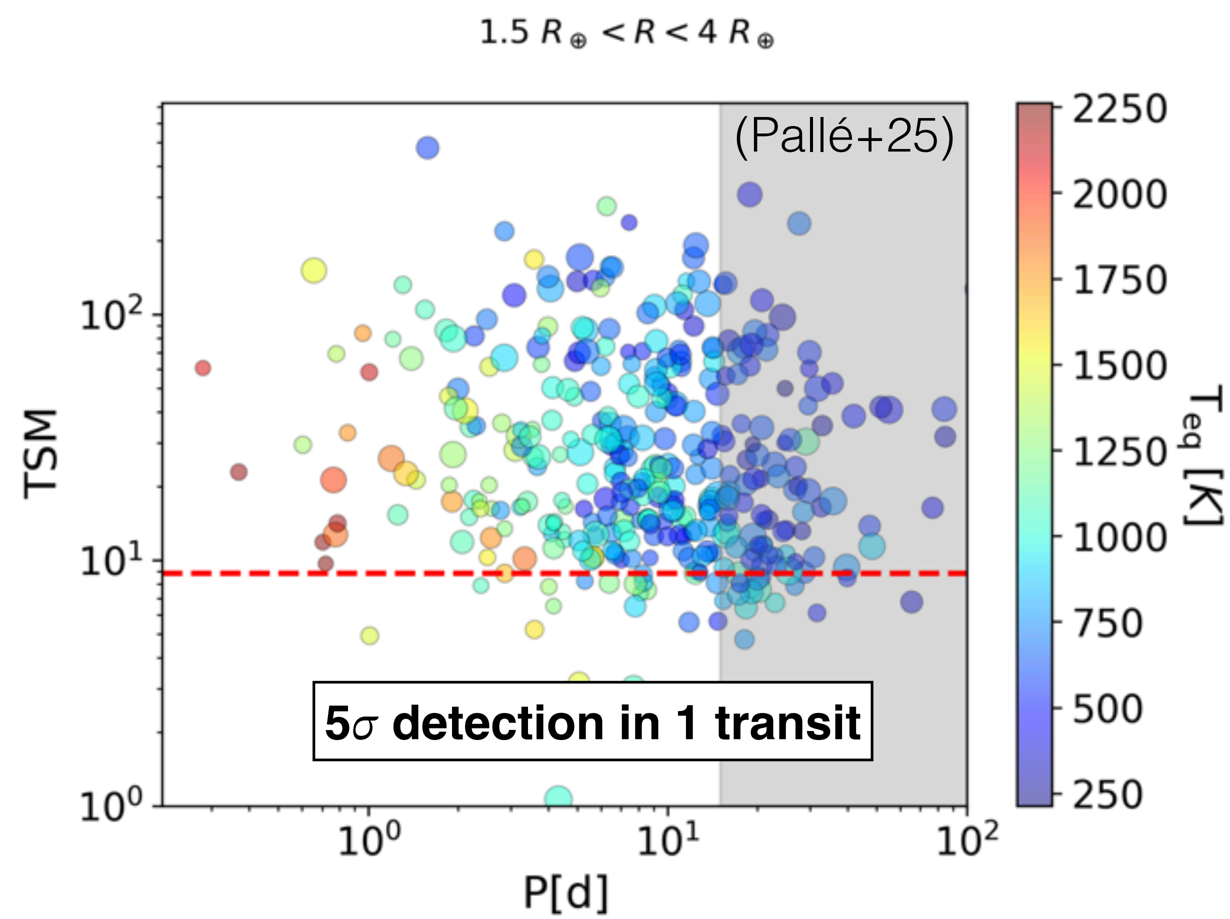
ANDES at the ELT (phase B, first light 2032)

High spectral resolution (100,000), 0.5-1.8 μm (0.35-2.5 μm possible)

Spatially <u>unresolved</u> mode: transmission and emission spectroscopy
with cross-correlation techniques (currently photon-limited to 1E-5 contrast)

Transmission spectroscopy of dozen of exoplanets at the rocky-gas transition

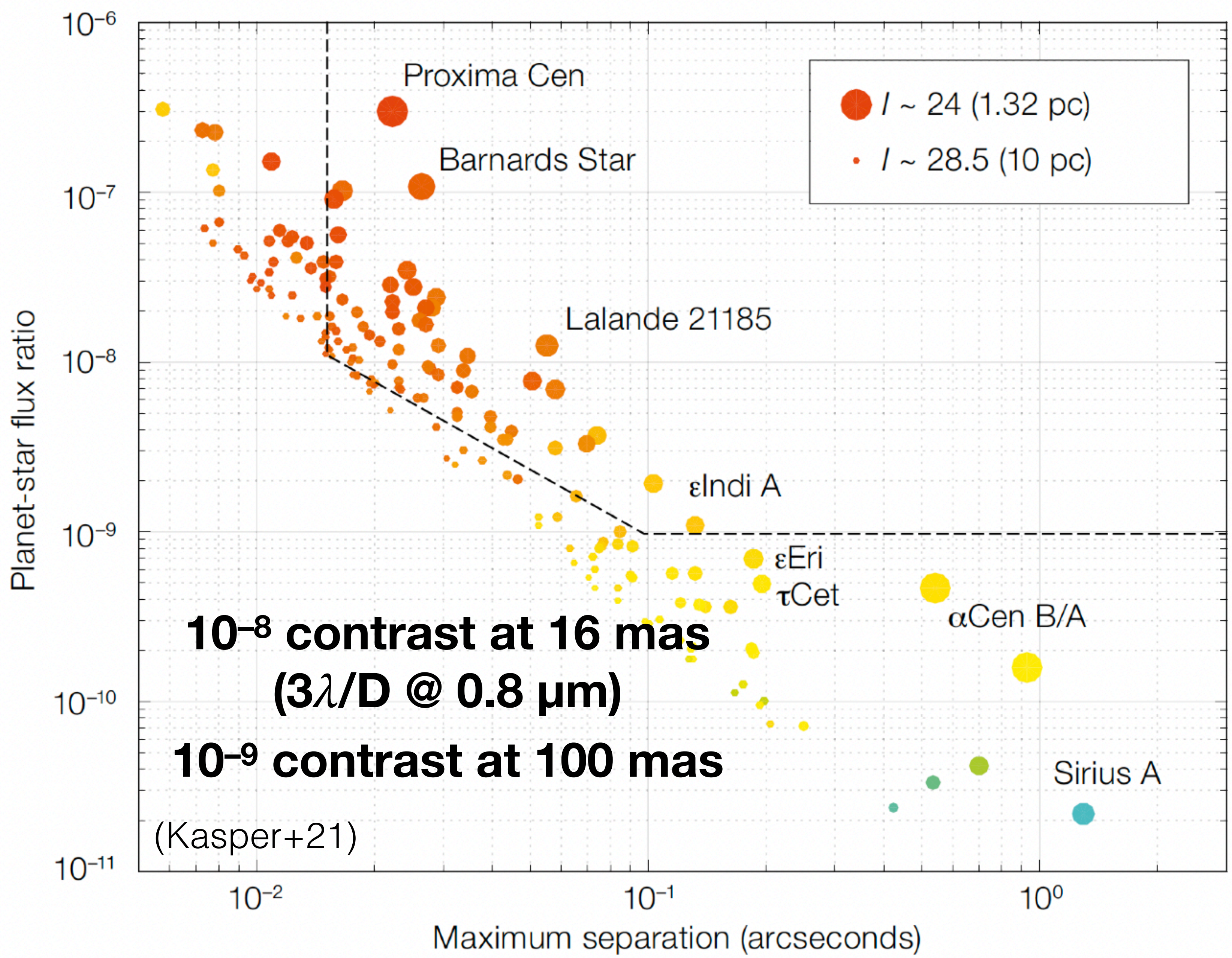




Extreme AO + IFU + cross correlation:
reflected light of 5 temperate exoplanets around nearby M-dwarfs

PCS at the ELT (pre-phase A, 203x)

Specs still TBD, but high-res spectroscopy + coronograph + XAO
Extreme contrasts reached with combination of spectral **and** spatial resolution
(assumed 10^4 gain from cross correlation)



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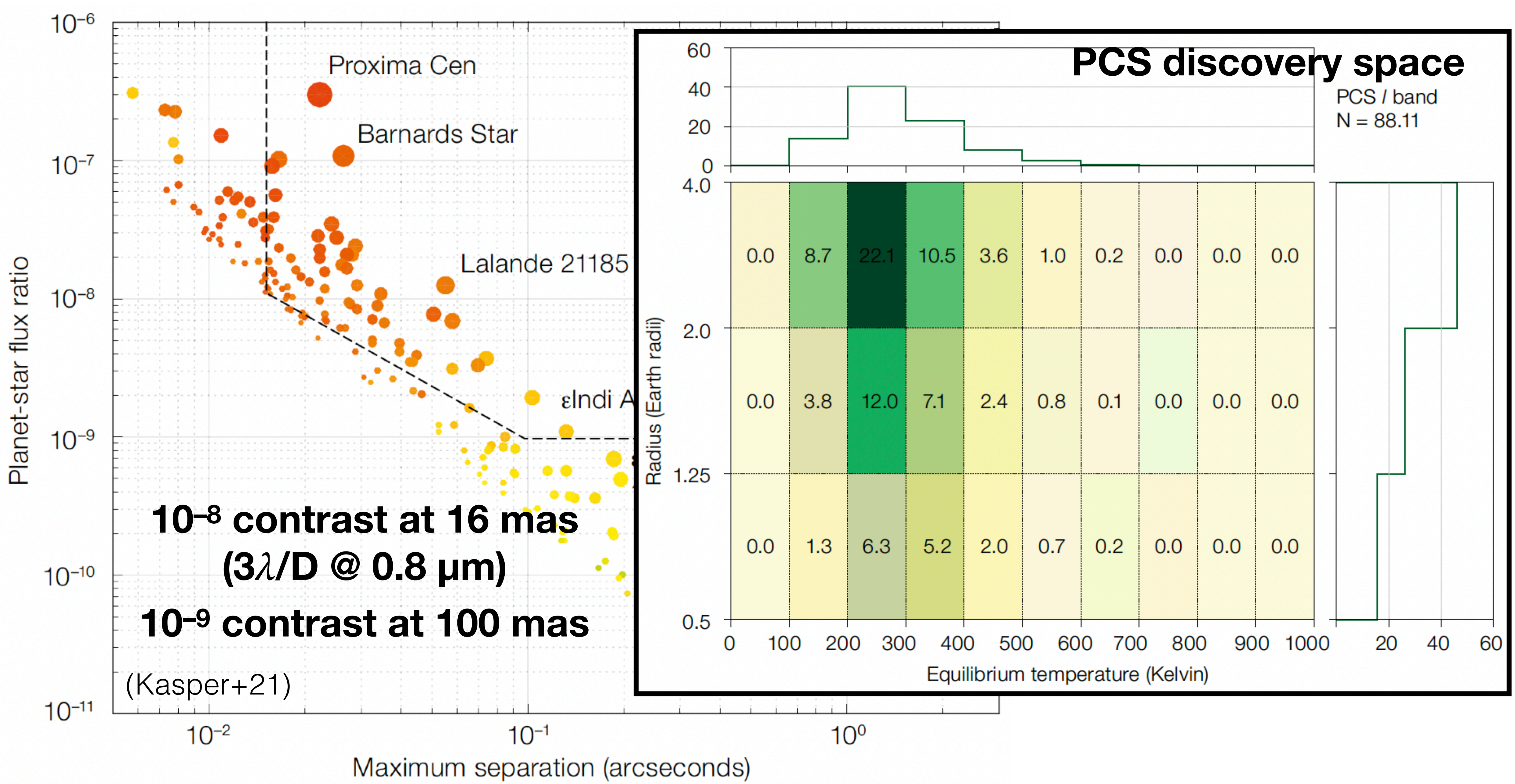

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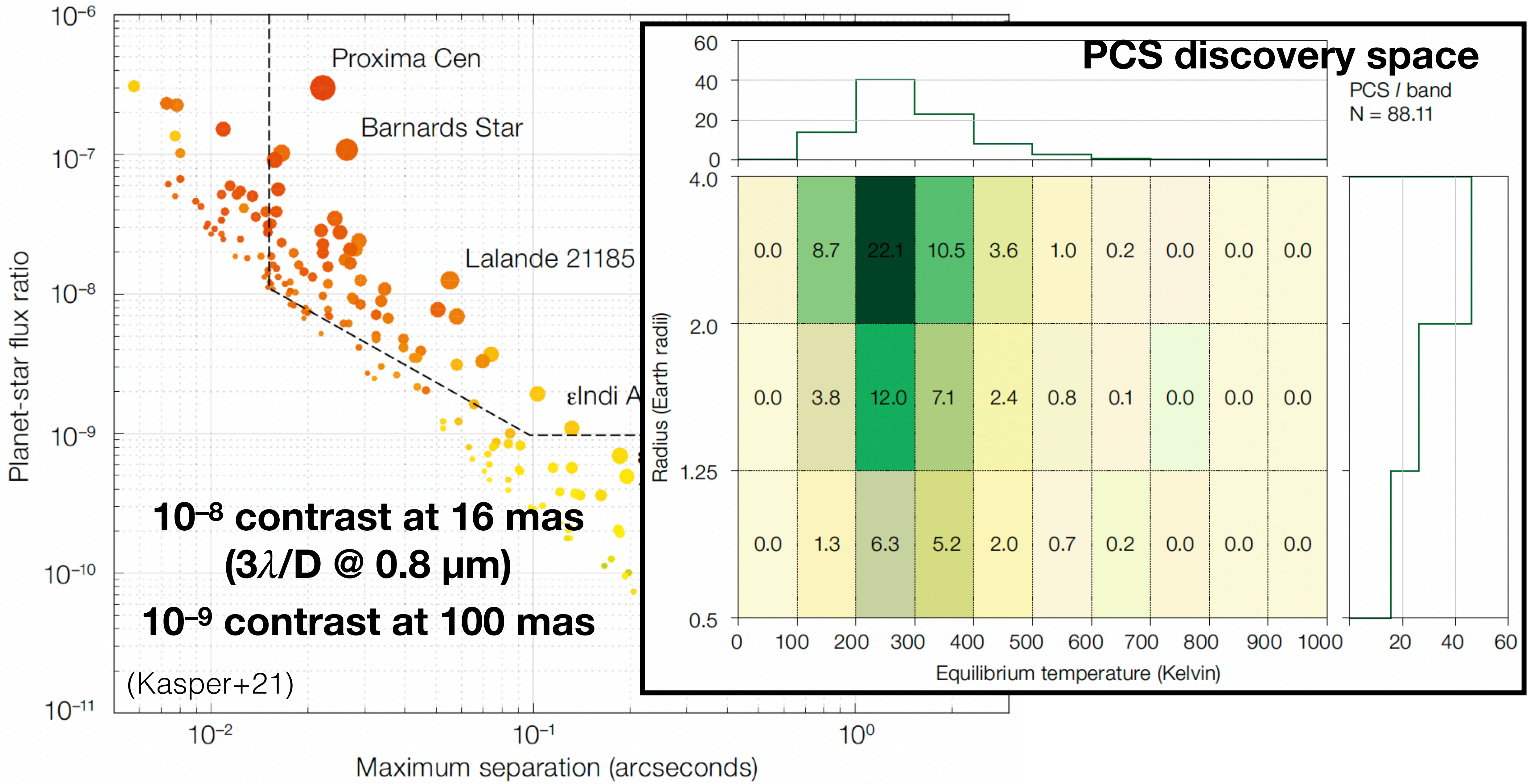
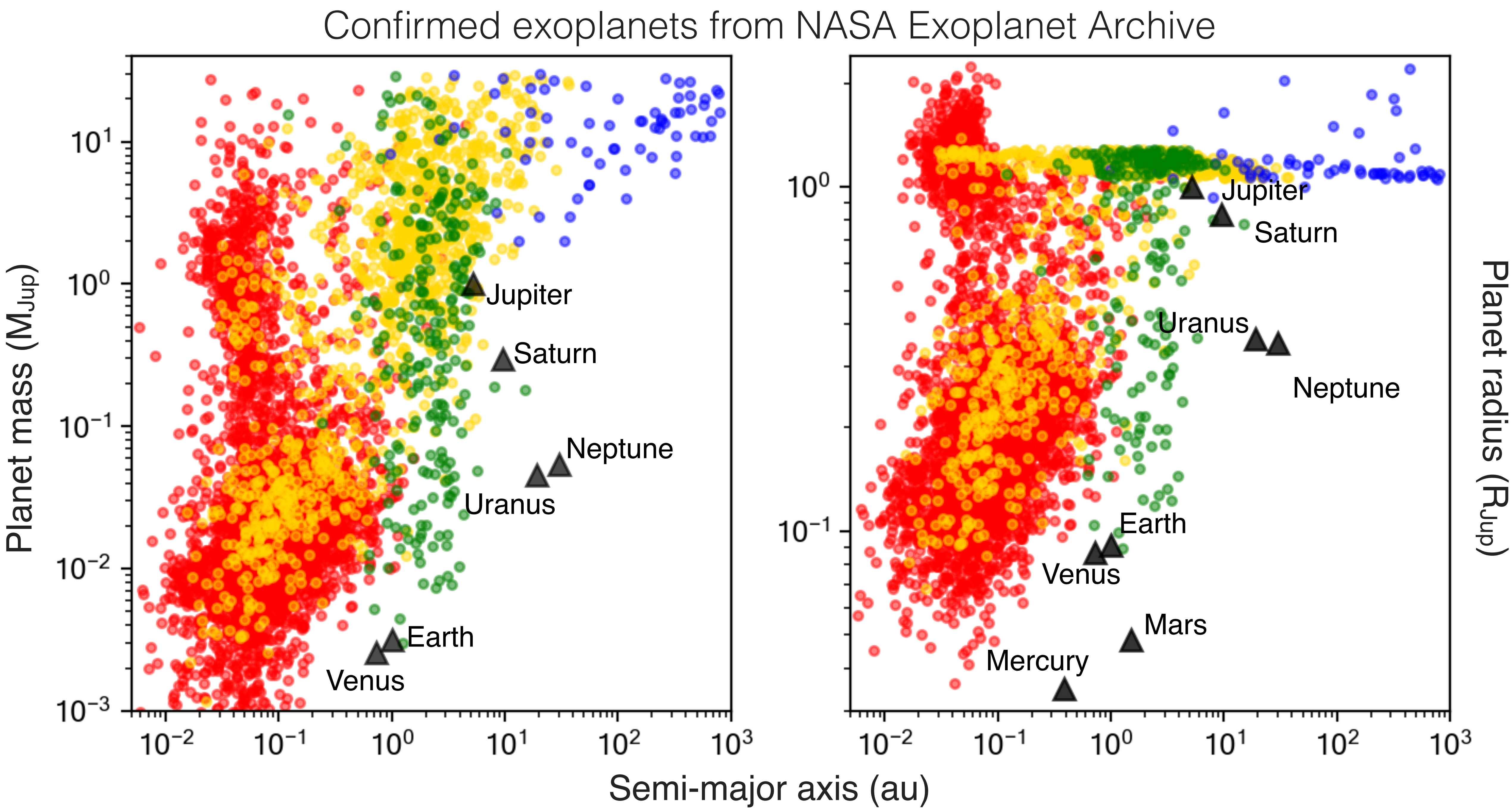


PCS can enable comparative characterisation of nearby temperate rocky planets
It can also discover a handful of such planets (still M-dwarf dominated)

We still do not know the solar-system analogues!



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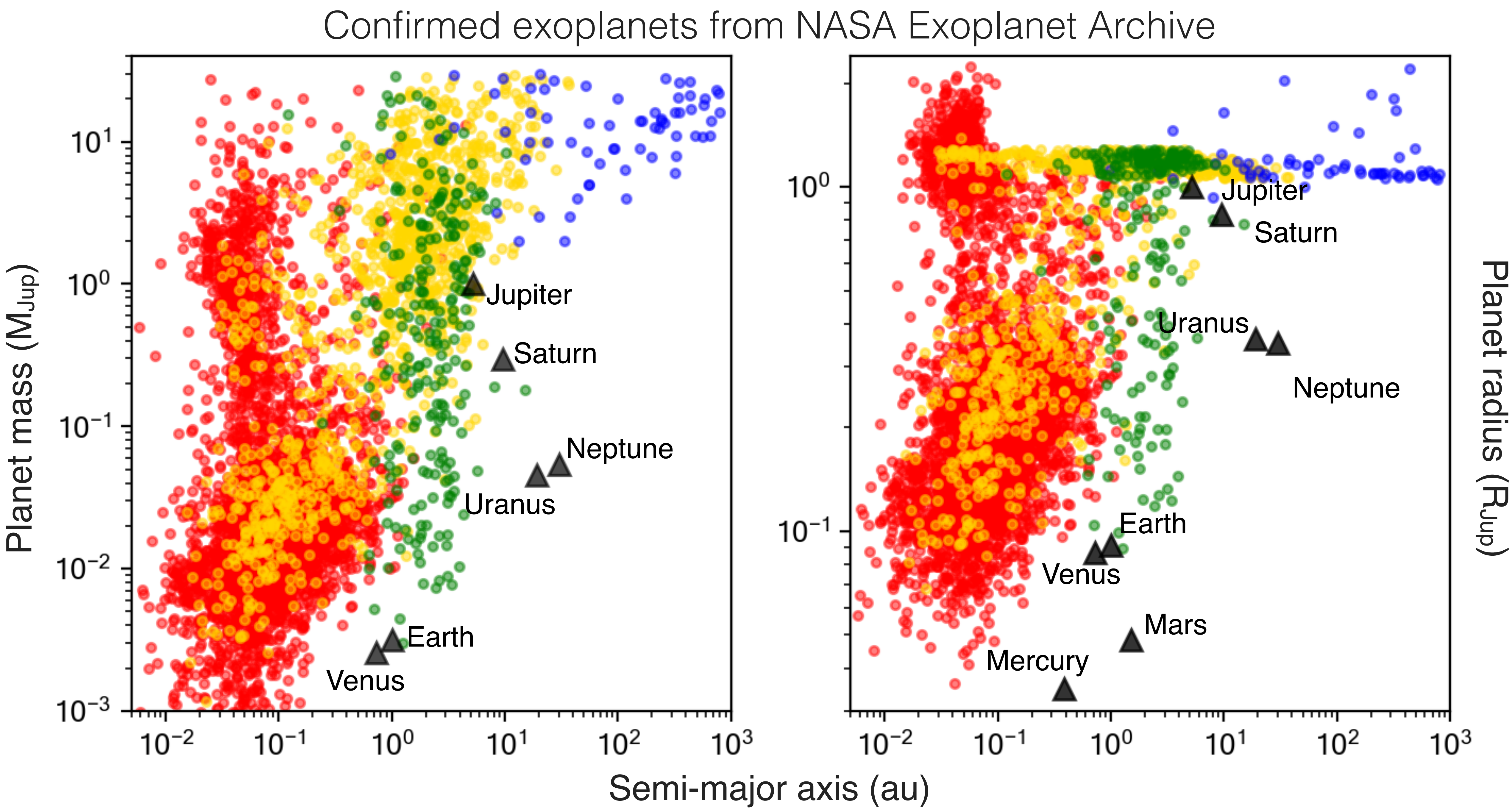

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Smaller and further away planets are harder to detect

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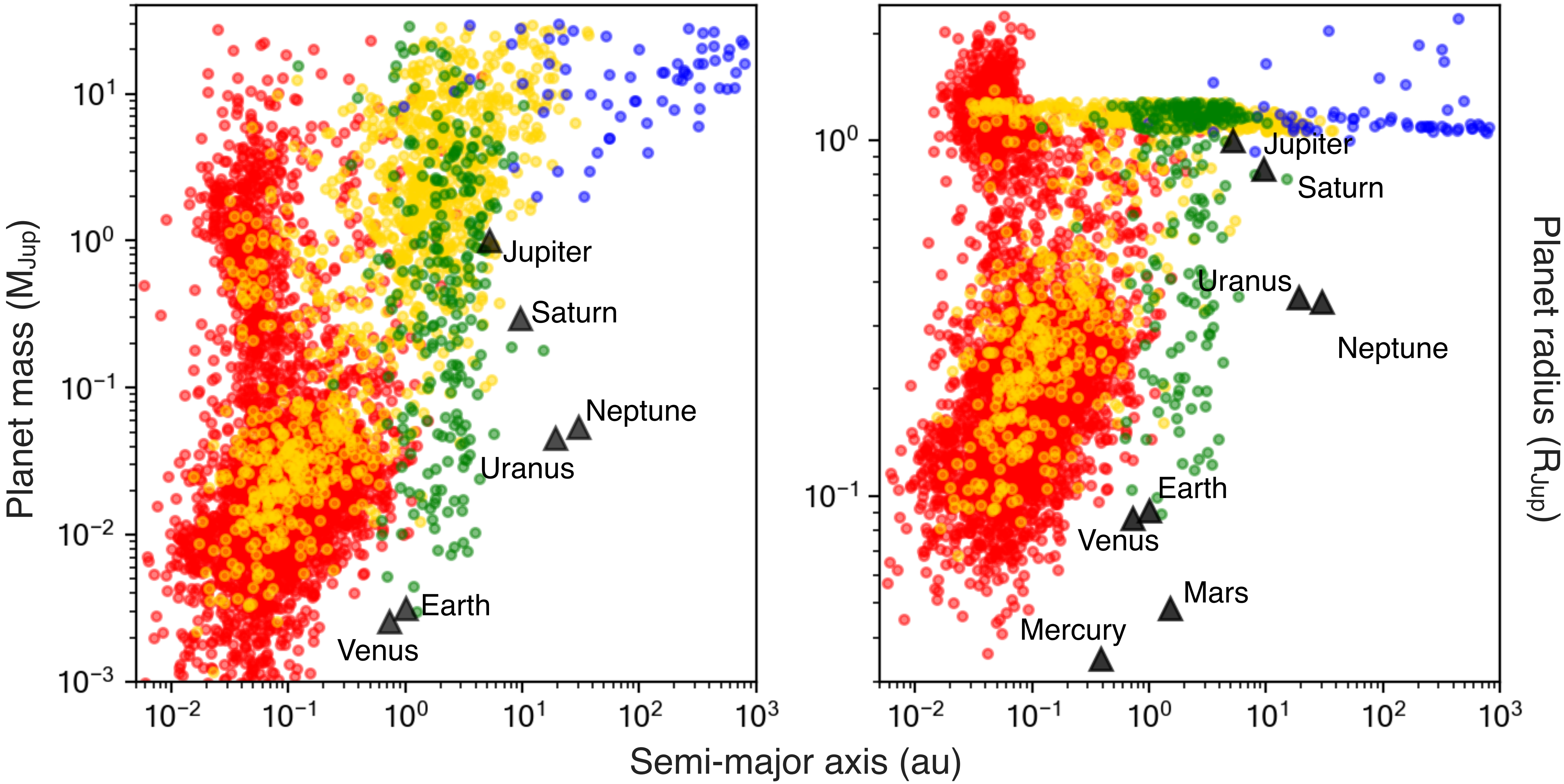
Confirmed exoplanets from NASA Exoplanet Archive



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We need to fill the gap to find real Earth analogues to characterise.

Finding solar system analogues in the next 10 years

PLATO (end of 2026, Rauer+25**)**

~1200 (4600) planets of all sizes for stars of V ≤ 11 (13) mag

up to ~100 planets < 2 R_{Earth} around V < 11 mag stars

Precise and accurate planet and host star characterisation

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GAIA (ended, Sozzetti+24**)**
~1000 warm and cold giant planets (0.5-5 AU) with
Data Release 4 (2026)
up to ~10,000 planets with Data Release 5 (date TBD)
Both contingent to pipeline development

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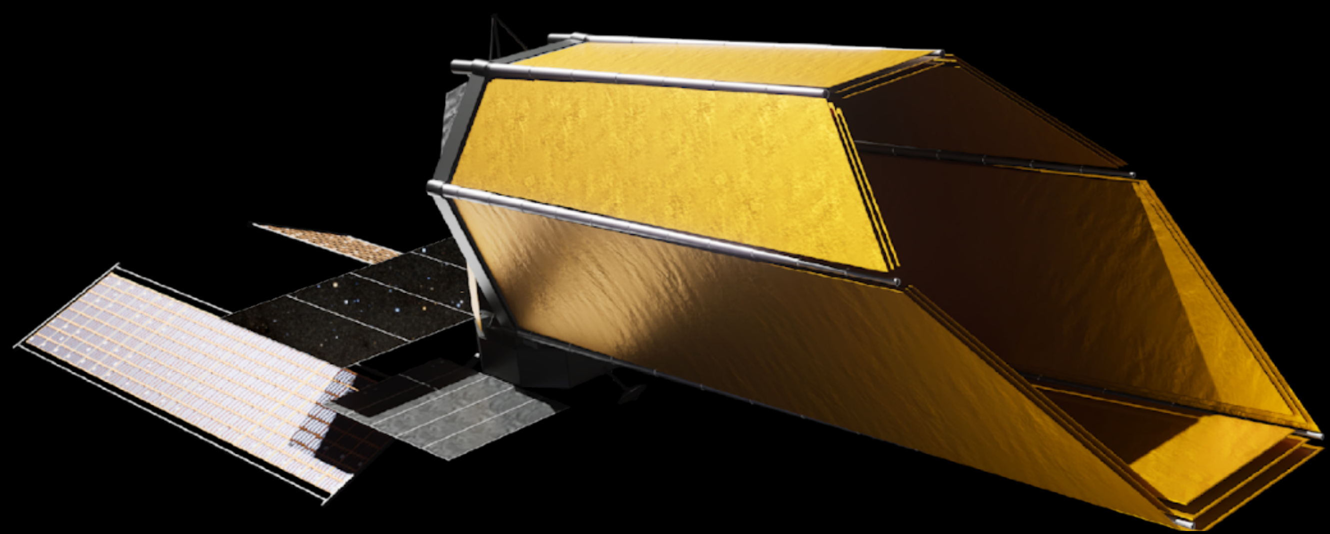
Ongoing RV surveys: more gas / ice giants on long orbits (e.g. Bonomo+23)
Extreme Precision RVs: goal of ~10 cm/s to find an Earth-Sun,
already possible on short period planets (e.g. P=11.2 d Proxima Cen, Faria+22).
Astrophysical noise and long-term stability are the main challenges in EPRVs

The big space missions of the 2040s

Habitable Worlds Observatory (HWO)



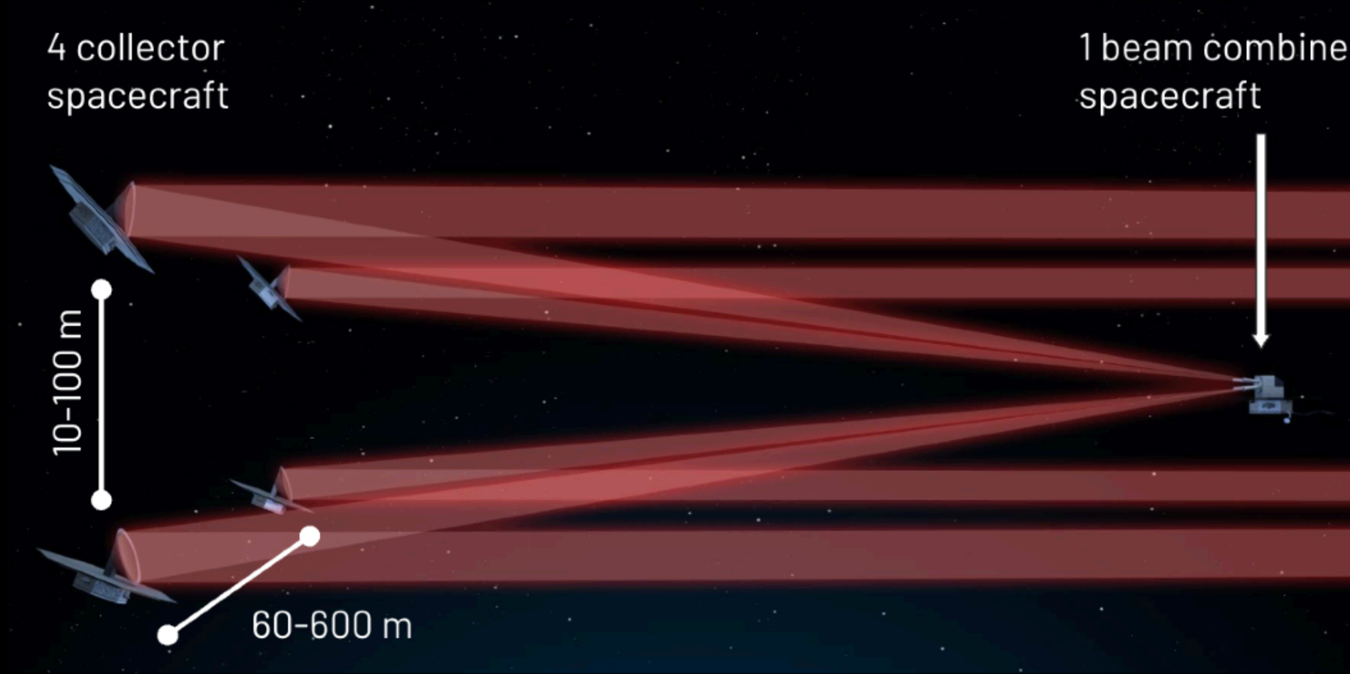
6-8m mirror

Coronograph w/ 10^{-10} contrast

Reflected light

0.2-1.8 µm, R = 70-200

Large Interferometer For Exoplanets (LIFE)



4 mirrors (2.0-3.5m)

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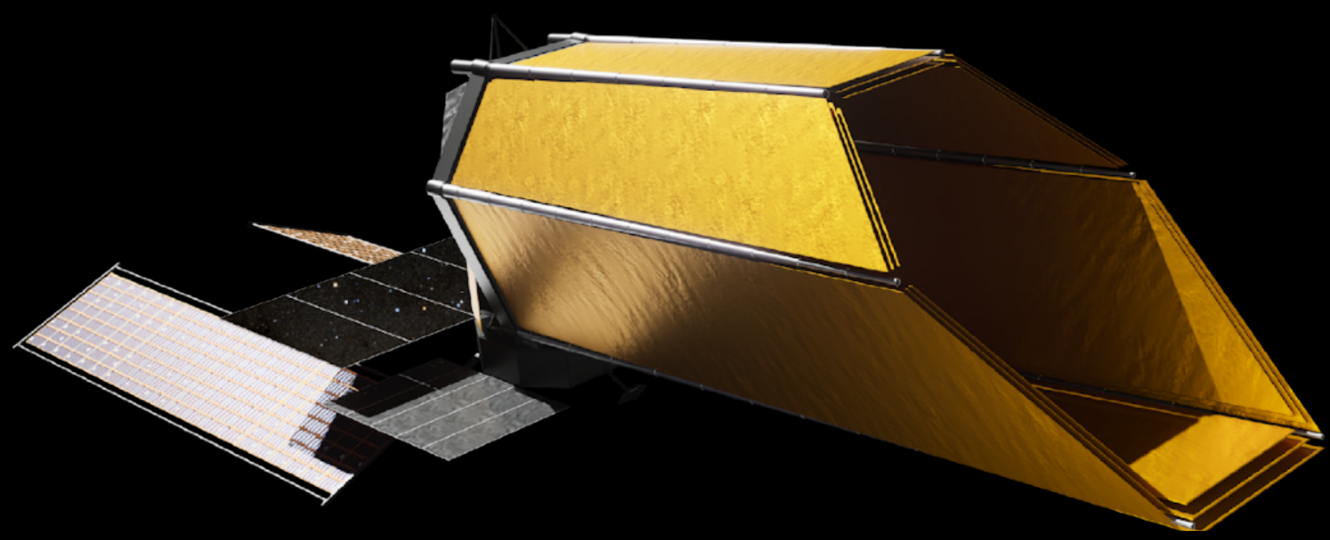

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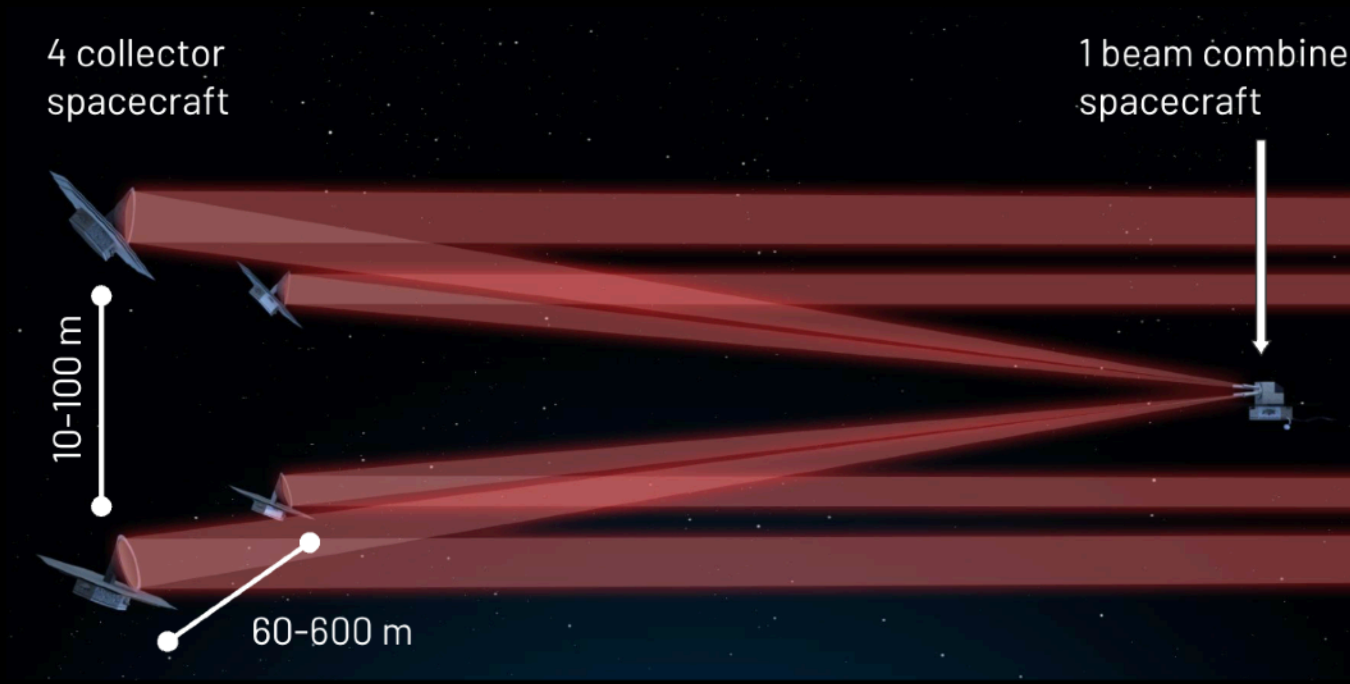

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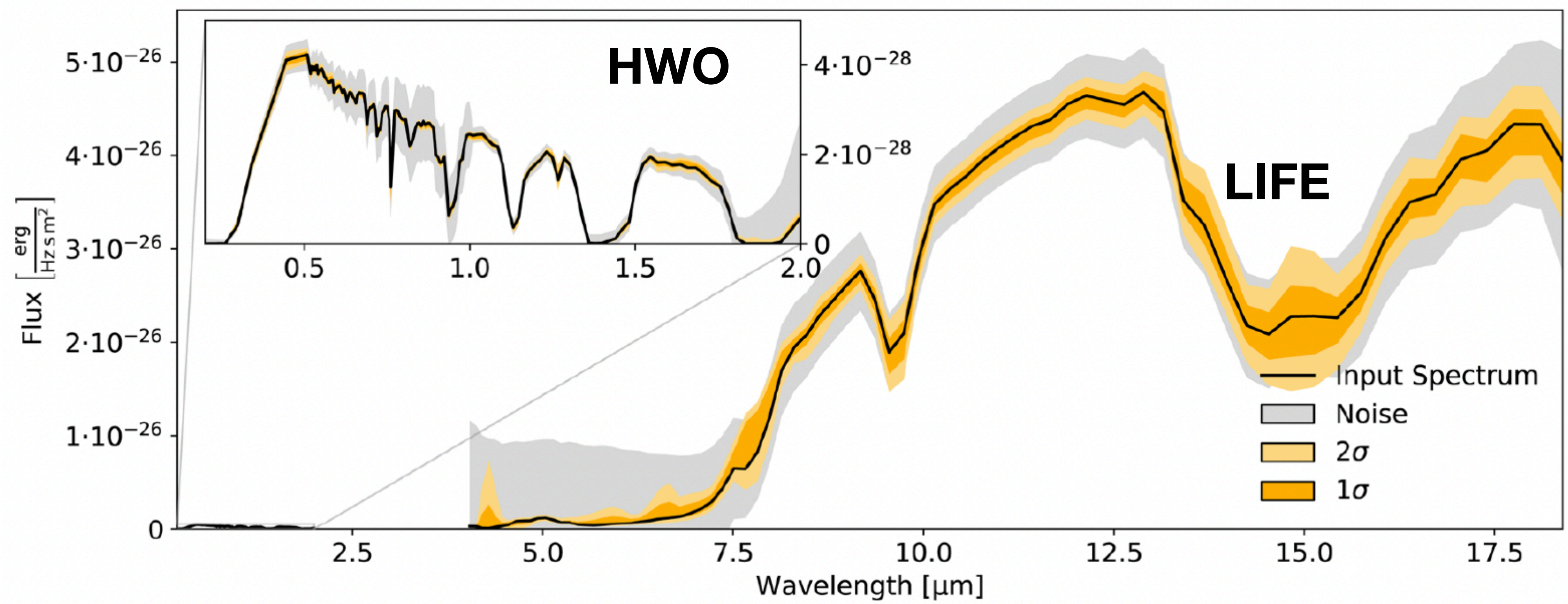
Find and **characterise** ~25 planets similar to the Earth

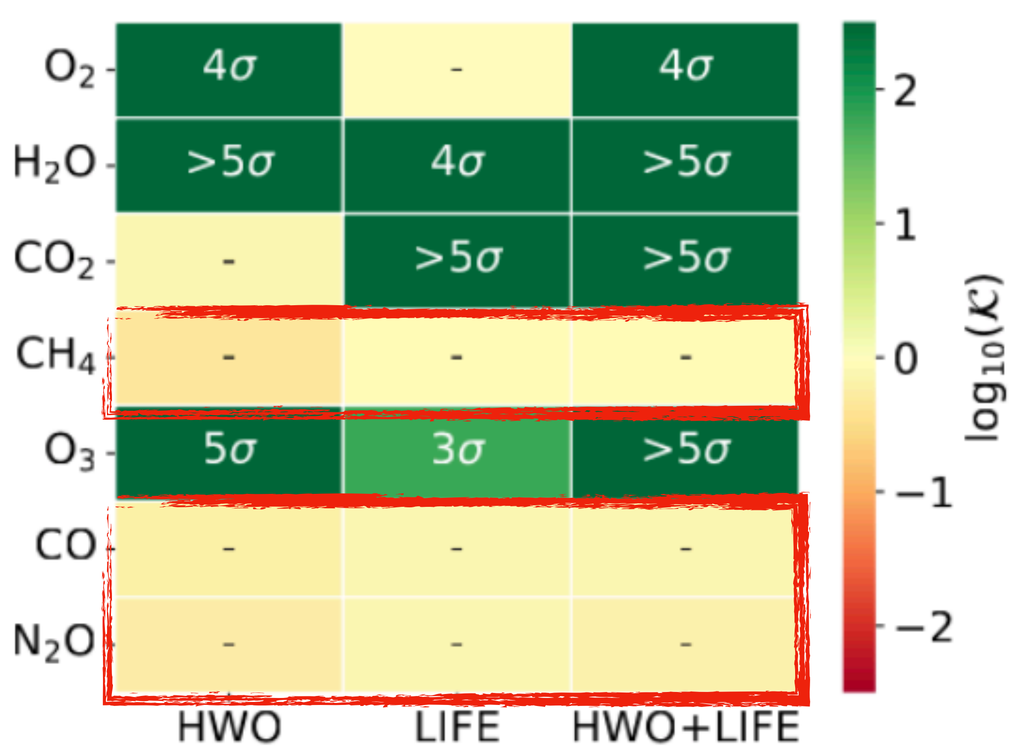
Identify biomarkers and anti-biomarkers

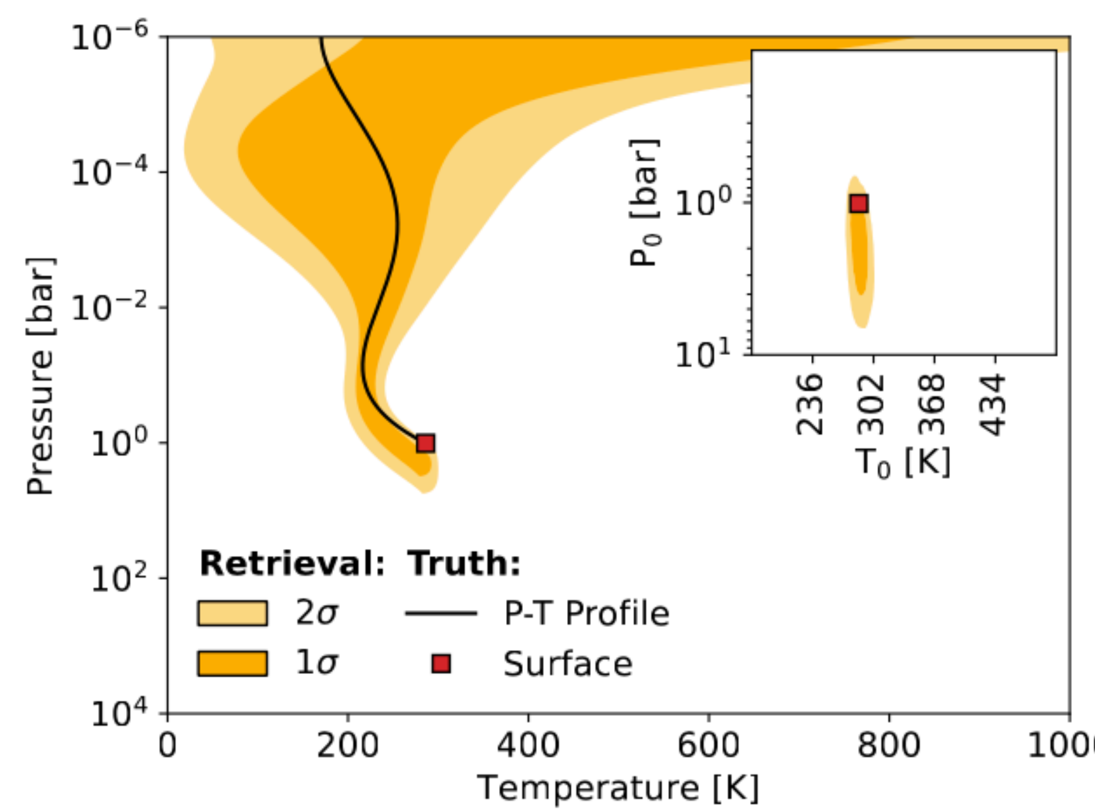
Measure temperatures and abundances unambiguously

Maximum scientific yield with HWO + LIFE combined

≤10 K uncertainty in surface temperature, ~1 dex uncertainty in gas abundance (Alei+24)







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Main atmospheric classes of exoplanet atmospheres

Fraction of rocky planets retaining an atmosphere

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Wavelength gap @ 2-3 μm: CH_4 difficult to measure, CO impossible
Known false positives hard to disentangle; Earth through time challenging

Low resolving powers: degeneracy between overlapping species

Small collective areas: long integration, ultra-low noise detectors

Weaknesses of planned facilities ⇒ opportunities

The obvious facility to exploit is still the ELT

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ANDES-IFU: fibre number / density and R constrained by physical detector size
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Are there scientific cases still unexplored?

e.g. what is the occurrence of planets in other Galactic environments?

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An ELT instrument successor to PCS?

Are there techniques we can think about from the ground?

e.g. is it crazy ti think about <u>nulling interferometry</u> with ESO facilites in the 2040?
What R&D would we need to plan to make it possible?

Are there scientific cases still unexplored?

e.g. what is the occurrence of planets in other Galactic environments?

Questions? Ideas?