Towards comparative studies of exoplanet atmospheres

Lorenzo Pino: lorenzo.pino@inaf.it
INAF – Osservatorio Astrofisico di Arcetri

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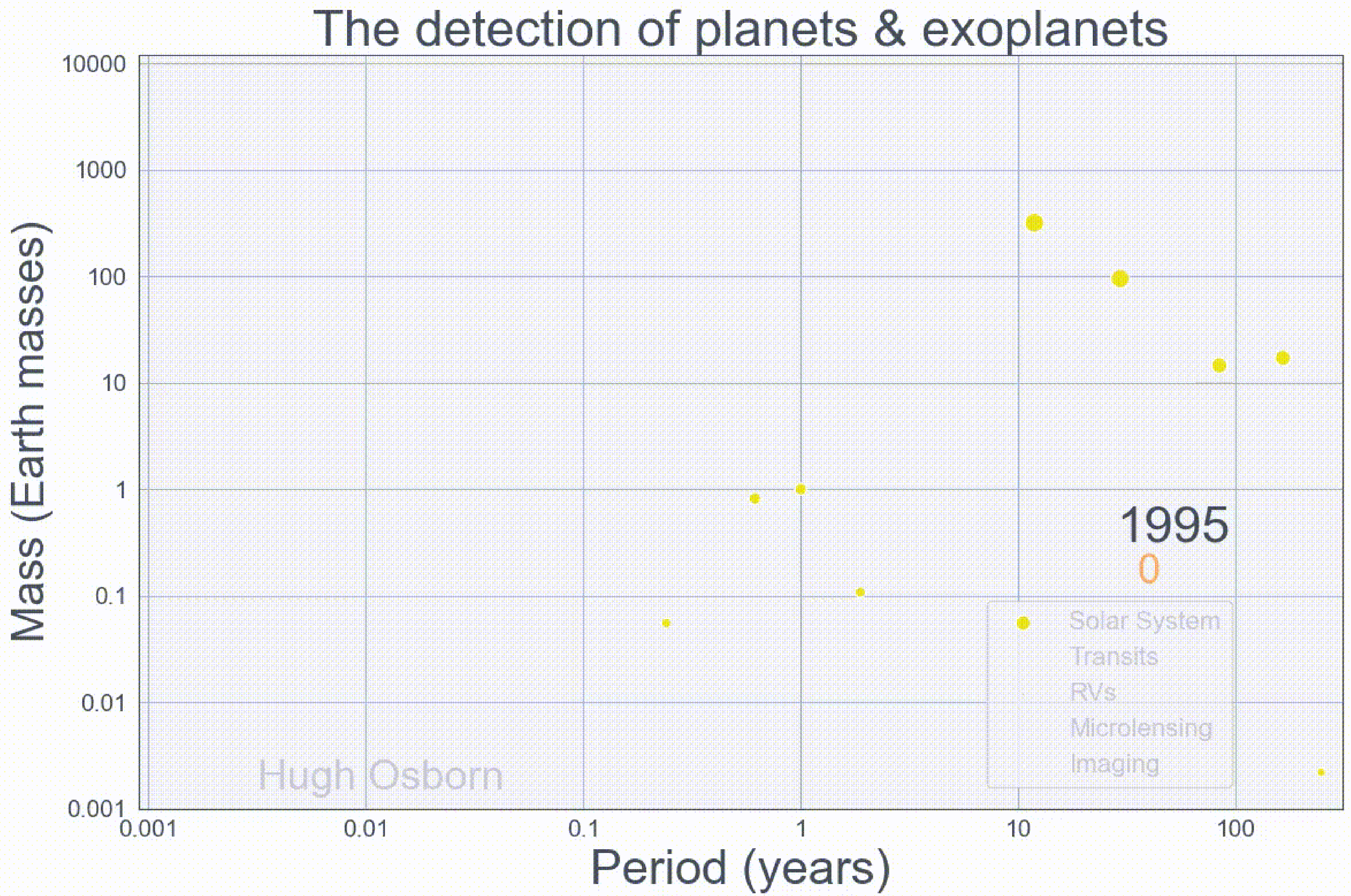
ISTITUTO NAZIONALE
DI ASTROFISICA

GAPS
GLOBAL ARCHITECTURE OF PLANETARY SYSTEMS


The detection of planets & exoplanets
Mass (Earth masses)
10000
1000
100
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
10
100
Period (years)
1995
0
Solar System
Transits
RVs
Microlensing
Imaging
Hugh Osborn

Comparative planetology: a naïve view

A naïve schematic that compares comparative planetology approaches between Solar System and exoplanets might go:

Solar System:

- High-fidelity, very detailed information via remote sensing and in-situ observations.
- Relatively small sample size (4 giants, 4 rocky planets + Moons).

Exoplanets:

- Large sample size (> 6000 planets known, hundreds followed-up with spectroscopy).
- Low-accuracy, low-precision, disk-integrated information.

Comparative planetology: a more modern view

Take home messages:

Exoplanets: With improved instrument and techniques, we can now effectively use exoplanets to perform comparative planetology in the gas giant regime.

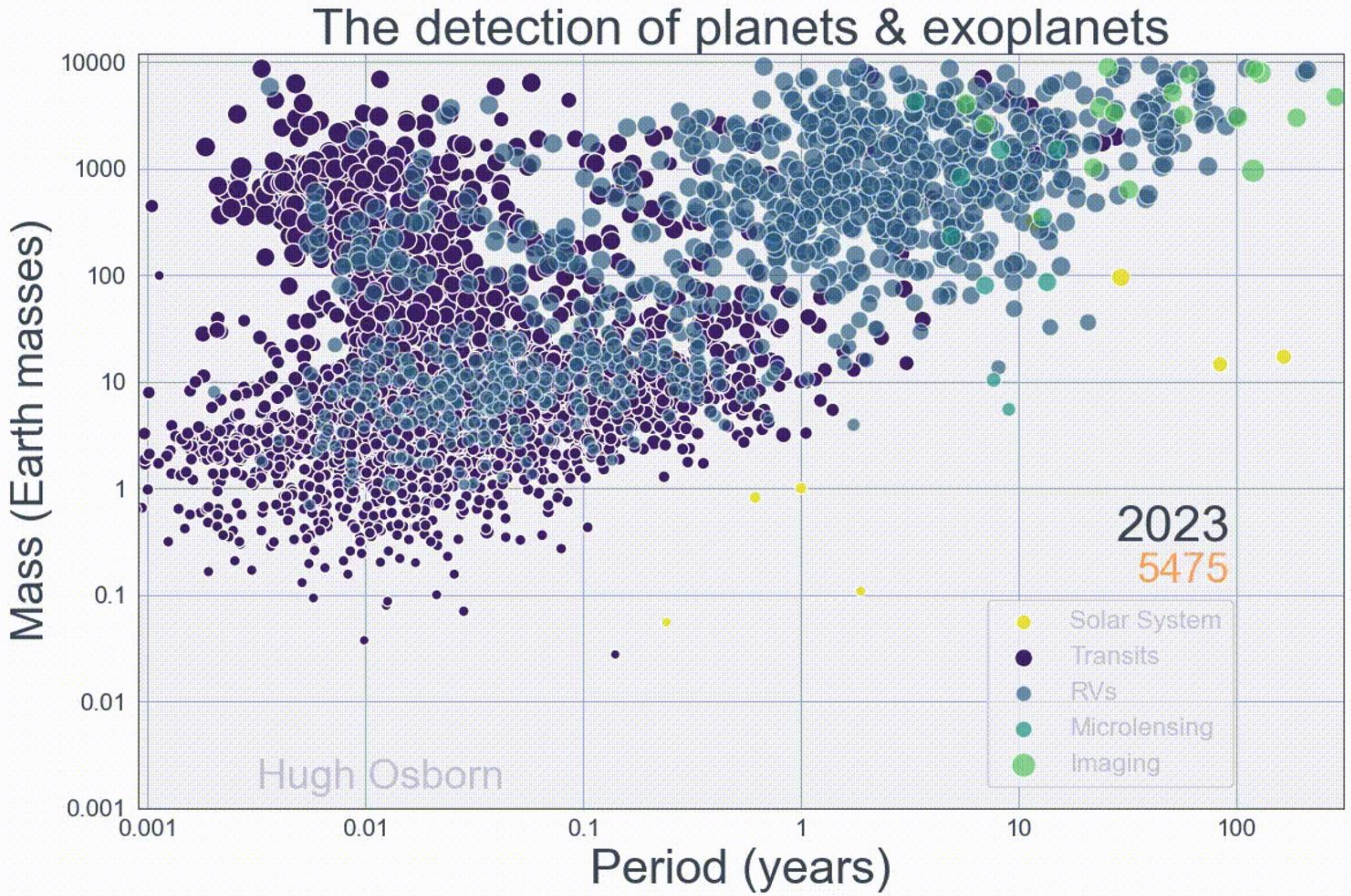
Solar System: To understand observations of exoplanet atmospheres and their possible biases, it is crucial to consider advancements in Solar System planetology.

Future: To understand the emergence of life outside of Earth, comparative planetology in and outside of the Solar System are both necessary.

Comparative planetology: my meaning

Comparative planetology existed before exoplanets. Term coined by George Gamow in 1948, in “Biography of the Earth”. With space exploration, this term cemented long before the first exoplanet was discovered.

Today, it is used somewhat Inhomogeneously, sometimes to indicate only studies across exoplanets, sometimes more broadly. In this talk, I use it exclusively to indicate studies encompassing all planets known in a given population of interest.



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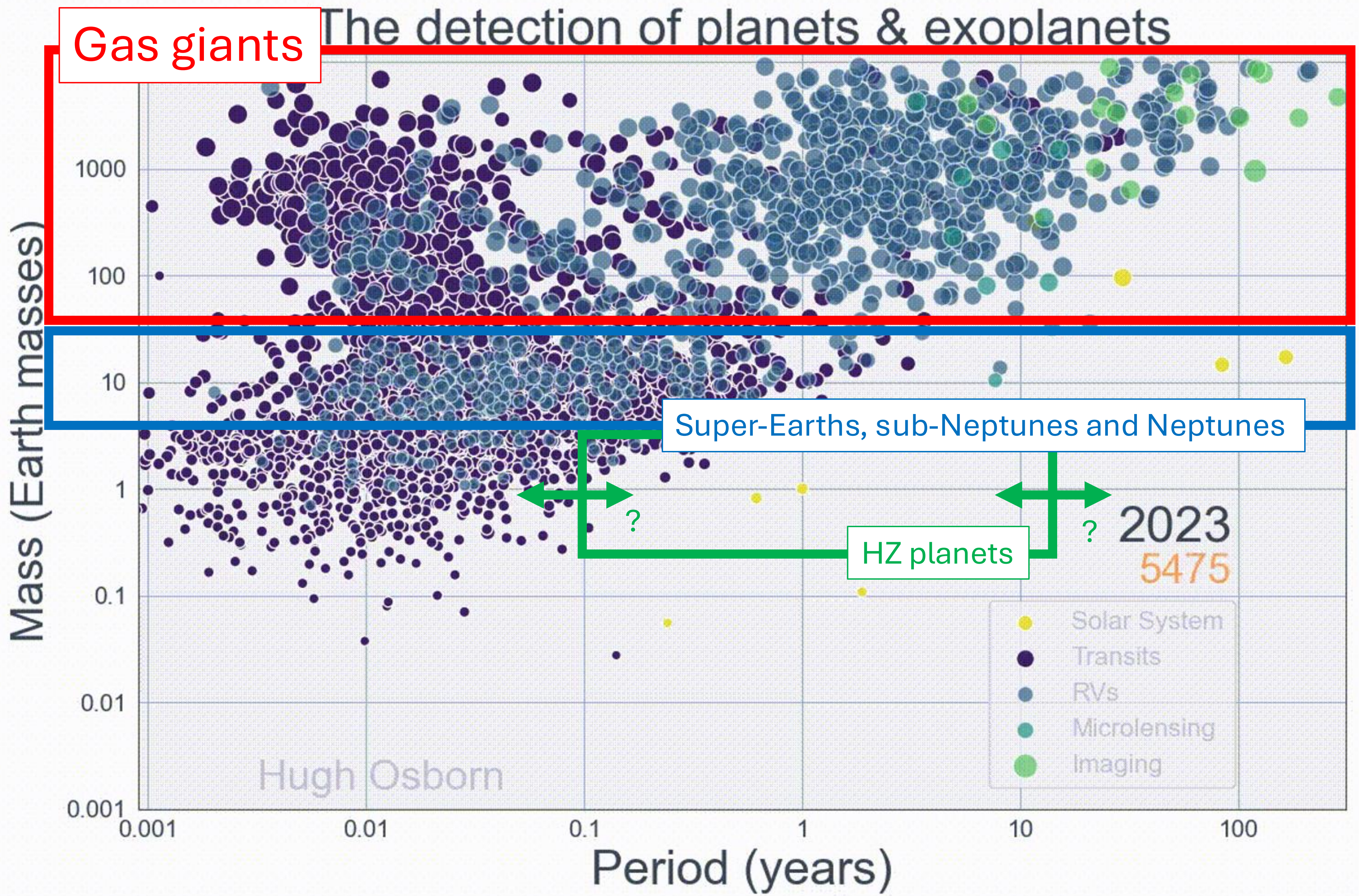

The detection of planets & exoplanets
Gas giants
Super-Earths, sub-Neptunes and Neptunes
HZ planets
?
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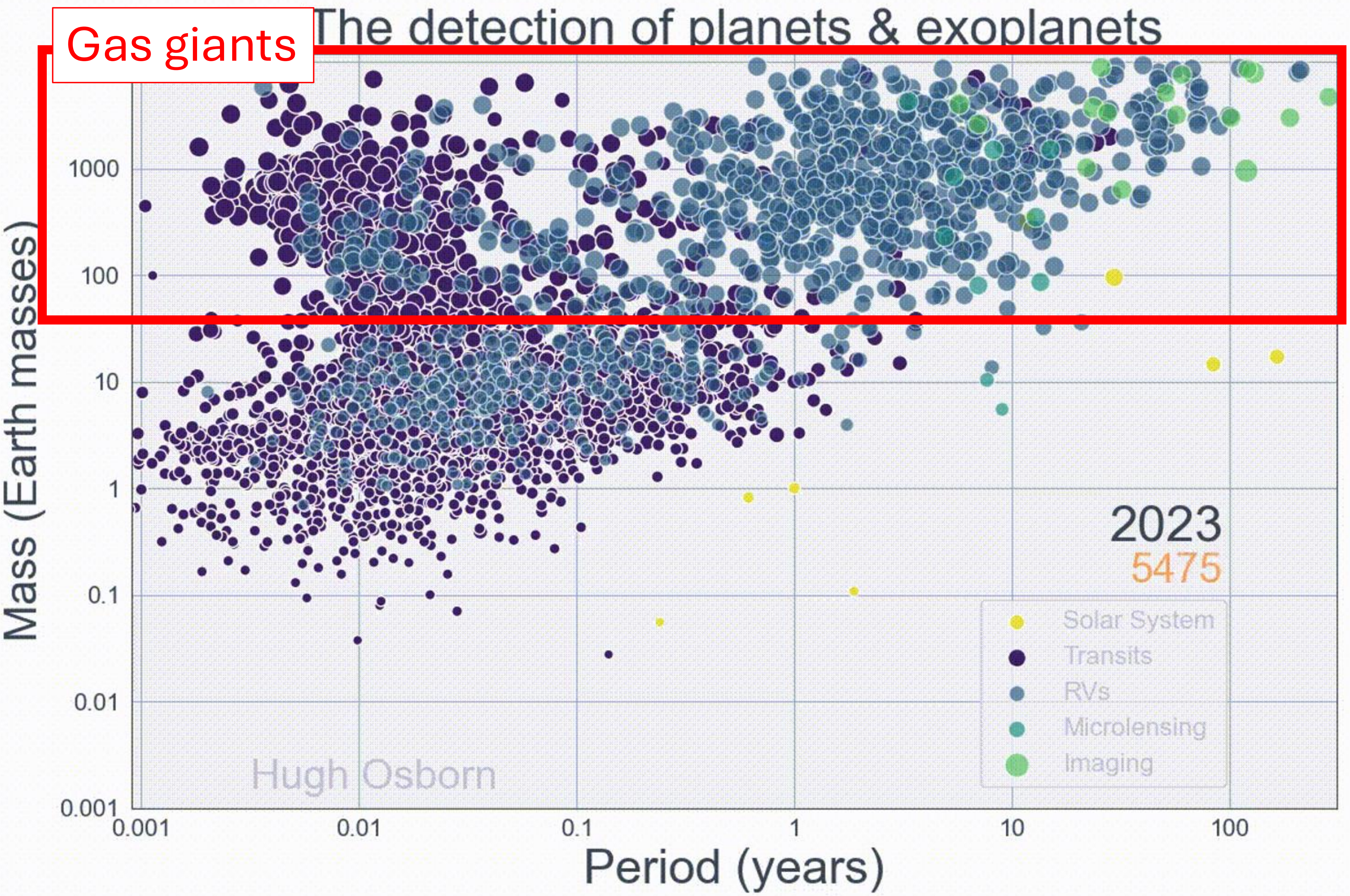

Gas giants
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An incomplete timeline of Jupiter's exploration

Timeline adapted from Ingersoll (2017)

≈ 1930	≈ 1960	Space era
Jupiter IR excess, CH_4 and NH_3.	Jupiter H_2, radio emission, three-layer cloud structure model	Detailed view of interiors (e.g. fuzzy core) and locally resolved properties

An incomplete timeline of Jupiter's exploration

Timeline adapted from Ingersoll (2017)

≈ 1930

≈ 1960

Space era

Jupiter IR excess, CH_4 and NH_3.

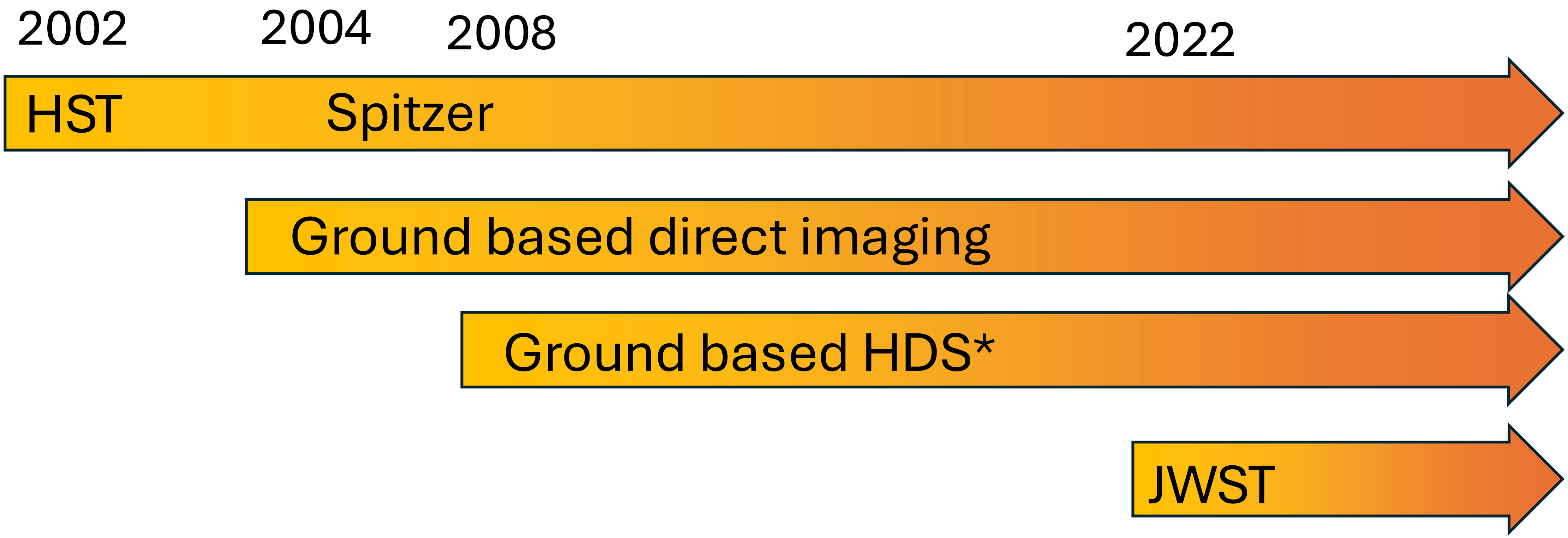
Jupiter H_2, radio emission, three-layer cloud structure model

Approximately our current knowledge of individual exoplanets

Detailed view of interiors (e.g. fuzzy core) and locally resolved properties

Very hard to constrain in exoplanets (and only remotely)

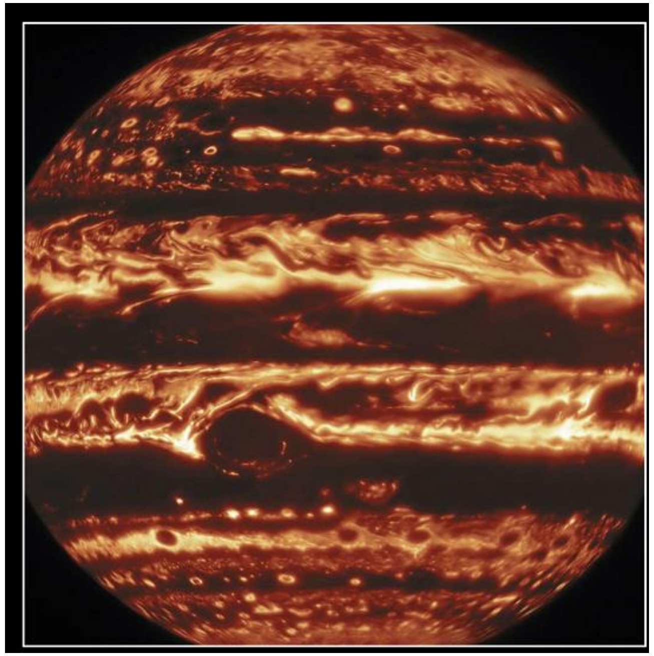
An incomplete and approximated timeline of gas giant exoplanets exploration



Charbonneau et al. (2002), Chauvin et al. (2005a, b), Snellen et al. (2008), JWST Transiting Exoplanet Community Early Release Science Team (2023), *see also Charbonneau et al. (1999)

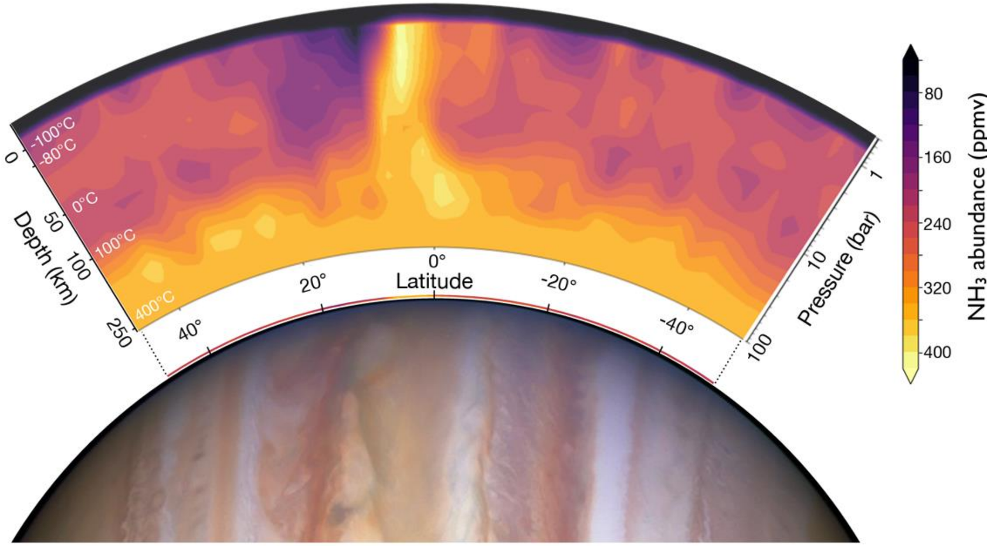
Caveats from Solar System observations

- Possible biases in atmospheric abundances: some regions are brighter than others, and will dominate the photon budget. They might be chemically distinct (e.g. the $5\ \mu\mathrm{m}$ hot spot regions in Jupiter).



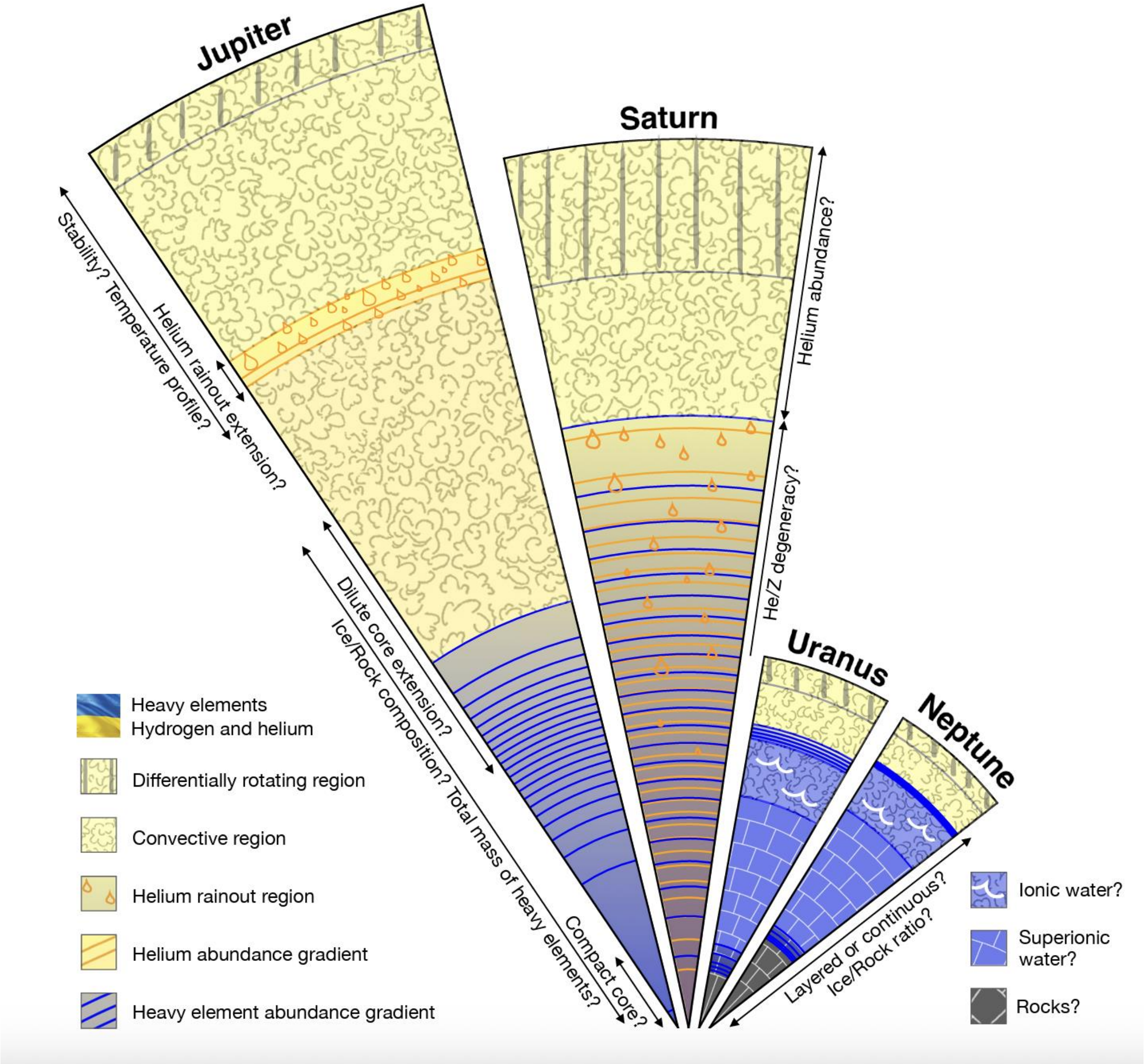
Caveats from Solar System observations

- Possible biases in atmospheric abundances: some regions are brighter than others, and will dominate the photon budget. They might be chemically distinct (e.g. the $5\ \mu\mathrm{m}$ hot spot regions in Jupiter).
- Possible biases in atmospheric abundances: cloud condensation deviates from equilibrium (vertical gradients and spatial variability for deep condensates, unexpected altitudes for aerosol layers)

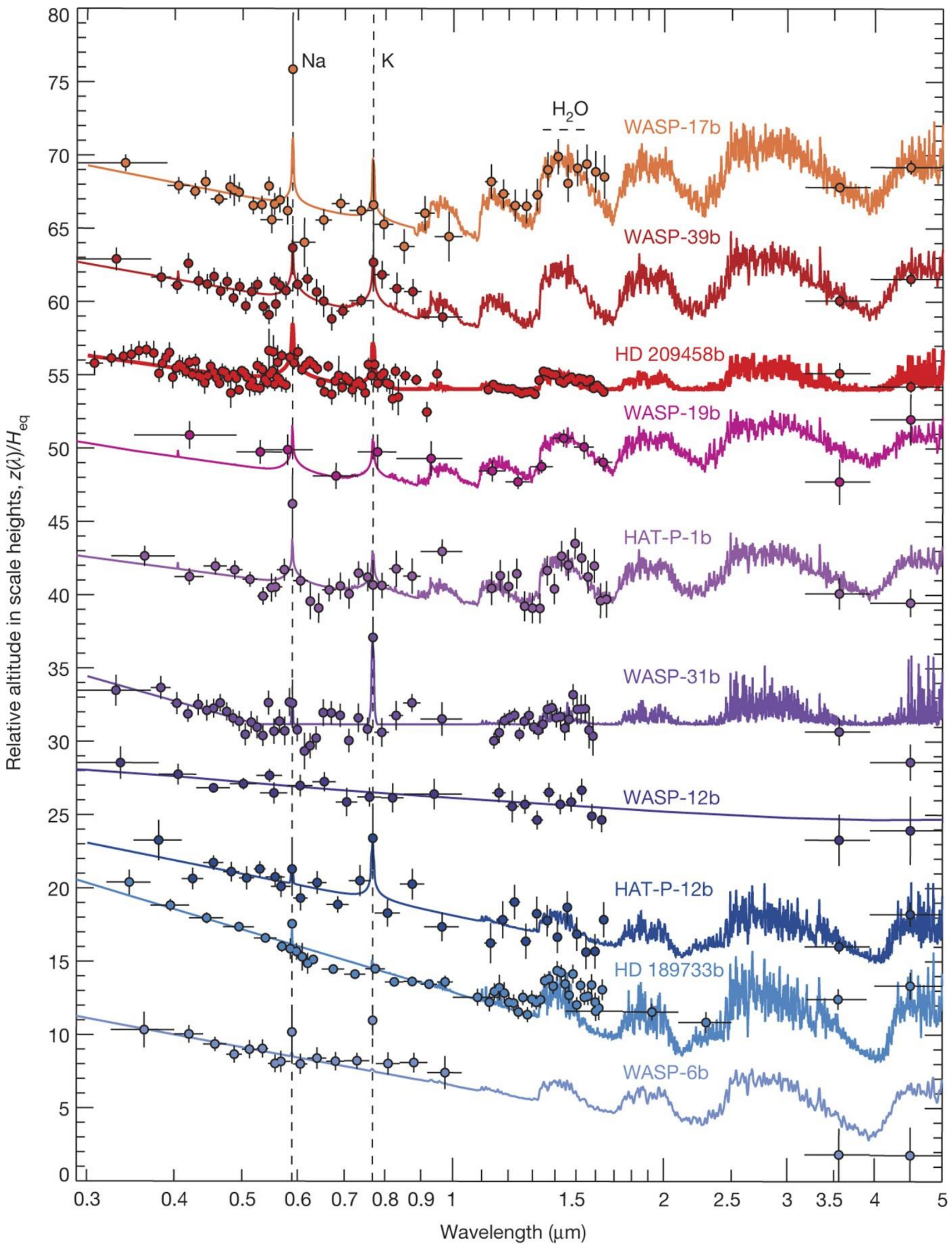


Caveats from Solar System observations

- Possible biases in bulk abundances: structure models typically assume 2 to 3 separate layers, while observations in the Solar System suggest diluted cores and potentially semi-adiabatic convection layers.



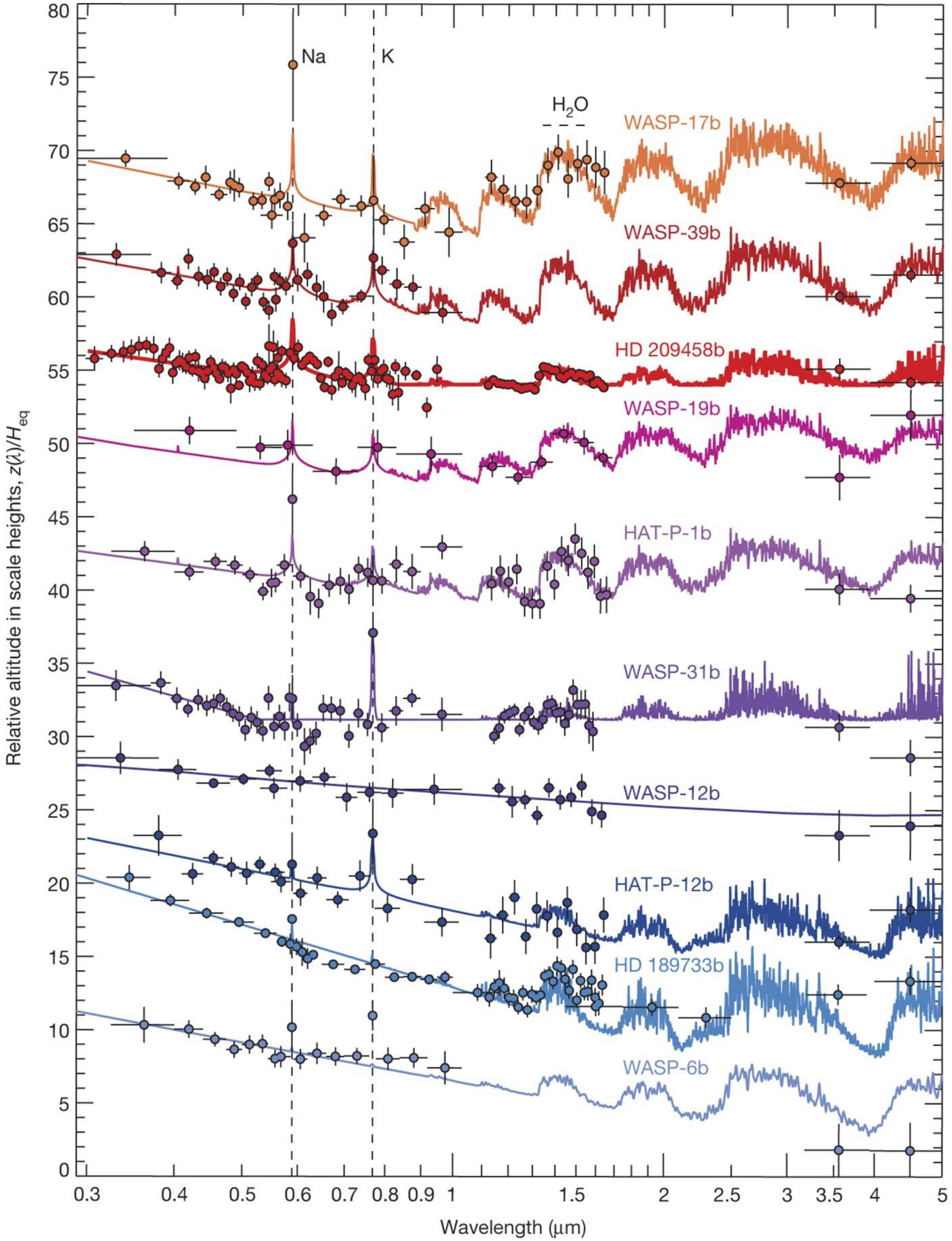
HST/Spitzer comparative studies highlight 1: where is the water?



Comparitive hot Jupiter studies with HST/Spitzer

HST and Spitzer were limited in **spectral resolution** and **wavelength coverage**.

Mostly had access to H_2O and photometry in the CO_2 band.

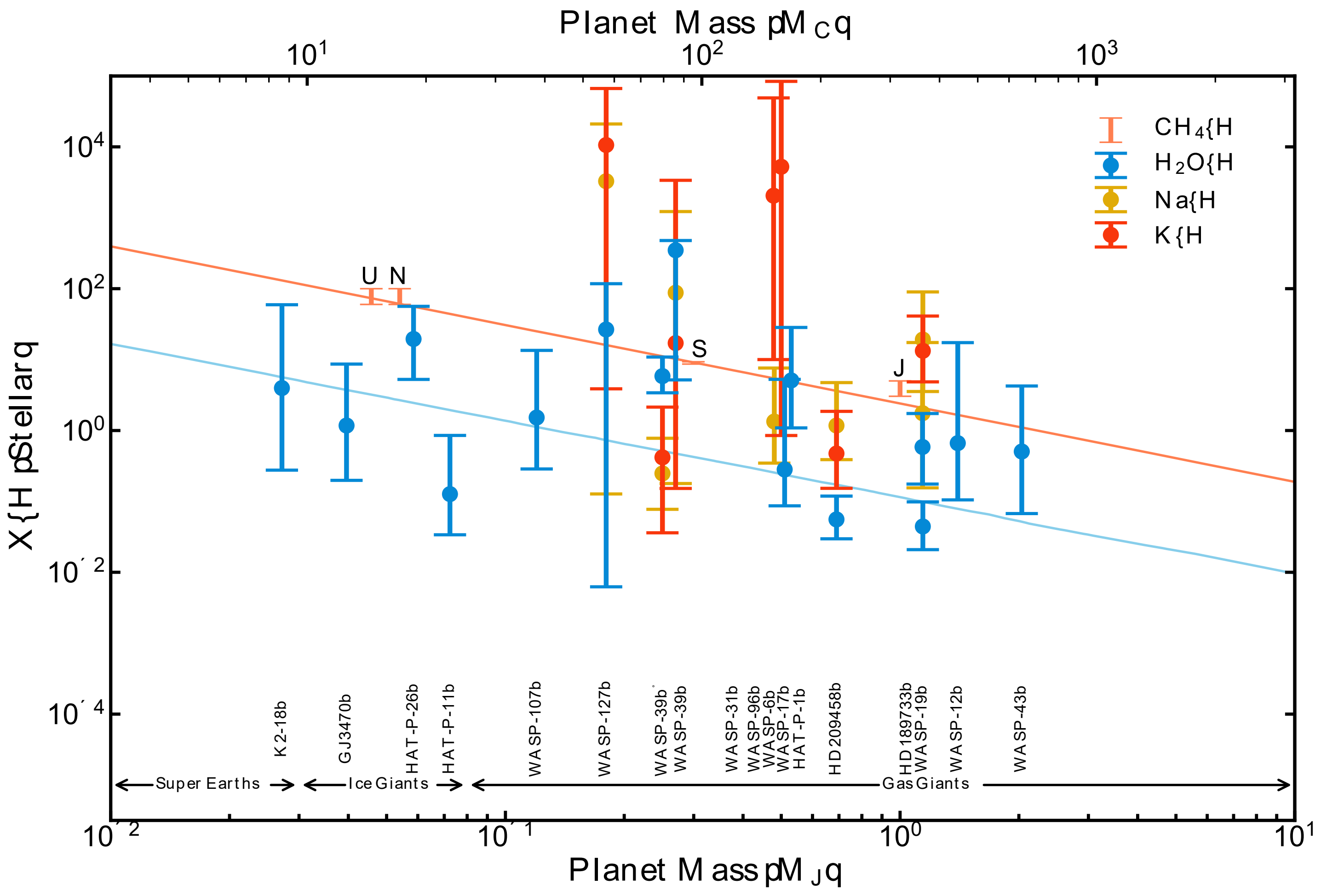


Comparative hot Jupiter studies with HST/Spitzer

Sing et al. (2016) published a first panchromatic comparative study of hot Jupiters, revealing:

- Diversity even among HJ atmospheres.
- A prevalence of ***muted*** water features in HJ spectra. Where is the water?
  - Cloudy/hazy atmospheres.
  - Original depletion of O/H.

Comparative hot Jupiter studies with HST/Spitzer

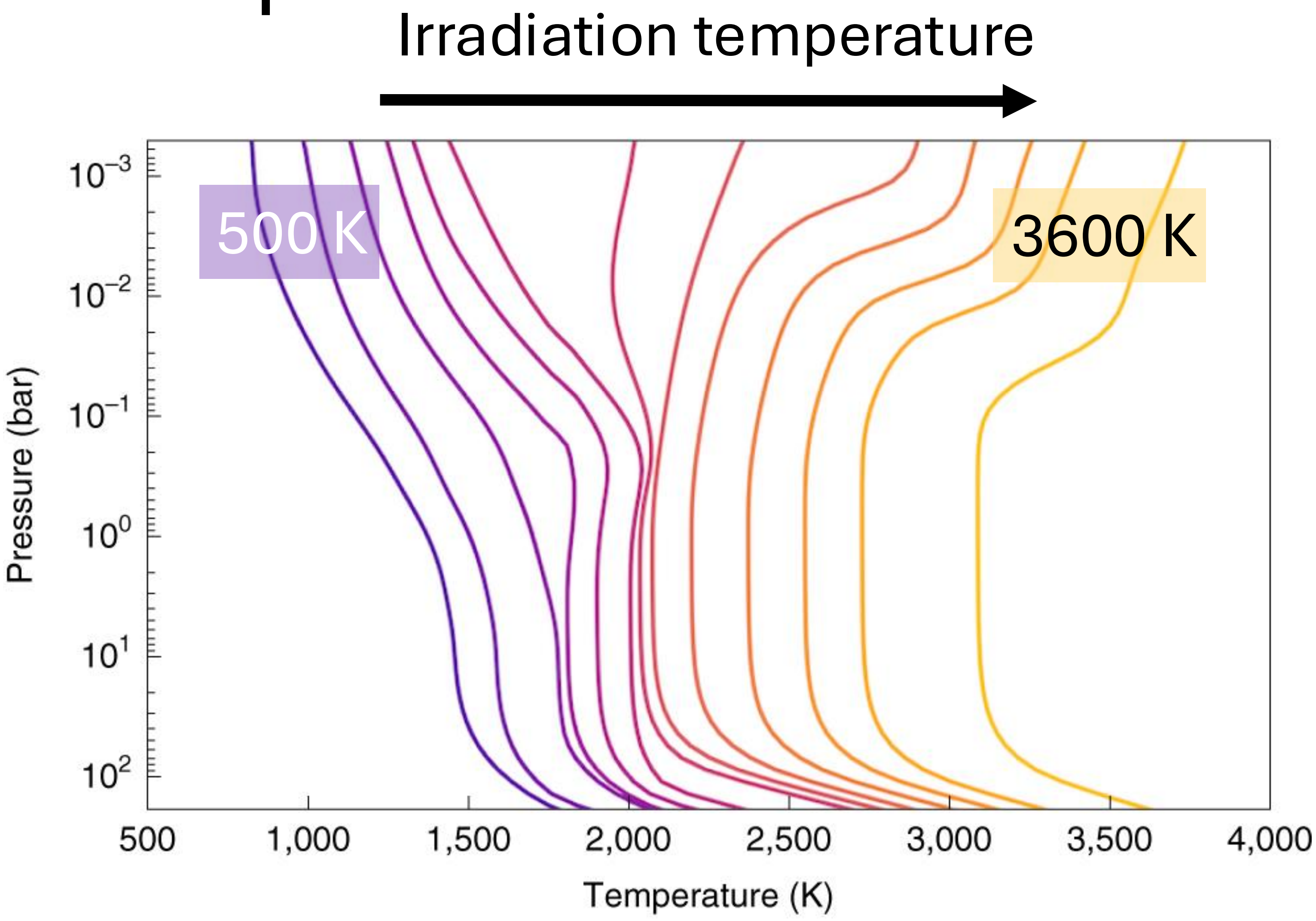


Welbanks et al. (2019) shows the intrinsic degeneracies to HST data analysis, but favors a depletion in O/H (compared to other elements).

Do HJs have a different metallicity compared to Solar System planets?

HST/Spitzer comparative studies highlight 2: the emergence of ultra-hot Jupiters

Comparative hot Jupiter studies with HST/Spitzer

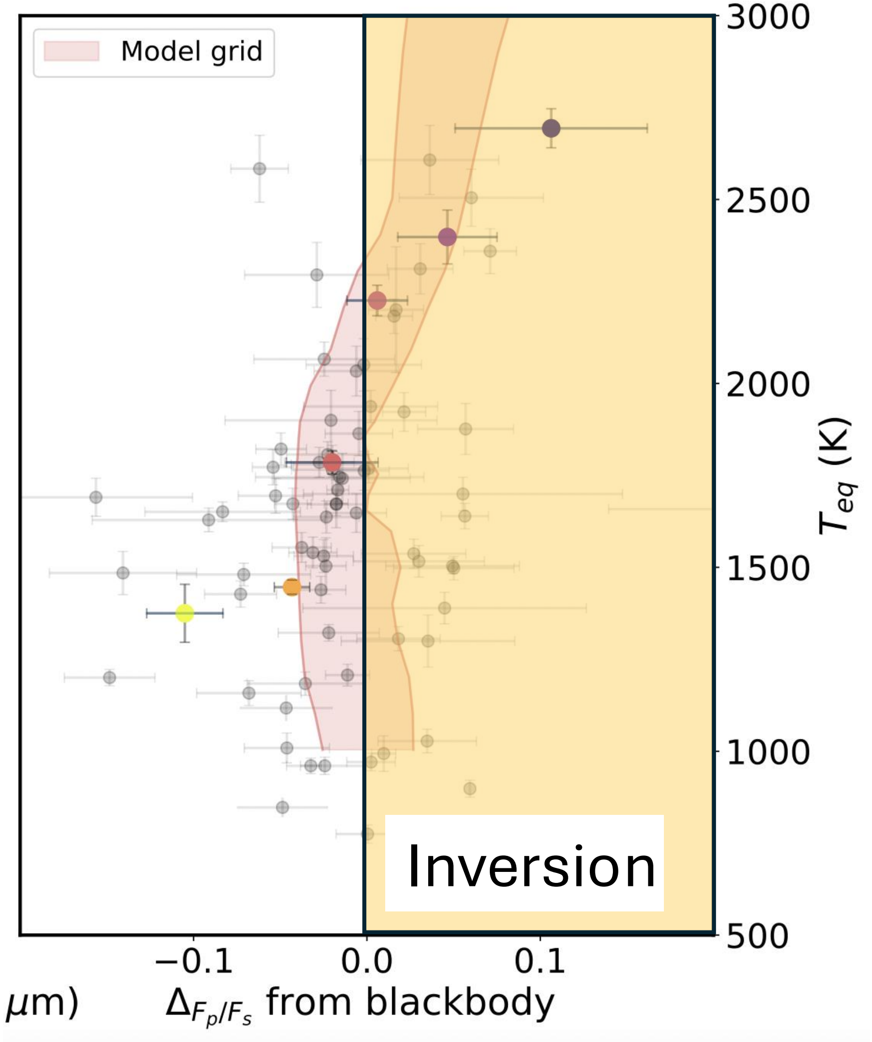


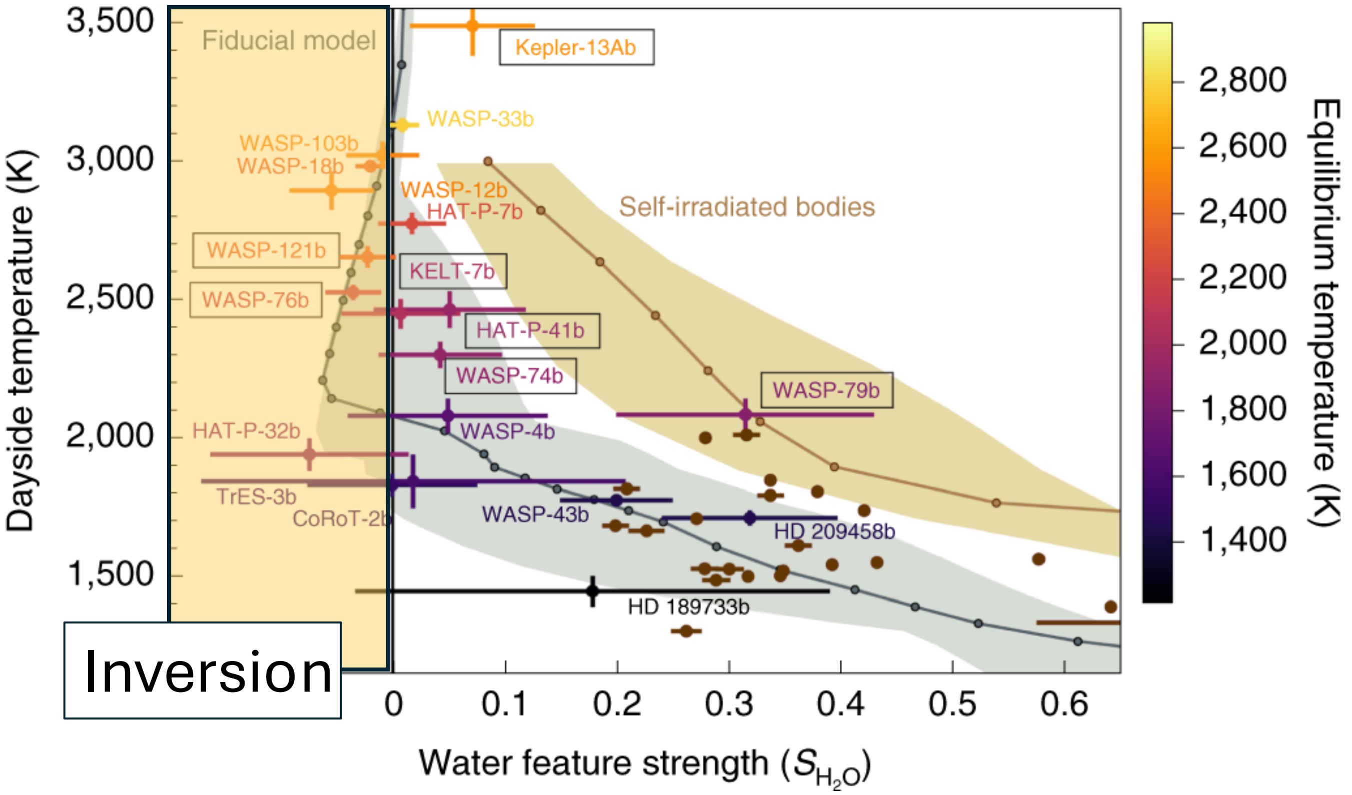
«Thermal inversions» predicted in ultra-hot planets

Hubeny et al. (2003), Fortney et al. (2008)

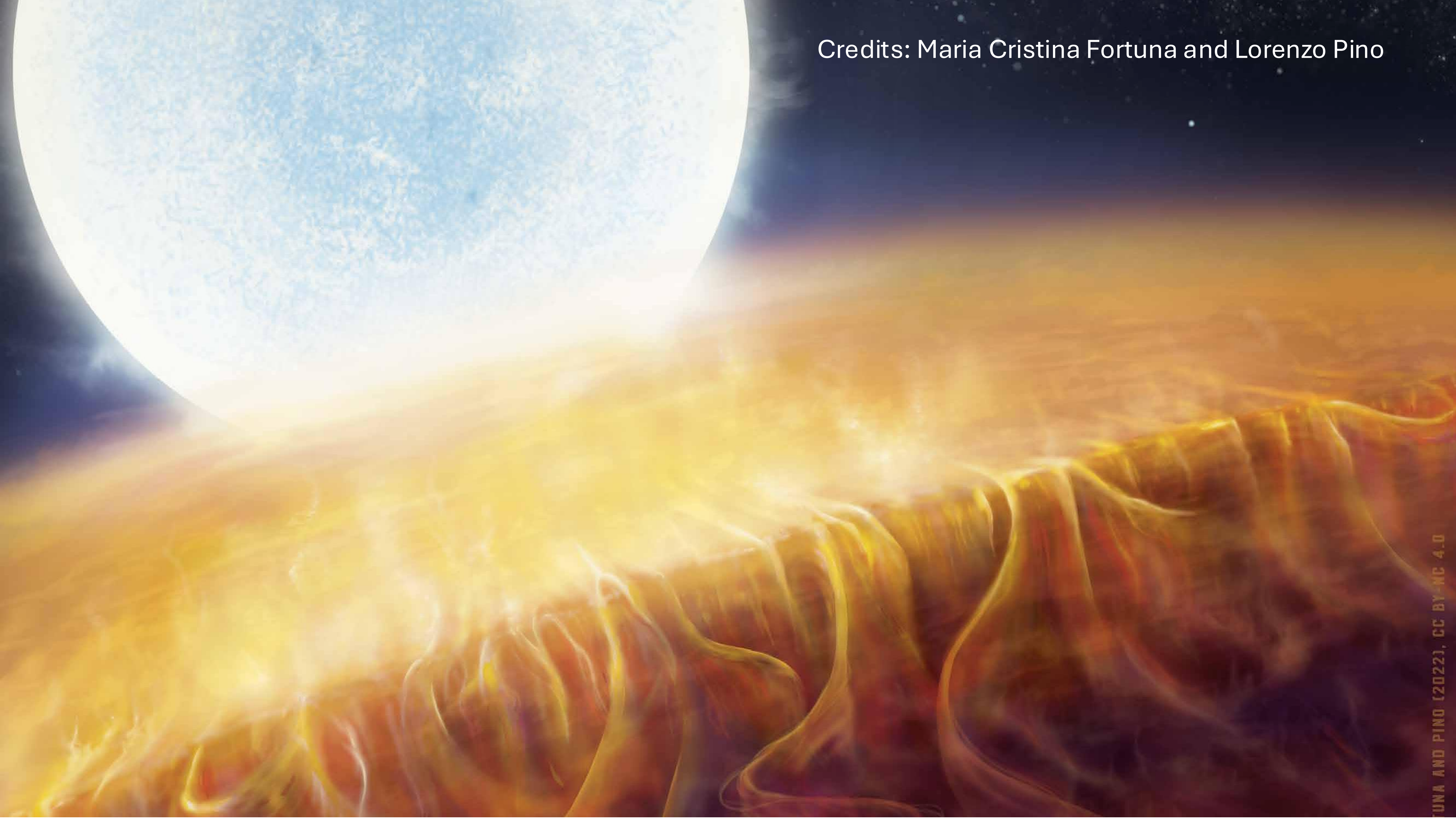
Baxter et al. (2020)
Mansfield et al. (2021)

Comparative hot Jupiter studies with HST/Spitzer





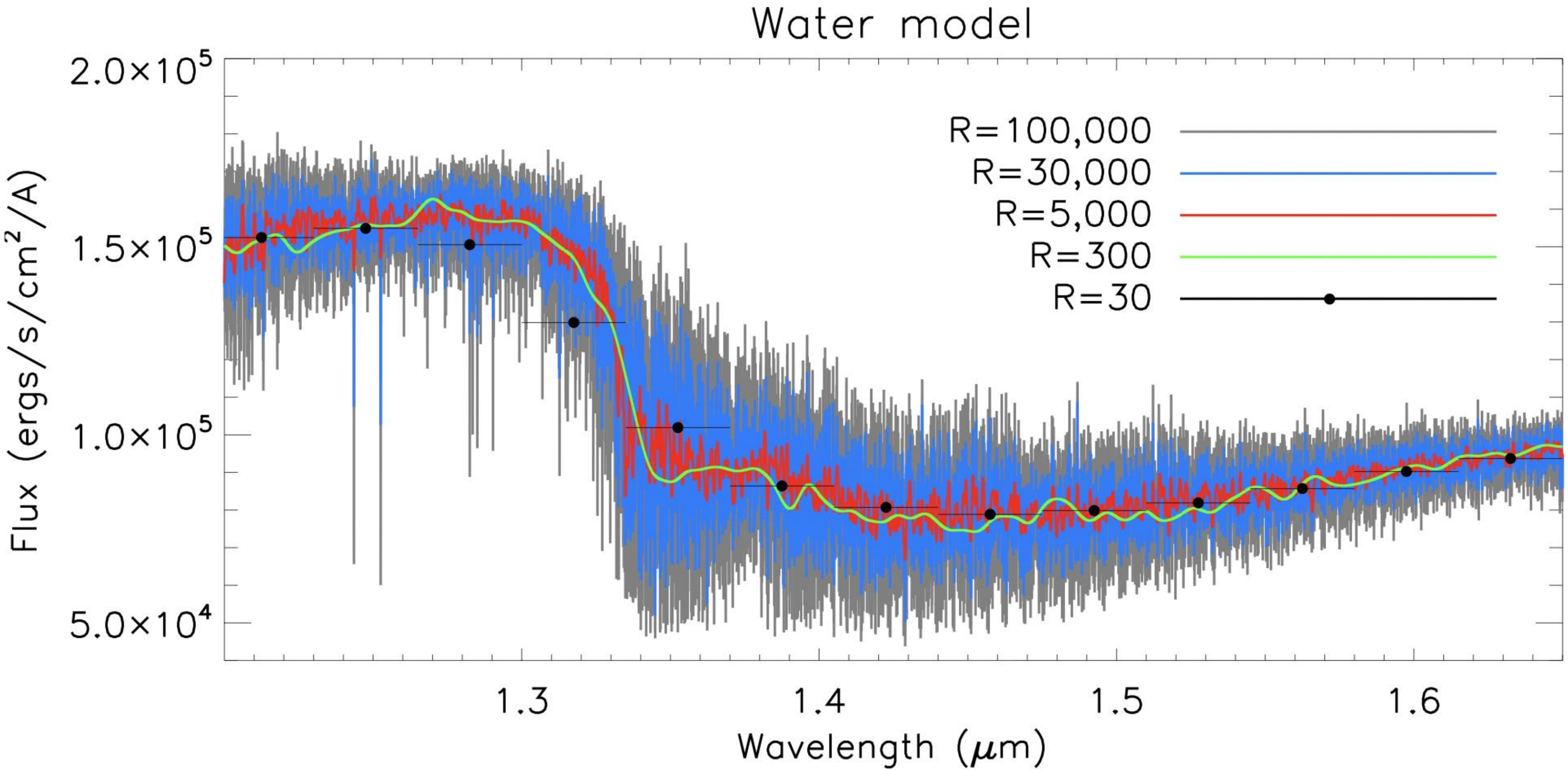
Baxter et al. (2020)
Mansfield et al. (2021)


Credits: Maria Cristina Fortuna and Lorenzo Pino

Intermezzo: high dispersion spectroscopy (HDS, $R \sim 100{,}000$)

High dispersion spectroscopy (HDS) studies

Birkby et al. (2024)



High dispersion spectroscopy (HDS) studies

Total flux of the system

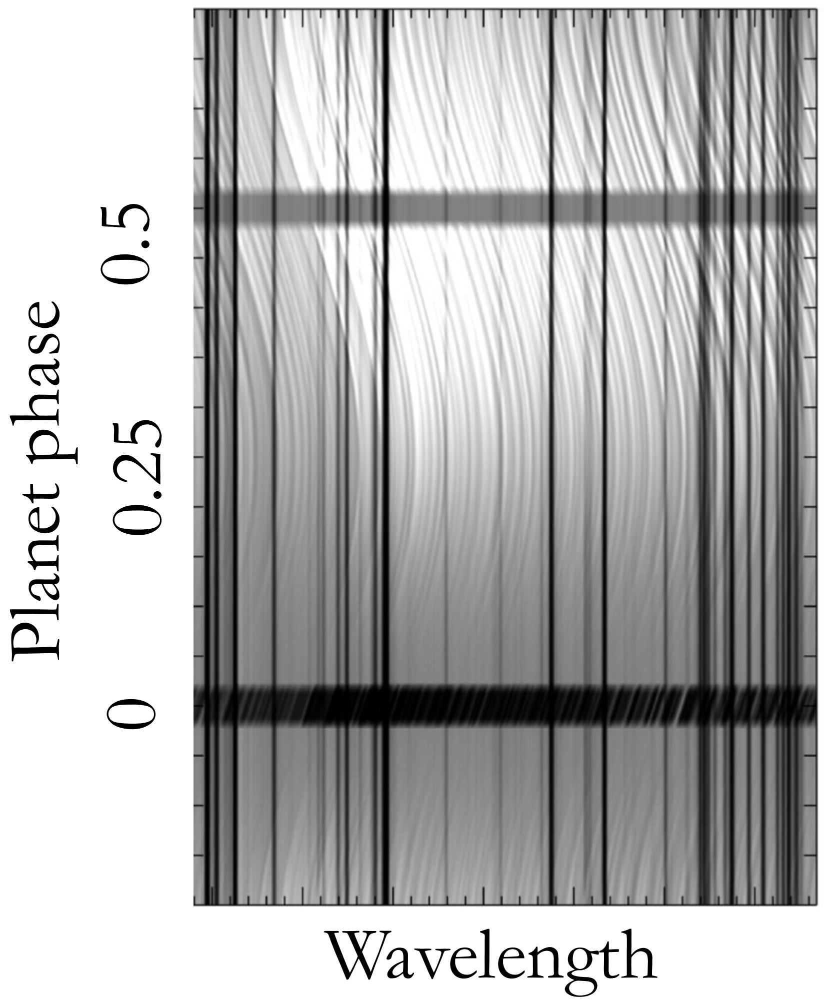
Vertical lines (stationary):

Telluric lines (Earth)

Stellar lines

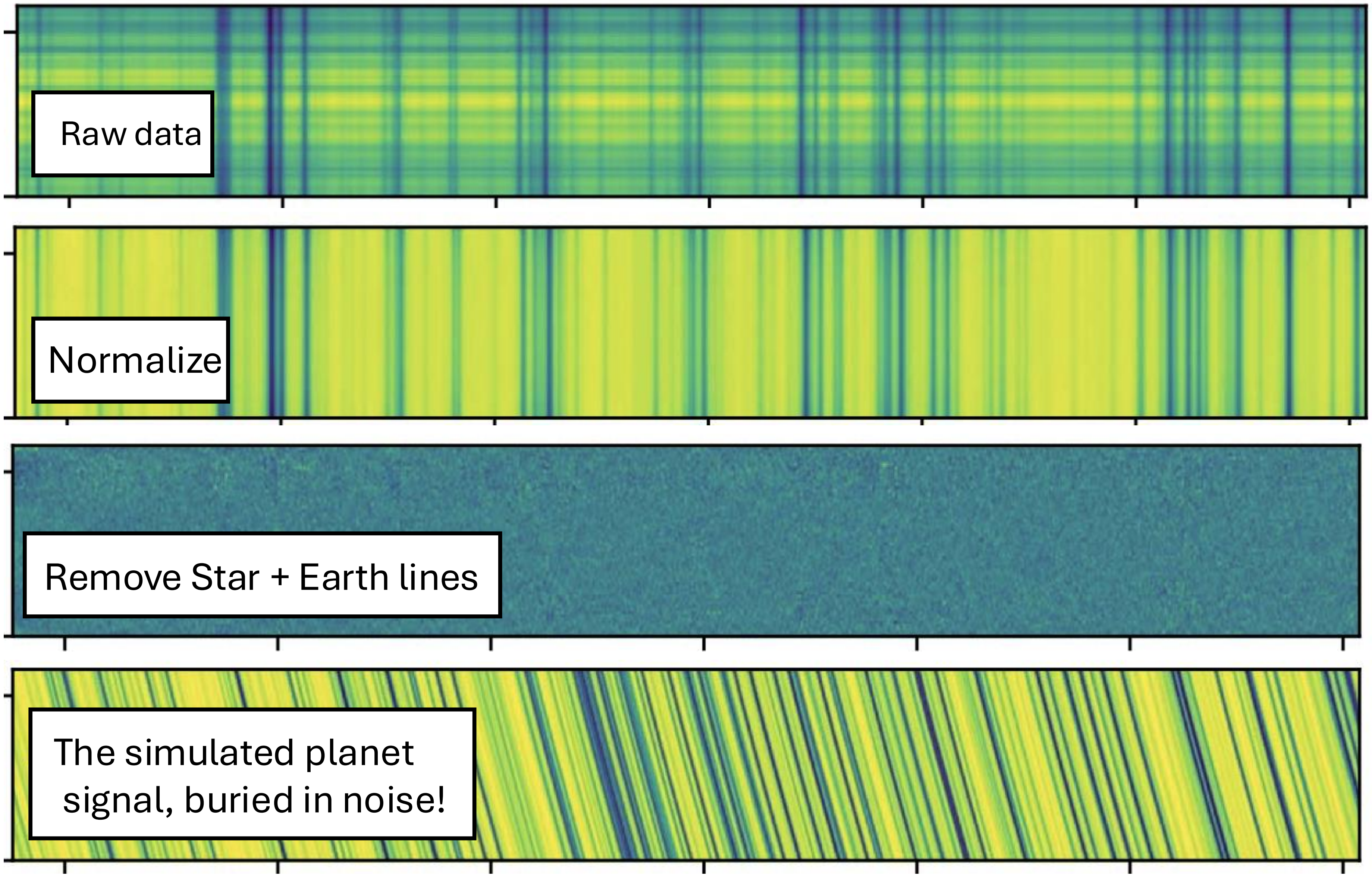
Wobbly lines:

Planetary lines

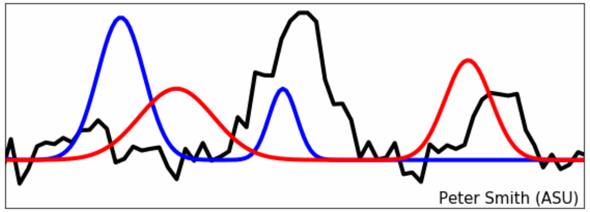


Hoeijmakers et al. (2015)

A primer on HDS data analysis: data reduction



Need for cross-correlation: stacking planet lines across wavelengths



A primer on HDS data analysis: CCF

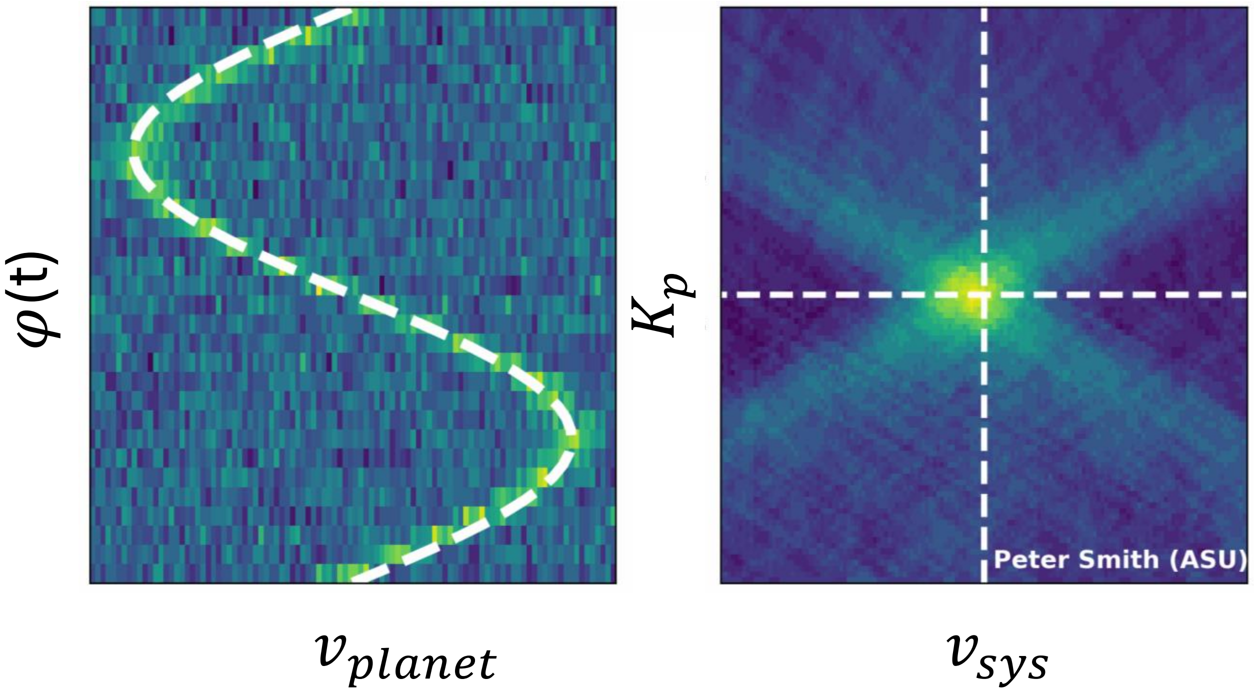
To sum the planet signal coherently, we need to move to its rest frame:

Keplerian velocity, systemic velocity:
A prior is known from orbital solution,
but we prefer to leave them as variables.

$$v_{planet} = K_p \sin(2\pi\varphi(t)) + v_{bary}(t) + v_{sys}$$

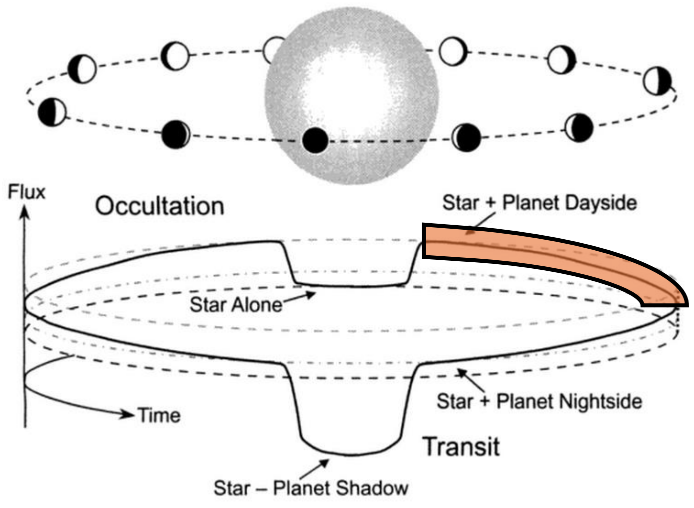
Orbital phase:
know from orbital solution (errors might not be negligible

Earth Barycentric radial velocity:
know at high precision and accuracy



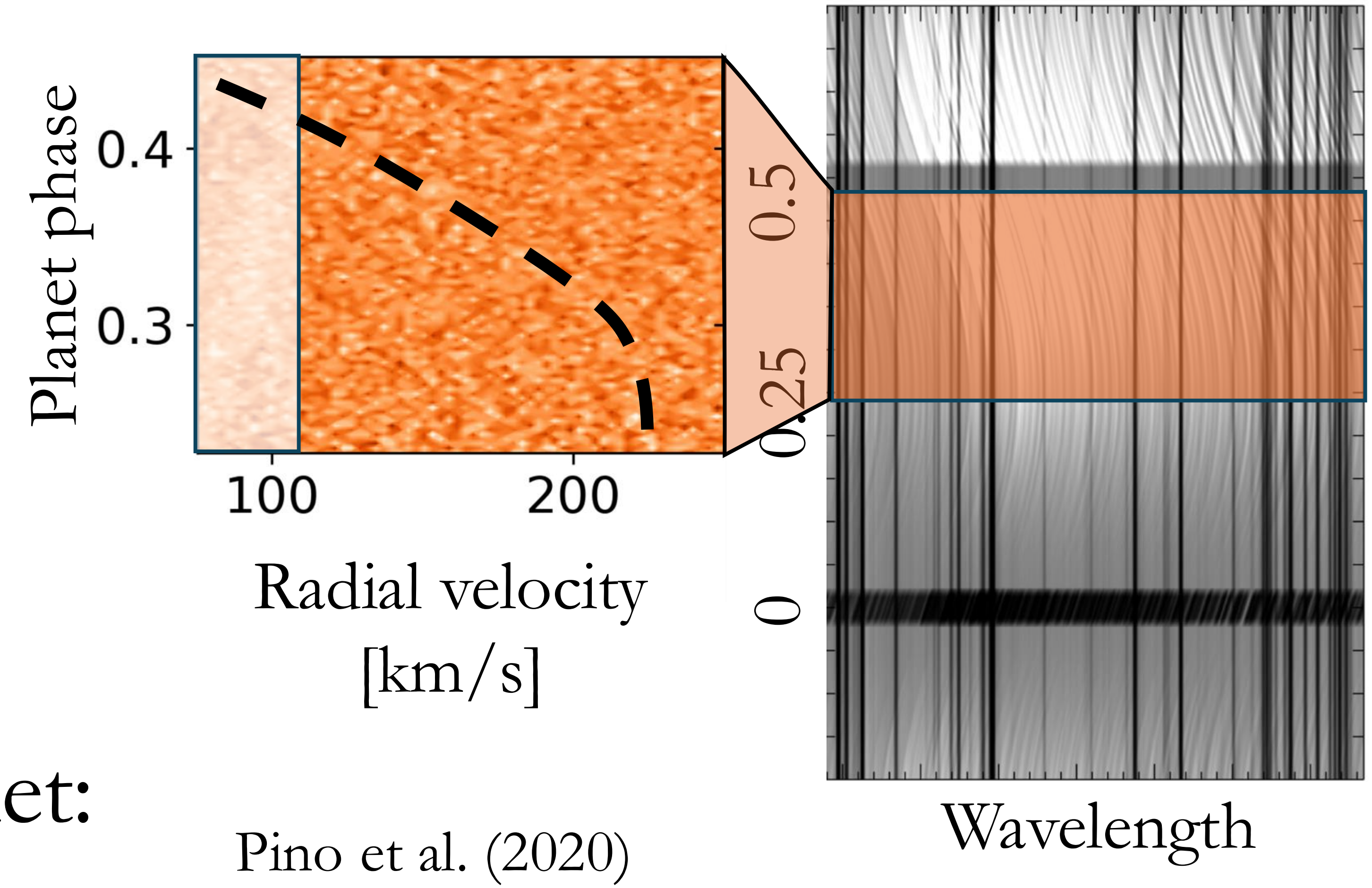
HDS comparative studies highlight 1: unambiguous detection of thermal inversions

KELT-9b with HARPS-N



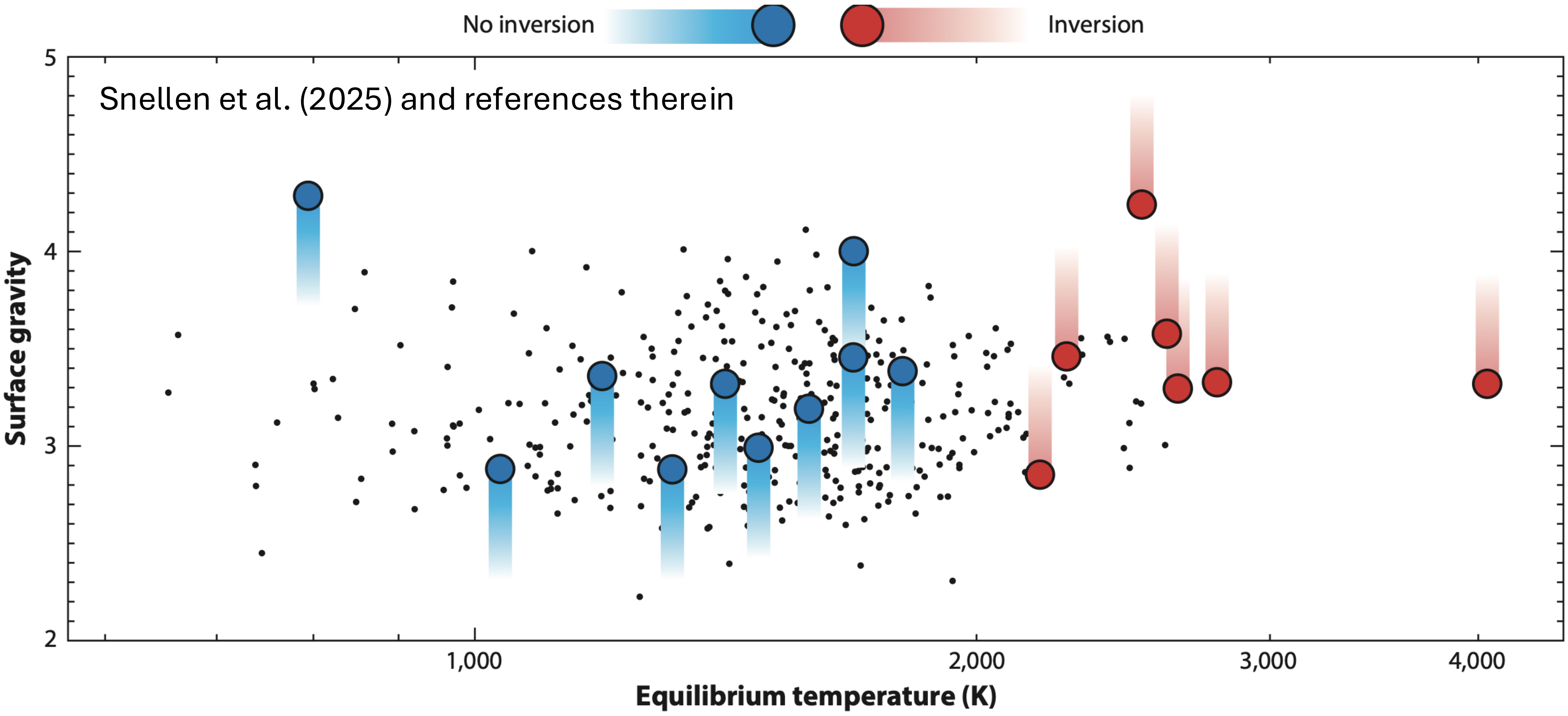
Credits: Joshua Winn

The first optical emission spectrum of a planet: iron lines!



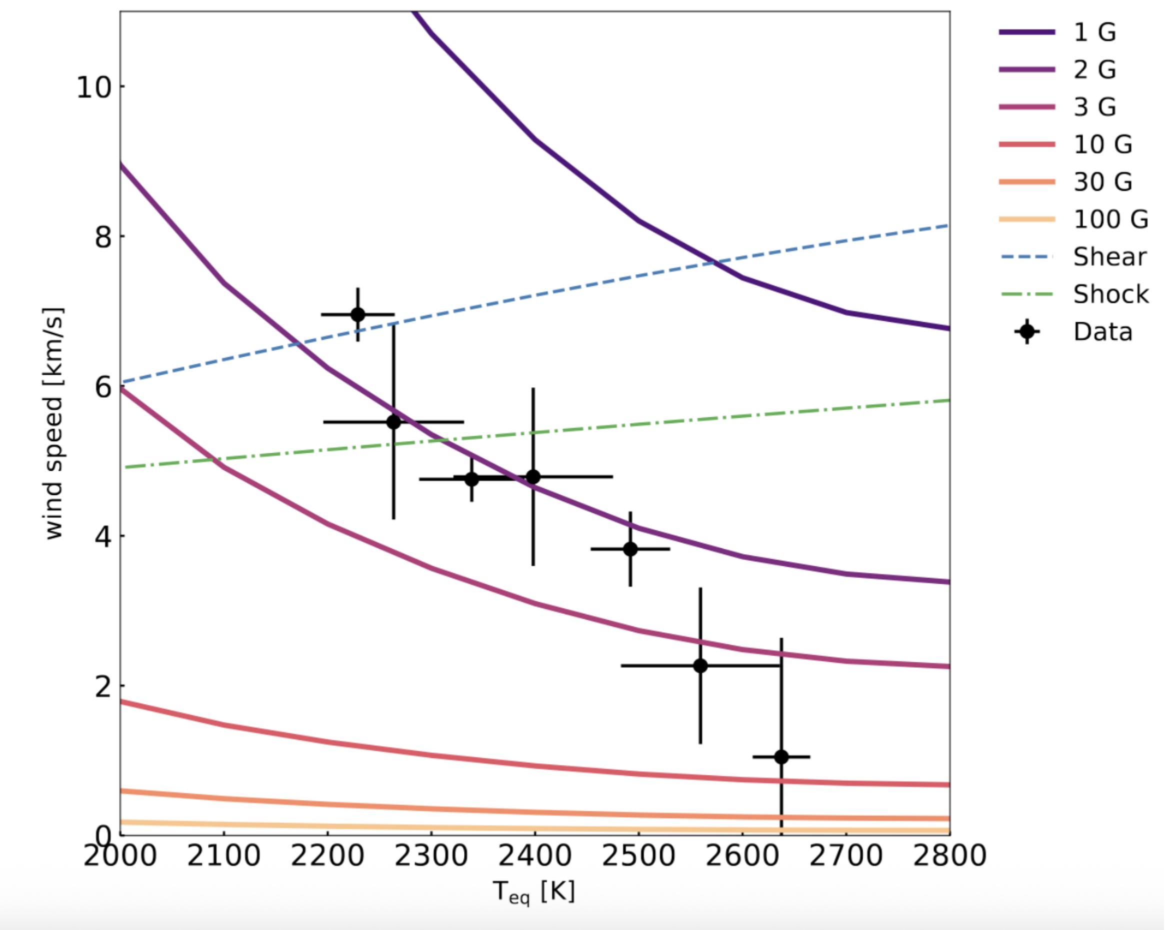
Pino et al. (2020)

Comparative hot Jupiter studies with HDS



HDS comparative studies highlight 2: direct measurement of winds

Comparative hot Jupiter studies with HDS



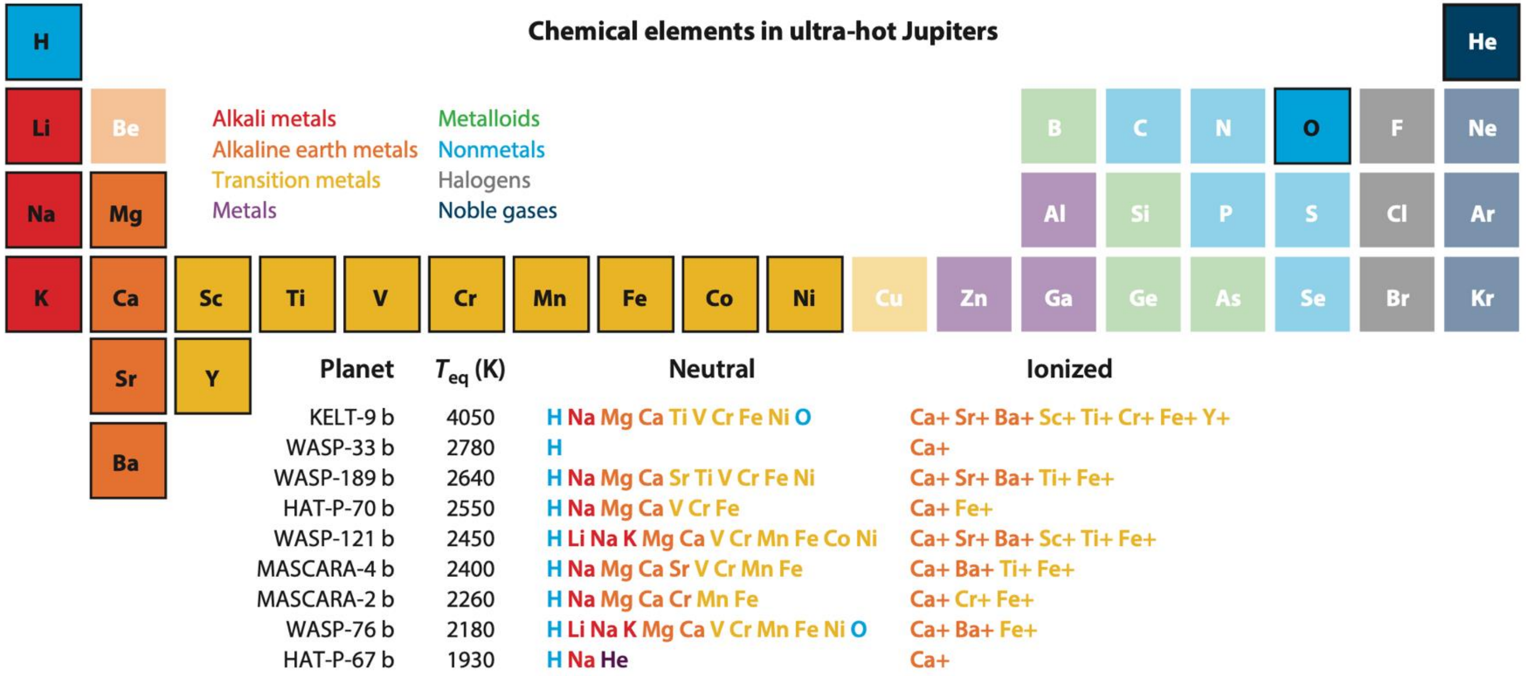
Wind strength decreases with temperature in UHJs. To date, only atmospheric magnetic fields can explain this behaviour.

$$B_{atm} = B_{\mathrm{dipole}} + B_{\mathrm{induced}}$$

→ Most likely scenario is that the dipole field is of a few *G*, or fine tuning required

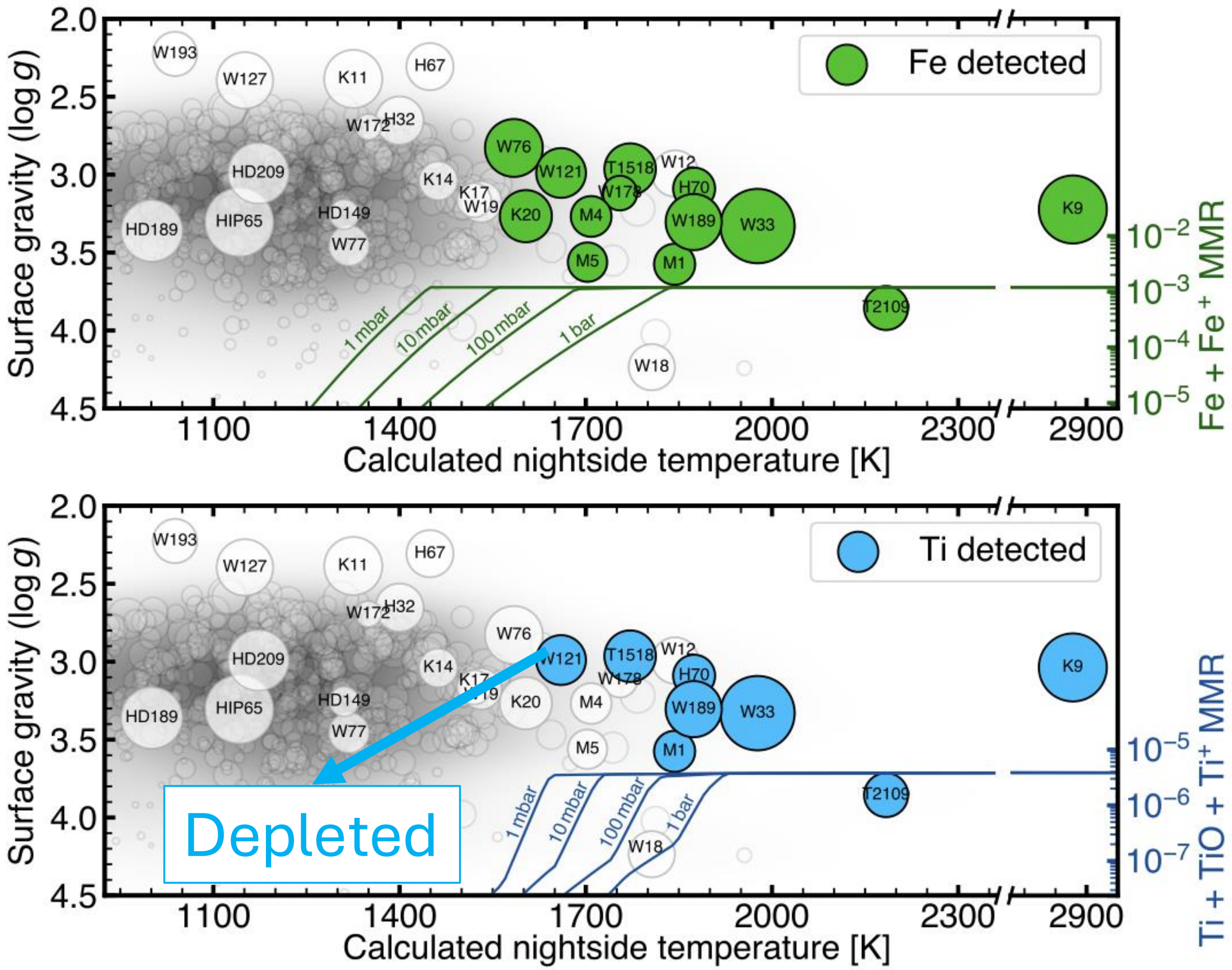
Seidel et al. (2026)

HDS comparative studies highlight 3: potential night-side cold-trap of titanium

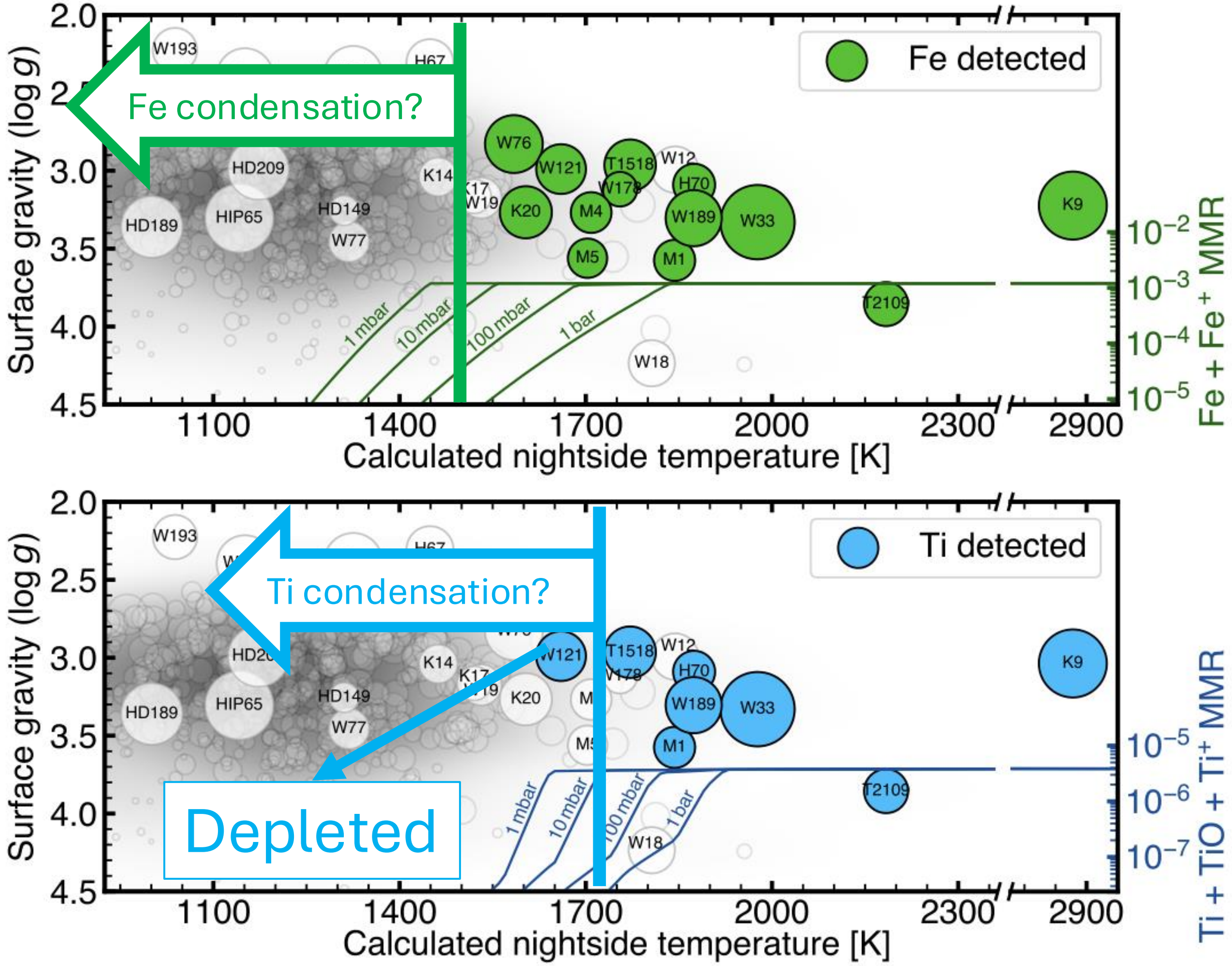


Snellen et al. (2025)

Comparative hot Jupiter studies with HDS



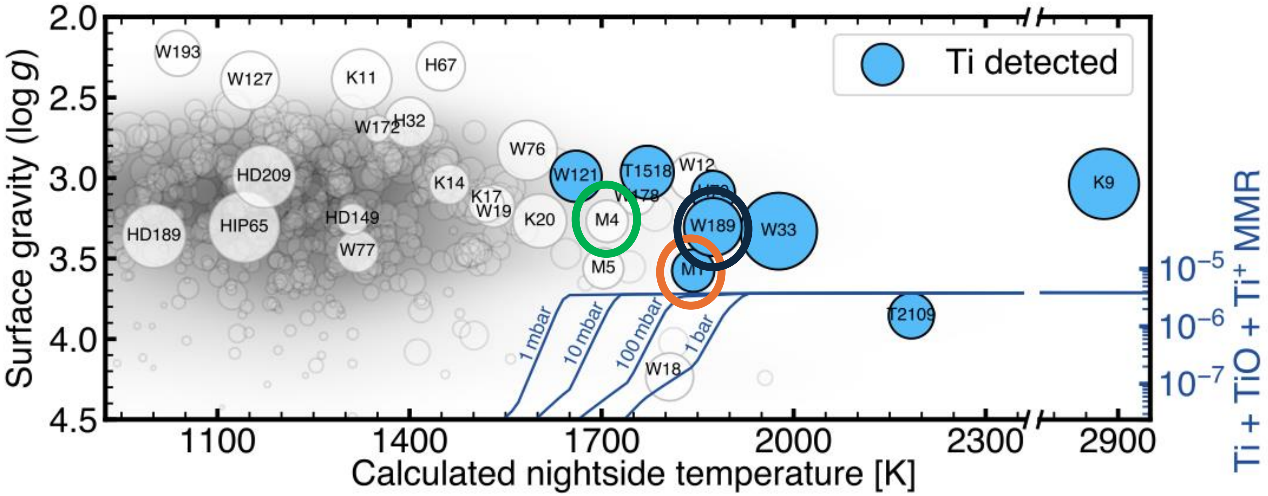
Comparative hot Jupiter studies with HDS



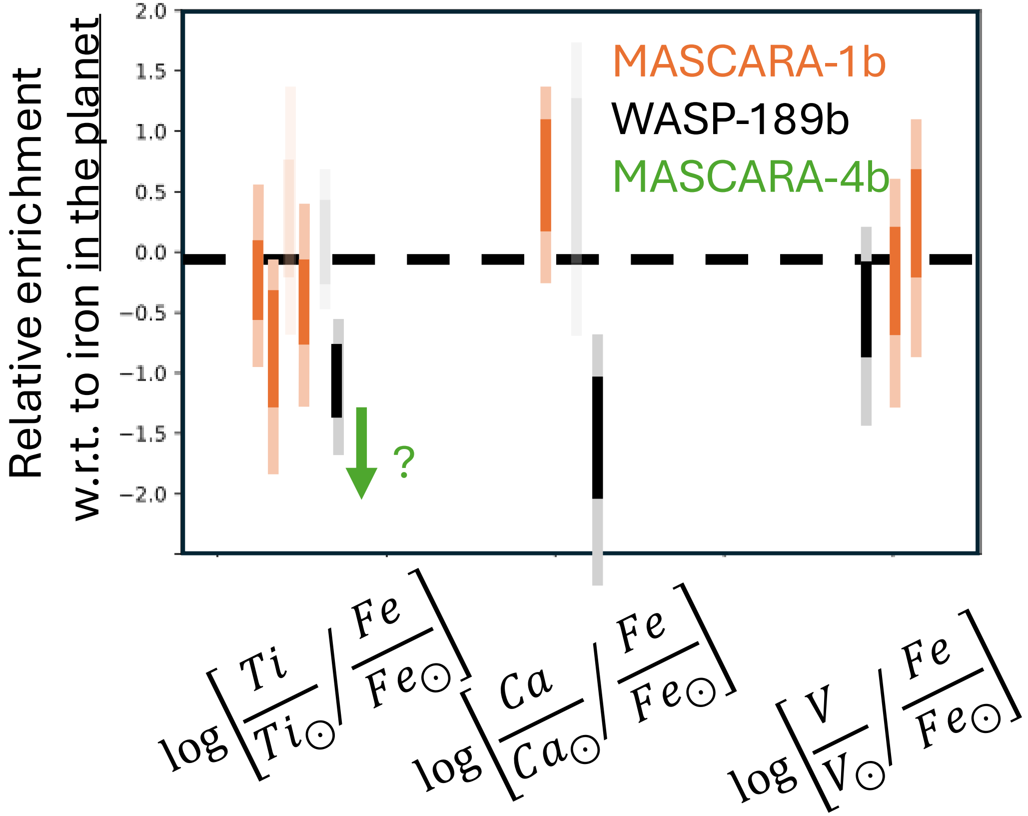
Titanium and iron are solely delivered by solids in the protoplanetary disk.

Differentiation most likely due to night-side condensation

Comparative hot Jupiter studies with HDS



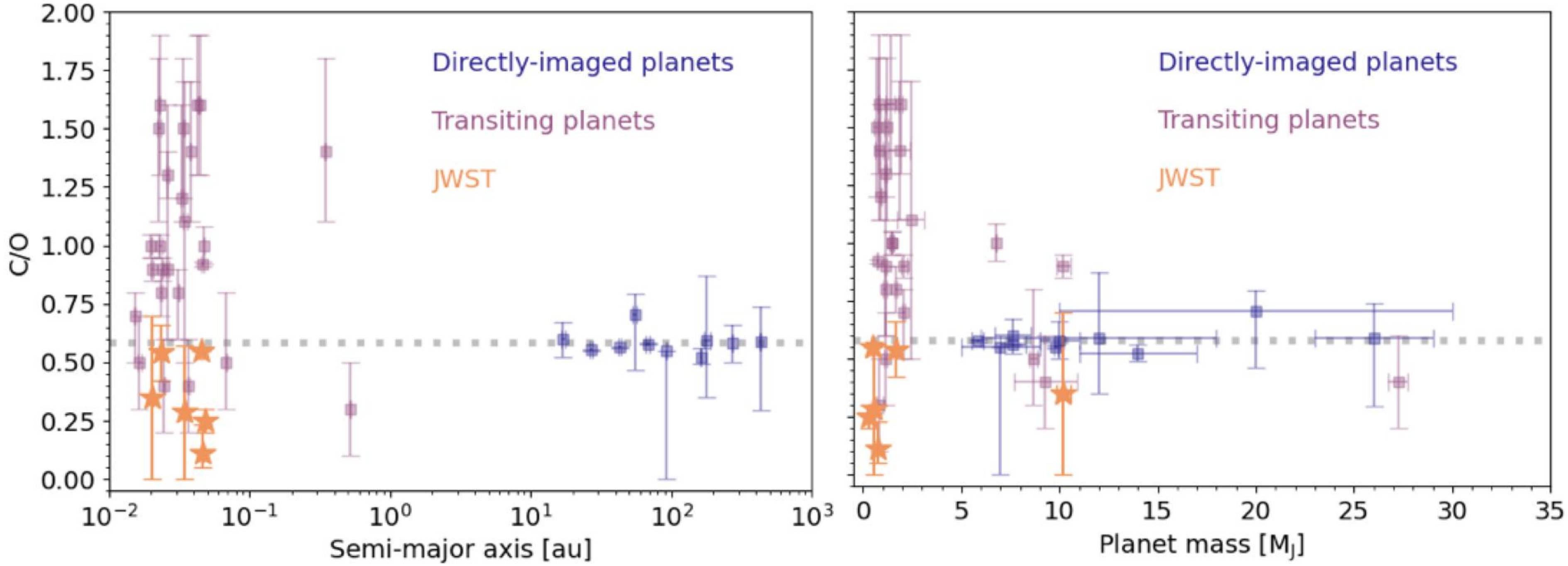
Miceli, Pino et al. (in prep.),
Pino et al. (in prep.):
perhaps the story might be
more complex...



Comparative studies in giant: JWST and beyond

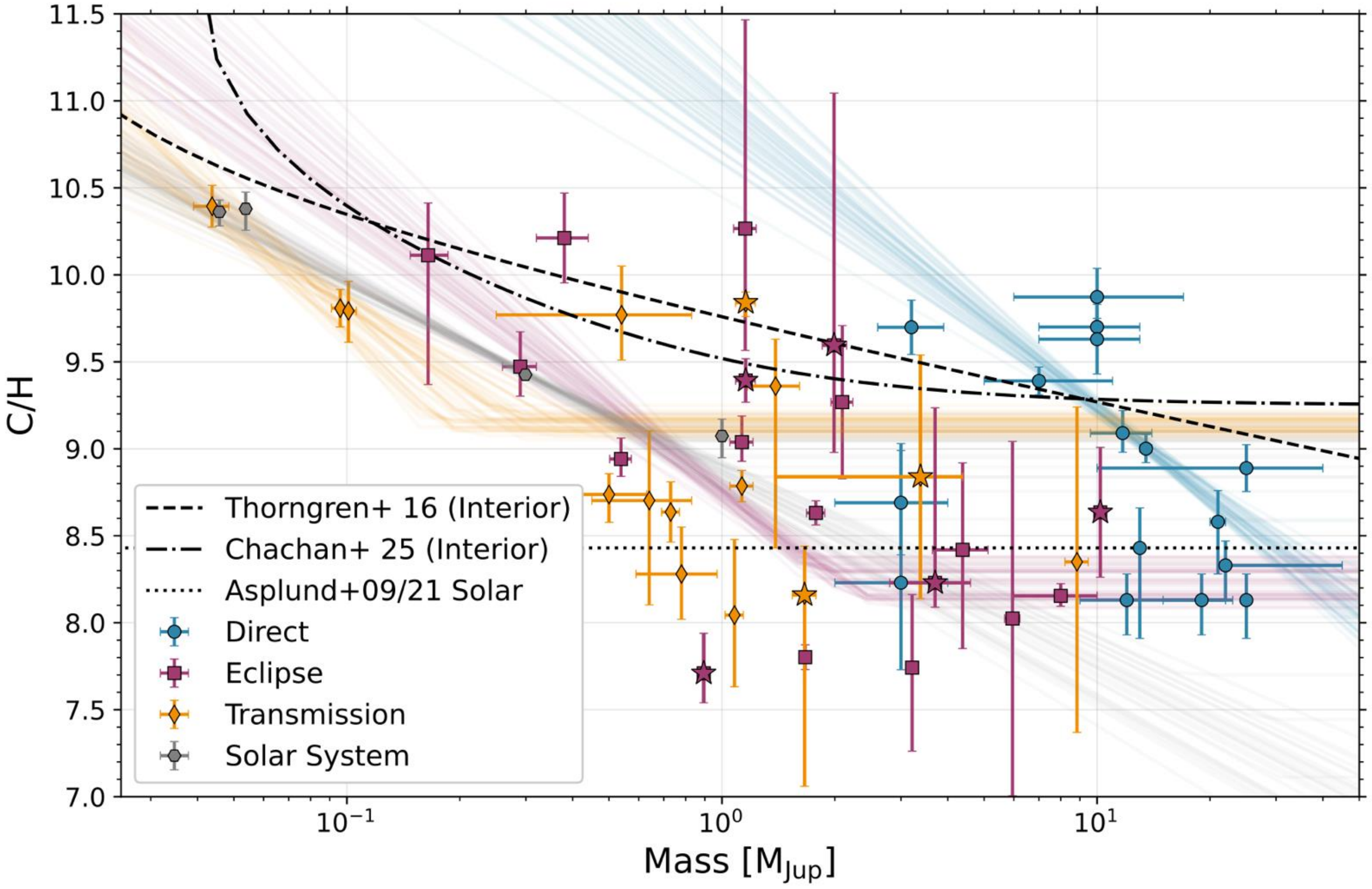
JWST: more precision, more accuracy

The HST missing water: likely a bias due to limited wavelength coverage



Walsh et al. (2025)

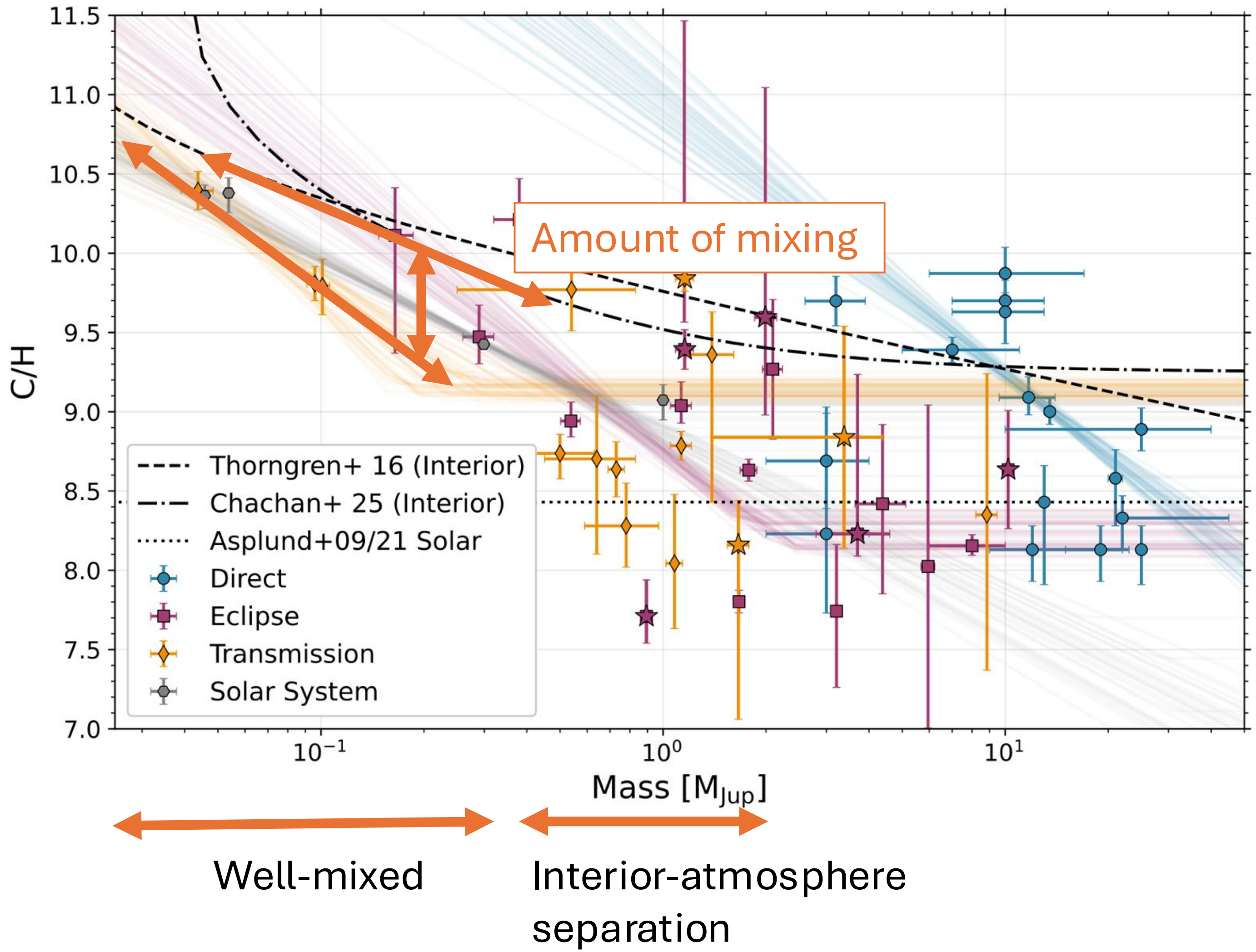
Putting it all together: first attempts



Lothringer et al. (2026): the mass-metallicity relationship found in the Solar System is now confidently confirmed via multiple techniques

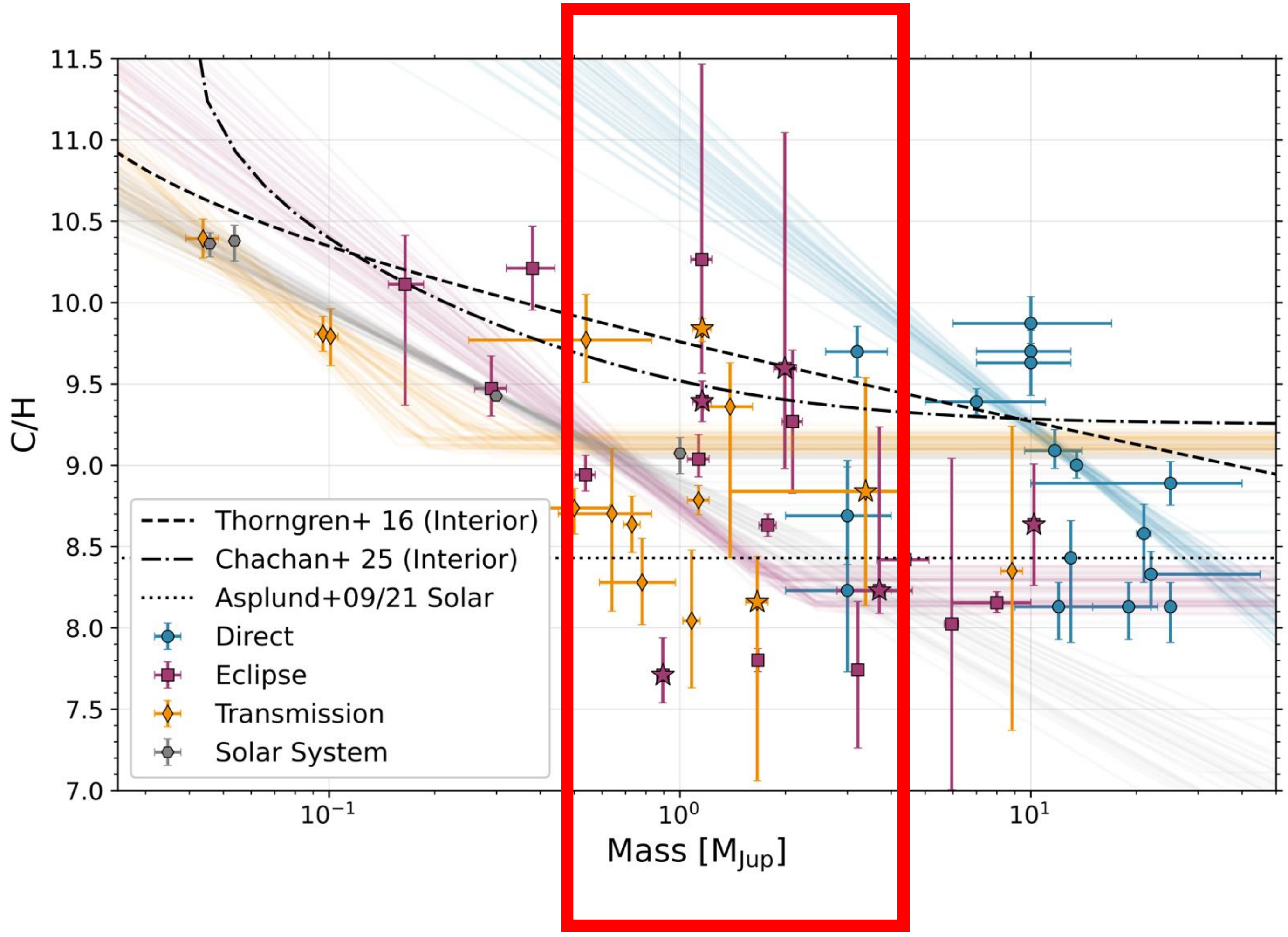
See also Hoch et al. (2023), Walsh (2025), Fu et al. (2025)

Putting it all together: first attempts



Comparison with bulk metallicity from modelling of masses and radii reveals a potential gradient of internal mixing with mass

Putting it all together: first attempts



At $M = 1\ M_J$ a large scatter indicates a potential diversity of planetary/atmospheric structure (e.g. different amount of internal mixing.

Slide by Giovanna Tinetti, ESA M4 ARIEL meeting (2018)

ARIEL – ESA M4 mission

- 1-m telescope, spectroscopy from VIS to IR
- Satellite in orbit around L2
- ~1000 exoplanets ob… …s)
- Simultan… …icron
- Pay… 16 ESA countries + NASA under study

Launching in 2031

Slide by Giovanna Tinetti, ESA M4 ARIEL meeting (2018)

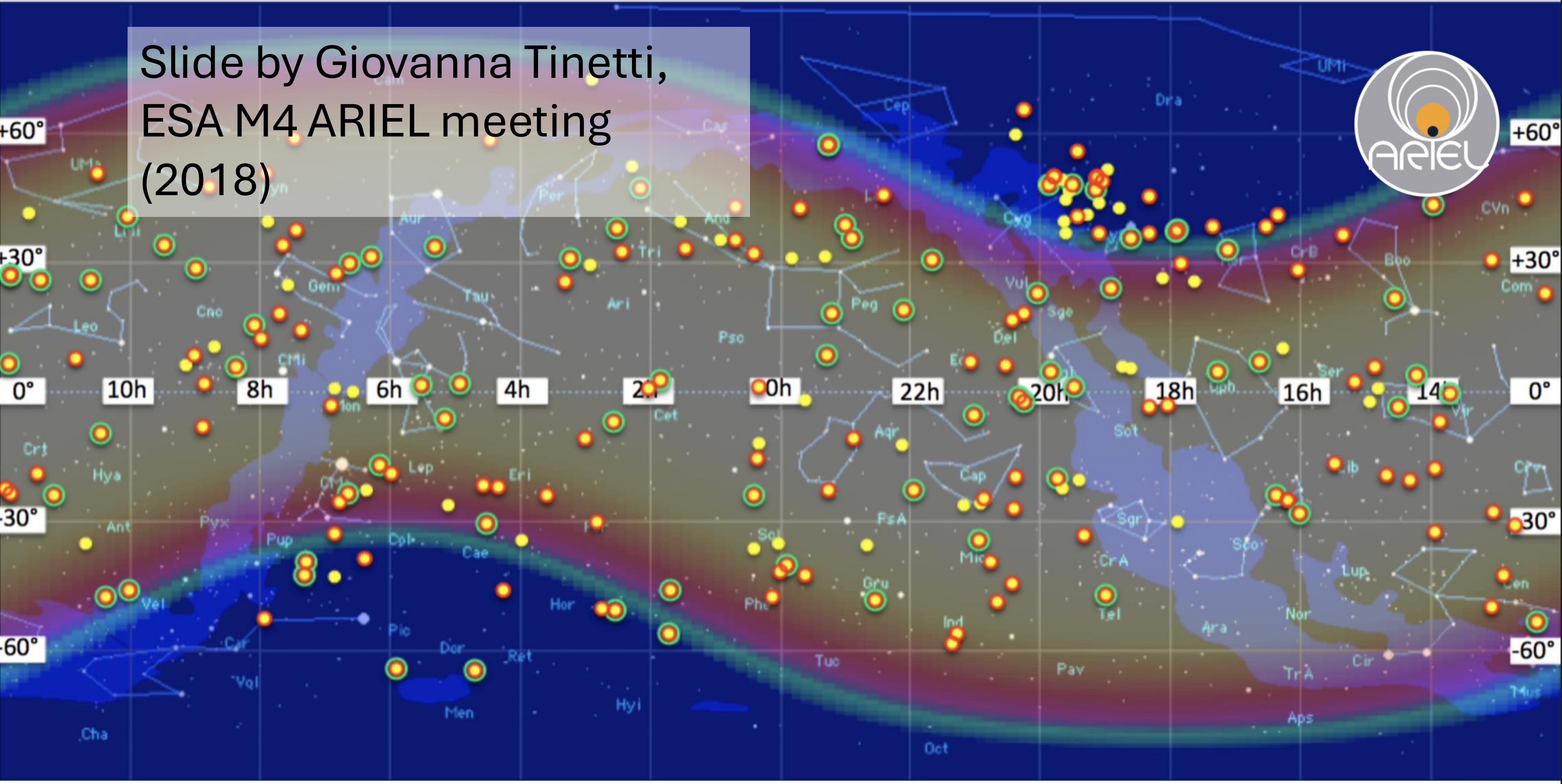
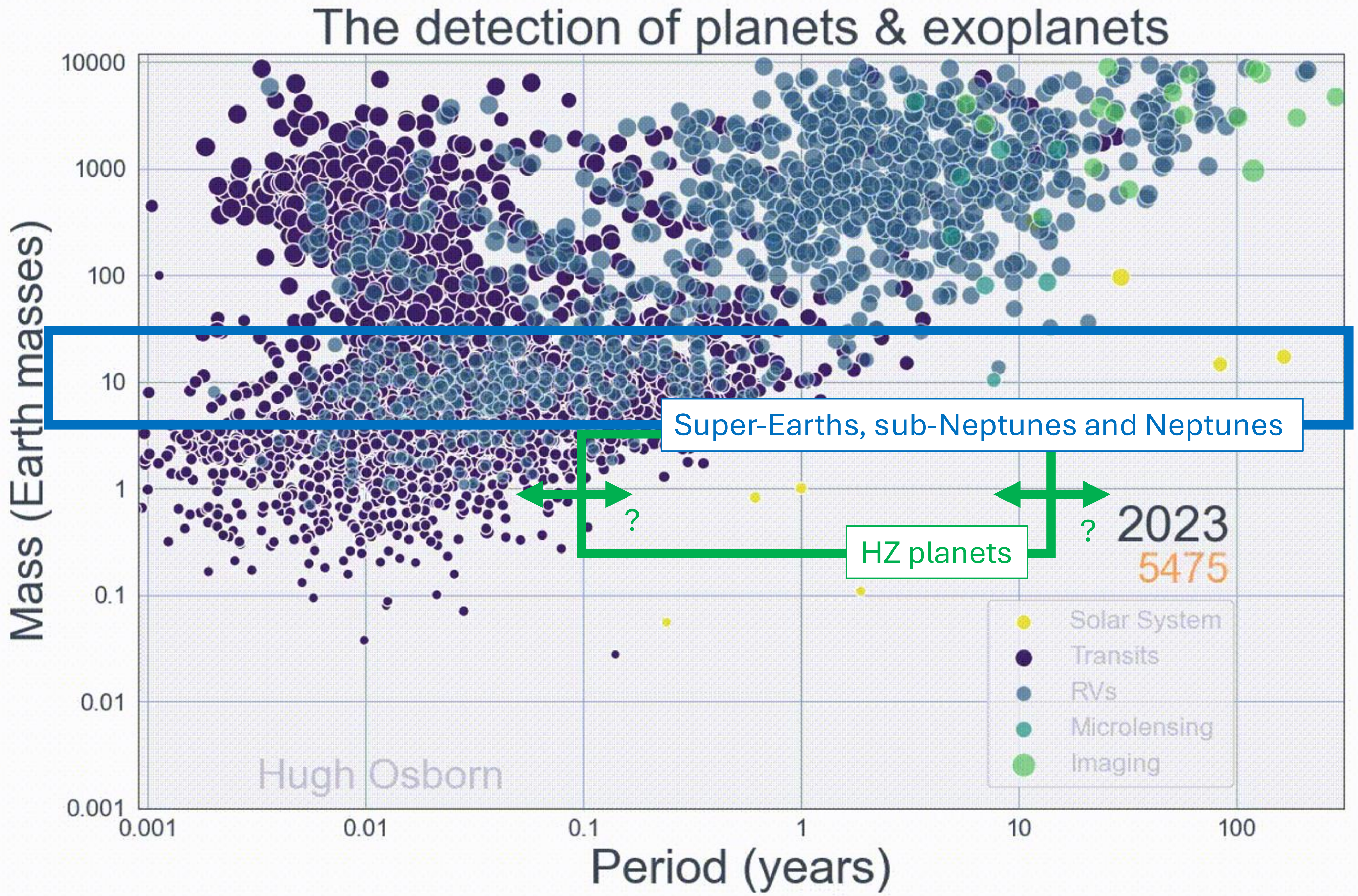


Figure by M. Ollivier

Instantaneous Sky Visibility

100% 80% 60% 40%

- Survey
- Deep
- Benchmark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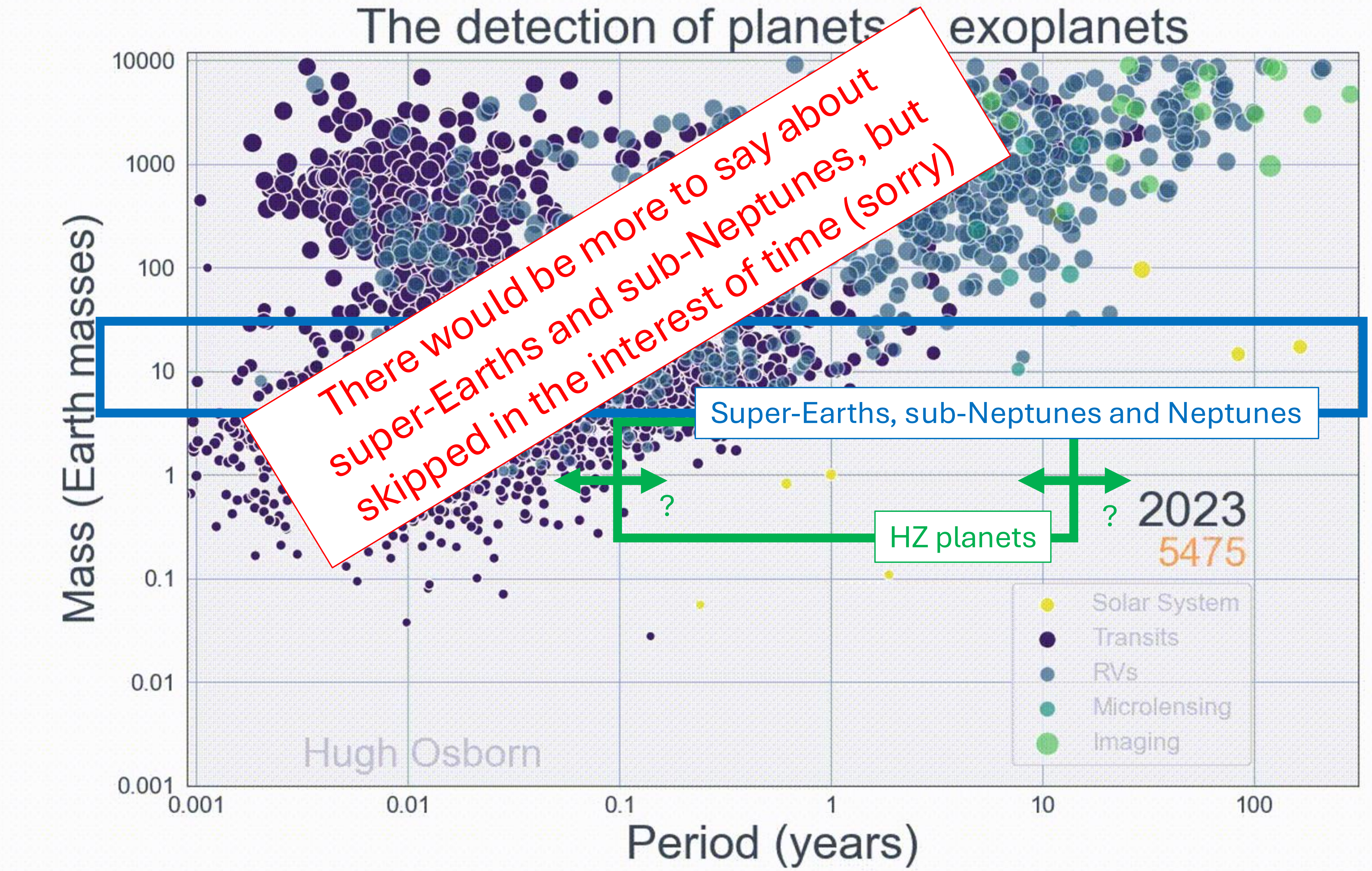

The detection of planets exoplanets
There would be more to say about super-Earths and sub-Neptunes, but skipped in the interest of time (sorry)
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The search for life in exoplanets IS a comparative planetology problem

Example 1: Finding the cosmic shoreline

An empirically derived ”line” that separates planets able to retain an atmosphere from those that lose it. Originally derived in the Solar System (Zahnle & Catling, 2017), and found to lie around $I_{XUV} \sim v^4$.

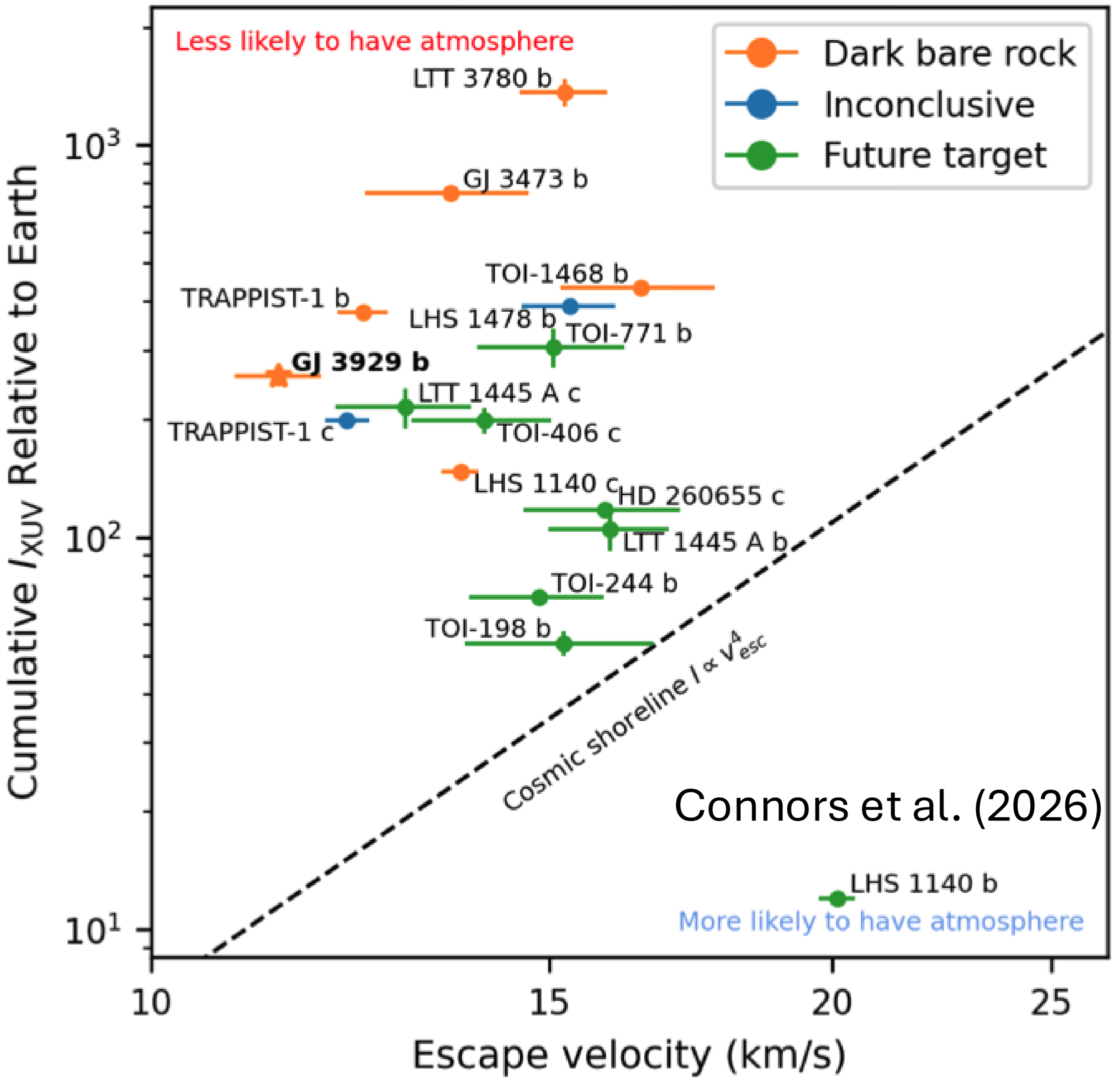
Does this relation apply to M-dwarfs? Is it optimistic or pessimistic? (Pass et al., 2025; Berta-Thompson et al., 2025; X. Ji et al., 2025)

Example 1: Finding the cosmic shoreline

Rocky Worlds DDT

Searching for atmospheres in rocky exoplanets orbiting small M-dwarfs

Planets in the lower part of the plot are cooler, and therefore dimmer.



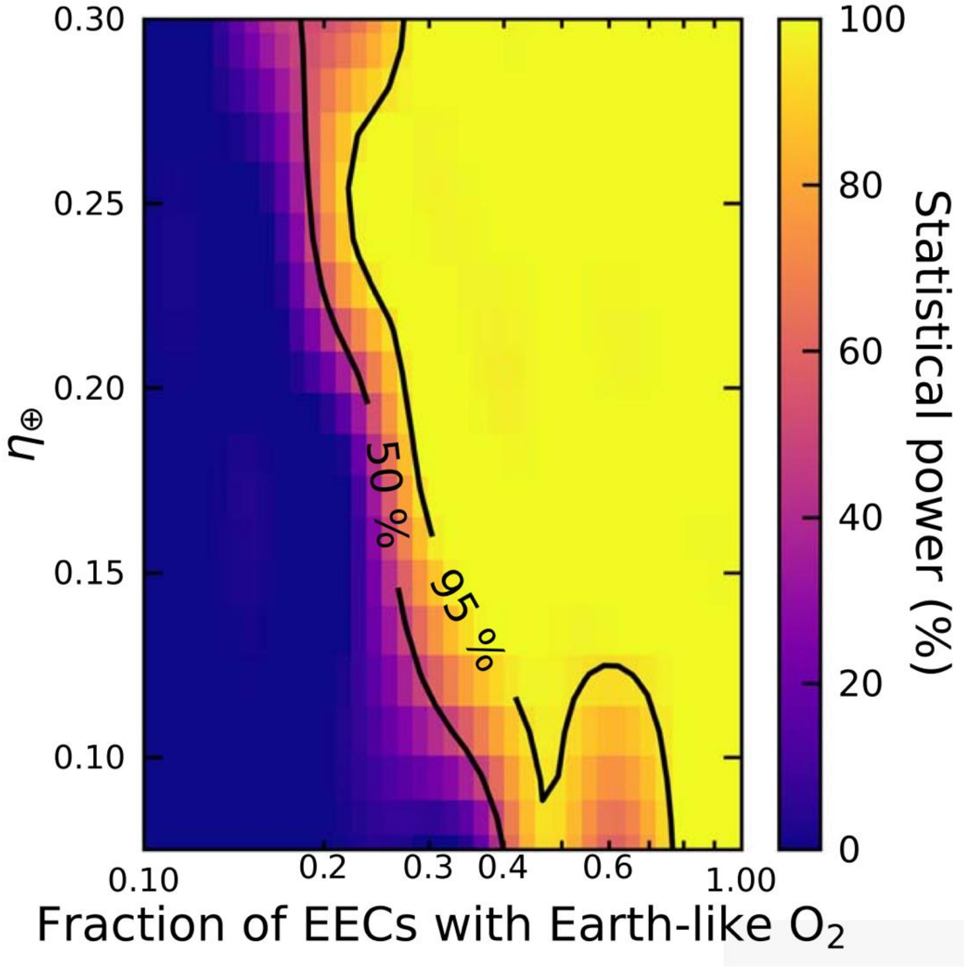
Example 2: the empirical habitable zone

For individual planets, we may always have ambiguous or challenging interpretations of data, or the possibility that we are observing an “odd-ball”.

Future telescopes should be designed to shift our questions from single targets to populations. E.g.: “Does planet XXX, found in the HZ of its star, host O_2 in its atmosphere?” to “Are planets in the HZ of their hosts more likely to host O_2 compared to planets outside of the HZ of Sun twins?”

E.g. Bean et al. (2017), Hardegree-Ullman (2025)

Example 2: the empirical habitable zone



Hardegree-Ullman (2025)

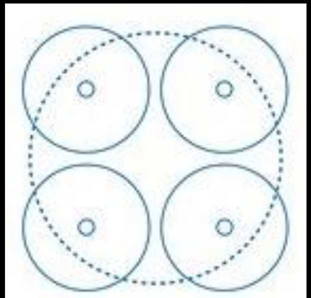
Monte Carlo simulation of capability to reject an M-dwarf HZ hypothesis for a 10-year survey with ELT.

If oxygen-bearing planets in the HZ are as common as 33 to 50%, the hypothesis can be tested with the ELT.

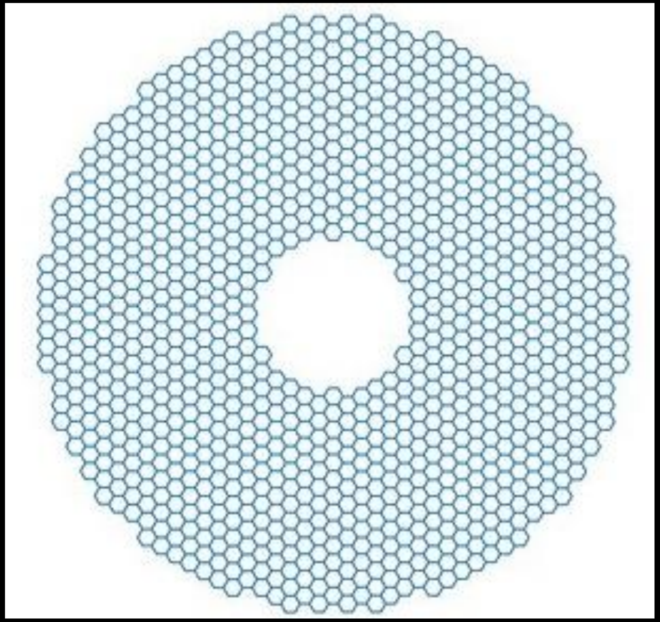
The ELT: what will it change for exoplanet atmospheres at HDS?

2.4 meters

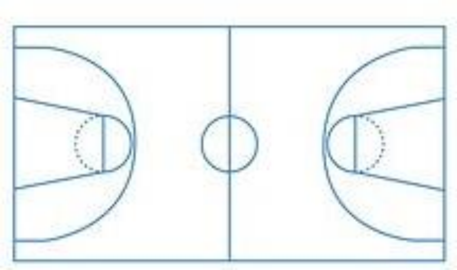
Hubble space telescope (2.4 m)



Very Large Telescope (VLT, 8m each)

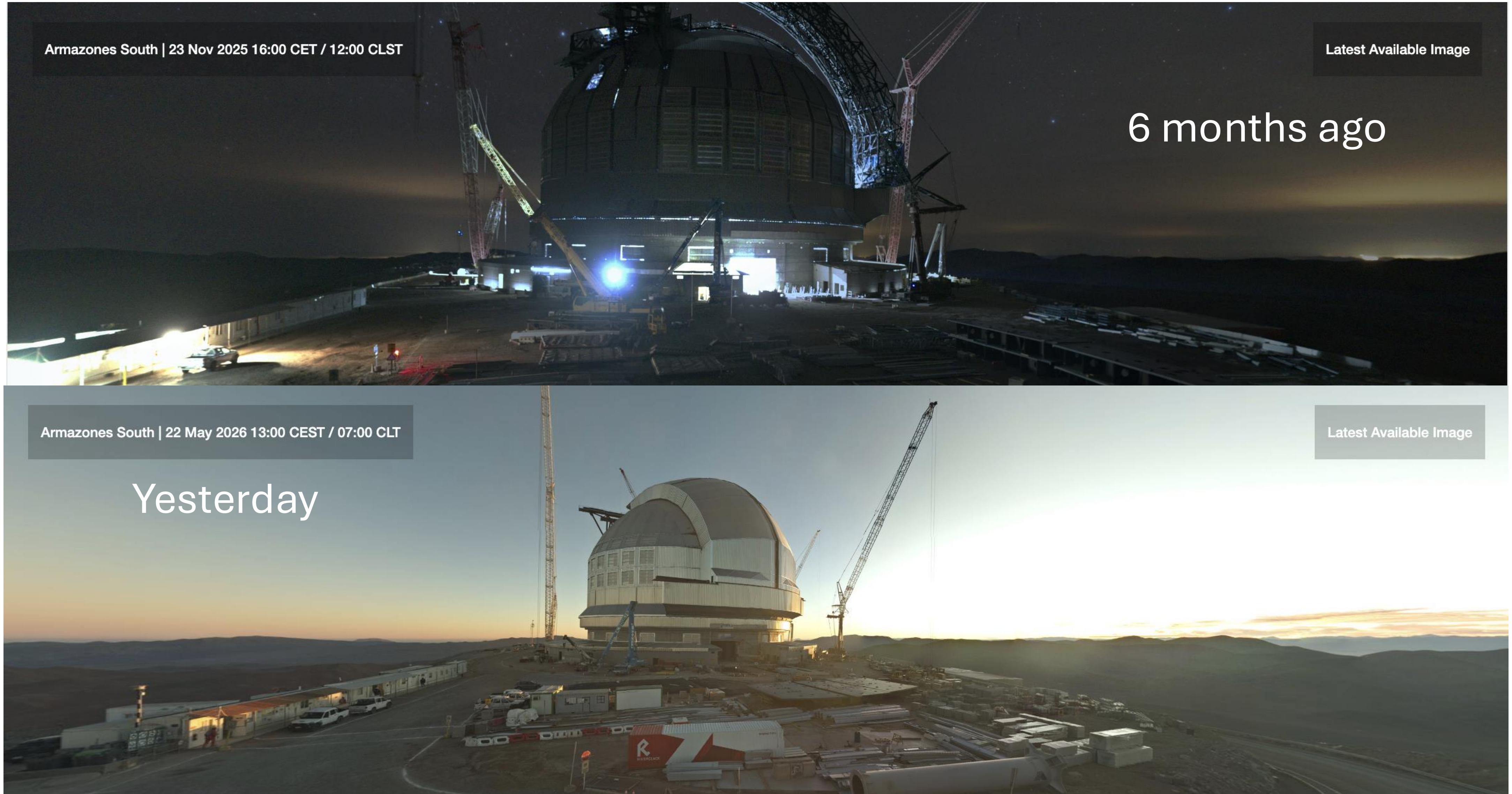


Extremely Large Telescope (ELT, 39m)

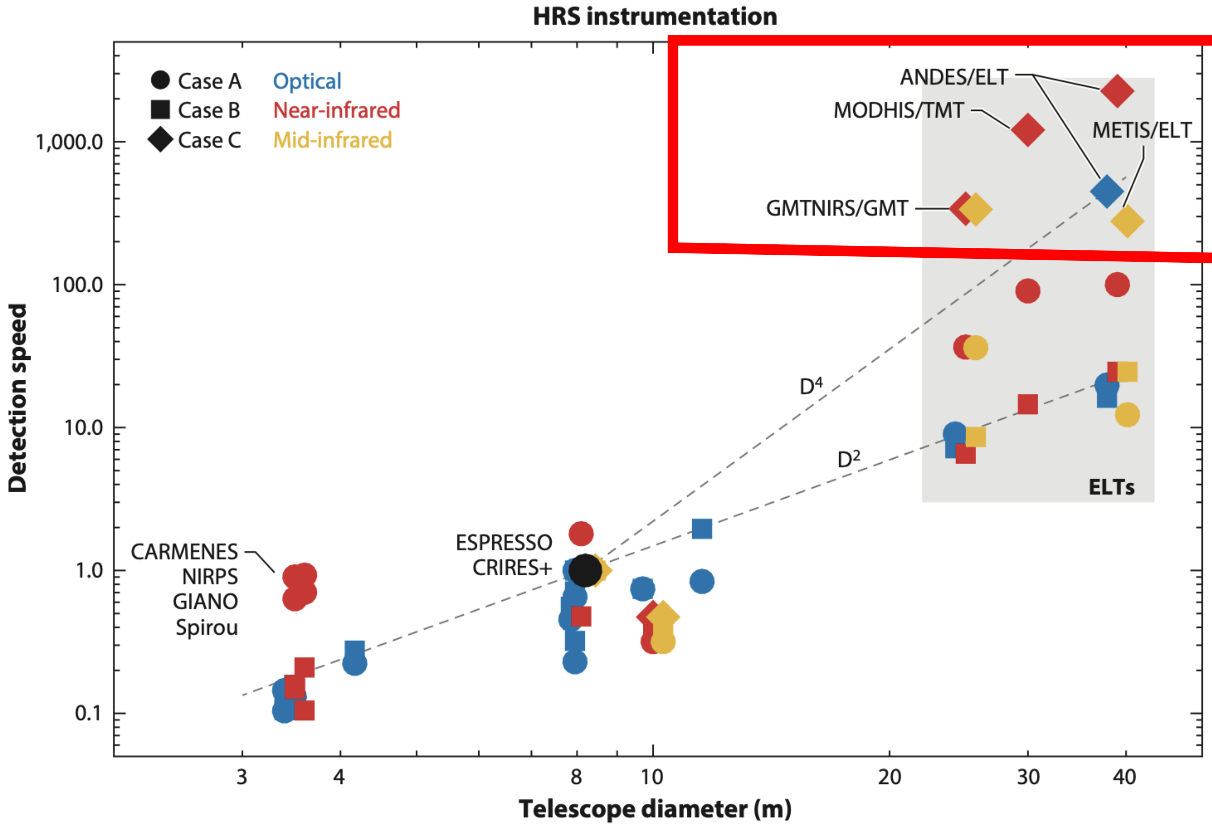


The ELT is a phenomenal step forward in terms of technology of ground-based telescopes. As an effort, it’s comparable to a space mission.

The ELT yesterday



The ELT revolution in atmospheric studies of wide separation planets

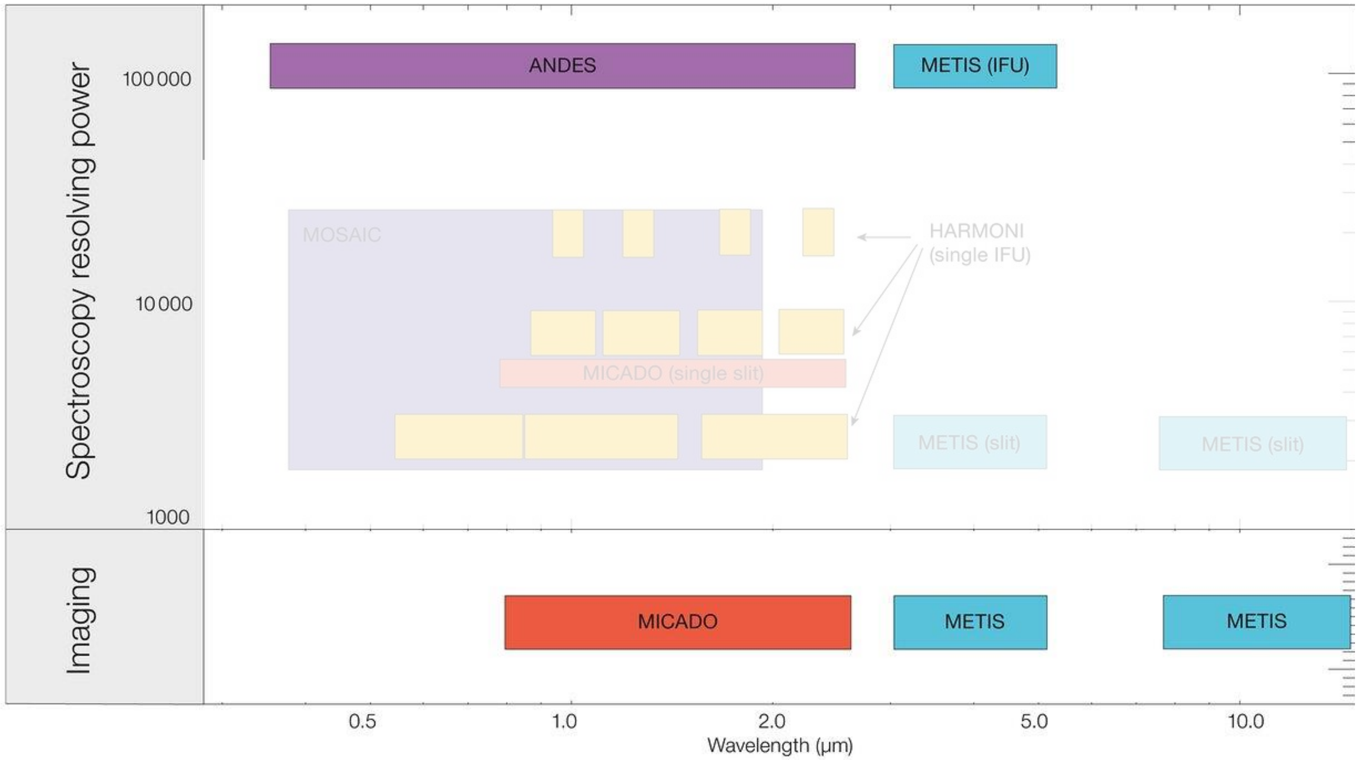


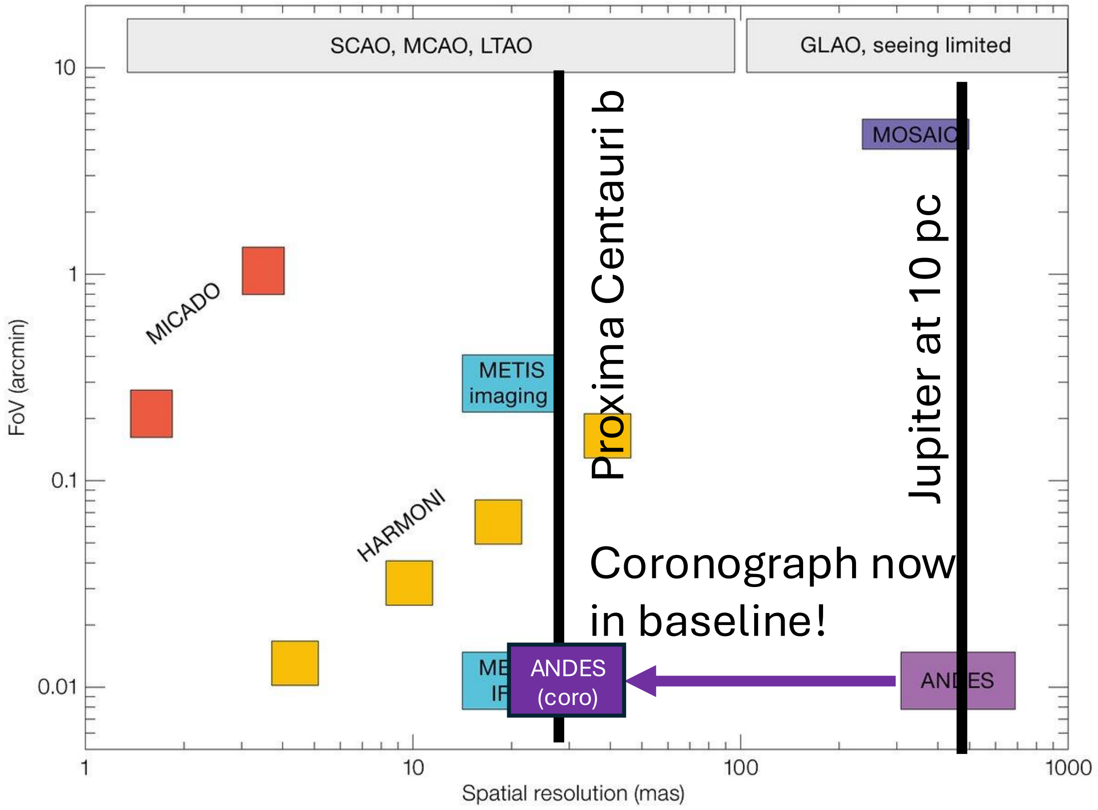
Snellen et al (2025)

Speed for spatially unresolved planets scales as D^4. We will gain 3 orders of magnitude in sensitivity.

We will probe real Jupiter-analogues, and HZ planets around M/K dwarfs.

The ELT revolution in atmospheric studies of wide separation planets

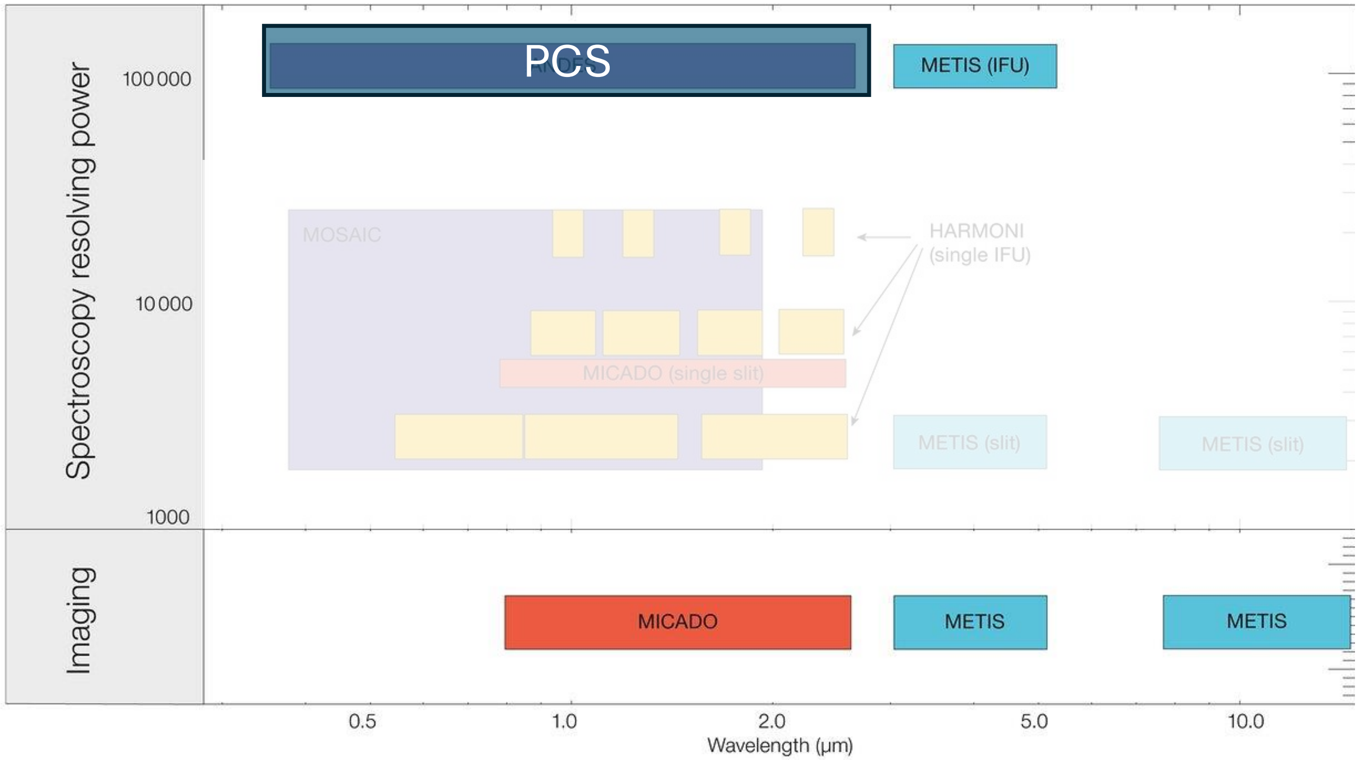


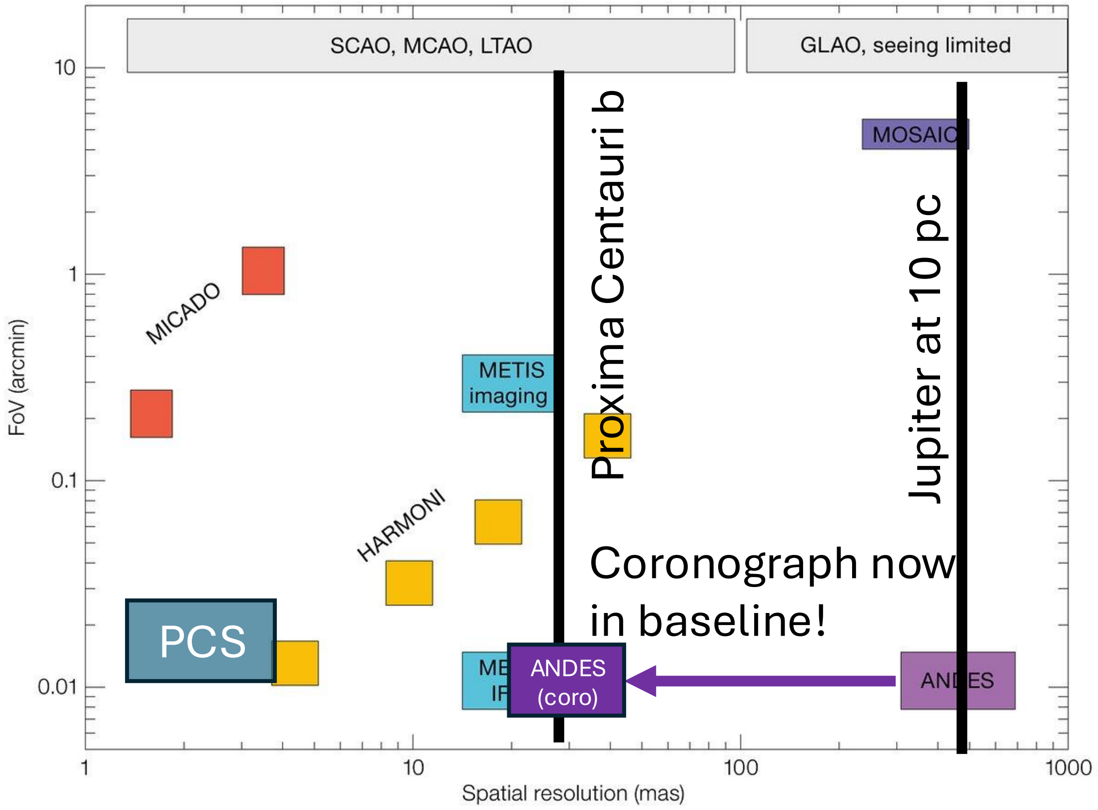


Pallè et al. (2025)

ANDES + METIS are the dream combo for this science!
(PCS in the future) → ask me more if interested

The ELT revolution in atmospheric studies of wide separation planets





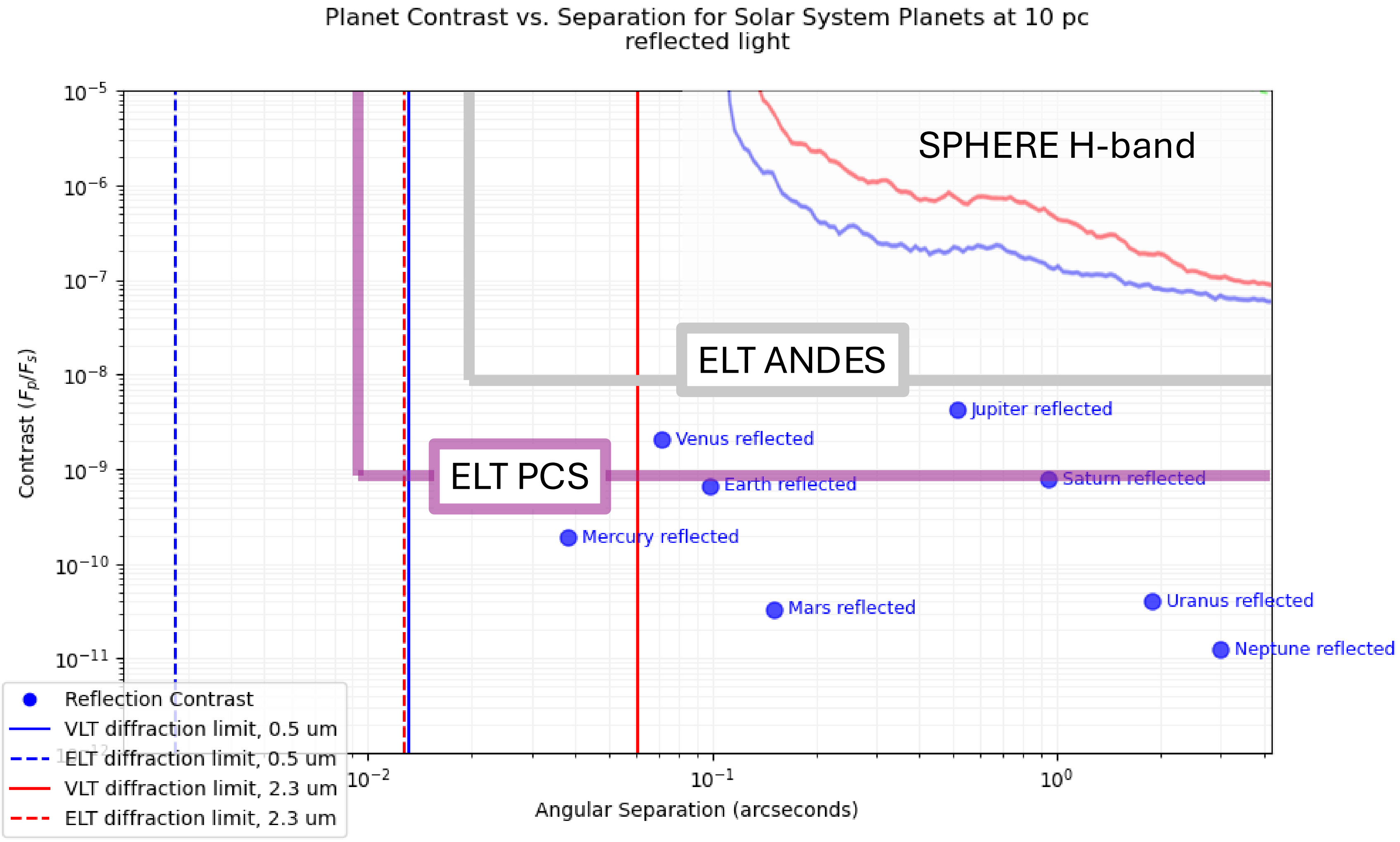
Pallè et al. (2025)

Planetary Camera for Science is a third generation instrument that combines the best of the worlds

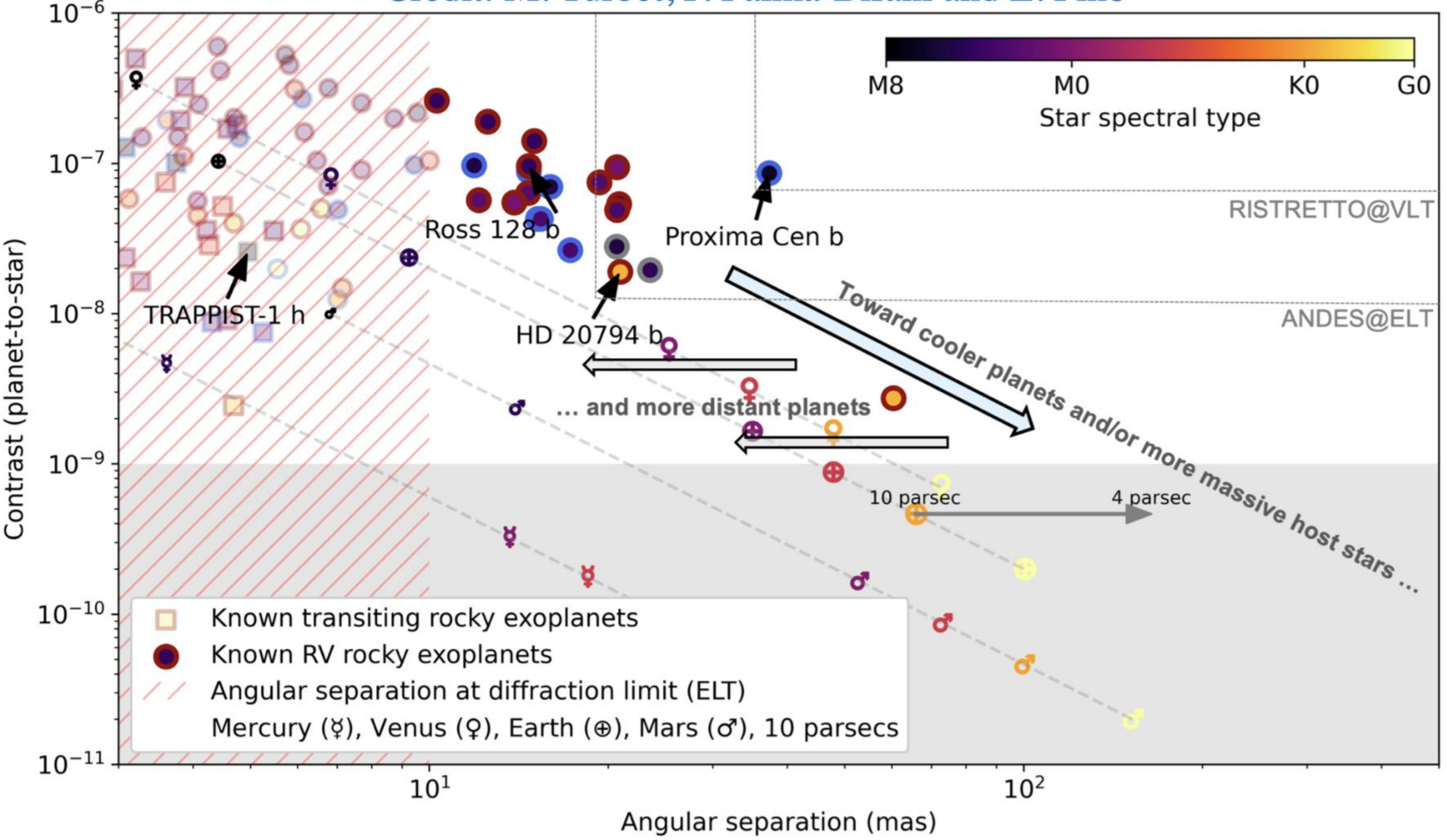
Observing Solar System analogues in reflected light

With ELT PCS, we will get close to the sensitivity required to acquire spectra of an Earth-twin at 10 pc distance from Earth.

So why did we design them like this?

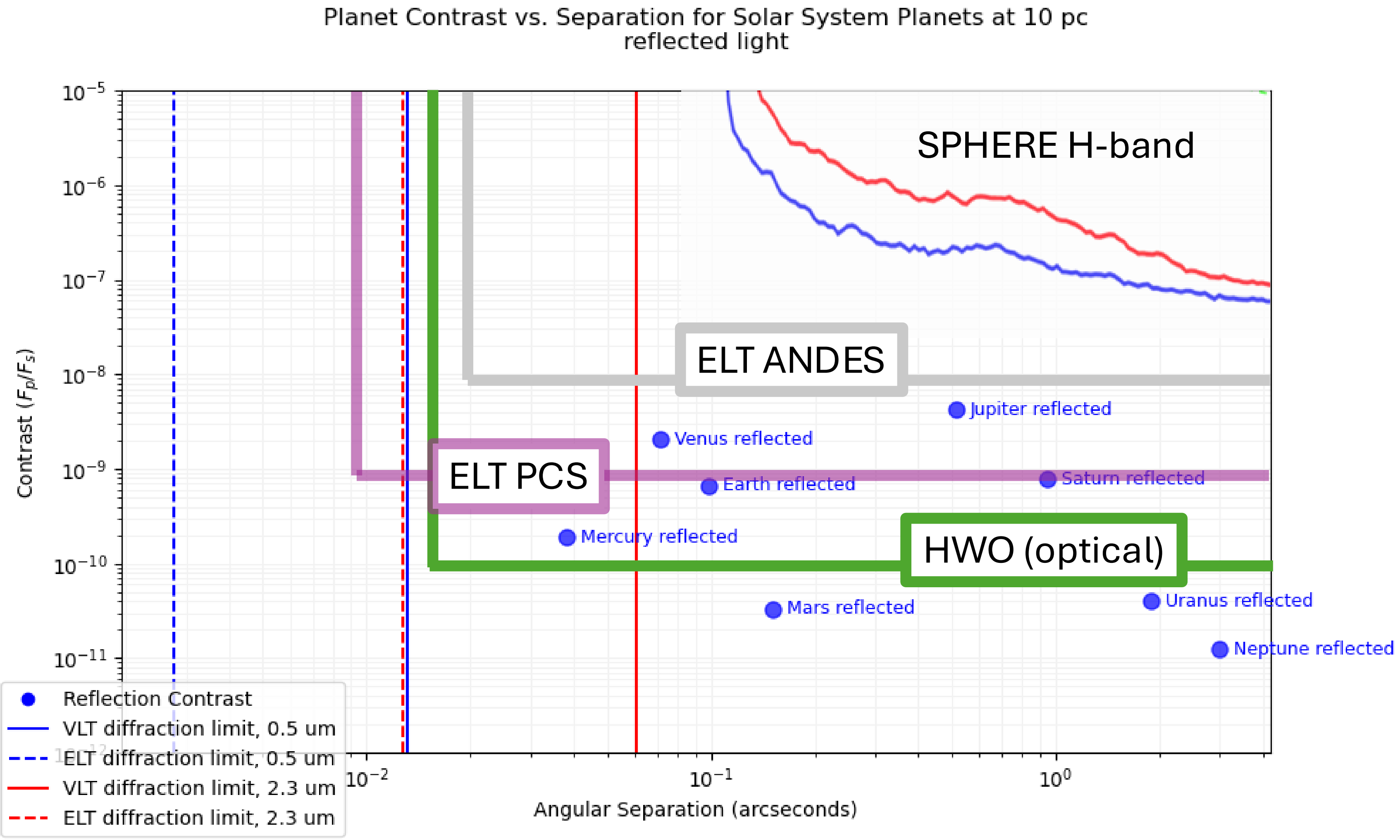


Credit: M. Turbet, P. Palma-Bifani and L. Pino

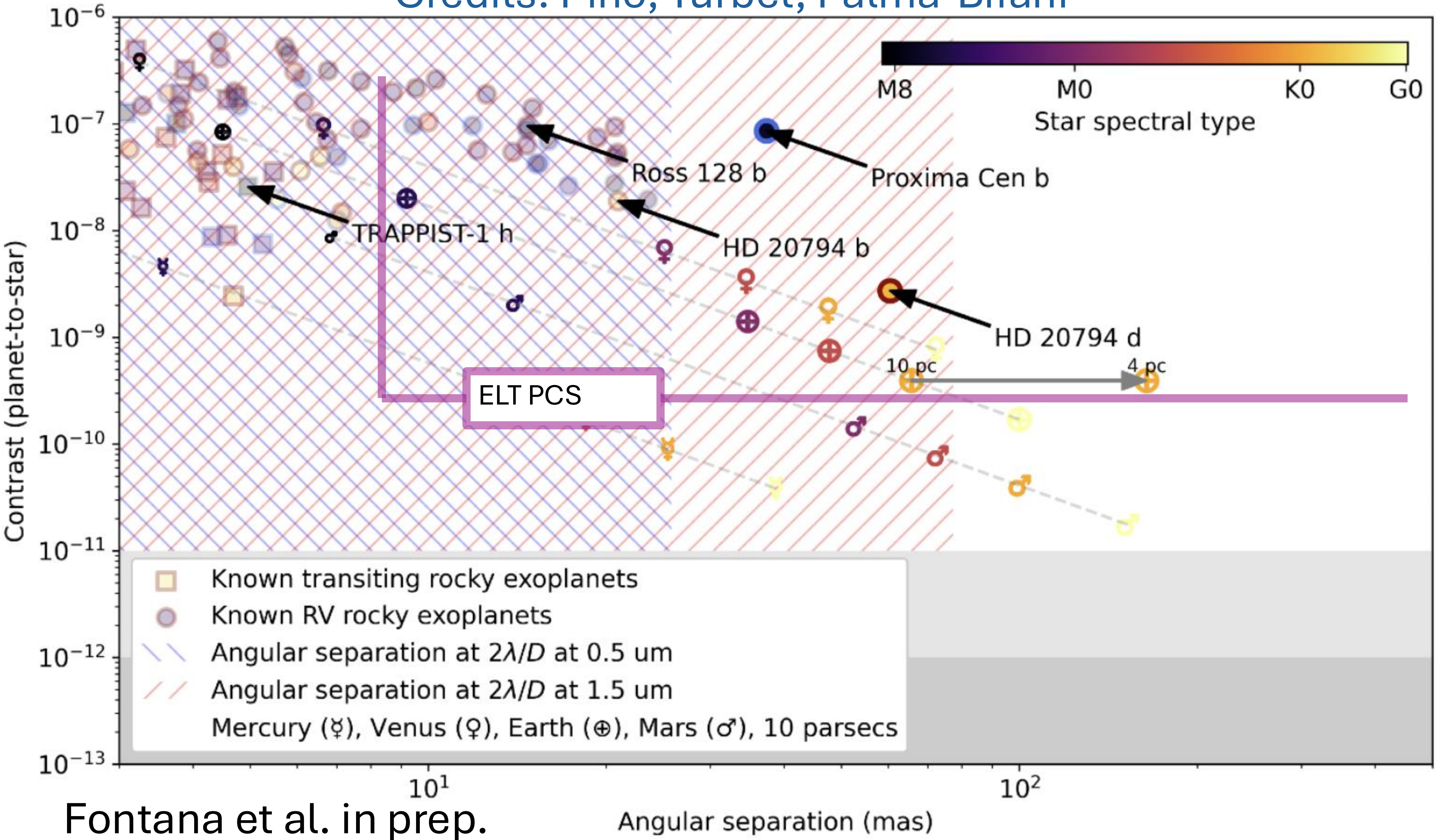


Observing Solar System analogues in reflected light

To do better we can only go to space: the Habitable Worlds Observatory is the instrument that could detect the atmosphere of a true Earth-analogue.



Credits: Pino, Turbet, Palma-Bifani



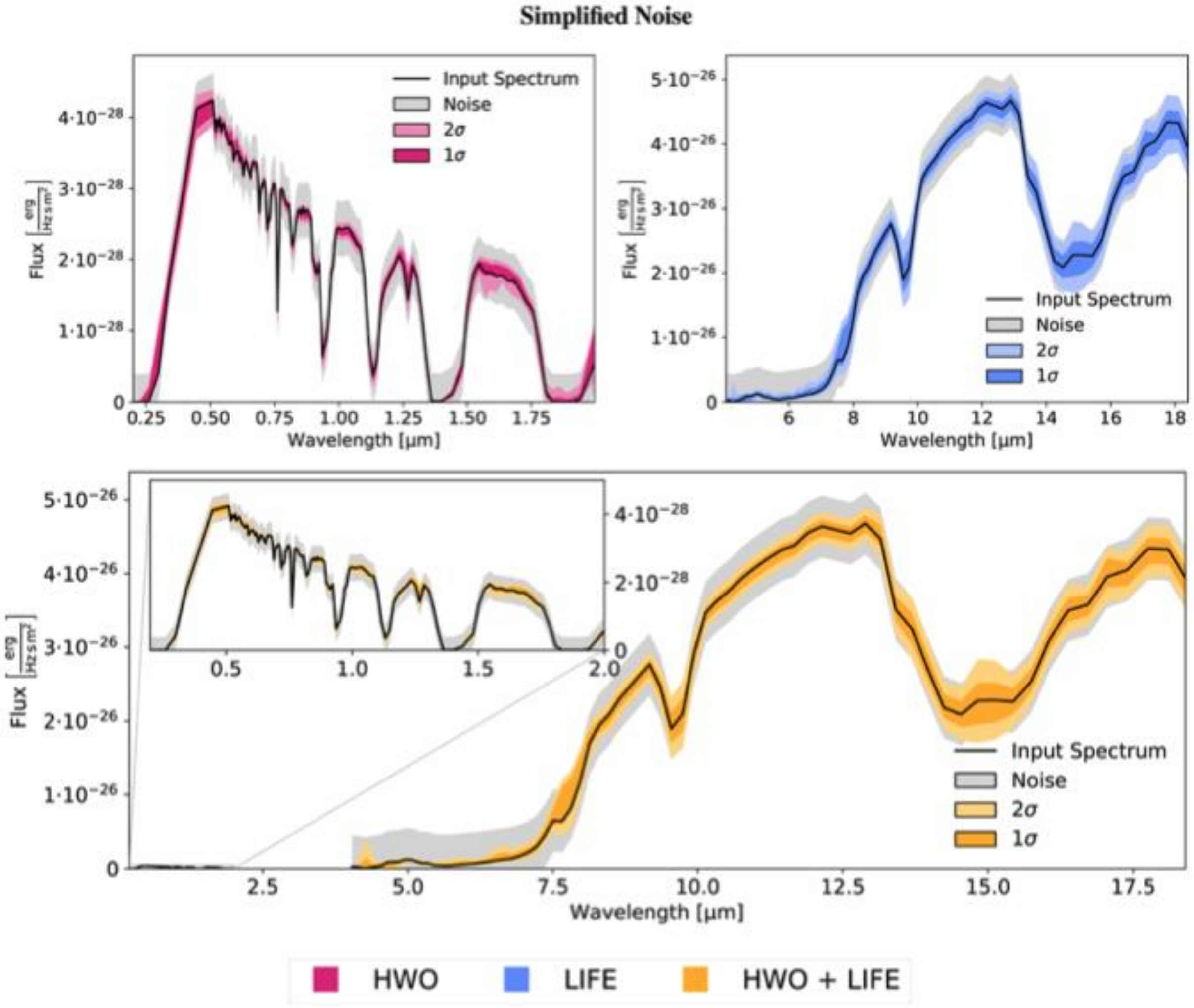
Fontana et al. in prep.

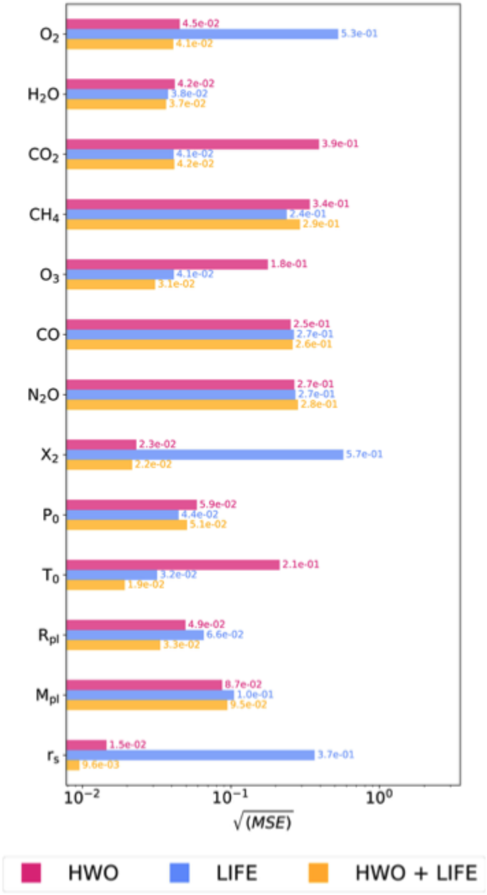
Habitable Worlds Observatory

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

If we get all of our observatories, we might be able to say a lot about single targets as well!

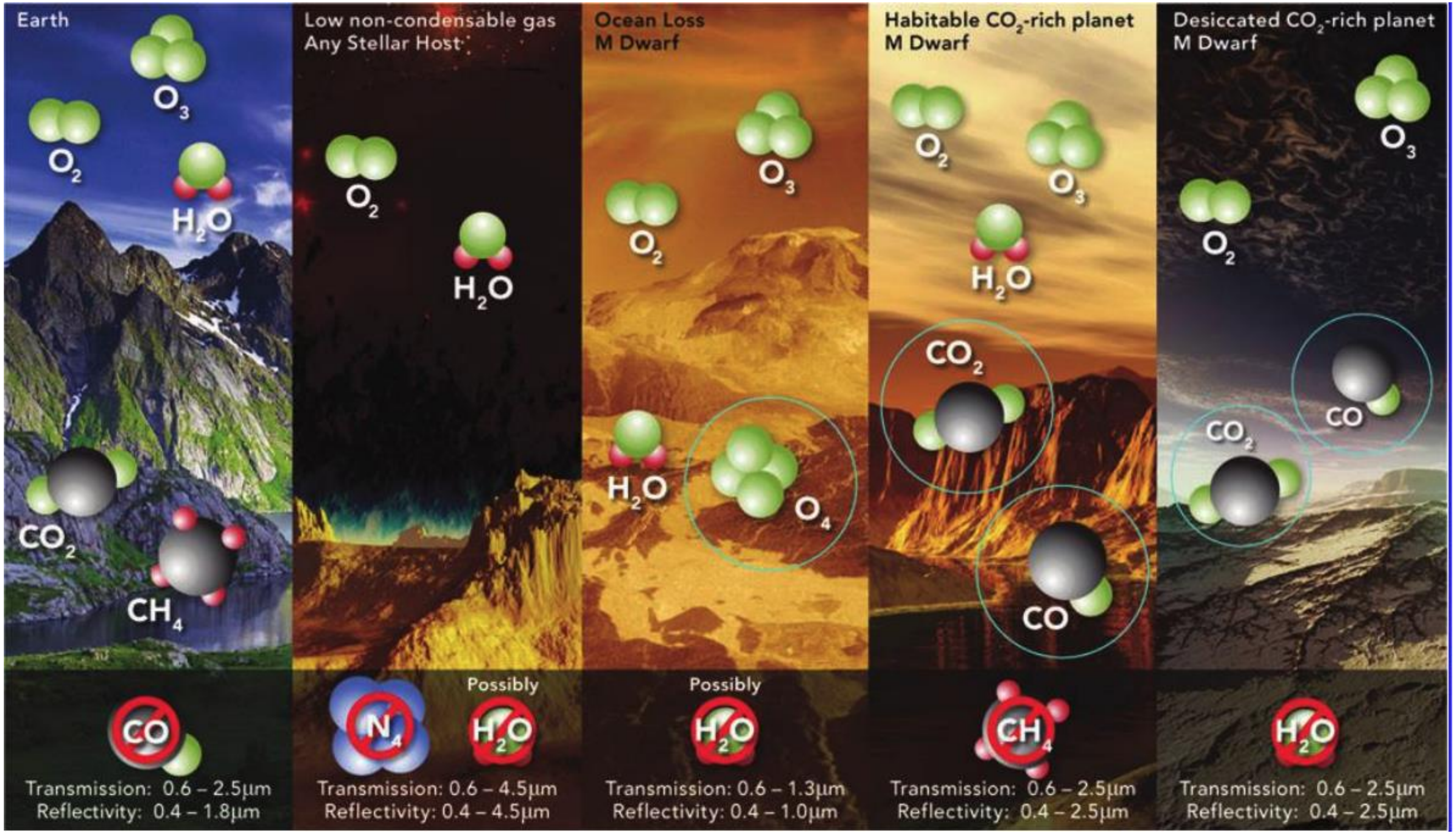
HWO + LIFE: potential perspectives





Alei et al. (2024): the combination of thermal infrared (LIFE) and reflected light (HWO) is key to measure precise atmospheric abundances in Earth-twins.

False positives (Meadows et al., 2017)



MASSIVE EXOPLANET MEME EXHIBITION

Conclusions

- We are in a golden era of comparative planetology, driven by advancements from both exoplanets and Solar System planets.
- The high quality of spectra of gas giant exoplanet atmospheres, combined with the unique conditions in which they are found, currently provides a valid and valuable sample for comparative planetology.
- Thanks to new missions and instruments we will sample larger and larger populations of cooler and smaller planets, down to habitable—zone planets with the ELTs, HWO and LIFE.