Proxima Cen b: theoretical spectral signatures for different atmospheric scenarios

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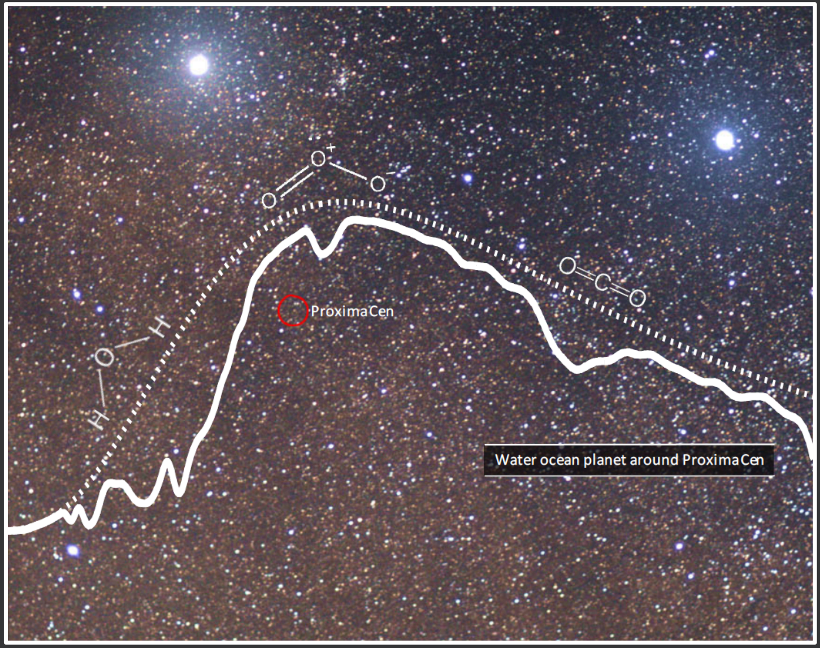

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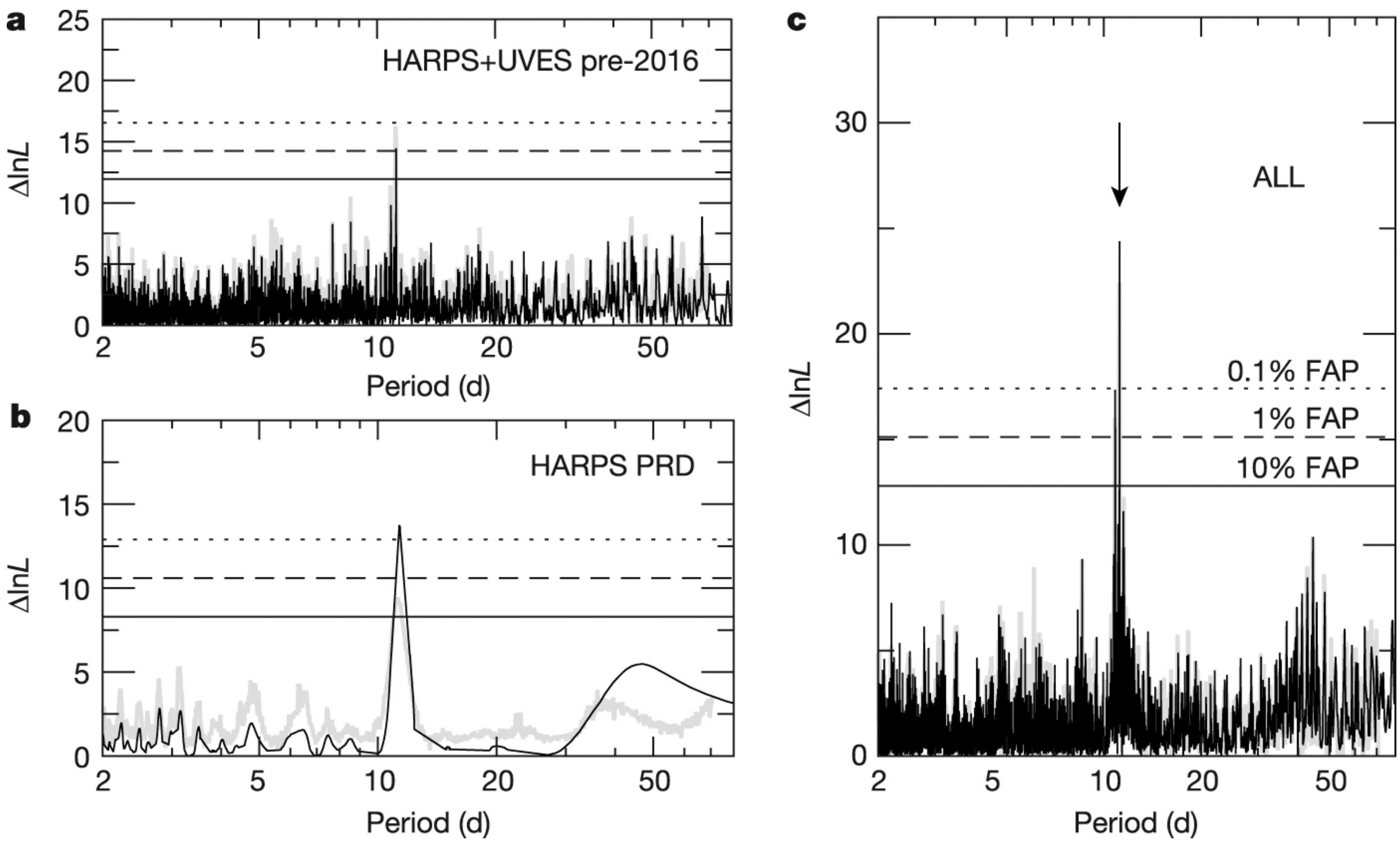
EWASS – Prague

Overview

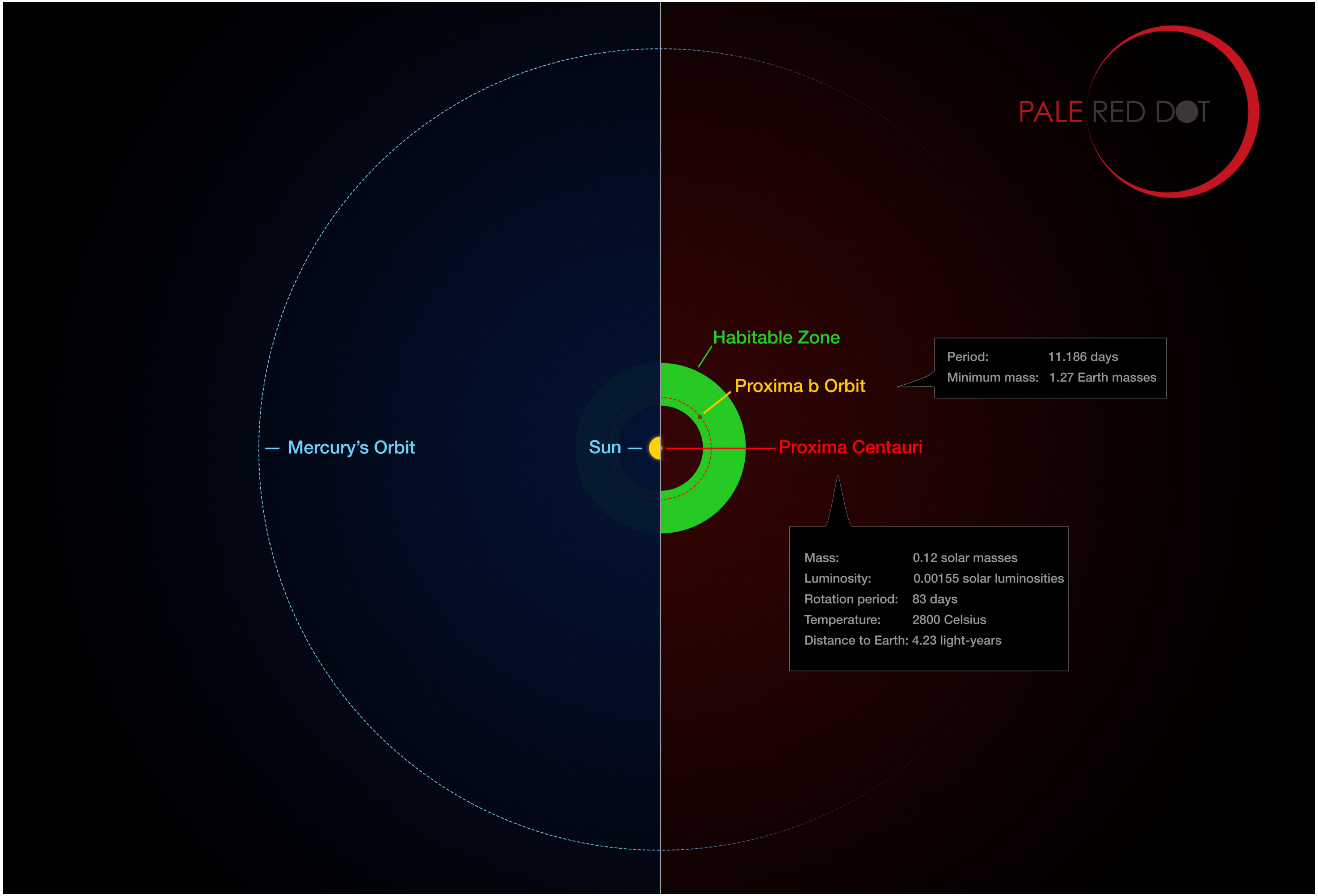
1. Proxima Cen b: status
2. Possible spectral signatures
3. Prospects for direct detection

Proxima Cen b: discovery (1/2)

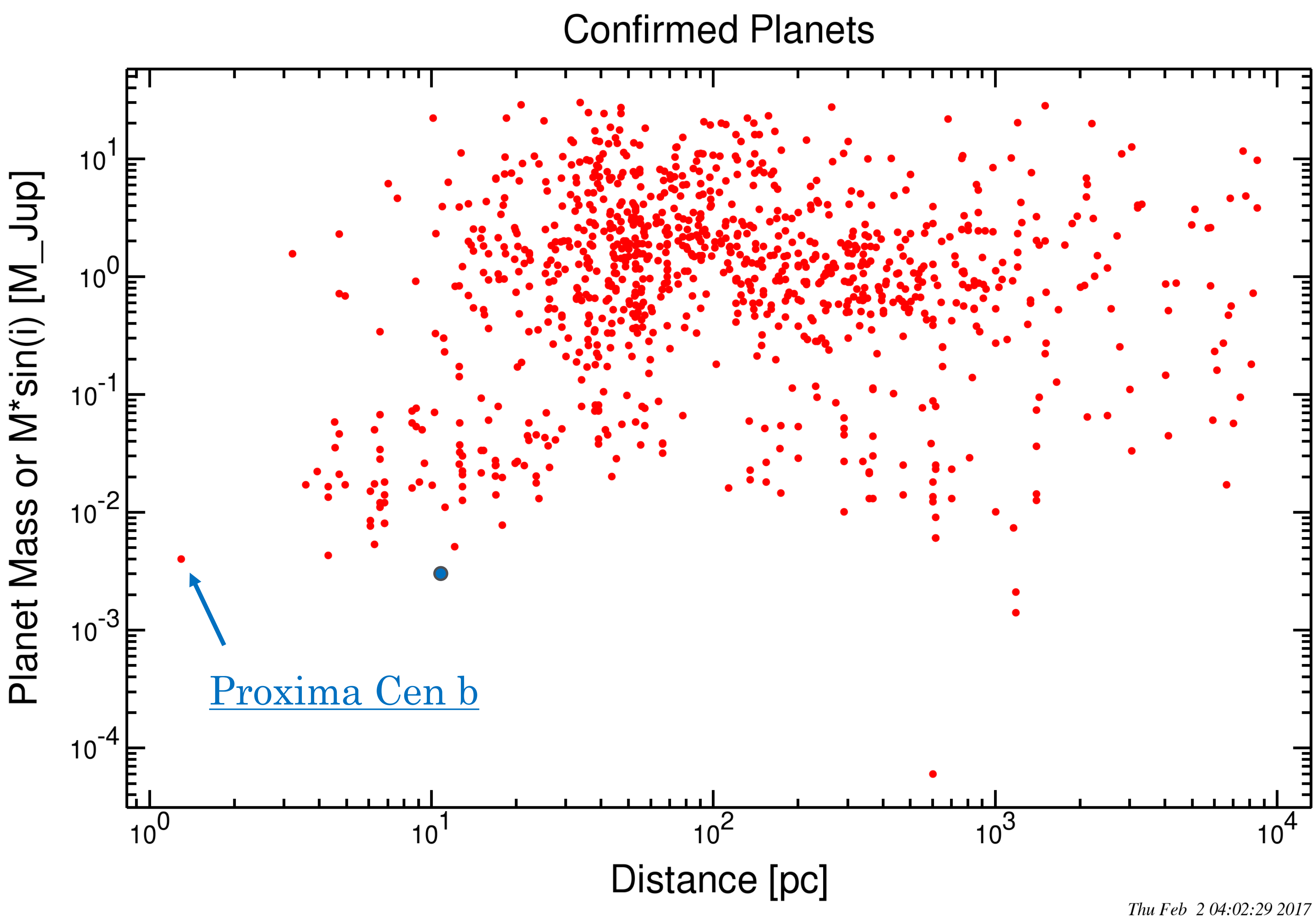
- Proxima Cen: M6V, 1.3 pc (4.2 al)
- Detection of a Doppler signal at 11.2 days (Anglada-Escudé *et al.* *Nature* **536,** 437–440, 2016).



Proxima Cen b: discovery (2/2)

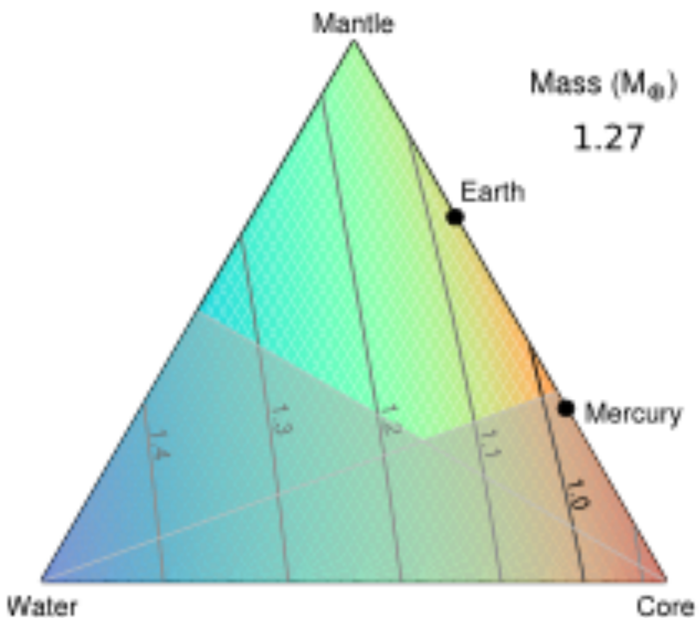


Nearby HZ rocky exoplanets?

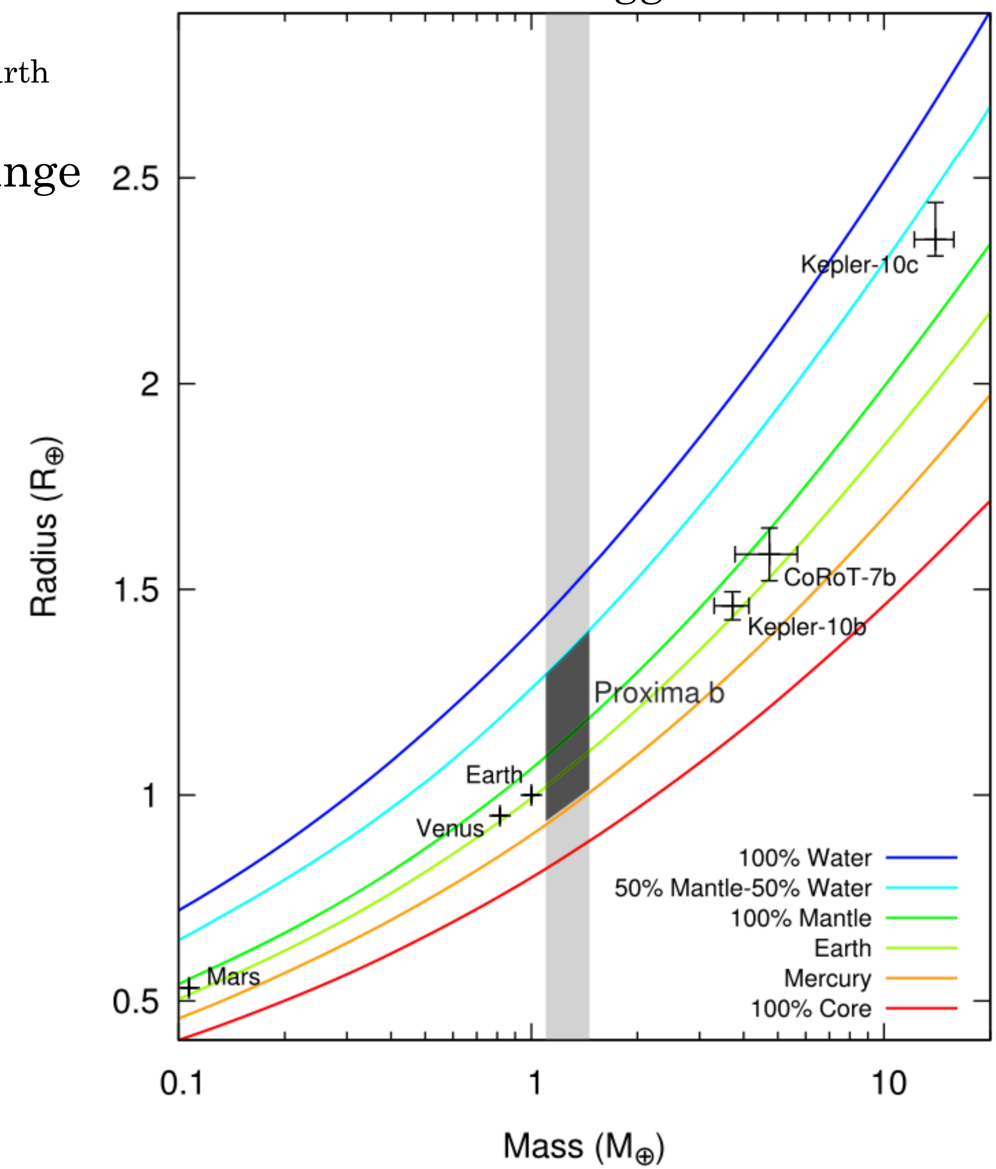


Internal structure

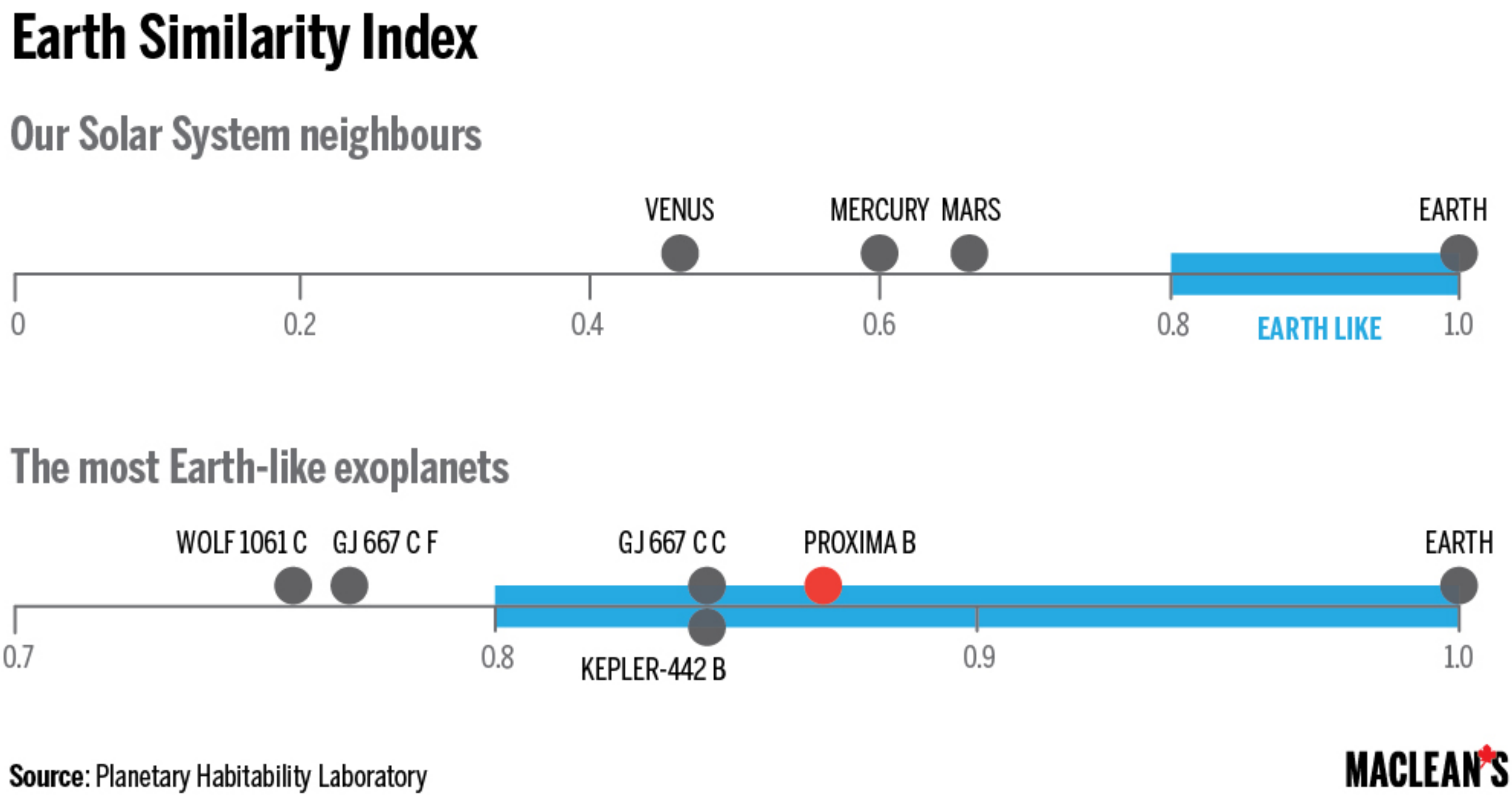
- Min. mass: 1.10 – 1.46 M_{Earth}
- Radius ~0.94–1.40 R_{Earth} range (if solid)



Brugger et al. 2016



Earth similarity index



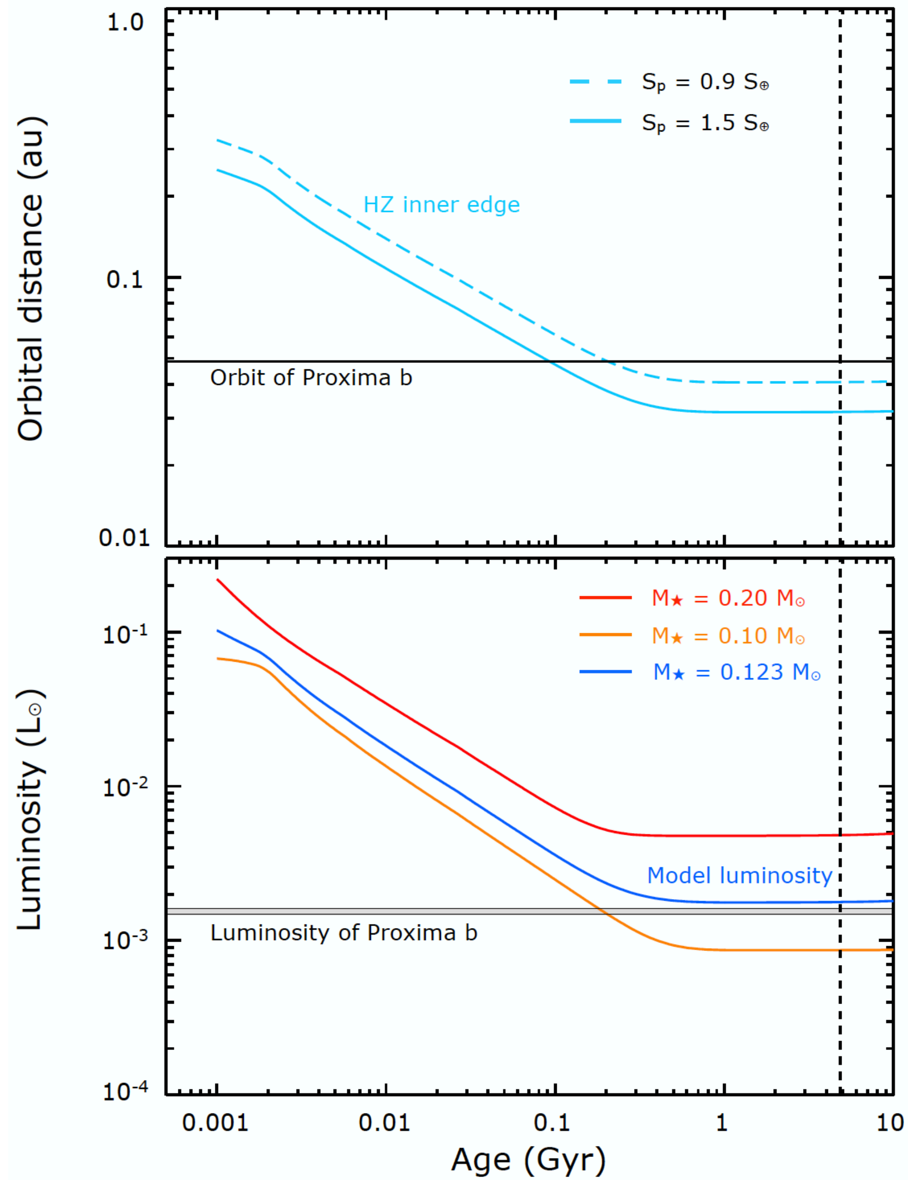
Proxima Cen b: habitability (1/5)

- Receive 30 times more EUV and 250 more X-rays than Earth
- Proxima Cen: 3050K => 0.65 to 0.7 S_{Earth} at 0.05 AU (HZ between 0.9 to 1.5 S_{Earth} and 0.2 S_E, Kopparapu et al. 2016)
- Viable habitable planet: likely lost less than Earth's ocean worth of hydrogen before reaching the HZ (100 to 200 Myr after formation, Ribas et al. 2016)

Proxima Cen b: habitability (2/5)

During the first few million years after the protoplanetary disk dispersion the planet is too hot for surface liquid water to exist; and (2) After the first few million years the planet enters the HZ. During these two phases Proxima b experiences atmospheric loss.

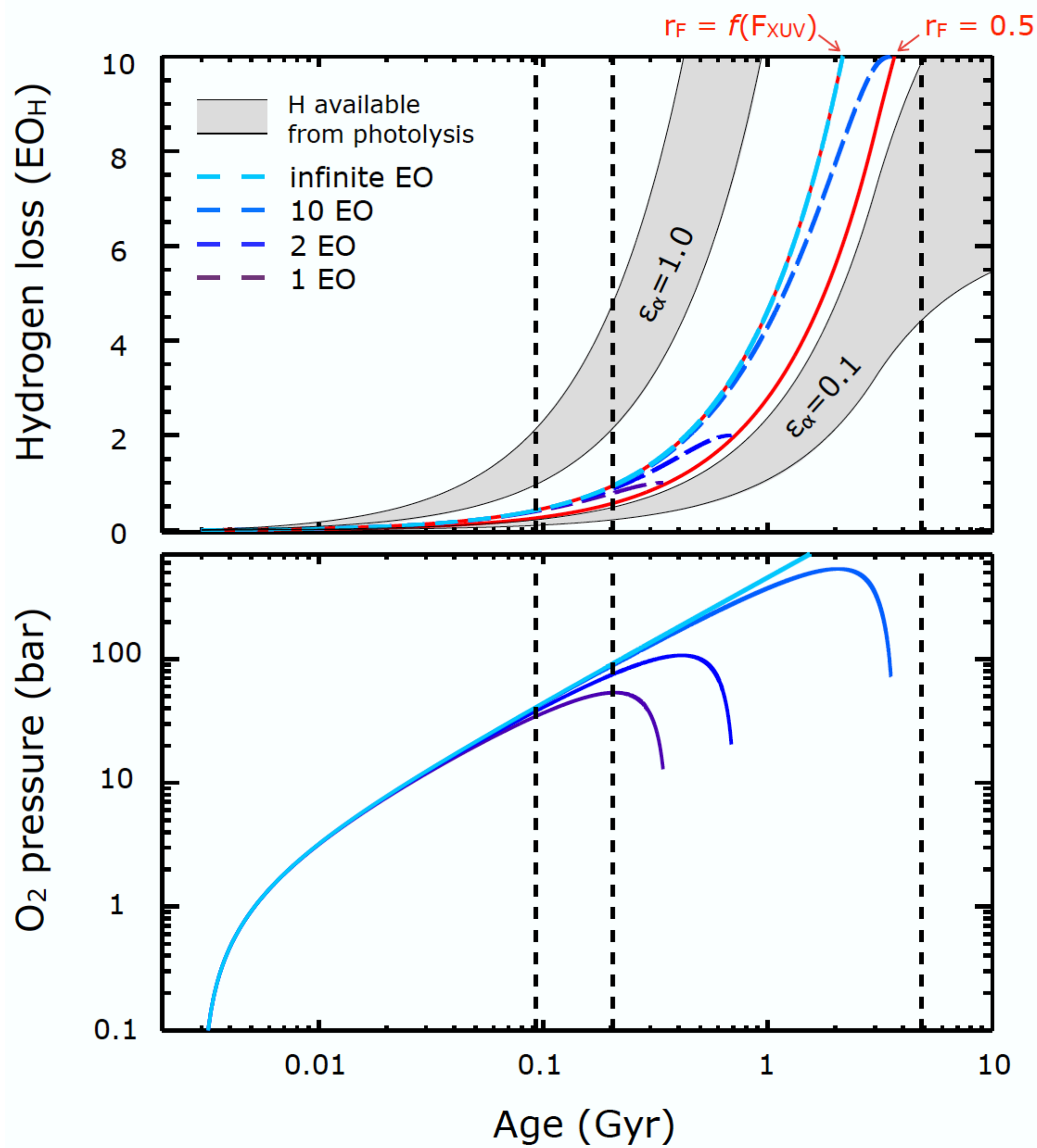
Ribas et al. 2016



Proxima Cen b: habitability (3/5)

Hydrogen loss

Oxygen pressure

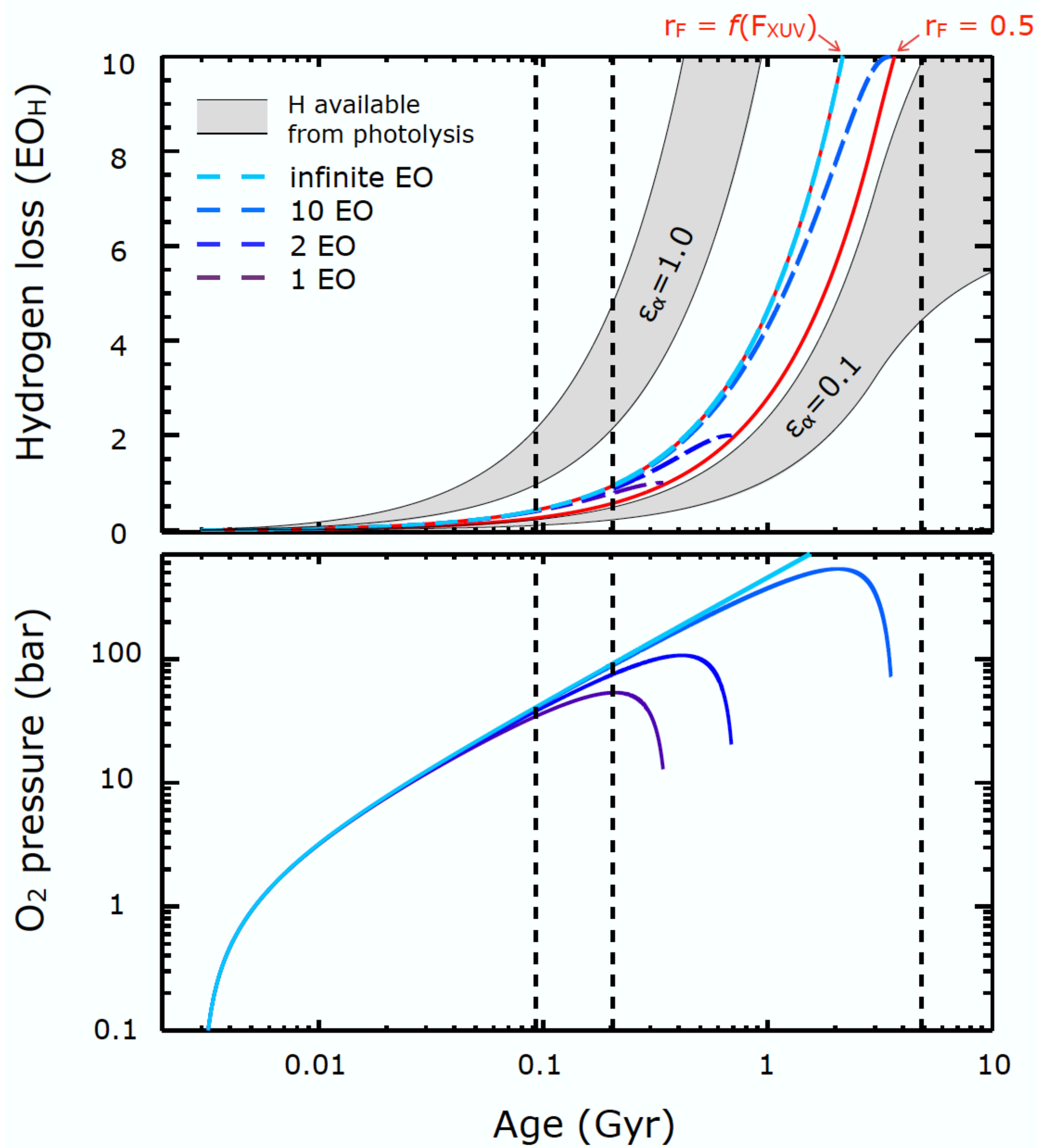


Proxima Cen b: habitability (4/5)

Two astrobiological consequences:

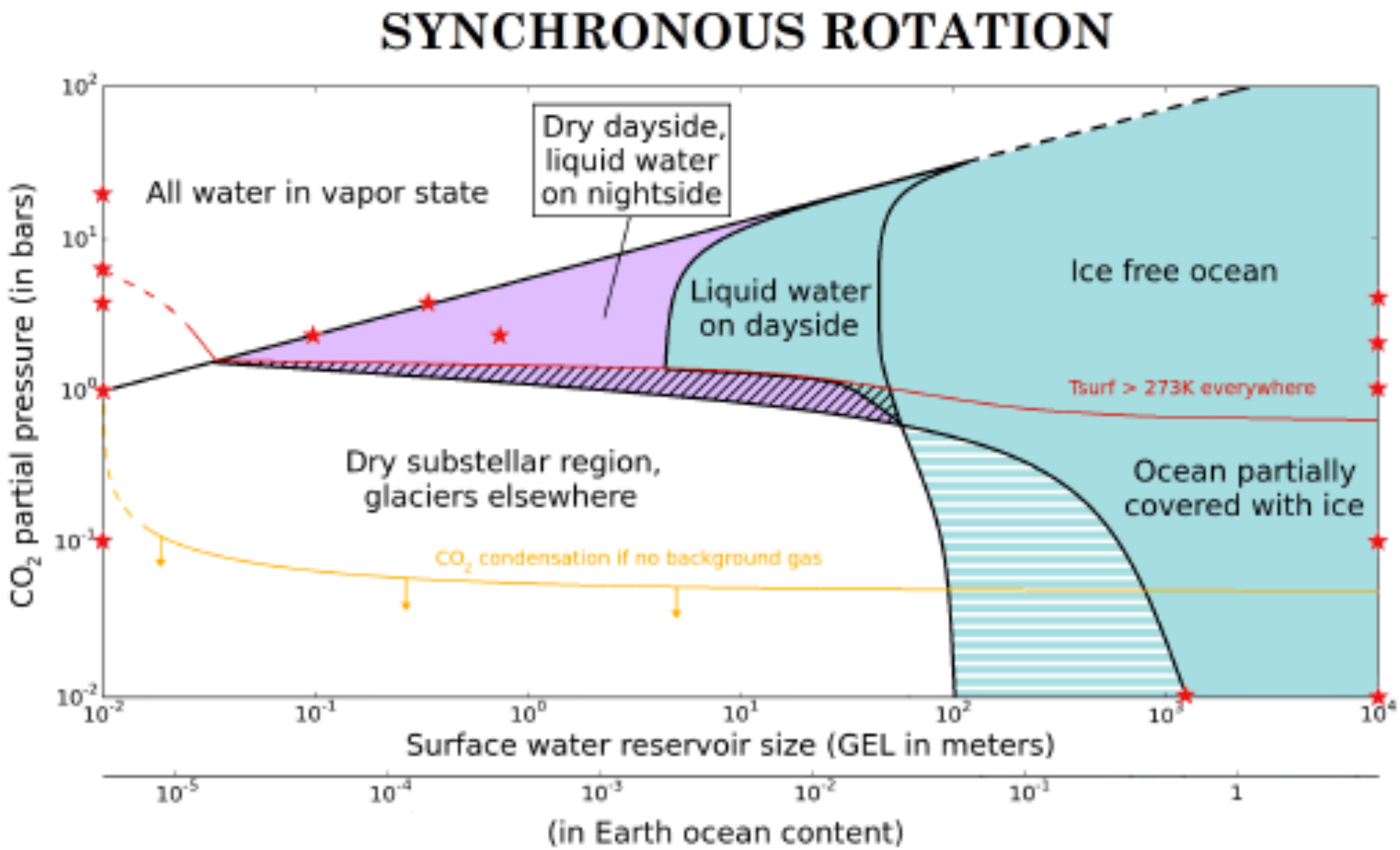
(1) the atmosphere, surface, ocean, and crust could have been strongly oxidized at the time the planet entered the HZ, which could prevent prebiotic chemical processes important for the origin of life.

(2) A search for biosignatures must account for a possible abiotic build-up of O_2 and the consequent formation of an ozone layer



Proxima Cen b: habitability (5/5)

- Broad range of atmospheric pressures and compositions allows habitability (3D Global Climate Model, Turbet et al. 2016):



Modelling tools

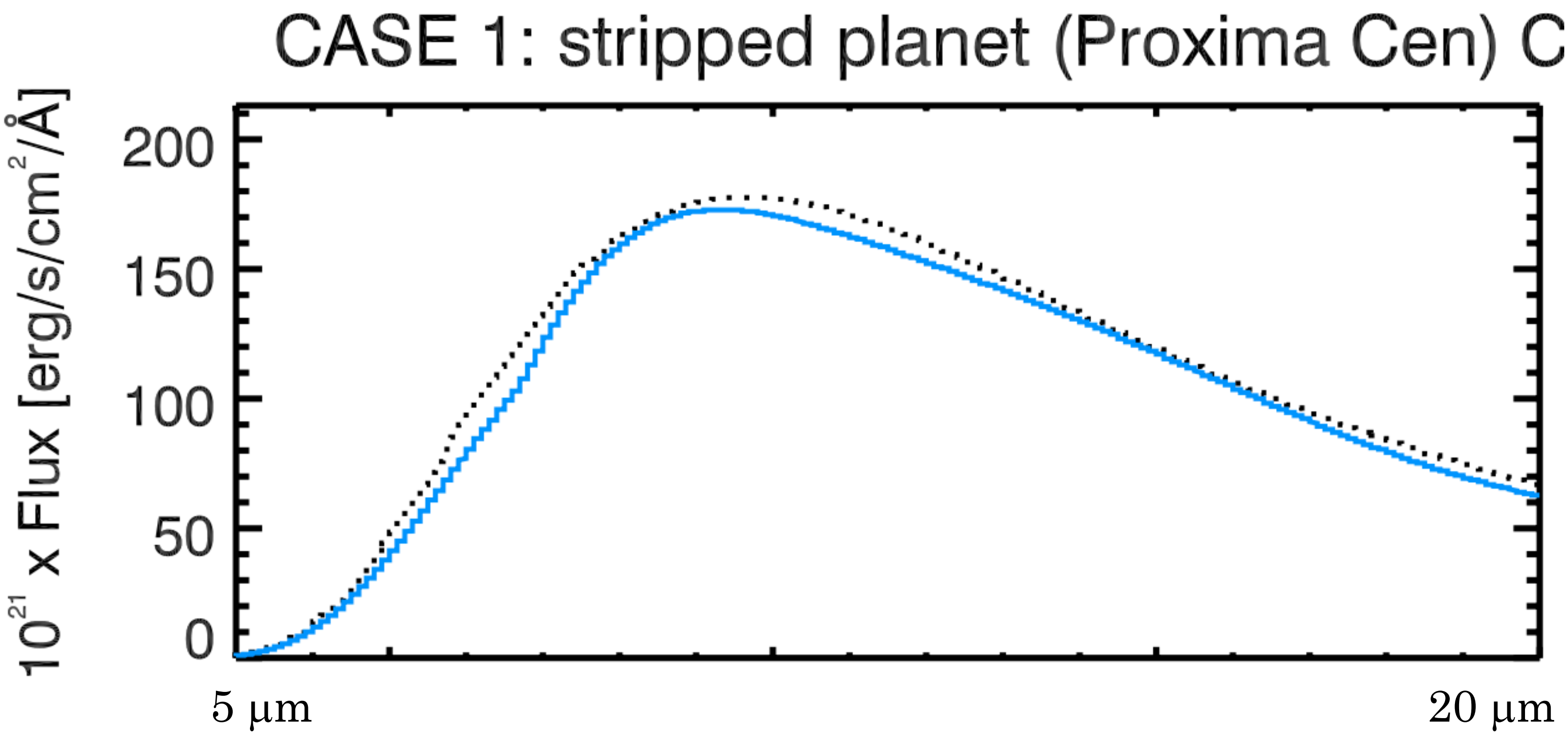
- Simulated mid-infrared spectra of planets with various atmospheric properties computed by coupled climate chemistry models:

    1. *Potential bio-signatures in super-Earth atmospheres. I. Spectral appearance of super-Earths around M dwarfs* (Rauer et al. 2011).

    2. *High stellar FUV/NUV ratio and oxygen contents in the atmospheres of potentially habitable planets* (Tian et al. 2014).

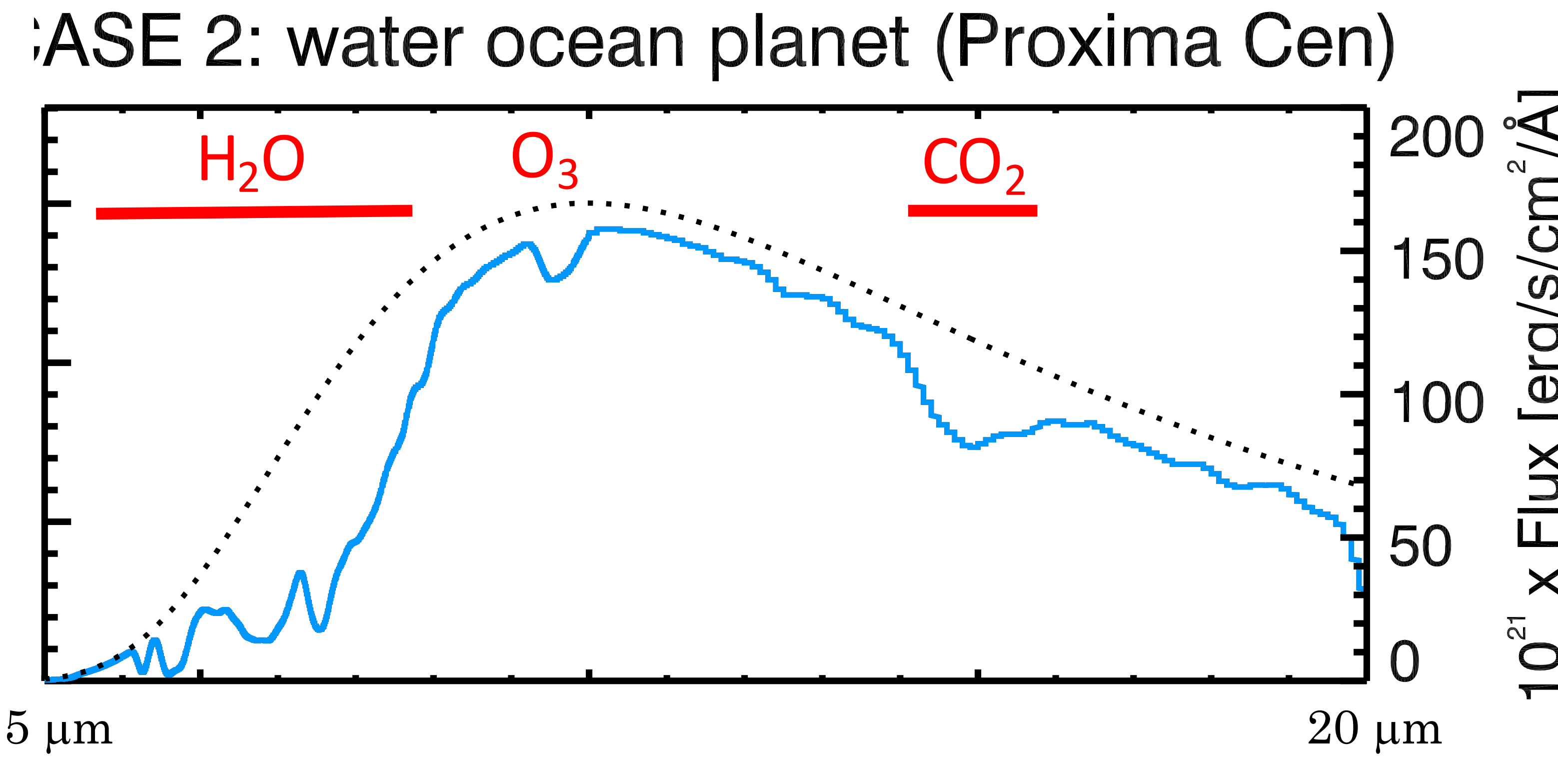
Possible spectral signatures (2/5)

Case 1: a rocky planet ($M=4.0M_E$, $R=1.5R_E$) in the HZ. The stellar insolation is 65% of that of Earth and T_s=240 K. No atmosphere (stripped planet), using Apollo Moon sample 15071 for IR emissivity.



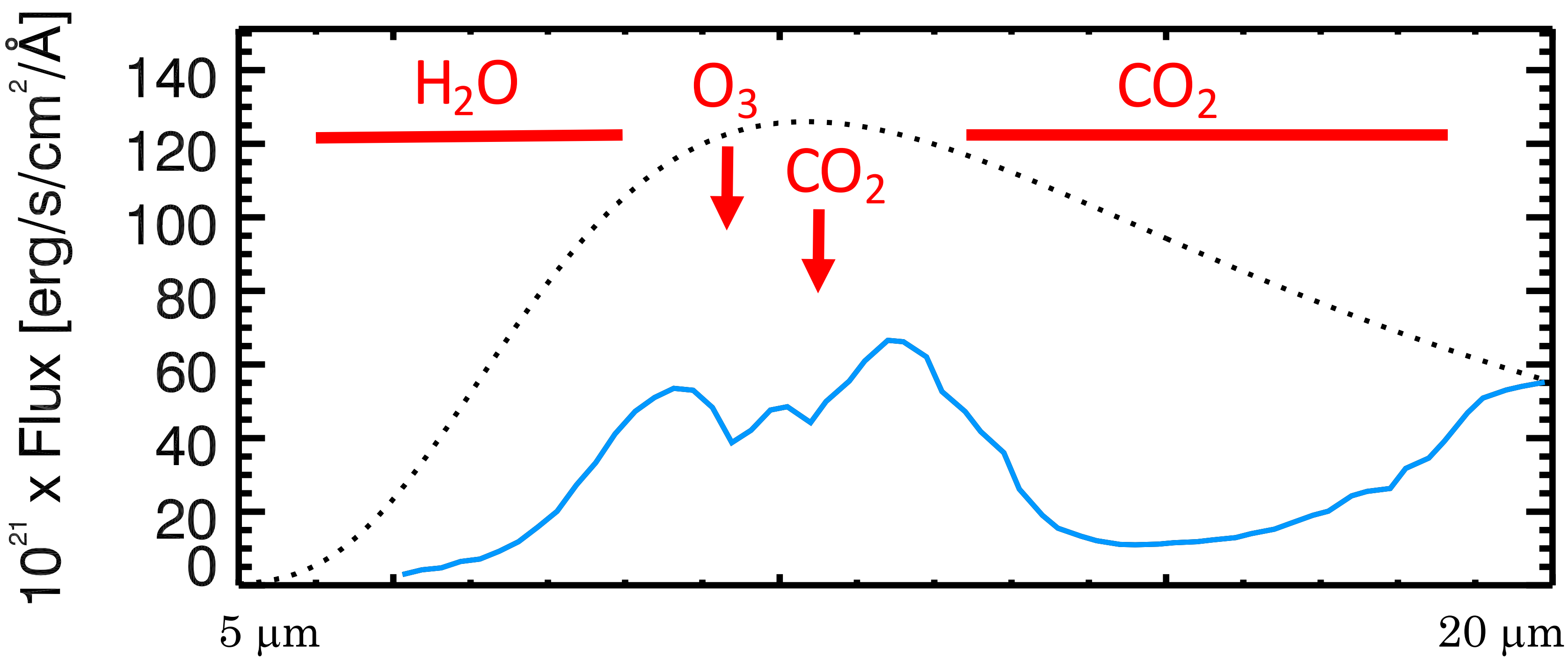
Possible spectral signatures (3/5)

Case 2: Water-ocean planet ($M=2.0M_E$, $R=1.5R_E$) in the HZ ($S=1.05S_e$) with arbitrary O_2 input that could be due e.g. to strong H escape. Atmosphere: $P_{N2}=1$ bar, $P_{O2}=200$mbar, 1 ppm P_{CO2}, saturated H_2O vapour, $T_s = 290$ K, calculated O_3 with coupled chemistry.



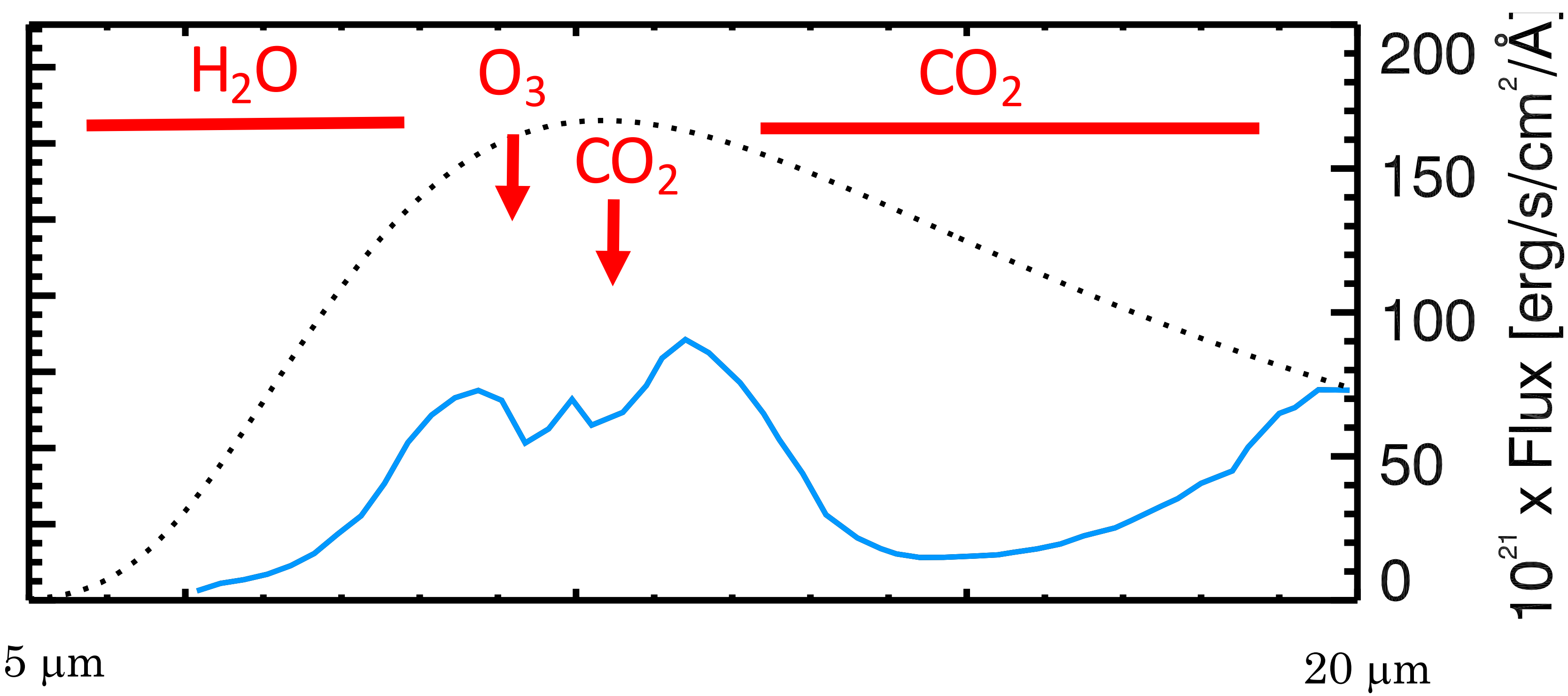
Possible spectral signatures (4/5)

Case 3: a large **Earth-analog** planet ($M=4.0M_E$, $R=1.5R_E$) in the HZ ($S=0.65S_e$), but with a strong CO_2 Greenhouse effect bringing T_s to 280 K. Atmosphere: P_{CO2}=300mbar, P_{N2}=500mbar, P_{O2}=200mbar (possibly biotic), H_2O from vapor pressure, calculated O_3 with coupled chemistry.



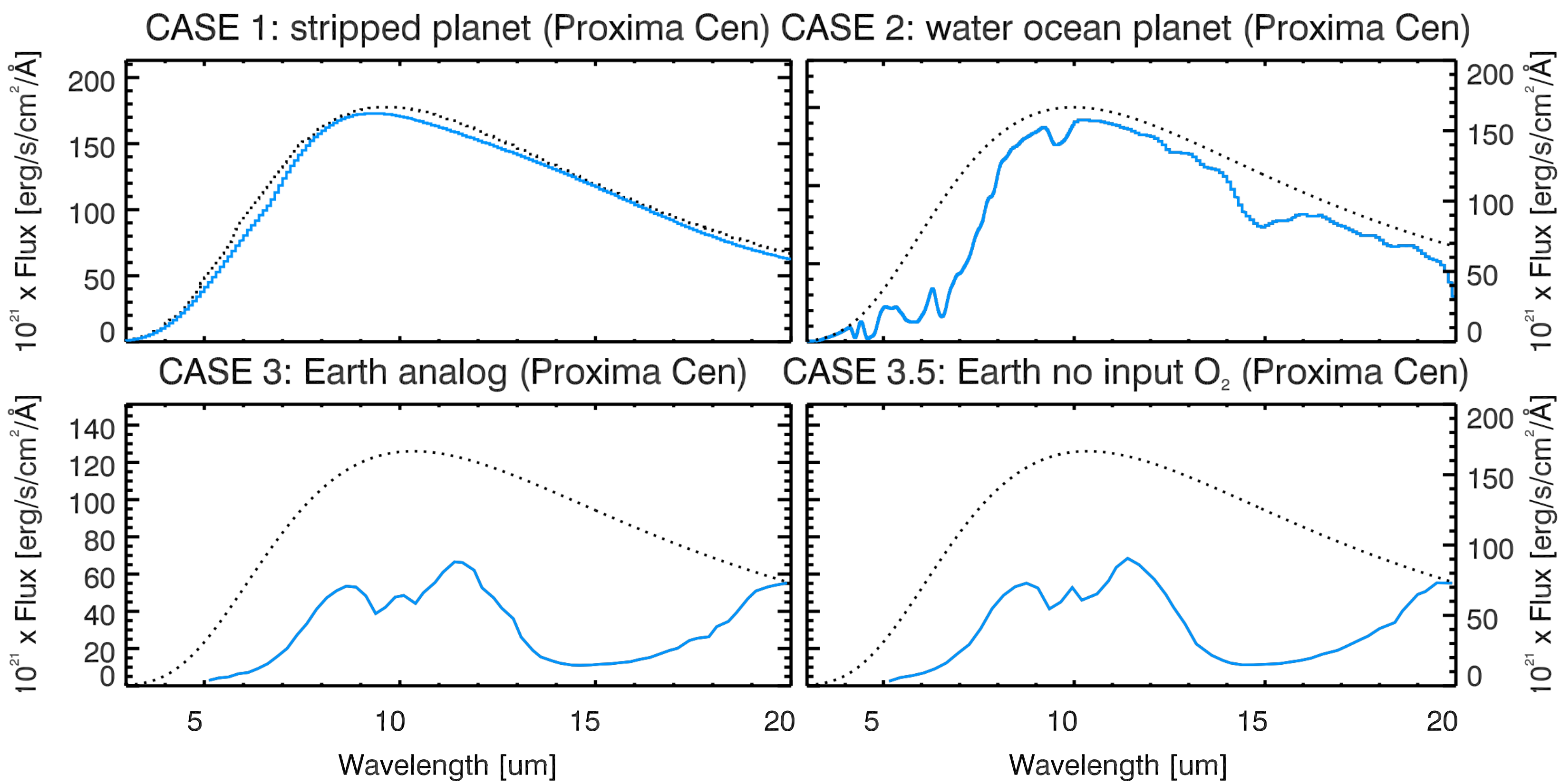
Possible spectral signatures (5/5)

<u>Case 3.5</u>: **a rocky planet** in the HZ ($S=0.65S_e$), with P_{CO_2}=300mbar bringing T_s to 280 K, H_2O from vapour pressure, **no O_2 input**, calculated O_2 and O_3 from coupled chemistry induced by the UV of the M star.



Detecting biosignatures

- Three atmospheric scenarios could be clearly distinguished
- Case 3 and case 3.5 (abiotic) yield to the same spectrum!
- Triple signature (O_3, CO_2, H_2O) can be a false positive!

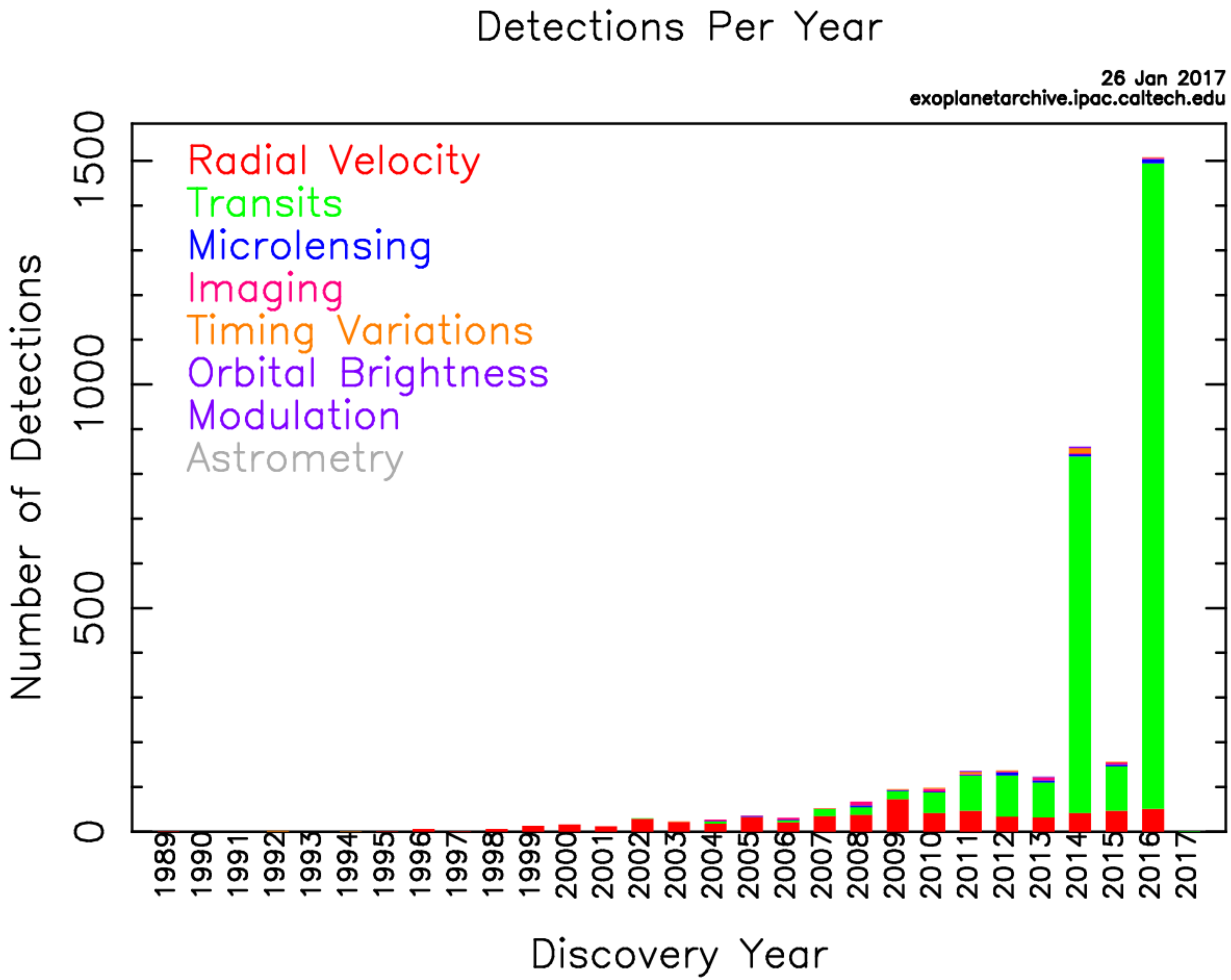


Summary

- Models show that Proxima Cen b can be habitable
- Atmospheric composition of Proxima Cen b can be constrained by remote sensing
- Biosignatures could be detected but how to rule out false positives? (abiotic build-up of O_2!)

Backup slides

Exoplanet detection rate



Exoplanet zoo: fact sheets

- A Sun-like star has a $\approx$10% chance of having a giant planet with a period shorter than a few years and a $\approx$50% chance of having a compact system of smaller planets with periods shorter than a year.
- The giant planets have a broad eccentricity distribution, ranging from around 0 to 0.9 with a mean of $\approx$0.2. The smaller planets have lower eccentricities ($\lesssim$0.1), particularly those in multiplanet systems.
- In compact systems of small planets, the orbits are typically aligned to within a few degrees. Giant planets may occasionally have larger mutual inclinations.
- The ratios of orbital periods are often in the range of 2–3 but are occasionally closer to unity, flirting with instability.
- Giant planets are more often found in mean-motion resonances than smaller planets, which show only a slight preference for being near resonances.
- The stellar rotation axis can be grossly misaligned with the planetary orbital axis, particularly for close-in giant planets orbiting relatively hot stars ($T_{\rm eff} \gtrsim 6{,}100$ K).
- Close binary stars host circumbinary giant planets just outside of the zone of instability, with an occurrence rate comparable with that of giant planets at similar orbital distances around single stars.

Next step: atmospheric studies (1/2)

VISIBLE (and UV)

- Presence of clouds (or haze layers) via Rayleigh-scattering;
- Atmosphere evaporation and wind via Lyman α line (0.121 um);
- Albedo and day-night temperatures via light curves;
- Atoms and molecules:
  - Na, K.
  - In wind: H, H_2, C II, Si III

INFRARED

- Presence of water via diagnostic water features at 1.1 and 1.6um;
- Presence of clouds (or haze layers) via absence of 1.4um water feature;
- Temperature map and non equilibrium chemistry via light curves (2.6, 4.5, 8, and 24um);
- Weather features (wind) via Doppler measurements;
- Thick clouds from direct imaging;
- Atoms and molecules: H_2O, CO

Lessons learned

1. Cloud-free models usually don't work. Spectral masking and hazes seem ubiquitous.
2. Planetary atmosphere are diverse!
3. Only high spectral resolution led to robust detections;

4. <u>Burrows, Nature 513, 2014</u>: "*Good spectra are the essential requirements for unambiguous detection and identification of molecules in exoplanet atmospheres, and these have been rare.* ***Determining abundances is also difficult, because to do so requires not only good spectra, but also reliable models.*** *Errors in abundance retrievals of more than an order of magnitude are likely, and this fact has limited the discussion of abundances in this paper.*"

5. <u>Pont et al., MNRAS 432, 2013</u>: "*Beware of incomplete spectra. It is clear that fitting a suite of synthetic spectra to a restricted subset of the data considered in this paper would lead to very misleading conclusions. Each time more extended data has been forthcoming, it has flatly defeated the expectation. This has implications for the design of instruments and space missions for the study of exoplanet atmospheres. It would tilt the balance* ***towards an extended spectral coverage, not too narrowly focused on expected features and model predictions****, and keeping the possible presence of condensates in mind when calculating detection capabilities. This may also extend to the search for biomarkers in habitable exoplanets.*"

What do we need to know?

STEP 1

- Better understand the origin, evolution, and diversity of planetary atmospheres (=> observe a lot of planets);

- Confront concepts of habitability and habitable zones to observations (=> measure temperatures, correlate with spectral type of the parent star, degree of stellar activity, processes that influence atmospheric escape, the temperature/pressure structure of the atmosphere of the planet, the circulation and heat transfer of the atmosphere of the planet, the atmospheric chemistry and photochemistry, plate tectonics, outgassing of atmospheric species);

- Identify important molecules (=> high-spectral resolution);

STEP 2

- Identify interesting candidates for careful observations and search for atmospheric properties related to biological activity;

List of papers with atmosphere detection

UPPER ATMOSPHERES (TRANSIT)

1. Charbonneau et al., ApJ 568, 2002: sodium in planetary atmosphere lower than expected for a cloud-free atmosphere (HD 209458, Na, 0.59um, transit);
2. Pont et al., MNRAS 432, 2013: haze of condensate grains (HD 189733b, Na and K, UV to infrared, transit);
3. Pont et al., MNRAS 385, 2008: high-altitude haze (HD 189733b, 0.5 to 1.0um, transit);
4. Sing et al., A&A 527, 2013: alkali metals (XO-2b, K, 0.6 to 0.8um, transit);
5. Deming et al., ApJ 774, 2013: water feature at 1.4um but no corresponding 1.15um => haze (HD209458 and XO-1b, transit);
6. Kreidberg et al., Nature 505, 2014: clouds in the atmosphere of a Super-Earth (GJ1214b, 1.1-1.6um, transit);
7. Swain: Methane and water
8. Gibson: **No conclusive evidence for molecular features**

WIND (TRANSIT)

1. Vidal-Majar et al., Nature 422, 2003: escaping atmopshere (HD209458, Lyman a at 0.121um, transit);
2. Lecavalier Des Etangs et al, A&A 514, 2010: escaping atmopshere (HD189733, Lyman alpha at 0.121um, transit);
3. Fossati et al, ApJ 714, 2010: escaping atmopshere (WASP-12b, MgII, 0.2 to 0.3um, transit);
4. Kulow et al, ApJ 786, 2014: escaping atmopshere (GJ436b, Lyman alpha at 0.121um, transit);
5. Ehrenreich and Desert. A&A 529, 2011: mass-loss rates (several hot jupiters, Lyman alpha);
6. Linsky et al., ApJ 717, 2010: mass-loss rate (HD 209458, C II, Si III , Lyman alpha);

PHASE LIGHT CURVES AND PLANETS MAPS

1. Esteves et al., ApJ 772, 2013: albedo and day-night temperatures (Kepler field, visible);
2. Knuston et al., Nature 447, 2007: temperature map (HD 189733, Spitzer, 8 um);
3. Knuston et al., ApJ 754, 2012: non-equilibrium chemistry (HD 189733, Spitzer, 3.6 and 4.6um);
4. Crossfield et al., ApJ 723, 2010: ~80 degrees phase offset (ups And b, Spitzer, 24um);

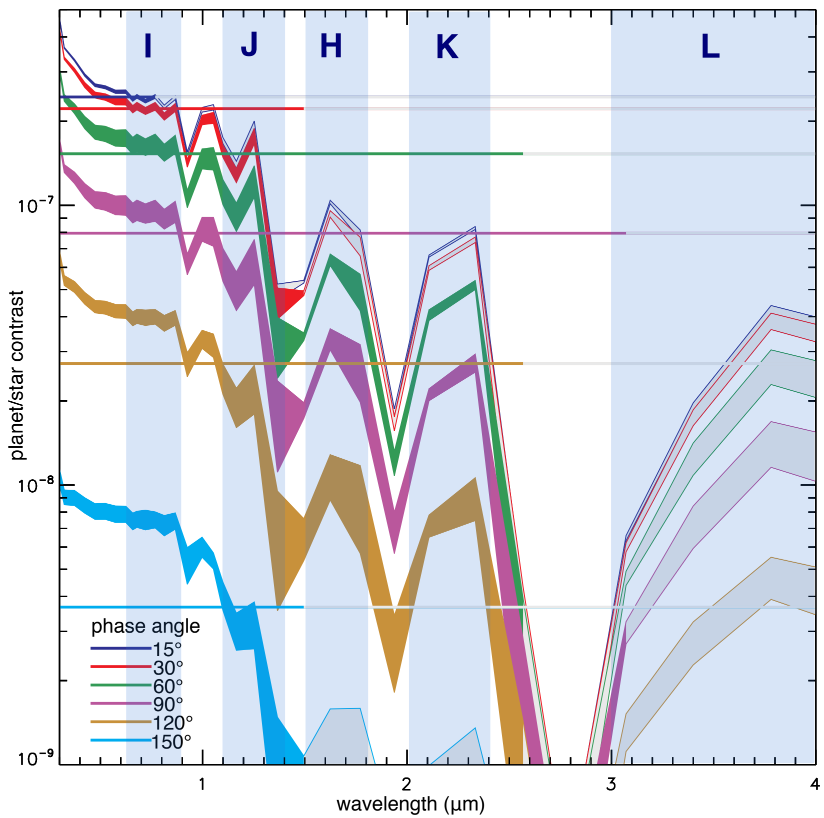
List of papers with atmosphere detection

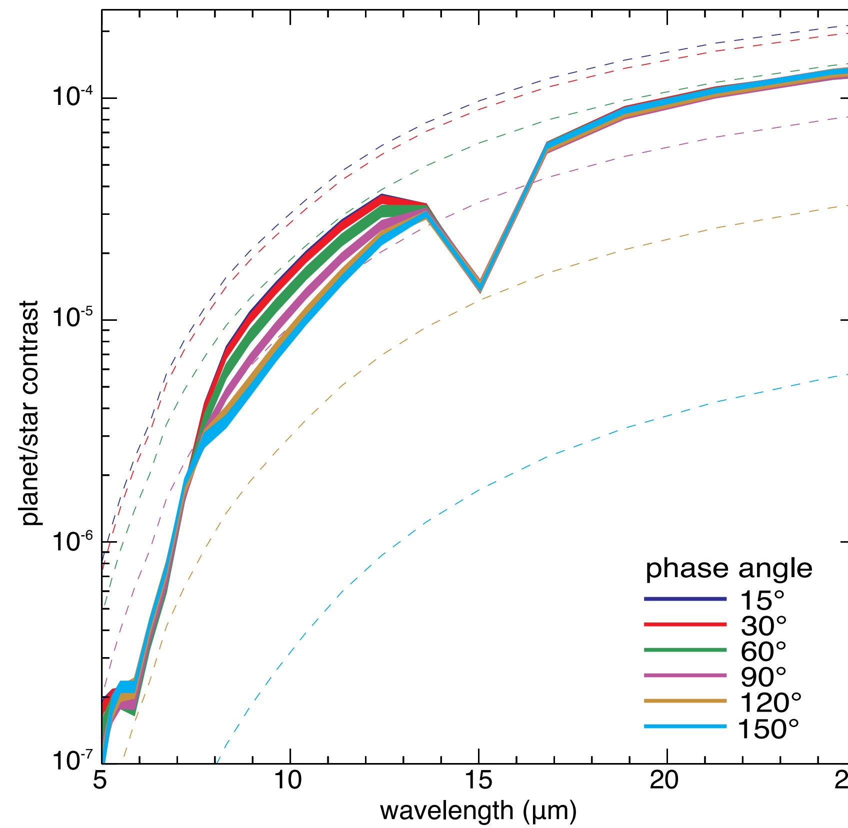
HIGH-SPECTRAL RESOLUTION TECHNIQUES

1. Snellen et al., Nature 465, 2010: high-alitiude wind and CO detection (HD 209468, 2.3um);
2. De Kok et al., A&A 554, 2013: CO detection (HD 189733)
3. Birkby et al., MNRAS 436, 2013: H2O detection (HD 189733, 3.2 um)

Prospects for direct detection

- Contrast favorable in the mid-infrared (only ~10^{-5})
- Reflection and emission spectra for the synchronous case with an Earth-like planet atmosphere (from Turbet et al. 2016):

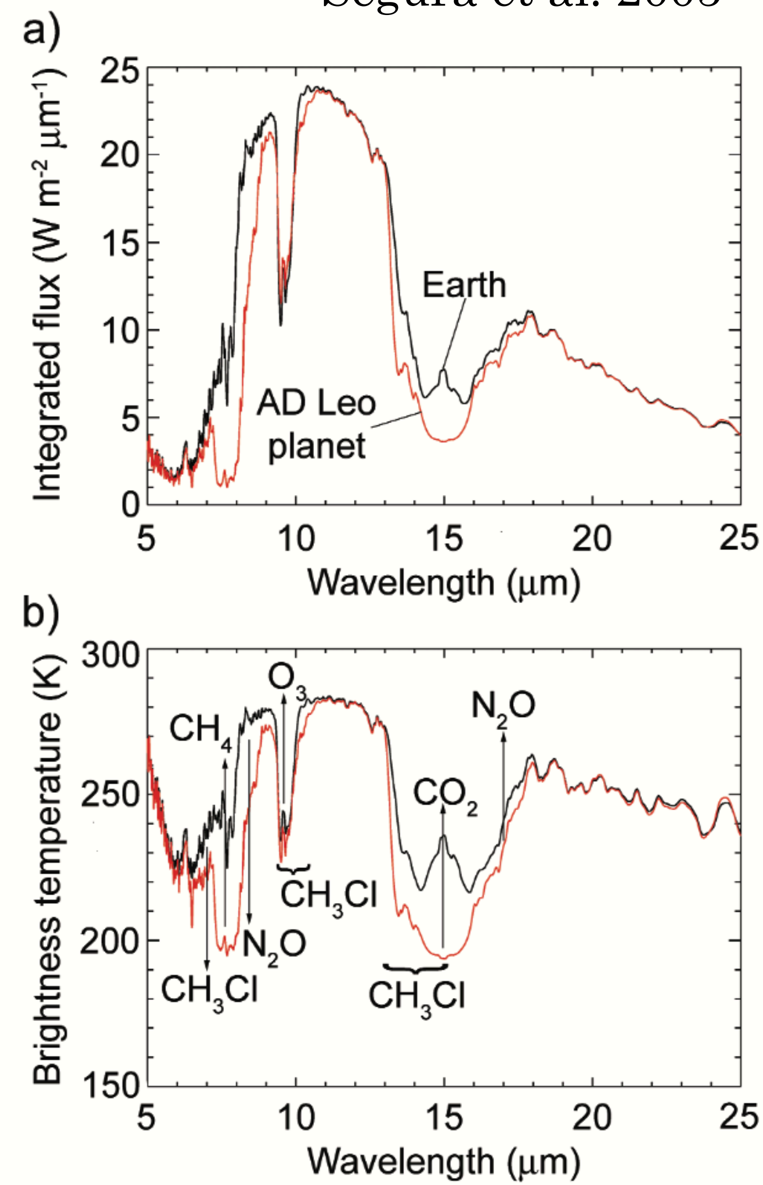




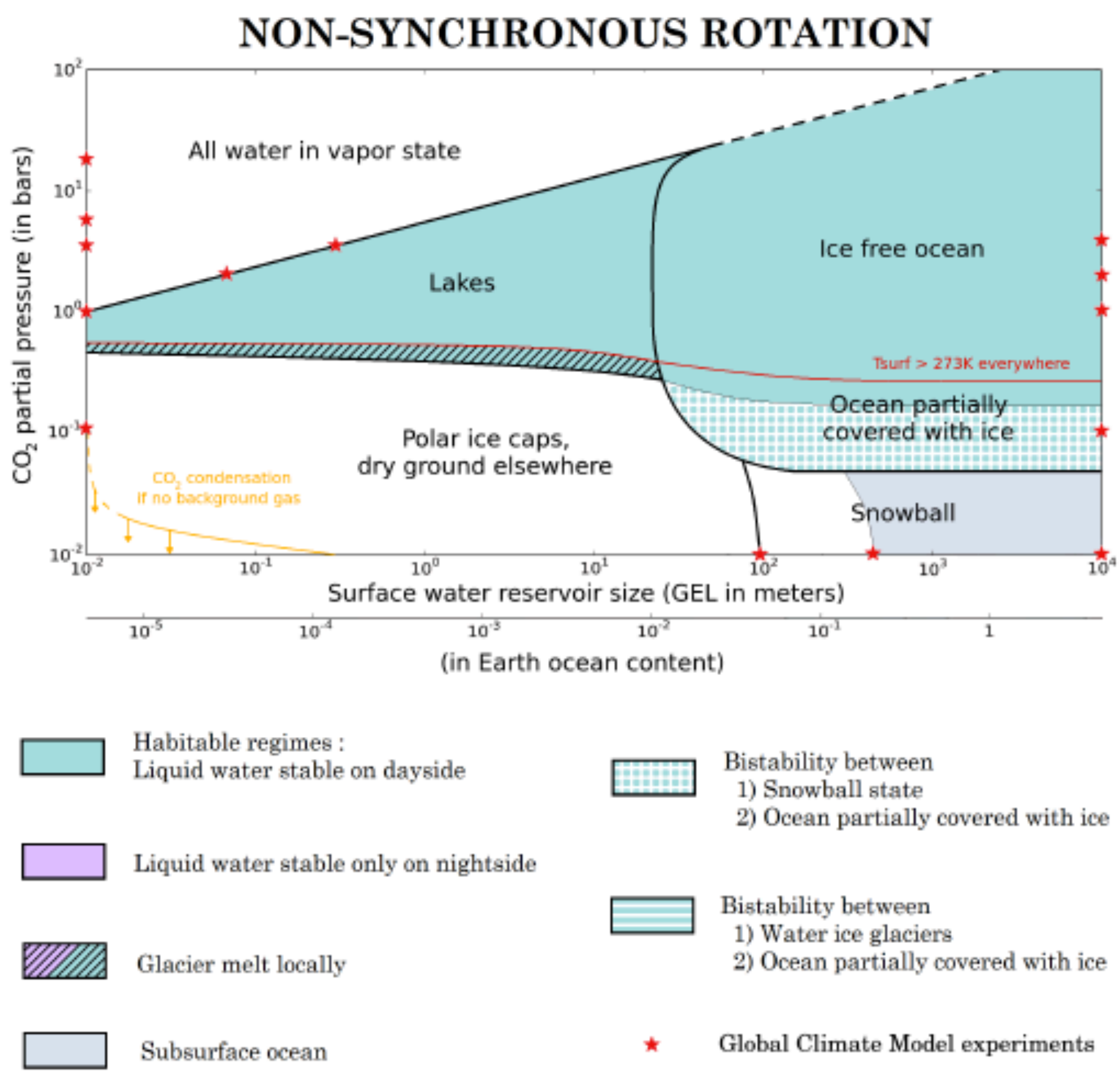
Modelling tools

Segura et al. 2005

The spectral distri- bution of these stars in the ultraviolet generates a different photochemistry on these planets. As a result, the biogenic gases CH_4, N_2O, and CH_3Cl have substantially longer lifetimes and higher mixing ratios than on Earth, making them potentially observable by space-based tele- scopes. On the active M-star planets, an ozone layer similar to Earth's was developed that re- sulted in a spectroscopic signature comparable to the terrestrial one.



Proxima Cen b: habitability (4/4)



The challenge