How to identify exoplanet surfaces: without directly seeing them

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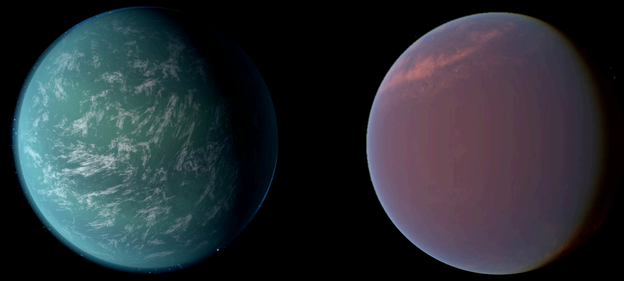
Image credit: ESO/M. Kornmesser

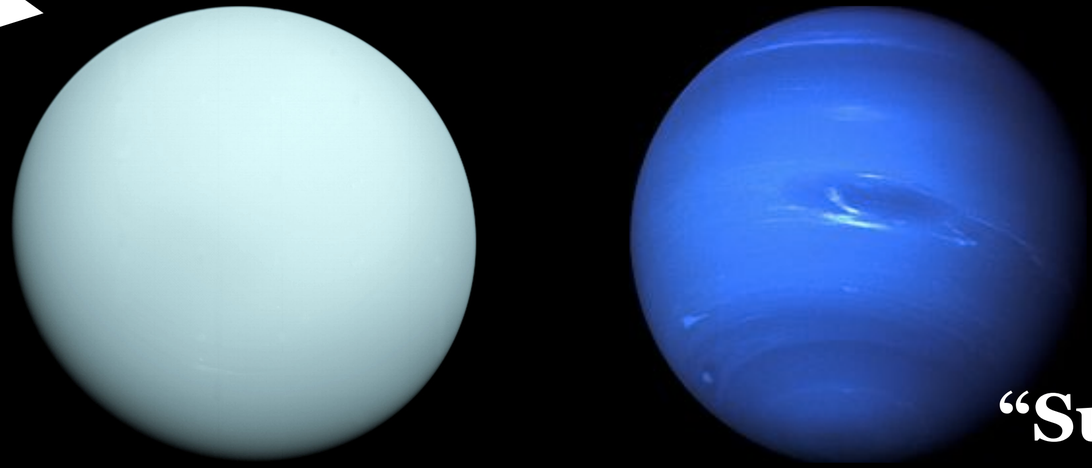
Do exoplanets in between Earth and Neptune sizes have surfaces?

Surface: < 100 bar

Super-Earth?
Mini-Neptune?

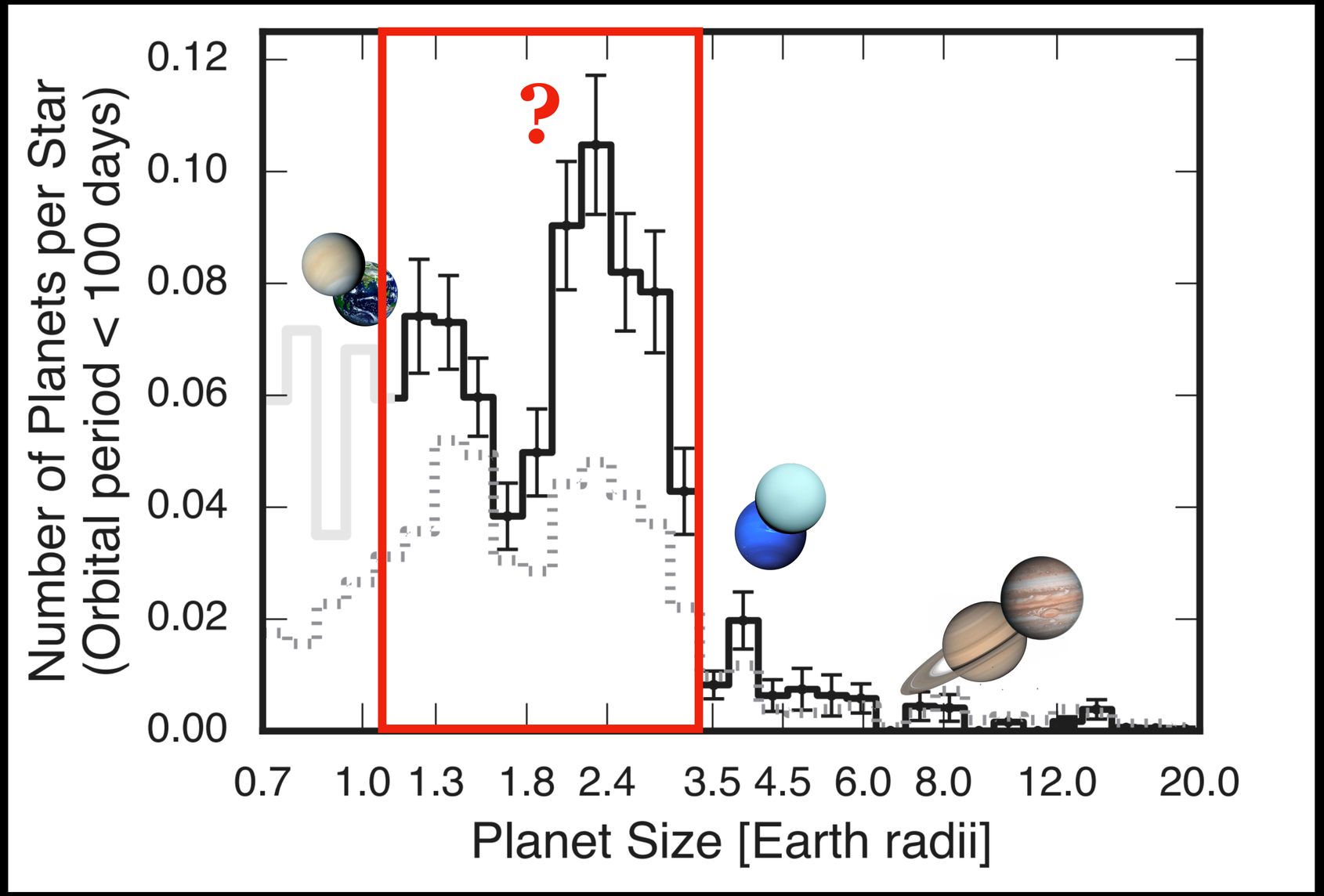


Surface: ???



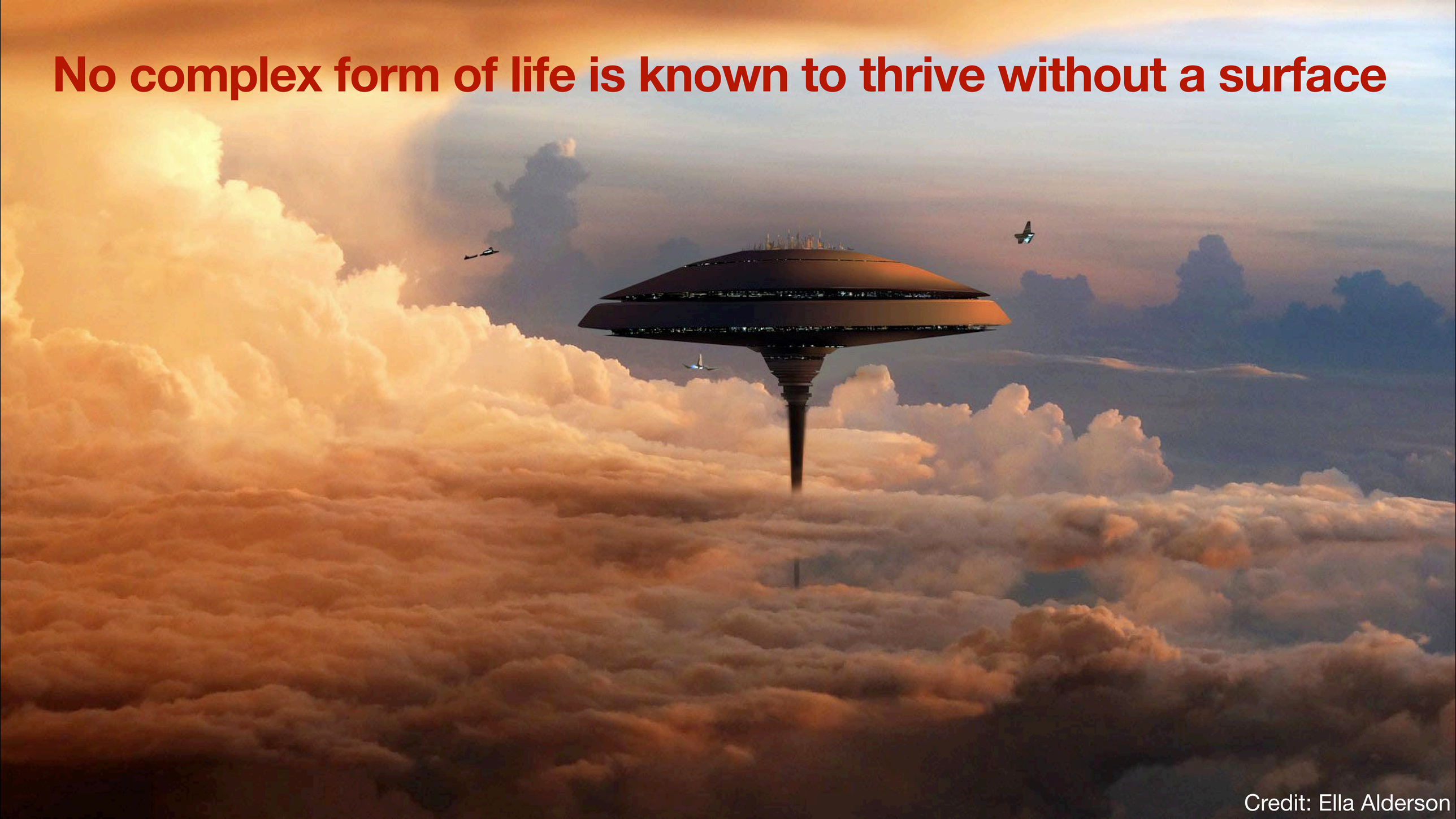
“Surface”: > 1000 bar

Do exoplanets in between Earth and Neptune sizes have surfaces?



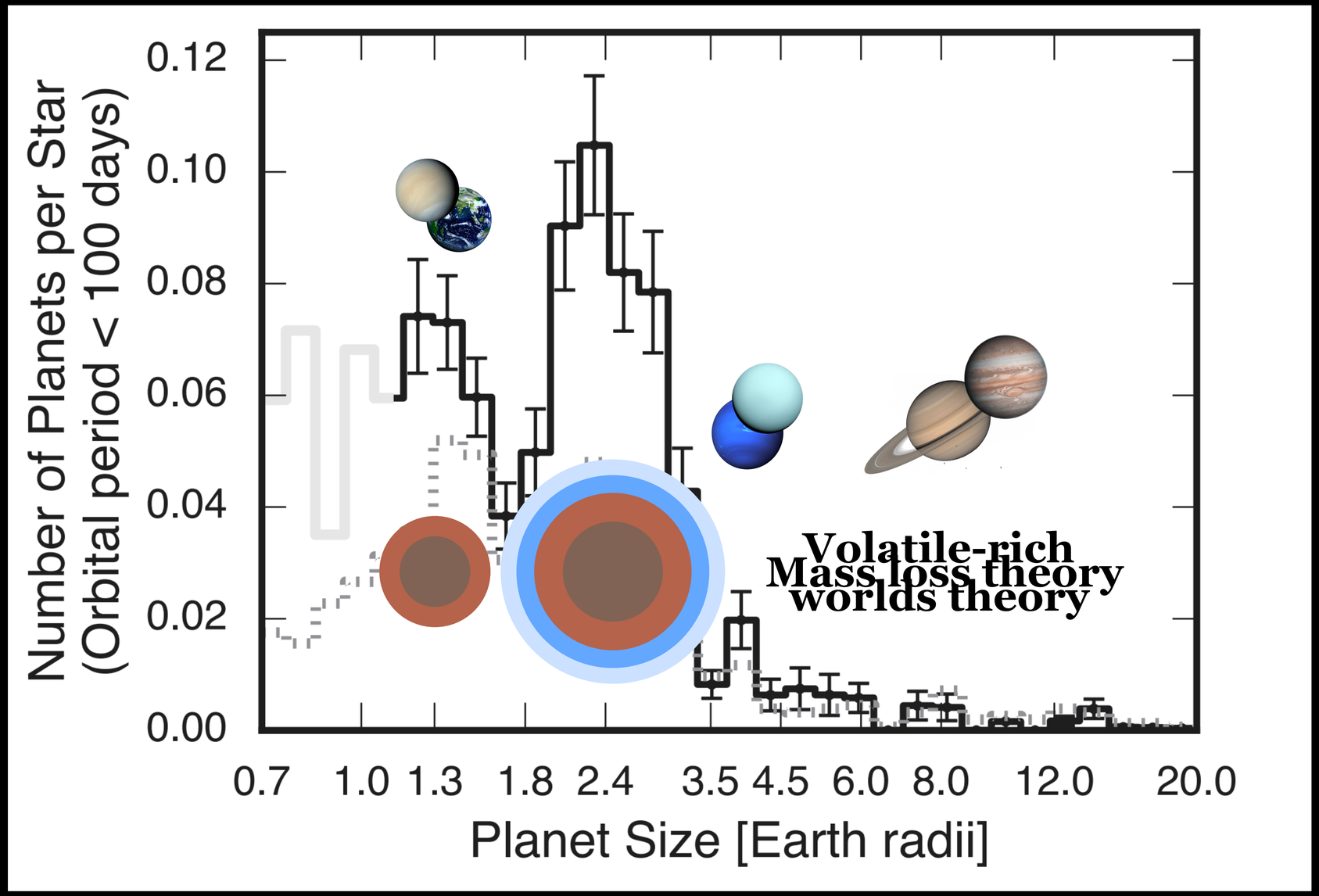
Fulton & Petigura, 2018

No complex form of life is known to thrive without a surface



Credit: Ella Alderson

Knowing the surface locations can tell us more about planet formation



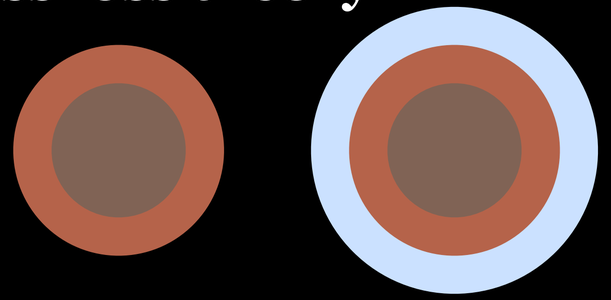
Iron

Silicate

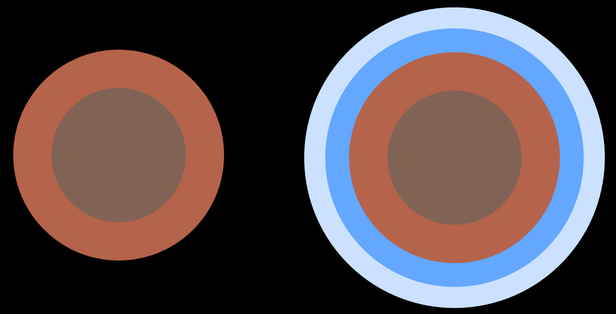
Ice

H/He atmosphere

Mass loss theory

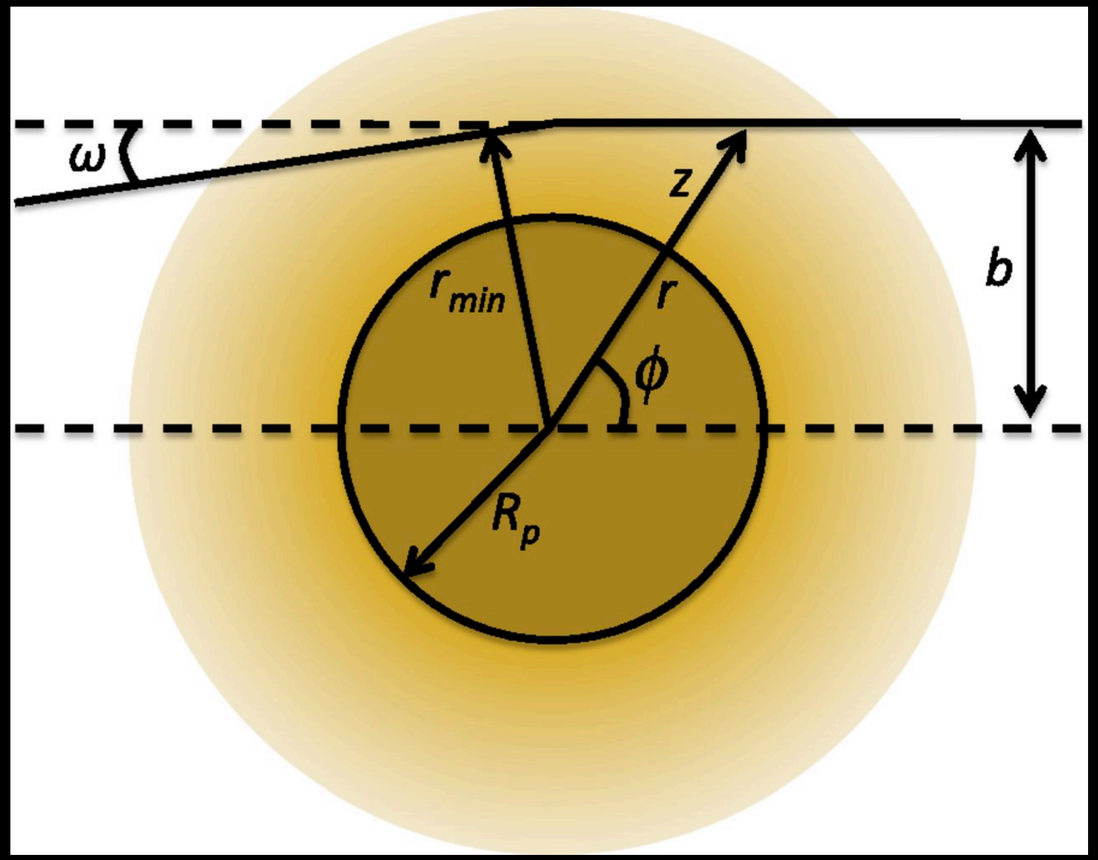


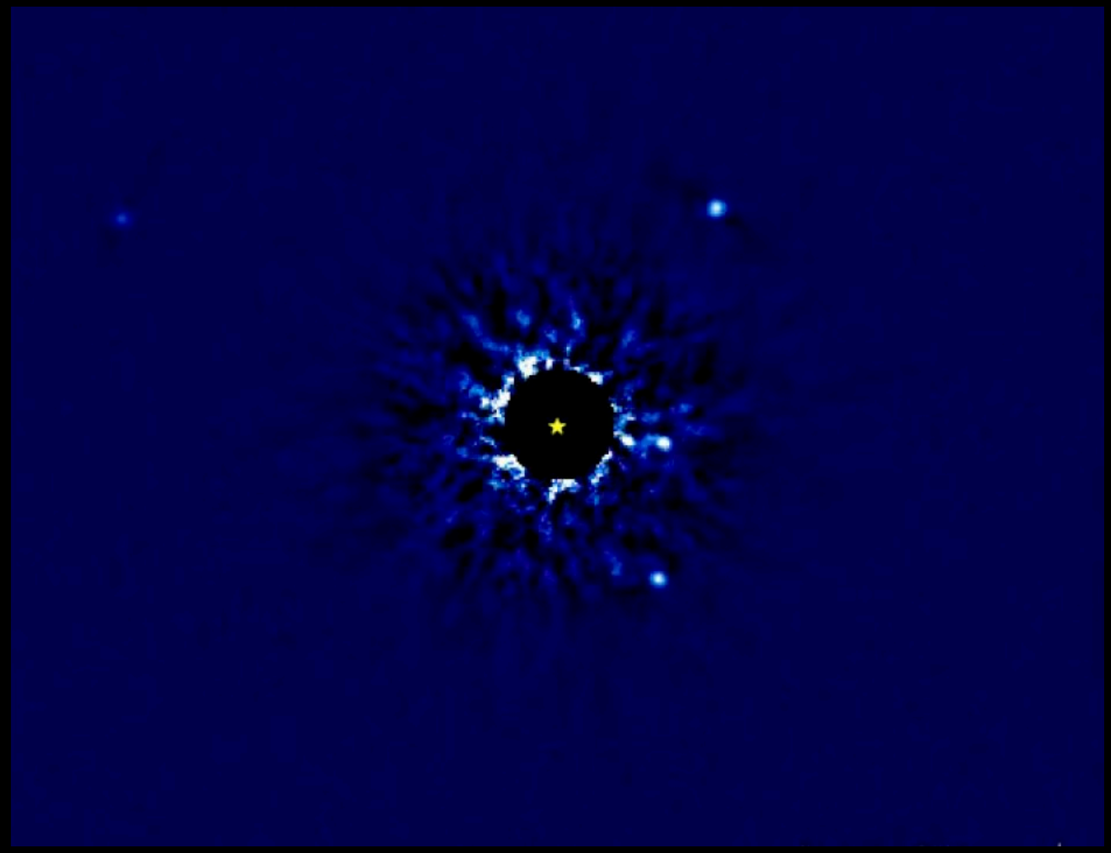
Volatile-rich worlds theory



Owen & Wu, 2013; Lopez & Fortney, 2013; Zeng et al 2019

It is hard for upcoming observations to identify surfaces on exoplanets

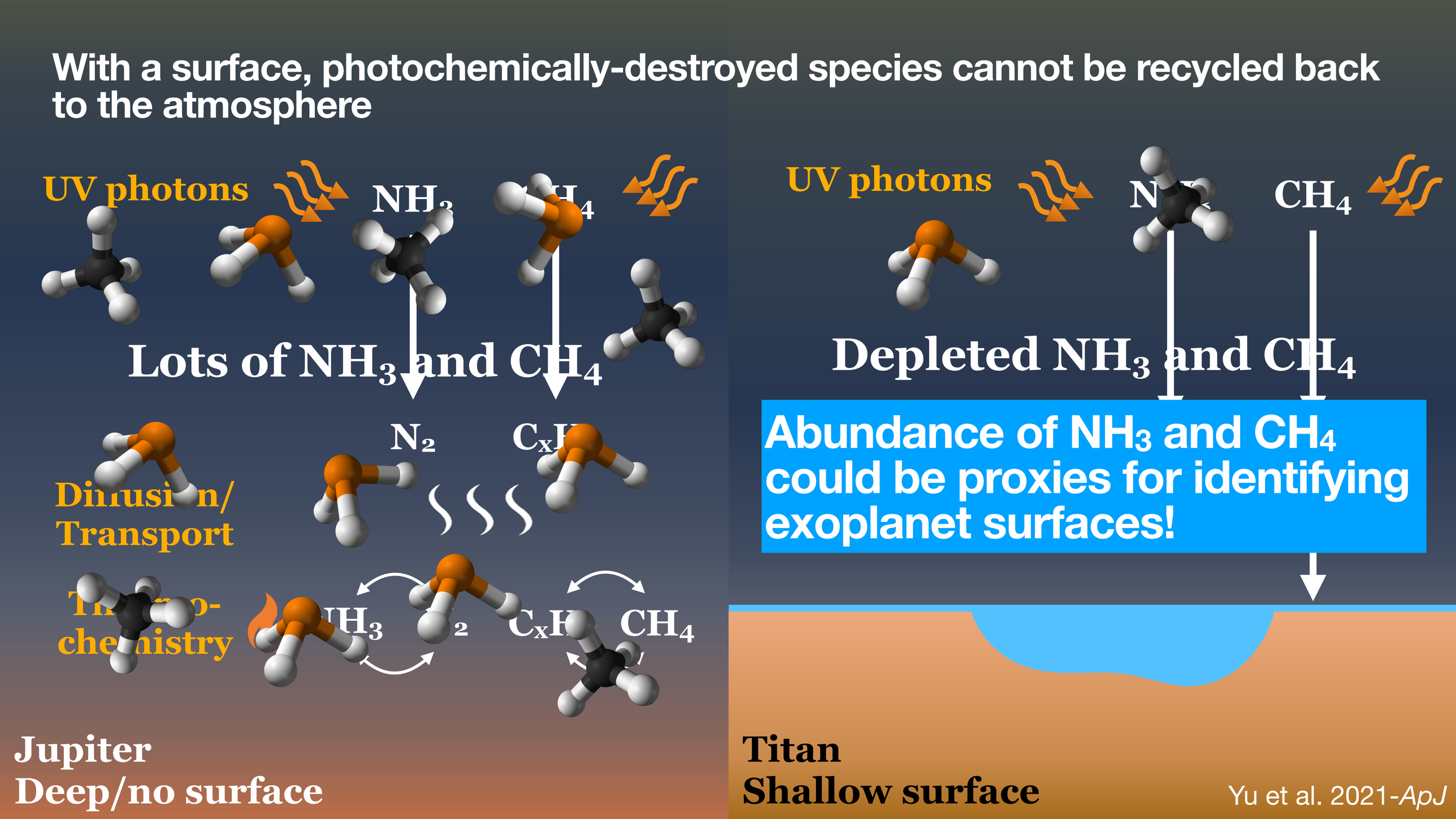




Transit (Hubble, JWST, ARIEL):
1) not sensitive to surface
2) cloud/haze block signal

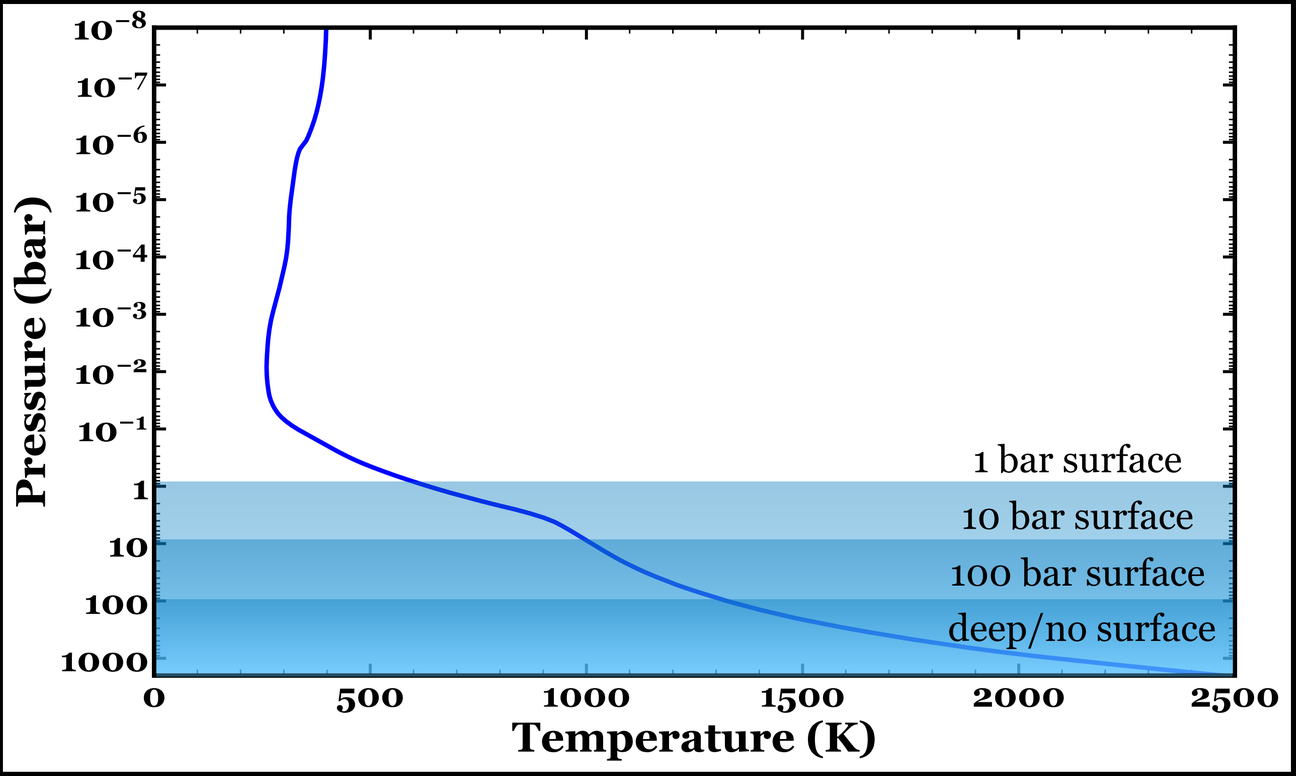
Direct Imaging (LUVOIR?):
Cannot see the surface if atmosphere too thick

With a surface, photochemically-destroyed species cannot be recycled back to the atmosphere



Yu et al. 2021-*ApJ*

Use a photochemical model to test a model planet with/without surfaces



- **Caltech/JPL KINETICS model**

Photochemistry+transport+thermochemistry

- **K2-18b**

T_{eq} ~ 255 K with albedo=0.3

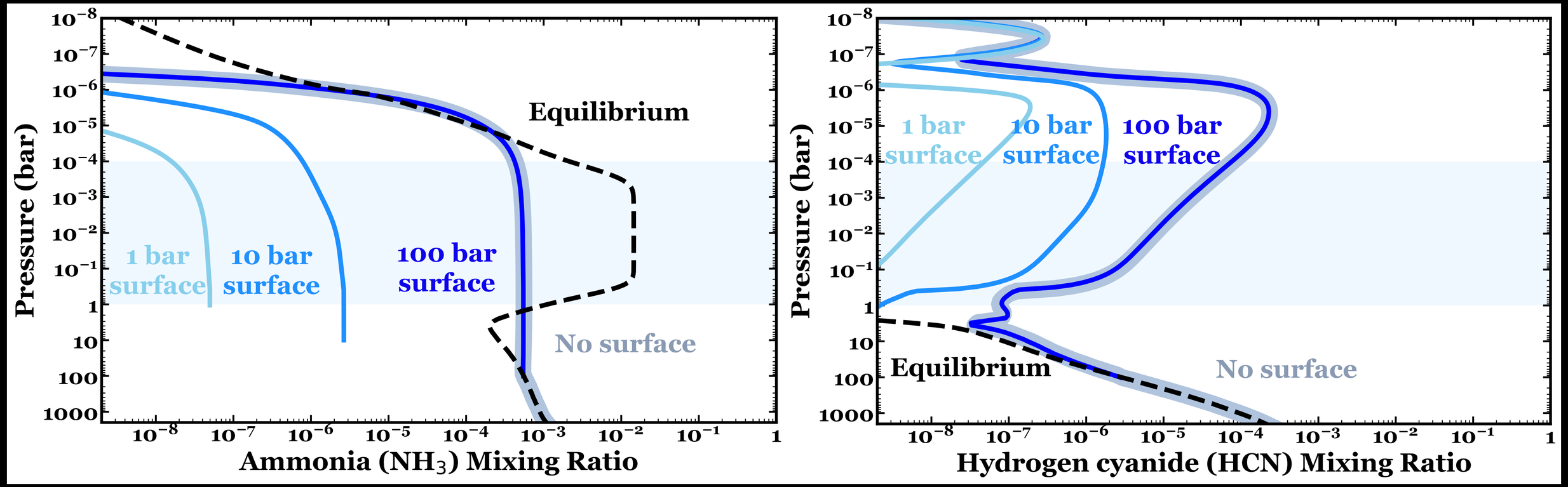
2.6 Earth radius

8.6 Earth mass

Water vapor detected

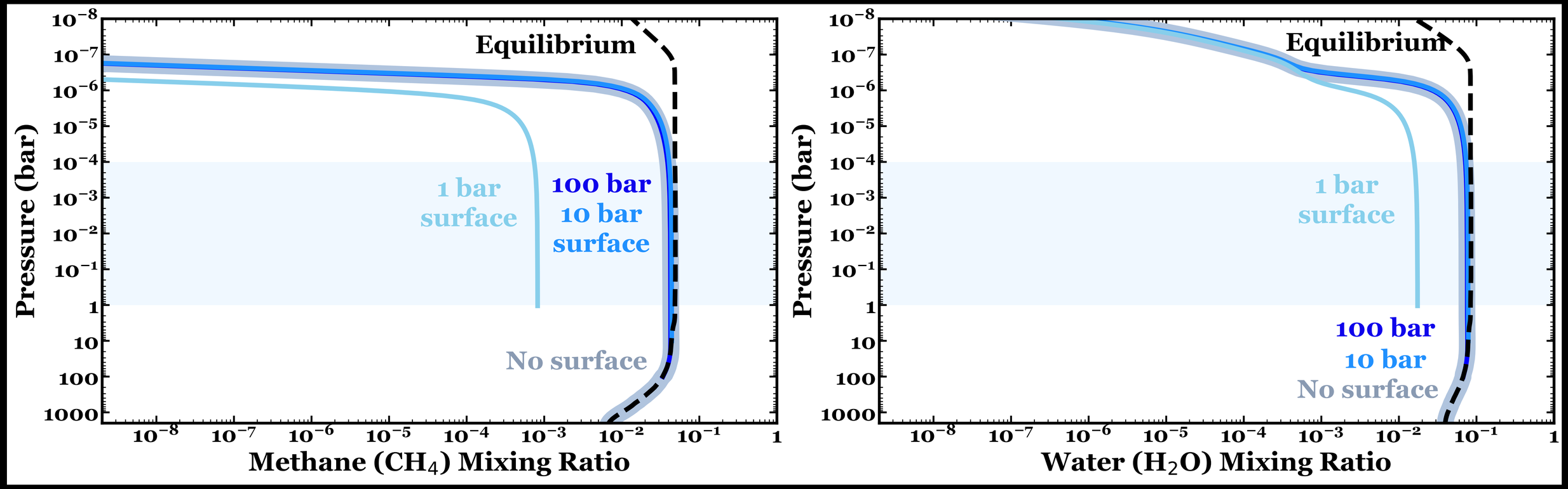
Clotier et al., 2019; Tsiaras et al., 2019; Benneke et al., 2019

NH_3 and HCN abundances are sensitive to surface with P < 100 bar



Yu et al. 2021-*ApJ*

CH_4, H_2O: sensitive to surface with P < 10 bar, with decreased abundances



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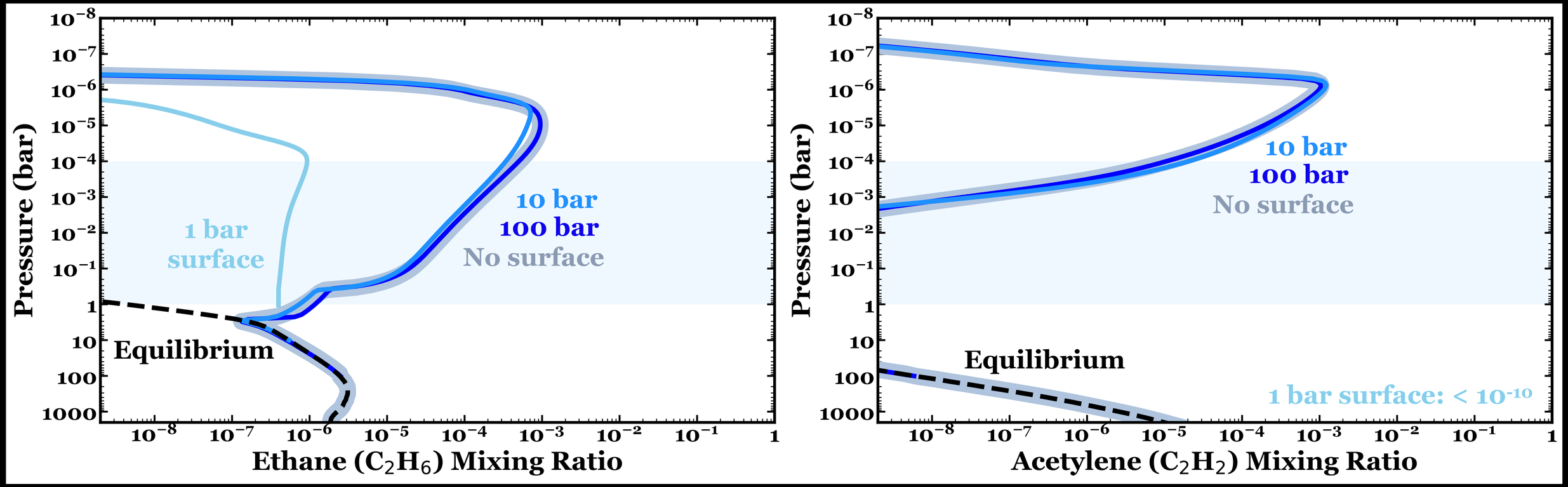
C_xH_y (hydrocarbons): sensitive to surface with P < 10 bar, with decreased abundances



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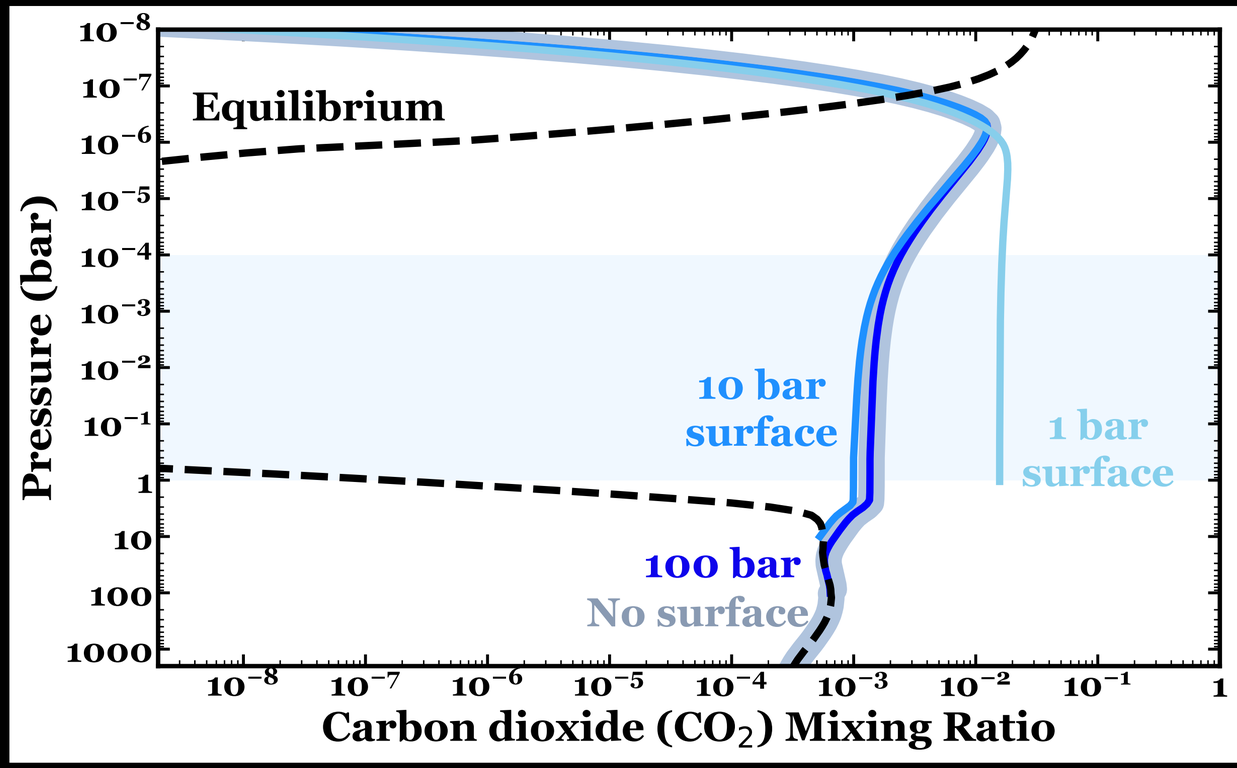
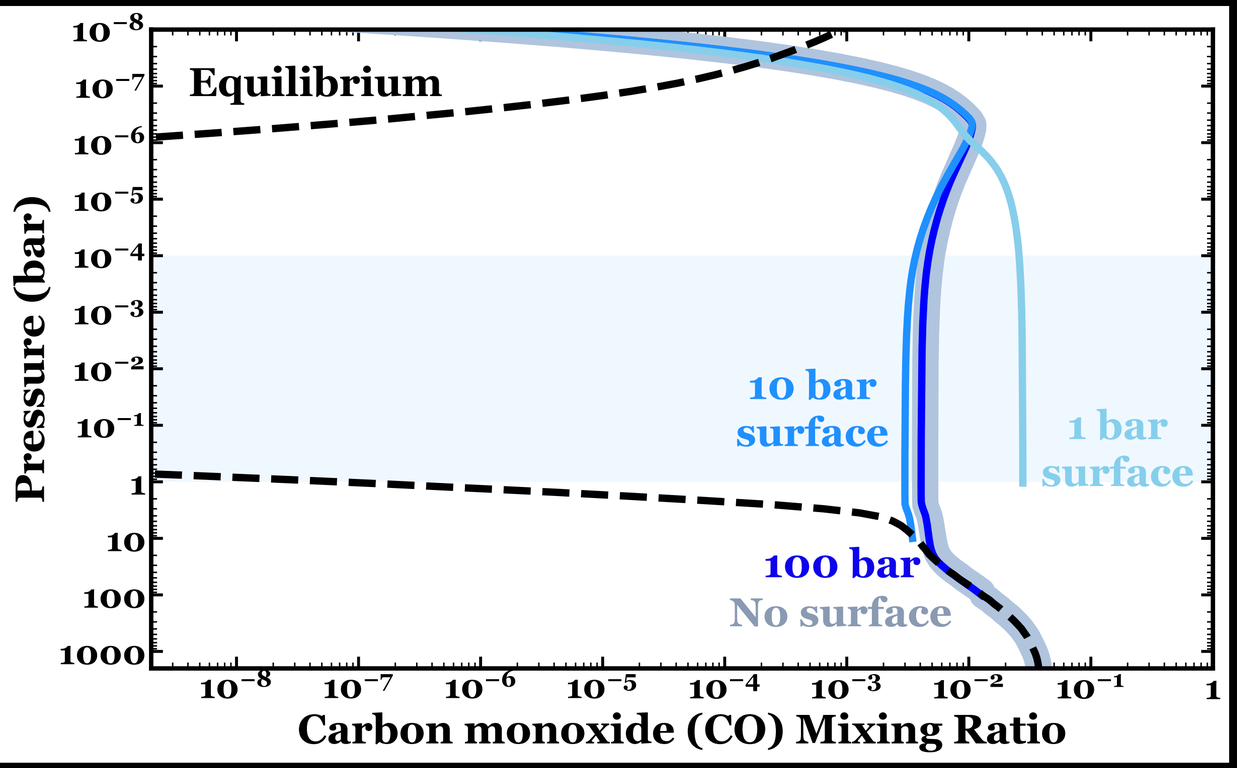
CO and CO_2: sensitive to surface with P < 10 bar, with increased abundances





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Species are grouped into four groups with different responses to the existence of a surface

Group 1	sensitive to all surface levels	NH_3, HCN
Group 2	Only sensitive to 1-bar surface with decreased abundances	H_2O, CH_4, C_xH_y
Group 3	Only sensitive to 1-bar surface with increased abundances	CO, CO_2
Group 4	Not sensitive to all surface levels	H_2, N_2, He

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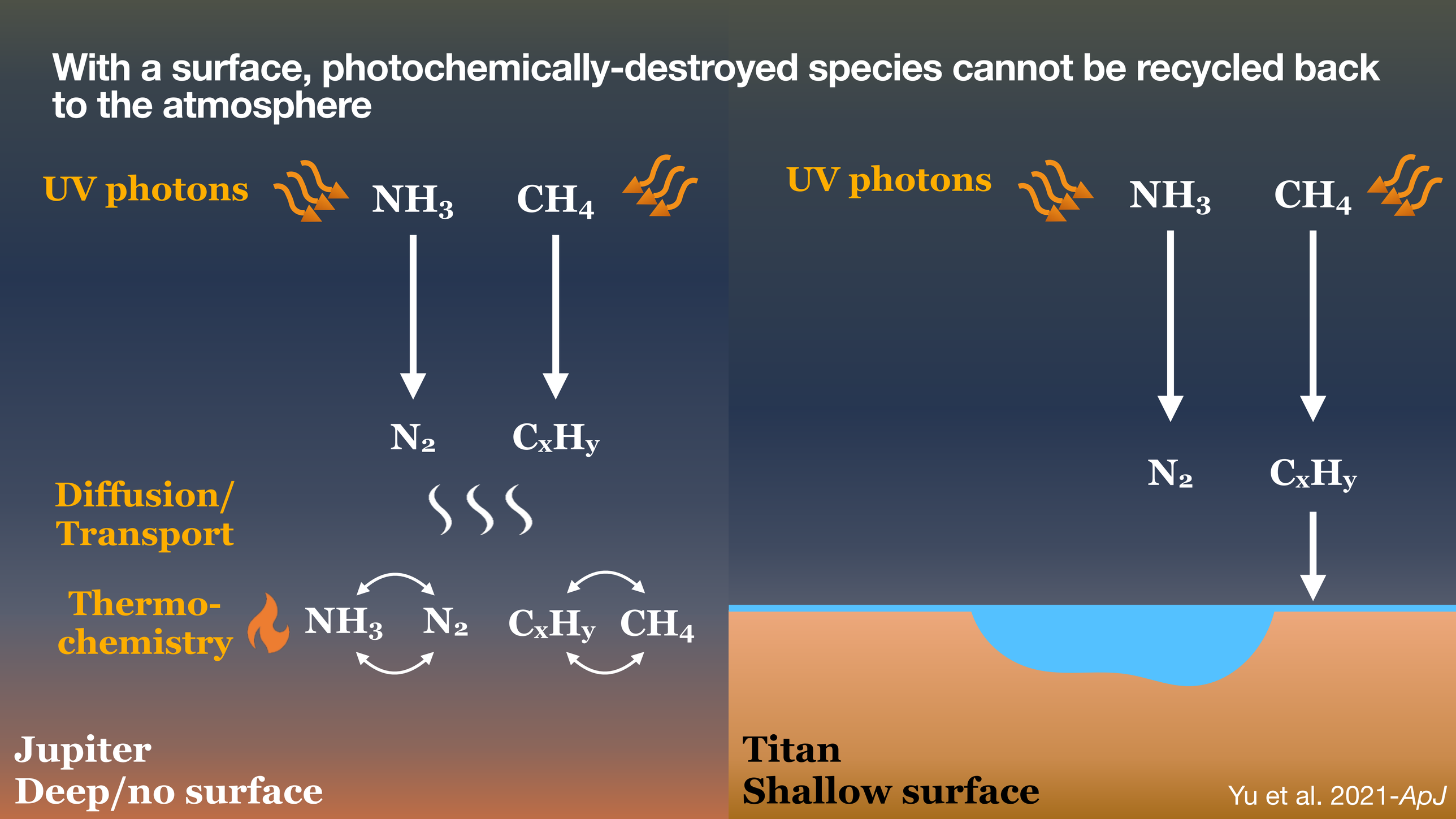
With a surface, photochemically-destroyed species cannot be recycled back to the atmosphere



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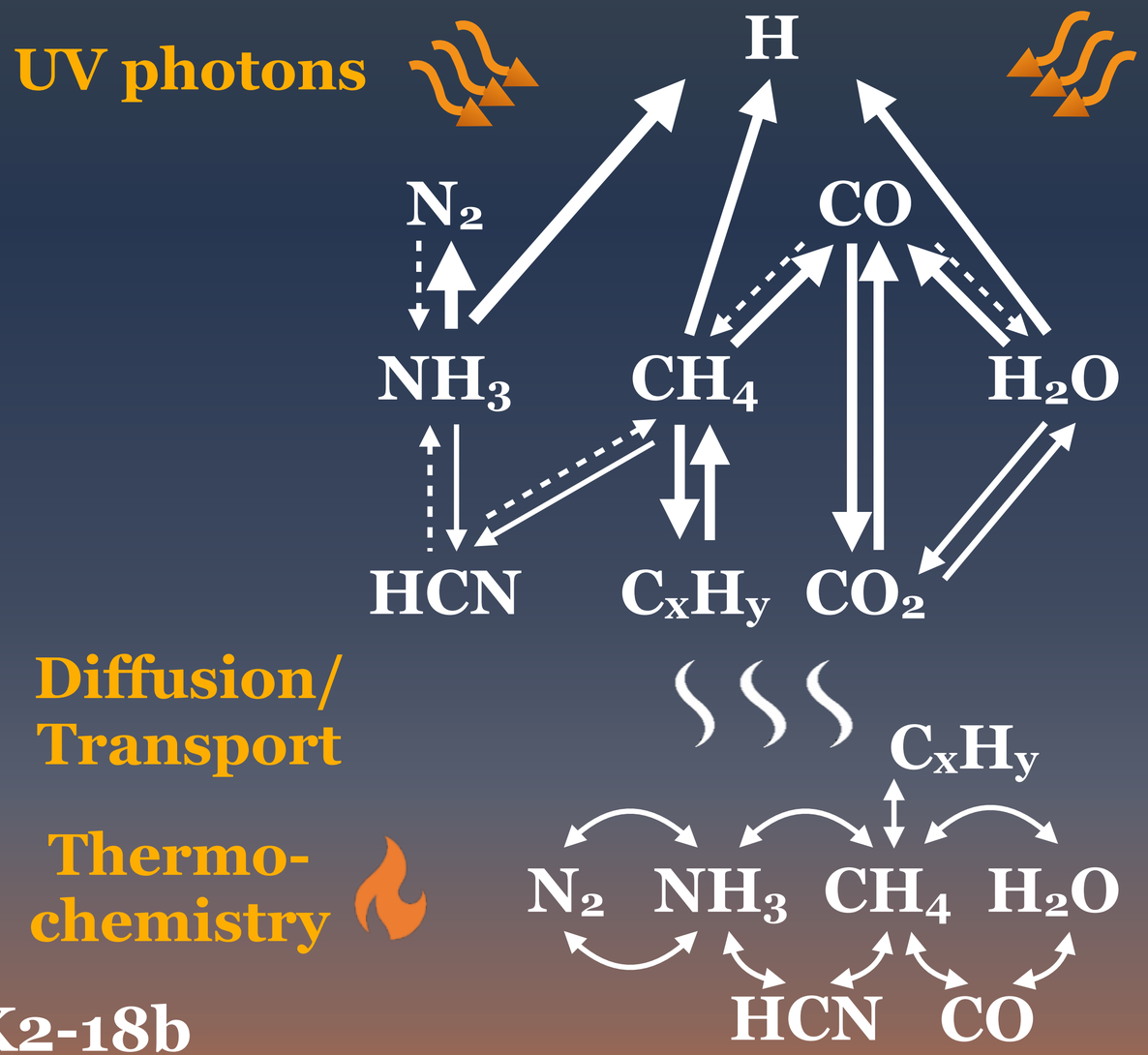
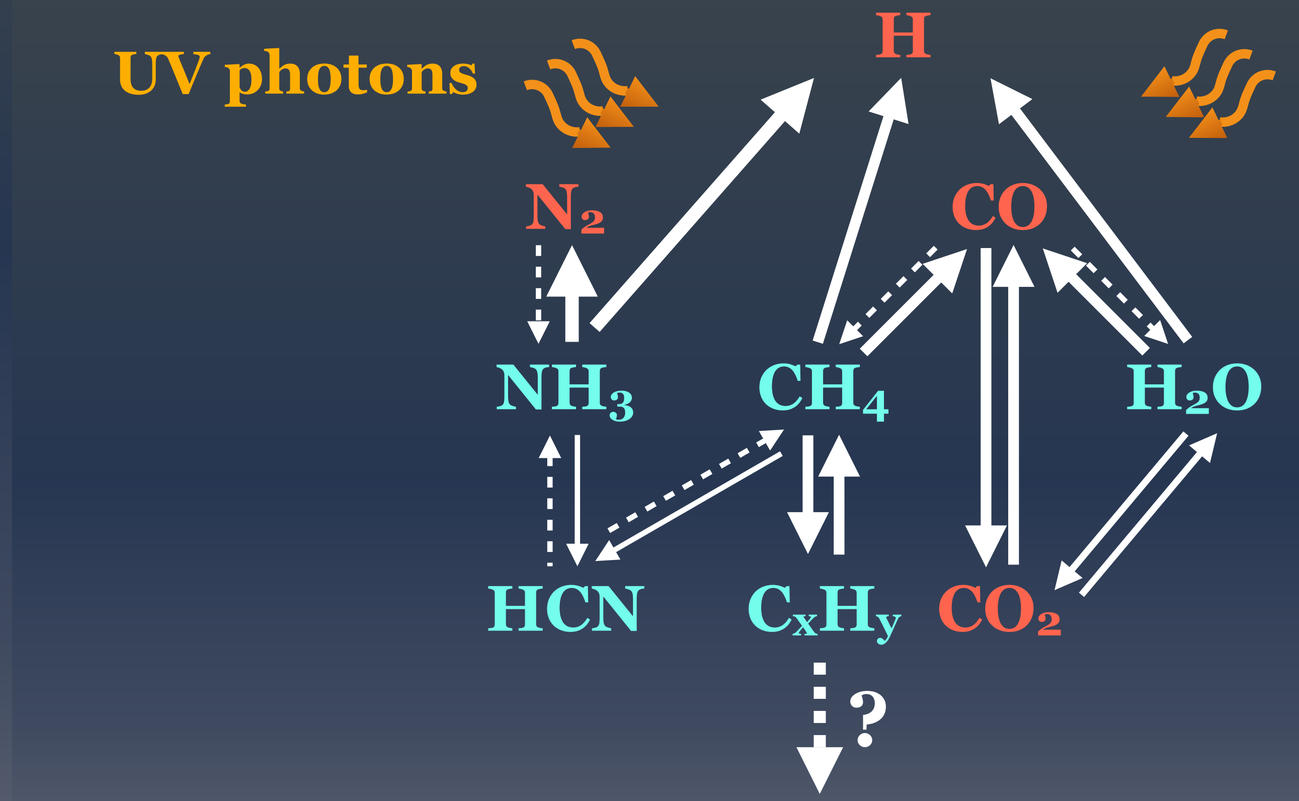
With a surface, photochemically-fragile species (CH_4, NH_3, H_2O) are converting to photochemically-stable species (CO & CO_2)



K2-18b
Deep/no surface



K2-18b
Shallow surface

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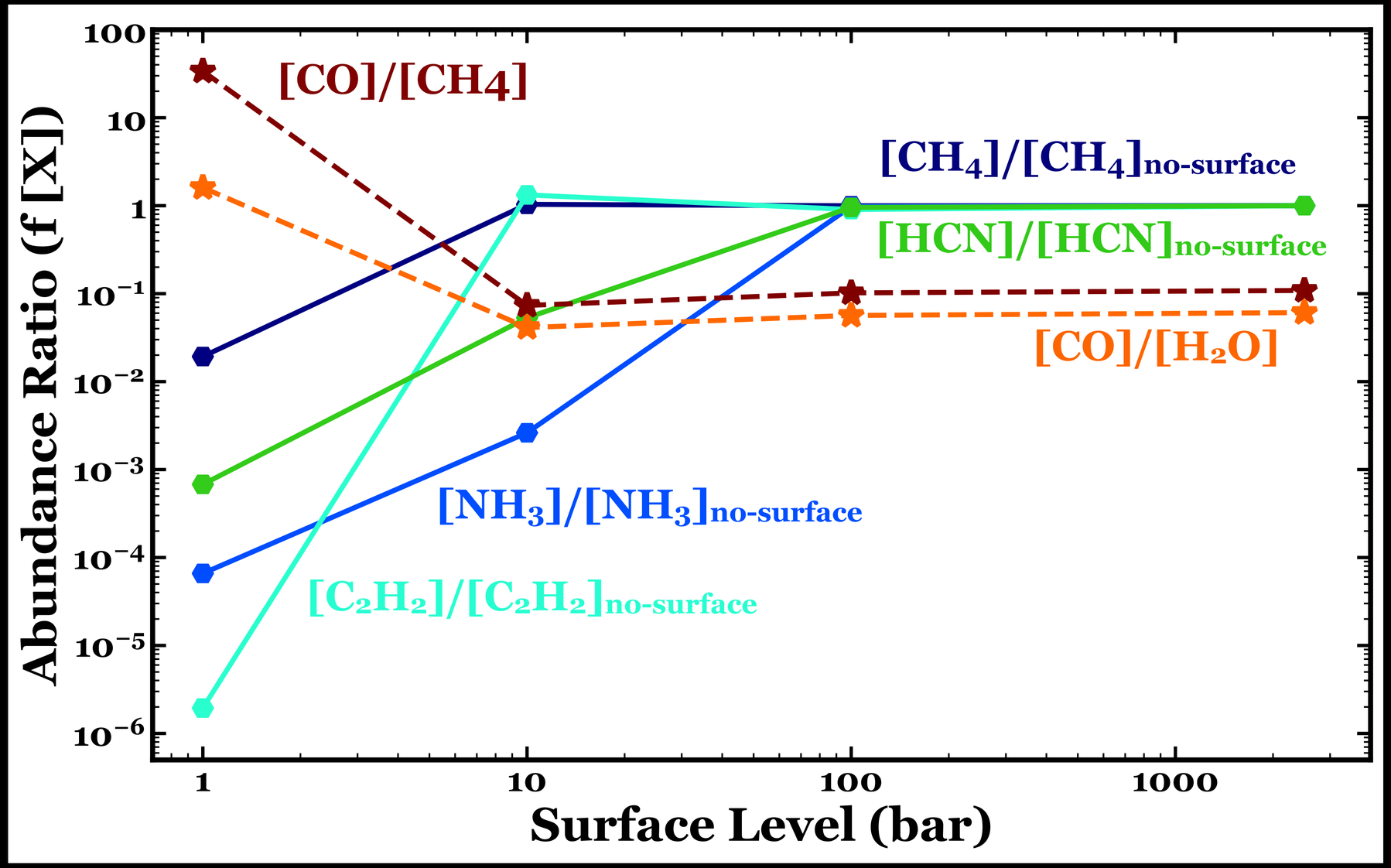
Seven trace species abundance criteria for identifying surface conditions



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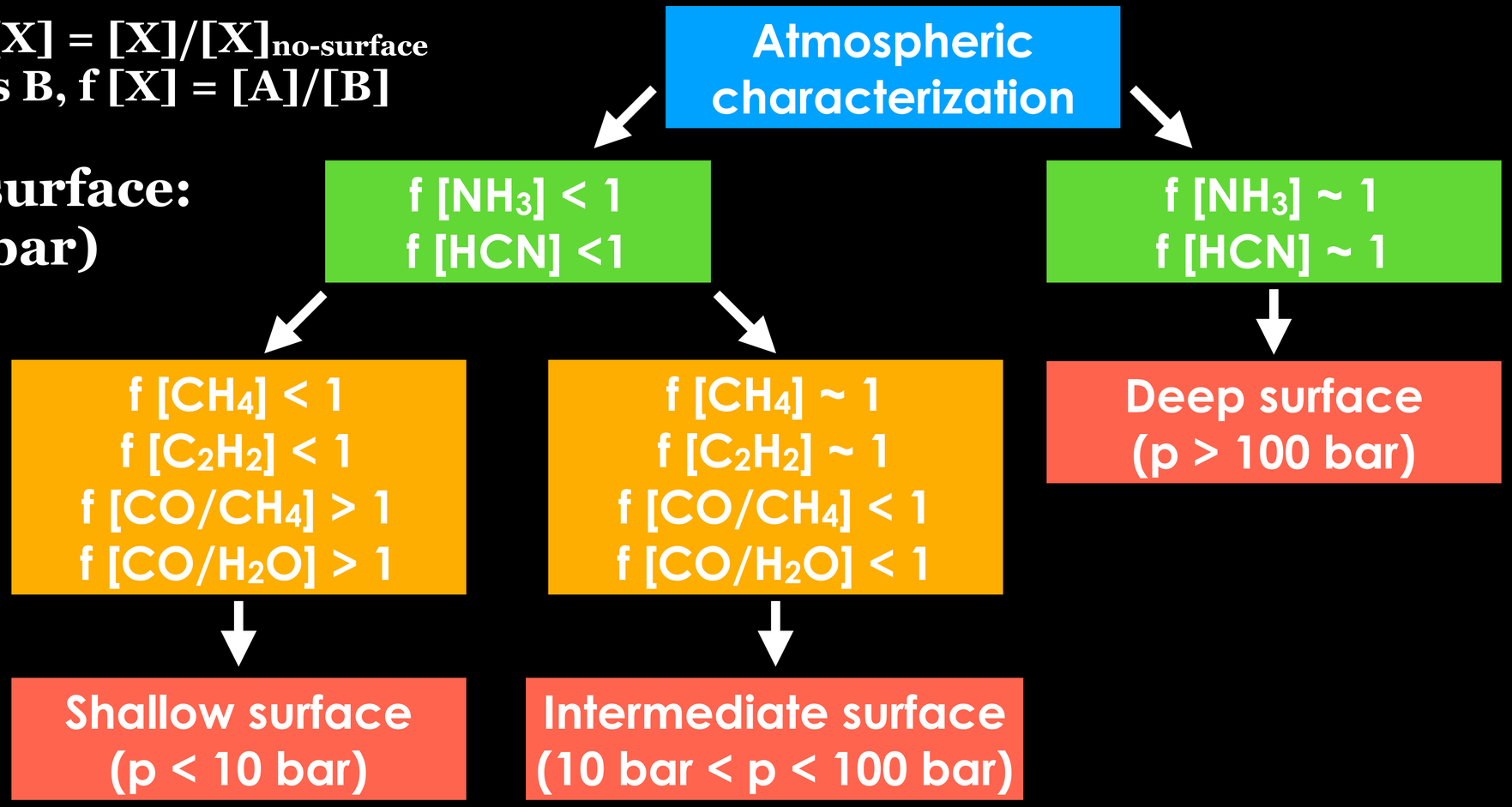
Use observed species abundances/ratios to determine existence of a surface & surface conditions

When X=single species, f [X] = $[X]/[X]_{no\text{-}surface}$
When X=species A/species B, f [X] = [A]/[B]

- **Sensitive to a deep surface: NH_3, HCN (p < 100 bar)**
- **Sensitive to a shallow surface: CH_4, C_xH_y, H_2O, CO, CO_2 (p < 10 bar)**



*** Only works for a H_2-dominated K2-18b like exoplanet**

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Takeaways

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- **Inclusion of a surface in an exoplanet will significantly change the chemical make-up of an atmosphere compared to no-surface case/thermochemical equilibrium.**
- **We identified several key species for exoplanet surface identification: NH_3 and HCN (for identifying a deep surface), CH_4, C_xH_y, H_2O, CO, CO_2 (for identifying a shallow surface).**
- **This framework could be applied to identifying surfaces on exoplanets inside/ at the edge of the photo-evaporation valley (1-3 Earth radius).**

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