CARBON-RICH SUB-NEPTUNE INTERIORS:
CONCEPTS, STRUCTURAL MODELS, AND OBSERVATIONAL SIGNATURES

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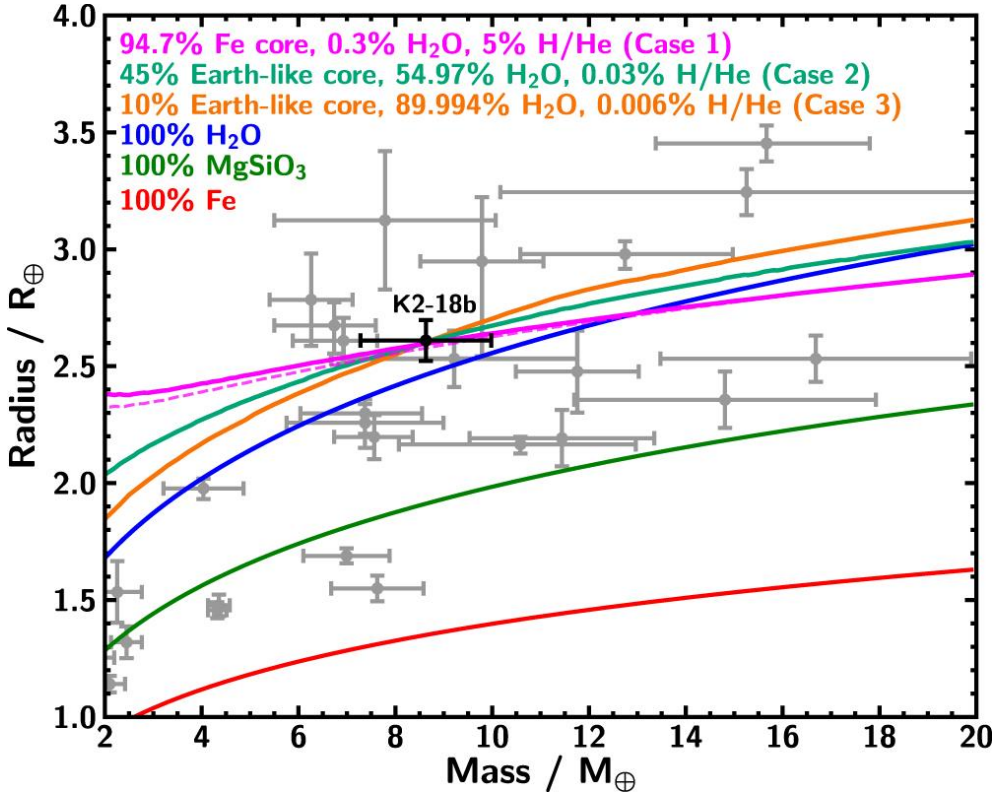
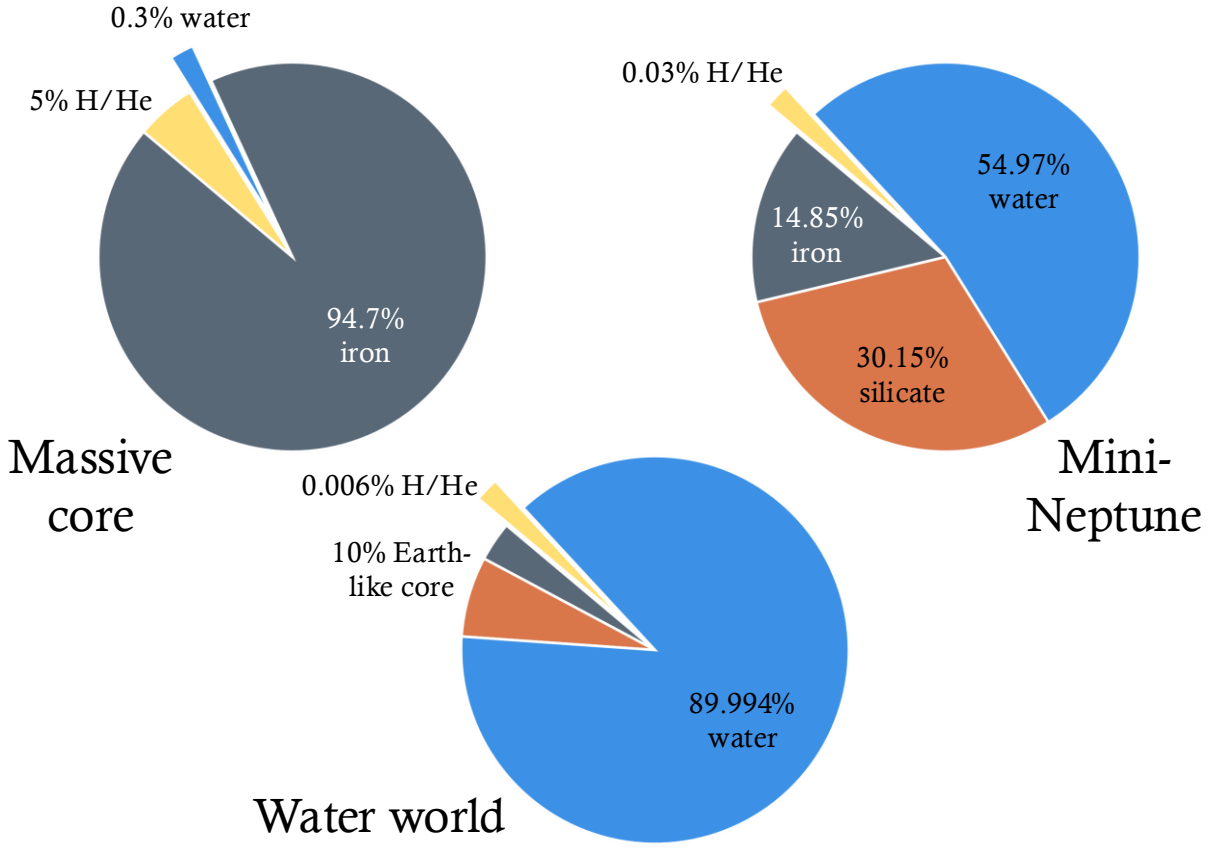
Sub-Neptune Interiors Are Highly Degenerate



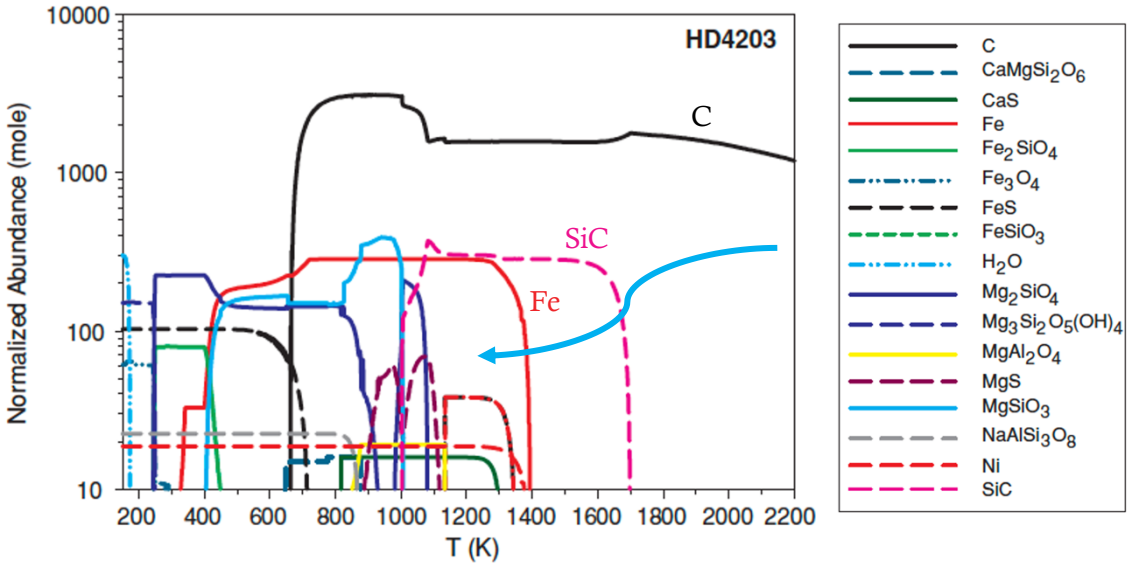
Madhusudhan et al. (2020)



Carbon Adds to the Degeneracy

- "Carbon planets" can form in protoplanetary disks with **high ($\gtrsim$ 1) C/O ratios*** (Kuchner & Seager, 2005)
- Some early measurements reported >1 C/O ratios for exoplanet host stars
- However, more up-to-date measurements found that **FGK stars in solar neighborhood have C/O < 0.8** (e.g., Bedell et al. 2018; Suárez-Andrés et al. 2018)

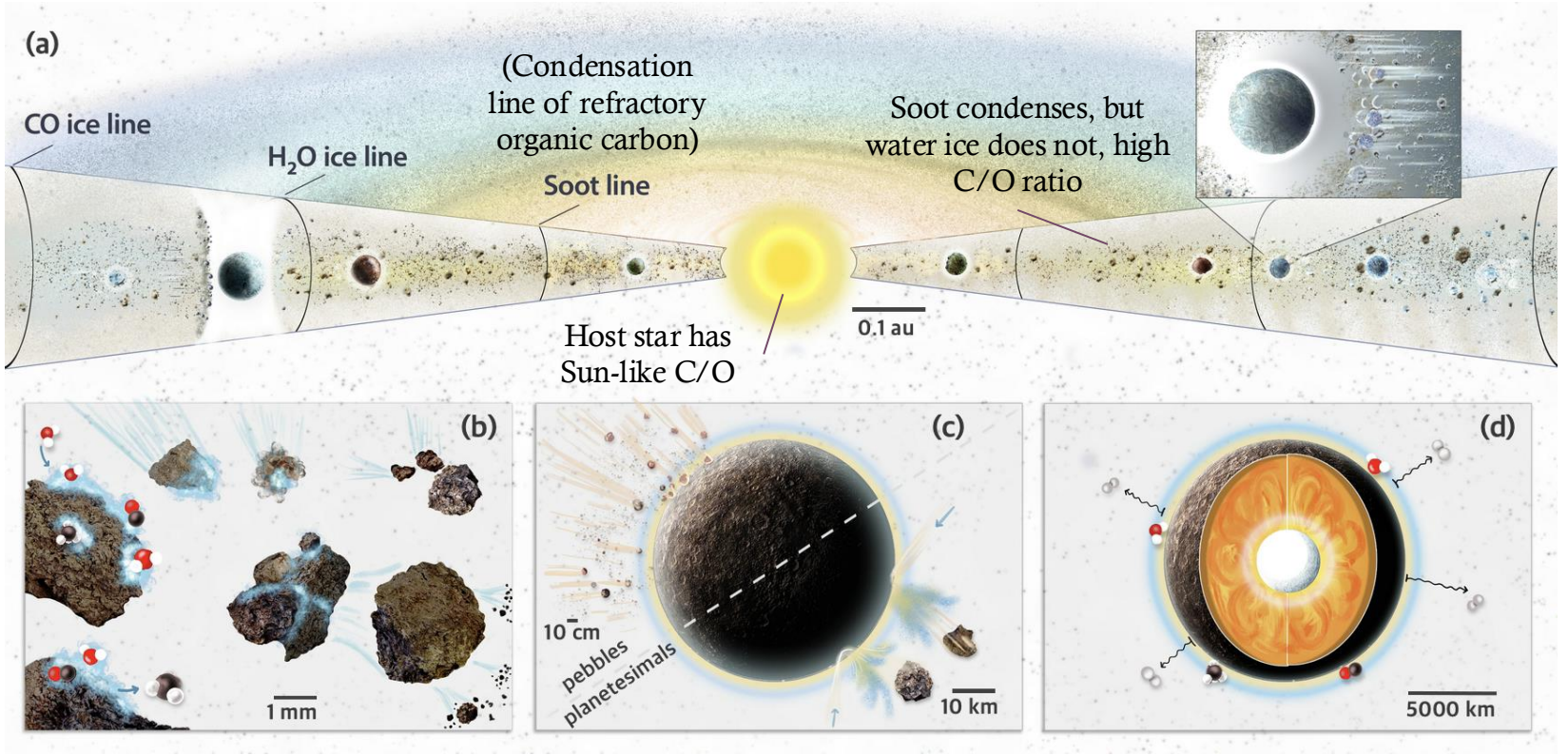
Condensation sequence, C-rich (C/O=1.86) disk



Bond et al. (2010)

*Solar C/O is ~0.55 for reference

Refractory Carbon ("Soot") Enrichment



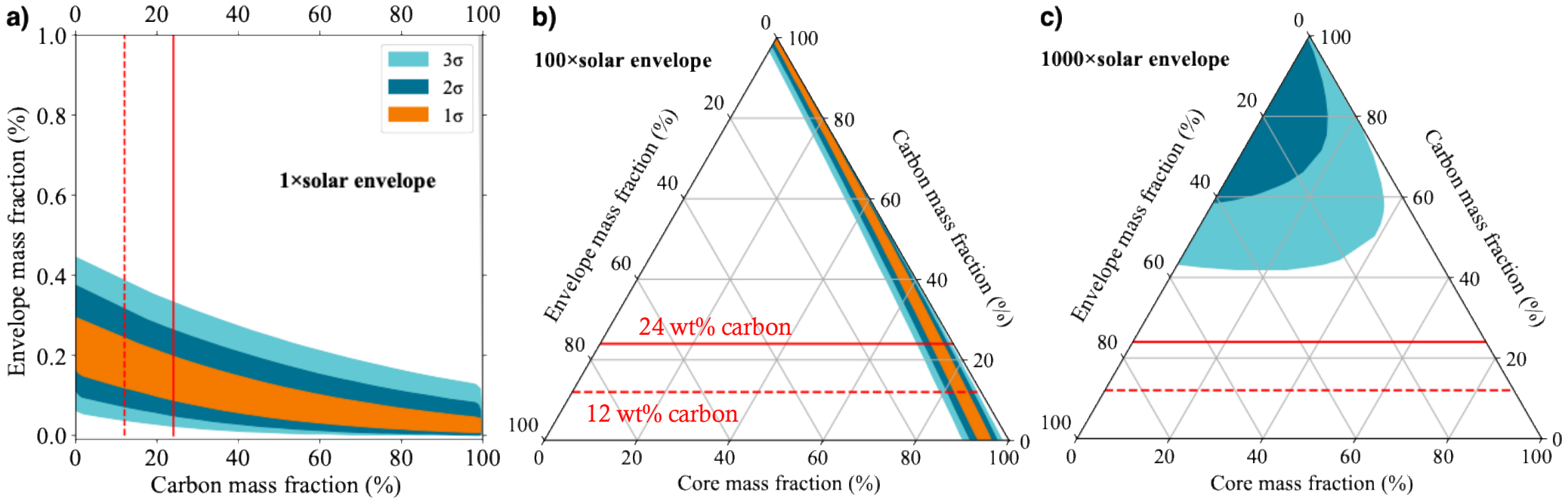
ARAA review by Bergin et al. (2026); see also Kress et al. (2010), Li et al. (2021), Bergin et al. (2023)

Interior Models With a Carbon Layer

- **CORGI** planetary interior model (Lin, Seager & Weiss, 2025)
- **Three-layer structure**: Earth-like core (33.2% iron + 66.8% silicate) + carbon layer + H/He envelope (1-1000× solar metallicity)
- Equation of state (EOS) for carbon:
  - Birch-Murnaghan graphite EOS at low pressure (Seager et al., 2007)
  - DFT diamond EOS at high pressure (Swift et al., 2022)
  - Phase transition at 10 GPa
- Three archetypical sub-Neptunes: **TOI-270 d, GJ 1214 b, K2-18 b**

https://github.com/Zifan-Lin/CORGI

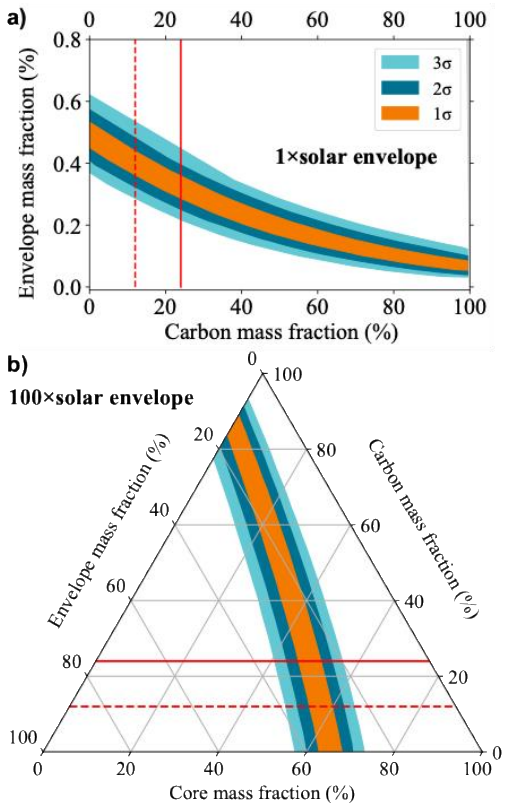
Interior Composition of TOI-270 d



Lin & Seager (2025)

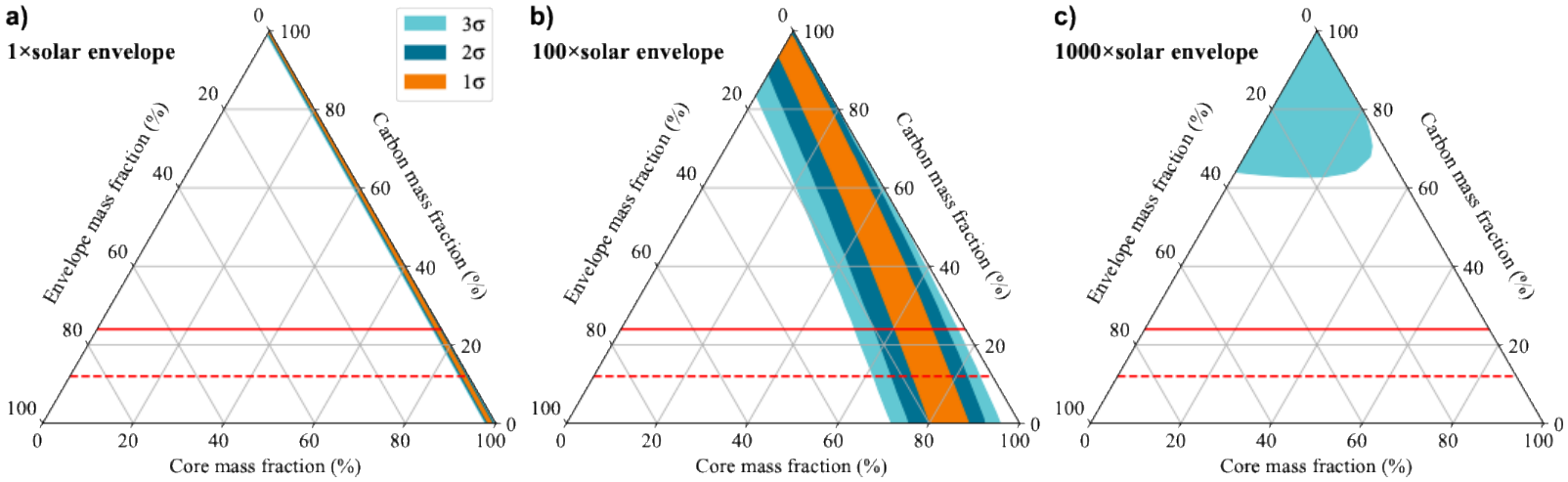
Takeaway: **carbon-rich interiors are consistent with M-R** if envelope metallicity ≤ 100 × solar

Interior Composition of GJ 1214 b and K2-18 b



GJ 1214 b

Similarly, GJ 1214 b and K2-18 b can be carbon-rich

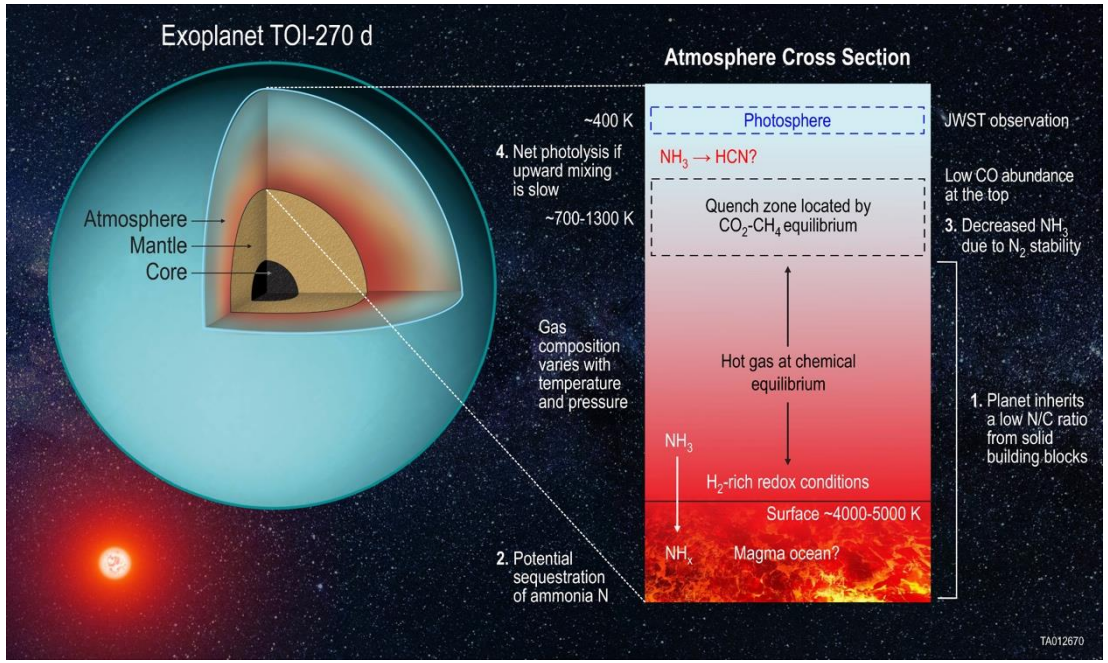


K2-18 b

Carbon-rich Atmospheric Composition

- **TOI-270 d, GJ 1214 b, K2-18 b** all have transmission spectra measured by JWST and/or HST
- By implication, carbon-rich interior should lead to carbon-rich atmosphere*
- We use *Photochem* (Wogan et al., 2023) to simulate atmospheric chemistry and *petitRADTRANS* (Mollière et al. 2019; Blain et al. 2024) to simulate transmission spectra

Schematic diagram of sub-Neptune interior-atmosphere exchange

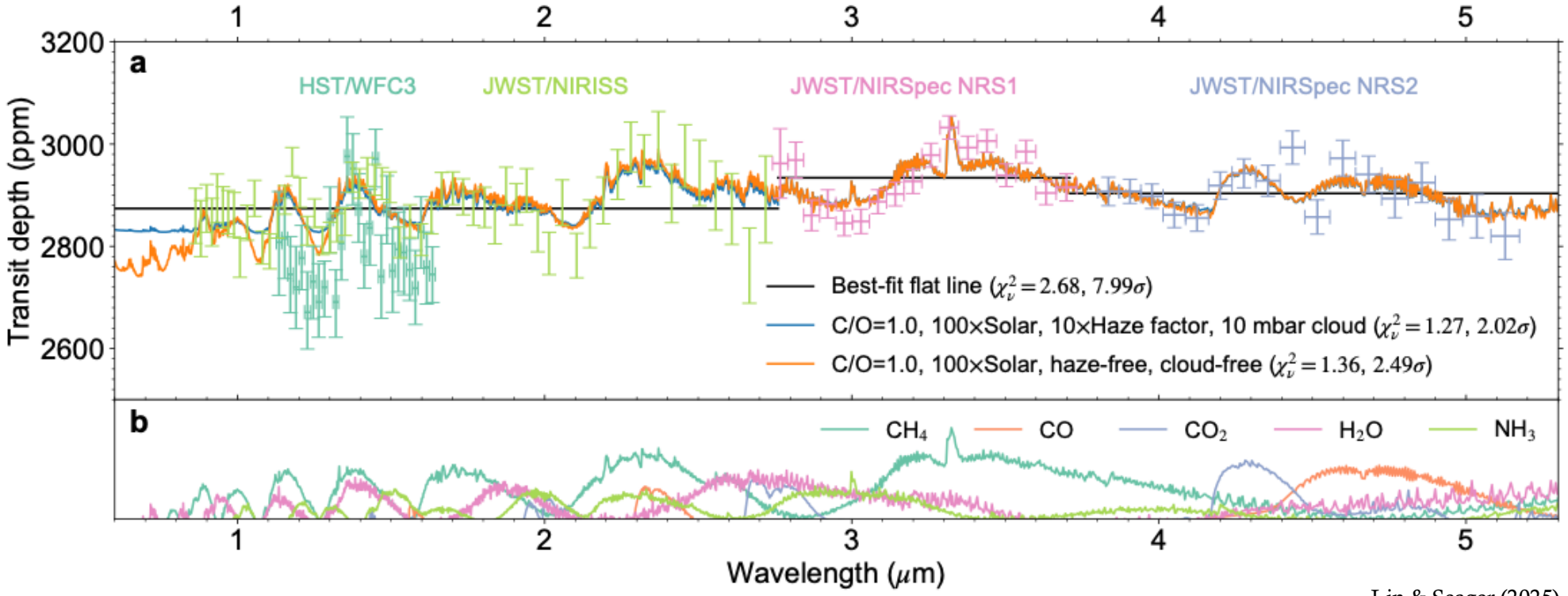


Glein, Yu & Luu (2025)

*We assume that atmospheric C/O equals bulk interior C/O. This is perhaps an oversimplification. Interior-atmosphere exchange and atmospheric carbon retention studies will be helpful.

C-rich Interiors Are Consistent with Observations

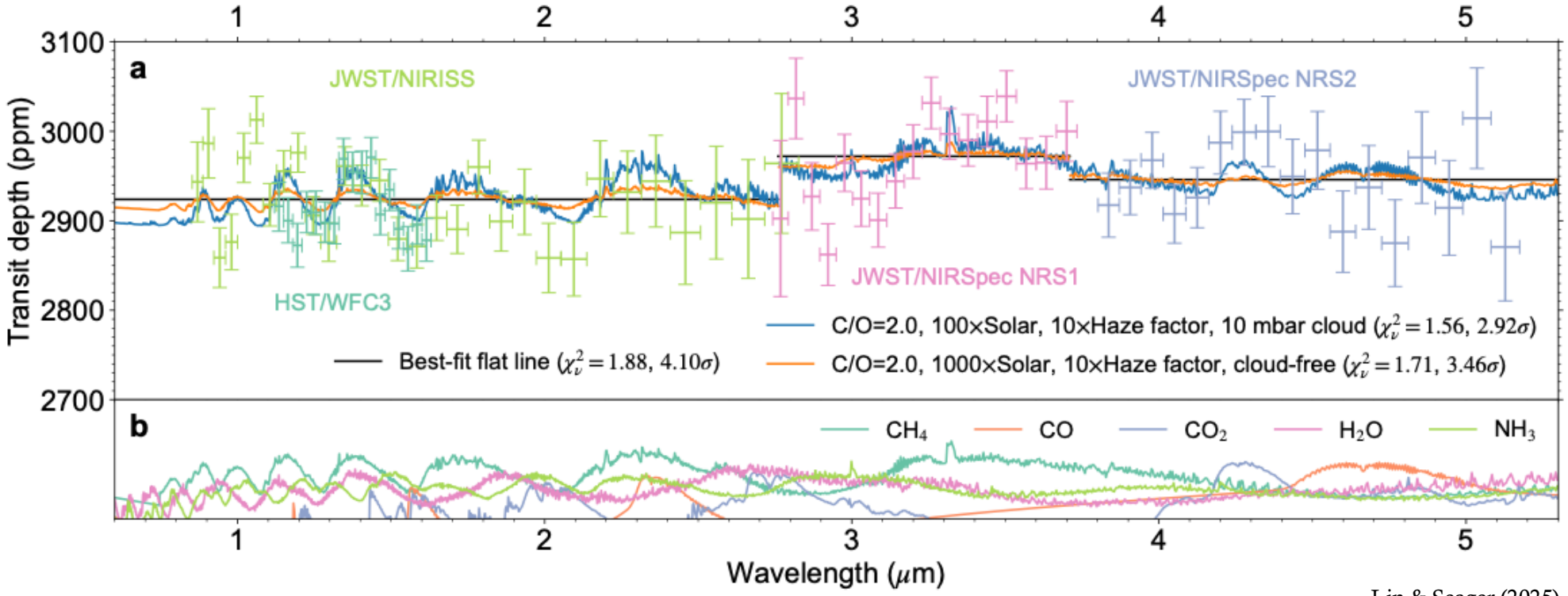
TOI-270 d C-rich model vs observation



Lin & Seager (2025)

C-rich Interiors Are Consistent with Observations

K2-18 b C-rich model vs observation

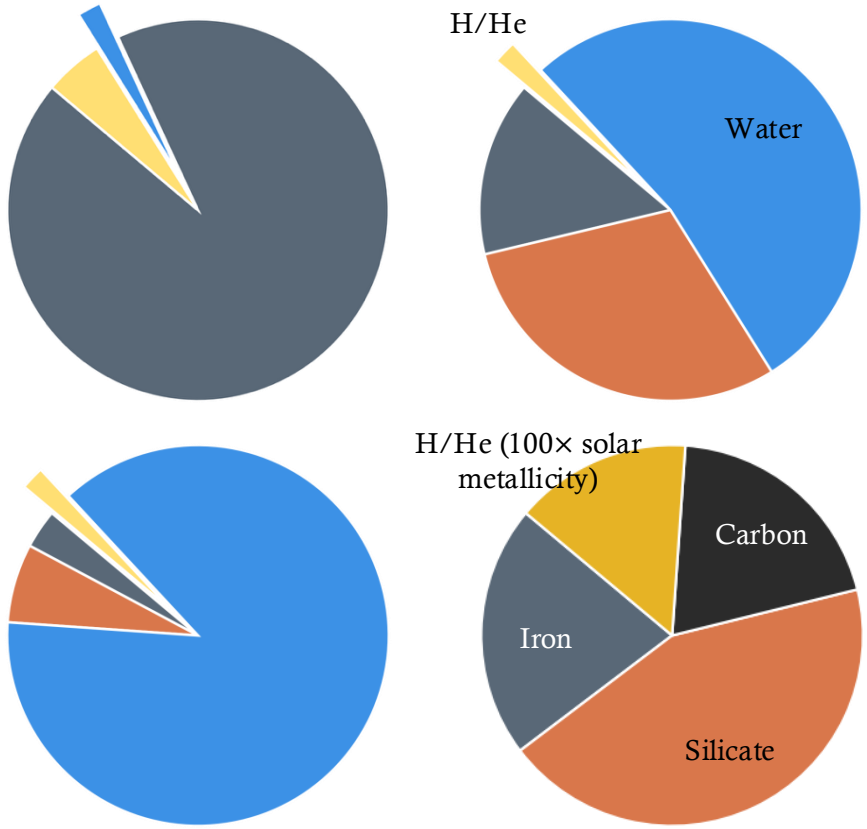


Lin & Seager (2025)

*GJ 1214 b is skipped due to hazy atmosphere.

Takeaway: C-rich Interior Fits Observations

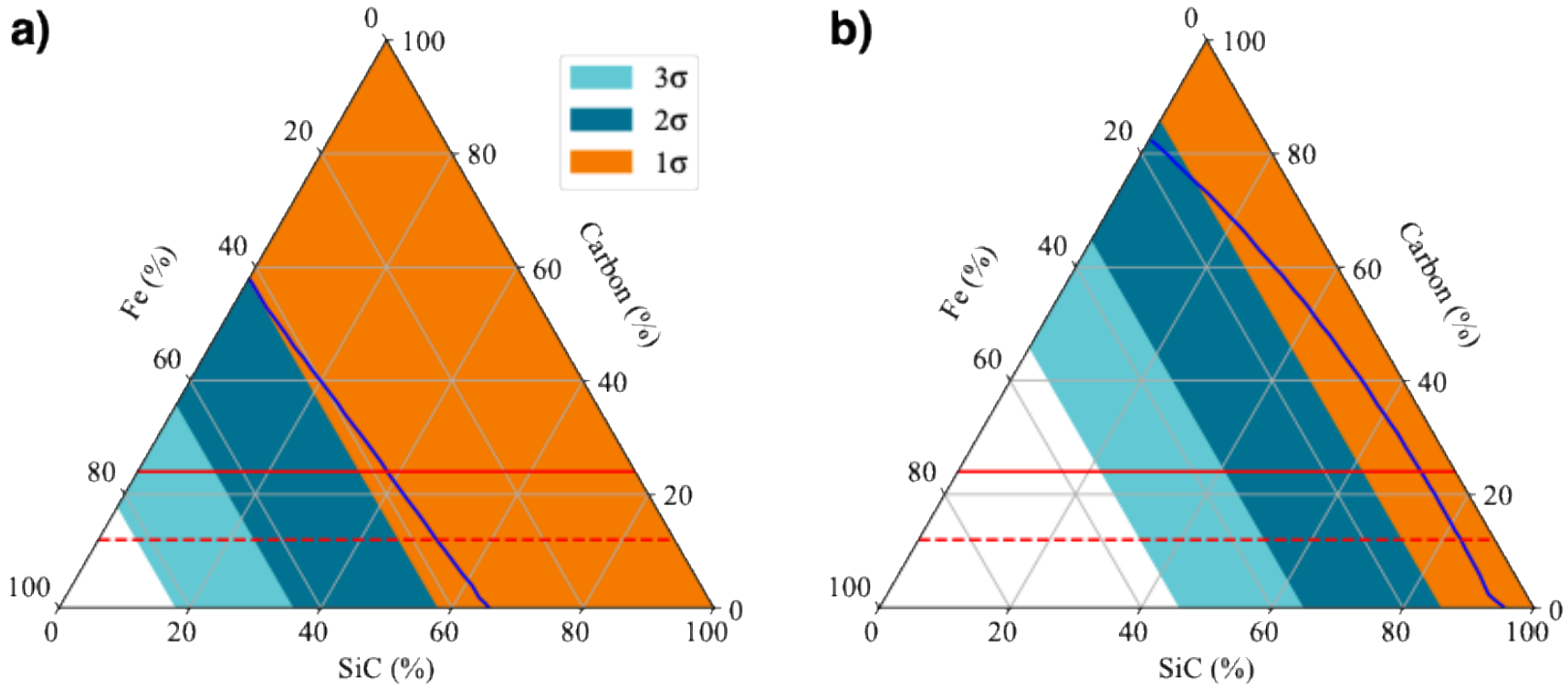
- Carbon-rich interior is compatible with **M-R measurements**
- Carbon-rich interior is compatible with **HST & JWST transmission spectra** (caveat: interior-atmosphere connection)
- Carbon-rich interior is possible according to **planet formation theories** (the "soot line" idea)
- Side evidence: JWST measured high C/O in low-mass young M dwarf disks (Tabone et al. 2023; Arabhavi et al. 2024; Kanwar et al. 2024)
- Carbon deserves a place in the pie charts



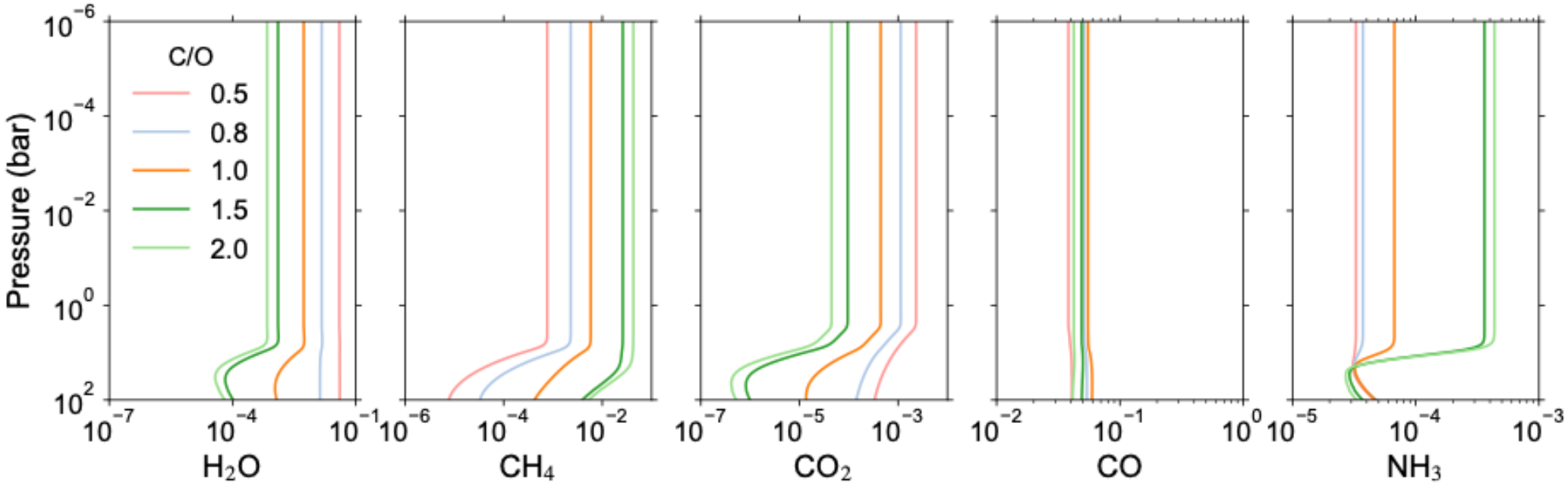
Backup Slides

Carbon & SiC EOS Validation

Compared with Madhusudhan et al. (2012) 55 Cnc e model (blue line)

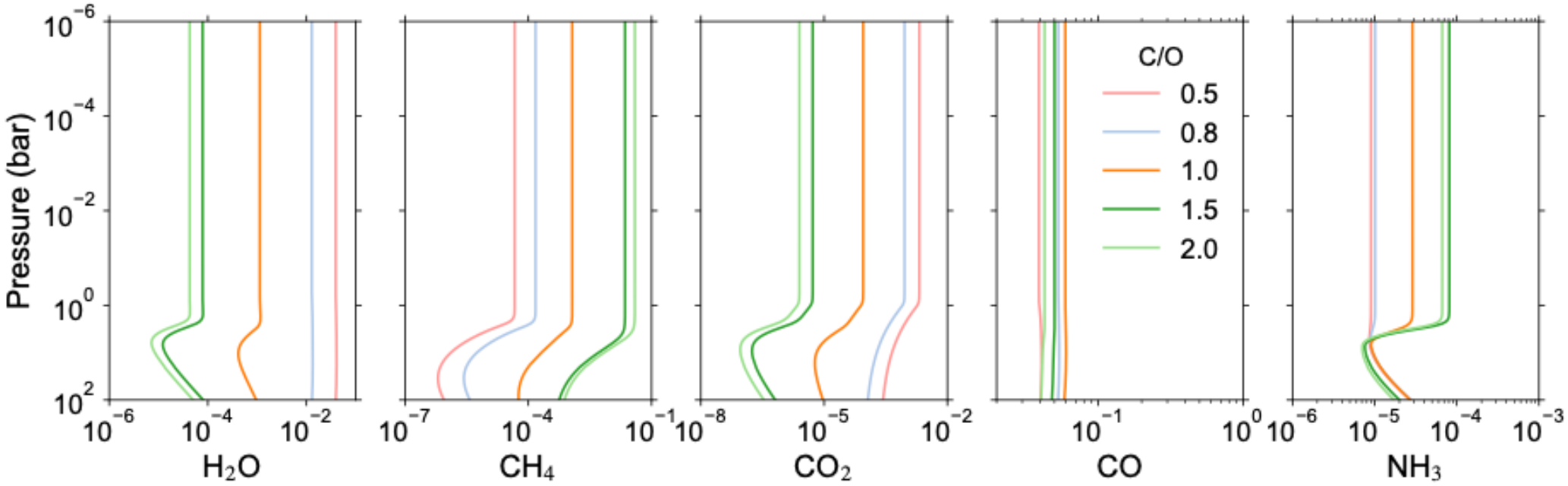


Chem Profile: TOI-270 d



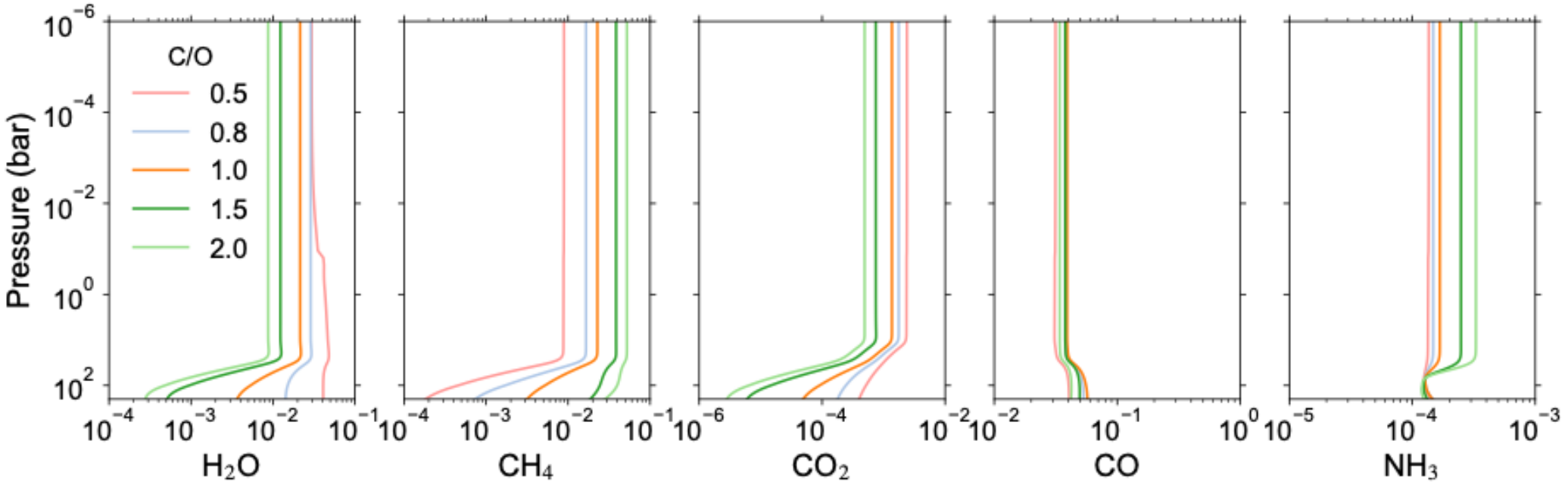
Lin & Seager (2025)

Chem Profile: GJ 1214 b



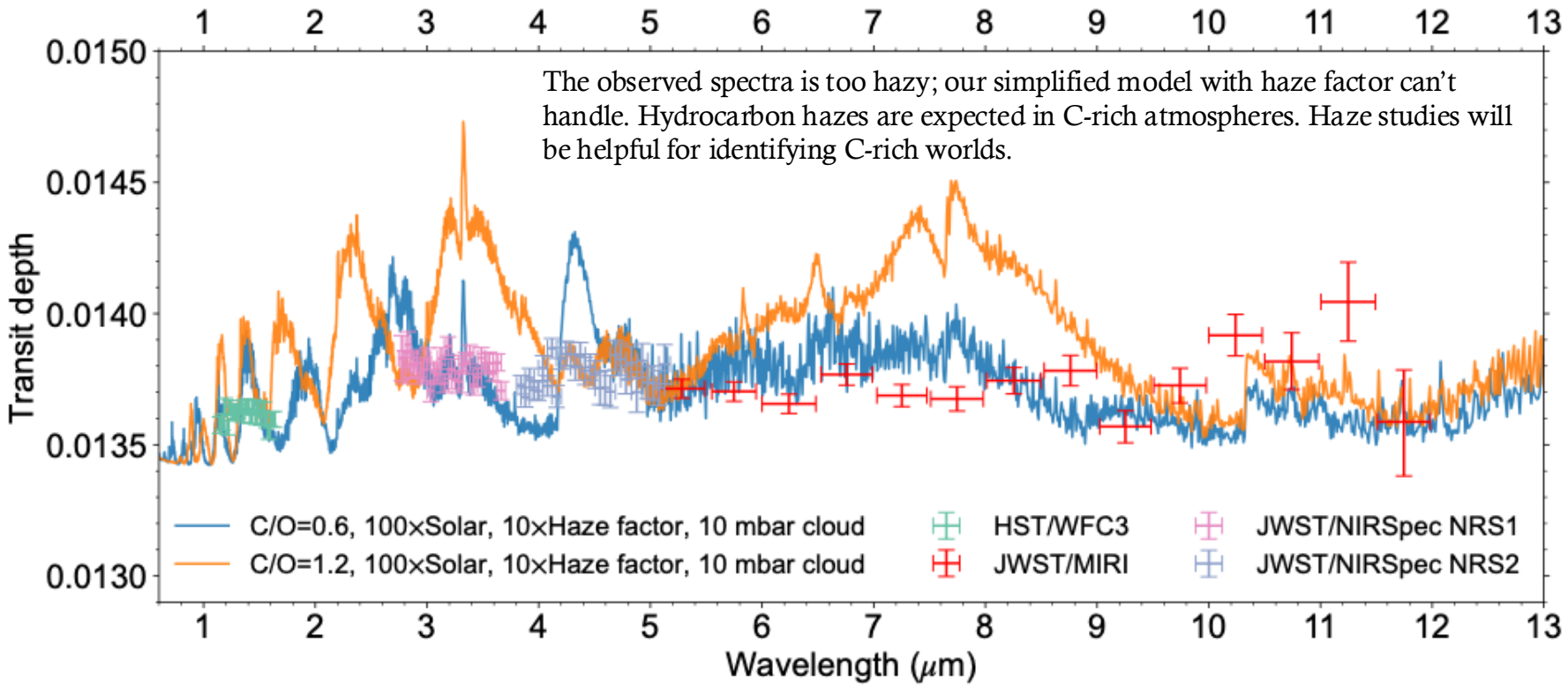
Lin & Seager (2025)

Chem Profile: K2-18 b



Lin & Seager (2025)

GJ 1214 b Transmission Spectrum



Lin & Seager (2025)