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UC San Diego

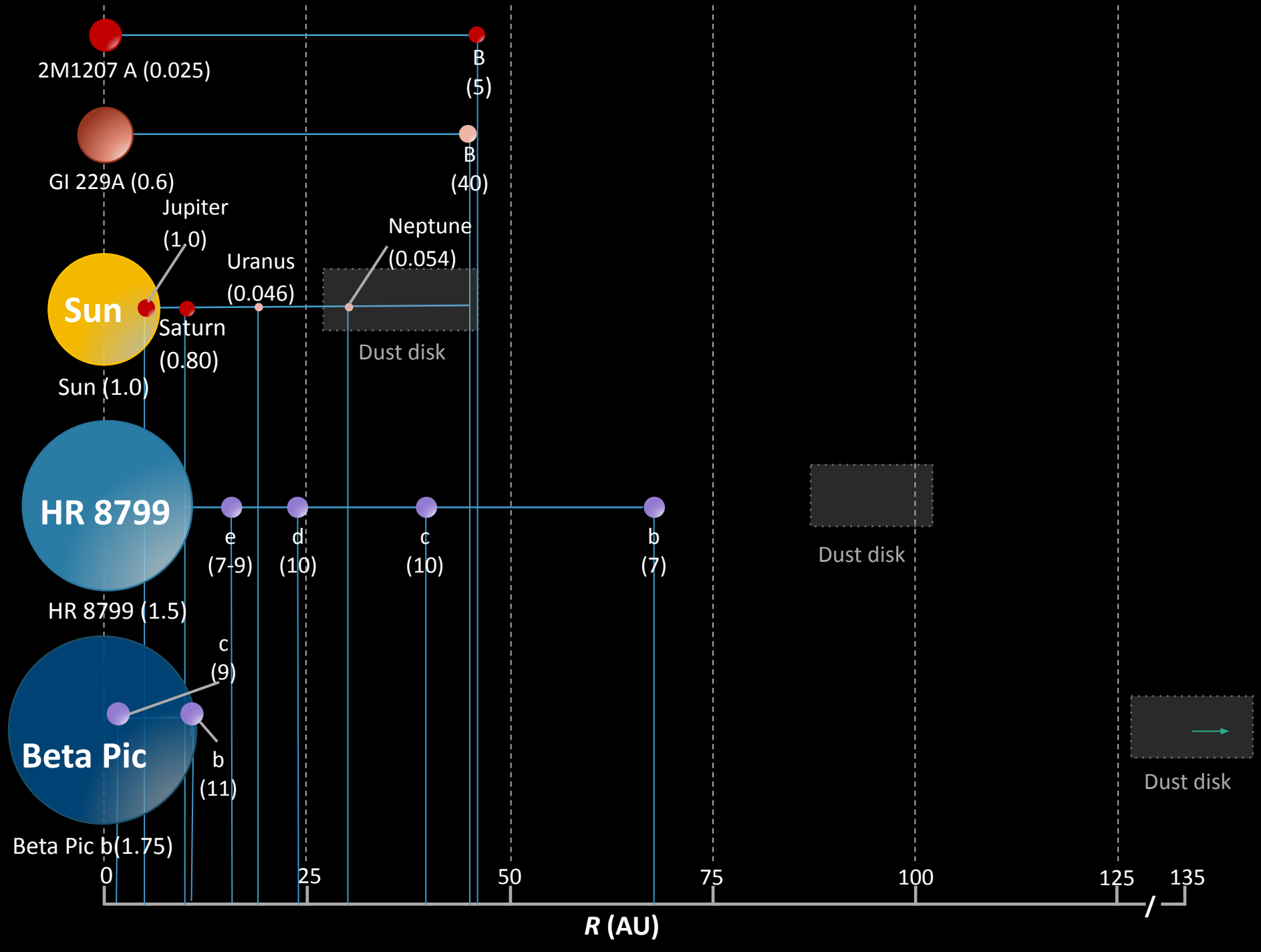
Moderate Resolution Spectroscopy of Directly Imaged Planets

Dr. Kielan K. W. Hoch

ExoPAG 27

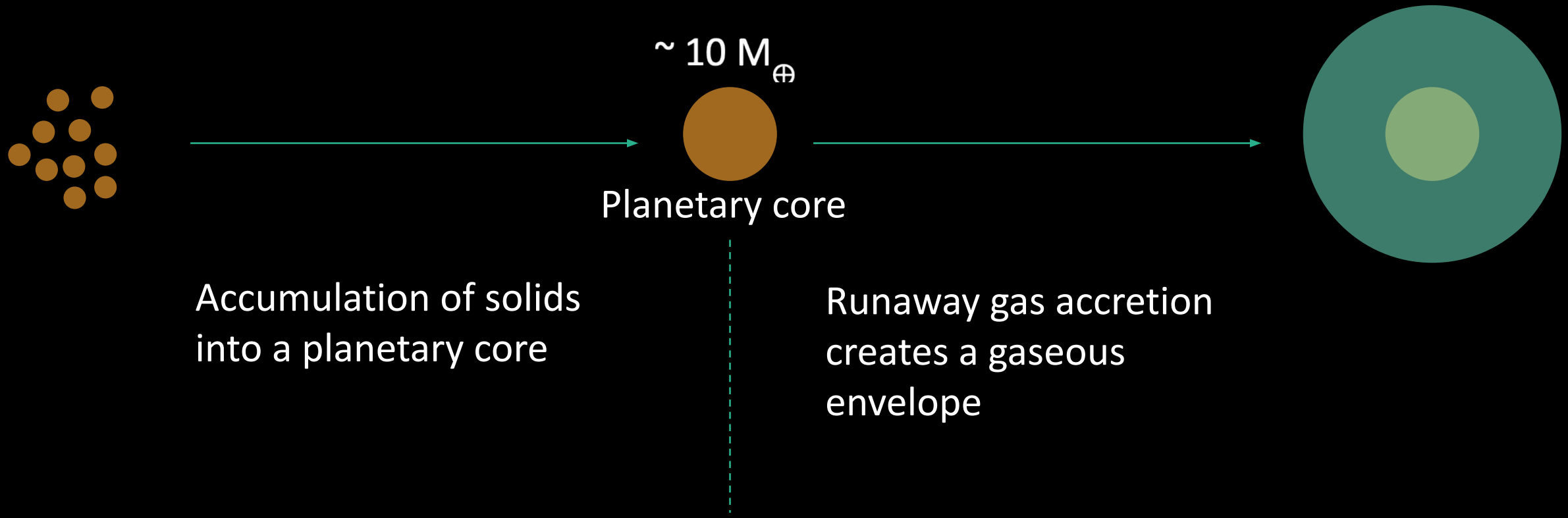
CASS

Direct Imaging has Revealed …



Core Accretion Scenario

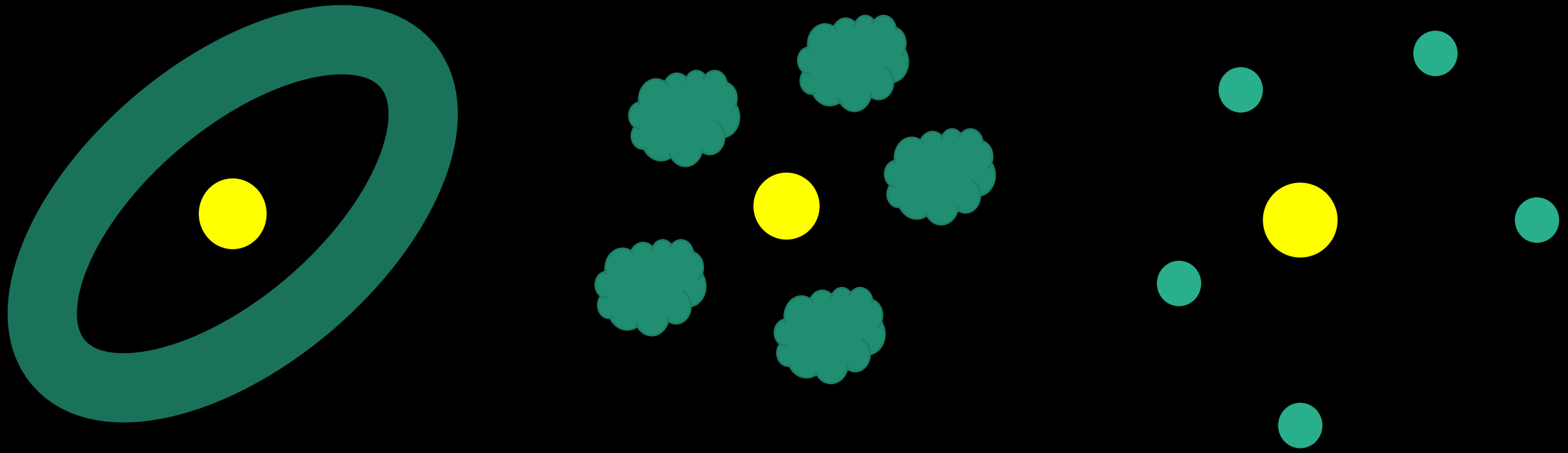
- The metallicity of planets should be enhanced



Öberg et al. (2011)

Gravitational Instability

- The metal content should be roughly the same as the host star



Protoplanetary disk

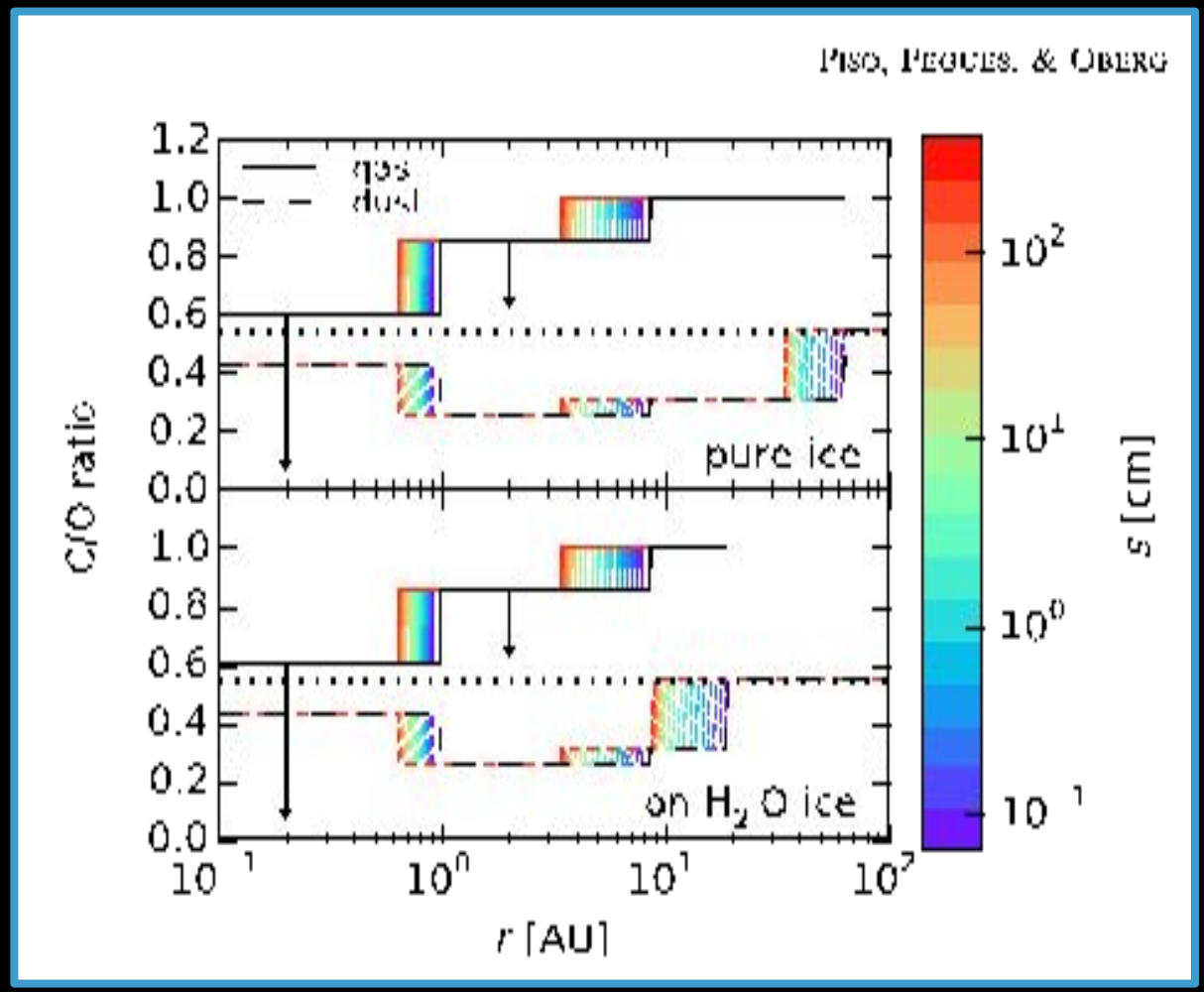
Gravitational instabilities cause clumping

Gaseous planets form

Öberg et al. (2011)

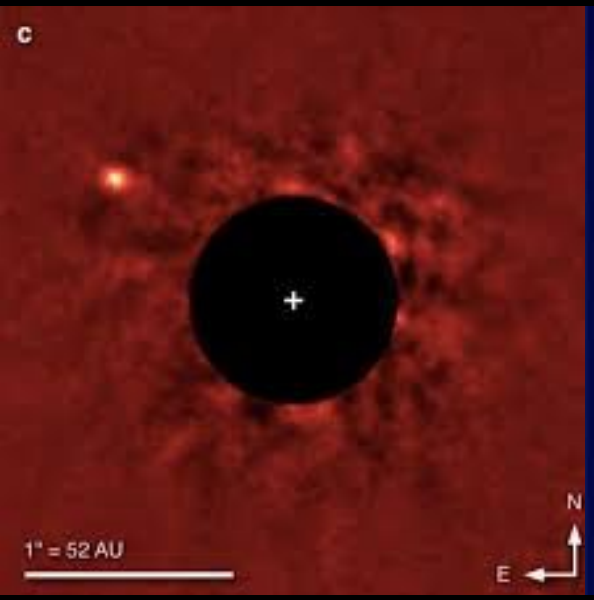
C/O Ratios

- If the *atmosphere* of a giant planet is *accreted after* the formation of a solid core enhanced C/O ratio relative to the host star
- If the planet forms through gravitational collapse the separation of solids and gases is irrelevant and the C/O ratio should be similar to the host star

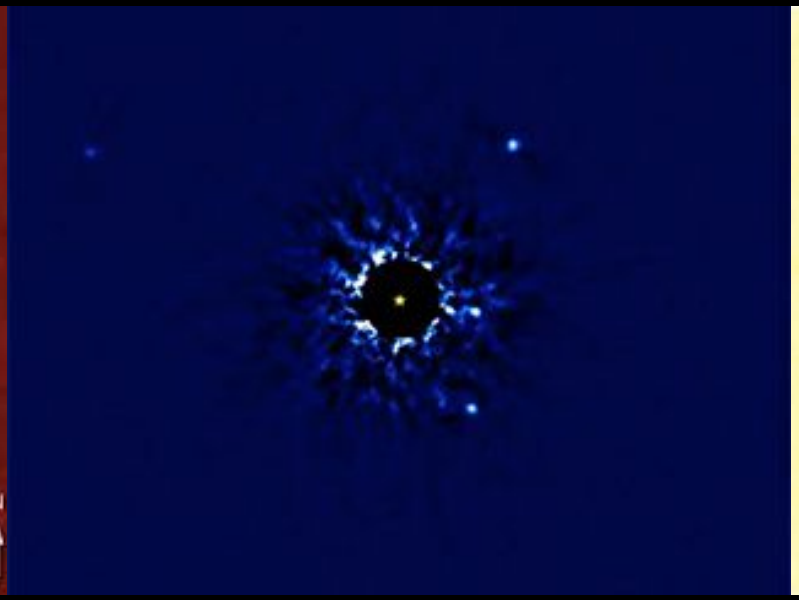


(Piso et al. 2016) C/O ratio estimates in gas (solid lines) and dust (dashed lines) as function of semimajor axis in a viscous disk, for CO as pure ice (top panel) or as water-dominated ices (bottom panel).

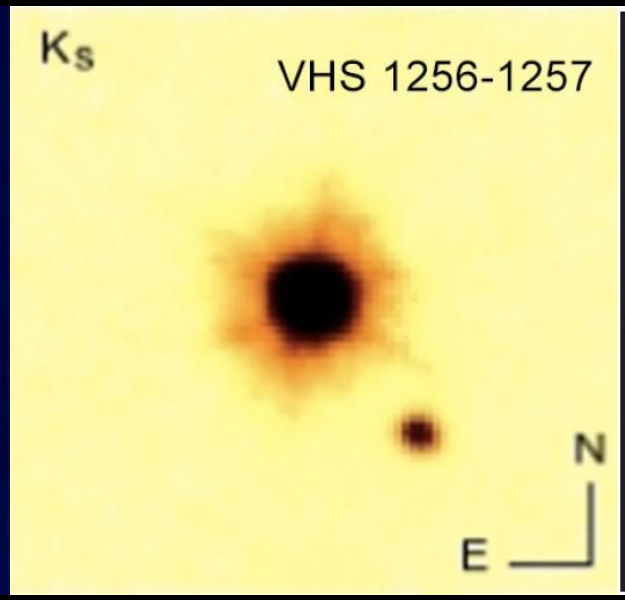
Imaging Spectroscopy Survey of Exoplanetary Atmospheres with Keck/OSIRIS



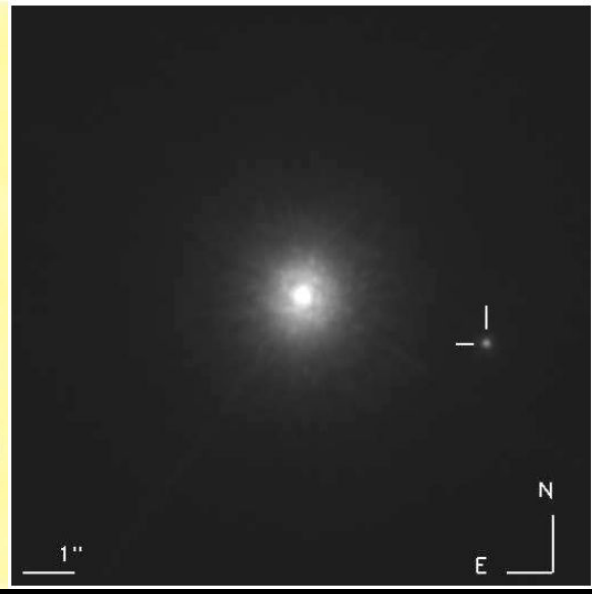
Carson et al. 2013



Jason Wang

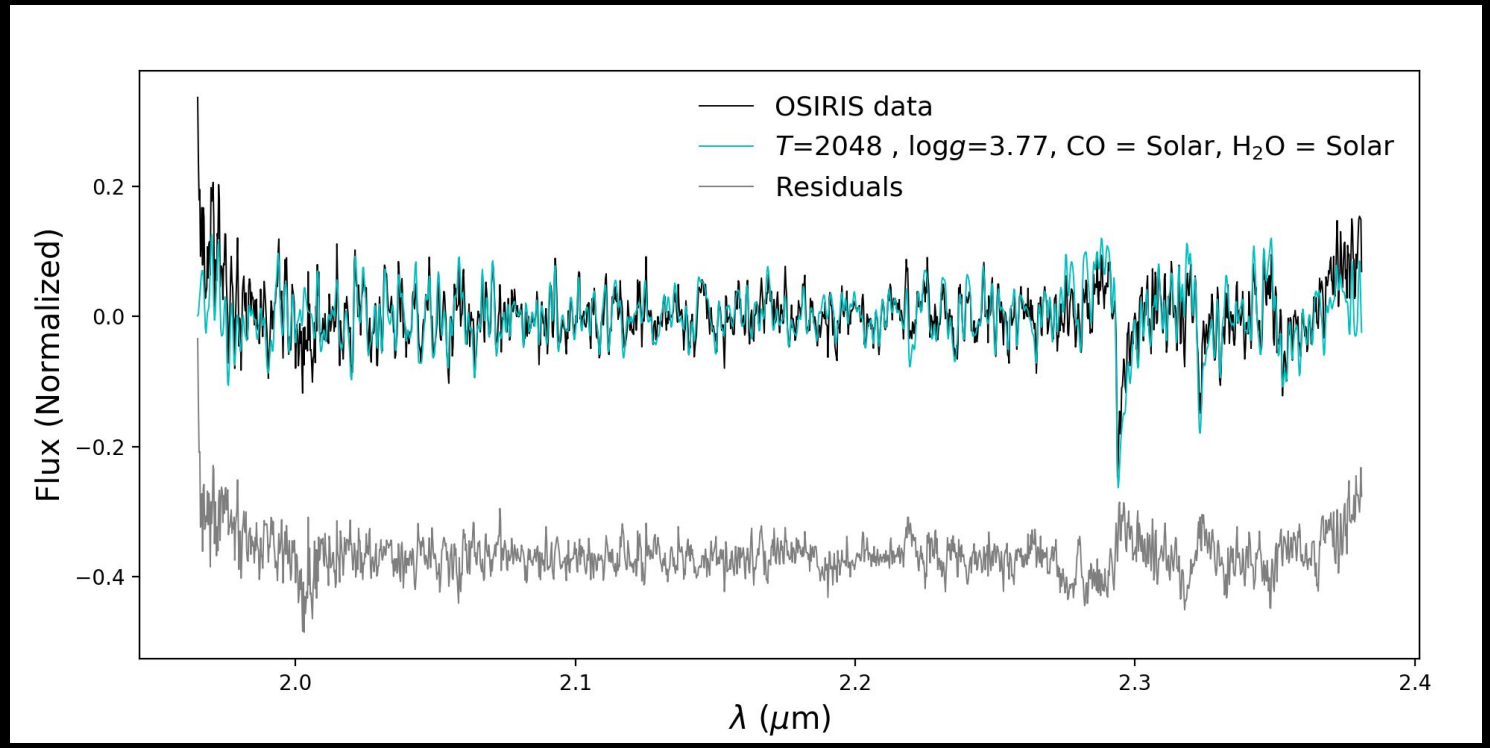


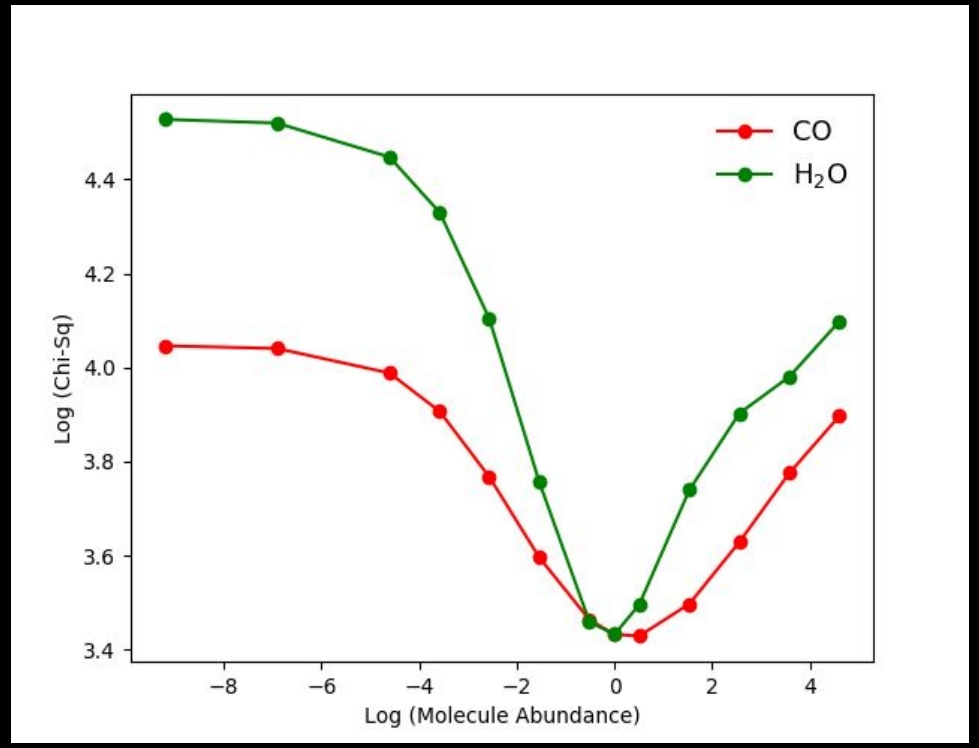
Gauza et al. 2015



Bonavita et al. 2014

Chi Squared CO and H_2O Mole Fractions





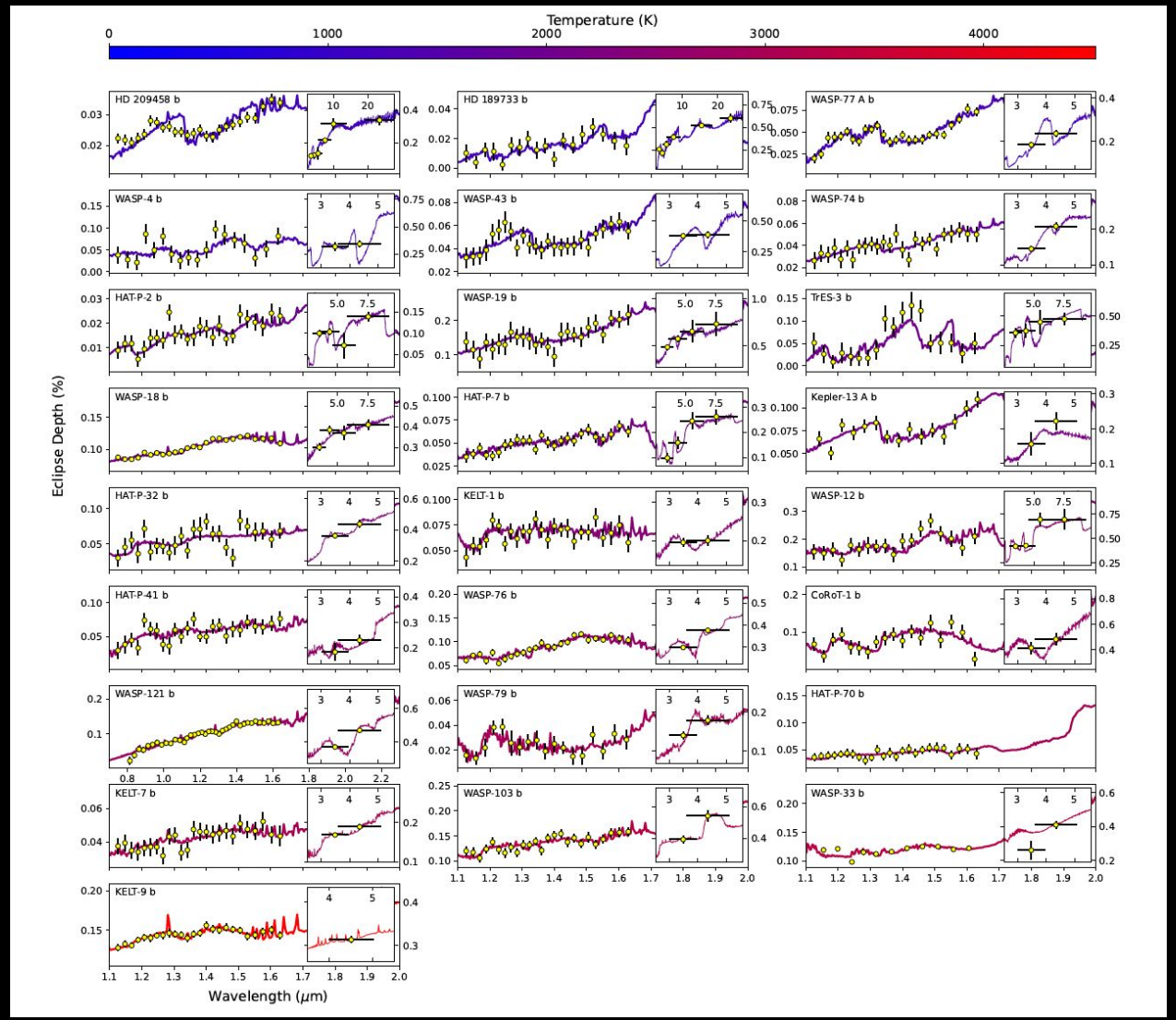
$$C/O = 0.704^{+0.09}_{-0.24}$$

C/O Ratios For Current Directly Imaged Planets

- Recent works on what could impact C/O:
  - The grain size distribution (Piso et al. 2015)
  - Migration of grains/pebbles (Booth et al. 2017)
  - Migration of planets (Cridland et al. 2020)
  - Accreted material from the midplane (Morbidelli et al. 2014; Batygin 2018)

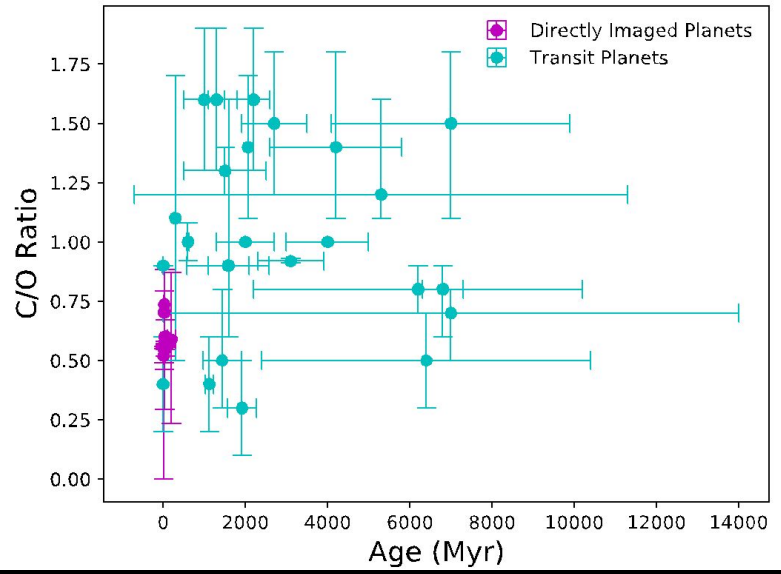
Planet	C/O	Reference	Host C/O
Kappa And b	0.704	Wilcomb et al. 2020	No
VHS 1256 b	0.590	Hoch et al. 2022	No
HD 284149	0.737	Hoch et al. submitted	No
HR 8799 b	0.578	Ruffio et al. 2021	0.5
HR 8799 c	0.562	Ruffio et al. 2021	0.5
HR 8799 d	0.551	Ruffio et al. 2021	0.5
HR 8799 e	0.60	Molliere et al. 2020	0.5
HIP 65426 b	≤0.55	Petrus et al. 2021	No
TYC 8998-760-1 b (YSES-1 b)	0.52	Zhang et al. 2021	No
AB Pic b	0.58	Palma-Bifani et al. 2022	No

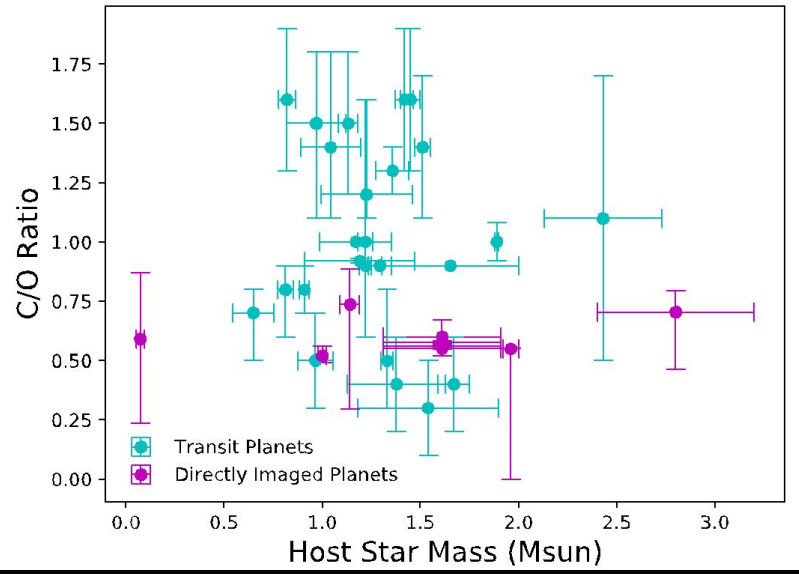
Some Transit planets have derived C/O ratios

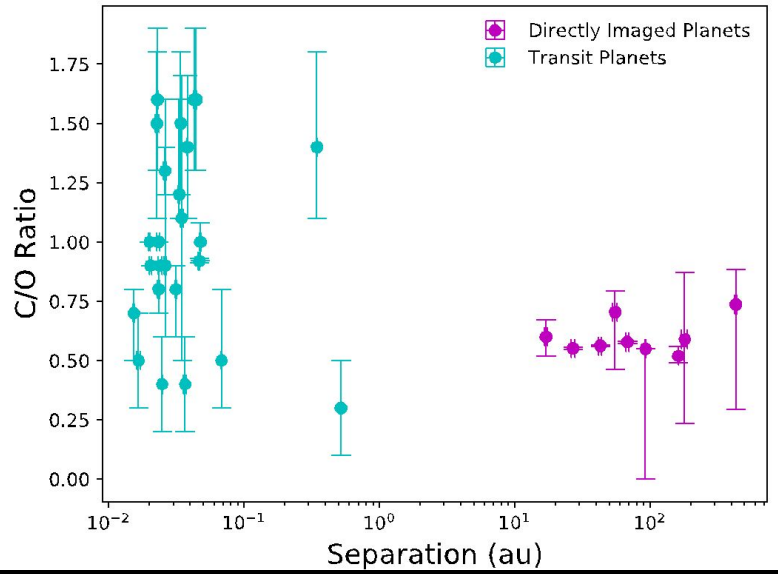


Changeat et al. 2022

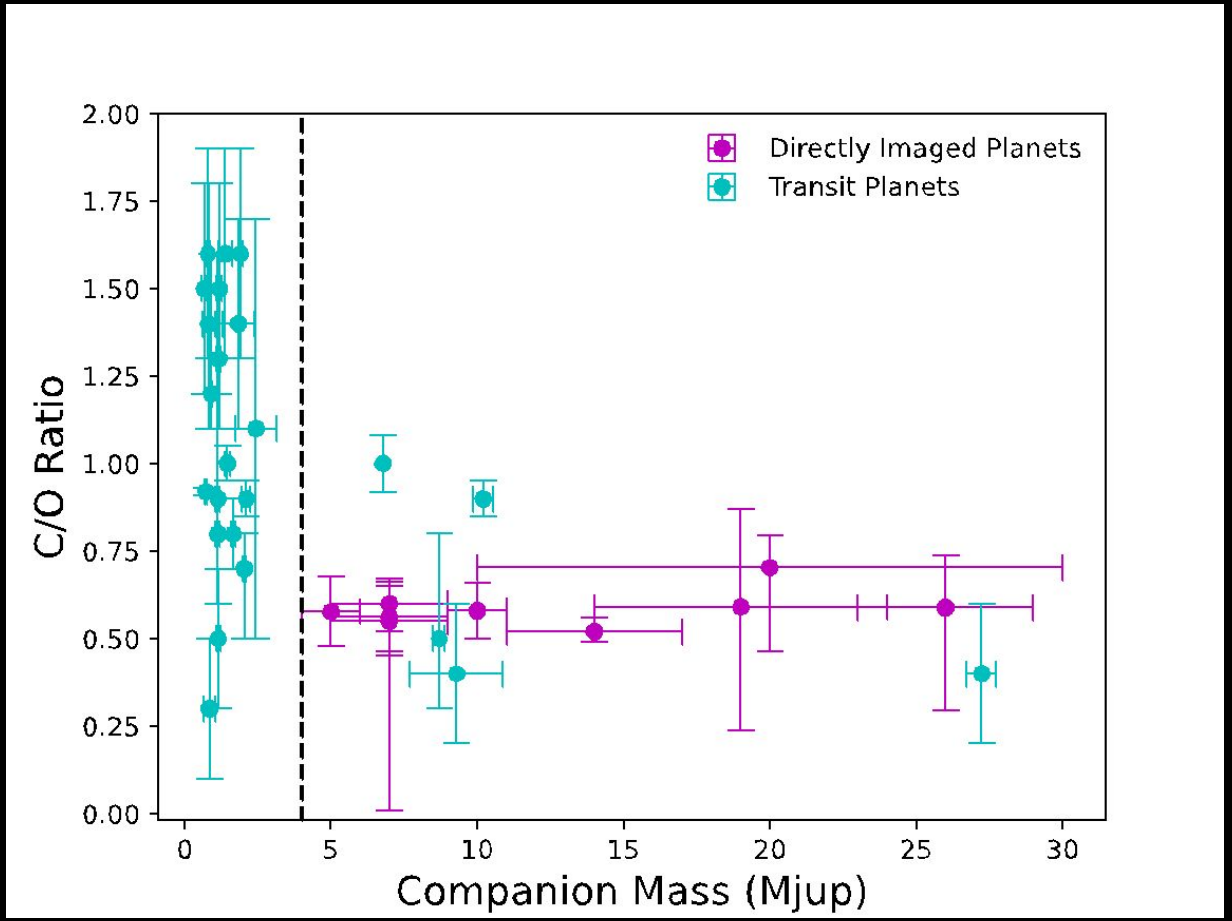
Comparisons of C/O ratios against system parameters





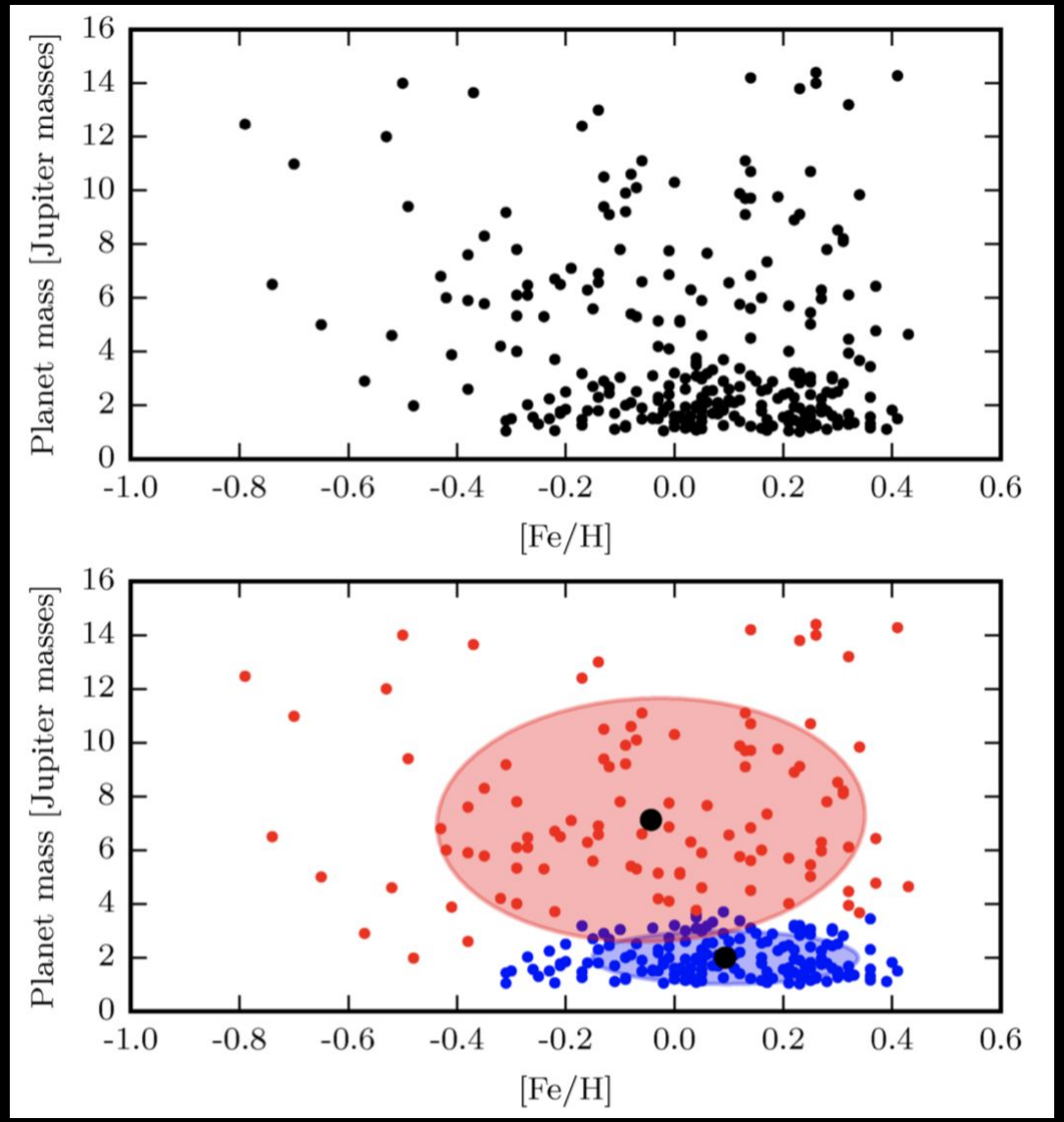


Possible trend between C/O and Companion Mass



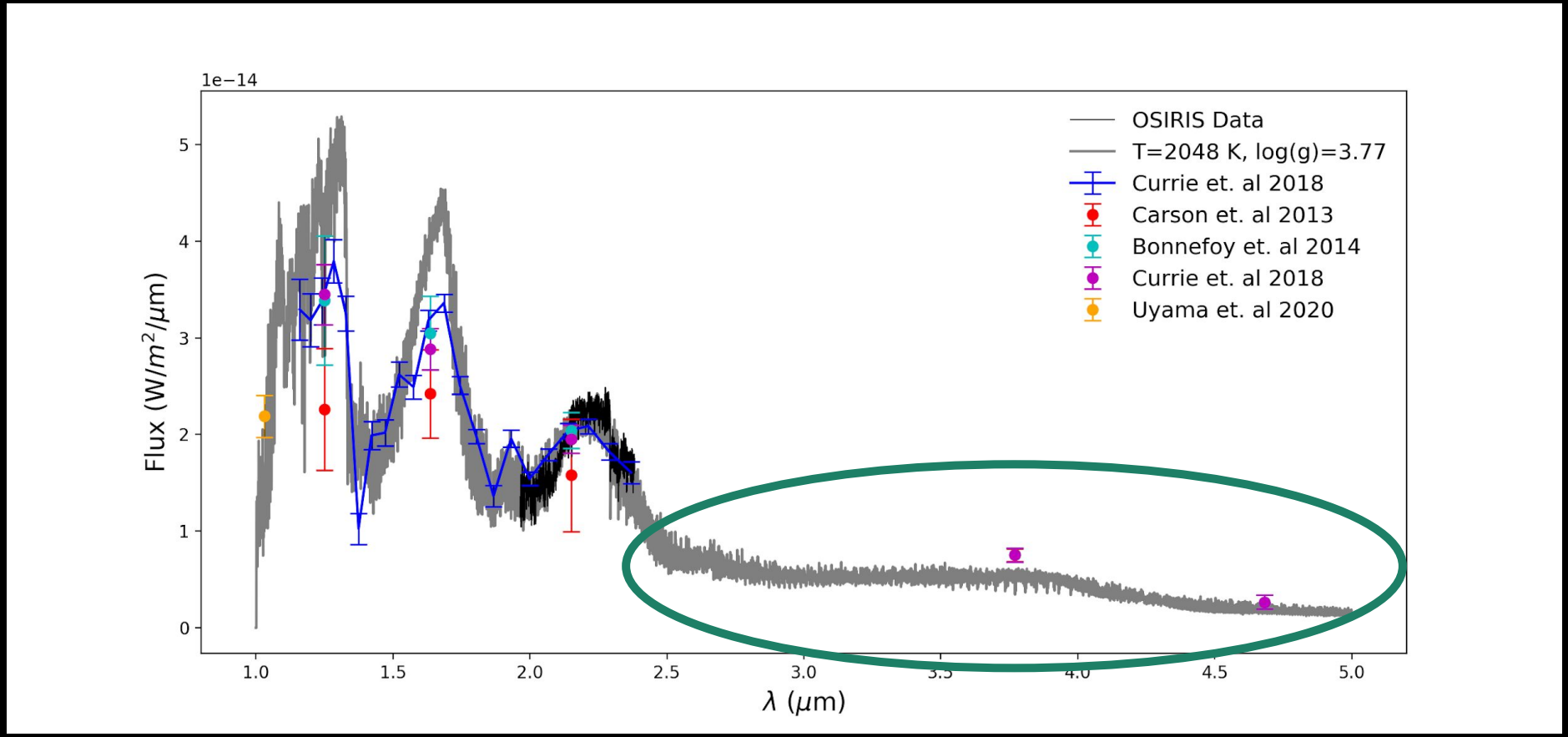
Hoch et al. submitted

Metallicity could also tell us about formation

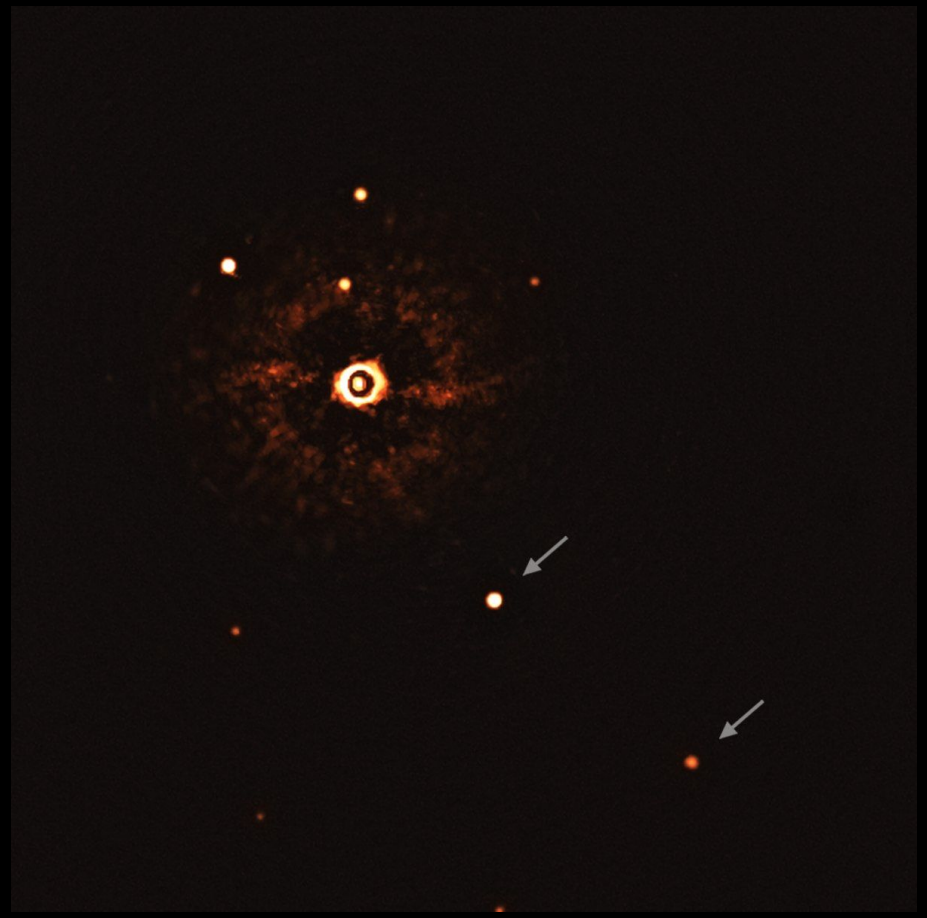


Santos et al. 2017

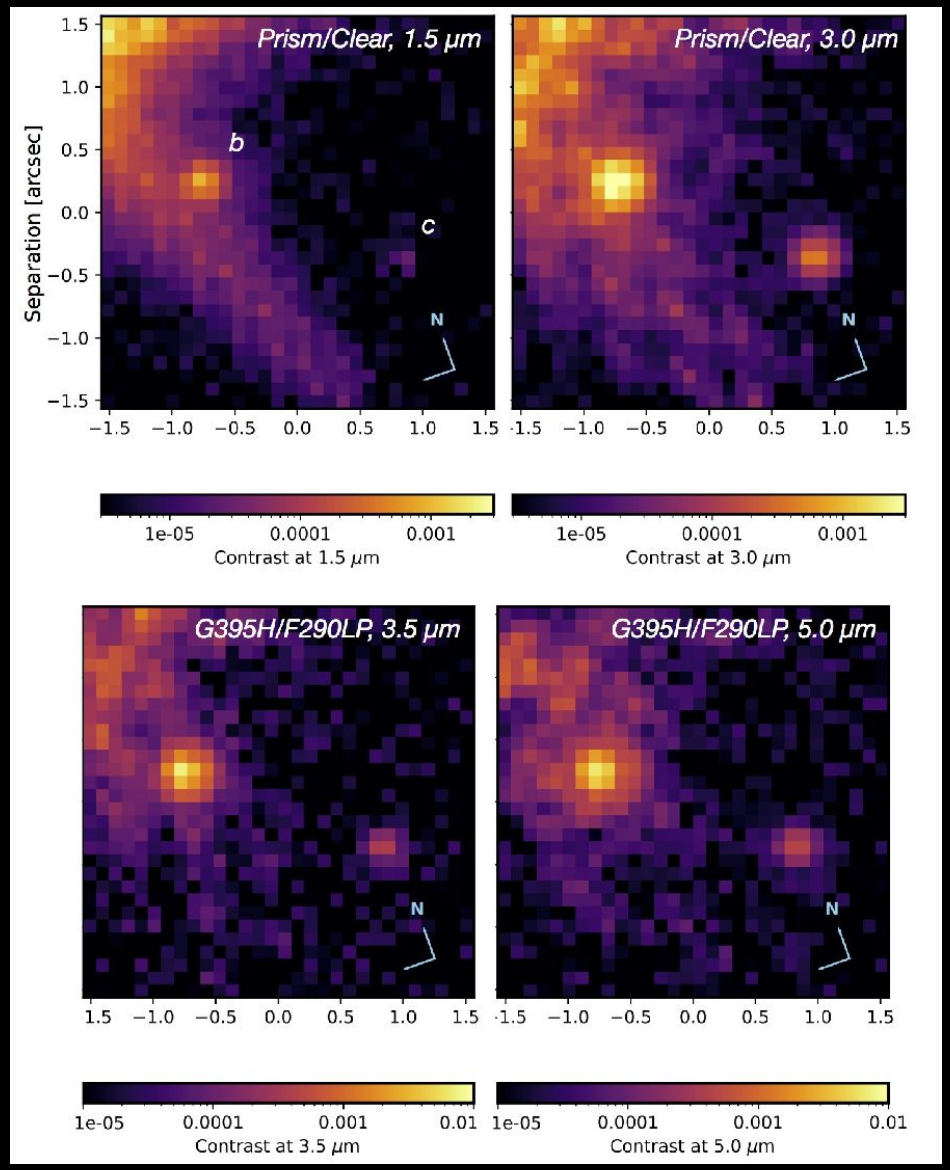
Ground-based Observations can only go so far…



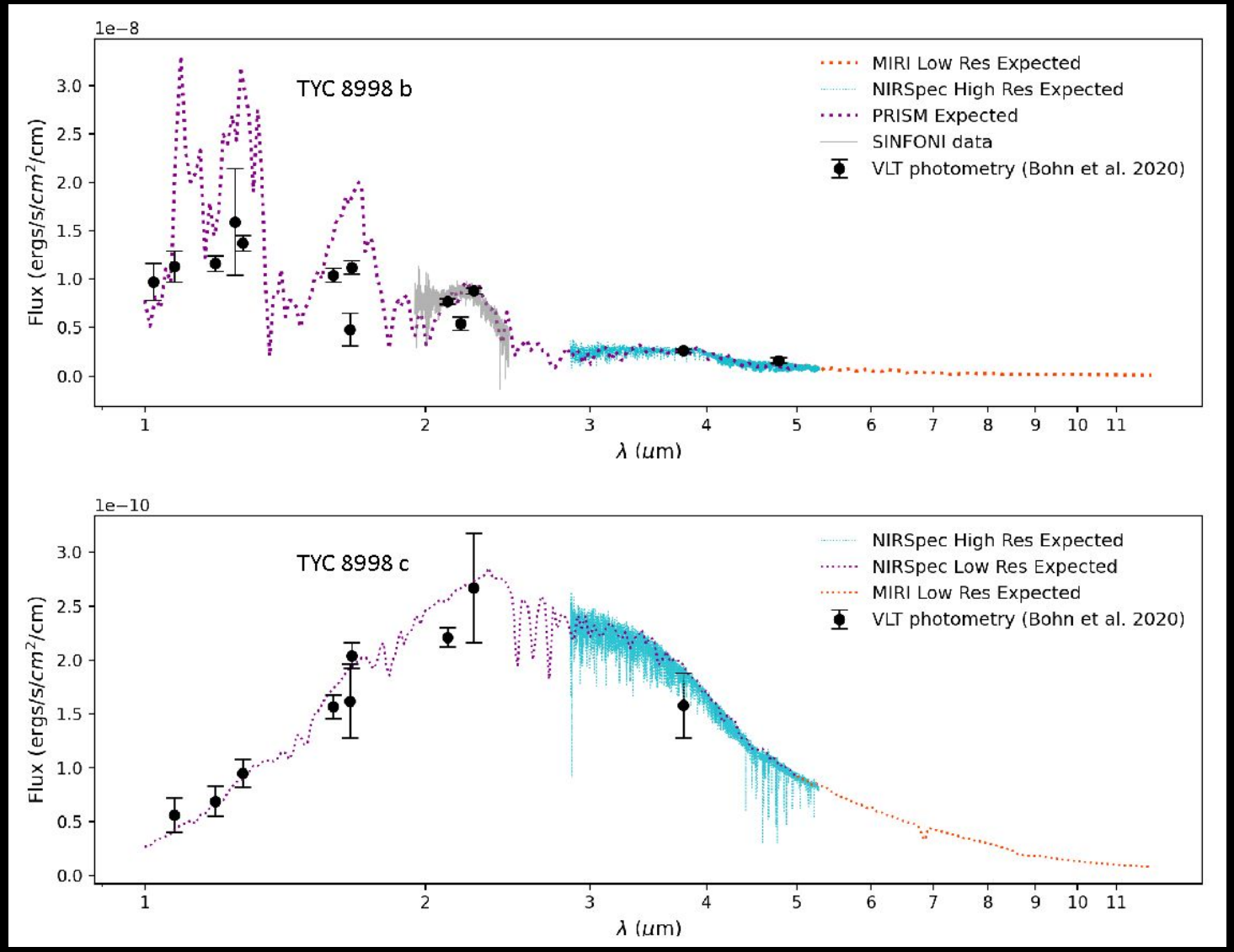
Characterization of the TYC 8998-760-1 (YSES-1) Multi-Planetary System



Bohn et al. 2020

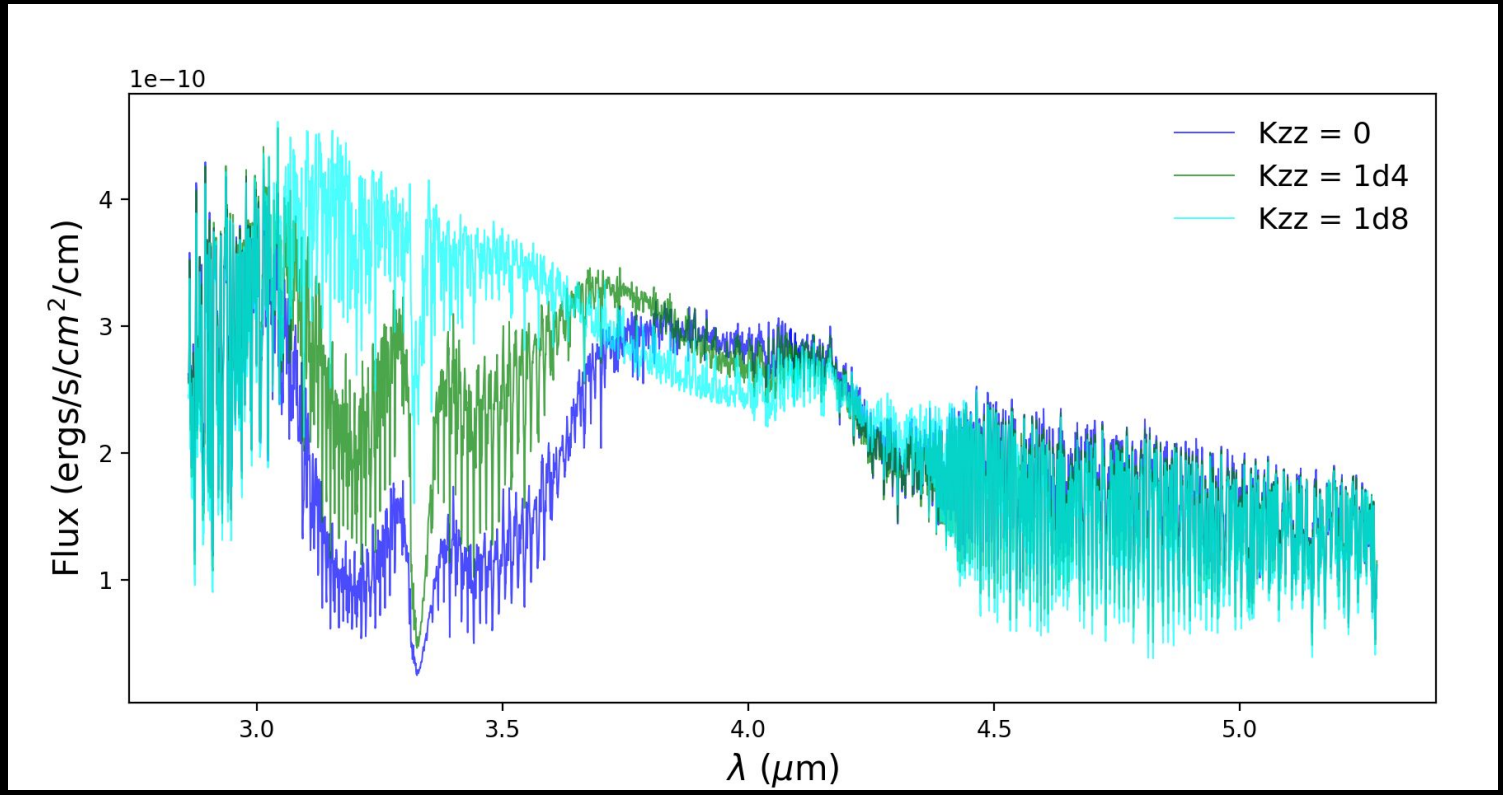


Expected Spectral Return

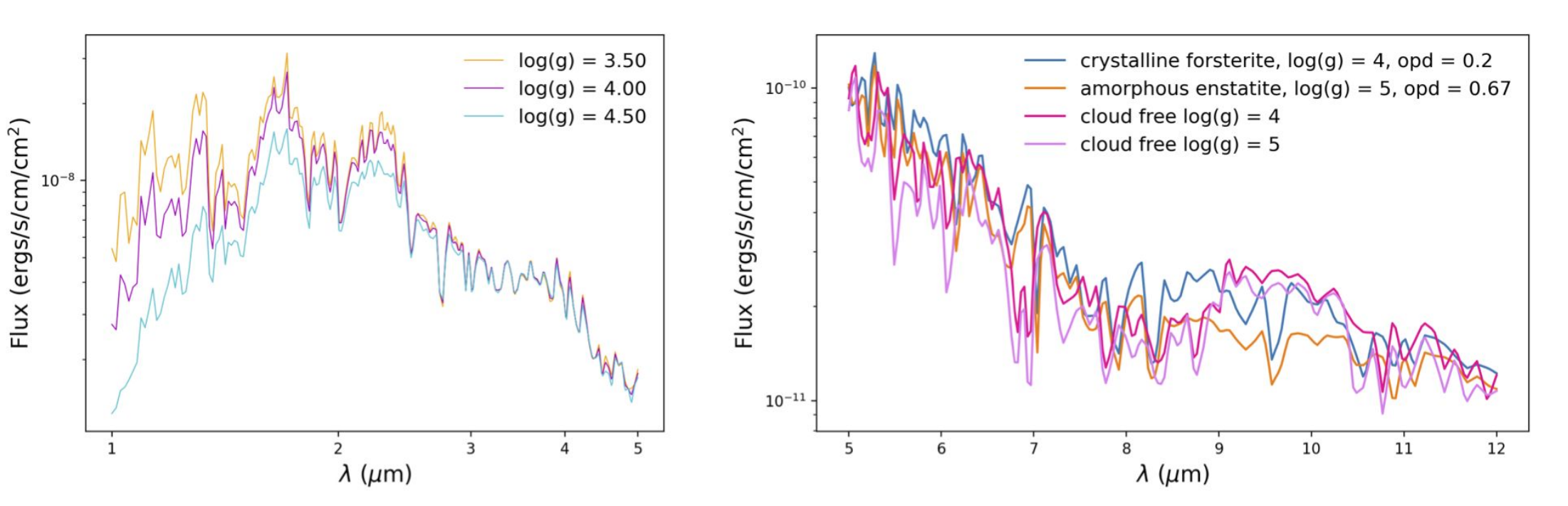


Moderate Resolution Spectroscopy: Detailed Chemistry

- Critical regime for diagnosing non-equilibrium chemistry between CO and CH4
- Vertical mixing (parametrized by Kzz), can displace methane from the photosphere with warmer, CO-dominated gas
- Constrained Kzz will allow for accurate measurement of C/O



Low-resolution spectroscopy: temperature, gravity, clouds, and more

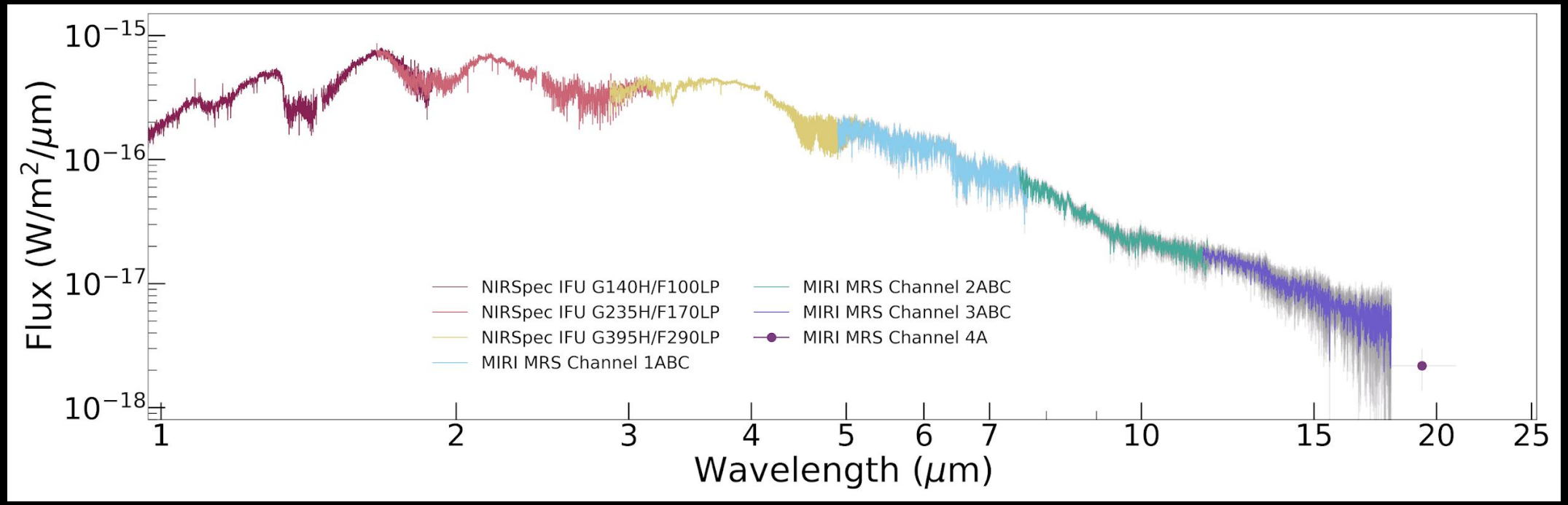


Models of TYC 8998 c: Low-resolution models varying in surface gravity and cloud properties

Summary

- Imaging Spectroscopy Survey of Exoplanetary Atmospheres with Keck/OSIRIS: measured C/O ratios of 6 of the 10 directly imaged planets with C/O ratios
- C/O ratios of host stars are needed for the full diagnostic
- C/O ratio may not tell us as much as previously hoped about formation
- C/O ratio and metallicity could reveal two distinct populations of exoplanets that could be coupled with how they formed
- JWST/space based observatories and future ground-based observatories will further constrain these measurements

JWST opens up spectroscopy beyond 3 microns



Miles et. al 2022