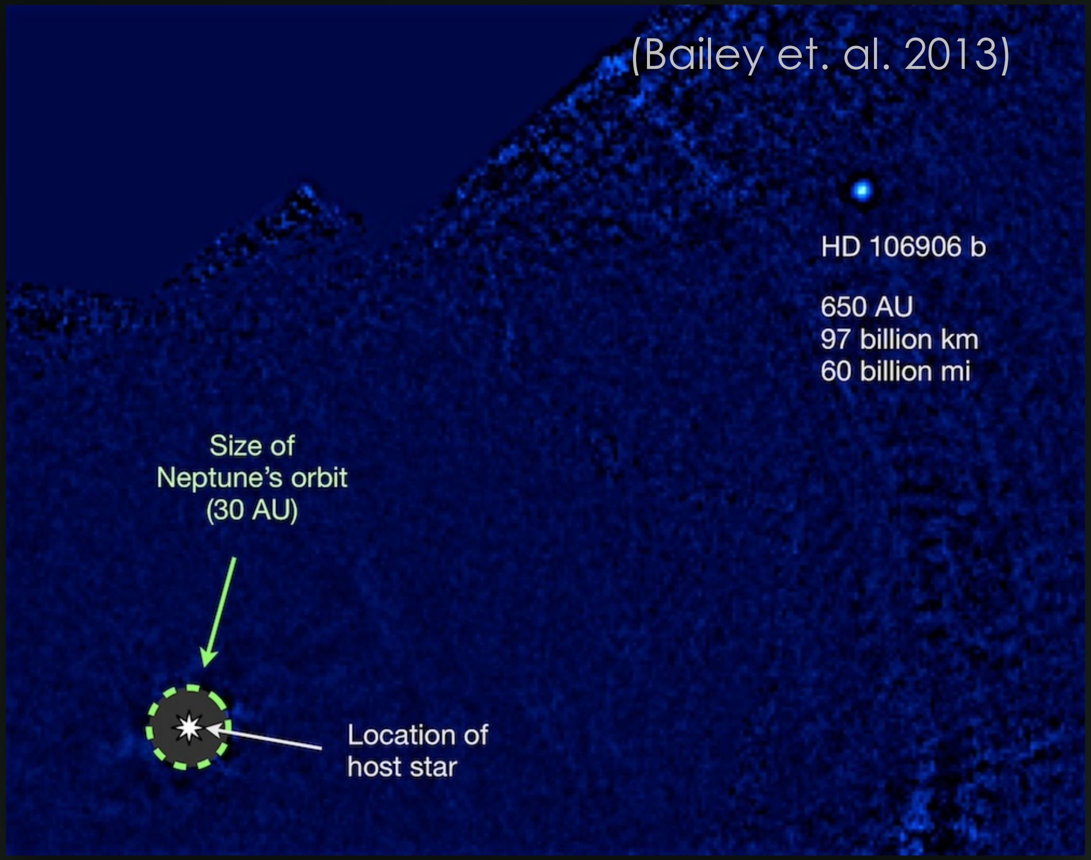
Constraining Formation Pathways for Widely Separated Companions



Arthur Adams, Michael Meyer (University of Michigan),
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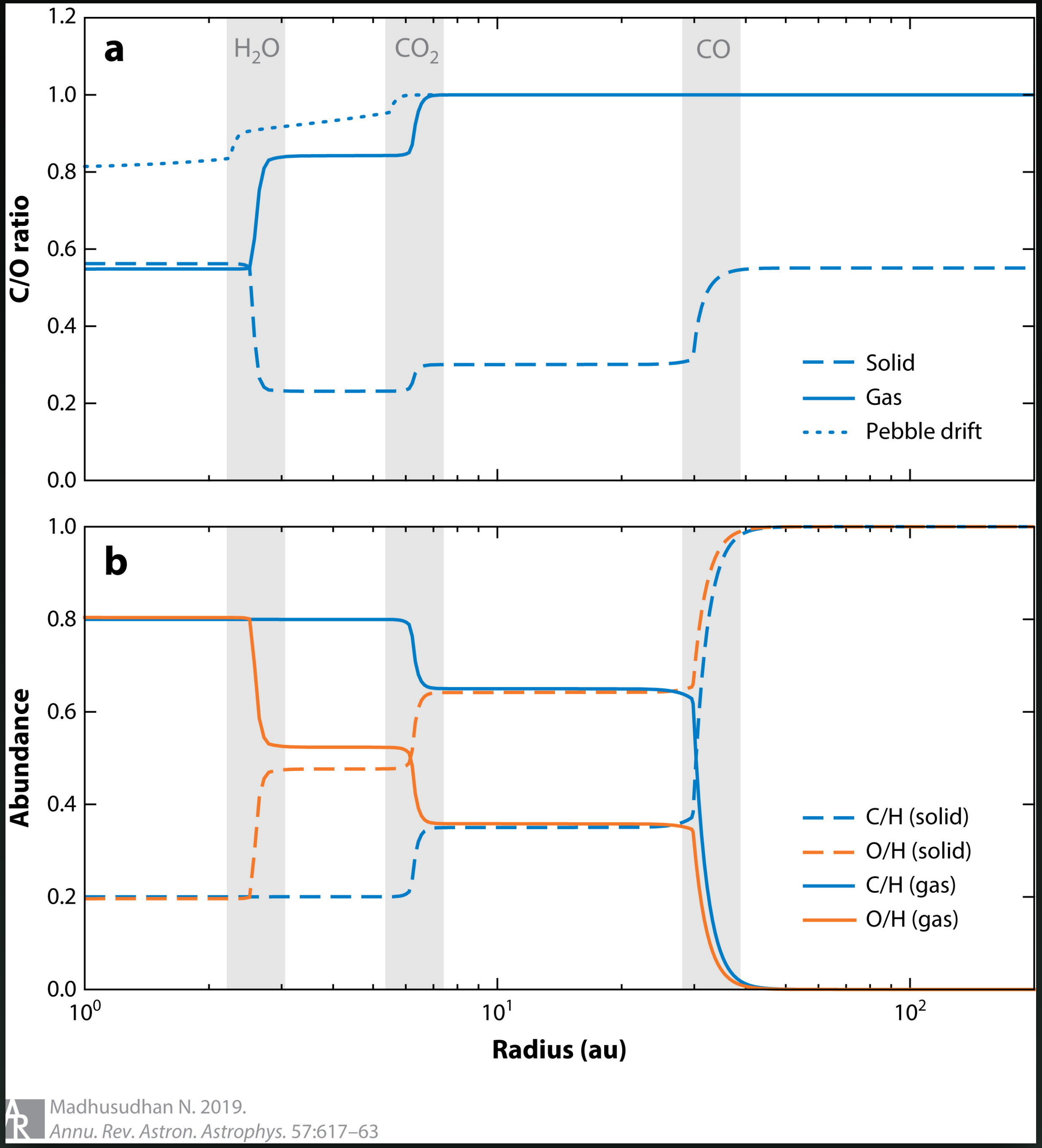
With special thanks to: Natasha Batalha (NASA Ames), Michael Line (ASU), Jonathan Fortney (UCSC), Mark Marley (NASA Ames), Ben Burningham (U. Hertfordshire)

C/O Ratios can Distinguish Formation Pathways

- Core accretion + migration encodes chemical evolution in disk: **O enhanced**



Madhusudhan et. al. (2019)

C/O Ratios can Distinguish Formation Pathways

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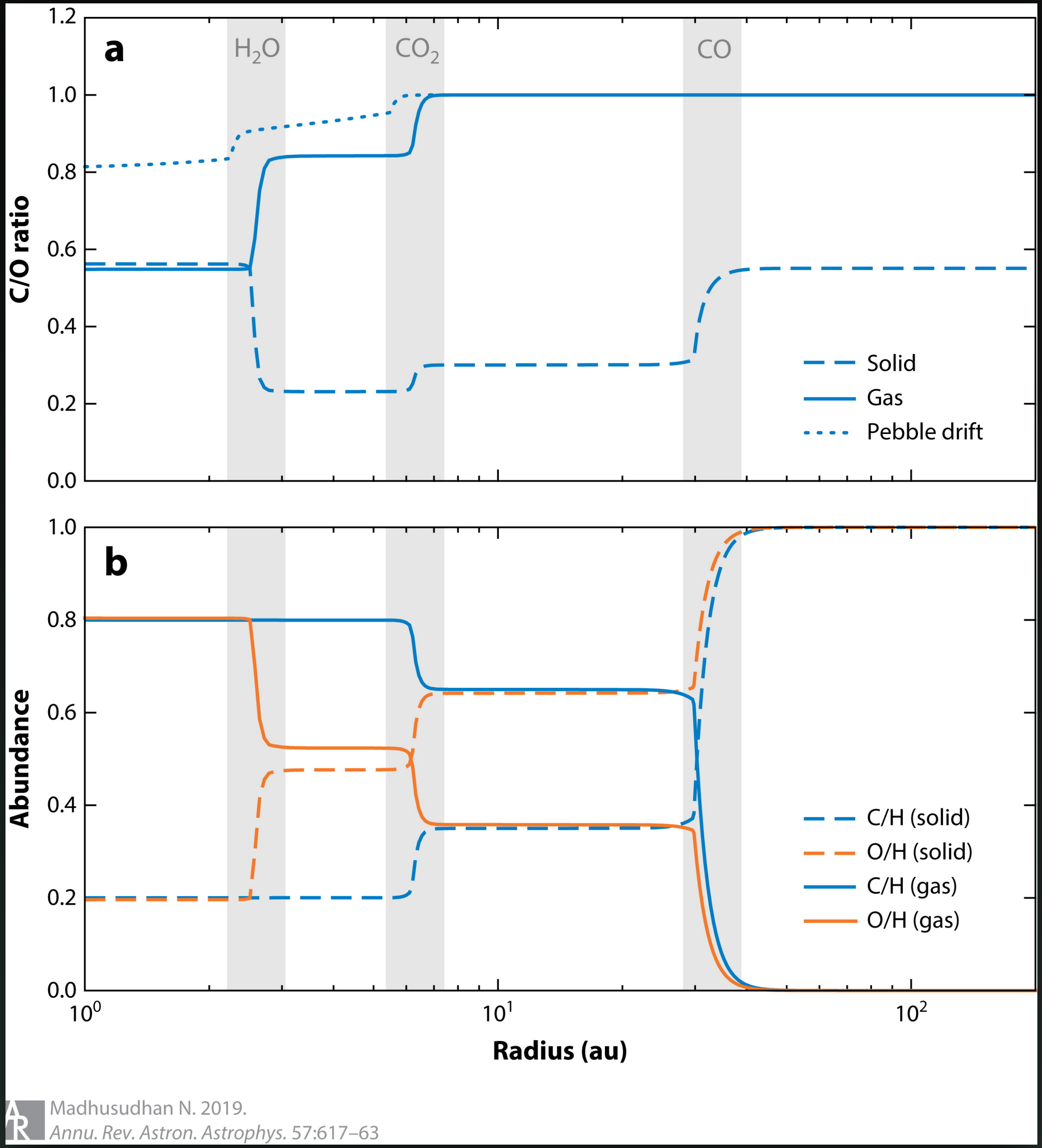
- Accretion at large separations can also push C/O → 1
- Gravitational instability (mostly) preserves **primordial C/O**



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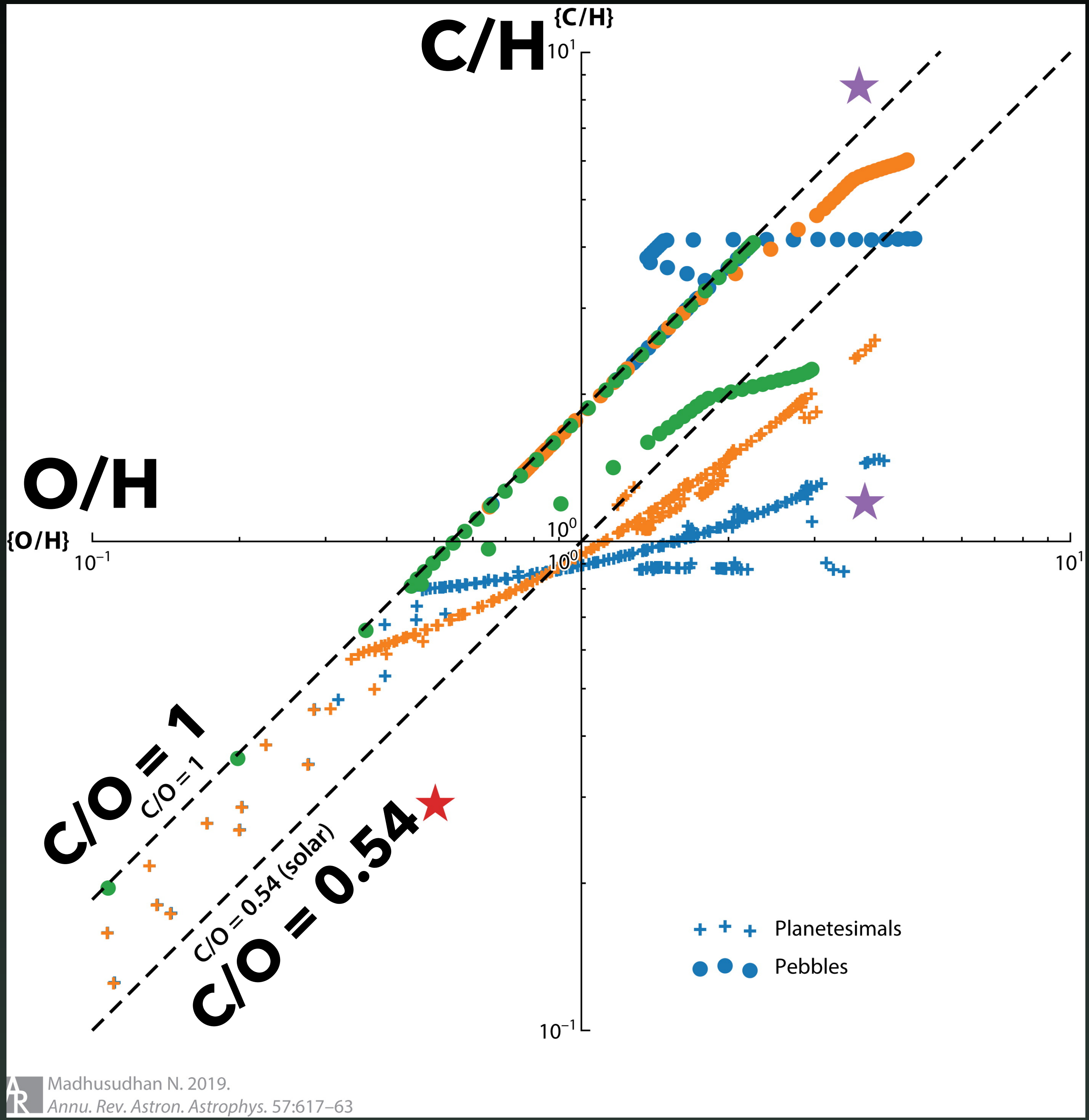
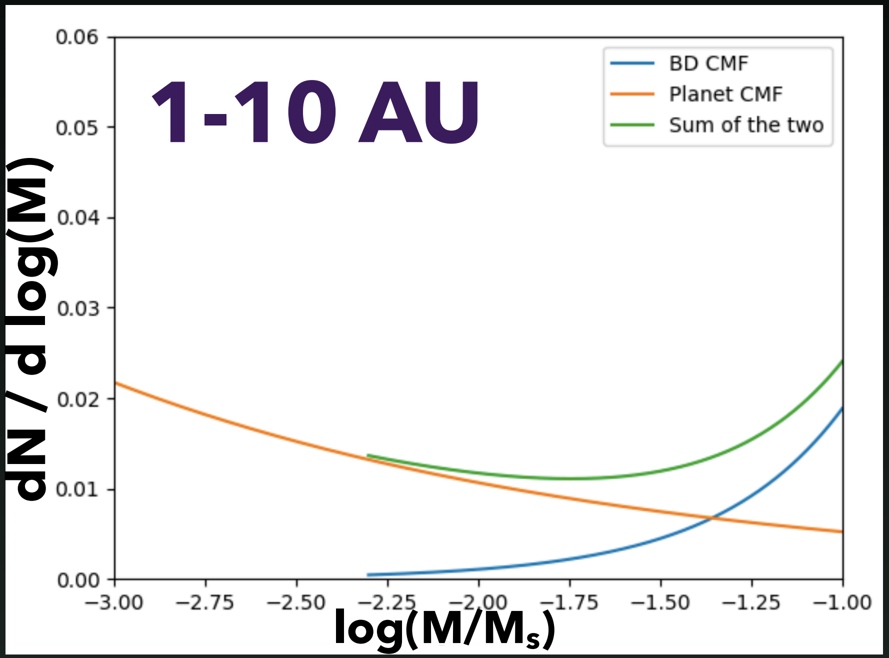
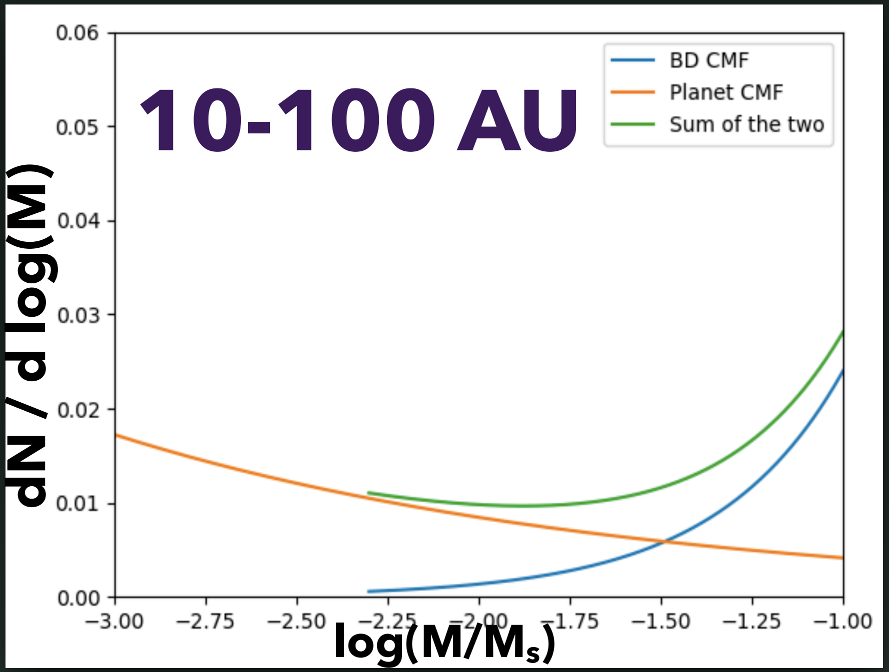


Madhusudhan et. al. (2019)

Bridging Planetary vs. Stellar Formation: Intermediate Masses

- RV, microlensing probe low-mass companions at 1-10 AU (Suzuki+ 2016, Wittenmyer+)
- Direct imaging > 10 AU (Reggiani+2016, Vigan+2017, Nielsen+2019)
- Minimum in combined planet/BD mass function at **log(M/M$_s$) ~ -1.7** (~20 M$_J$ for solar host) (Sahlmann+2011, Shvartzwald+2016)

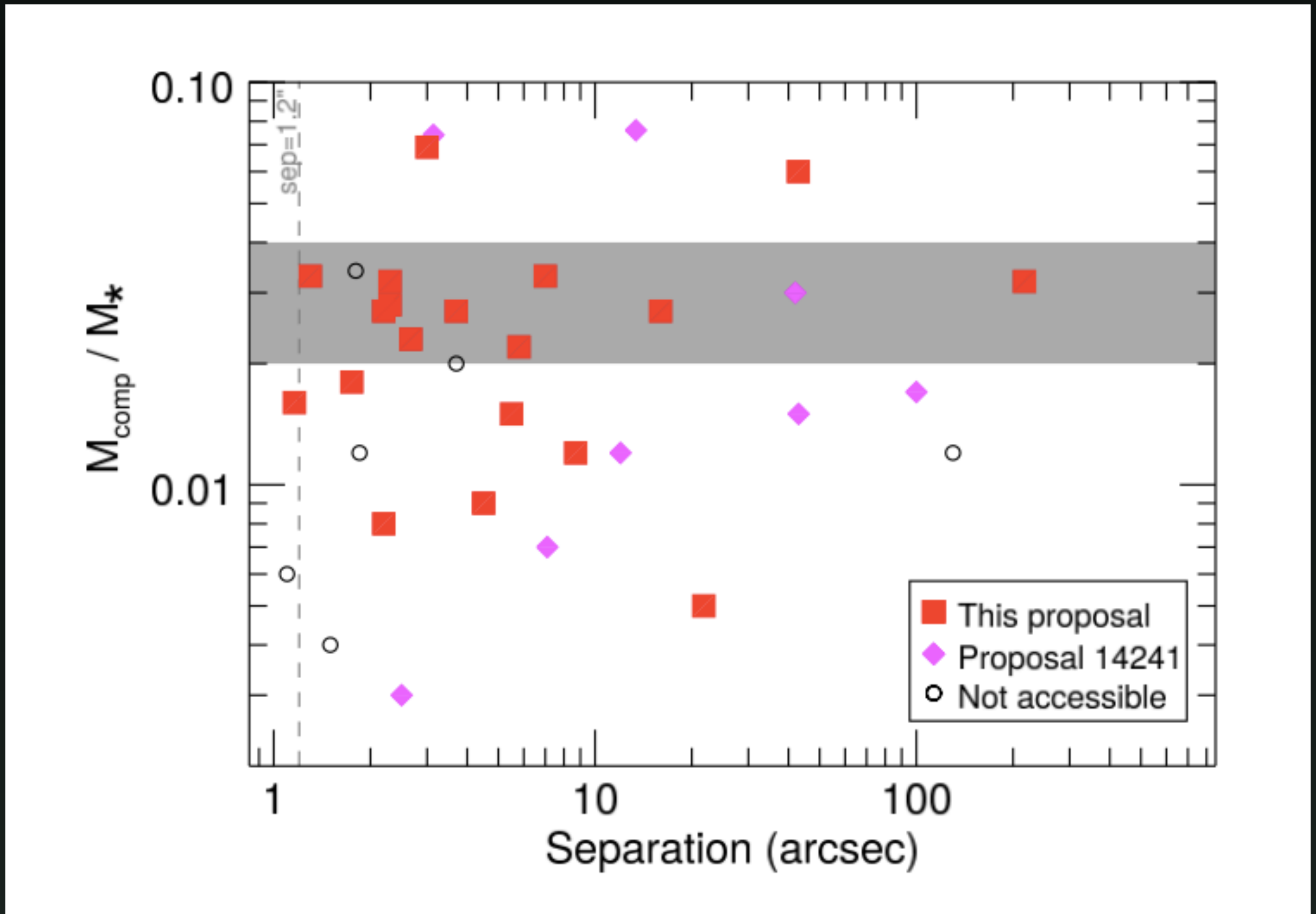




Meyer, Amara, Susemiehl, & Peterson (in prep)

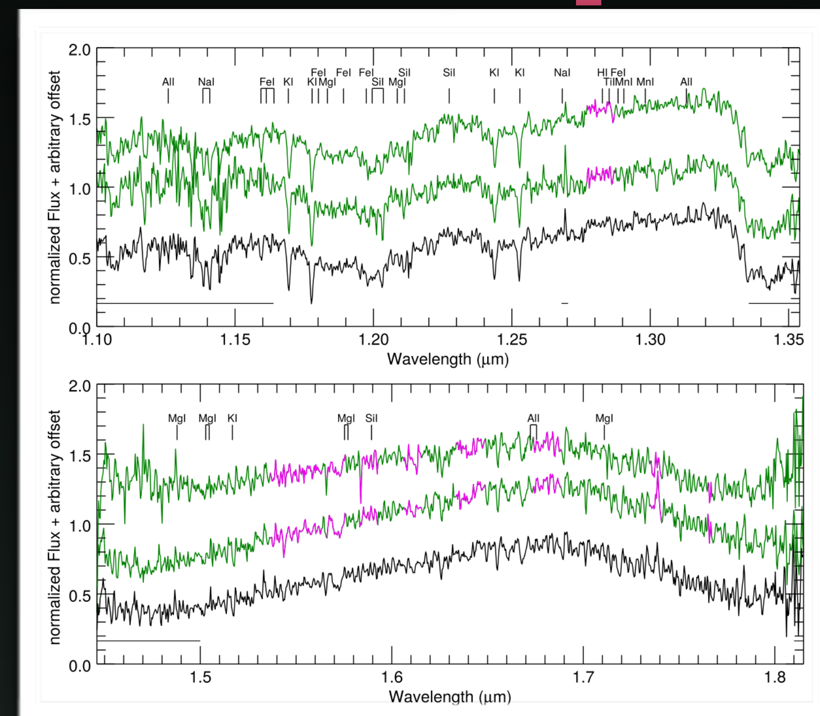
Bridging Planetary vs. Stellar Formation: Intermediate Masses

- Mutual minima in planet/BD mass functions at **log(M/M_s) ~ -1.7** (~20 M_J for solar host)
- Target selection: **M/M_s ~ 0.01** (trade-off between target selection and preferred mass ratio)

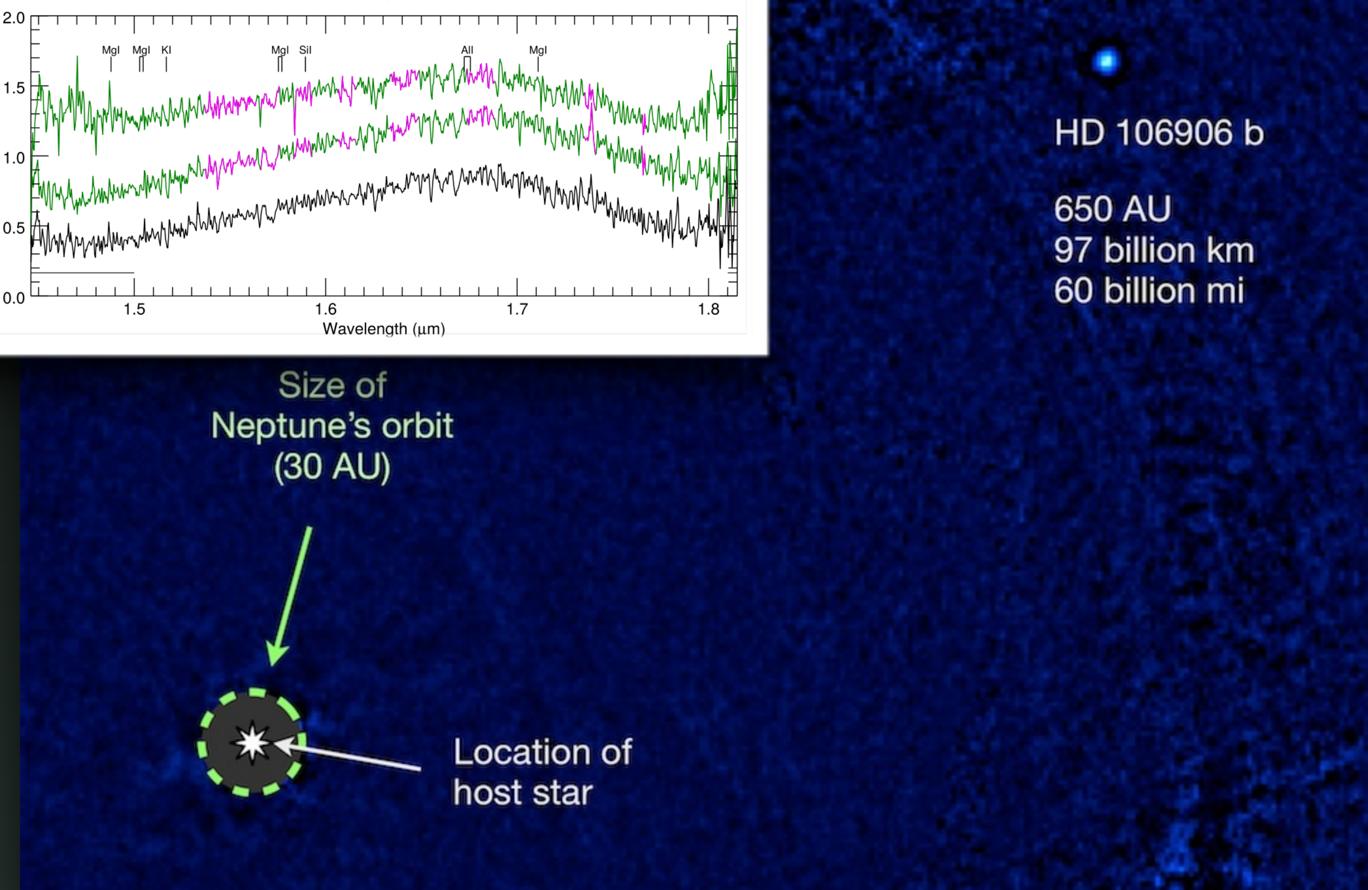


Characterizable Targets: Young, Distant Companions

- HD 106906 b
  - Host: F5 dwarf with debris disk
  - Age: 13 Myr
  - Distance: 92 pc
  - Companion: L1.5 BD (or giant planet)
  - Separation: 7.1″ (650 AU projected)
  - Temperature: 1820 K
  - Mass: 12-14 M_J (~0.01 of host)
- JHK spectrum from VLT/SINFONI (Daemgen et al. 2017)



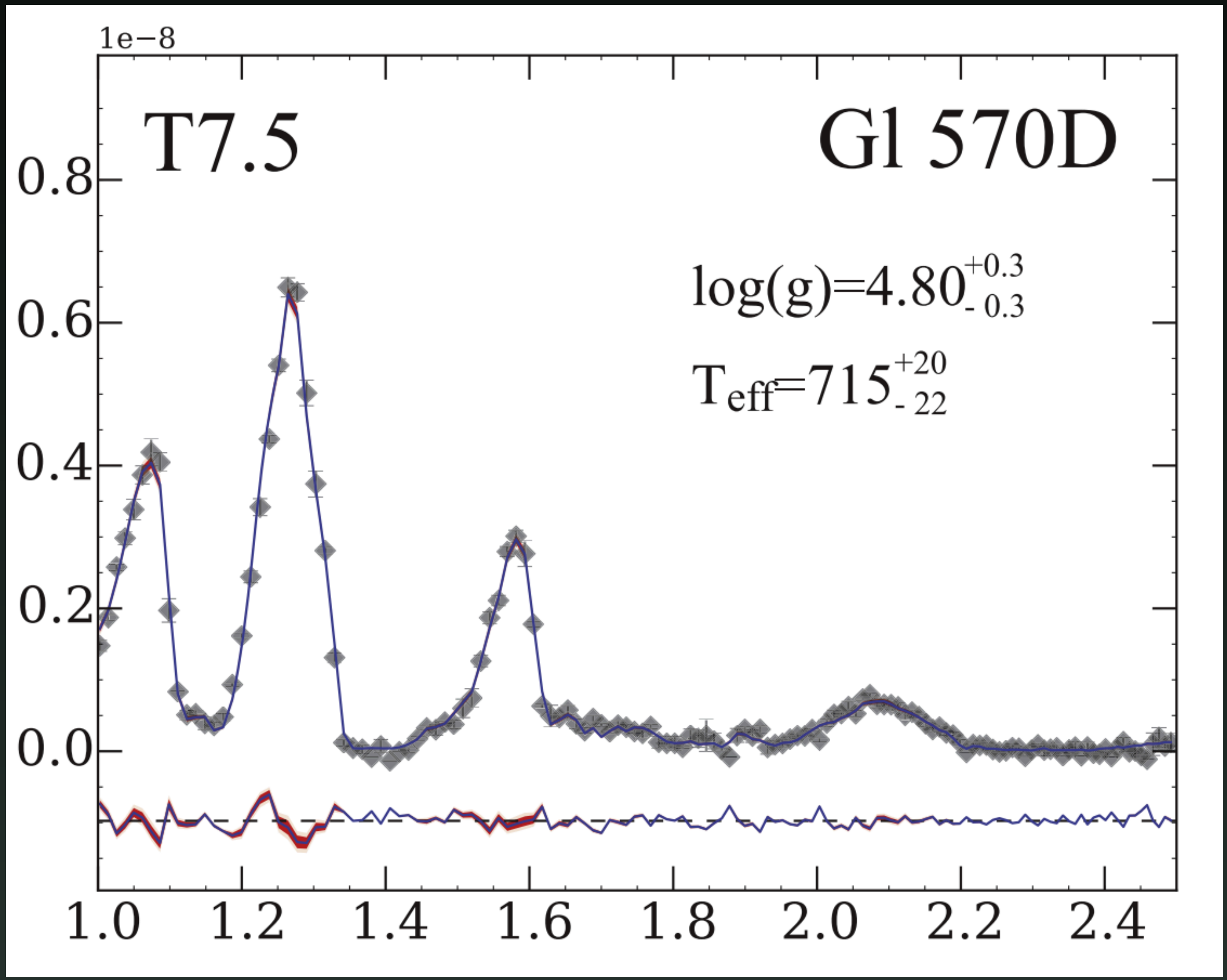
(Daemgen et. al. 2017)



Magellan image of the HD 106906 system (Bailey et. al. 2013)

Characterizable Targets: T Dwarfs

- Spectral types ≥ T5 generally have cloud-free photospheres
- CH_4, CO, CO_2, H_2S, NH_3, and alkali (Na+K) abundances
- Surface gravity (log g) constrainable within 0.3 dex

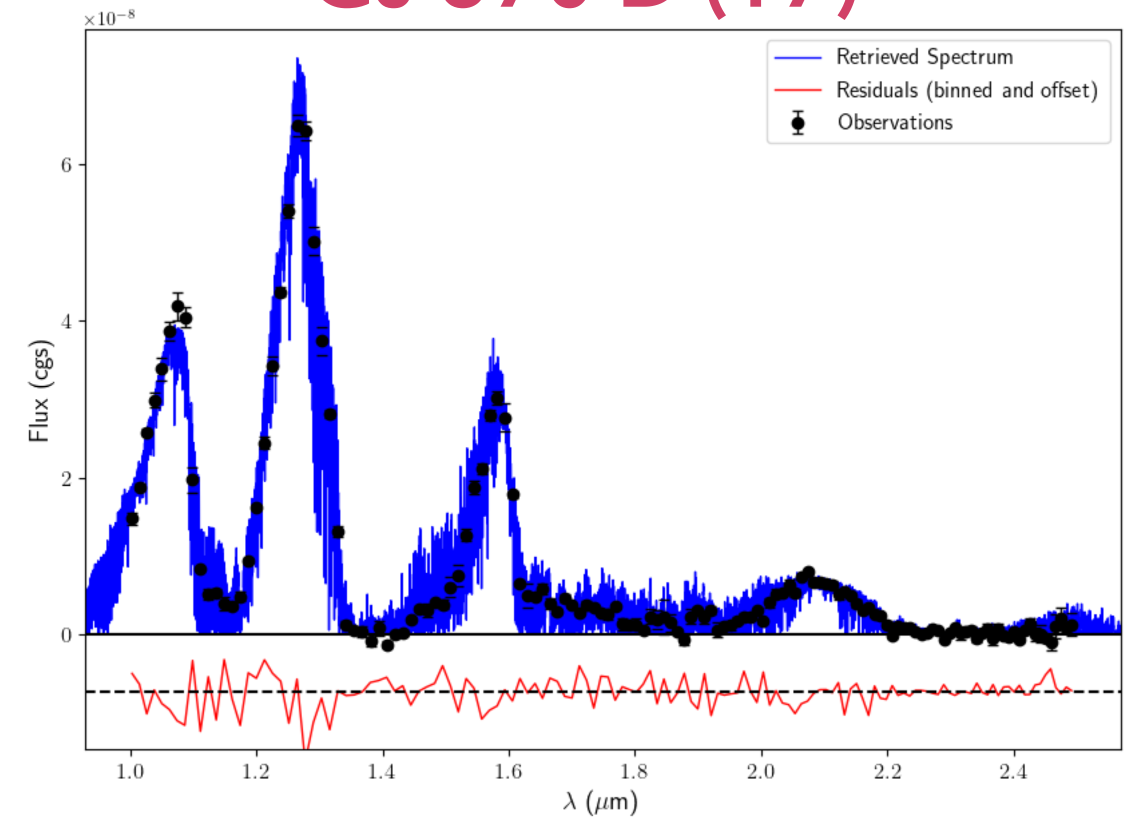


(Line et. al. 2017)

Spectral Retrievals with the APOLLO Code

- Development led by Alex Howe (see Howe+ 2017)
- MCMC retrieval code designed for transiting and directly imaged data
- Designed for flexibility in atmospheric modeling (1- vs. 2-stream radiative transfer, cloud physics, etc.)

GJ 570 D (T7)



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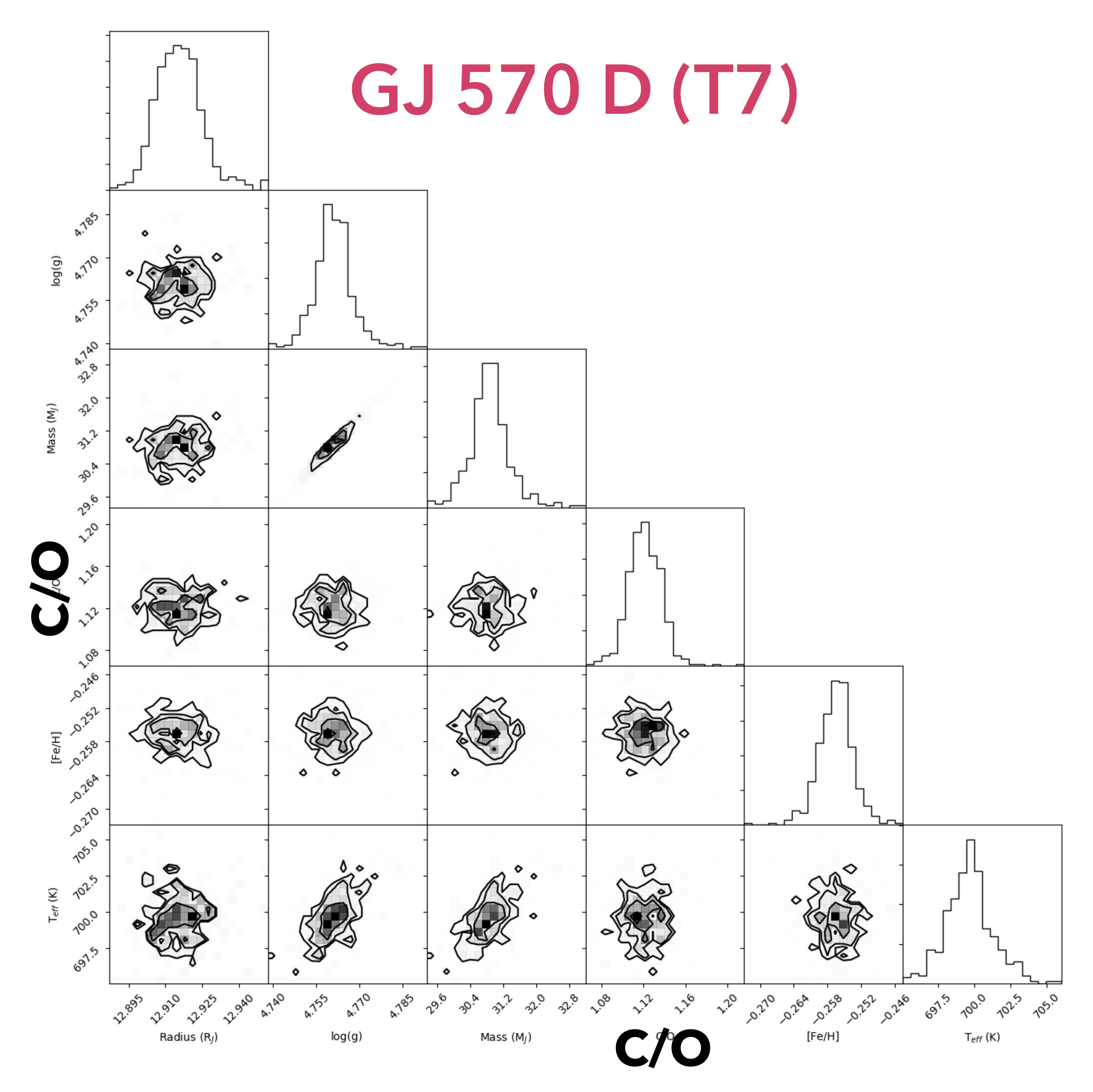
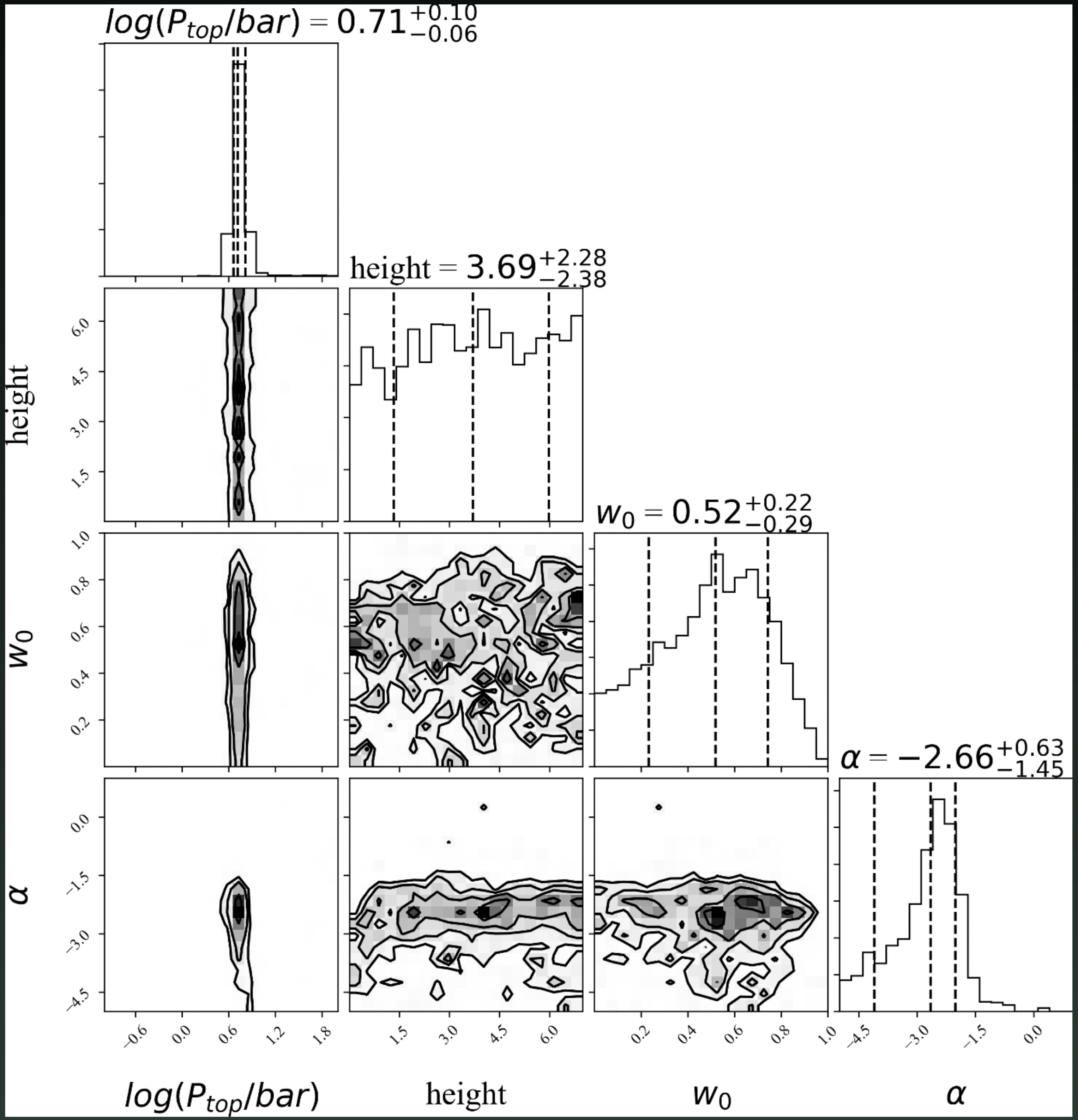


Characterizable Targets:
L Dwarfs

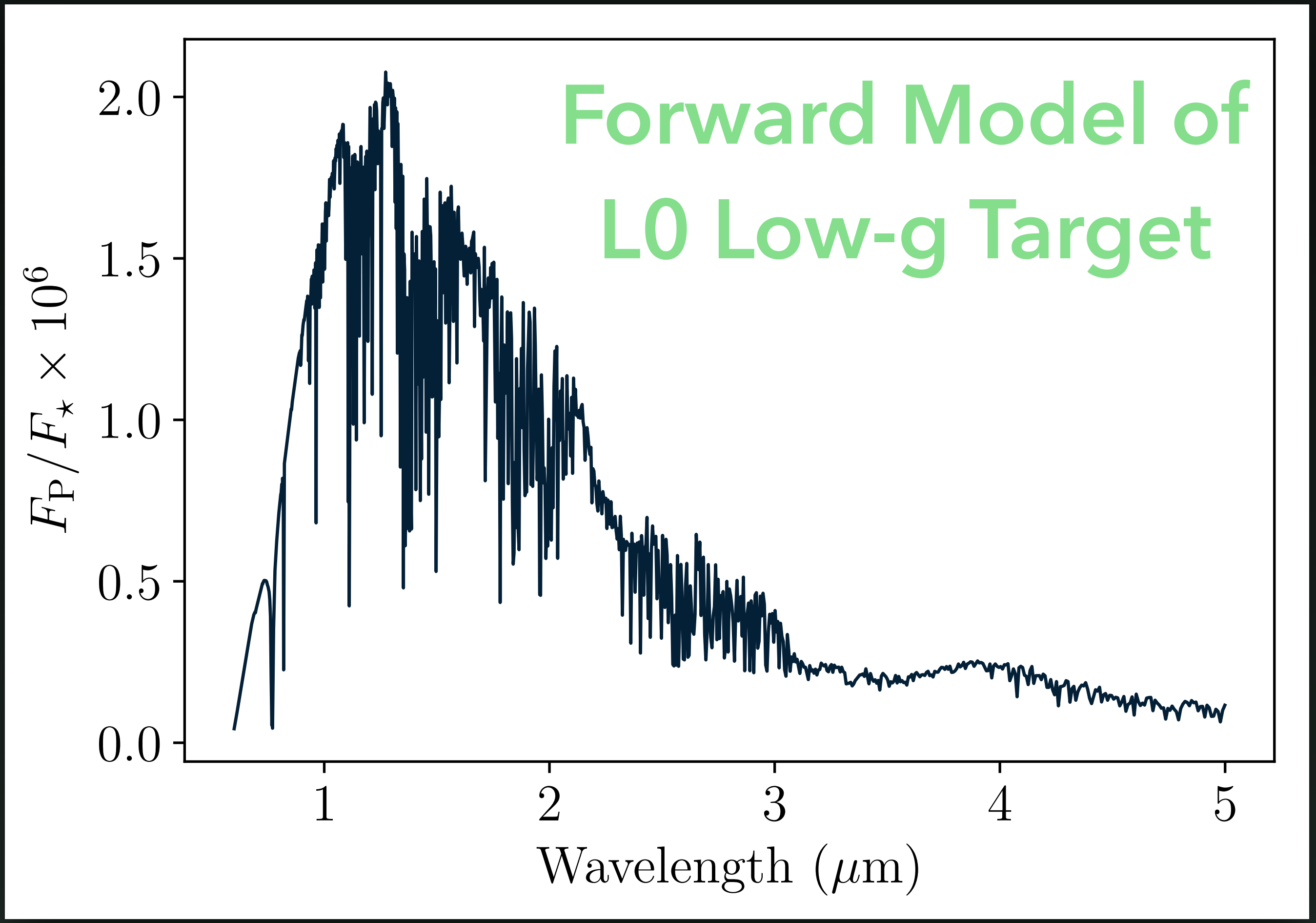
- Cloud opacity contributes significantly to emission
- Burningham+ (2017): 2 L-dwarf retrievals
  - Cloud top pressure constrained
  - Cloud layer depth unconstrained
- 2-stream cloud physics needed!



(Burningham et. al. 2017)

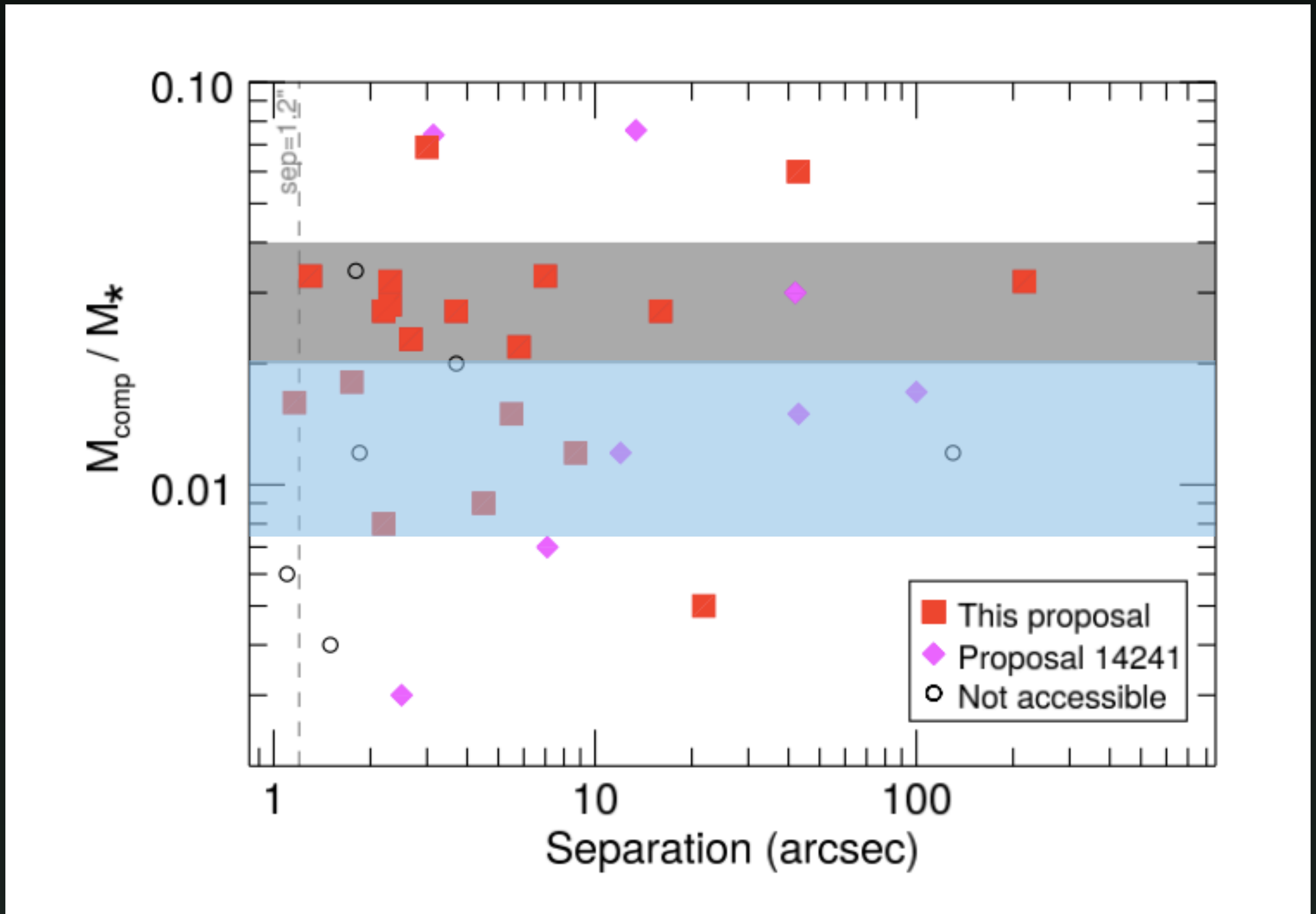
L Dwarf Retrievals with the APOLLO Code

- Atmospheric T-P parametrization informs consistent retrievals
- Extending APOLLO with 2-stream scattering for a variety of hazes for 0.6-5 μm
- Using APOLLO's built-in information content design for JWST modes for experimental design (see Howe+ 2017)



JWST Cycle 1 Proposal: Spectral Characterization of Low-Mass Companions

- JWST GTO+Cycle 1
  - NIRSpec PRISM (R~100, 0.6-5 microns)
- Observe companions with separations > 1", including key regime of mass ratio with primary (~0.01)
- Derive volatile abundances, compare with host stars'
- Complements ground-based AO with JWST's λ and precision!



Summary

- Intermediate companion mass ratios (~0.01 of host) lie at the tails of the planet and brown dwarf mass distributions
- Precise C/O ratios can distinguish their formation histories!
- Accurate 2-stream cloud retrievals can be used for accurate retrievals on L/T dwarf spectra
- JWST, ground-based AO observations will provide necessary resolution for spectral characterization of young resolved companions