Cool Giant Planets: From Interiors to Atmospheres

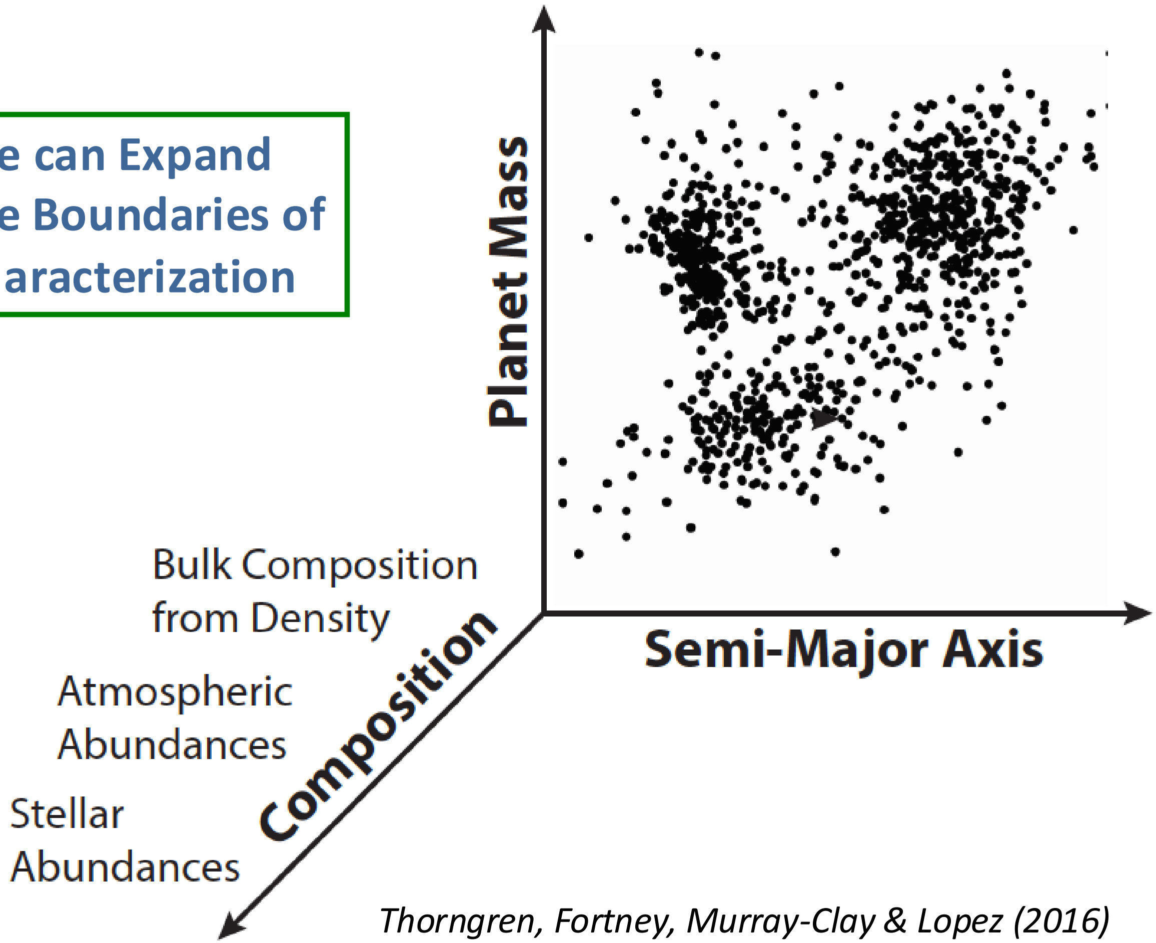
Thanks: Sagnick Mukherjee, Kazumasa Ohno, Callie Hood, Brianna Lacy

Jonathan Fortney
University of California, Santa Cruz
Department of Astronomy & Astrophysics
and Other Worlds Laboratory
@jjfplanet

Twenty Years Ago at OHP

- Visited OHP for the 10th anniversary meeting
- 2nd-year postdoc
- Hot Jupiter atmosphere models: HD 209458b, TrES-1b, HD 149026b -- summer after first Spitzer secondary eclipse detections

We can Expand the Boundaries of Characterization



Thorngren, Fortney, Murray-Clay & Lopez (2016)

Atmosphere/Interior Connection: Thinking Through the Fluxes

Flux from above

Total Planetary Flux

$$T_{\mathrm{eff}}^4 = T_{\mathrm{eq}}^4 + T_{\mathrm{int}}^4$$

Flux from below

Atmosphere/Interior Connection: Thinking Through the Fluxes

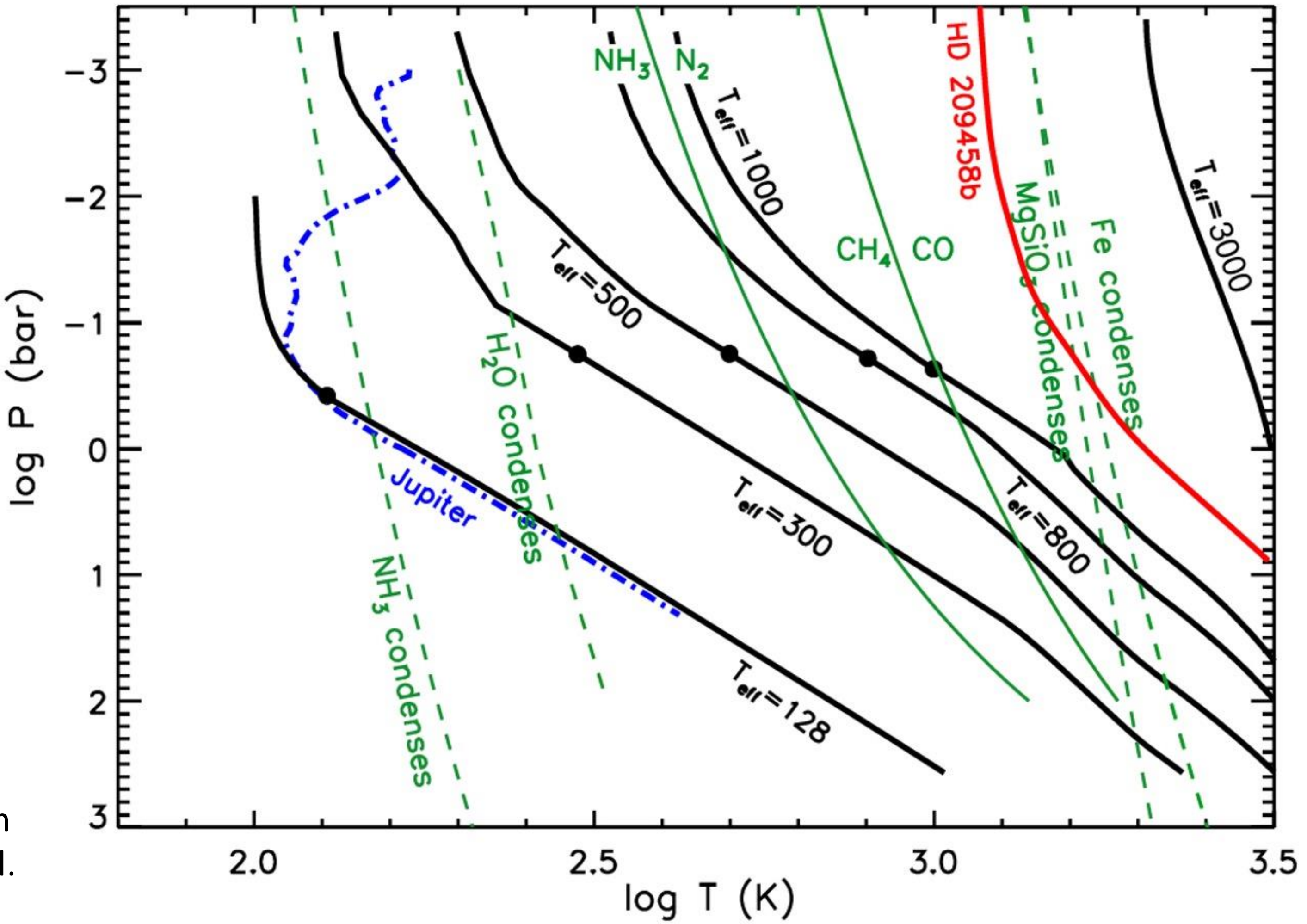
$$T_{\mathrm{eff}}^4 = T_{\mathrm{eq}}^4 + T_{\mathrm{int}}^4$$

Thermal evolution models modestly important

- Hot Jupiters: $T_{eq}^4 >> T_{int}^4$
- Warm Jupiters: $T_{eq}^4 >> T_{int}^4$
- (Old) Temperate Jupiters: $T_{eq}^4 > T_{int}^4$
- Jupiter itself: $T_{eq}^4 \sim T_{int}^4$
- Directly imaged planets: $T_{eq}^4 << T_{int}^4$

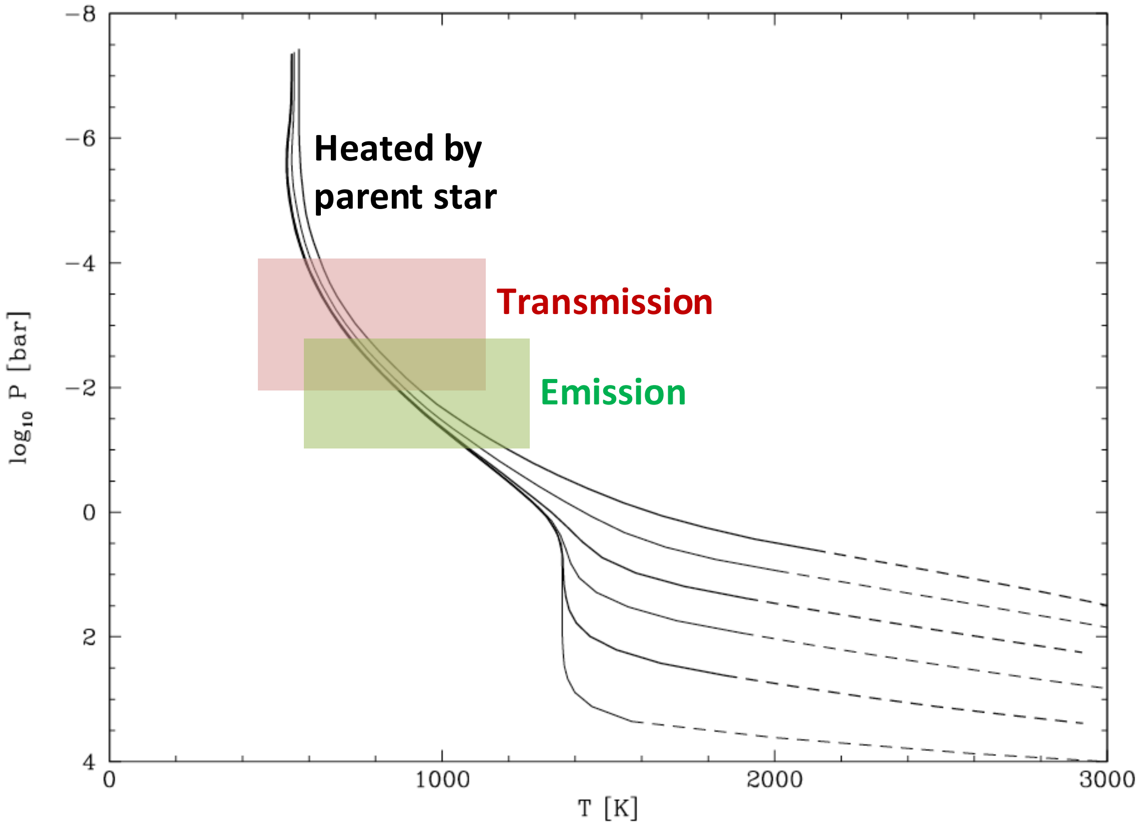
Thermal evolution models critical

Marley & Robinson (2015, ARAA)



Adapted from Hubbard et al. (2002)

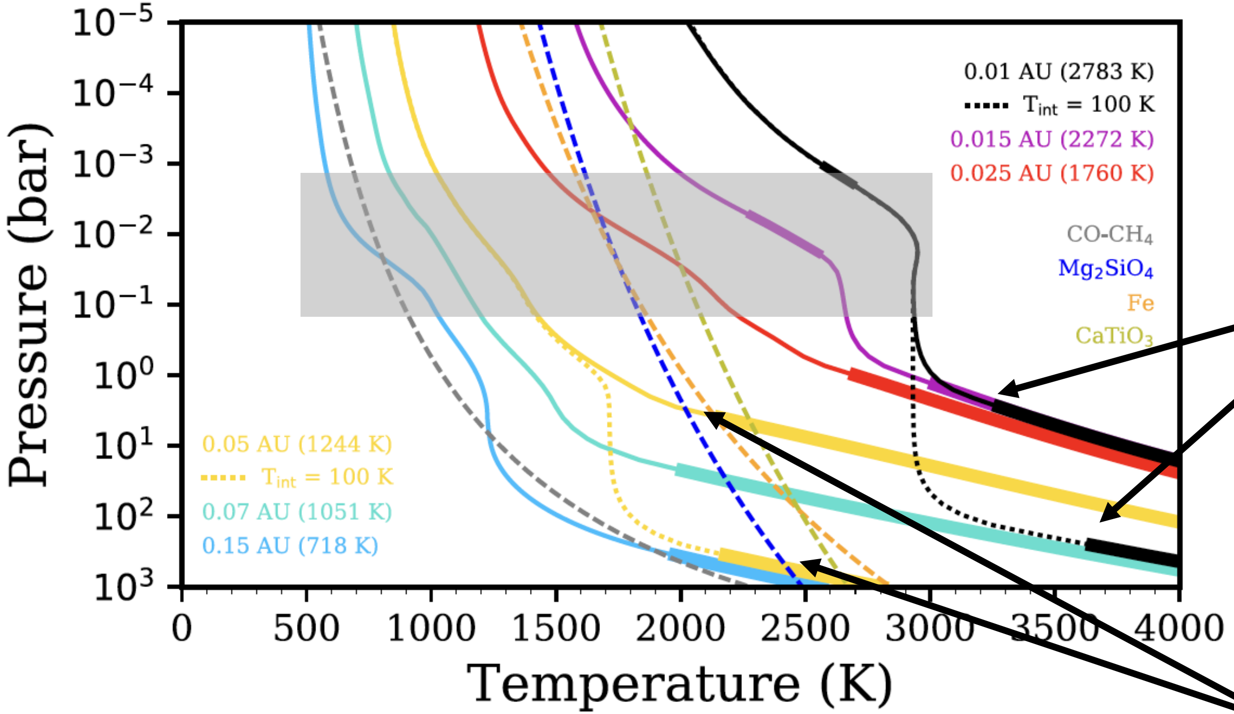
Atmosphere/Interior Energetics



Heating from interior wanes over time

Sudarsky et al. (2003)

Hot Jupiters

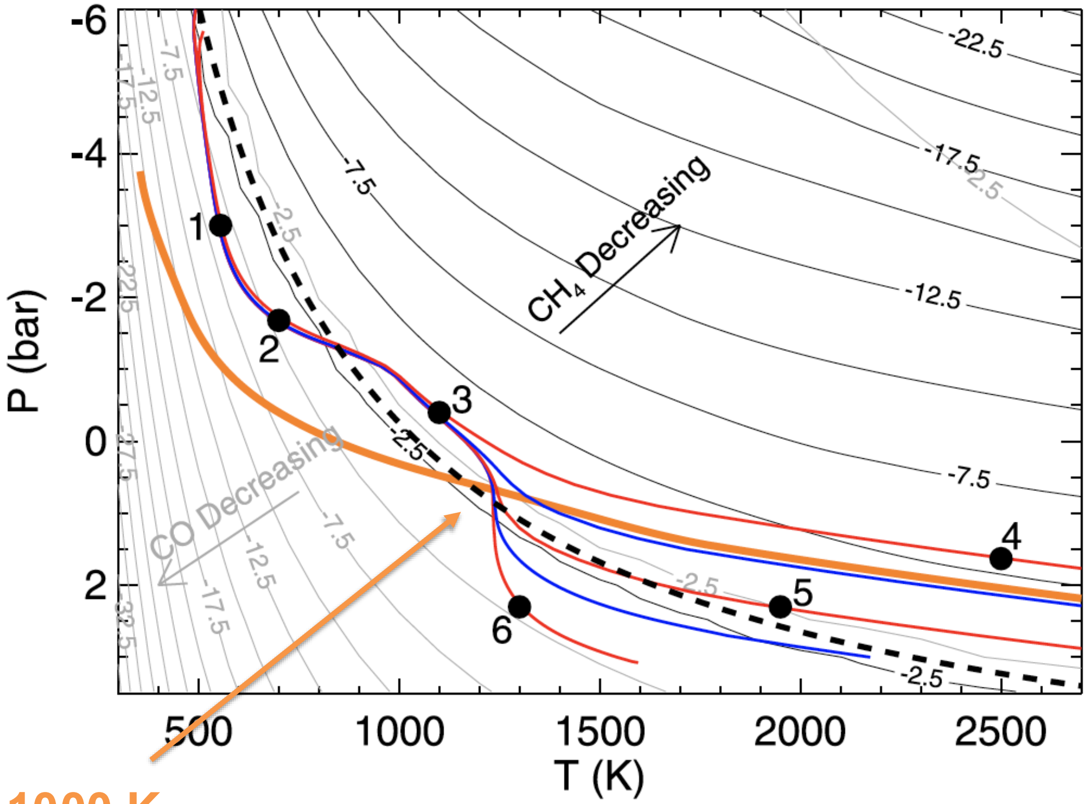


Interior adiabat effects the RCB → impacts atmospheric circulation

Further effects "cold traps" and where clouds condense in an atmosphere

Thorngren, Gao, & Fortney (2019)

Warm to Temperate Jupiters

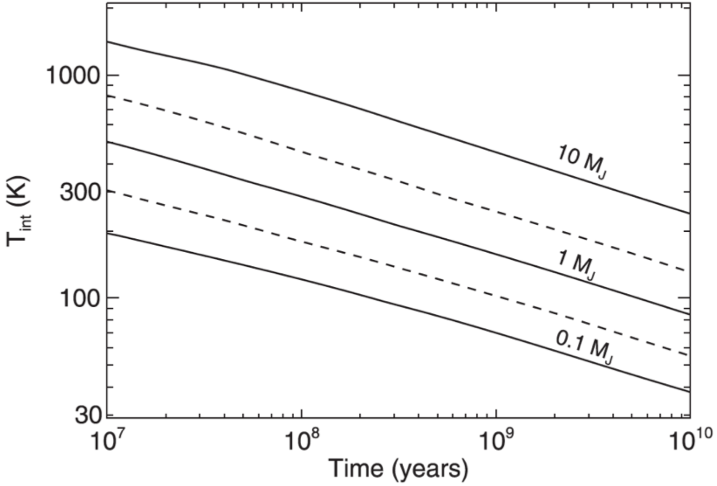


1000 K
Brown Dwarf

Fortney et al. (2020)

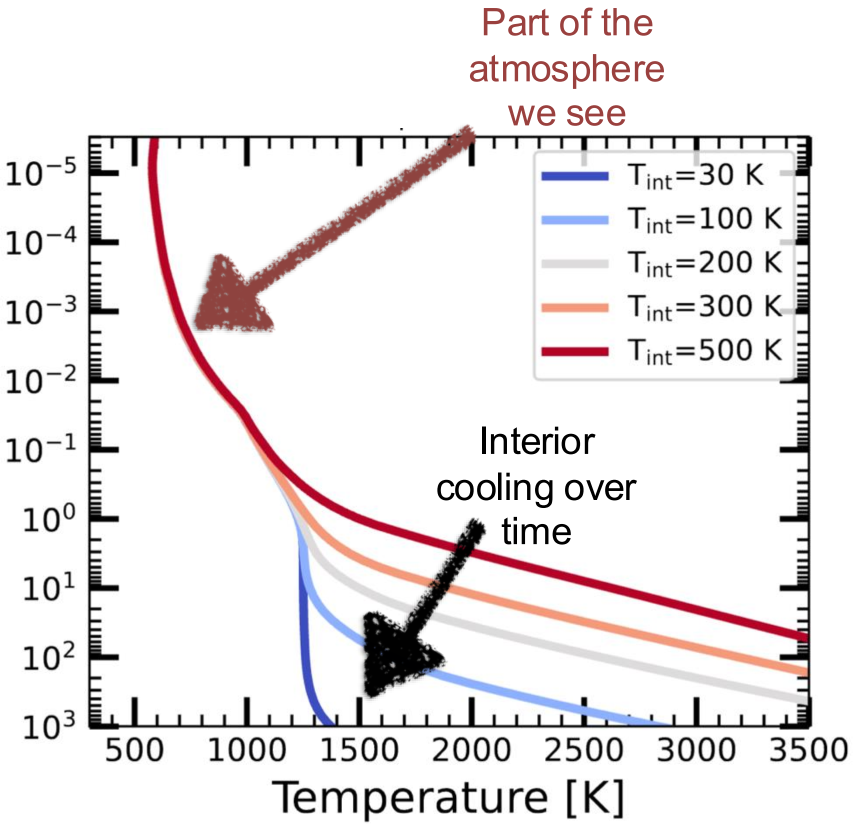
- Planets at the same T_{eq} but at:
  - Different ages, or with
  - Different masses,

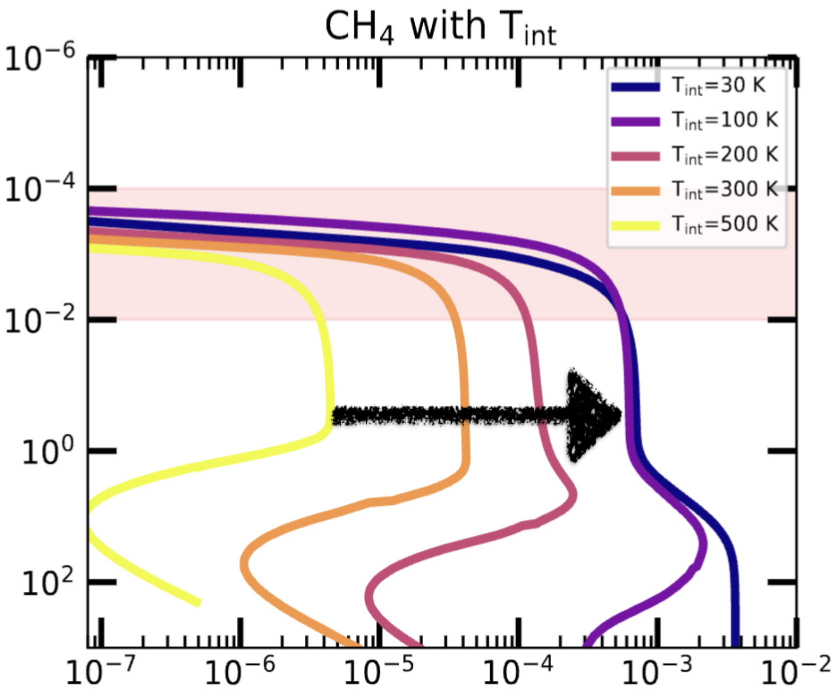
  will have different interior abiabats



T_{int} falls over time, and vertical mixing changes atmospheric abundances

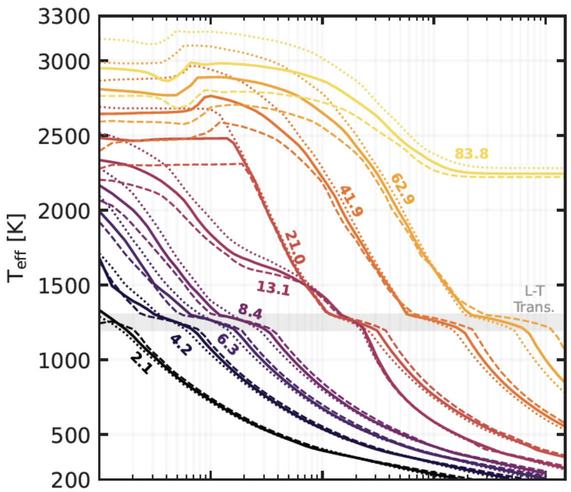
A Thought Experiment for a 700 K Transiting Planet (0.15 AU)

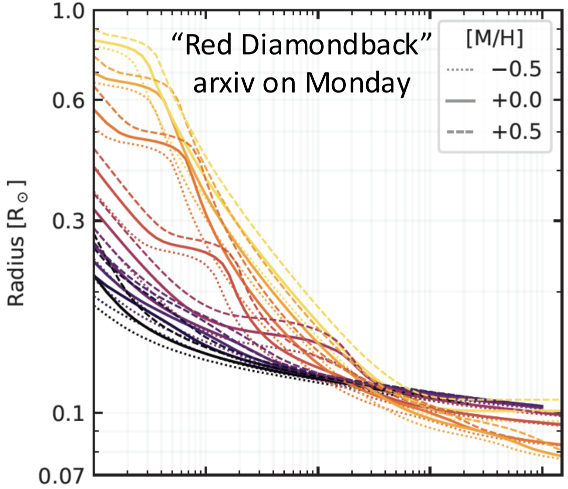


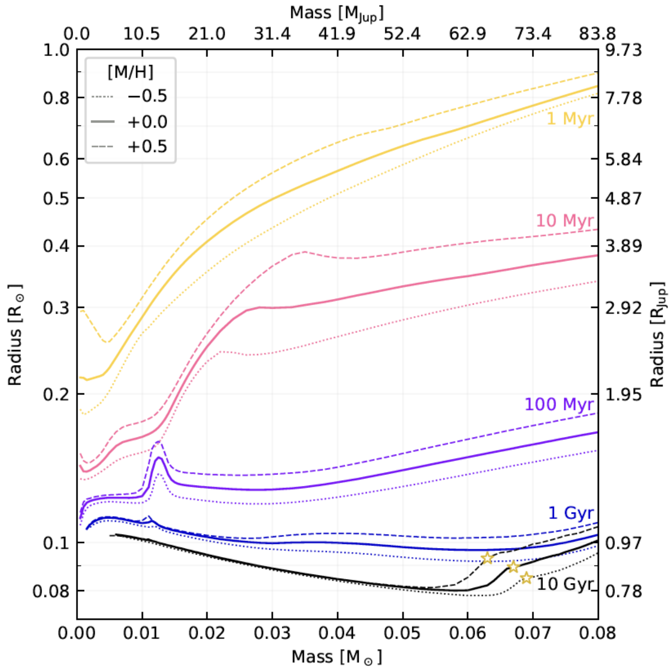


Mukherjee et al. (2025)

Imaged Planets







- **Flux from the planetary interior is all the flux you see**
- **Uncertainty is largest at young ages**
- Hot/cold start
- Early mixing of composition gradients?

- Sonora Bobcat (2021), Diamondback (2024), Flame Skimmer (2026), Chabrier+2023(w/ ATMO), DUSTY/COND, Baraffe+15, Burrows+97, BEX (Linder+2019), etc.

Thinking Through the Fluxes

$$T_{\mathrm{eff}}^4 = T_{\mathrm{eq}}^4 + T_{\mathrm{int}}^4$$

Thermal evolution models modestly important

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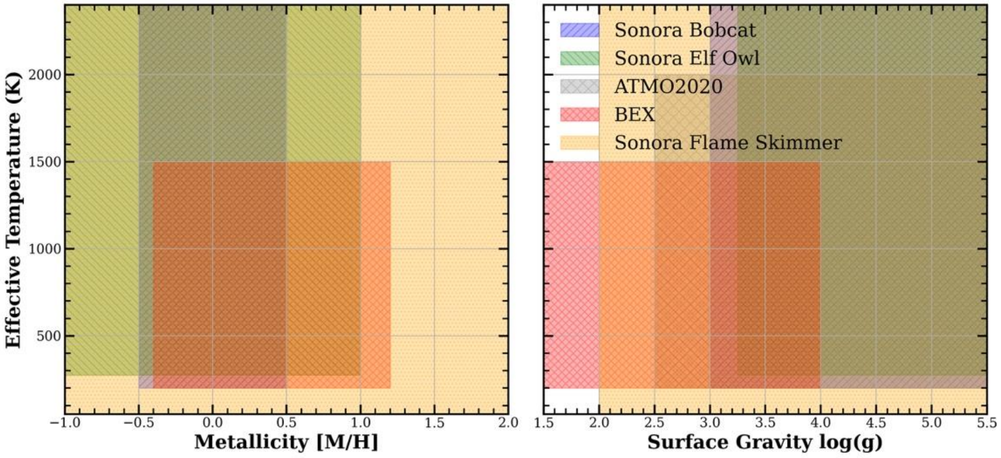
Thermal evolution models critical

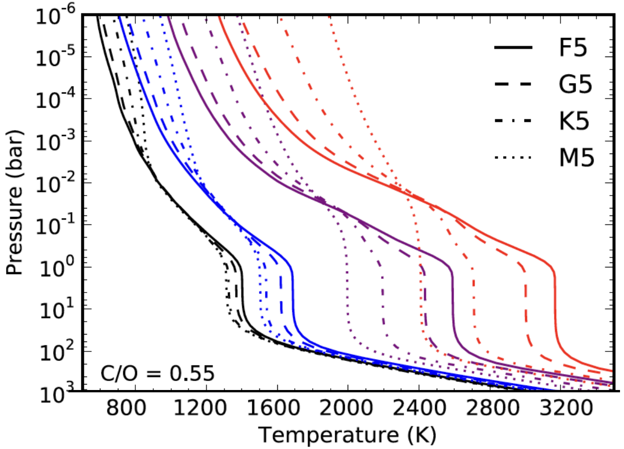
Modeling Differences

Mang+ (in prep)

- **Brown dwarfs and imaged planets are amenable to modeling via grids**
- T_{eff}, log g
- metallicity, C/O ratio
- cloud parameters (*Alice Radcliffe talk, Weds.)*
- vertical mixing, adiabatic index

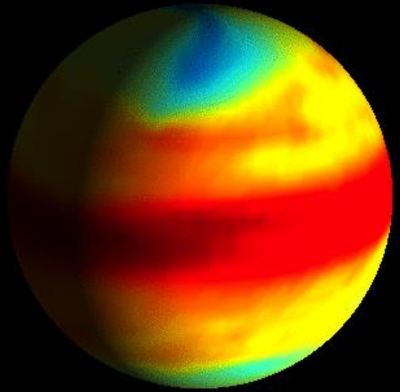
- Grids much trickier for irradiated planets
- Wavelength dependence of parent star spectra complicate atmospheres



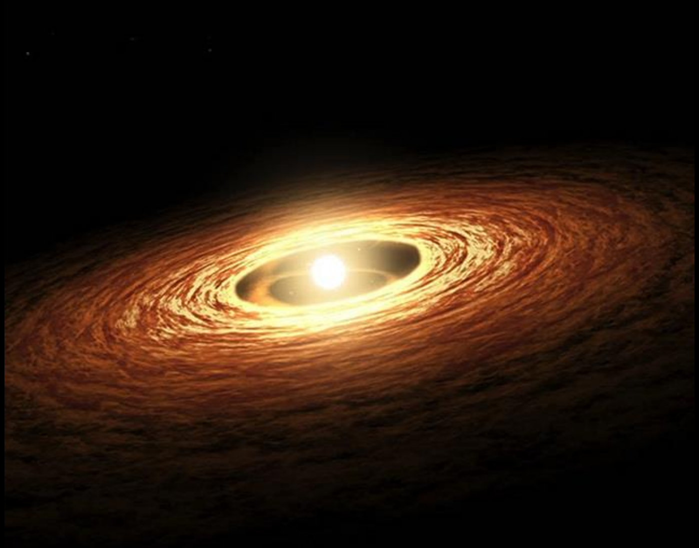


Molliere+ (2015)

Fundamental Themes for Exoplanet Atmosphere Characterization



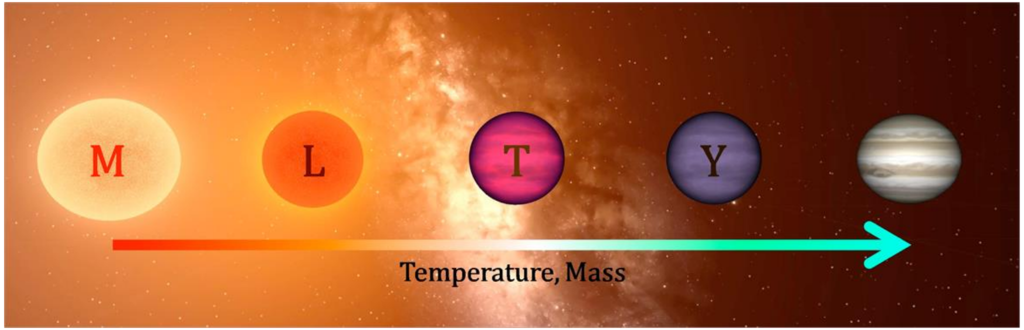
Determining thermal structures, dynamics, and abundances to understand planetary physics and chemistry

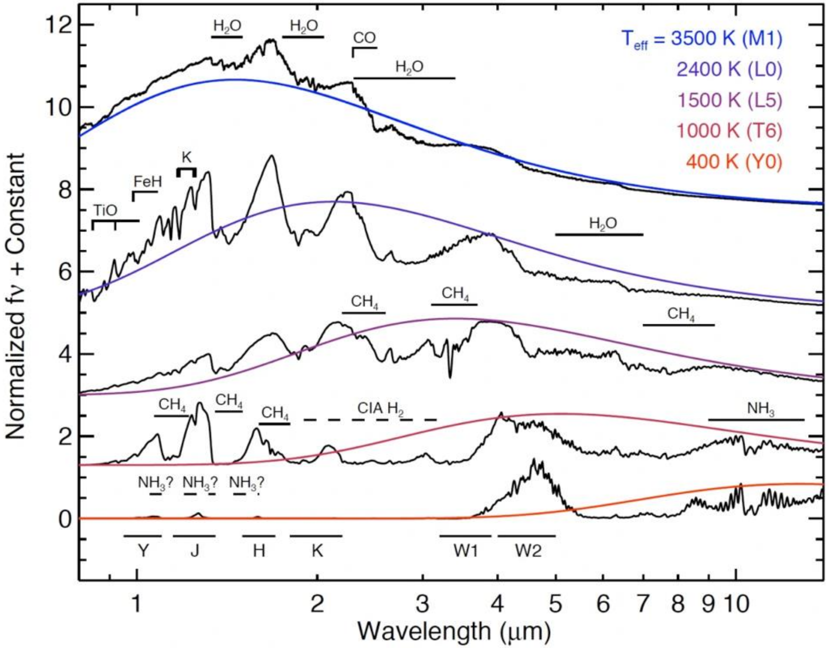


Measuring compositions to trace planet formation and evolution

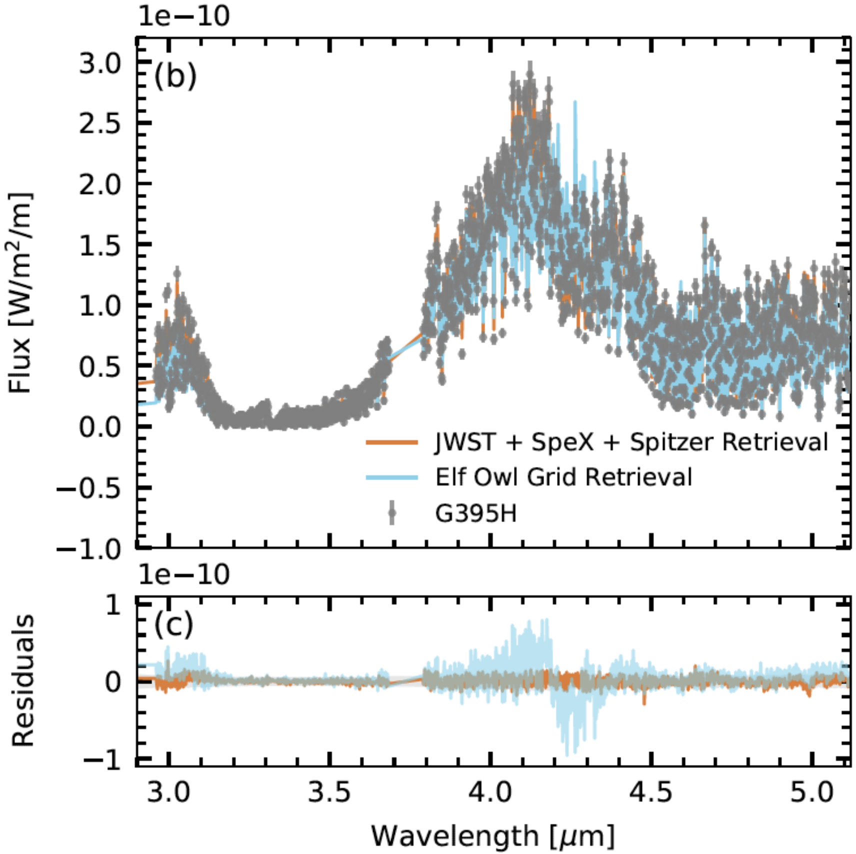
Complex Lessons for Cool Brown Dwarfs

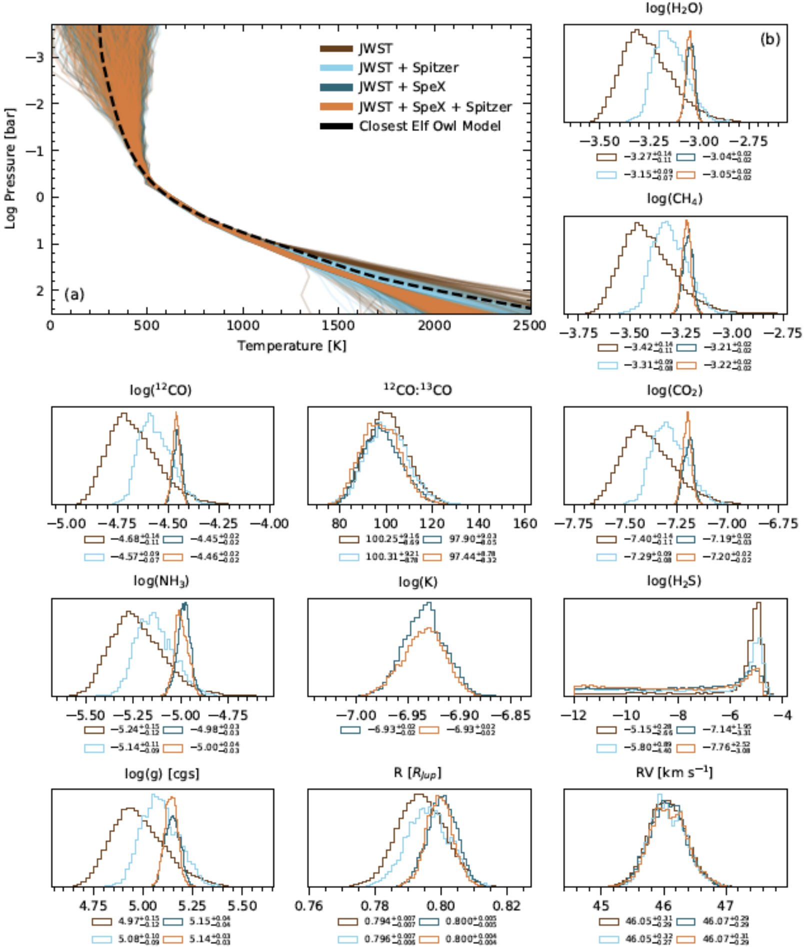
- Much of the general "changes in chemistry" with temperature have already been worked out and are currently being battle-tested against T- and Y-type brown dwarfs (T_{eff} ~1000-300 K) with amazing spectra
  - There are some very interesting findings, but models are doing mostly OK in this temperature range (no silicate clouds!)





JWST constraints on an 800 K late T-dwarf





- Hood et al. (arxiv 2402.05345)

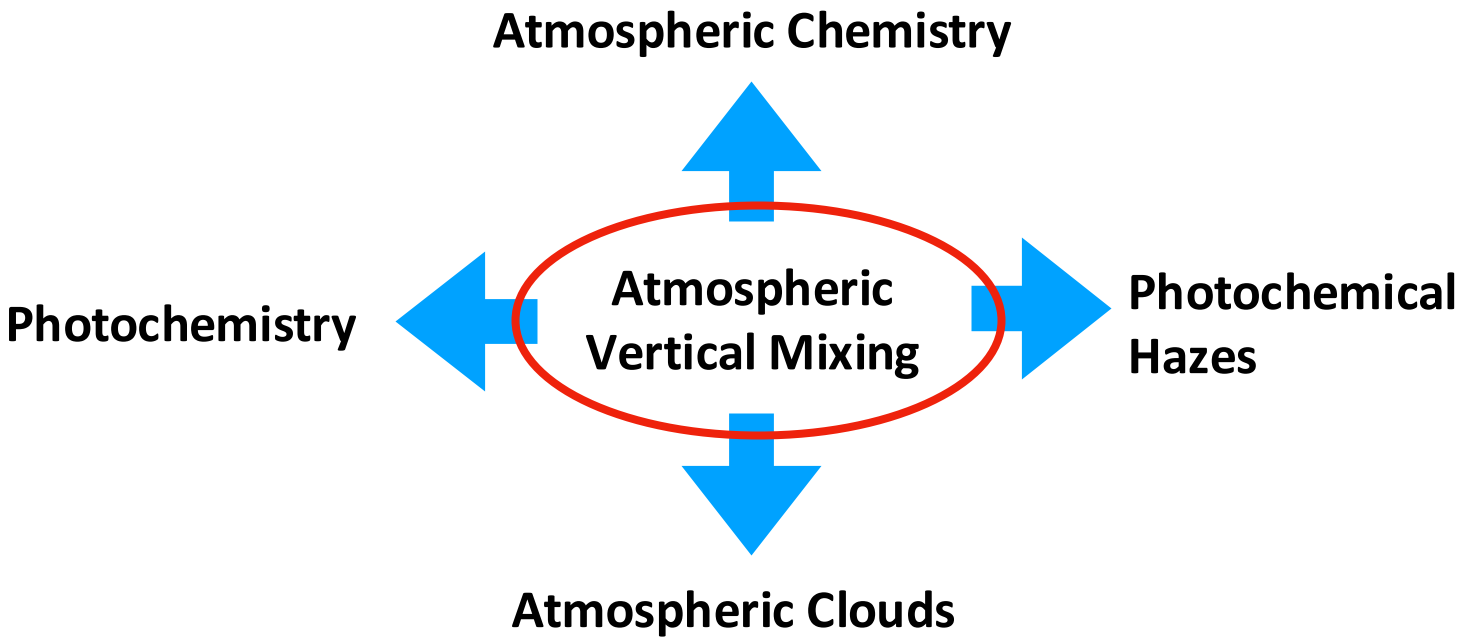
More Complex Lessons for Cooler Planets

- Much of the general "changes in chemistry" with temperature have already been worked out and are currently being battle-tested against T- and Y-type brown dwarfs (T_{eff} ~1000-300 K) with amazing spectra
    - There are some very interesting findings, but models are doing mostly OK in this temperature range (no silicate clouds!)

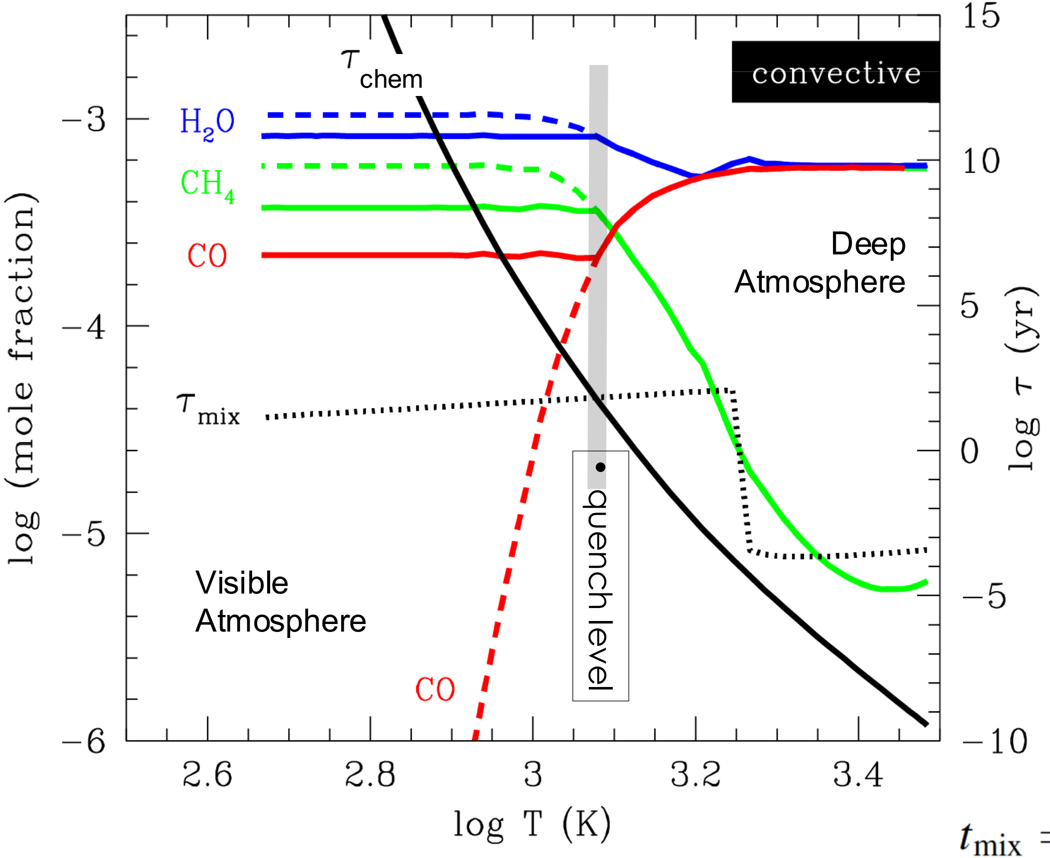
More Complex Lessons for Cooler Planets

- Much of the general "changes in chemistry" with temperature have already been worked out and are currently being battle-tested against T- and Y-type brown dwarfs (T_{eff} ~1000-300 K) with amazing spectra
  - There are some very interesting findings, but models are doing mostly OK in this temperature range (no silicate clouds!)
  - **However:**
    - **No parent stars (no UV photons) — no photochemistry!**
    - **Formation of BD's much better understood**
    - **BD's have the most elementary atmosphere/interior interaction**
    - **Most of the new BD phase space is metal-poor**

The Central Role of Vertical Mixing in Understanding Atmospheres



Non-equilibrium Chemistry



Saumon et al. (2003)

- In planets, radiative parts of atmospheres do readily mix, but not as quickly as due to convection
- Mixing is typically modeled as a diffusive process
  - Diffusion coefficient: K_{zz}
  - Higher K_{zz}, faster mixing
  - Currently unknown within a factor of 10^6
- Compare mixing timescale to chemistry timescale dramatically affects chemical abundances

$$t_{mix} = \frac{H^2}{K_{zz}}$$

$$CH_4 + H_2O \rightleftarrows CO + 3H_2$$

$$N_2 + 3H_2 \leftrightarrow 2NH_3$$

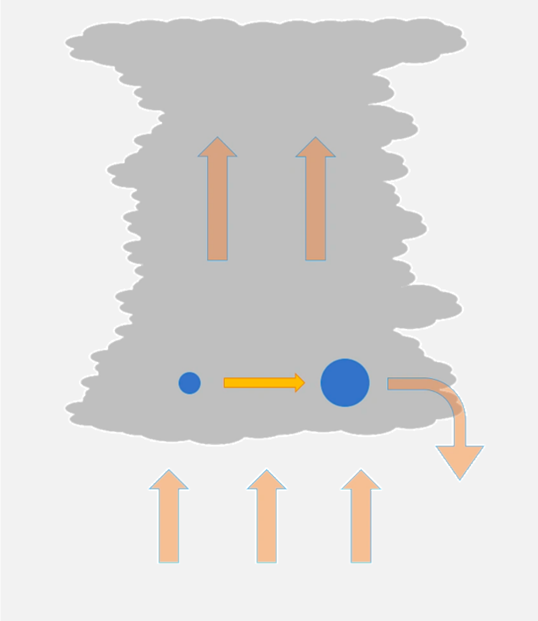
The Atmosphere Below Levels That We Can See

- As we probe cooler and cooler H/He planetary atmospheres, the atmospheric chemistry may be further from equilibrium

$$t_{\text{chem}} = A p^{-b} m^{-c} \exp(B/T),$$

$$t_{\text{mix}} = \frac{H^2}{K_{\text{zz}}}$$

- K_{zz} is important far beyond chemistry
- Dictates ability to keep cloud particles aloft and bring new cloud vapor up to condense



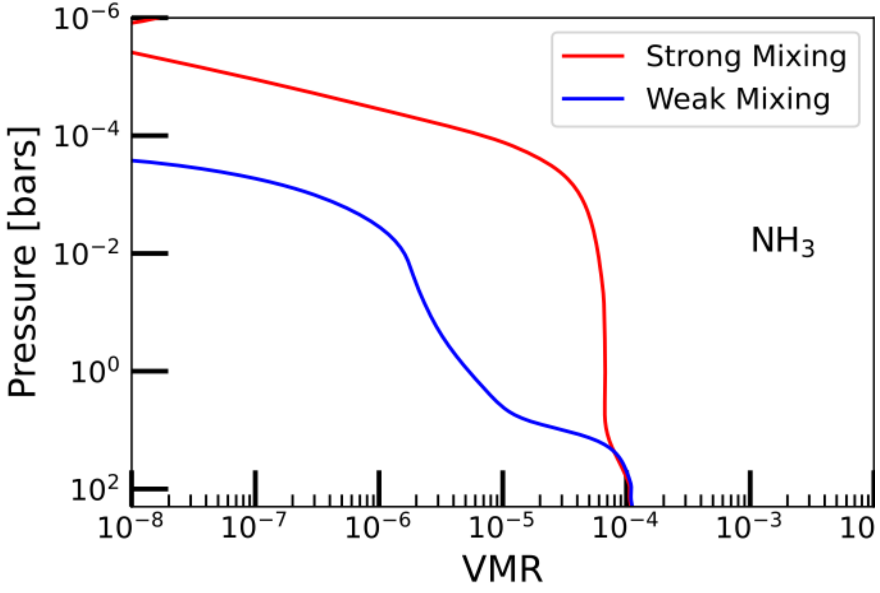
$$K_{zz} = \frac{1}{3} H \left(\frac{R_{\text{gas}} F_{\text{conv}}}{\mu \rho C_p} \right)^{1/3}$$

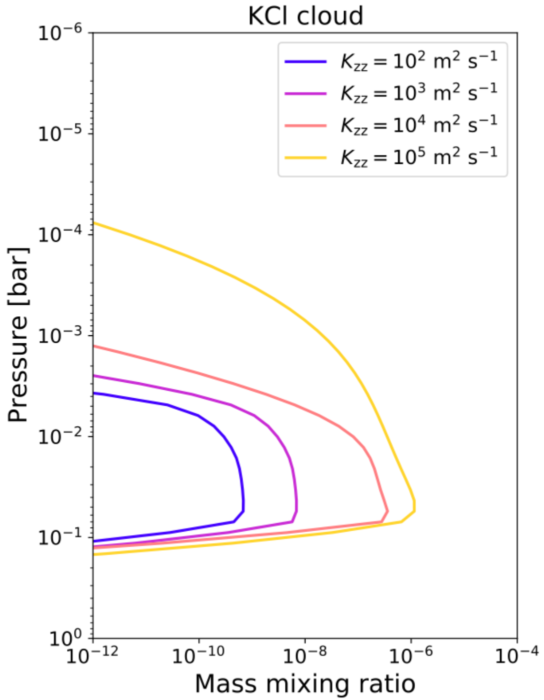
Mixing Length Theory in **convective zones**

$$K_{zz} = \ ?$$

Significant interes in **radiative zones**

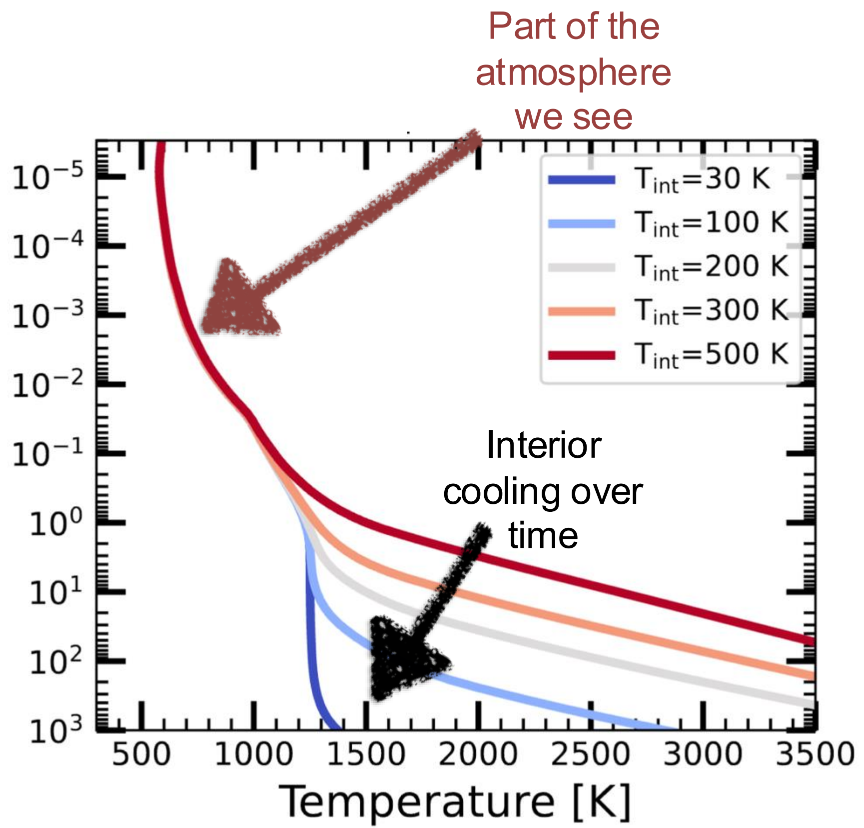
Vertical Mixing Effects Chemical & Cloud Abundances

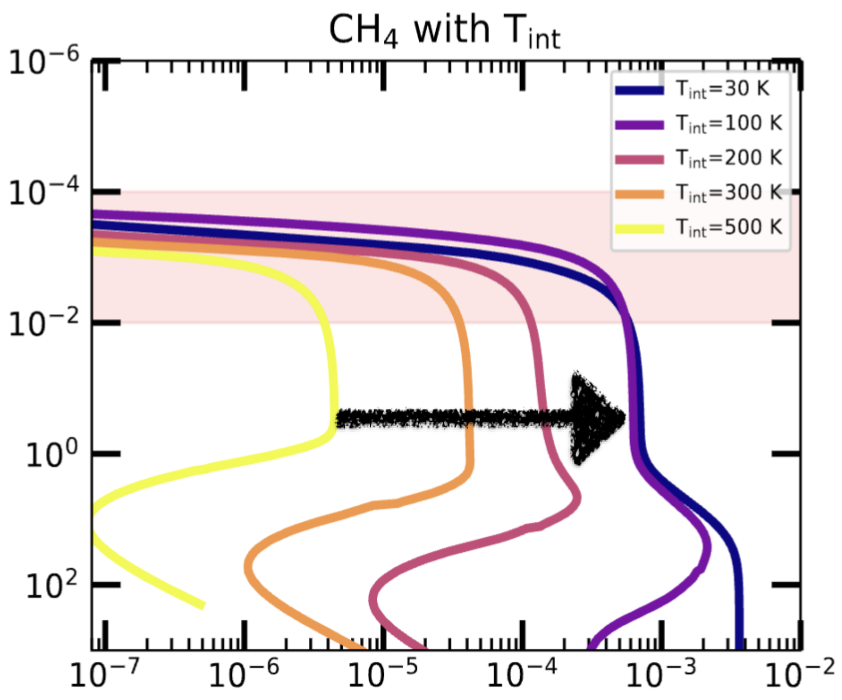




Ohno and Kawashima (2020)

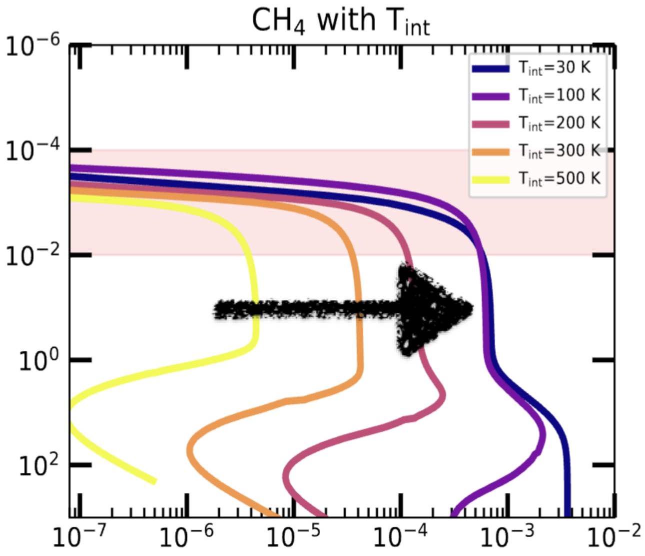
A Thought Experiment for a 700 K Transiting Planet (0.15 AU)

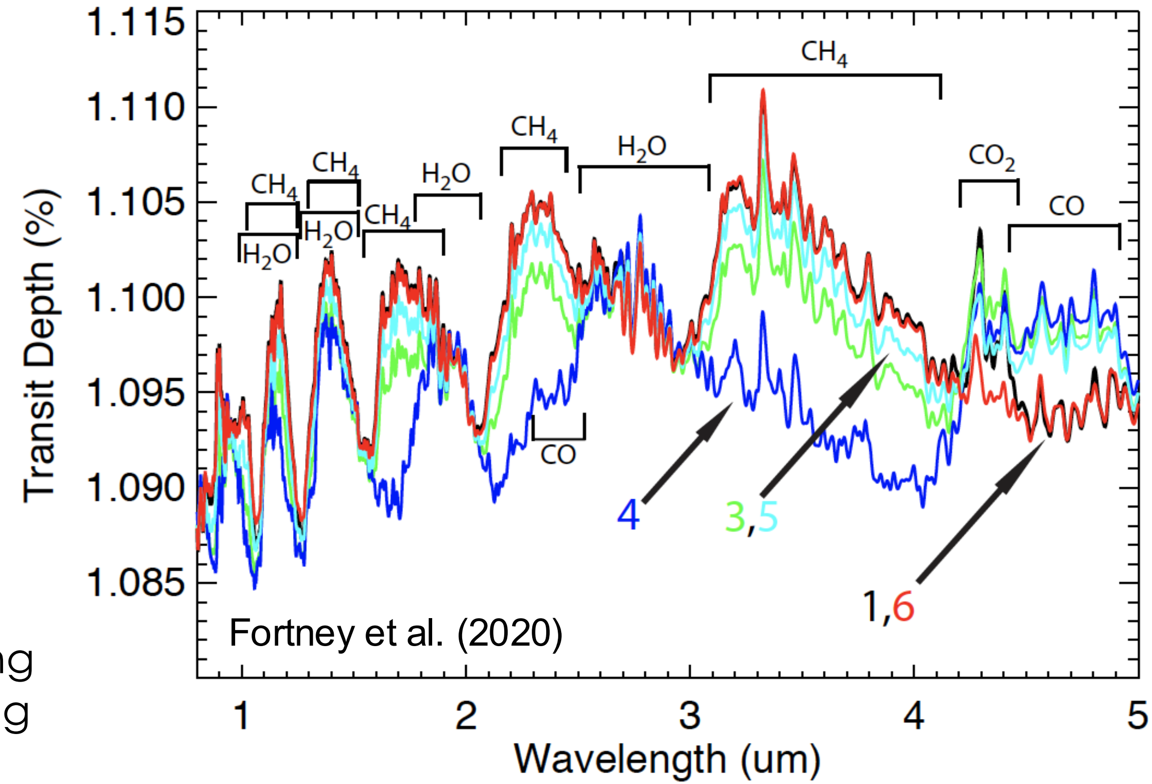




Mukherjee et al. (2025)

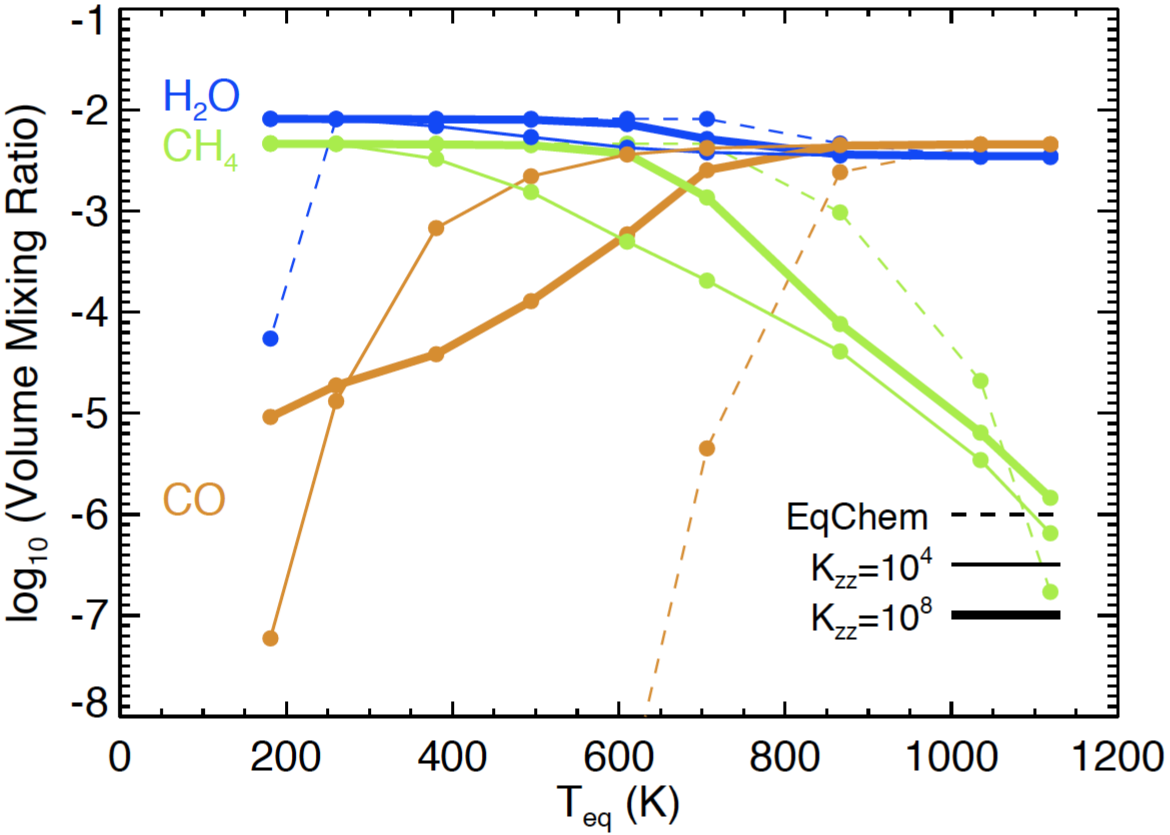
A Thought Experiment for a 700 K Transiting Planet (0.15 AU)





- A wide range of chemical abundances, and corresponding spectra, are possible, depending on "quench" pressure and temperature

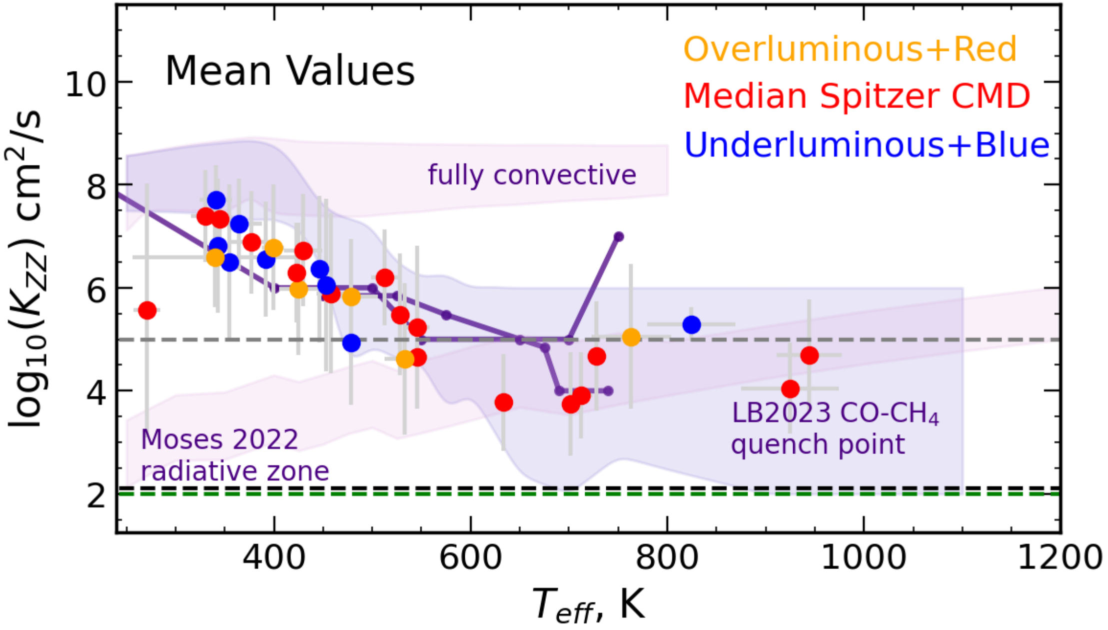
Mixing Ratios as T_{eq} Decreases, For a *Given Mass and Age*



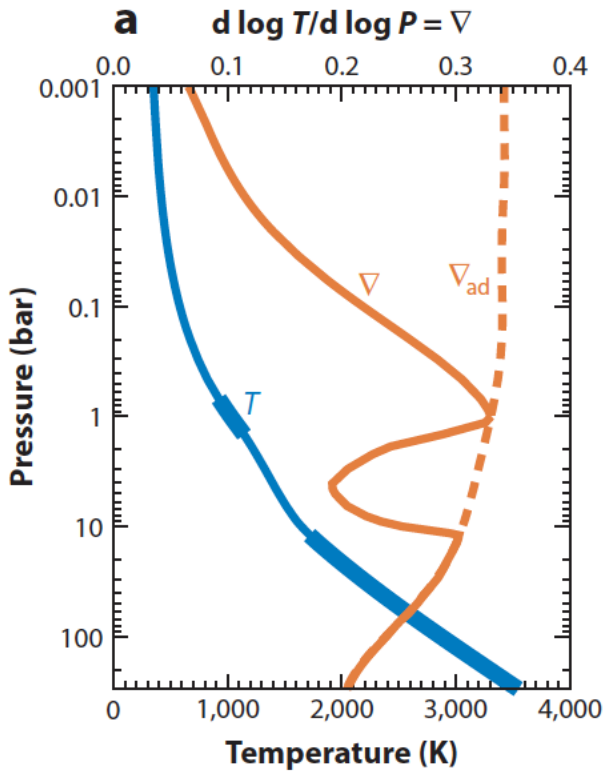
Fortney et al. (2020)

- For a population of giant planets with different masses, metallicities, and even ages, these trends may take a large sample size to disentangle

Mixing in Cool Brown Dwarfs, Teff = 300 – 1000 K

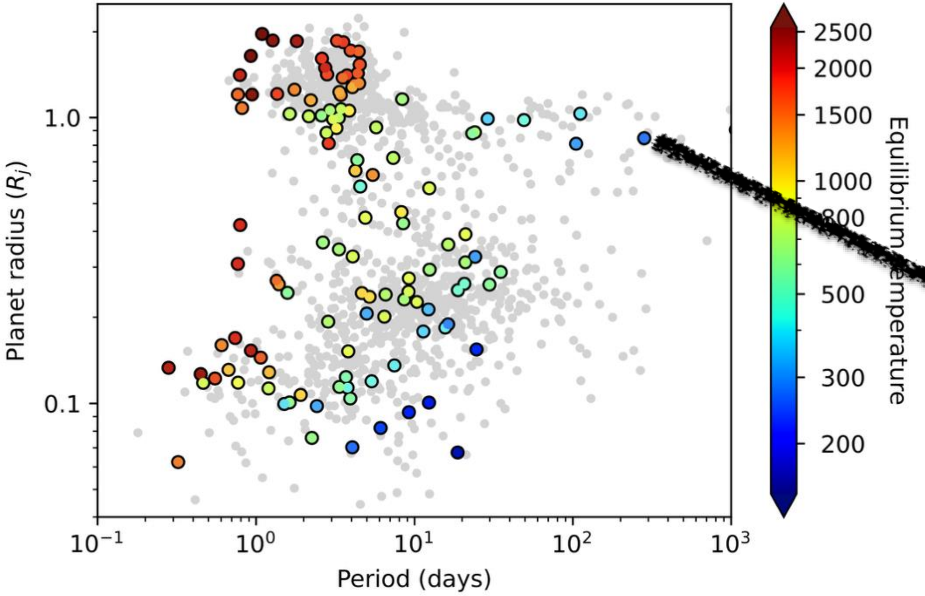


Brianna Lacy, et al, in prep

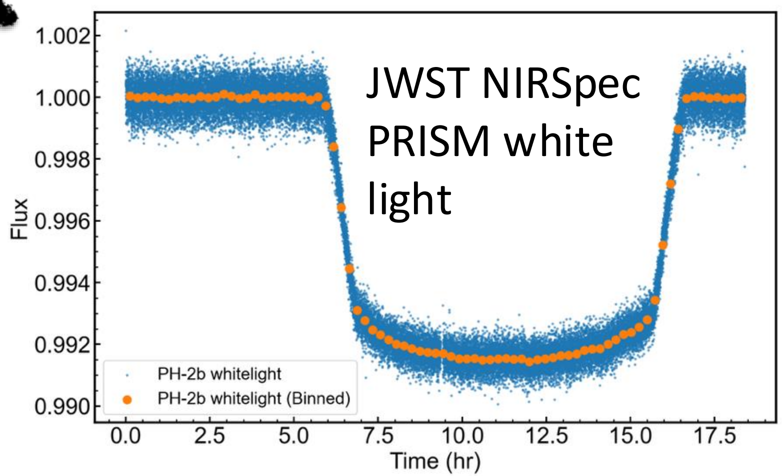


Marley & Robinson (2015)

PH-2b, the Coldest C1-C3 JWST Transiting Giant Planet Atmosphere Target, P_{orbit}=283 days



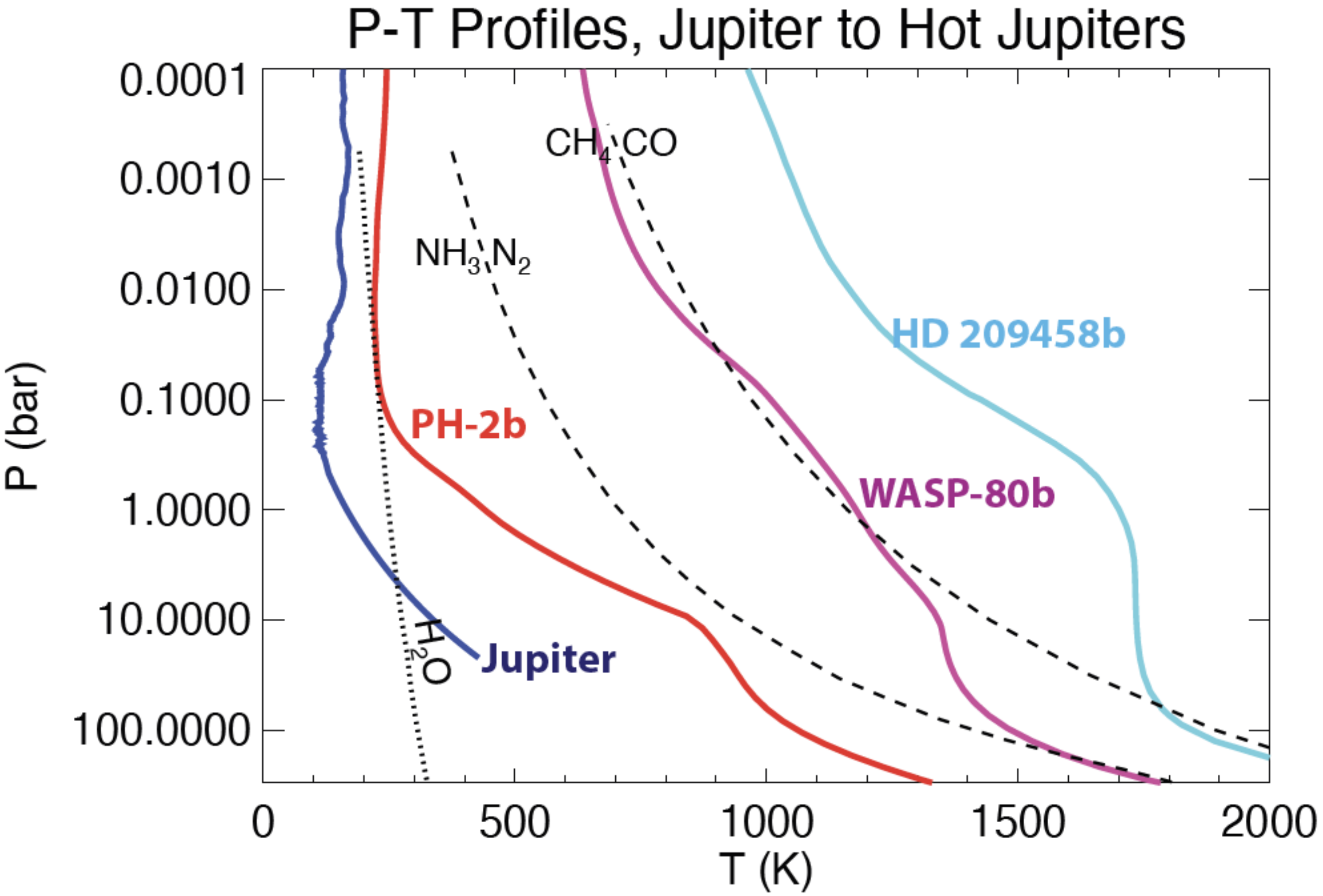
- T_{EQ}=280 K, PH-2b (Kepler 86-b)
- NIRSPEC transmission spectrum data from 0.6 to 5 um
- Coldest giant planet target with JWST (11 hour transit!)

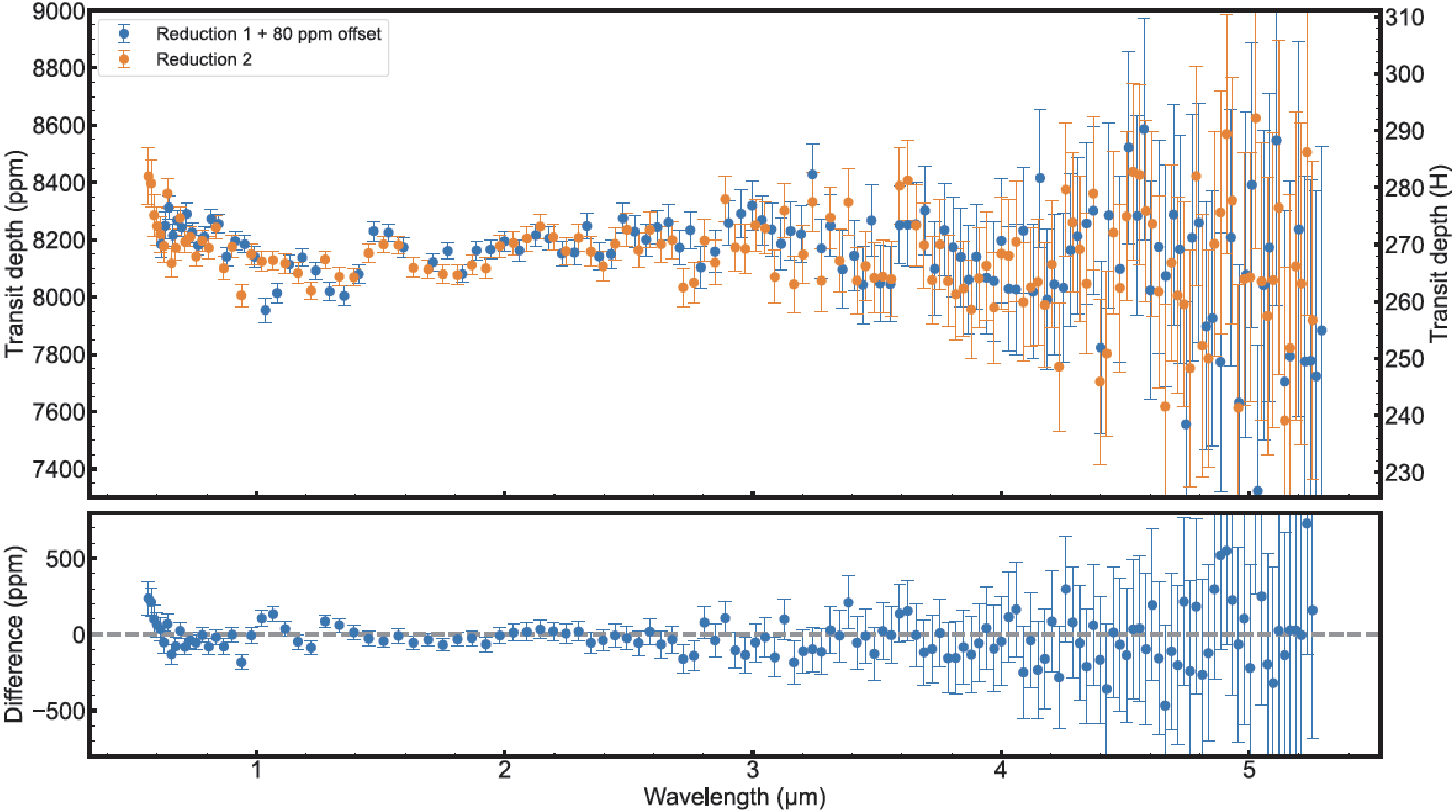


J. Wang et al. (2013, discovery)
P. Dalba et al. (2024, current mass)

- Given very cold planet (NH_3>>N_2), potential for the first C, N, O inventory in a transiting planet

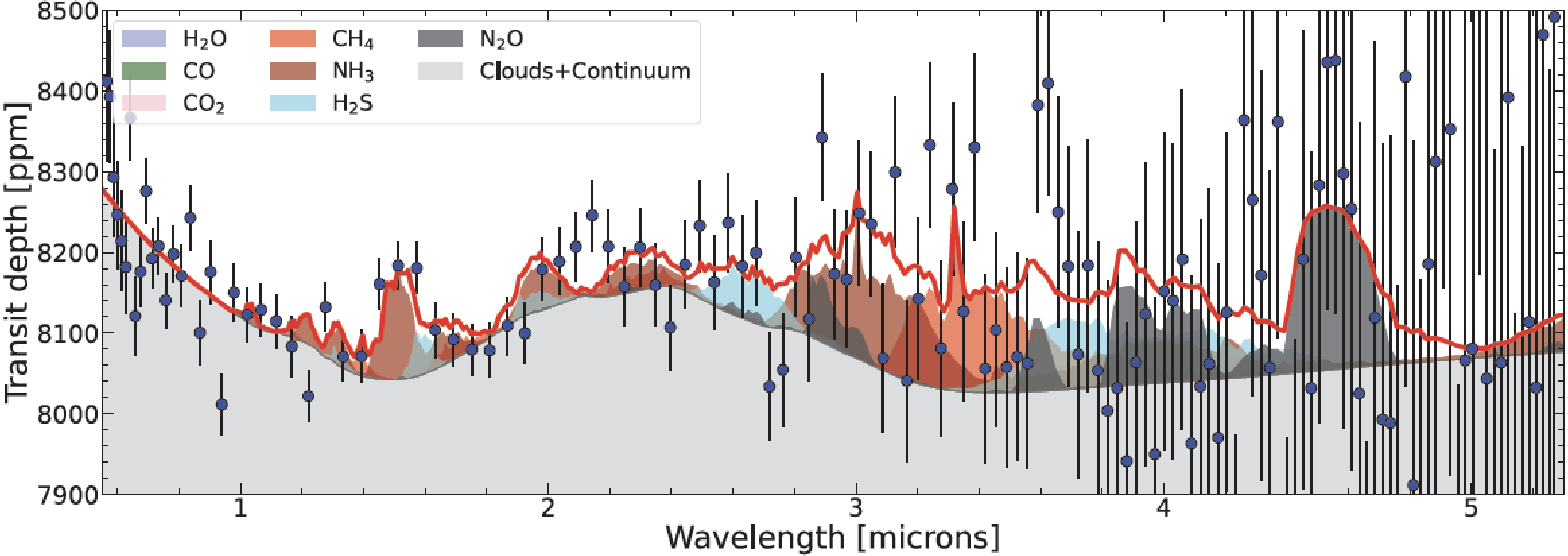
- "Bridge to Jupiter"





Reduction 1 + 80 ppm offset
Reduction 2
Transit depth (ppm)
Transit depth (H)
Difference (ppm)
Wavelength (μm)
9000
8800
8600
8400
8200
8000
7800
7600
7400
310
300
290
280
270
260
250
240
230
500
0
−500
1
2
3
4
5

PICASO Free Retrieval with "Typical" Molecules



- No moons down to Mars size
- No Saturn-like oblateness

Conclusions

Atmosphere/Interior connection gets discussed a lot for sub-Neptunes and rocky planets, but it is also critical for understanding aspects of giant planet physics, especially as we move to cooler objects

Imaged planet atmospheres and cool transiting planet atmospheres are steadily moving to similar phase space (which all overlaps with brown dwarfs)

- **-- Cooler transiting gas giants**
- **-- Imaging/spectra of RV planets**
- **-- Imaging/spectra of DR4 astrometric planets**
- **-- Roman gas giant reflection spectra**