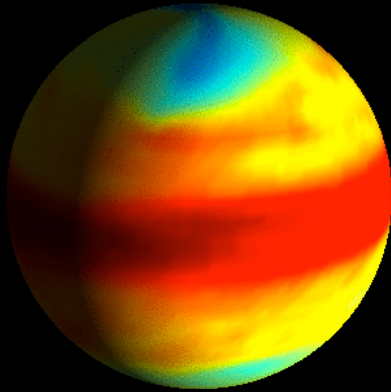


Exoplanet Atmosphere Models: Strengths, Weaknesses, and the Future

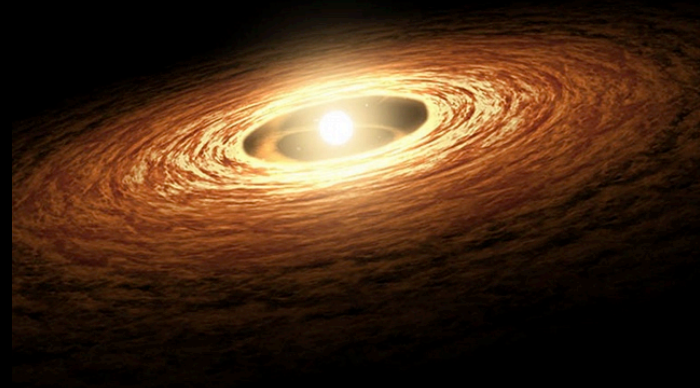


Jonathan Fortney
University of California, Santa Cruz
Department of Astronomy & Astrophysics
and Other Worlds Laboratory
 @jjfplanet 

Fundamental Themes for Exoplanet Atmosphere Characterization

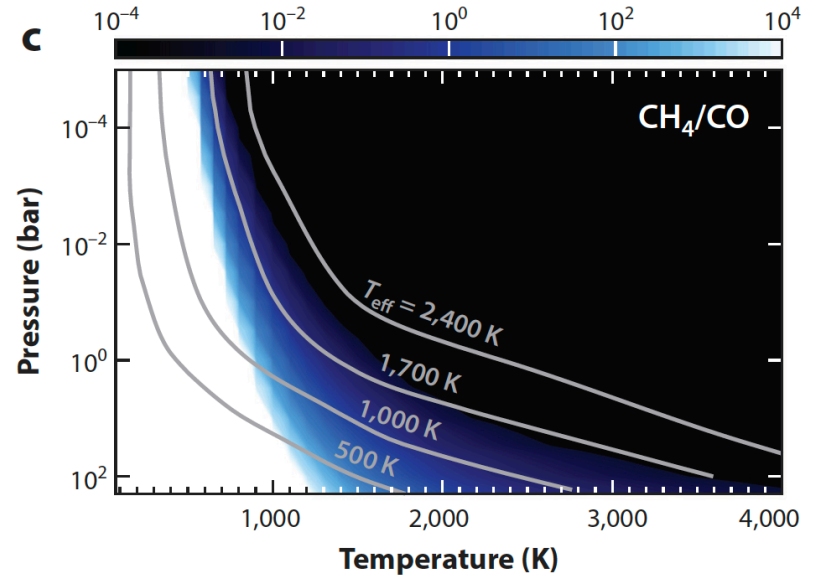
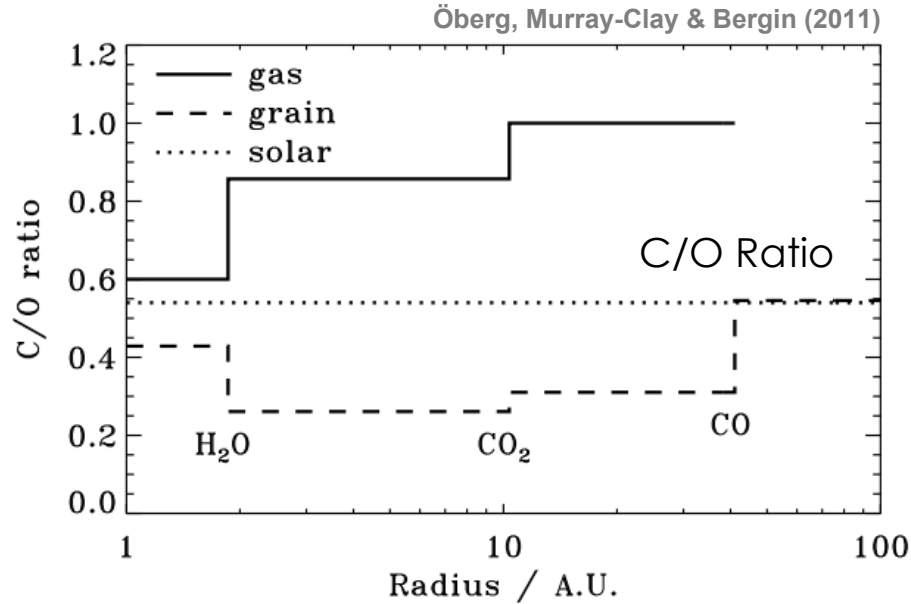


Determining thermal structures, dynamics, and abundances to understand planetary physics and chemistry



Measuring compositions to trace planet formation and evolution

Giant Planet Atmospheres: Formation and Physics/Chemistry



Marley & Robison (2015)

Based on these figures, both formation issues and atmospheric chemistry and mixing will alter the abundances of C- and O-bearing molecules

Ingredients in a Model Atmosphere

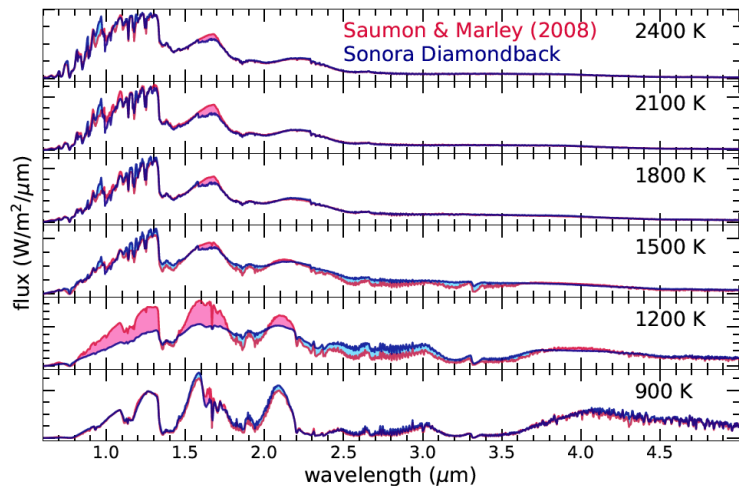
- Parent star incident flux, if any
- Flux from planetary interior
- Surface gravity
- Base elemental composition
- Treatment of chemistry
- Treatment of clouds
- Mixing processes
 - Adiabatic convection?
 - Radiative region mixing?
- Opacities for atoms/molecules
- Opacities for clouds



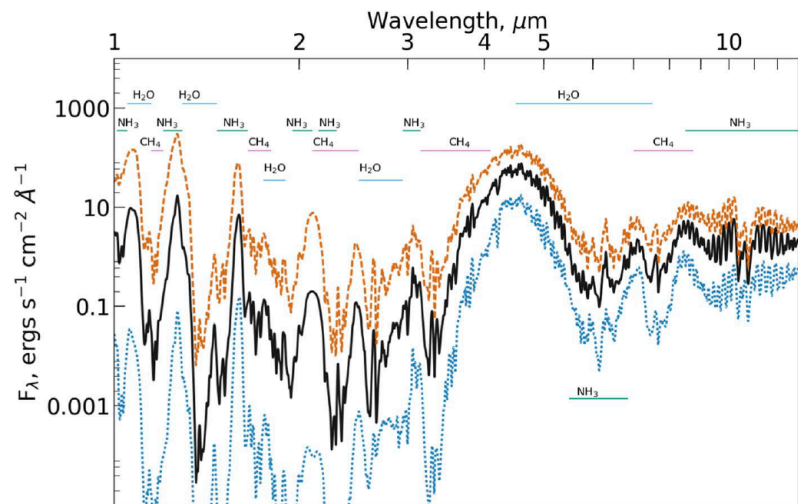
Rainbow of Flavors

- **Equilibrium Chemistry, Cloud Free**
- **Equilibrium Chemistry, Cloudy**
- **Non-Eq Chemistry, Cloud Free**
- **Non-Eq Chemistry, Cloudy**
- **Partly Cloudy**

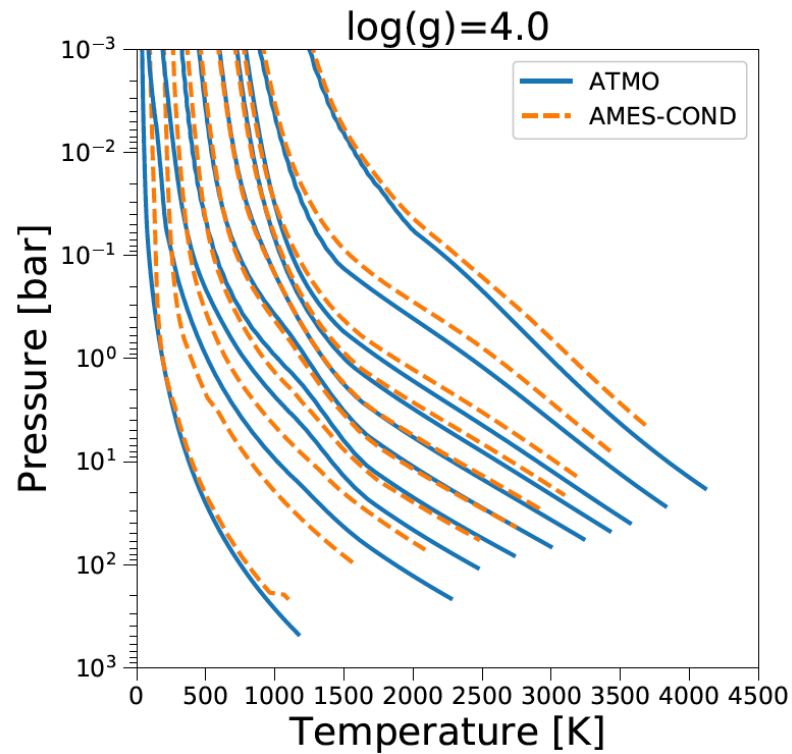




Morley+2024



Lacy &
Burrows,
2023



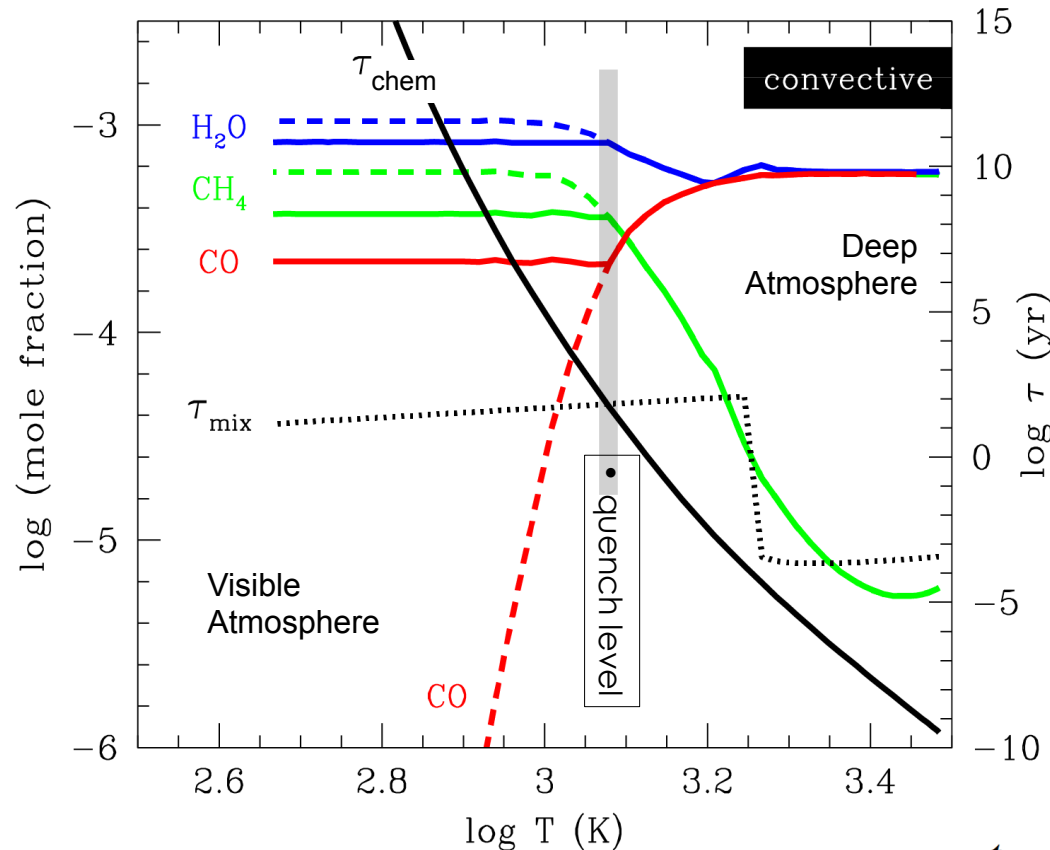
Phillips+2020

Rainbow of Flavors

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- Partly Cloudy



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 mixin
 - Currently unknown within a factor of 10^{3+}
- Compare mixing timescale to chemistry timescale dramatically affects chemical abundances

$$t_{\text{mix}} = \frac{H^2}{K_{zz}} \quad \text{CH}_4 + \text{H}_2\text{O} \rightleftharpoons \text{CO} + 3\text{H}_2$$

The Atmosphere Below Levels Than We Can See

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

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

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

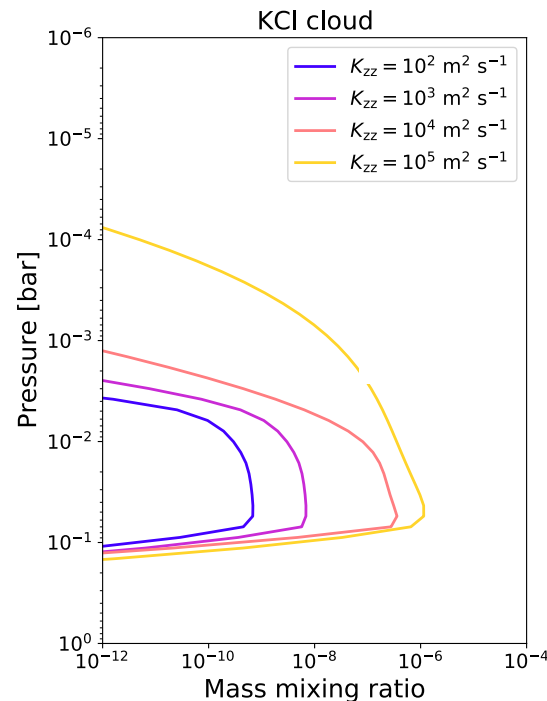
Mixing Length Theory
in **convective zones**

$$K_{zz} = ?$$

Significant interest
in **radiative zones**

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

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

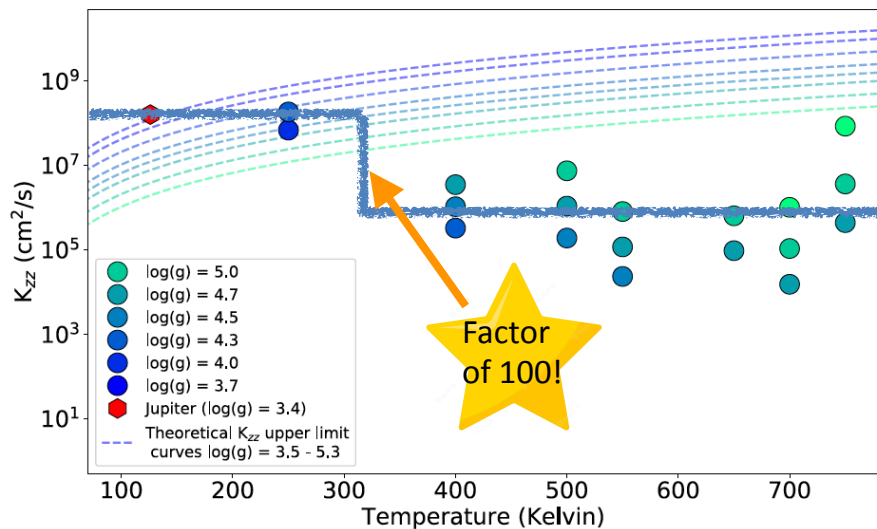




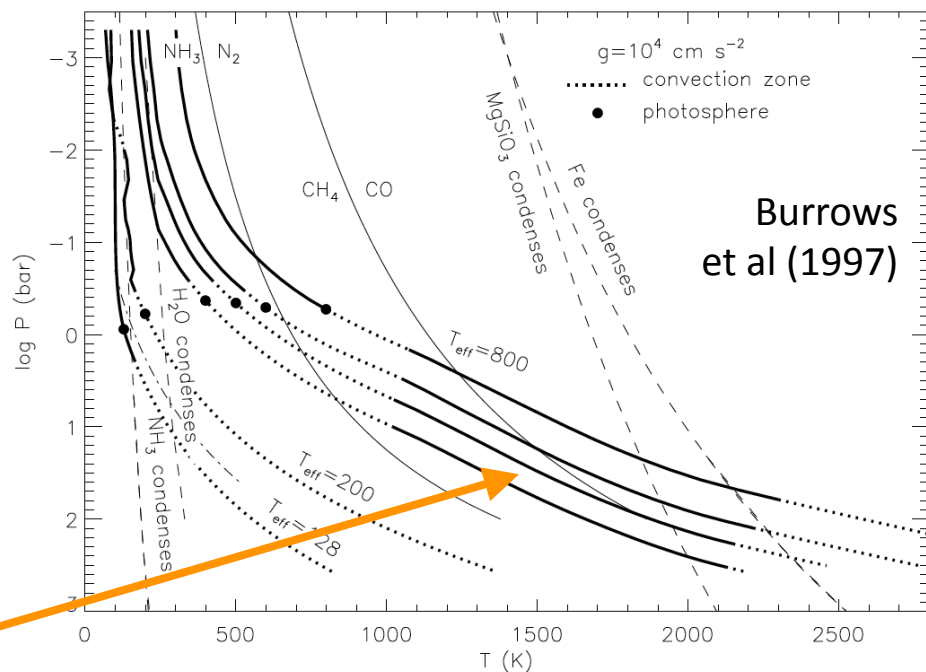
Observations of Disequilibrium CO Chemistry in the Coldest Brown Dwarfs

Brittany E. Miles¹ , Andrew J. I. Skemer¹ , Caroline V. Morley² , Mark S. Marley³ , Jonathan J. Fortney¹ ,
Katelyn N. Allers⁴ , Jacqueline K. Faherty⁵ , Thomas R. Geballe⁶ , Channon Visscher^{7,8} , Adam C. Schneider⁹ ,
Roxana Lupu¹⁰ , Richard S. Freedman^{3,11} , and Gordon L. Bjoraker¹²

¹University of California, Santa Cruz, Santa Cruz, CA 95064, USA; bmiles@ucsc.edu

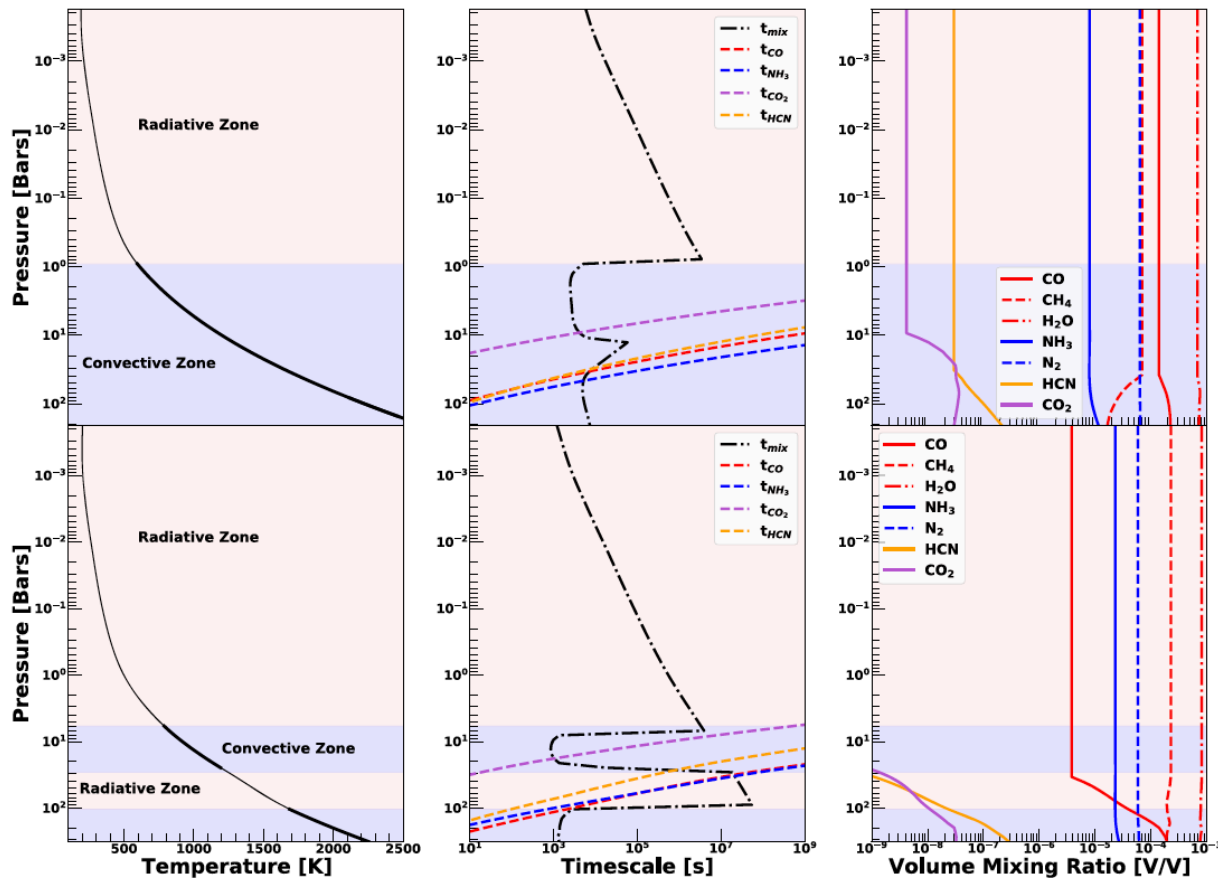


Deep radiative zone



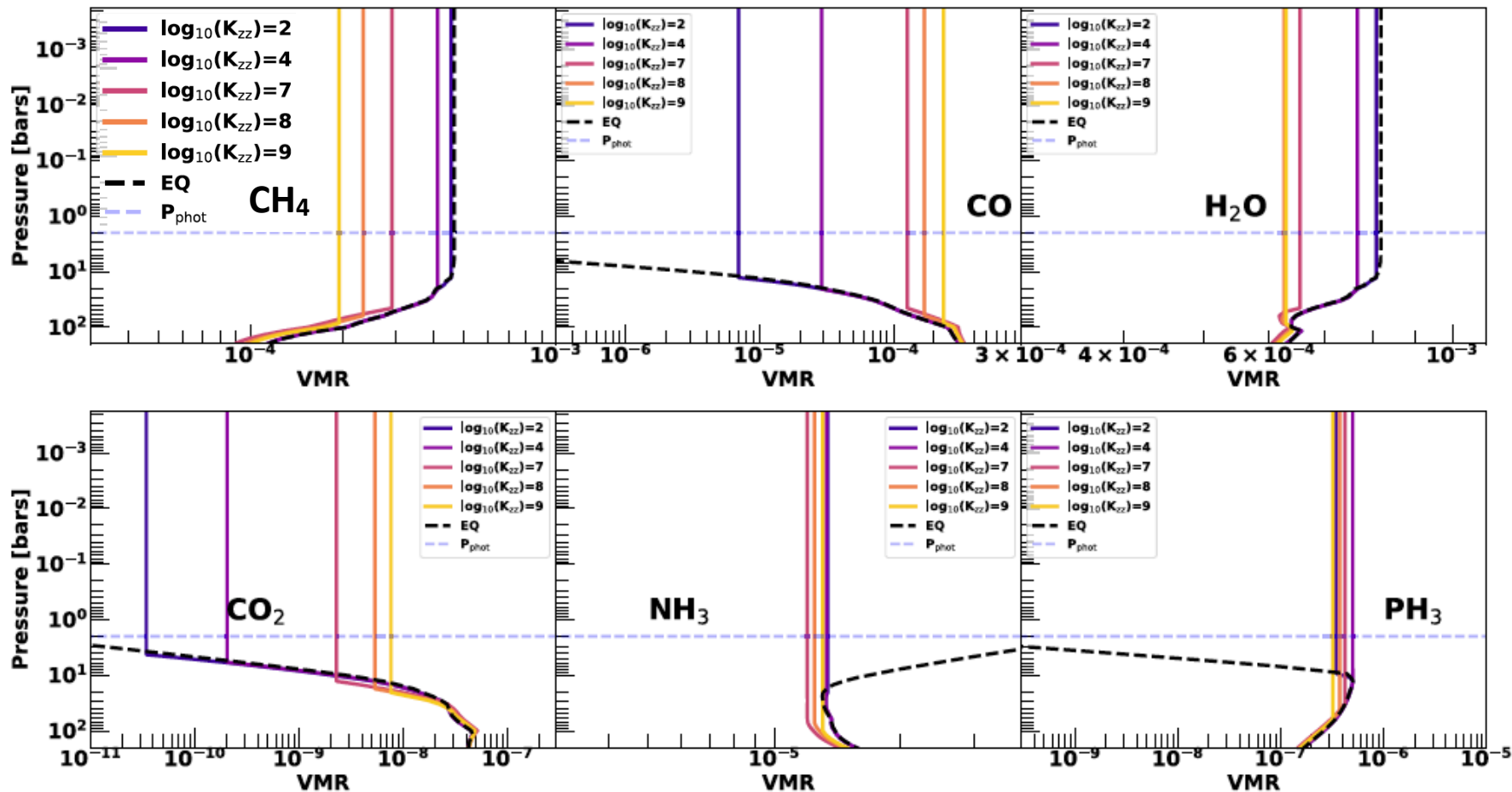
Burrows
et al (1997)

Interplay between t_{chem} and t_{mix} sets atmospheric abundances



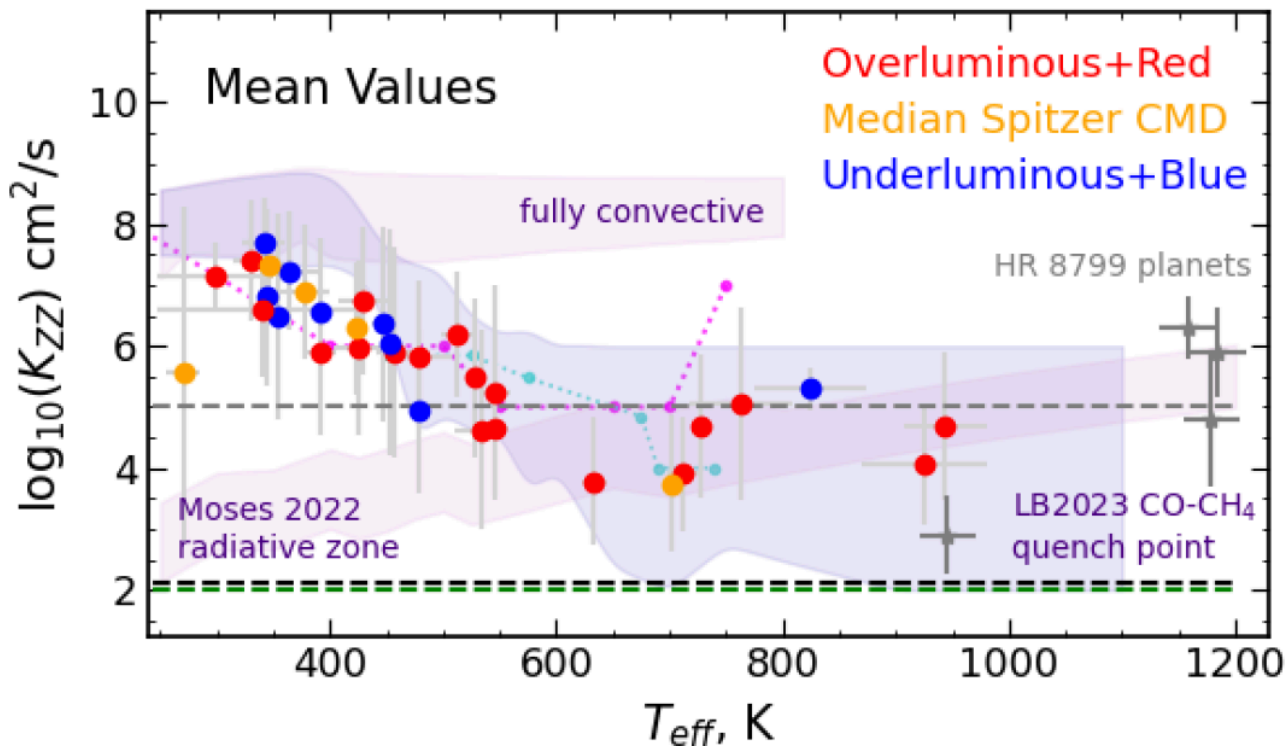
- t_{chem} from lab work or ab initio calculations
- t_{mix} from theory and from **empiricism**

$T_{\text{eff}} = 700 \text{ K}$, $\log(g) = 5.0$, $[M/H] = +0.0$, $C/O = 0.45$



Mukherjee, Fortney, et al. (2024): Sonora Elf Owl

A large sample of T and Y dwarfs with JWST spectra

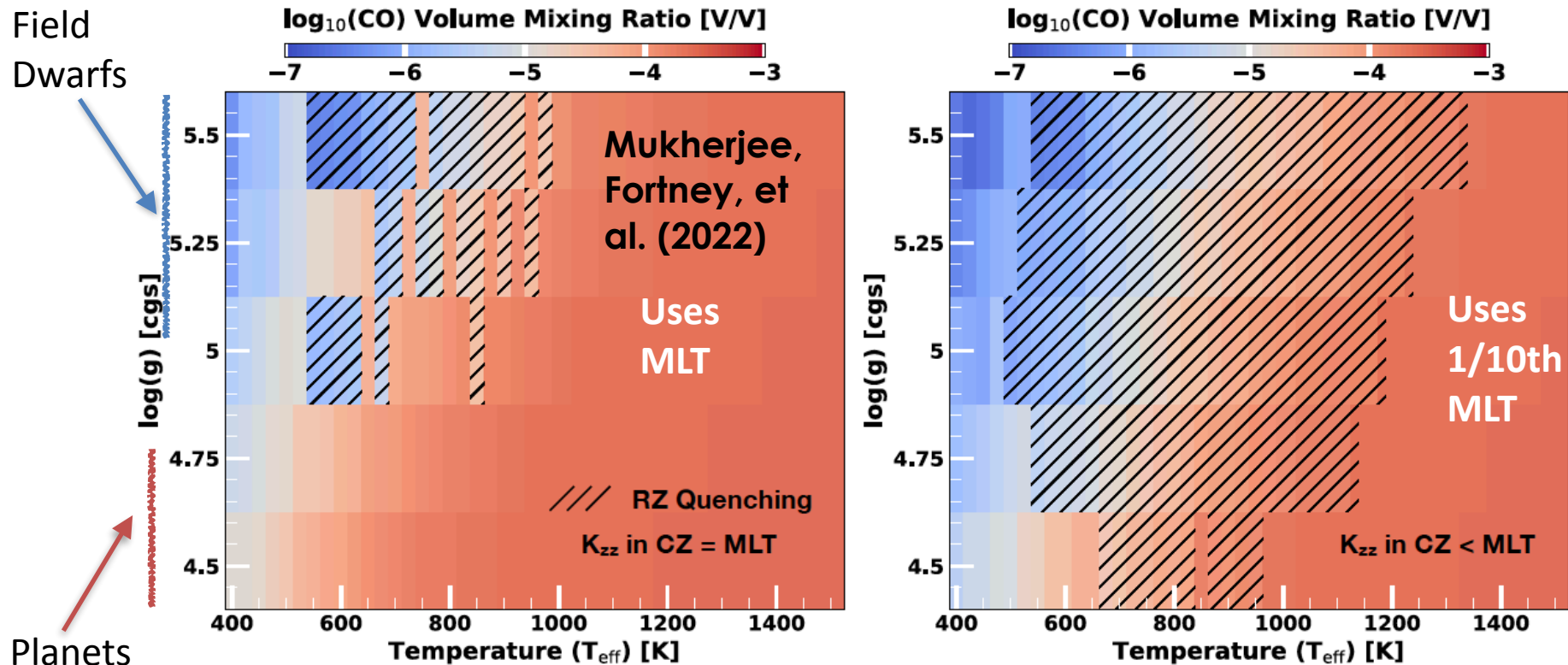


Lacy et al. (in prep)

- Trend is T_{eff} is robust across three different sets of models (Lacy & Burrows, Elf Owl, ATMO2020++)
- Coldest objects, with weakest interior fluxes, 10^3 - 10^4 faster mixing

Expect differences for brown dwarfs vs. imaged planets!

CO abundance sensitive to K_{zz} and *surface gravity*



Rainbow of Flavors

- **Equilibrium Chemistry, Cloud Free**
- **Equilibrium Chemistry, Cloudy**
- **Non-Eq Chemistry, Cloud Free**
- **Non-Eq Chemistry, Cloudy**
- **Partly Cloudy**



WHICH SONORA MODEL SHOULD I USE?

Caroline V. Morley, Mark S. Marley, Sagnick Mukherjee, James Mang,
Channon Visscher, Natasha Batalha, Evan Davis, Jonathan J. Fortney

Our greater modeling empire has provided a series of widely-used atmosphere and evolution models since 2020, starting with SONORA BOBCAT (Marley et al. 2021), SONORA CHOLLA (Karalidi et al. 2021), SONORA DIAMONDBACK (Morley et al. 2024), and SONORA ELFW (Mukherjee et al. 2024). Upcoming releases include RED DIAMONDBACK (Davis et al.), FLAME SKIMMER and GILA MONSTER (Mang et al.). Here, I describe each modeling release, and offer guidance about when to use each. All models presented calculate the temperature structures, chemical abundances, and spectra of atmospheres assuming radiative-convective equilibrium.

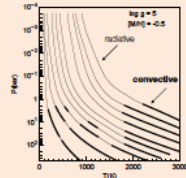
BOBCAT

SONORA BOBCAT is the O.G. SONORA grid, published by Marley et al. 2021. It describes the overall methodology and general updates, so please consider citing it regardless of your grid choice! It includes models of 3 different metallicities (-0.5, 0.0, +0.5, and C/O ratios (0.5, 1.0, and 1.5x solar). The paper describes the updated opacities and chemistry calculations. The models are cloud-free and assume chemical equilibrium.

BOBCAT includes evolution models, using the atmospheres as self-consistent boundary conditions.

Use for:

- 200-2400 K cloud-free objects
- disequilibrium chemistry isn't important
- if you need self-consistent evolution models



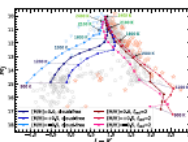
Use for:

- 900-2400 K cloudy objects
- disequ. chemistry isn't important
- if you need self-consistent evolution models

Young/hot object? Look out for RED DIAMONDBACK (Davis et al. submitted) which uses the SPINX M dwarf spectra and the Diamondback L dwarf spectra to better model the evolution of 2000-3000 K objects

DIAMONDBACK

SONORA DIAMONDBACK was published last year by Morley et al. 2024. This grid is the first SONORA model grid to include clouds, following the framework of Ackerman & Marley 2001 and including Al_2O_3 , Fe, MgSiO_3 , and MgSiO_2 clouds. We calculated evolution models including the effect of the clouds, and studied how the cloudy evolution and atmosphere models change at different metallicities (-0.5, 0.0, and +0.5). Key results of the paper include a lower hydrogen-burning minimum mass of 70.2 Jupiter masses (compared to 73.4 from Saumon & Marley 2008), closely matching the empirical limit of 70 M_J from Dupuy & Liu 2017.

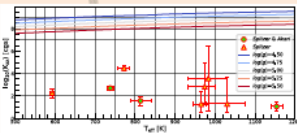


ELF OWL

ELF OWL is the biggest grid we have ever released, published by Mukherjee et al. 2024. It includes over 10,000 models from 275–2400 K, metallicities from -1 to +1, and C/O from 0.5–2.5x solar. It includes disequilibrium chemistry (with constant K_{eq}) that is coupled to the radiative-convective equilibrium calculation. A key result from Mukherjee et al. 2024 is that brown dwarf atmospheres have more inefficient mixing than previously thought ($K_{eq} \sim 10^4 - 10^6 \text{ cm}^2/\text{s}$), due to chemical quenching in their radiative layers (instead of convective layers). If there's CO_2 in your spectrum, please upgrade to the Wogan et al. 2025 grid which implements a "second quench" fix to the CO_2 chemistry.

Use for:

- 275-2400 K cloud-free objects
- disequilibrium chemistry is important
- you need a broad range of metallicities and C/O ratios
- if you do NOT need self-consistent evolution models (could use Bobcat or Diamondback evolution w/ Elf Owl spectra)



FLAME SKIMMER

FLAME SKIMMER and GILA MONSTER will be huge updates to look forward to later this year, but if you have an exciting result that needs models earlier, reach out to James Mang (lead) and Caroline Morley. These model grids extend our framework to cooler temperatures (50-250 K) and lower gravities (2-3.5) than ELF OWL. These models are ideal for the coldest directly imaged planets and brown dwarfs observed with JWST, and have already been applied to observations of 14 Her c (Bardalez-Gagliuffi et al. 2025) and TWA 7b (Crotts et al. 2025). We plan to include self-consistent evolution models for both grids. FLAME SKIMMER is cloud-free and GILA MONSTER will include clouds, including water clouds in the evolution models for the first time.

GILA MONSTER

Use for:

- 50-500 K objects
- cloud-free: FLAME SKIMMER
- cloudy: GILA MONSTER
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SONORA or PICASO?

PICASO is the name of an open-source atmosphere modeling code with legacy in the Fortran EGF code (Marley et al. 1999). We have branded the models themselves (pressure-temperature profiles, spectra, etc.) SONORA regardless of code used to create the models (Bobcat and Diamondback used EGF while Elf Owl, Flame Skimmer, and Gila Monster used PICASO).

Should I use CHOLLA?

CHOLLA (Karalidi et al. 2021) implemented disequilibrium chemistry coupled to the radiative-convective equilibrium model for the first time. The grid has been replaced by the Elf Owl models, which cover a broader range of metallicities, C/O ratios, and temperatures.

Caroline Morley's 2025 Exoclimates Poster

Equilibrium Chemistry, Cloud Free

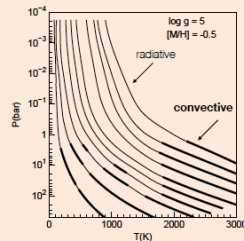
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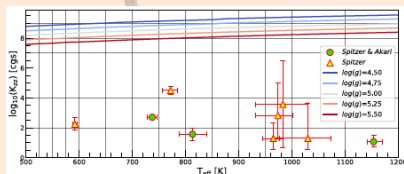


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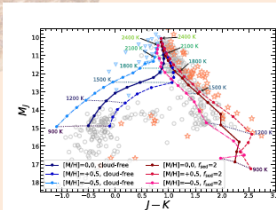
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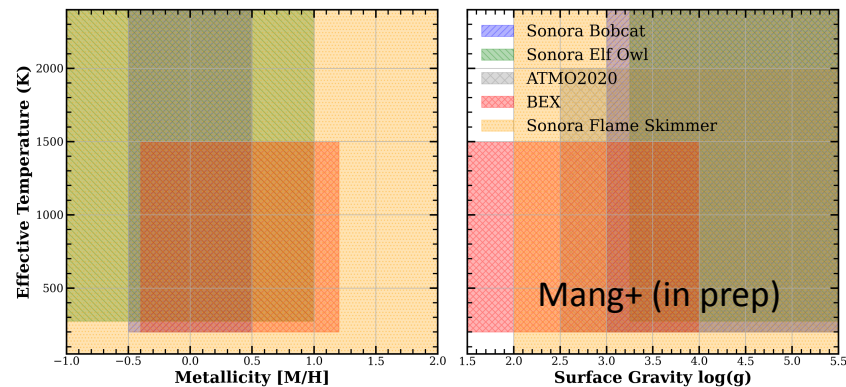
Equilibrium Chemistry, Cloudy

Non-Eq Chemistry, Cloud Free (colder + lower g)

Non-Eq Chemistry, Cloudy Partly Cloudy

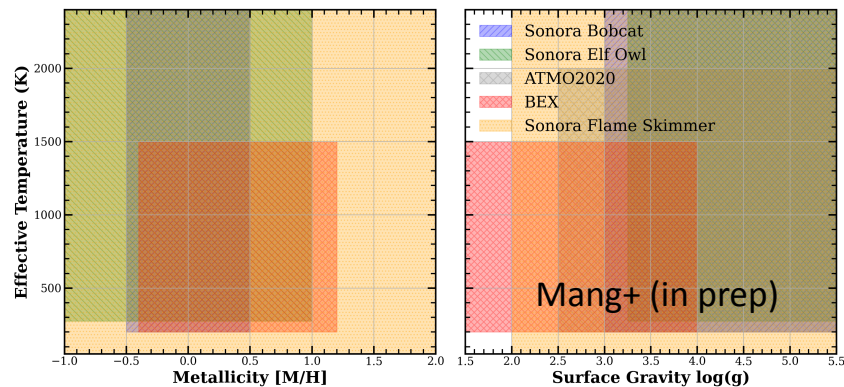
Kinds of Models

- Equilibrium Chemistry, Cloud Free
 - Sonora Bobcat (Marley+, 2021)
 - ATMO2020 CEQ (Phillips+, 2020)
 - BEX (Linder+2019, cold objects)
 - SAND (Gerasimov+2024)
- Equilibrium Chemistry, Cloudy (Silicates + Iron)
 - Sonora Diamondback (Morley+, 2024)
 - Exo-REM (Charnay+ 2018, 2026 in prep)
 - MSG/MARCS (Jørgensen+, 2024)
 - BEX (Linder+2019, Salts and Sulfides, Cold)
 - BT-Settl (Allard+, 2014)
 - DRIFT-PHOENIX (Wittke+, 2011)

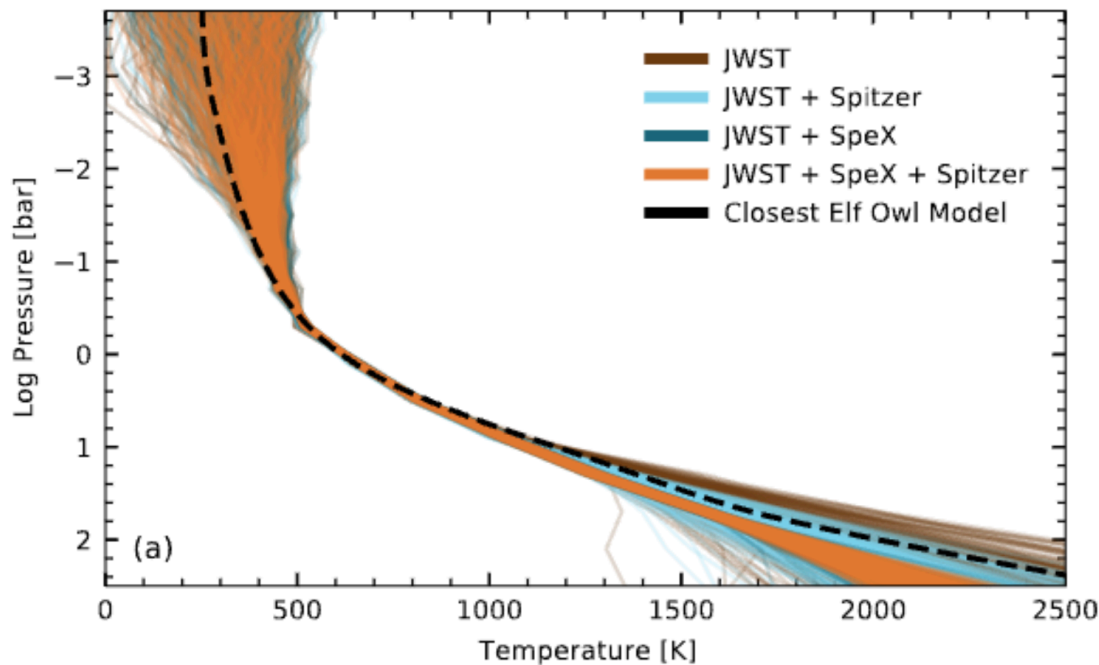


Kinds of Models

- Non-Eq Chemistry, Cloud Free
 - Sonora Elf Owl (Mukherjee+, 2024)
 - ATMO2020 NEQ (Phillips+, 2020)
 - Sonora Flame Skimmer (Mang+, 2026)
 - ATMO2020++ with sub-adiabatic (Tremblin+)
- Non-Eq Chemistry, Cloudy
 - Lacy & Burrows (2023), Lacy + (2026 in prep), Water Clouds (also cloud-free, eq. chem)
 - Sonora Gila Monster (Mang+, 2026 in prep), Water + Ammonia Clouds
 - MSG/MARCS, Silicates+Fe (Jørgensen+, 2024)
 - SAND (Gerasimov+2024)
- Partly Cloudy
 - Sonora Gila Monster (water)



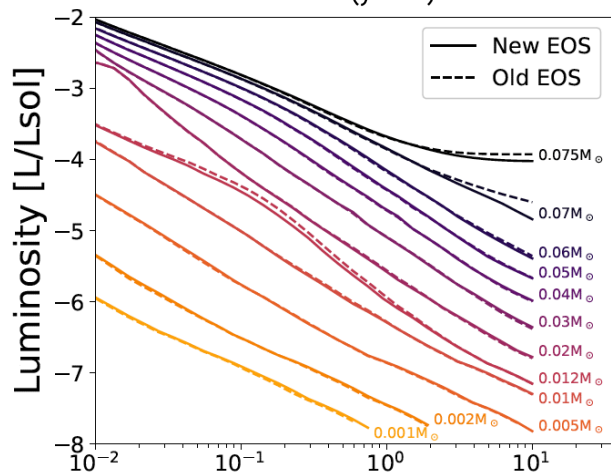
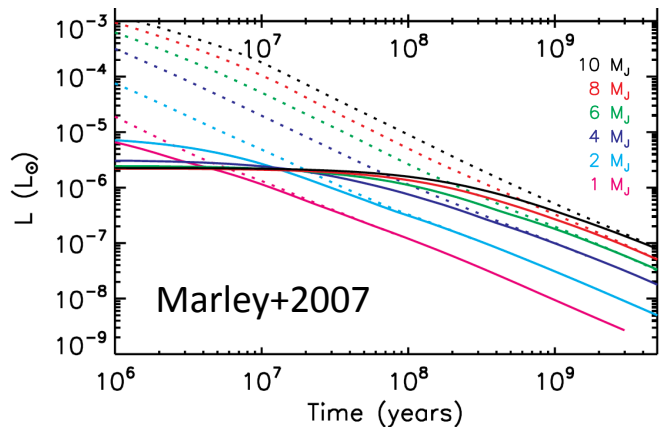
How to Help!



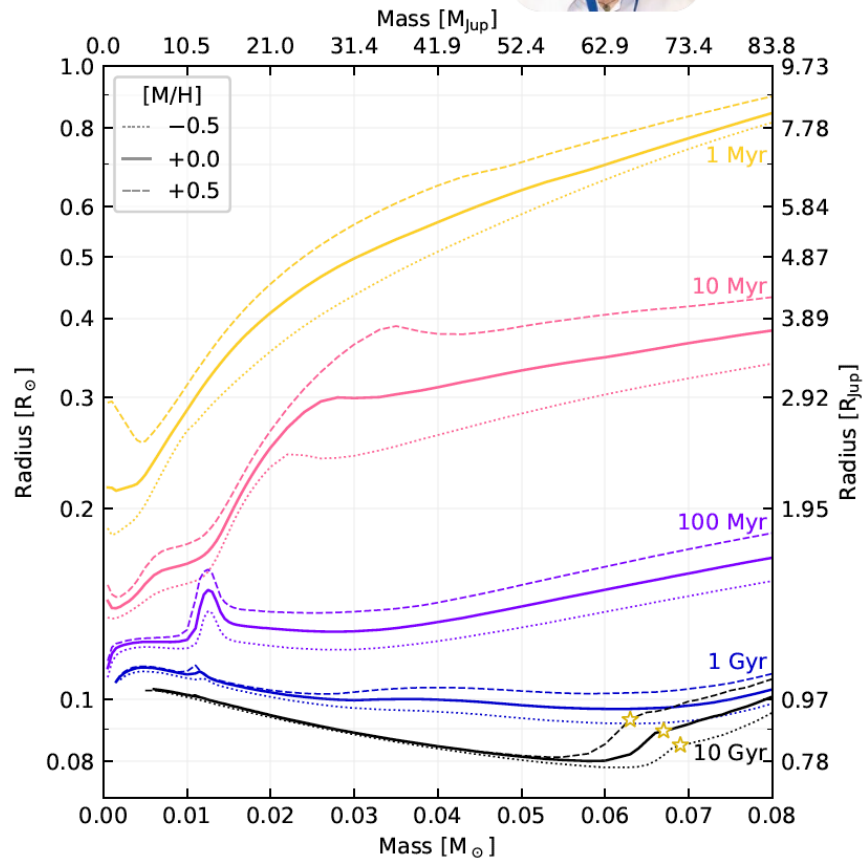
Hood+2023

Even without a “grid-treaval” to find the best-fit grid model, plotting a grid model P - T compared to the retrieved profile can help to build trends, if many folks do it, and improve model physics

Thermal Evolution Models

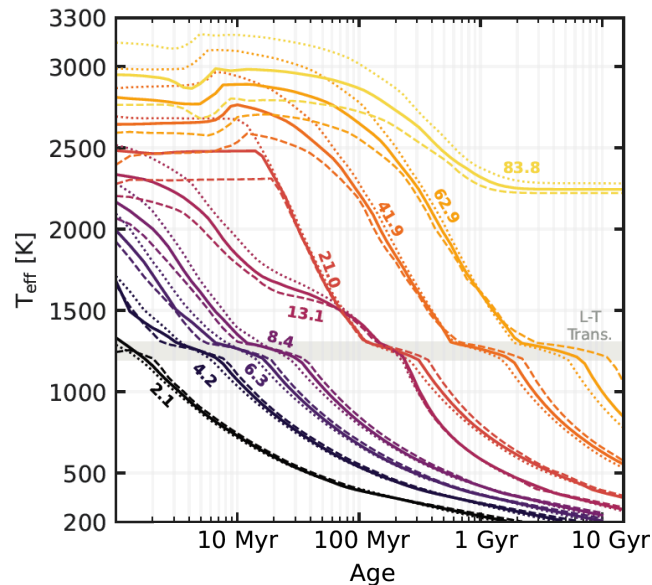


Red Diamondback,
Davis, Fortney+2025



Thermal Evolution Models

- Cloudy-to-Cloud Free atmospheres
 - Sonora Diamondback (up to 2400 K, Morley+, 2024, CMS19 EOS)
 - Sonora Red Diamondback (up to 4000 K, Davis, Fortney+, 2025, CMS19 EOS)
- Cloudy atmospheres
 - BEX (Linder+2019, cold objects)
 - SANDee (Gerasimov+2024)
- Cloud free atmospheres
 - Sonora Bobcat (Marley+ 2021, ScvH EOS)
 - ATMO2020 (Phillips+2020, CMS19 EOS)
 - Chabrier+2023 (Phillips atmosphere + CD21 EOS)
 - SANDee (Gerasimov+2024)
- Hot/Cold Start
 - Marley+2007 & Fortney+2008
 - Spiegel & Burrows (2012)
- Too Old to Use
 - DUSTY (Chabrier+2000), COND (Baraffe+2003), Burrows+97

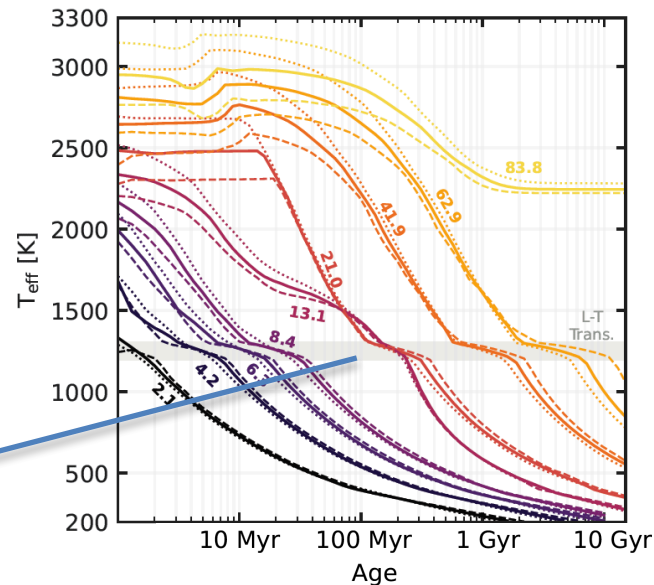
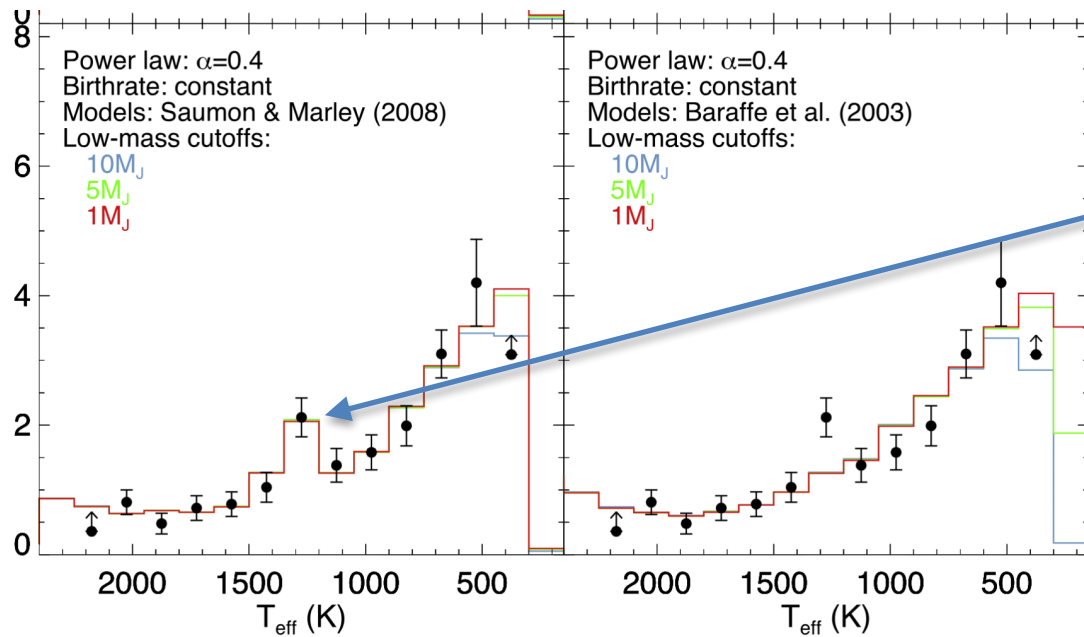


Red Diamondback, Davis, Fortney+ (2025)

Thermal Evolution Models

Red Diamondback, Davis, Fortney+ (2025)

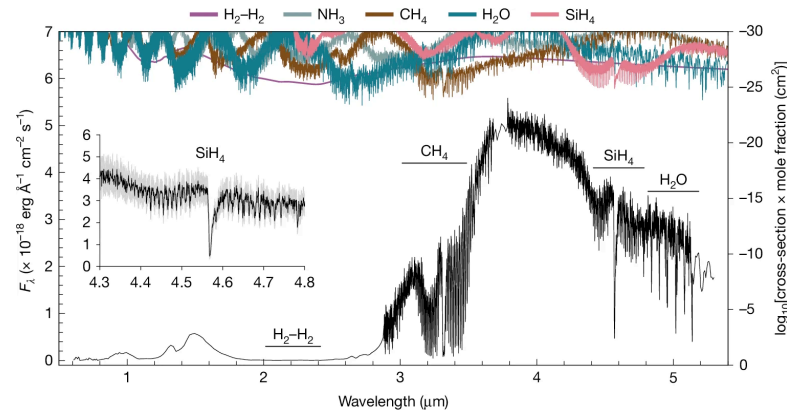
Atmosphere Choices Do Matter!



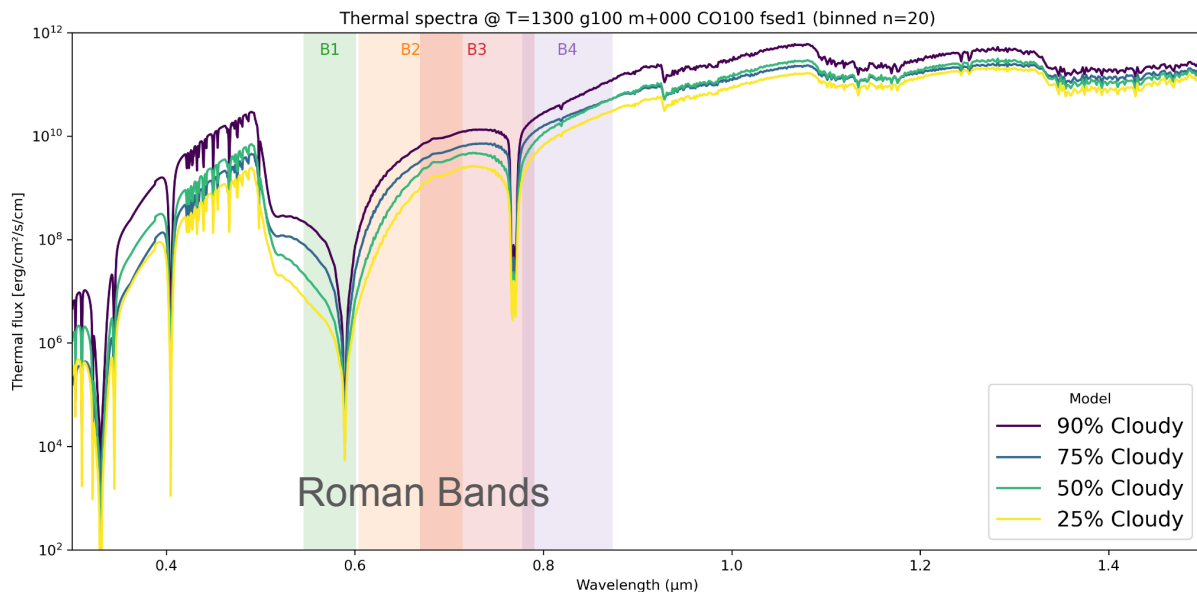
Kirkpatrick+2024, the 20 parsec sample

Where Are We Going?

- Some very low metallicity brown dwarfs are showing SiH_4 (silane) and PH_3 (phosphine)
 - Very low metallicity barely explored in models
- Some *isolated* brown dwarfs show temperature inversions and more isothermal upper atmospheres seem to be common
 - An additional heating mechanism that is another ingredient in the cake recipe
- New and different 1D cloud models
 - Coupled to 1D atmospheres
 - “Two-column” thick and thin
- Higher metallicities for cold “Neptunes”
- There will be a demand for 1D models for a long time, ever-more-informed by:
 - 3D models
 - 1D retrievals
- Exoplanet thermal evolution models “informed” by dilute cores of Saturn and Jupiter



Models Receptive to New Observations: A Roman-Ready Self-Luminous Atmosphere Grid



T: 1000–1800 K
log g: 3–5
[M/H]: −0.5–1.0
C/O: 0.5–2
Cloud fraction: 0–100%

Zarah Brown et al. (in prep)

- 10,000+ self-consistent EGP climate models that include **fractional clouds**
- High-resolution PICASO spectra in the optical and NIR/MIR

Takeaway Messages

- Beyond merely “detecting” equilibrium chemistry, CO/CH₄/H₂O/CO₂/NH₃ can be a very sensitive probe of mixing
 - Really impressive ongoing progress with JWST
 - Mixing inexorably tied into cloud physics too!
 - Could be considerable differences between field dwarfs and planets due to gravity and metallicity
- If you’re doing retrievals, you should also be comparing to a few grid models
 - Pointing out at least P-T profile and spectral deficiencies — helps to understand the physics
- Folks are always putting efforts into new and improved models, please use them and tell us how to make it easier to use them