Advances in Modeling the Atmospheres and Evolution of Brown Dwarfs

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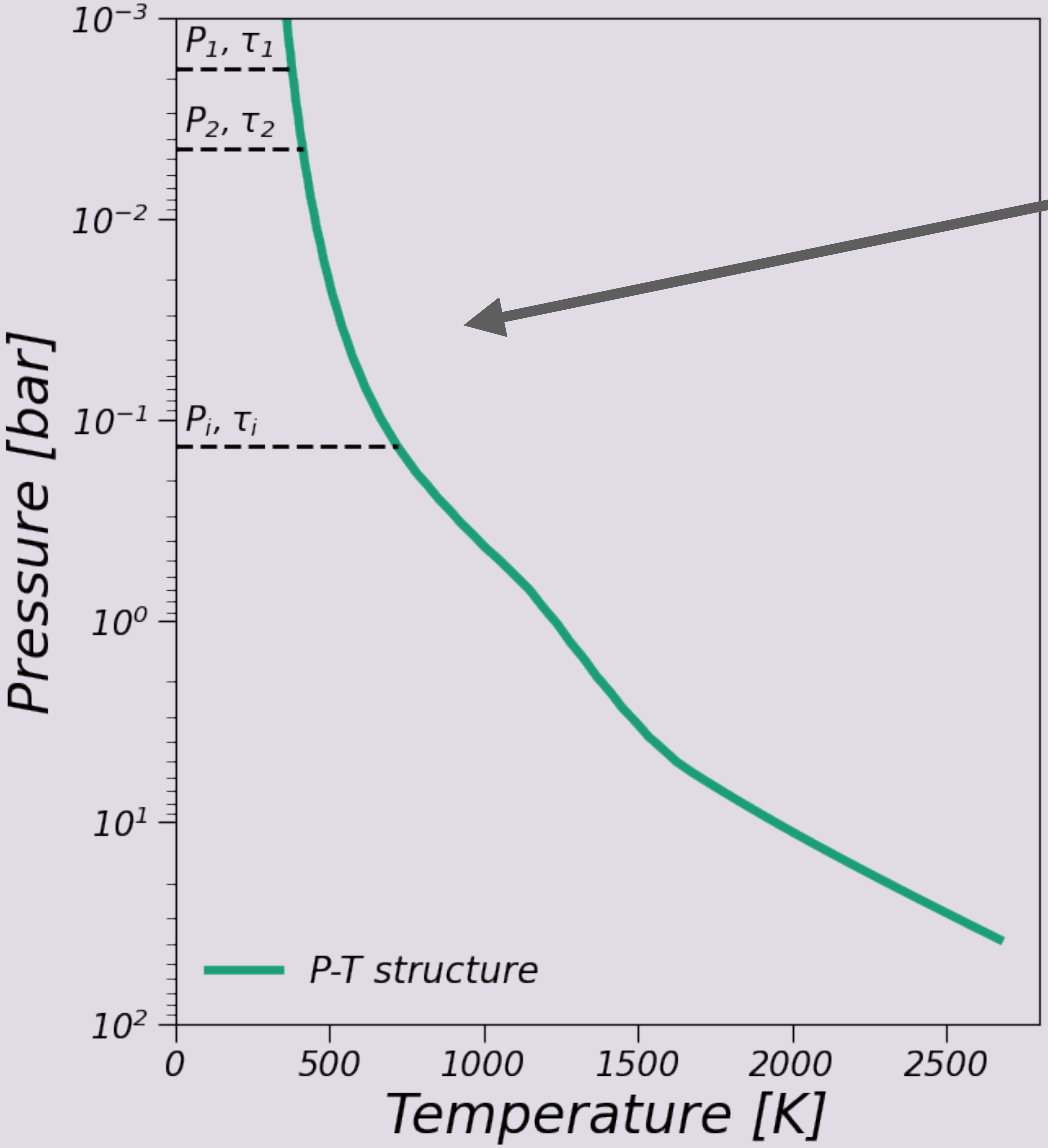
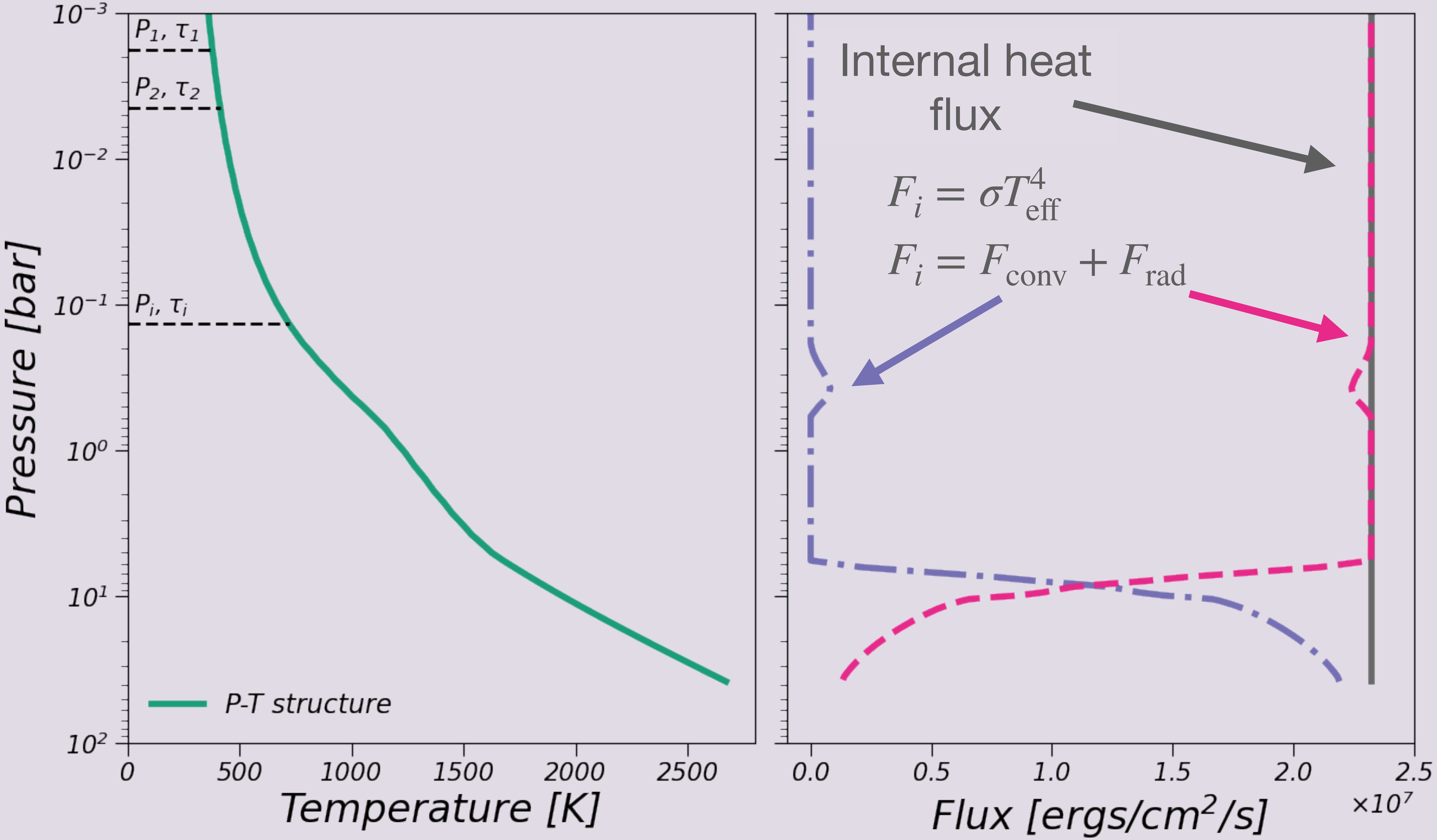
Collaborators: Isabelle Baraffe, Pascal Tremblin, Gilles Chabrier, Sandy Leggett, Michael C. Liu, Trent Dupuy, Nafise Sedighi, Eduardo Martin

A 1D Atmosphere Model

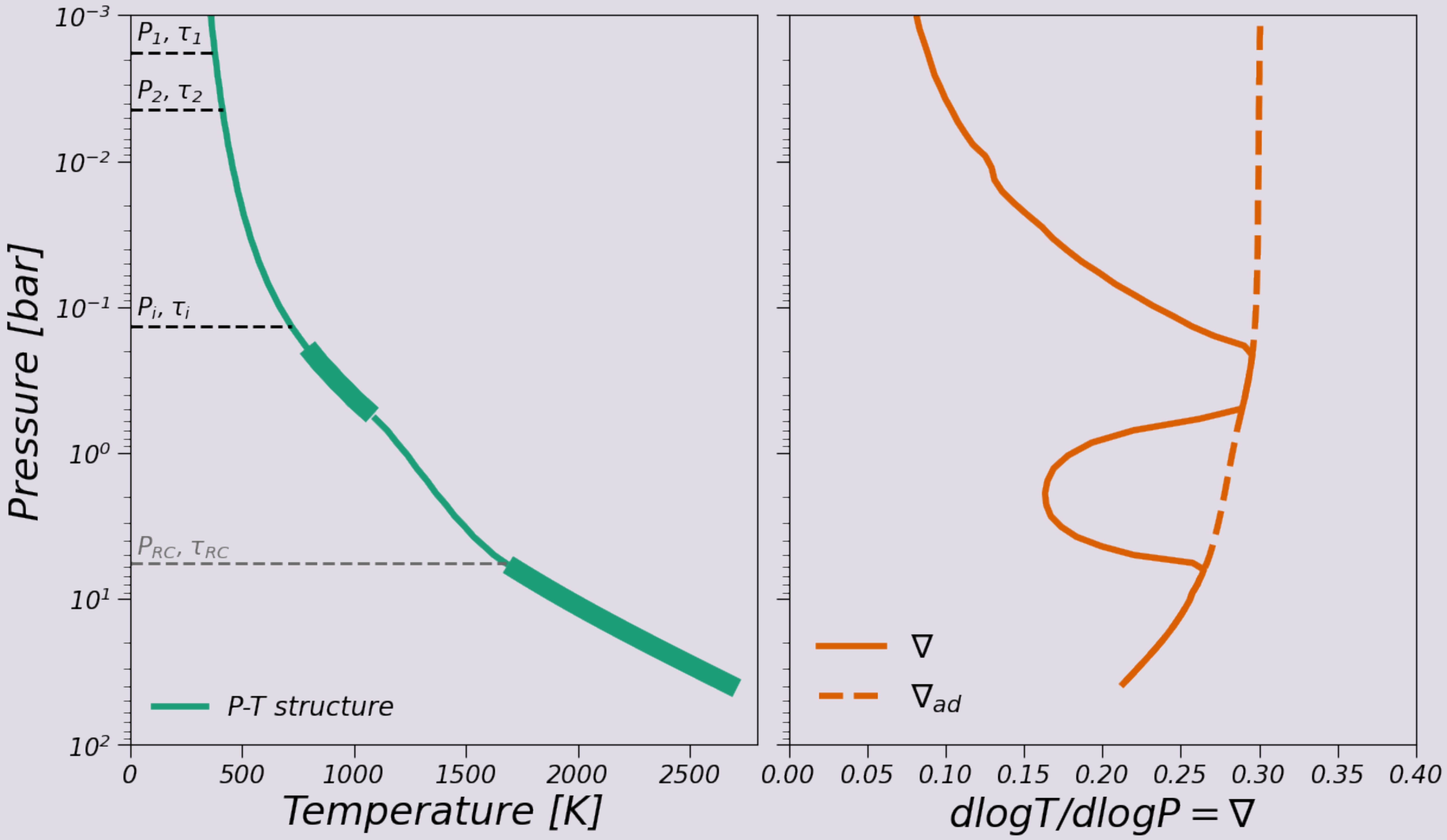


Vertical column of gas split into a grid of model levels defined in pressure, altitude or optical depth

Radiative-Convective Equilibrium



Convection



Large internal heat flux leads to convection

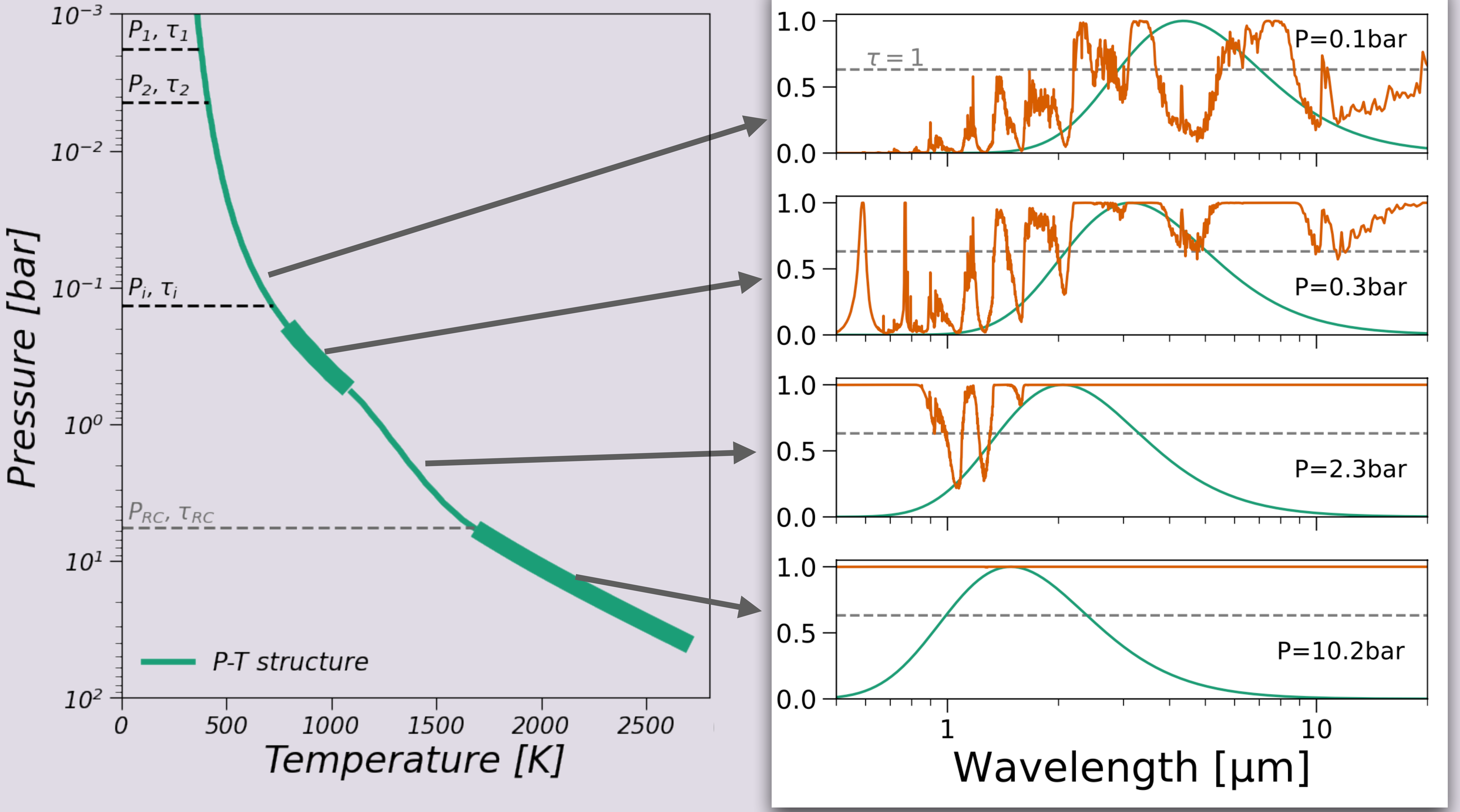
Convection in brown dwarfs is adiabatic

The condition for convection to ensue is…

$$\nabla = \frac{d \log T}{d \log P} > \frac{R_s}{c_p} = \nabla_{ad}$$

Convective flux can be calculated with mixing length theory

Radiative Transfer



The radiative flux is calculated by solving the radiative transfer equation in each model level

This is typically done in plane parallel geometry assuming isotropic scattering

Plank function

Column absorptivity

$A_\lambda = 1 - e^{-\tau}$

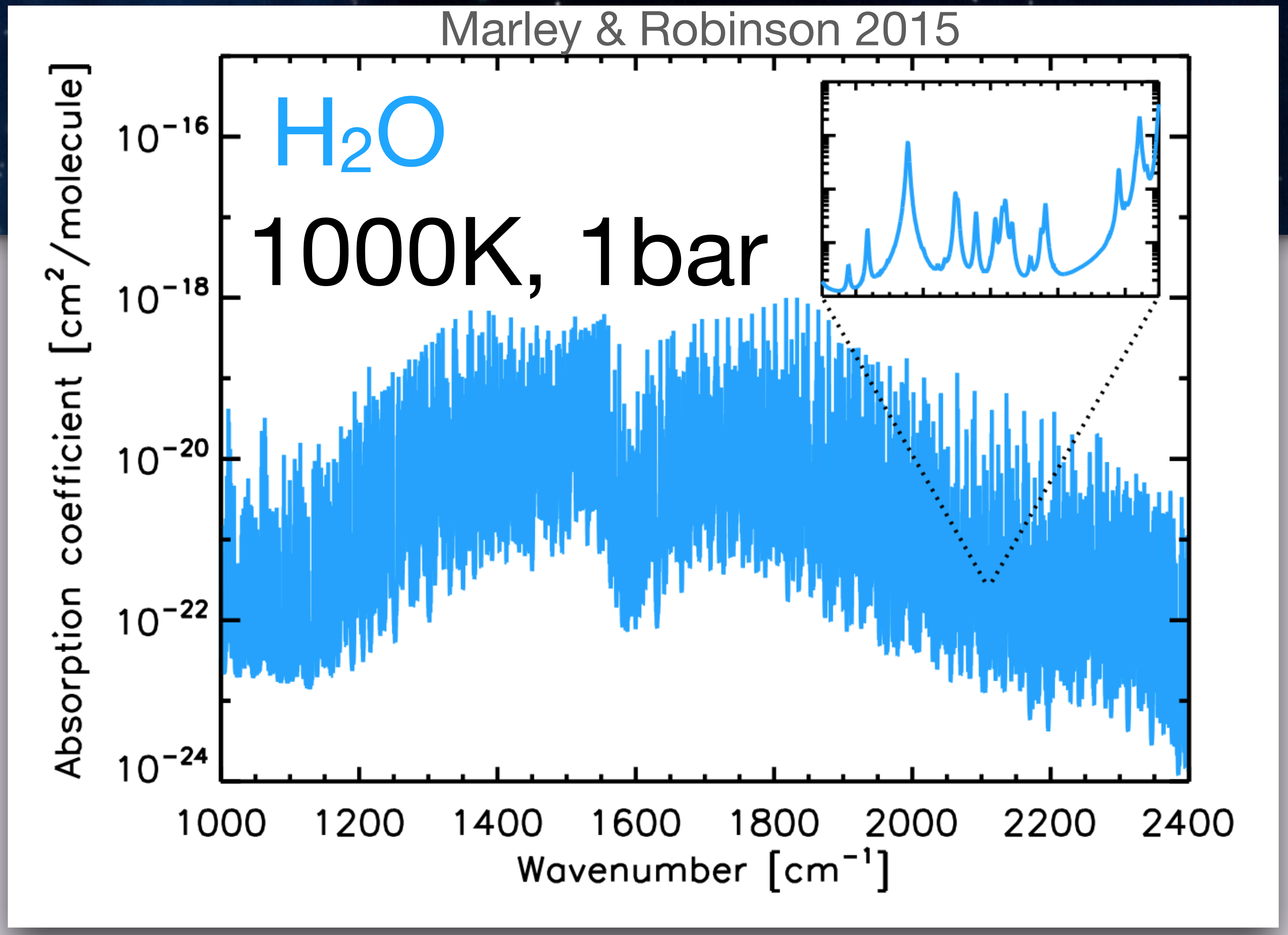
Opacities

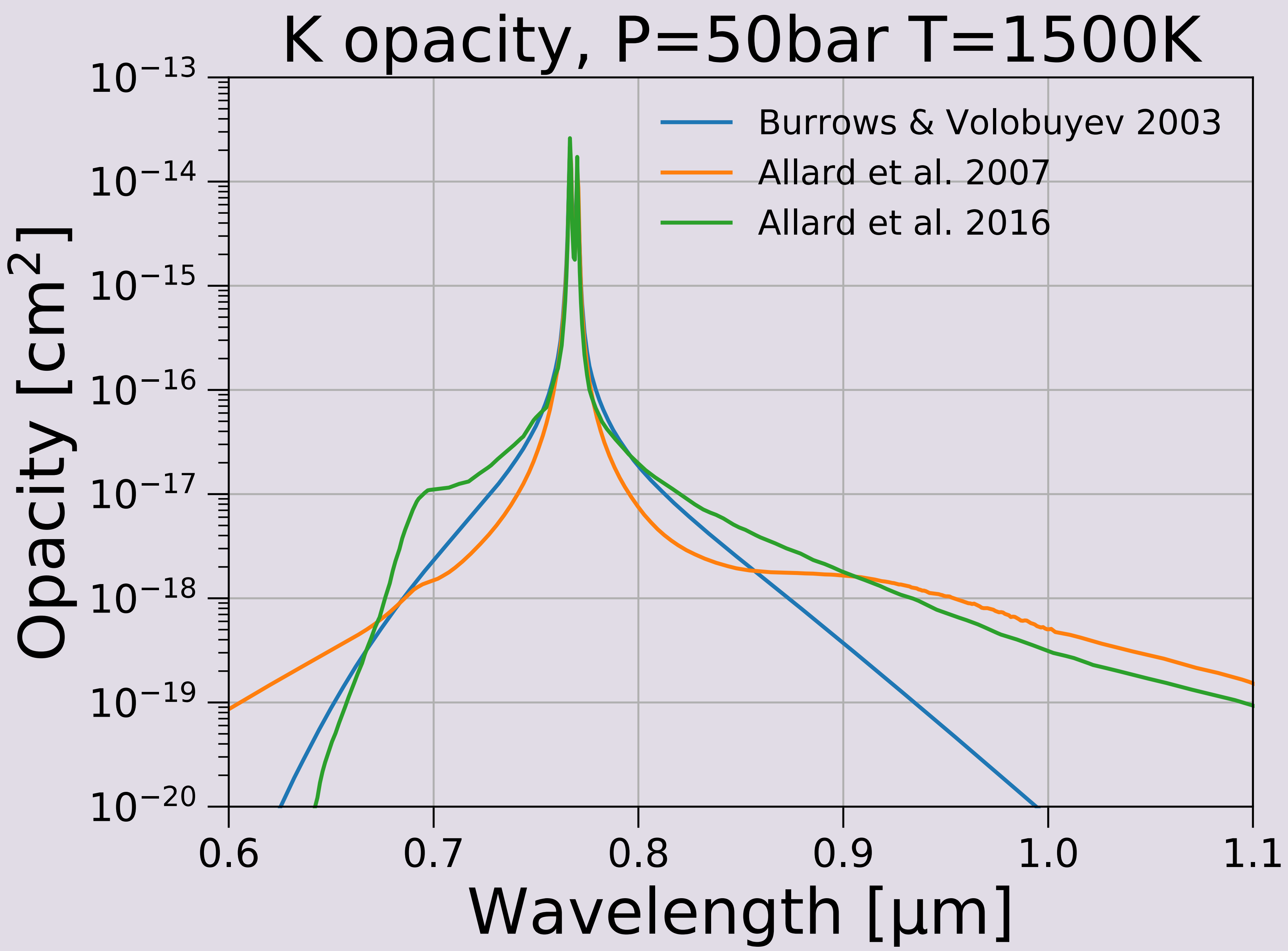
Atmospheric opacity arises from atomic and molecular line transitions

Line transitions are tabulated in large databases called linelists, provided by HITEMP, ExoMol

Linelists are large! CH_4 contains over ~50 billion lines (Yurchenko+ 2024)

Each line must be Doppler & pressure broadened for a given atmospheric layer





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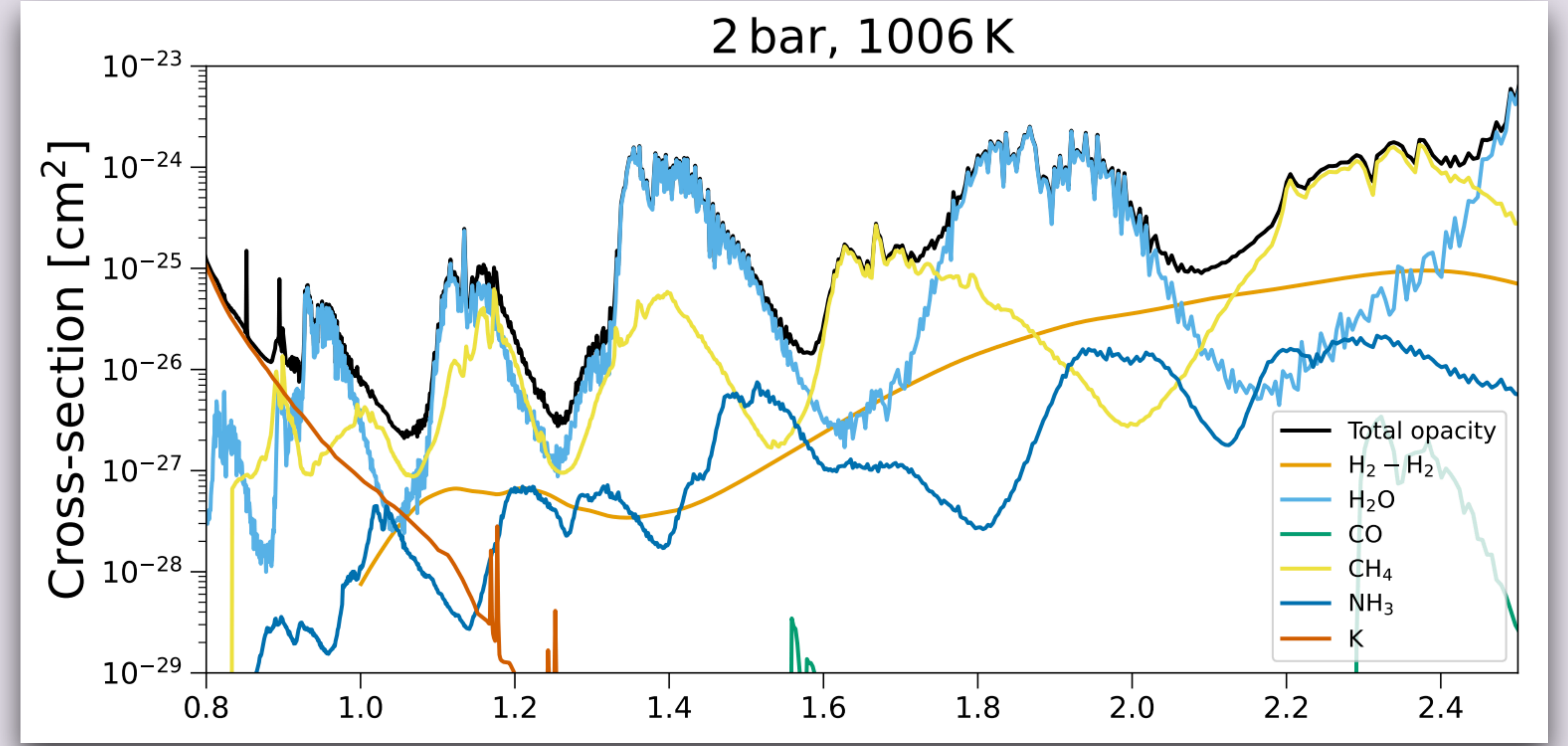
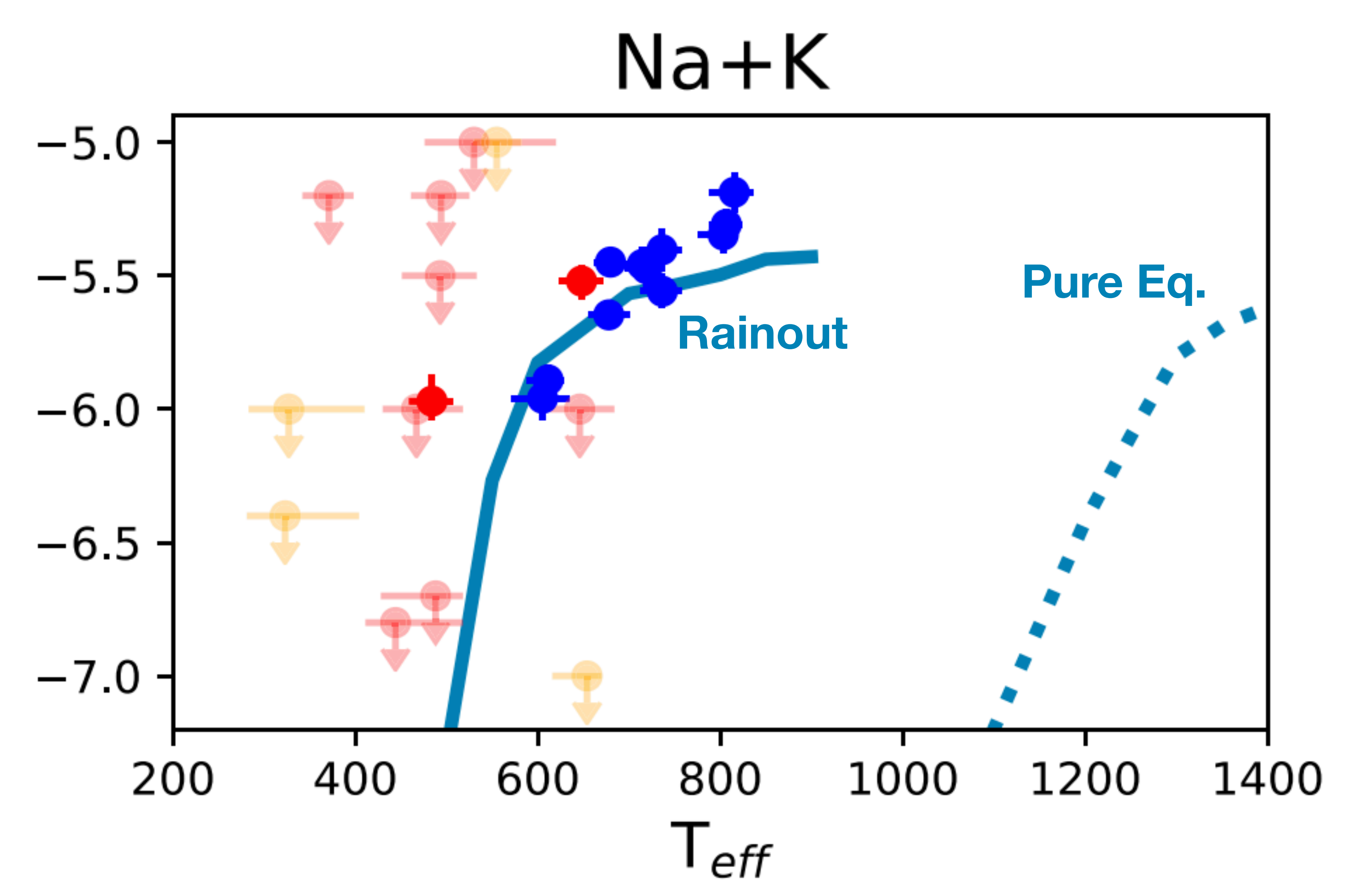


Chemistry

Chemical equilibrium

- Minimize the Gibbs free energy
- Rainout chemistry for condensate species
- Evidence for rainout chemistry in the retrieved alkali abundances of late-T & Y dwarfs (e.g. Zalesky+2019)



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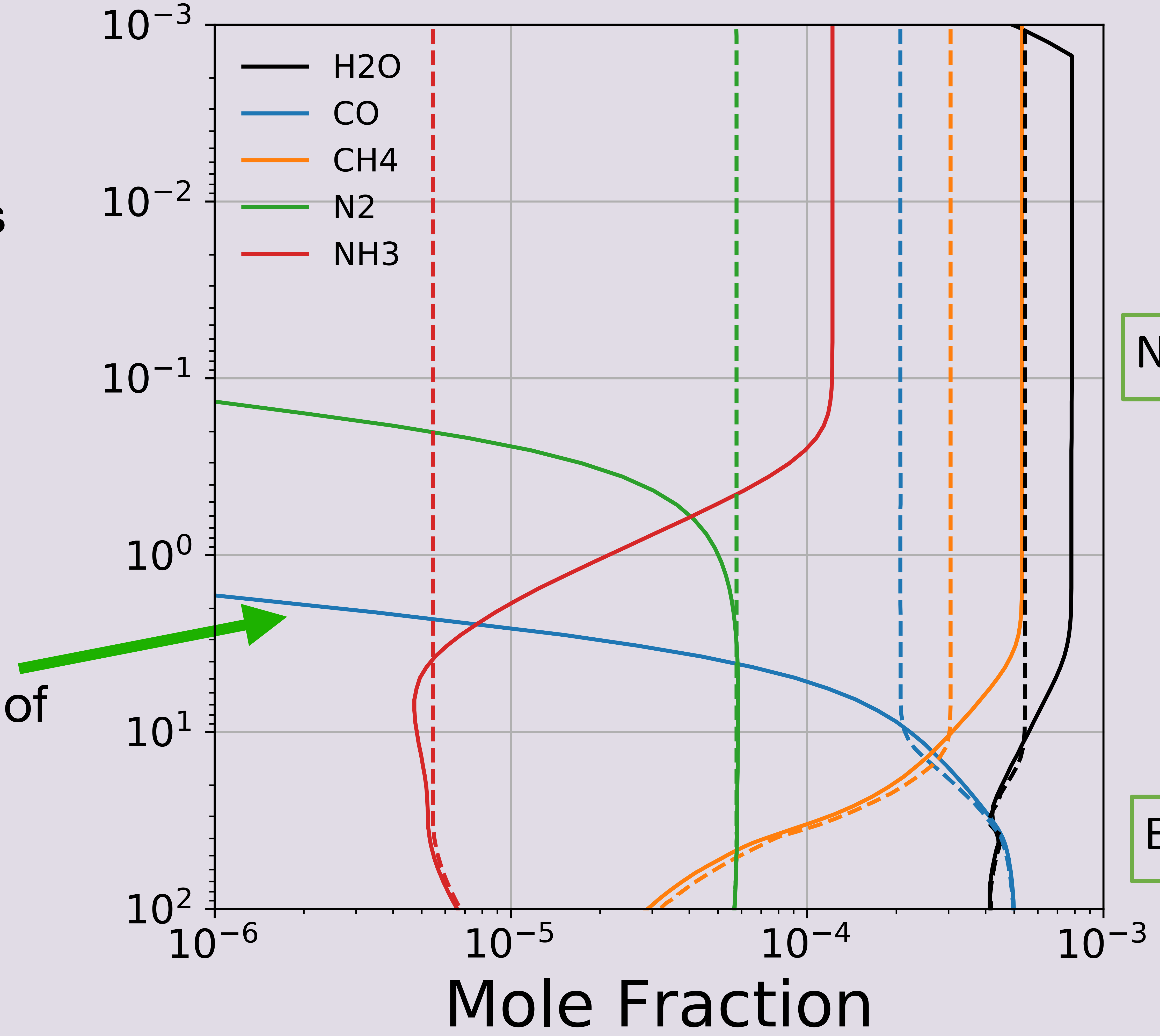
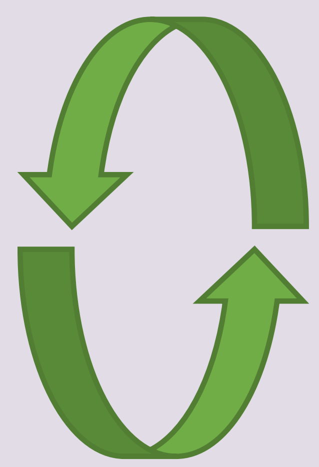
Chemical disequilibrium

- Vertical mixing drives the atmosphere out of equilibrium



Quenching



NEQ: $t_{mix} < t_{chem}$

EQ: $t_{mix} > t_{chem}$

Chemistry

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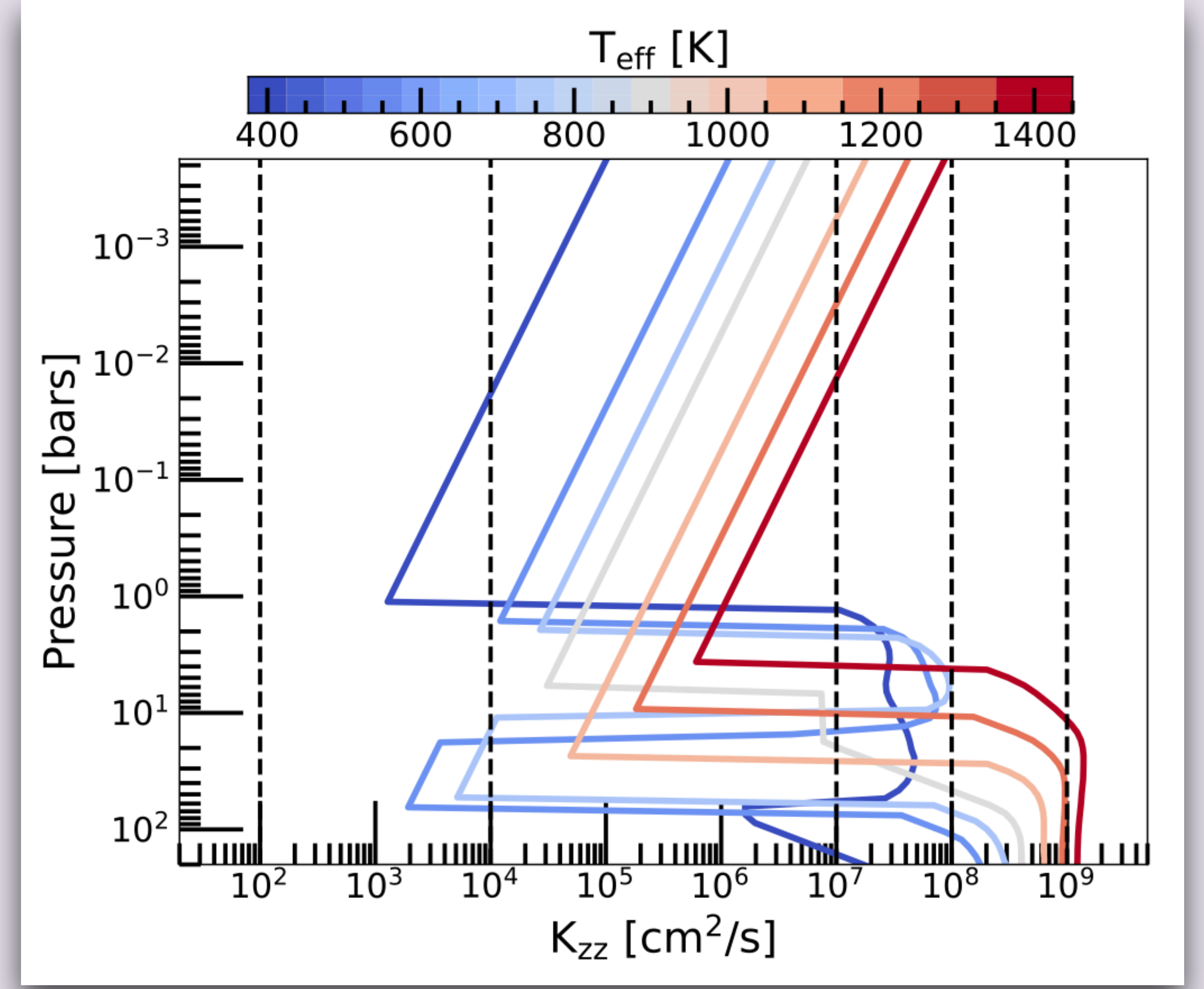
Chemical disequilibrium

- Vertical mixing drives the atmosphere out of equilibrium
- Parameterised with the eddy diffusion coefficient K_{ZZ}, largely unconstrained and treated as a free parameter



Mukherjee+2024

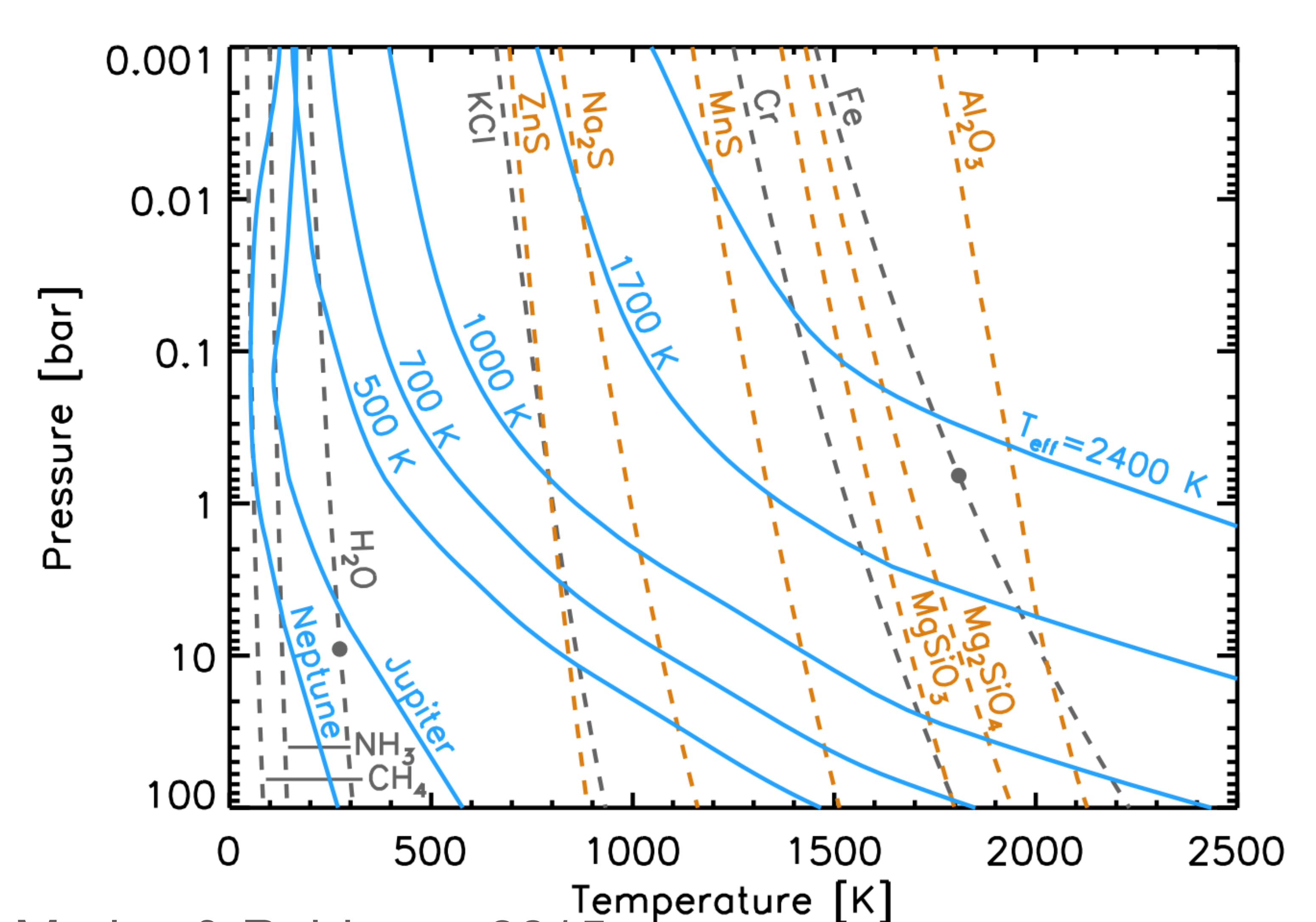
Clouds

Clouds are ubiquitous in substellar objects

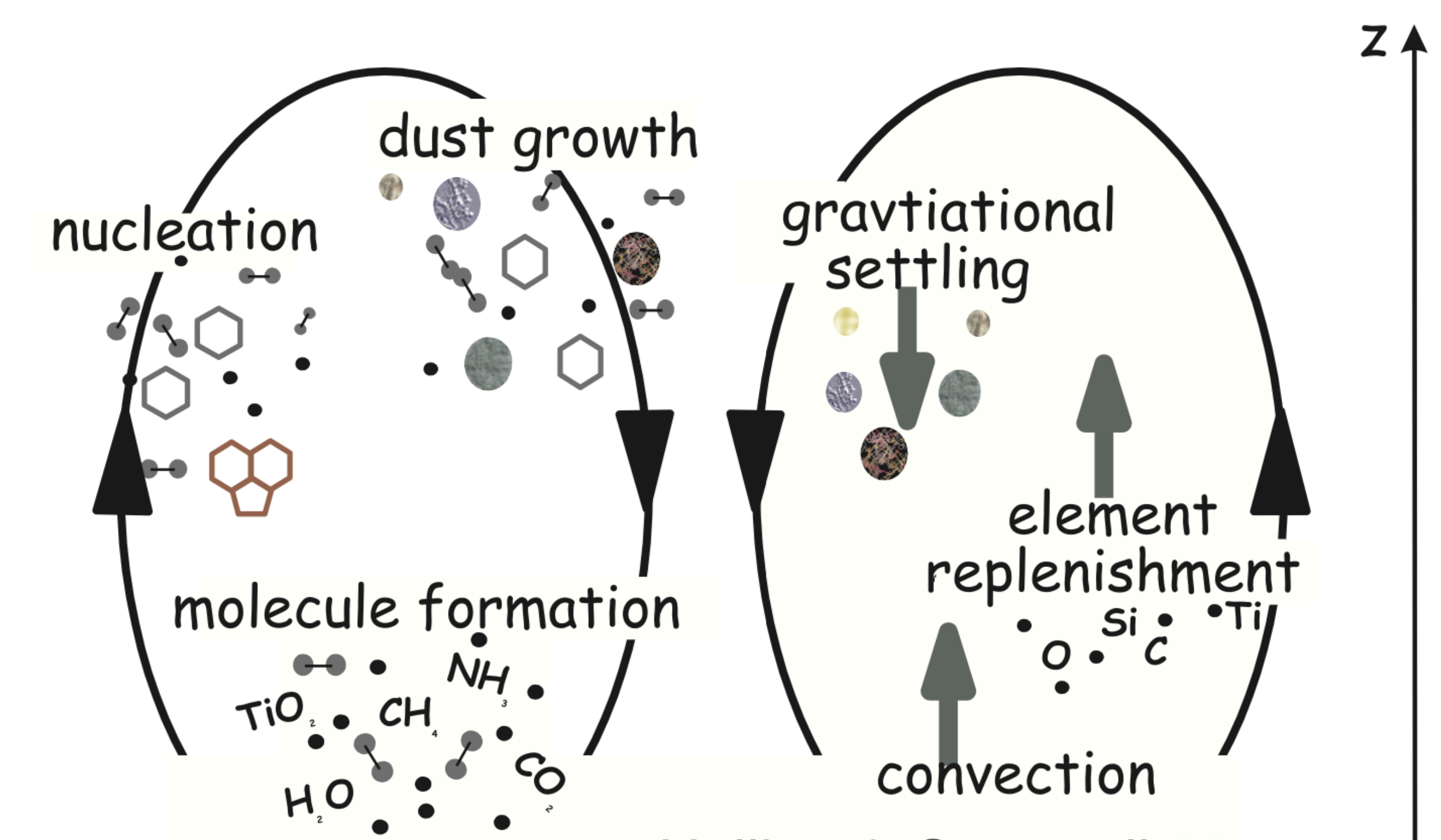
Review Paper - Gao, Wakeford, Moran & Parmentier 2021

Modelling approaches (non-exhaustive)

- Empirically describe clouds with P_{base}, P_{top}, particle size and vertical extent *(Tsuji 2002, Burrows+2006, Lacy & Burrows 2023)*
- Balance upward and downward transport of condensates with f_{sed} *(Ackerman & Marley 2001, Morley+ 2024, Batalha+ 2025)*
- Microphysical approach modeling the nucleation and growth of condensate ‘seed particles’ (Helling & Woitke 2006, Campos Estrada+ 2025)

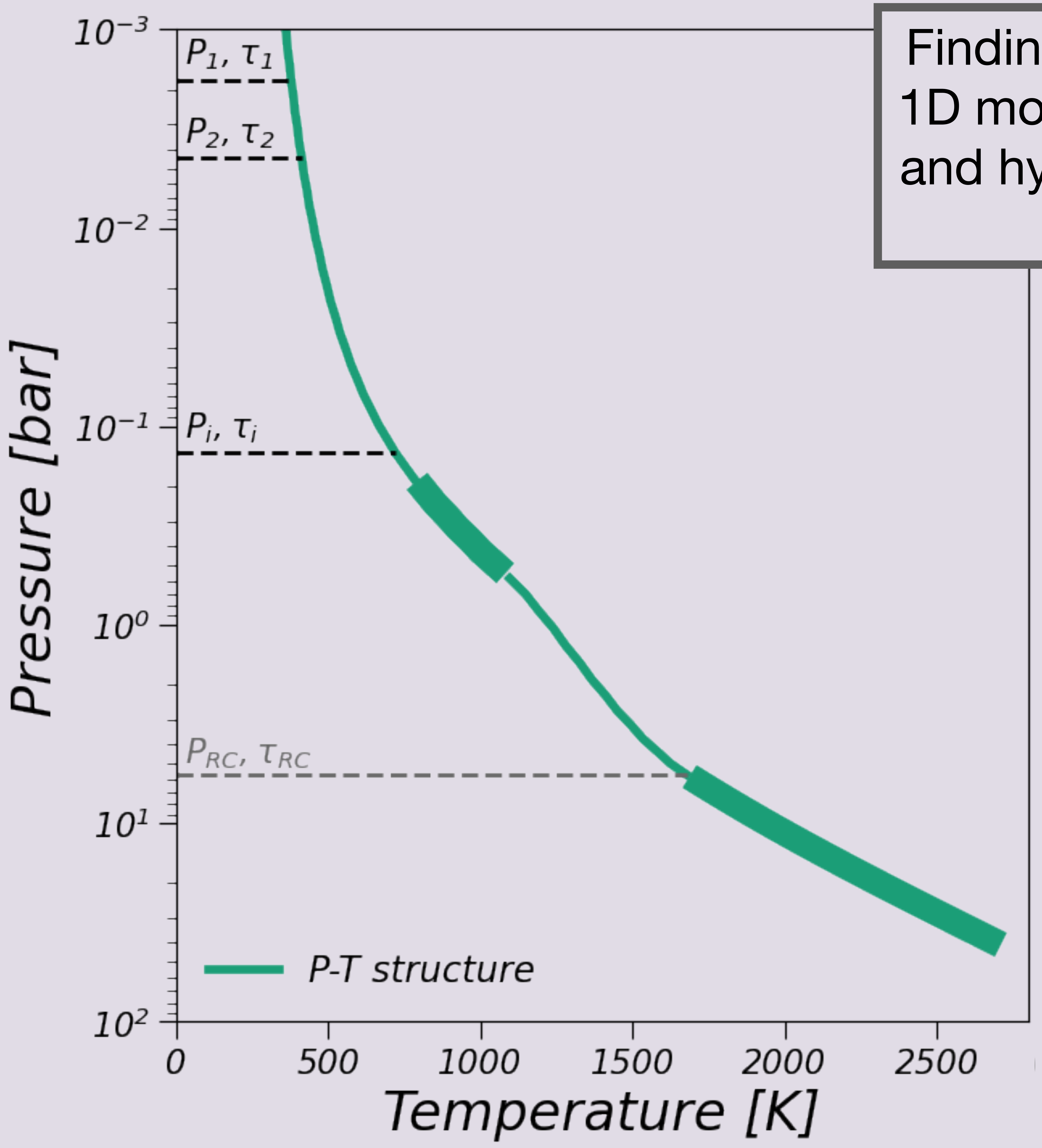


Marley & Robinson 2015



Helling & Casewell 2008

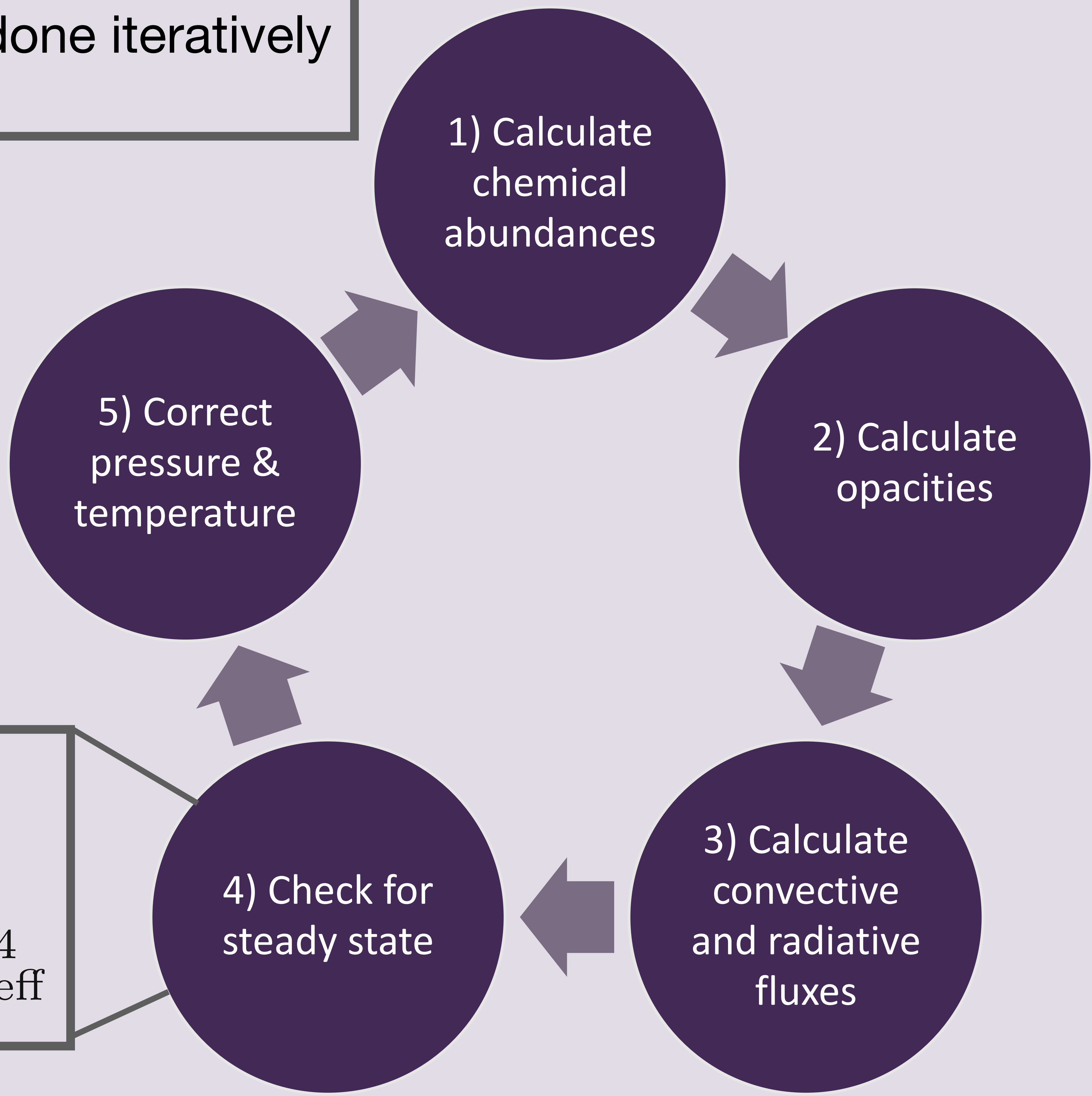
Finding the profile



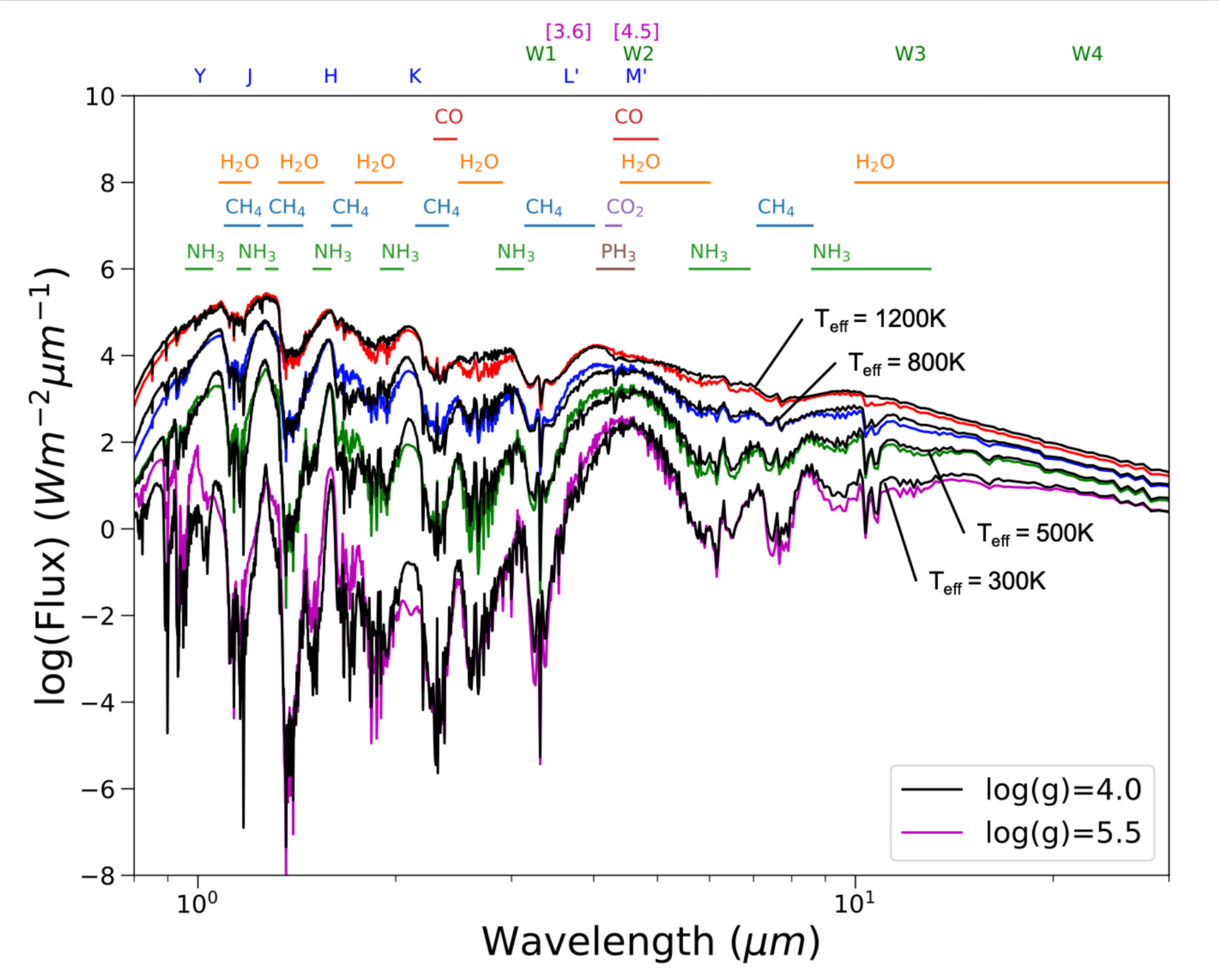
Finding the pressure-temperature profile of a 1D model atmosphere in radiative-convective and hydrostatic equilibrium is done iteratively

$$\frac{\mathrm{dP}}{\mathrm{dz}} = -\rho g$$

$$\mathrm{F_{rad}} + \mathrm{F_{conv}} = \sigma \mathrm{T_{eff}^4}$$



Model Grids



Equilibrium Chemistry + No Clouds
- ATMO 2020 (Phillips+ 2020)
- Sonora Bobcat (Marley+ 2021)
- Lacy & Burrows (2023)
- Linder+ (2019)

Disequilibrium Chemistry + No Clouds
- Lacy & Burrows (2023)
- Sonora Elf Owl (Mukherjee+2024)
- ATMO 2020 (Phillips+2020)

Equilibrium Chemistry + Clouds
- MARCS-DRIFT (Campos Estrada+2025)
- Sonora Diamondback (Morley+2024)
- Linder+ (2019)
- Morley+ 2012,2014
- BT-Settl (Allard 2014)
- Saumon & Marley (2008)

Disequilibrium Chemistry + Clouds
- Exo-REM (Charnay+2019)

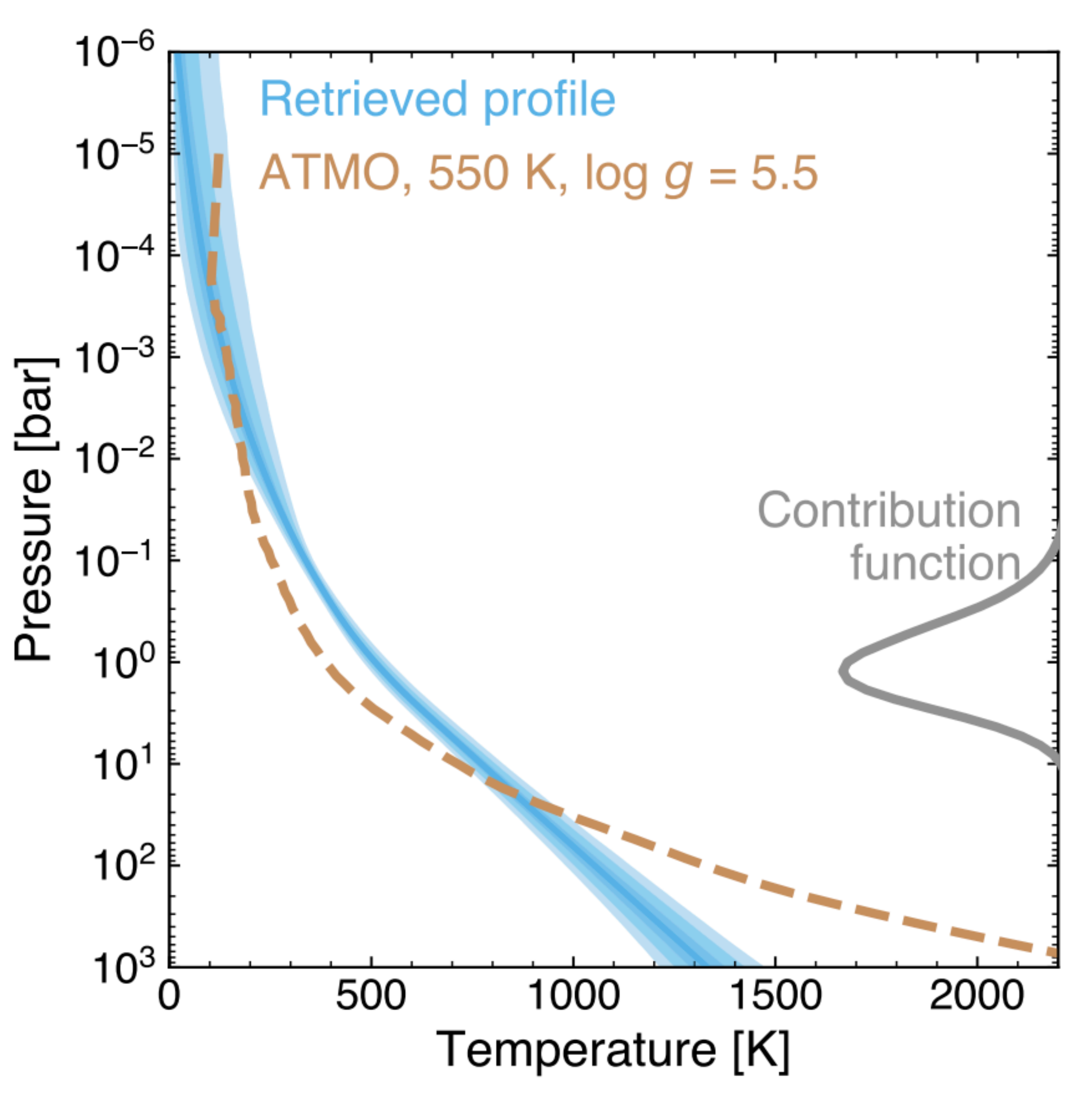
Disequilibrium Chemistry + Diabatic Thermal Structure
- ATMO 2020++ (Leggett+2021, Meisner+2023)

Low-metallicity
- Phoenix (Gerasimov+2020)
- LowZ (Meisner+2021)

Atmospheric retrievals

- Grid models impose physical assumptions onto the resulting fits of observational data
- Inverse retrieval methods allow an independent, data driven method of extracting atmospheric information
- Use optimal estimation & MCMC techniques to obtain parameterised P-T profiles and chemical abundances
- Grid models and retrievals are highly complementary

Line+2015, 2017, Burningham+ 2017, Zalesky+2019, Hood+ 2023, Adams+ 2023, Matthews+ 2025, Kühnle+2025



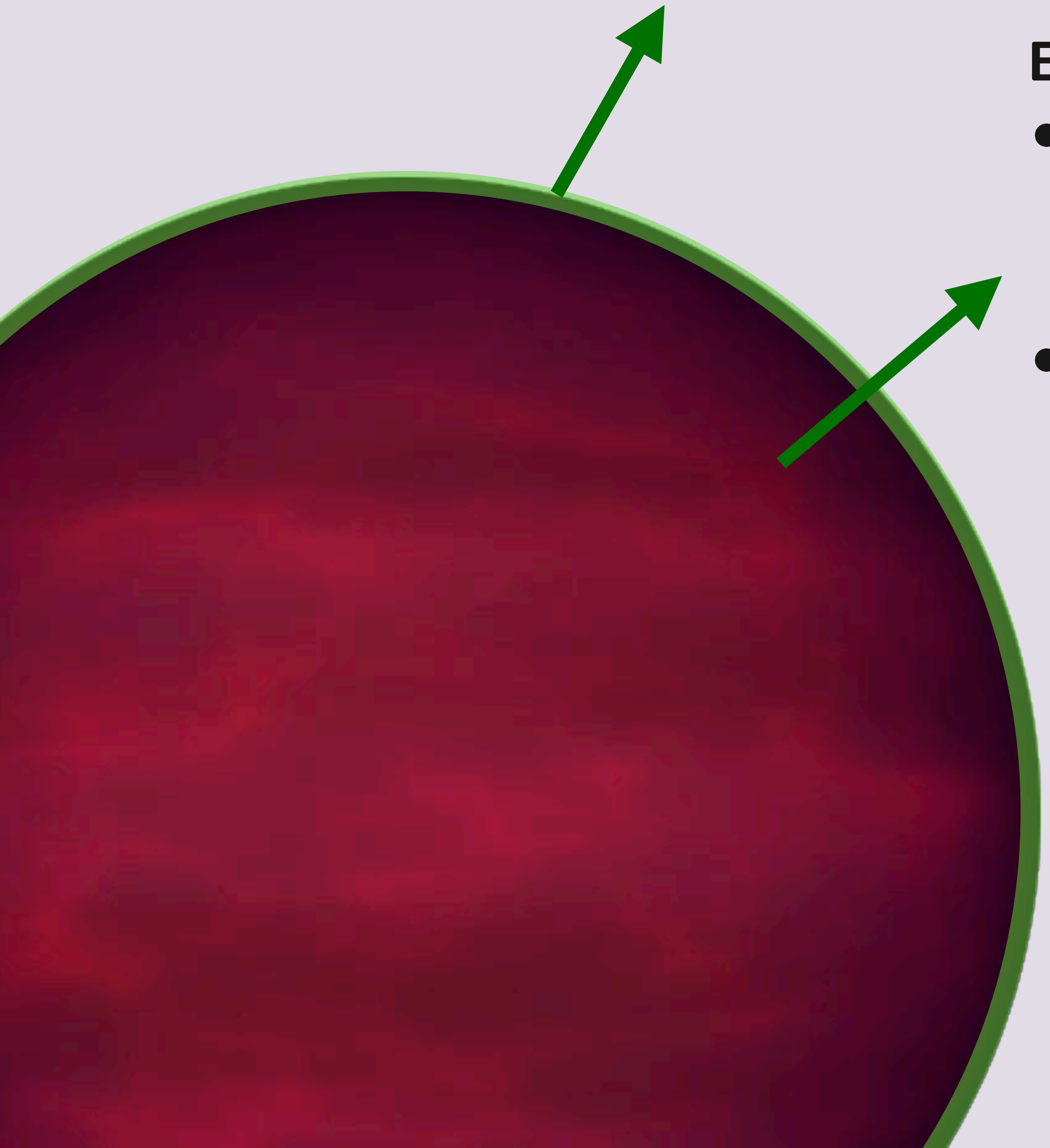
Matthews+ 2025

Coupled Atmosphere & Evolution Models

Radiative-convective atmosphere models

Inputs: T_{eff}, log(g), [M/H]

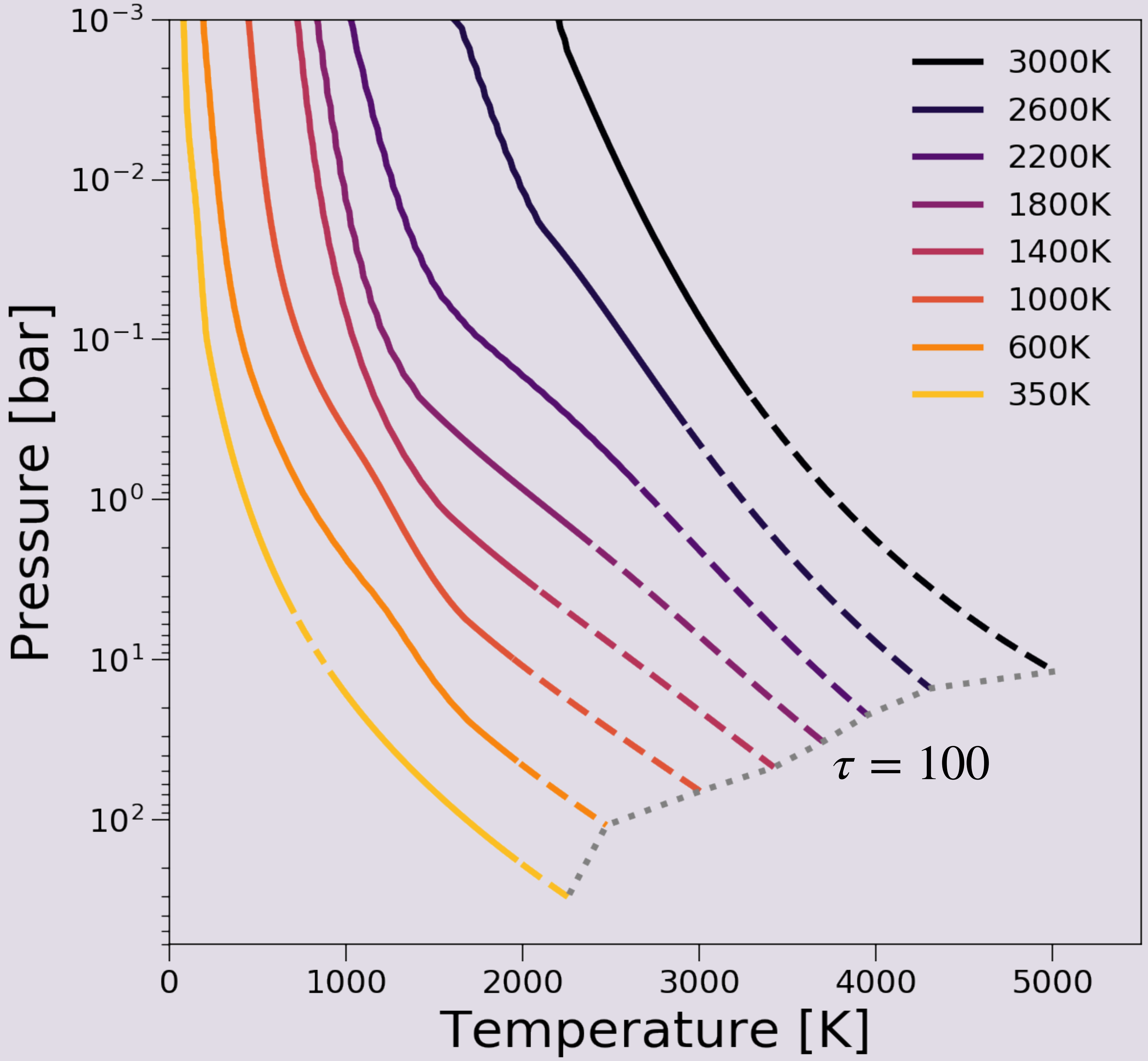
Outputs: PT profiles, abundances, emission spectra



Evolution models

- Calculate the interior structure, nuclear burning, Time evolution
- Provide mass, age, radius, luminosity

Model atmosphere provides the outer boundary condition for the interior model



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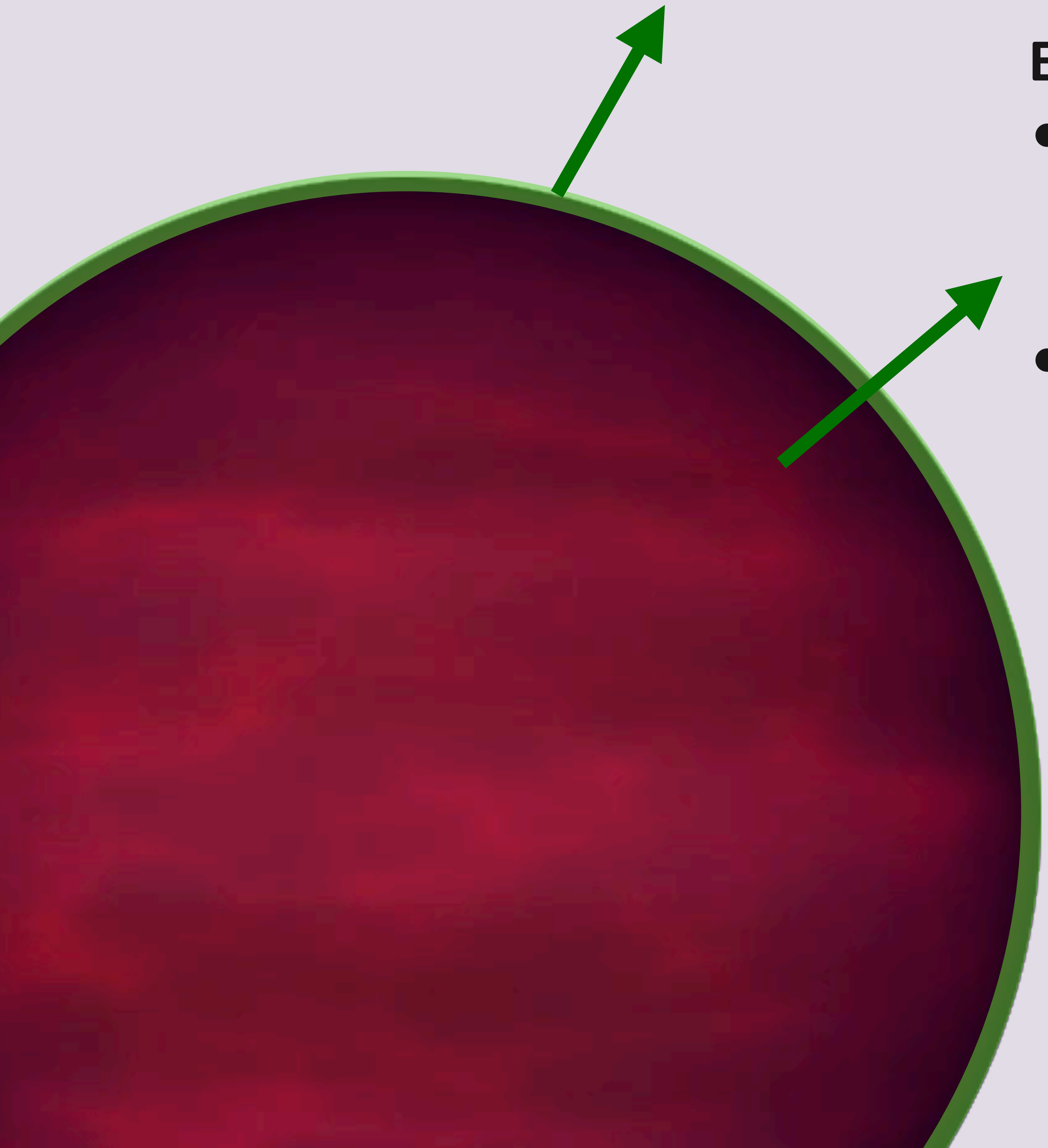
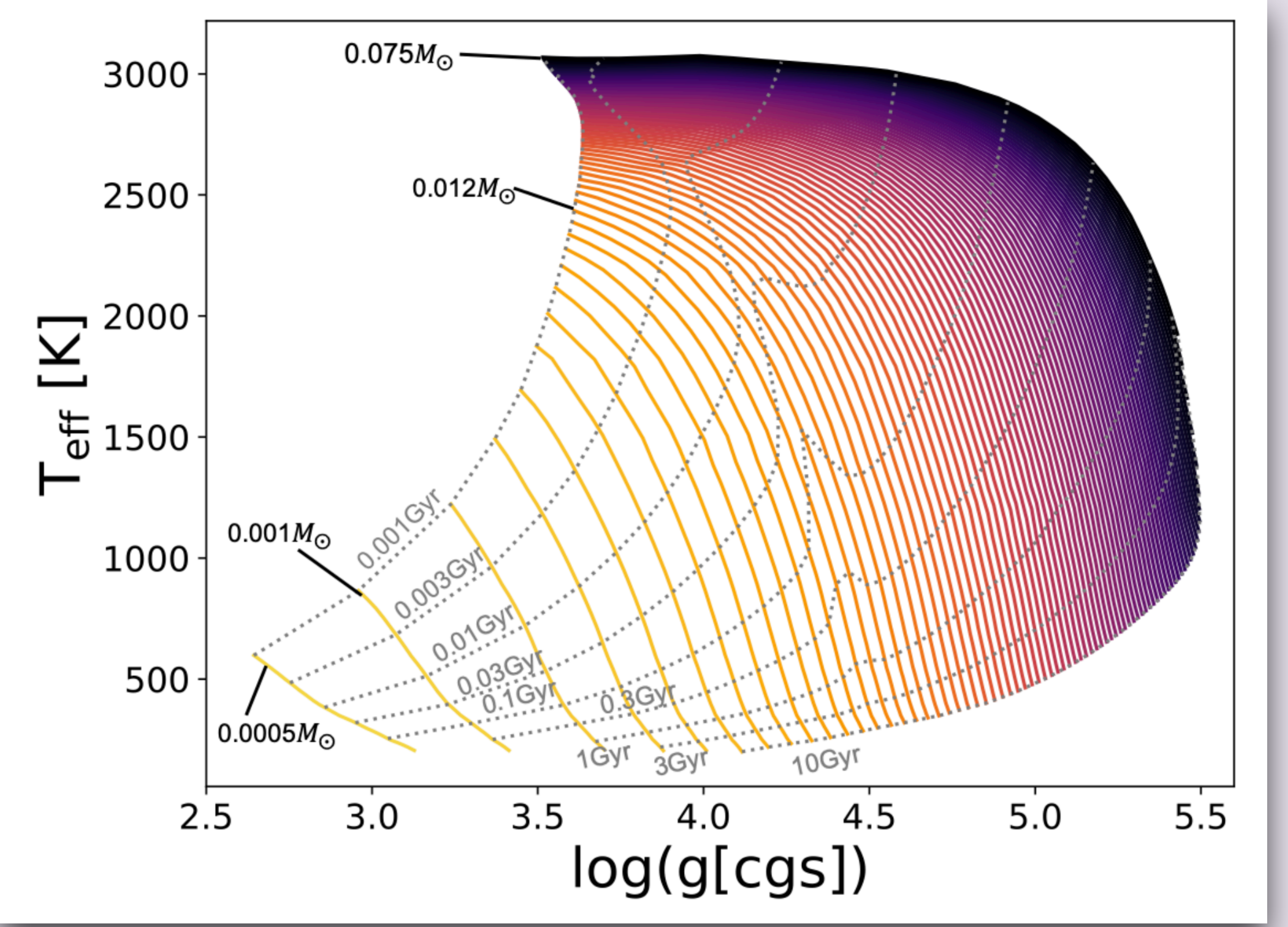




Cloud-free evolution to ~Jupiter masses
ATMO 2020 (Phillips+ 2020)
Sonora Bobcat (Marley+ 2021)

Cloudy Evolution
Sonora Diamondback (Morley+ 2024)
BHAC (Baraffe+2015)
Saumon & Marley 2008

Evolutionary Tracks

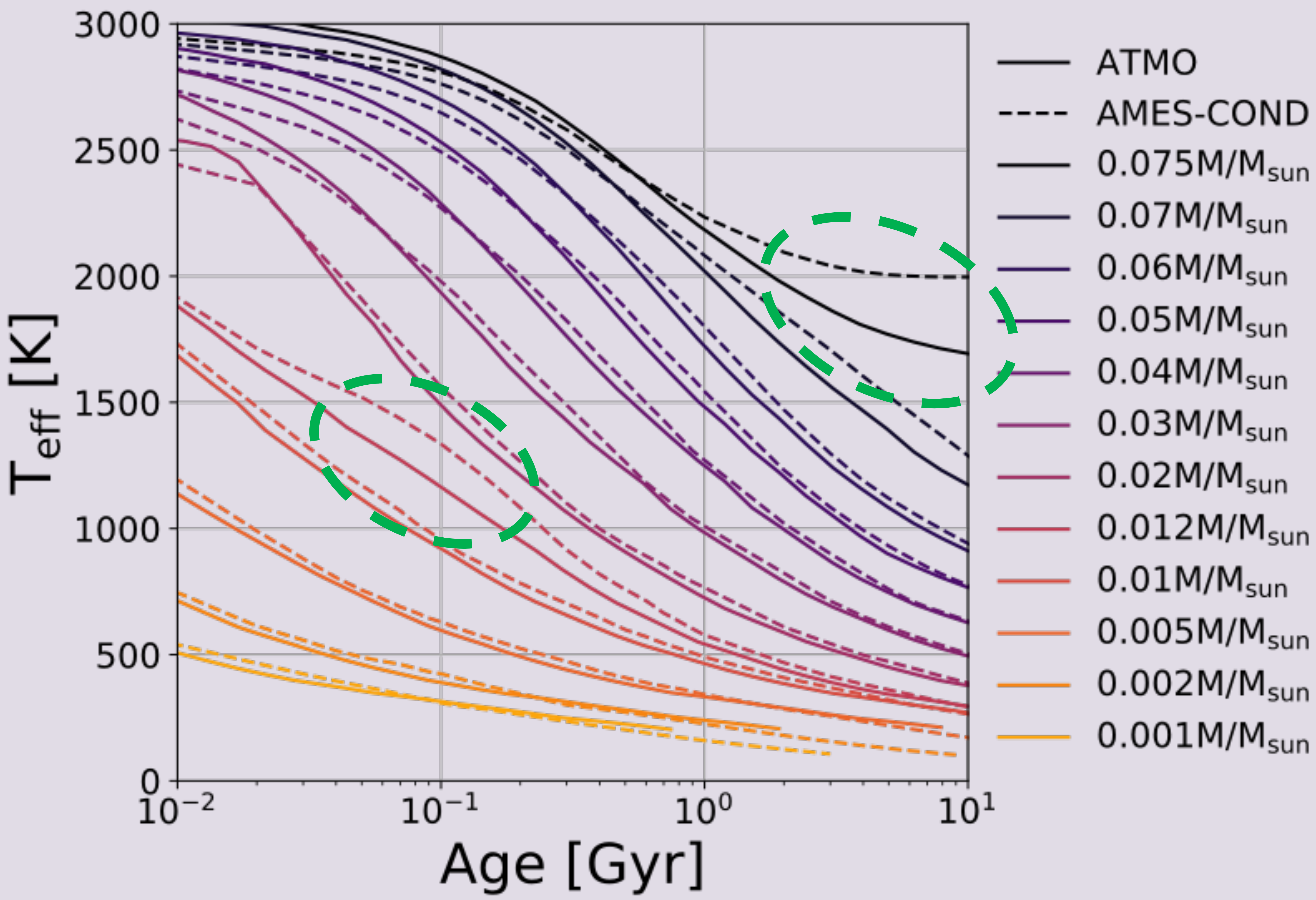
Model Comparisons

- Comparison with AMES-COND models from Baraffe et al. (2003)

- Changes in the Evolutionary tracks due to two model improvements:

1. Warmer atmospheric outer boundary conditions

2. Usage of a new EOS (Chabrier+2019, Chabrier+2023) in the interior structure model has altered the hydrogen and deuterium burning minimum mass



Phillips+2020

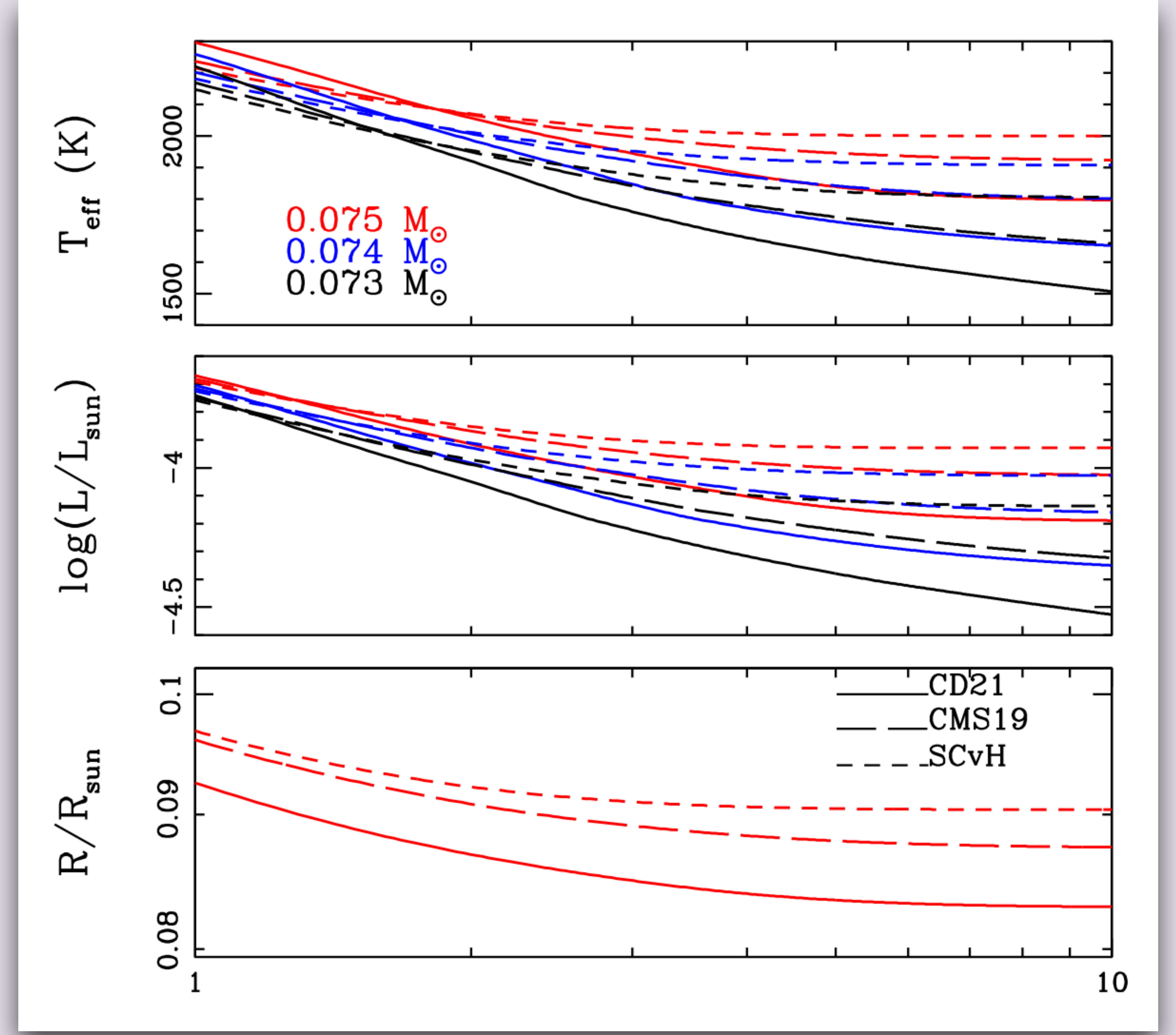
New Equation of State

Updates to the EOS include

1. Ab initio quantum molecular dynamics calculations in the regime of pressure dissociation and ionization
2. Taking into account interactions between hydrogen and helium species

- New EOS predicts a cooler, denser more degenerate core given mass and age
- This has raised the theoretical stellar/substellar boundary

EOS	$M_{HBMM}/M_{\odot}$
SCvH+COND (Baraffe et al. 2003)	0.072
SCvH+ATMO	0.073
CMS'19+ATMO (Phillips et al. 2020)	0.074
CD'21+ATMO (present)	0.075



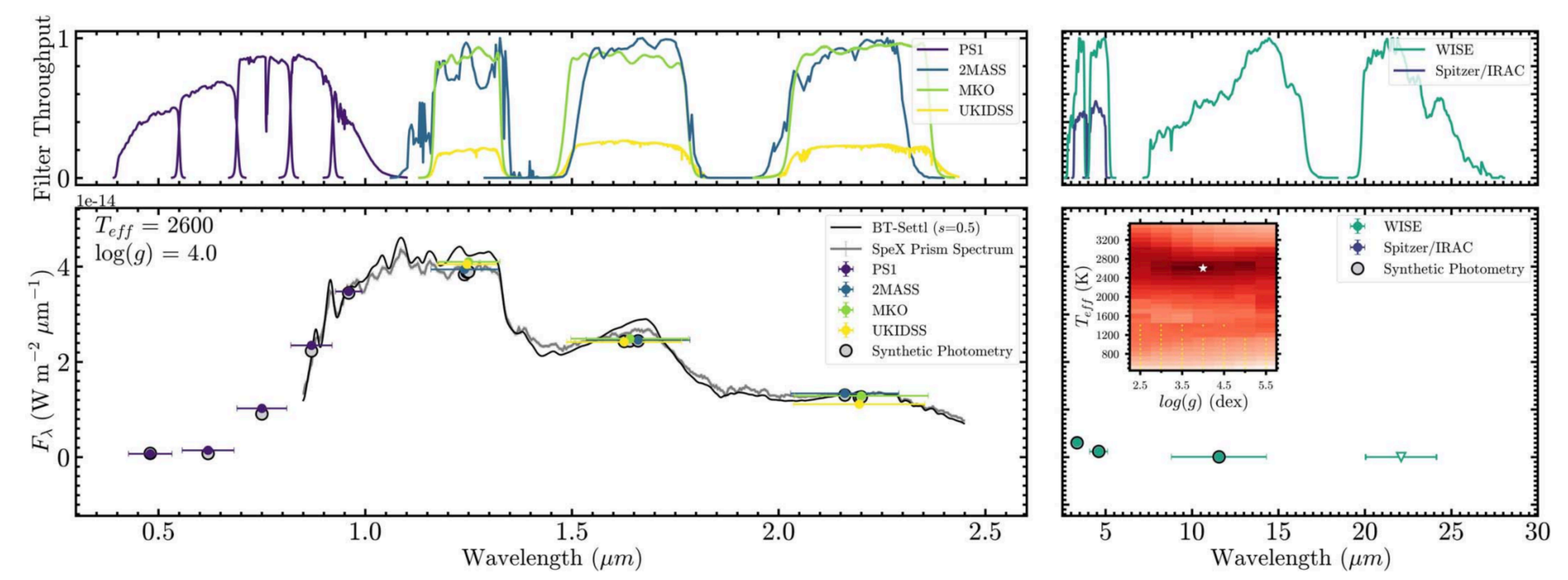
Chabrier, Baraffe, Phillips & Debras (2023)

Model Performance

Sanghi+ 2023 used SEDs of 865 field-age & 189 young ultra cool dwarfs to derive fundamental parameters

1) Atmosphere Models: BT-Settl & ATMO 2020 chi^2 fits give T_{eff}, log(g), R

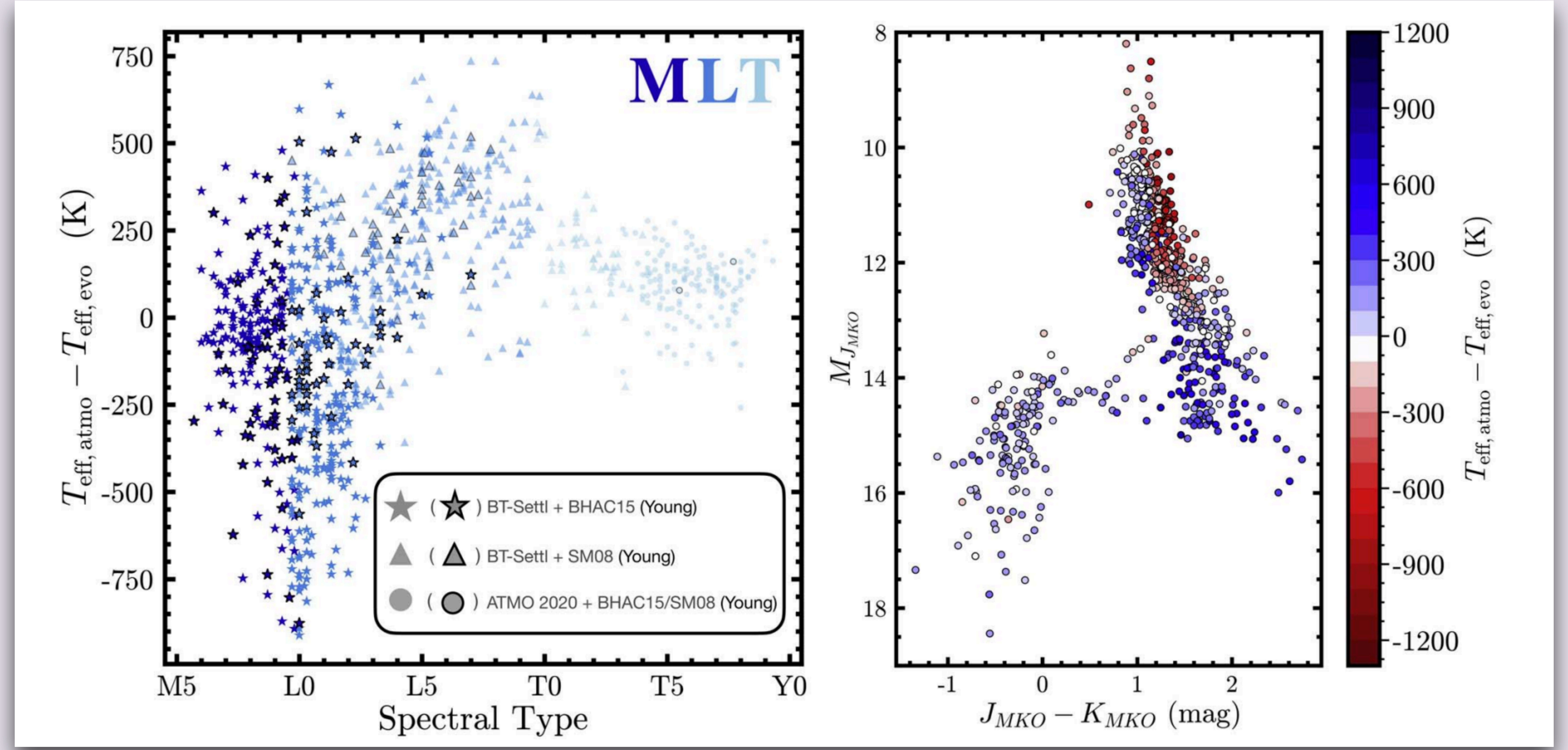
2) Evolutionary Models: Bolometric luminosities and age estimates give T_{eff}, log(g), M, R



Sanghi+ 2023

Model Systematics

Effective Temperature



Atmosphere model systematics in the derived effective temperature and radii

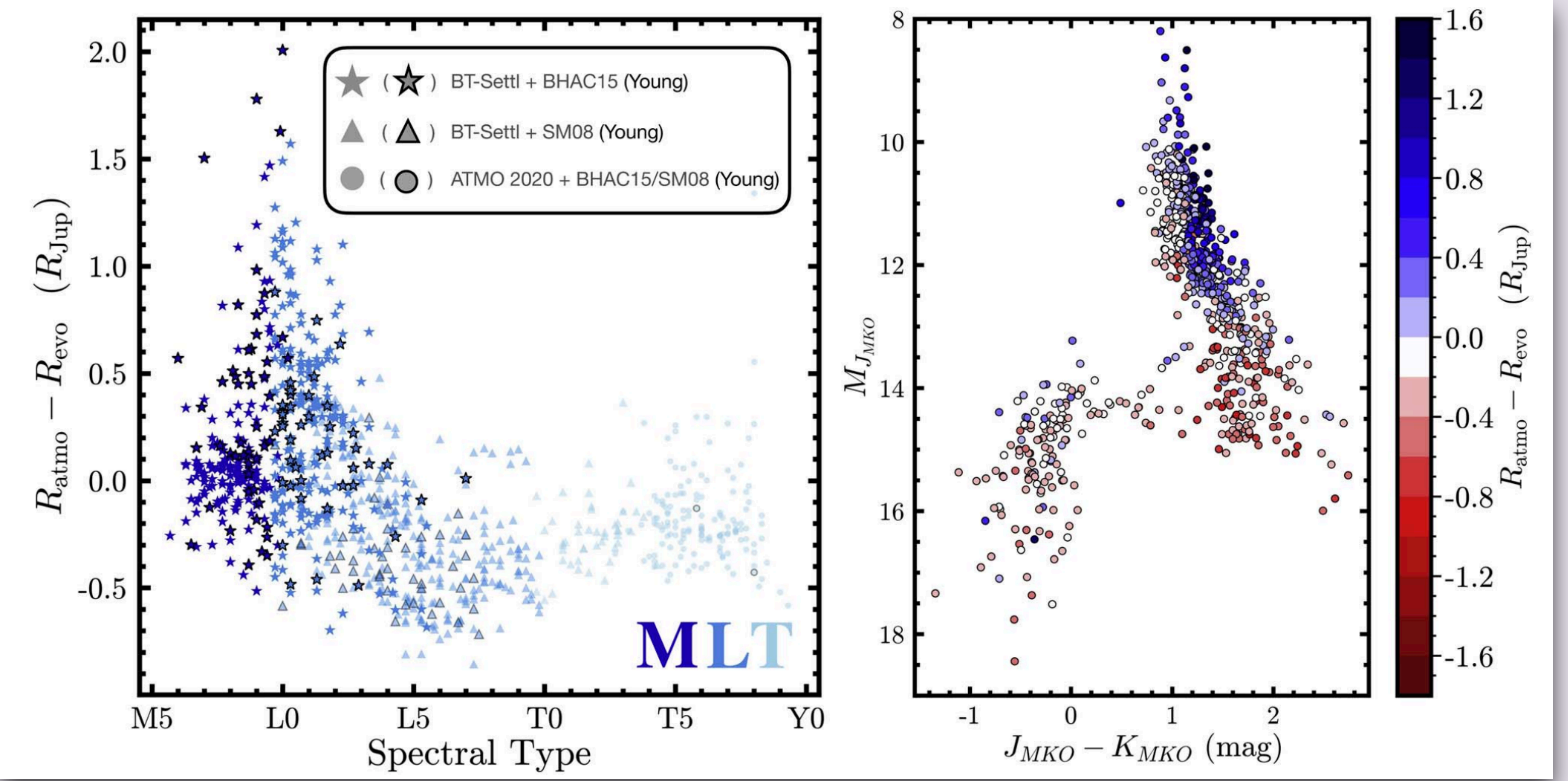
Largest discrepancy ~800K at M-L transition

T dwarfs have lower systematics

Sanghi+ 2023

Model Systematics

Radius



Sanghi+ 2023

Atmosphere model systematics in the derived effective temperature and radii

Largest discrepancy ~2RJup at M-L transition

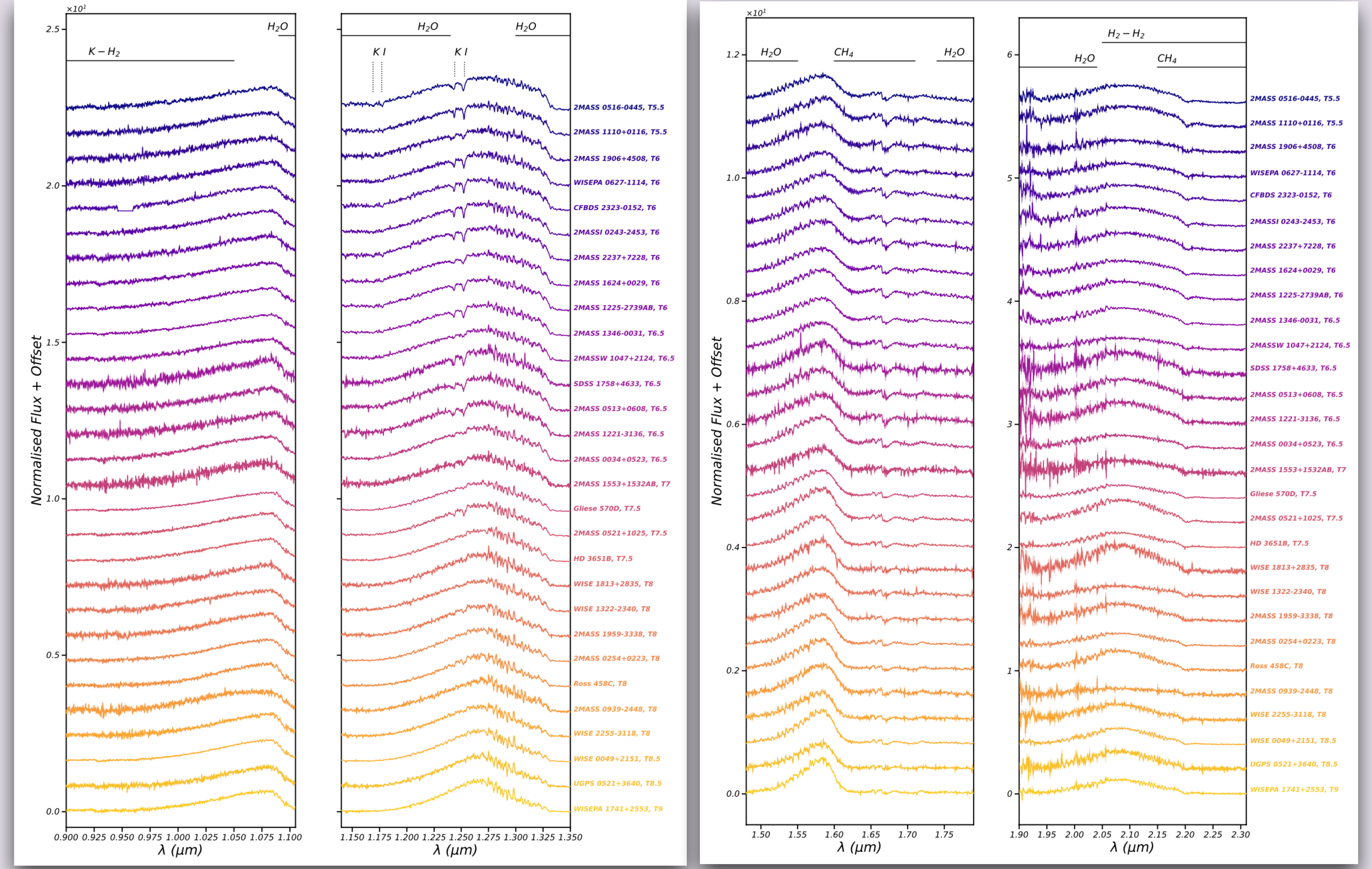
T dwarfs have lower systematics

Spectroscopy of T dwarfs

GNIRS spectroscopy, Phillips+ 2024, Phillips+ in prep

- ➡ GNIRS cross-dispersed spectroscopy
- ➡ R~1700
- ➡ High S/N
- ➡ Near-infrared spectra (0.8-2.5 microns)
- ➡ ~30 >T6 brown dwarfs (J~14-17)

Y band J band H band K band



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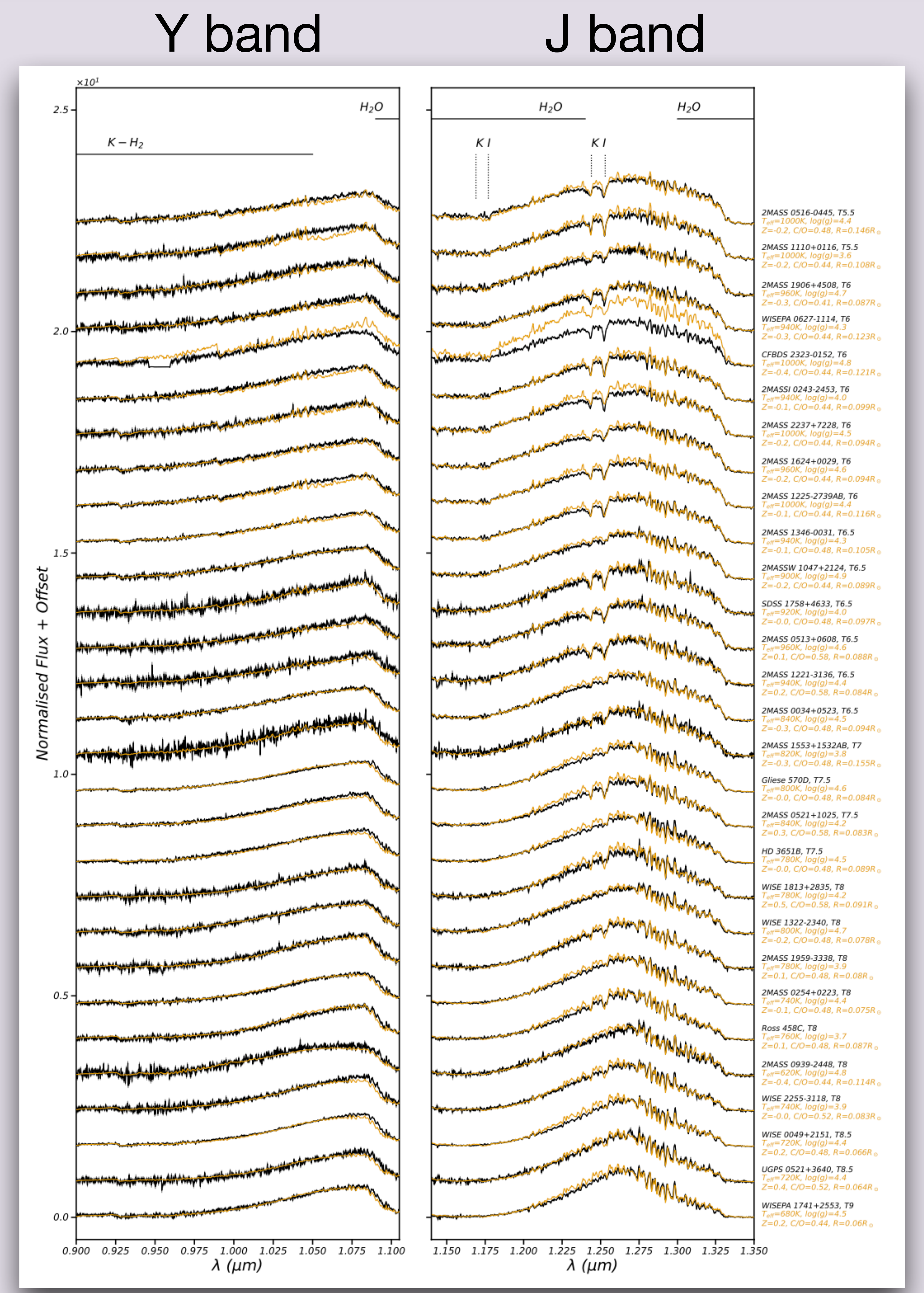
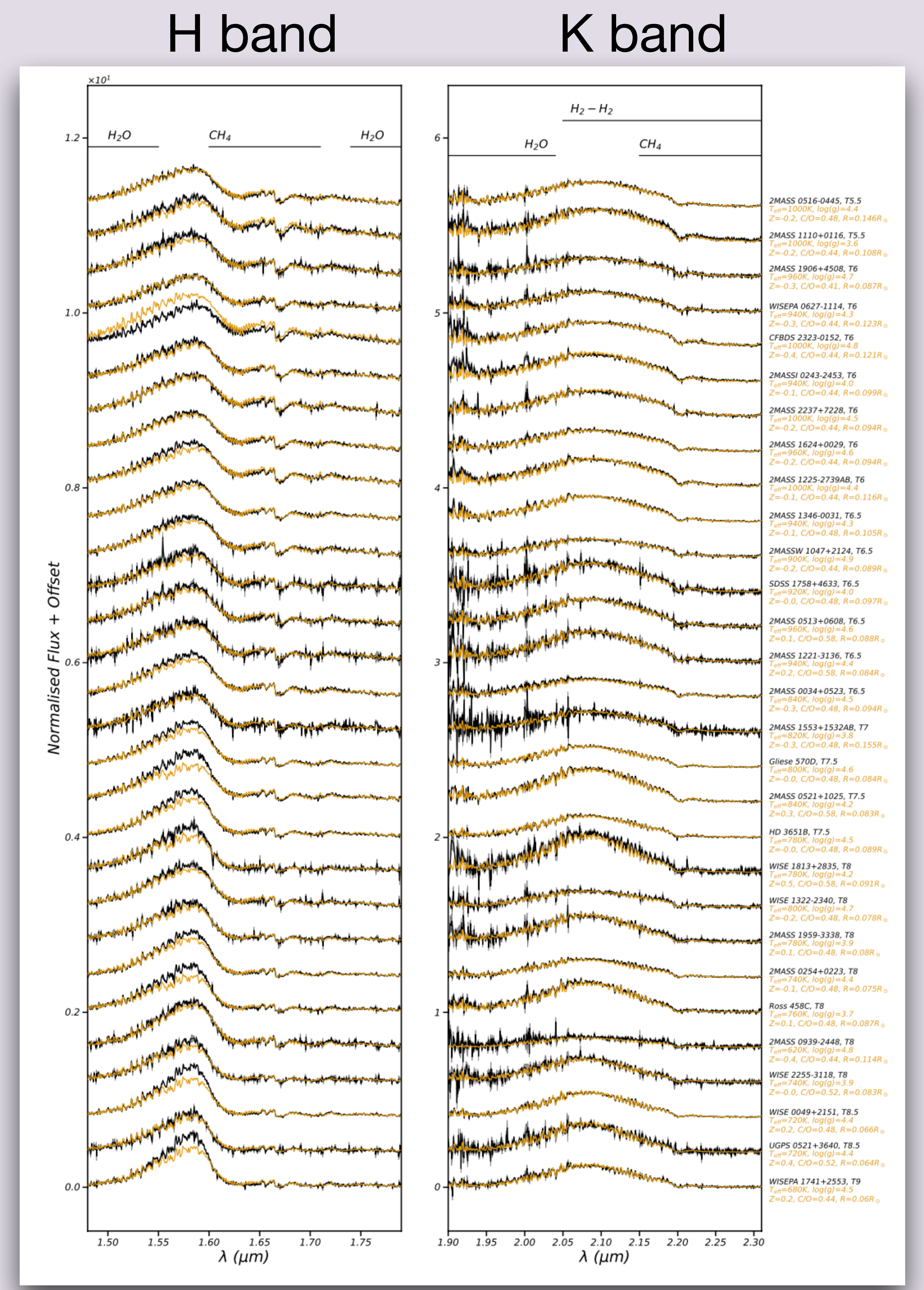


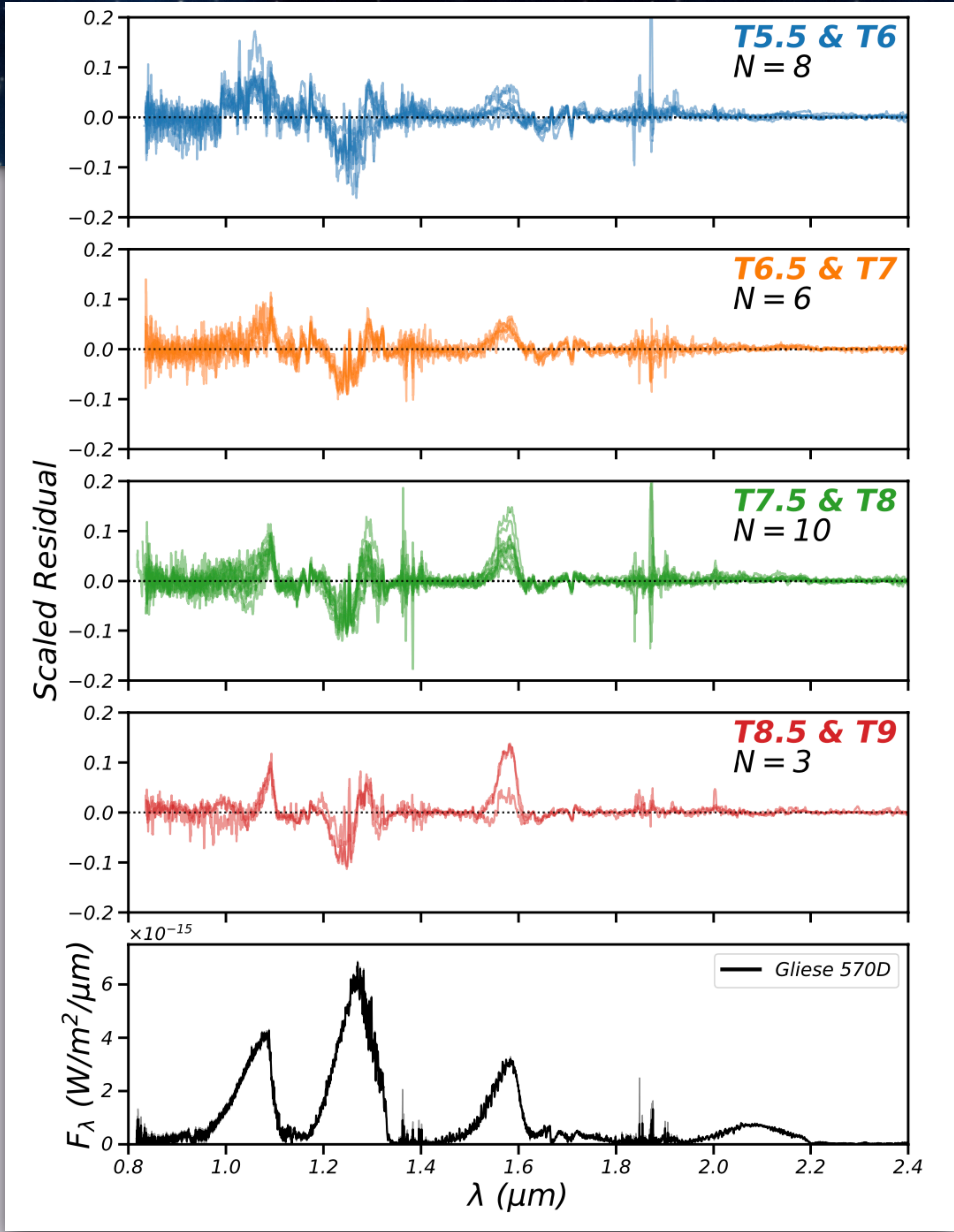


Models

- ATMO 2020, incl M/H and C/O

Spectroscopy of T dwarfs

Residuals show consistent model-data discrepancies …

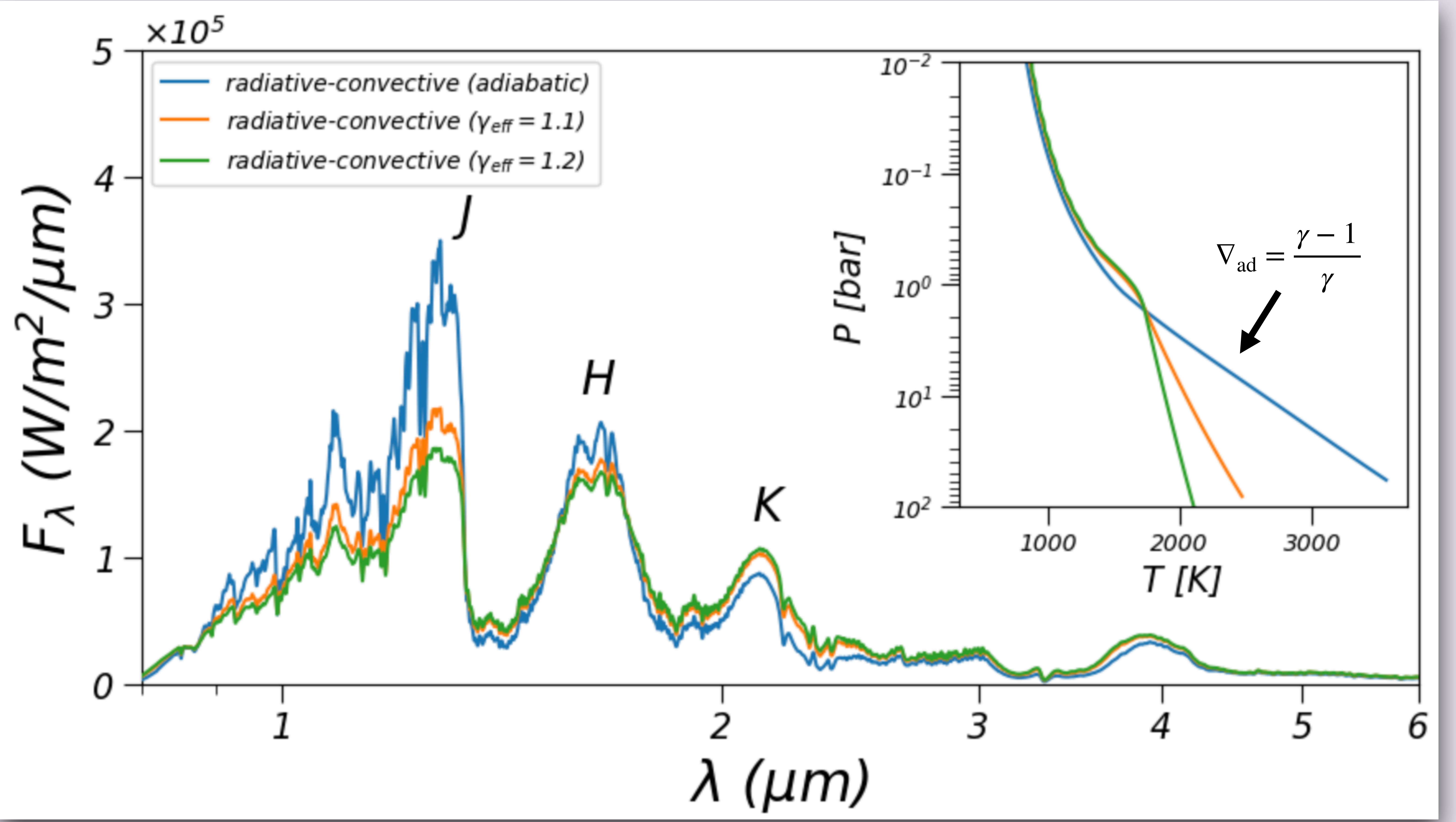


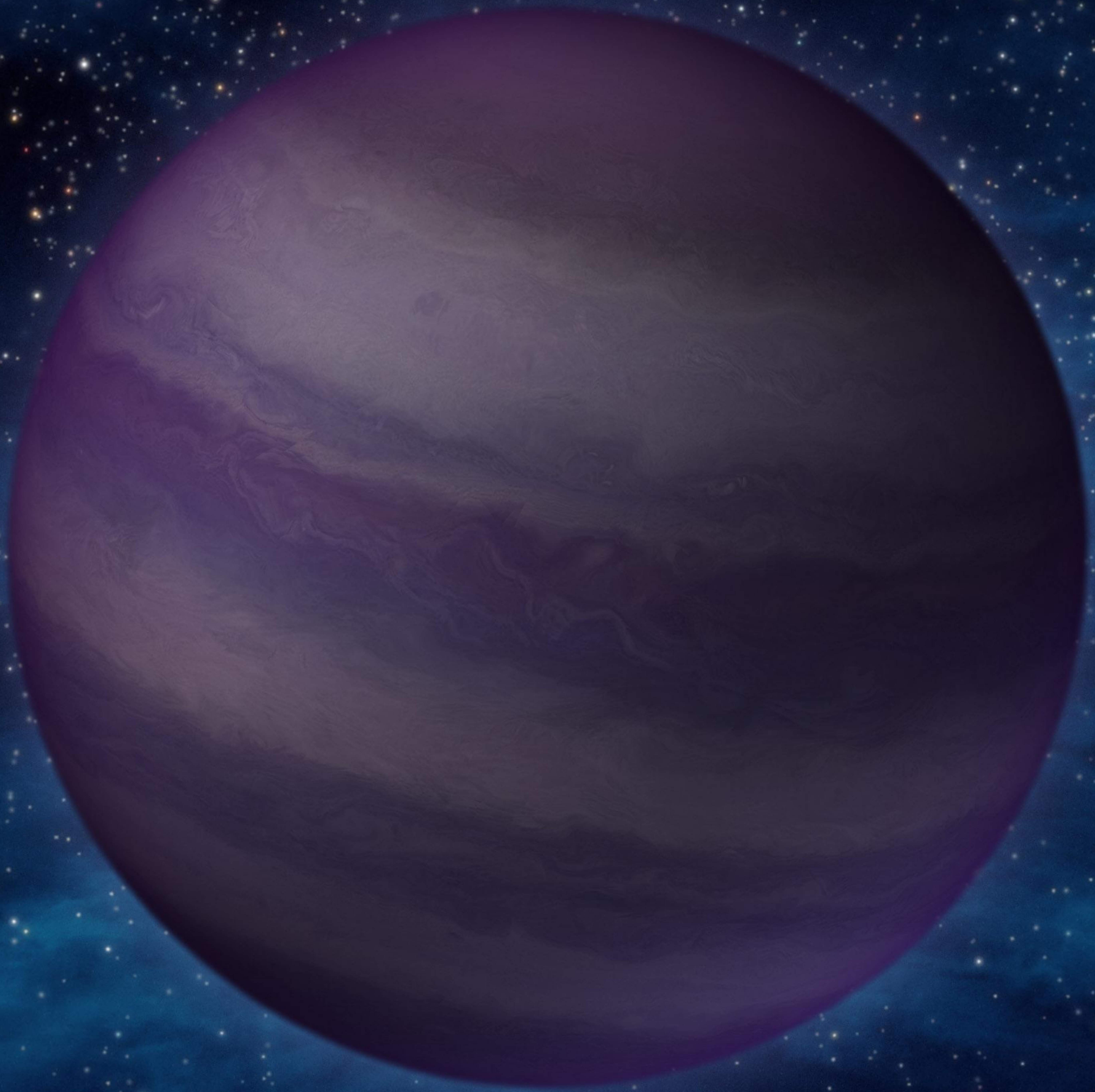
Phillips+ in prep

ATMO++ models

The emission spectra can be reddened by reducing the temperature gradient of the atmosphere through the effective adiabatic index γ_{eff}

Tremblin+2015, 2016, Leggett+2021,
Leggett & Tremblin 2024





Summary & Conclusions

1. There is a diversity in 1D radiative-convective atmosphere models that can be utilized by the community
2. Coupling 1D models with evolutionary models allows us to constrain fundamental parameters
3. There are known systematics in the derived fundamental parameters from atmosphere models
4. JWST continues the observational drive for atmosphere and evolution models

Image Credit: NASA/JPL-Caltech