A Fully-Consistent 1D Radiative-Convective Equilibrium Model for Planetary Atmospheres

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Exoplanetary Atmospheres and Habitability 2015

Outline

- ATMO
  - a new 1D model for sub-stellar atmospheres
- Fully-consistent non-equilibrium chemistry
  - feedback of chemistry onto background atmosphere
  - application to hot exoplanet atmospheres
- Chemistry and GCMs

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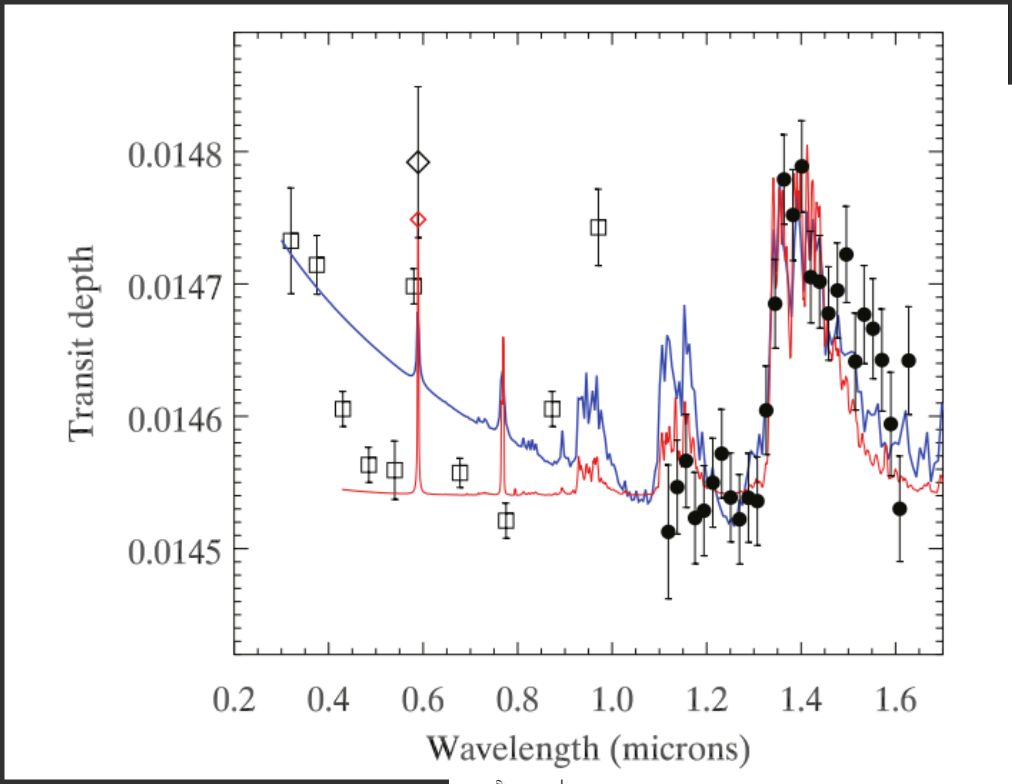
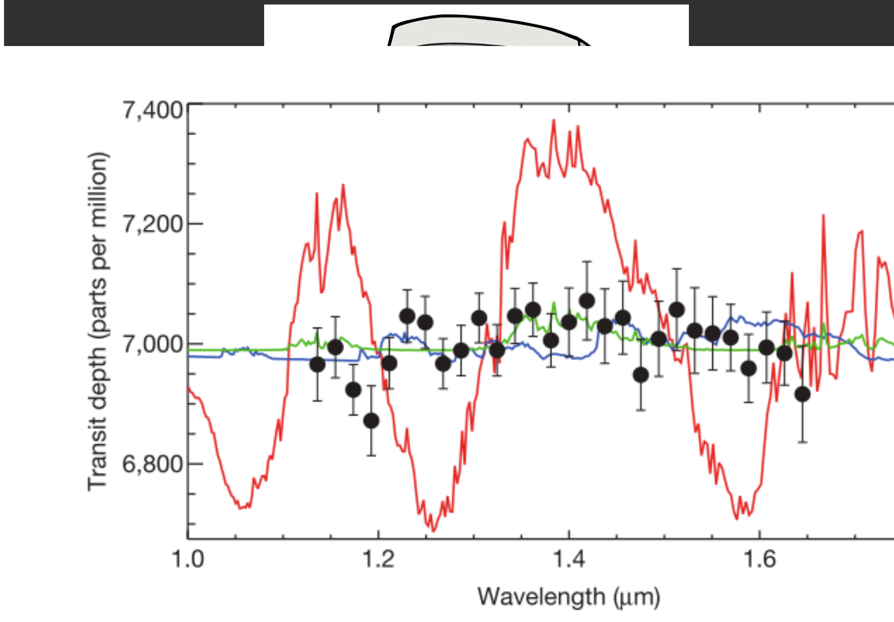
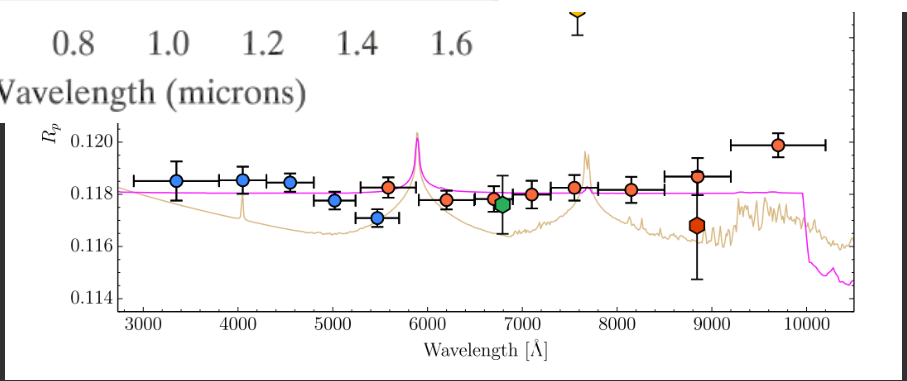
Exoplanet Atmospheres



HD 209458b
Deming et al., 2013

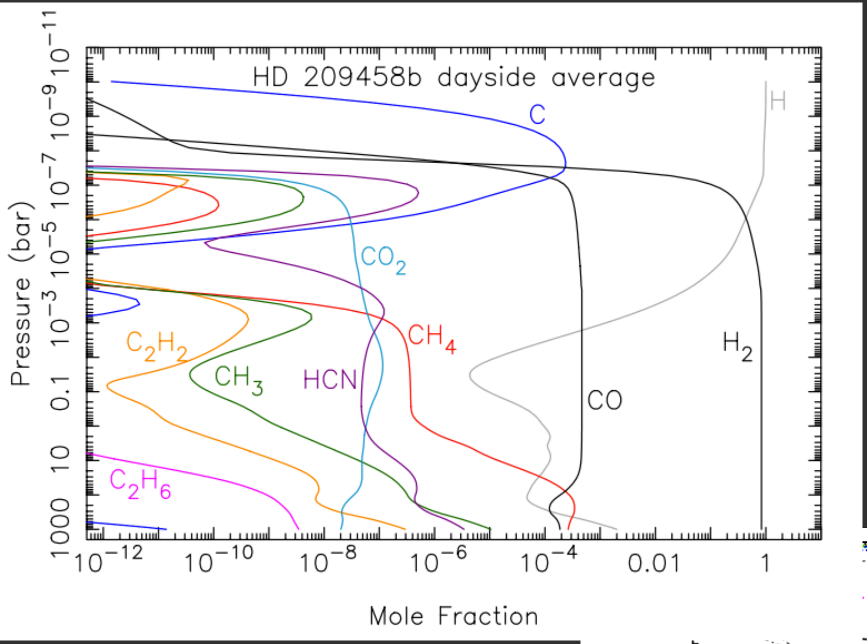


GJ 436b
Knutson et al., 2014

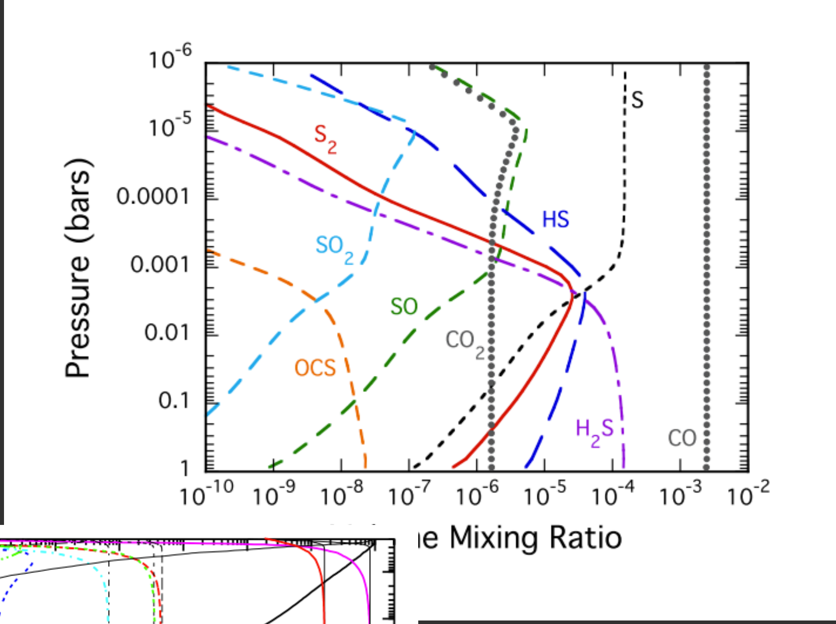


HAT-P-1b
Wilson et al., 2015

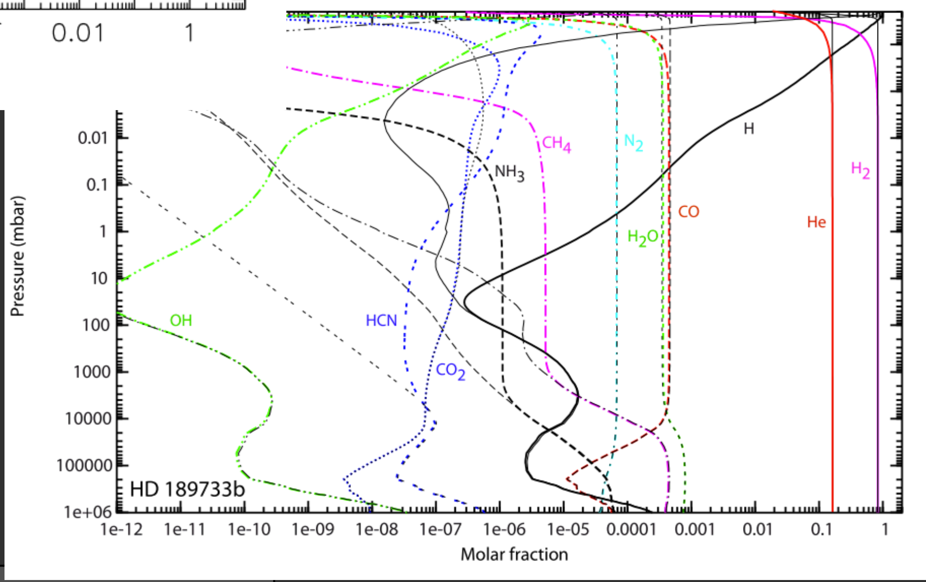
1D Photochemical Models



Moses et al., 2011



Zahnle et al., 2009



Venot et al., 2012

1D Photochemical Models

INPUT: Temperature, Elemental Abundance

OUTPUT: Chemical Abundances

Calculate chemical abundances based on input temperature structure

Simple Constructions e.g. isothermal

1D Radiative-Convective Codes

Averaged from 3D GCM simulations

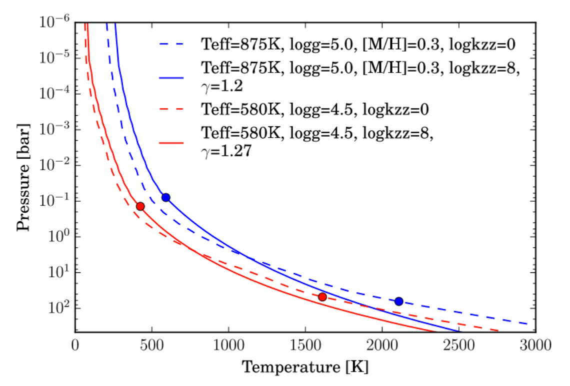
ATMO

- 1D Atmosphere Model

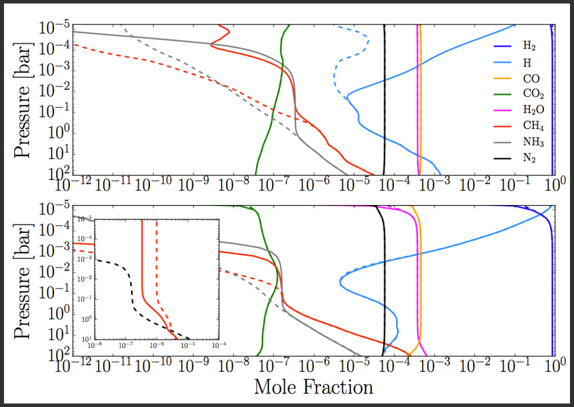
Pressure Temperature Profiles

Equilibrium and Non-equilibrium Chemistry

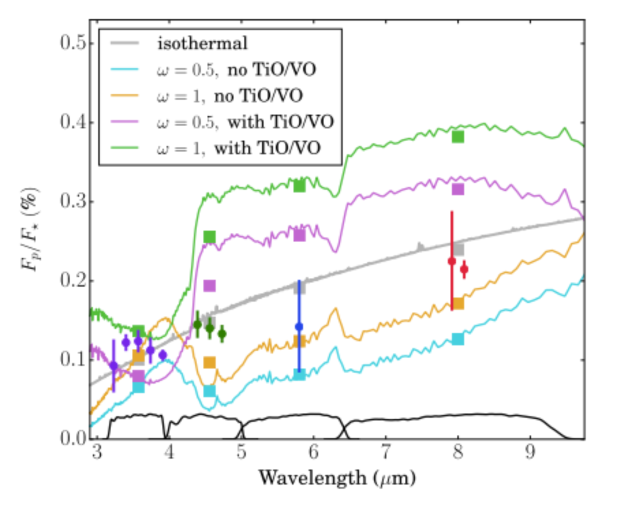
Synthetic Observations



Tremblin et al., 2015, *ApJL*



Drummond et al., 2015, *ApJL, submitted*



Evans et al., 2015, *MNRAS*

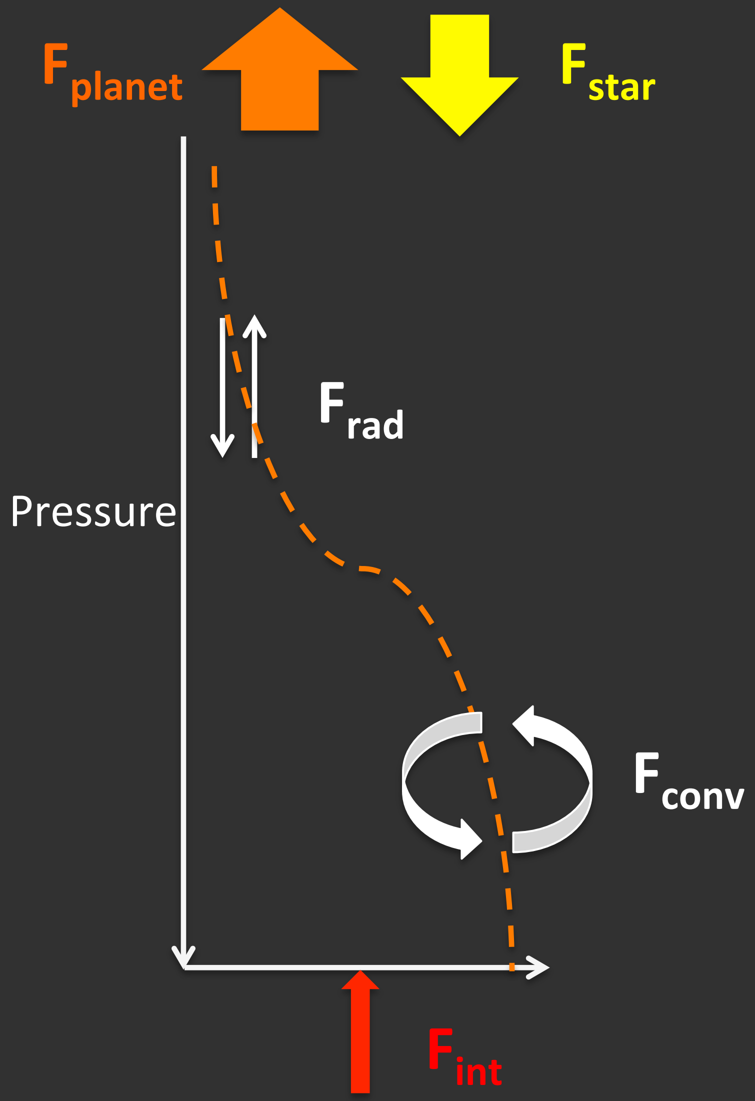
ATMO

- 1D Atmosphere Model
  - Hydrostatic Equilibrium

$$\frac{dP_{gas}}{dz} - \rho g = 0$$

  - Energy Balance

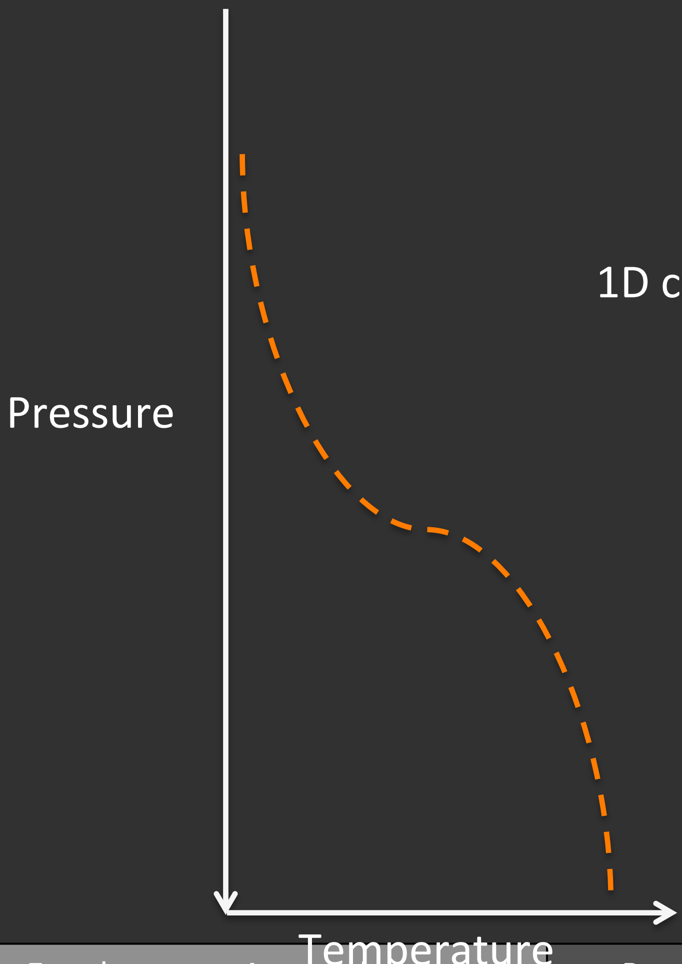
$$F_{star} + F_{rad} + F_{conv} = F_{int}$$



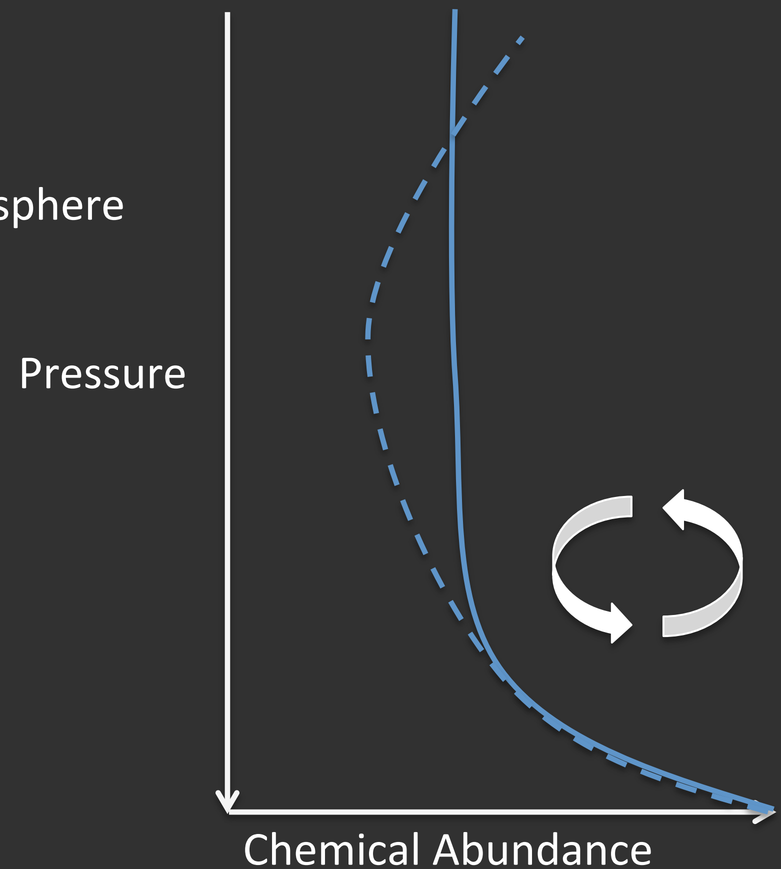
ATMO

- 1D Atmosphere Model
  - Equilibrium Chemistry
    - Gibbs Energy Minimisation
    - Including formation of condensates
  - Non-Equilibrium Chemistry
    - High-temperature chemical network of Venot et al., 2012, *A&A*
      - *See next talk*
    - Including vertical mixing and photodissociations
  - Radiative Transfer
    - Opacities binned using correlated-k method
    - Radiative transfer solved using discrete-ordinate method: Amundsen et al., 2014, *A&A*
    - Including scattering

Photochemical Modeling



1D column of atmosphere



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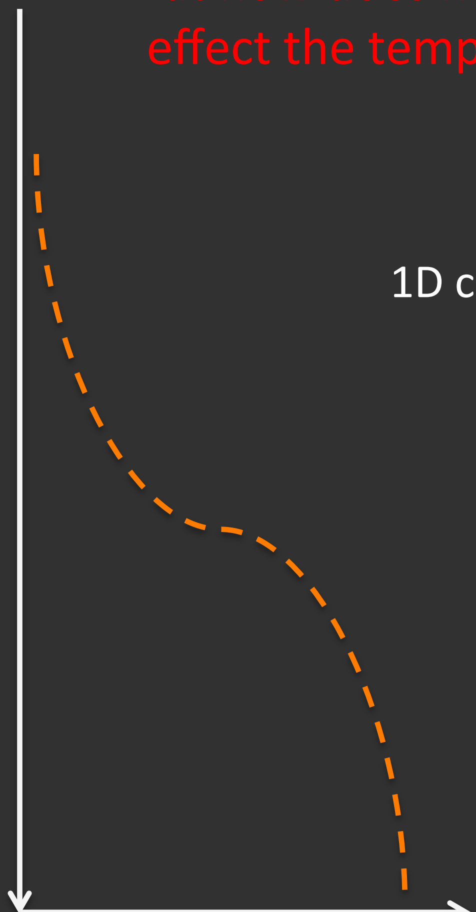
Photochemical Modeling

But how does non-equilibrium chemistry effect the temperature of atmosphere?

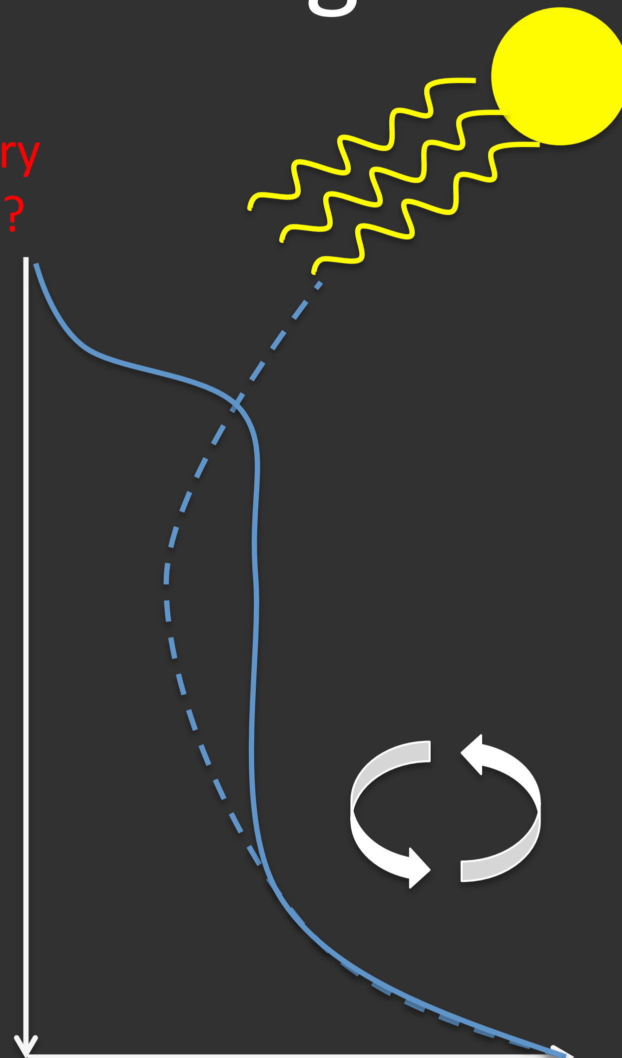
Pressure



Temperature

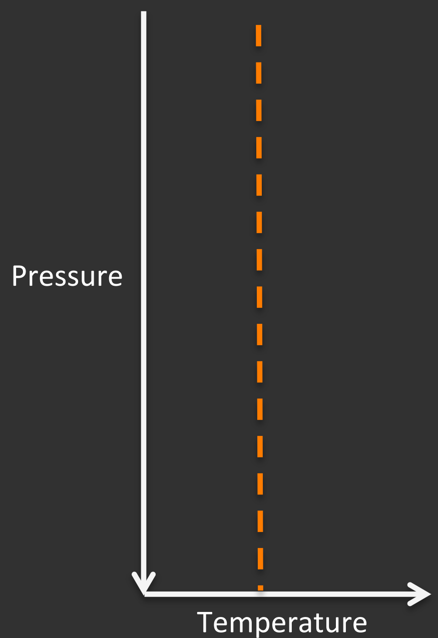
1D column of atmosphere

Pressure



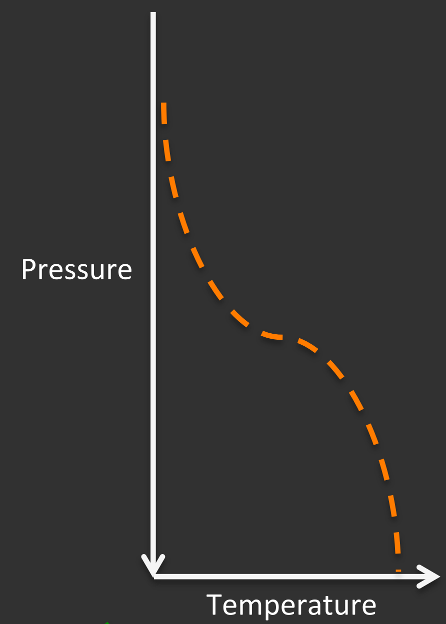
Chemical Abundance

Method



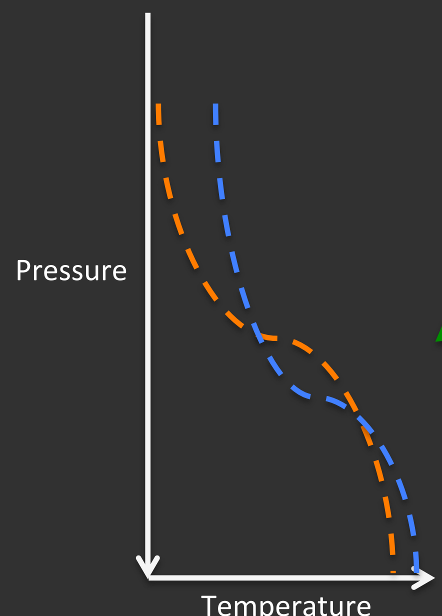
Calculate equilibrium chemistry

Solve for hydrostatic equilibrium
+
Solve equations of radiative transfer



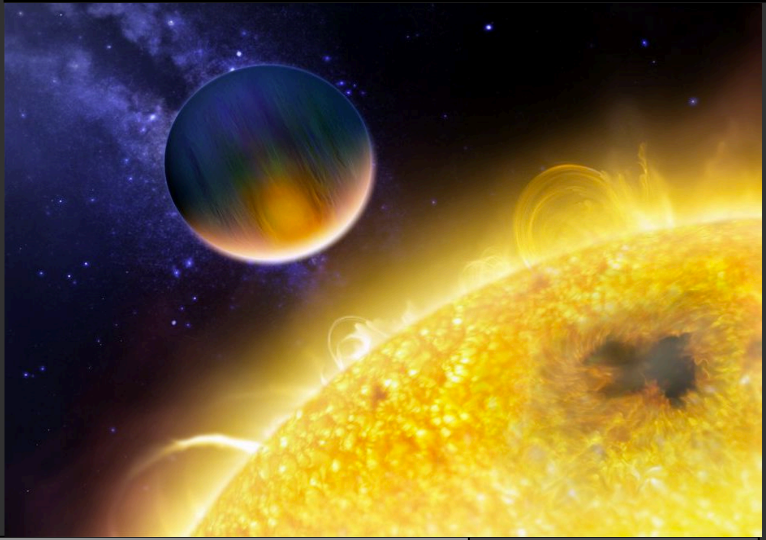
Switch to non-eq chemistry

Reconverging PT profile throughout



Test Case Planets

	HD 209458b	GJ 436b
Mass M_J	0.71	0.078
Radius R_J	1.38	0.37
Semi-major axis AU	0.047	0.030
Gravity (log g)	3.03	3.17
Host Spectral Type	G0 V	M2.5



- Short orbital periods of ~ few days or less
- Highly irradiated
- Tidally-locked – strong horizontal gradients
- Hot Jupiters ~ Jupiter mass planets
- Hot Neptunes ~ Neptune mass planets

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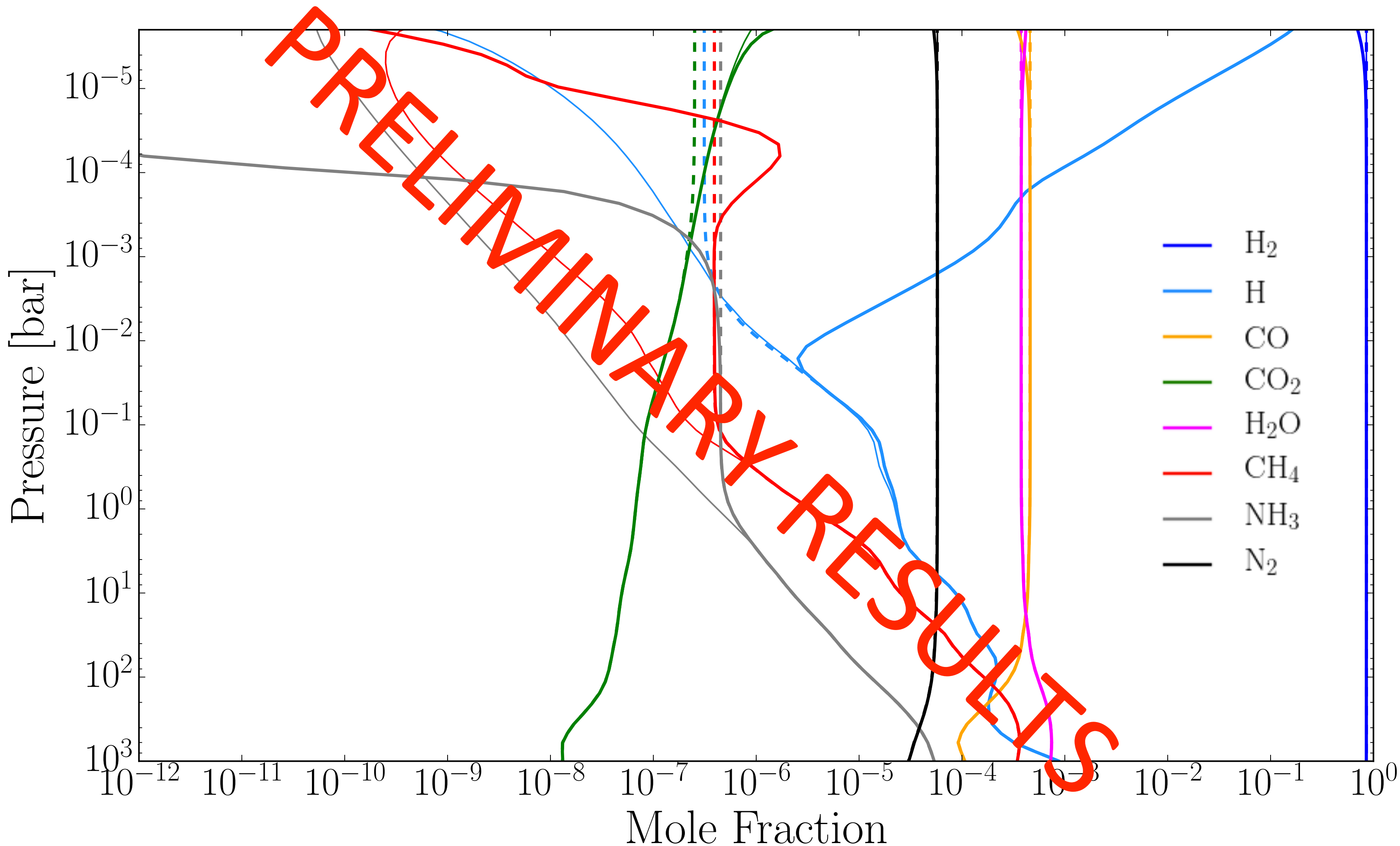
HD 209458b

Chemistry



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PT Profiles

HD 209458b

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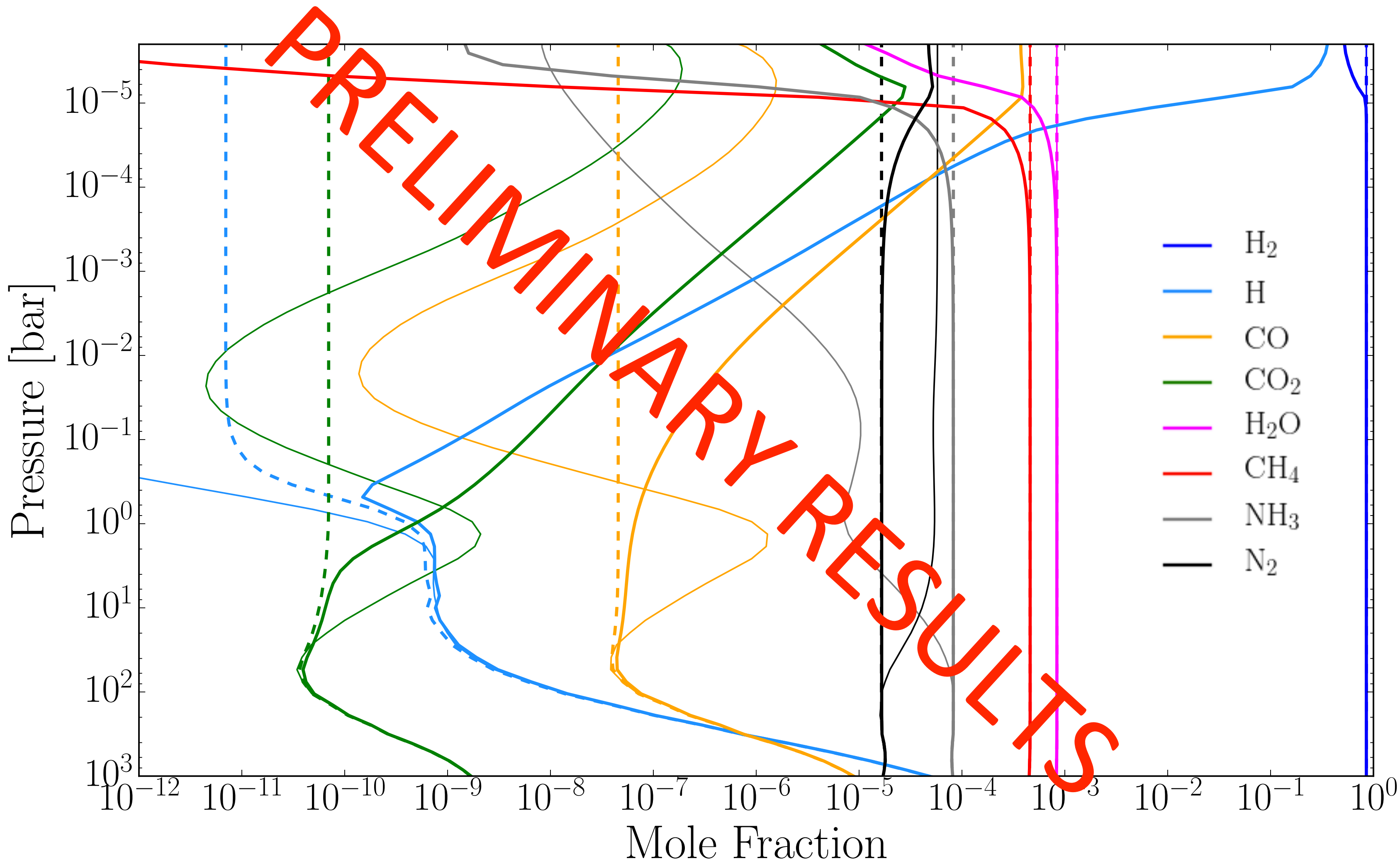
GJ 436b

Chemistry

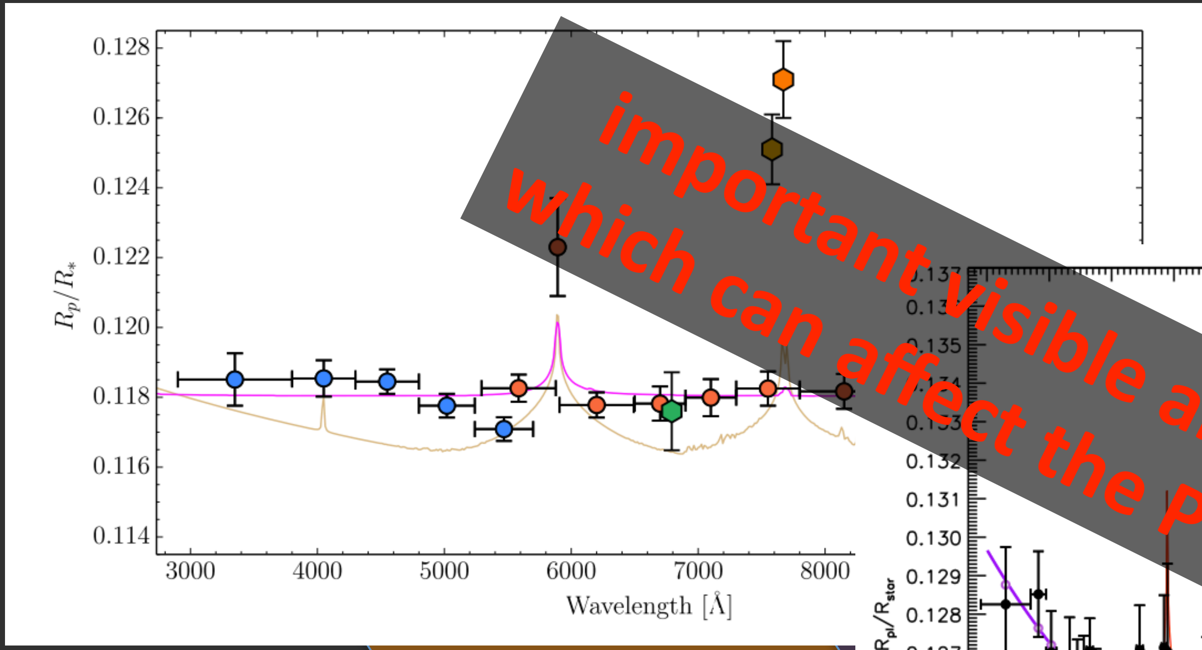


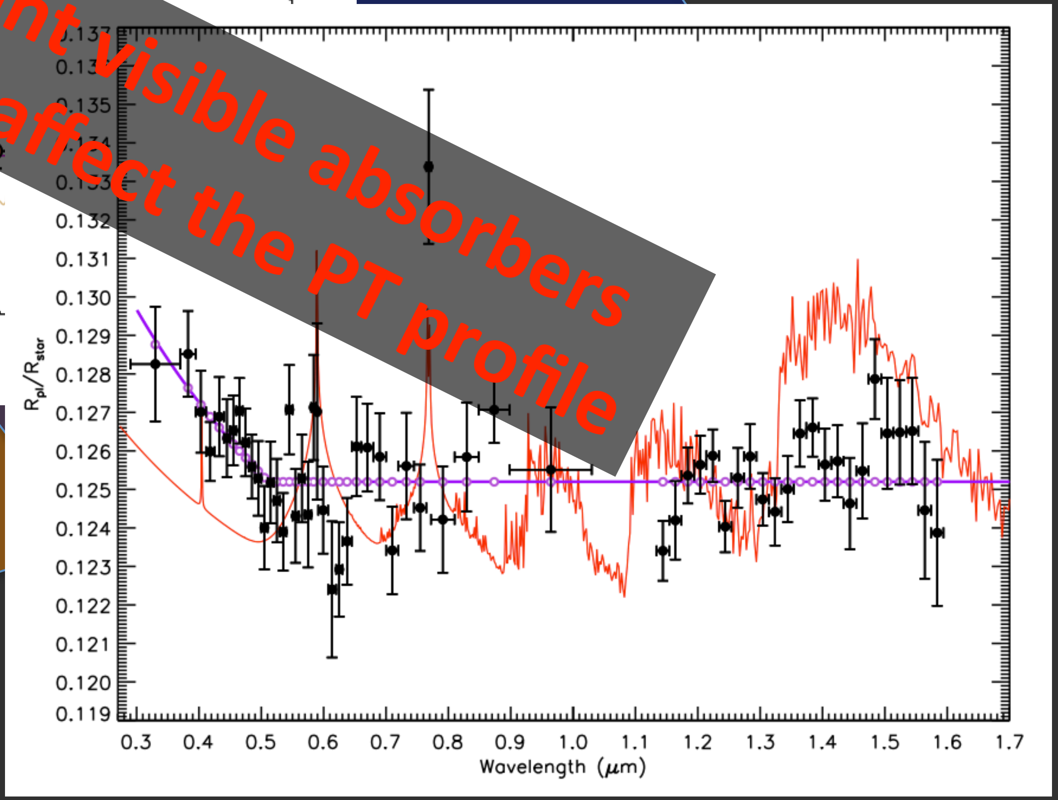
GJ 436b

PT Profiles

Alkali Chemistry

- Important detections





important visible absorbers which can affect the PT profile

Alkali Chemistry

- <u>Alkali Chemical Kinetics</u>
  - Chemical network of Glarborg and Marshall, 2005
  - High temperature kinetics for gas phase Na and K species
    - Na, NaCl, NaOH, NaO, NaH
    - K, KCl, KOH, KO, KH
    - 47 reactions

$$\boxed{\begin{gathered}\mathrm{Na + OH + M \leftrightarrow NaOH + M} \\ \mathrm{Na + HCl \leftrightarrow NaCl + H}\end{gathered}}$$

e.g

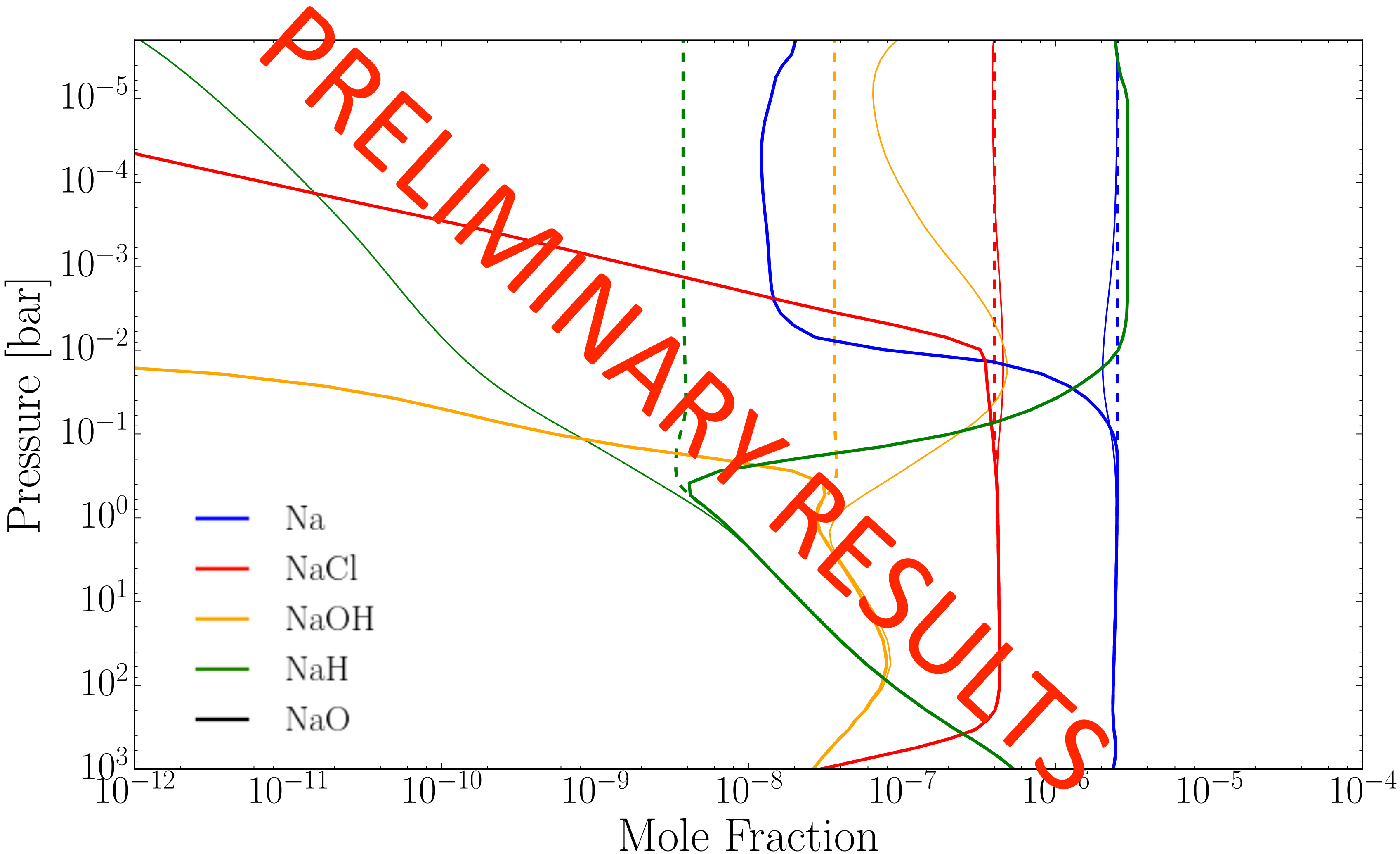
  - Also include reactions of chlorine species (Lavvas et al., 2014)

$$\boxed{\begin{array}{ll}\mathrm{HCl} + h\nu \rightarrow \mathrm{H + Cl} & \mathrm{HCl + OH \leftrightarrow H_2O + Cl} \\ \mathrm{H + HCl \leftrightarrow H_2 + Cl} & \mathrm{HCl + M \leftrightarrow H + Cl + M}\end{array}}$$

  - For hot atmospheres (e.g. HD 209458b), atomic Na and K dominate (e.g. Lavvas et al., 2014)
  - For cooler atmospheres (e.g. GJ 436b), molecular forms can become important (e.g. NaCl, NaOH, …)

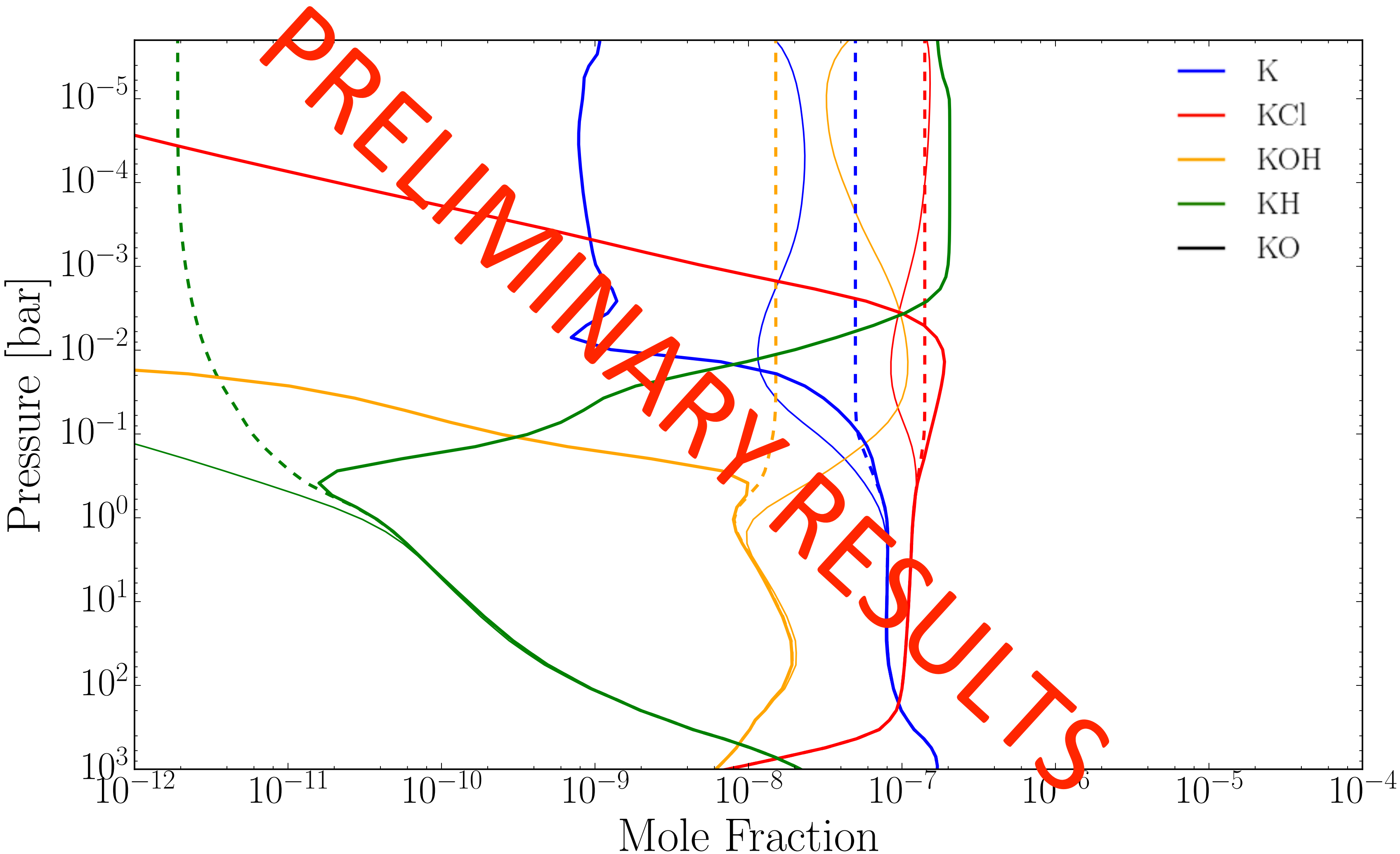
GJ 436b

Alkali Chemistry



Alkali Chemistry

GJ 436b



GJ 436b

PT Profiles

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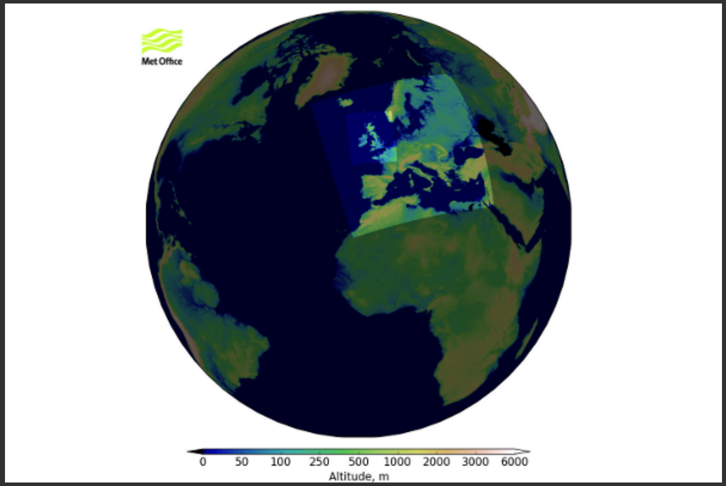
Summary

- ATMO
  - a new fully-consistent 1D radiative-convective equilibrium model
- Fully-consistent non-equilibrium chemistry
  - gas phase non-equilibrium chemistry can have a (small, ~1%) effect on the temperature profile
  - formation of photochemical haze or condensation of clouds likely has more influence
  - missing chemical/opacity data for important absorbing species?
- What Next?
  - couple non-equilibrium chemistry with the UM

Chemistry and GCMs

- The Unified Model (UM)
  - A non-hydrostatic, deep atmosphere general circulation model (GCM)
  - Developed by the UK Meteorological Office for global climate predictions and local weather forecasting
  - Applications of dynamical core to hot exoplanet atmospheres (Mayne et al., 2014a, 2014b)
  - Adapted radiation scheme to high temperatures 10^3 K (Amundsen et al., 2014)

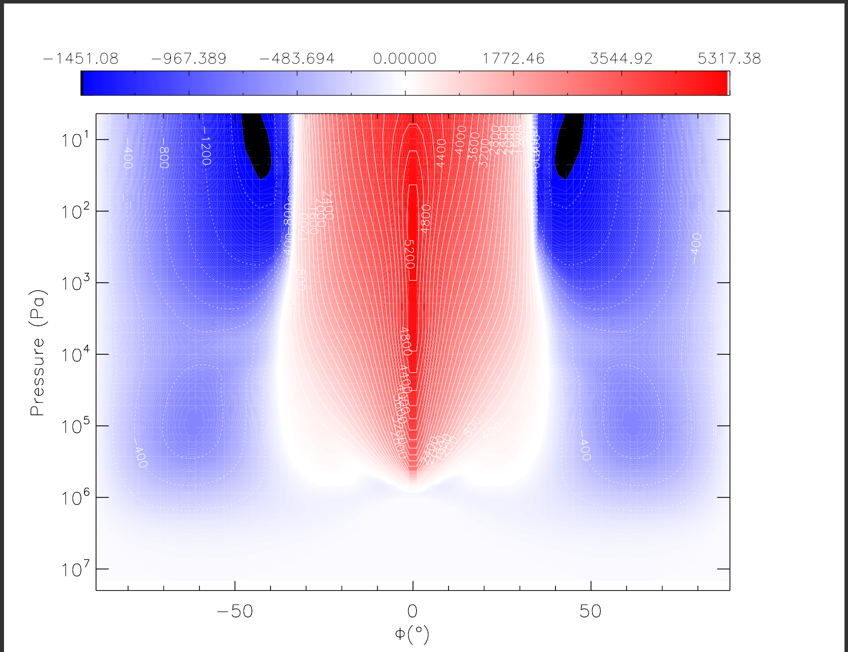


Chemistry and GCMs

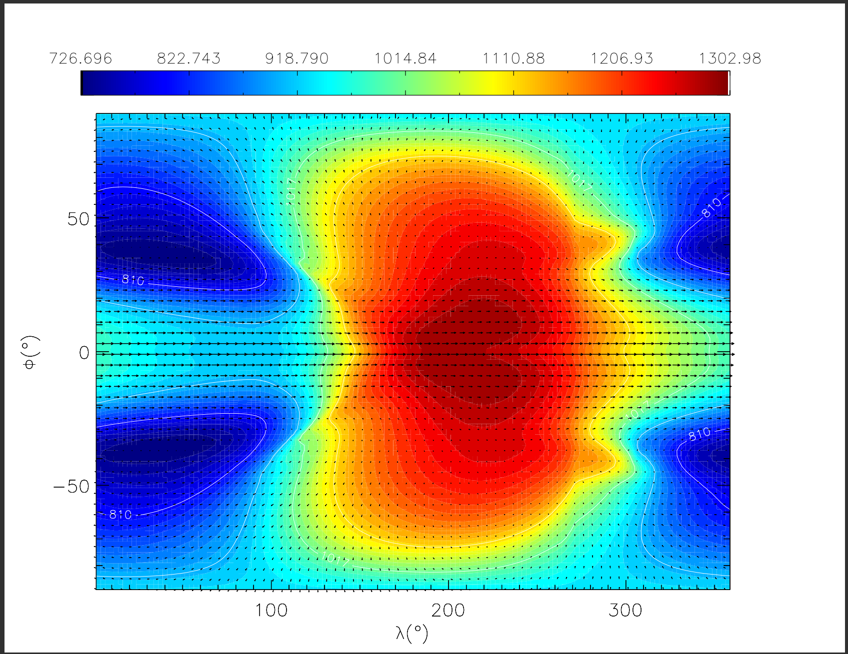
- The Unified Model (UM)

HD 189733b

Zonal Mean Zonal Wind



Temperature at 30 mbar

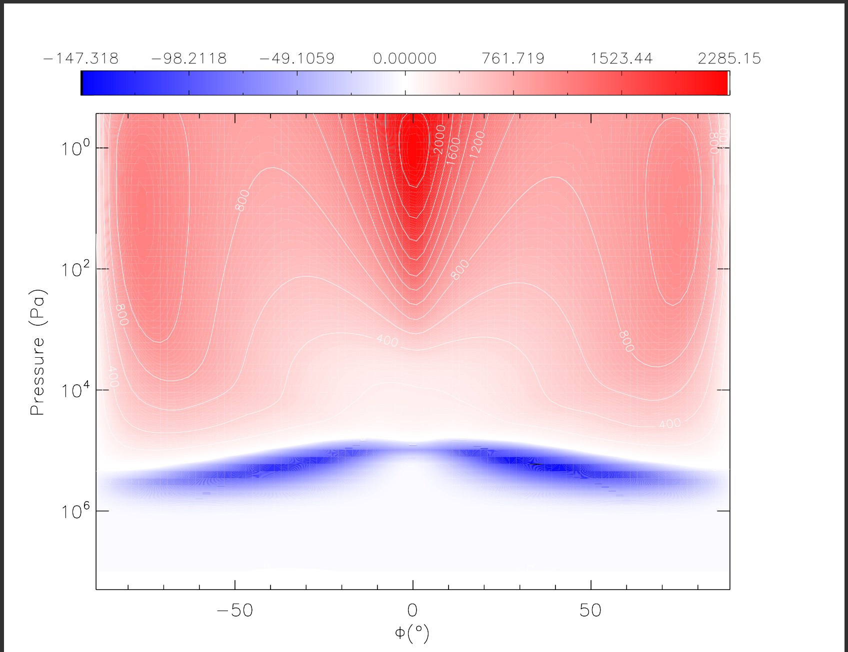


Chemistry and GCMs

- The Unified Model (UM)

GJ 436b

Zonal Mean Zonal Wind



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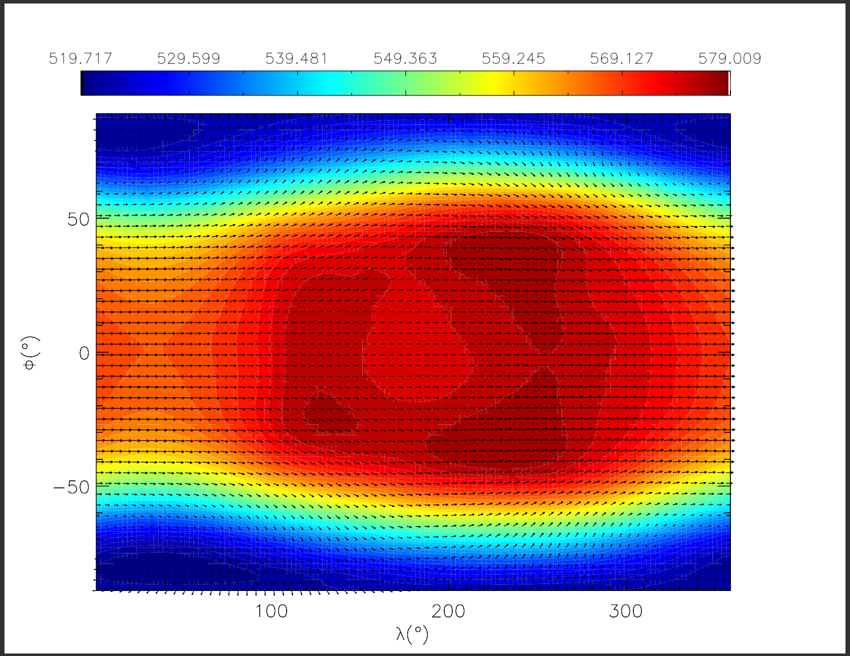

Chemistry and GCMs

- The Unified Model (UM)
  - Next stage: Couple chemical kinetics to track 3D advection of important chemical species

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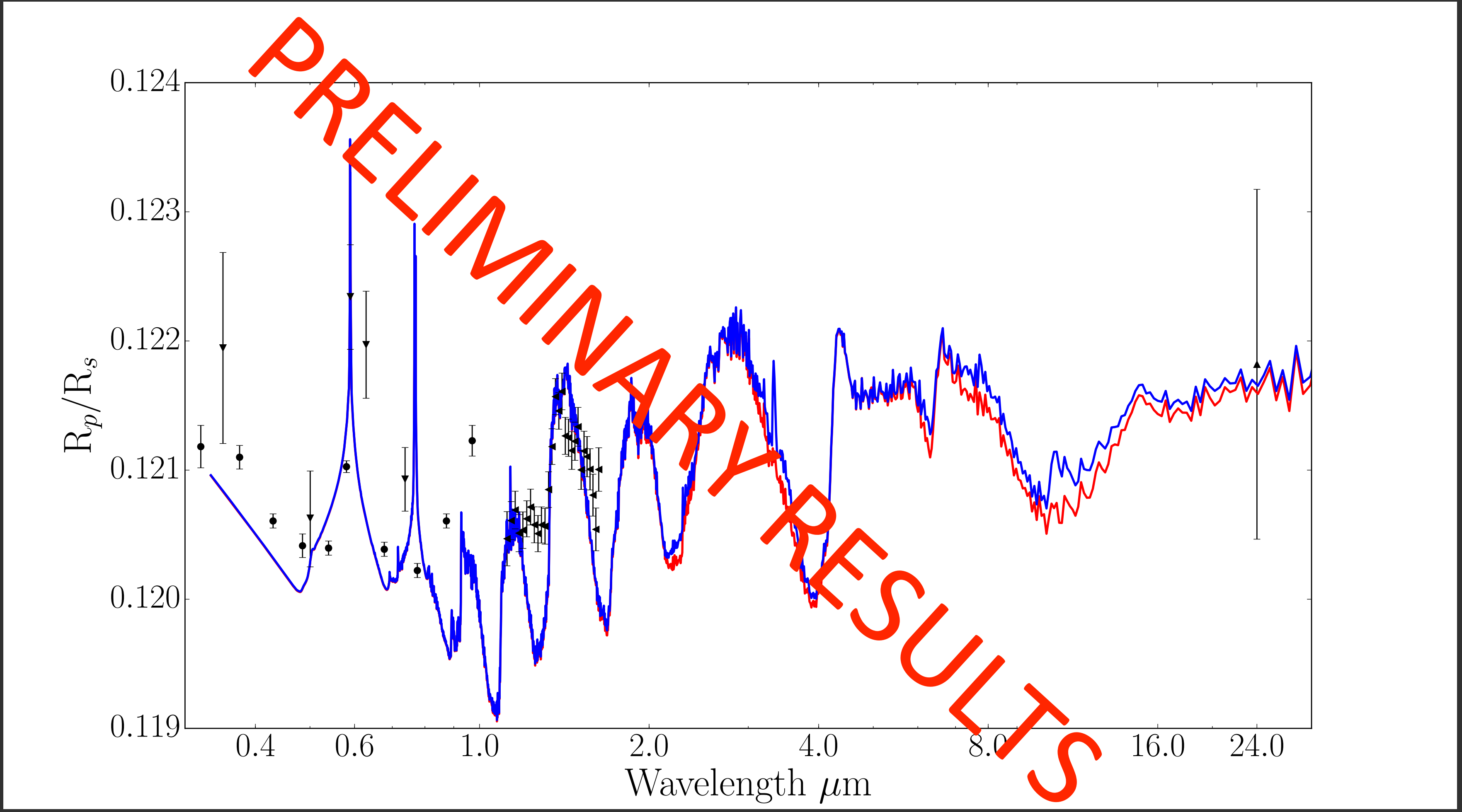
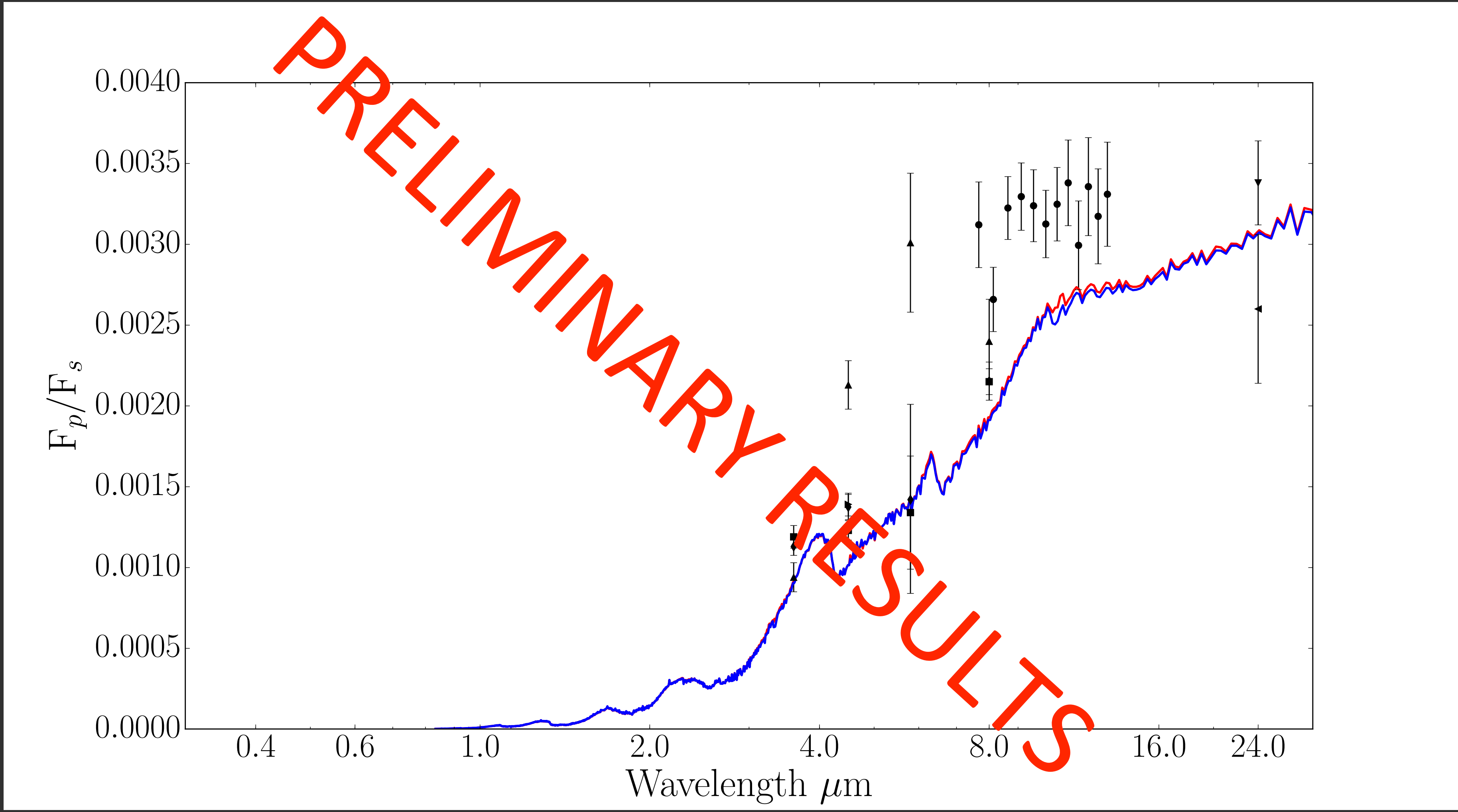
HD 209458b

Model Spectra



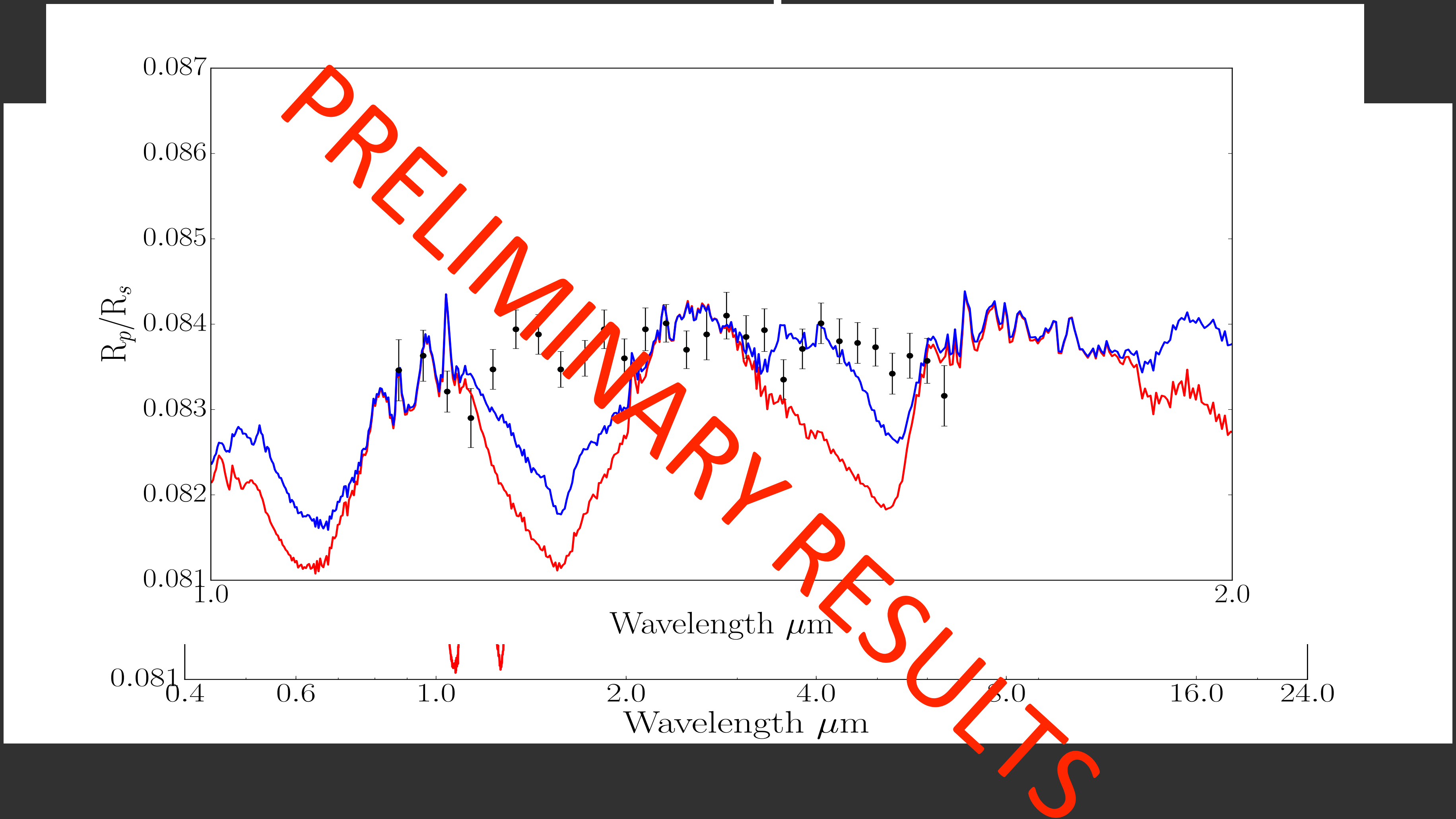
HD 209458b

Model Spectra



GJ 436b

Model Spectra



GJ 436b

Model Spectra