Modeling Exoplanetary Atmospheres

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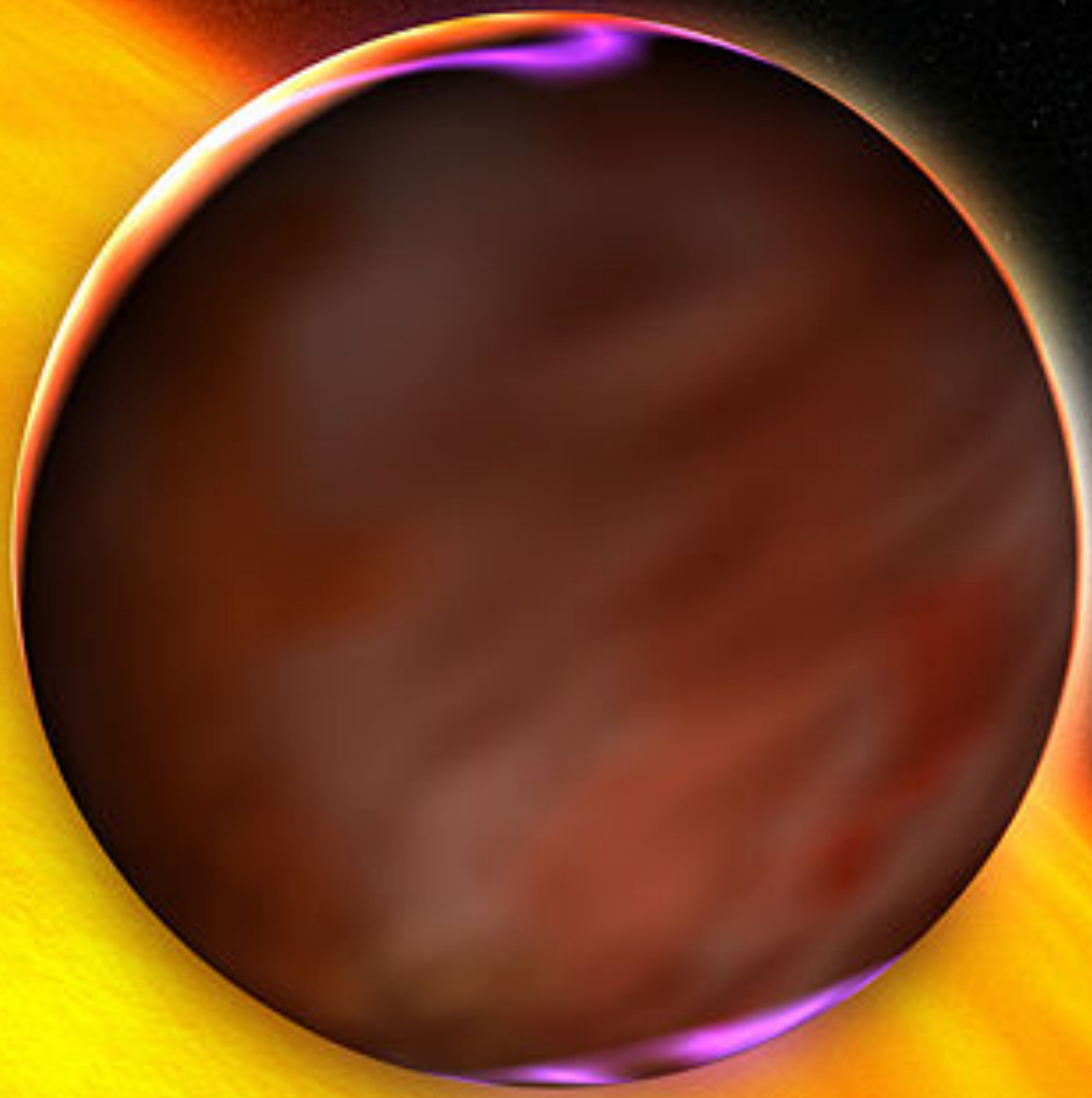

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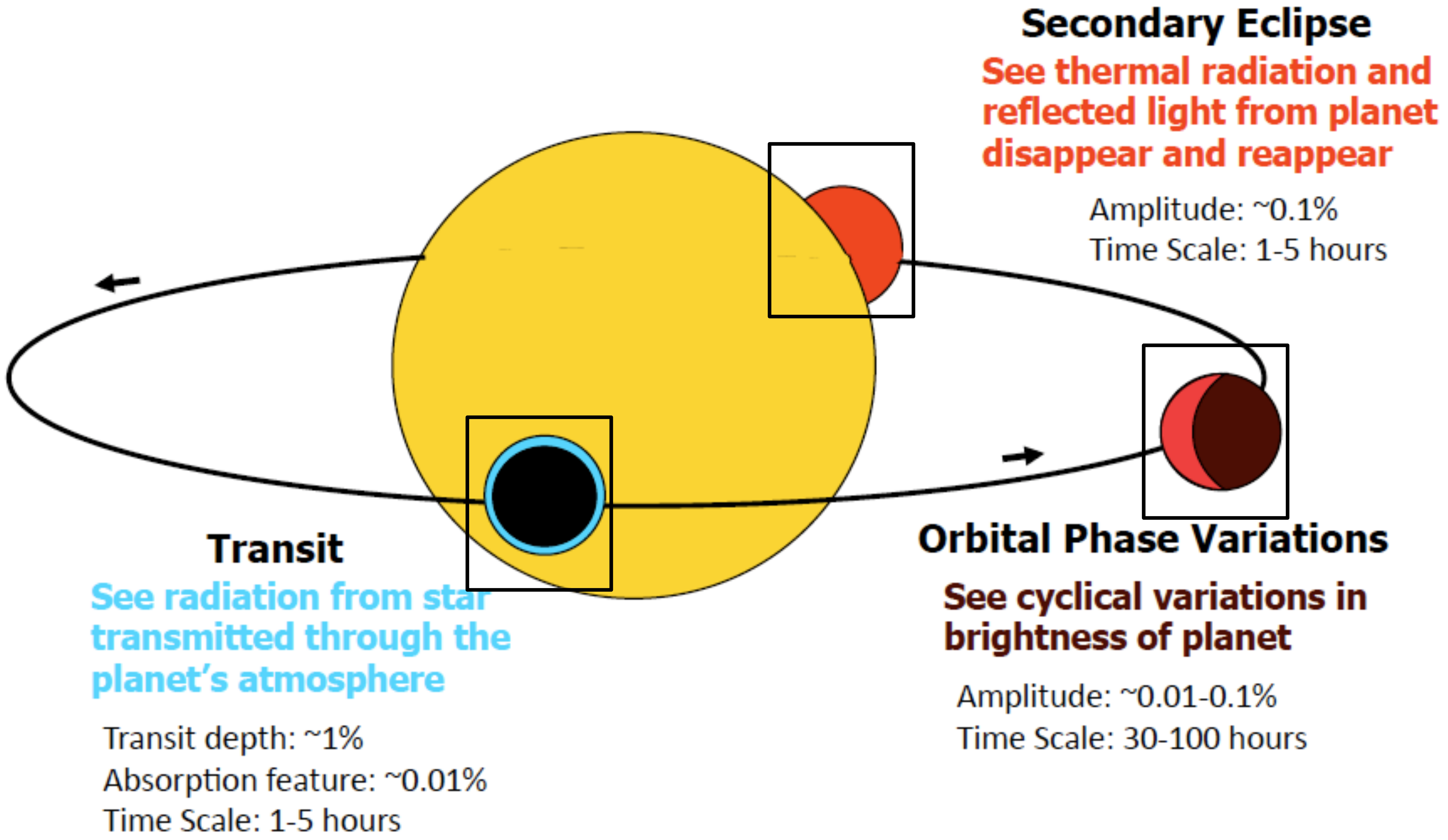
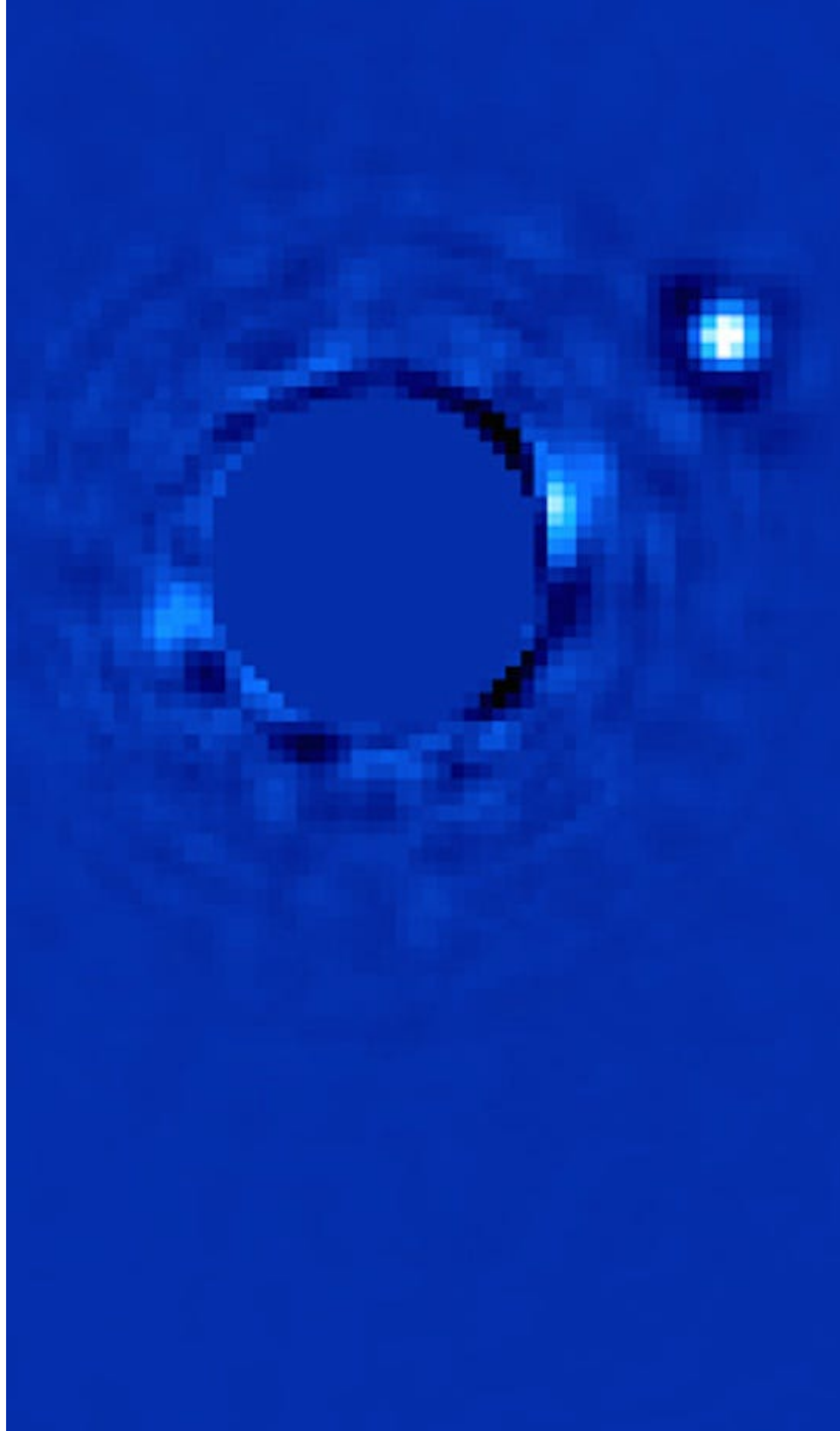
LABORATORY

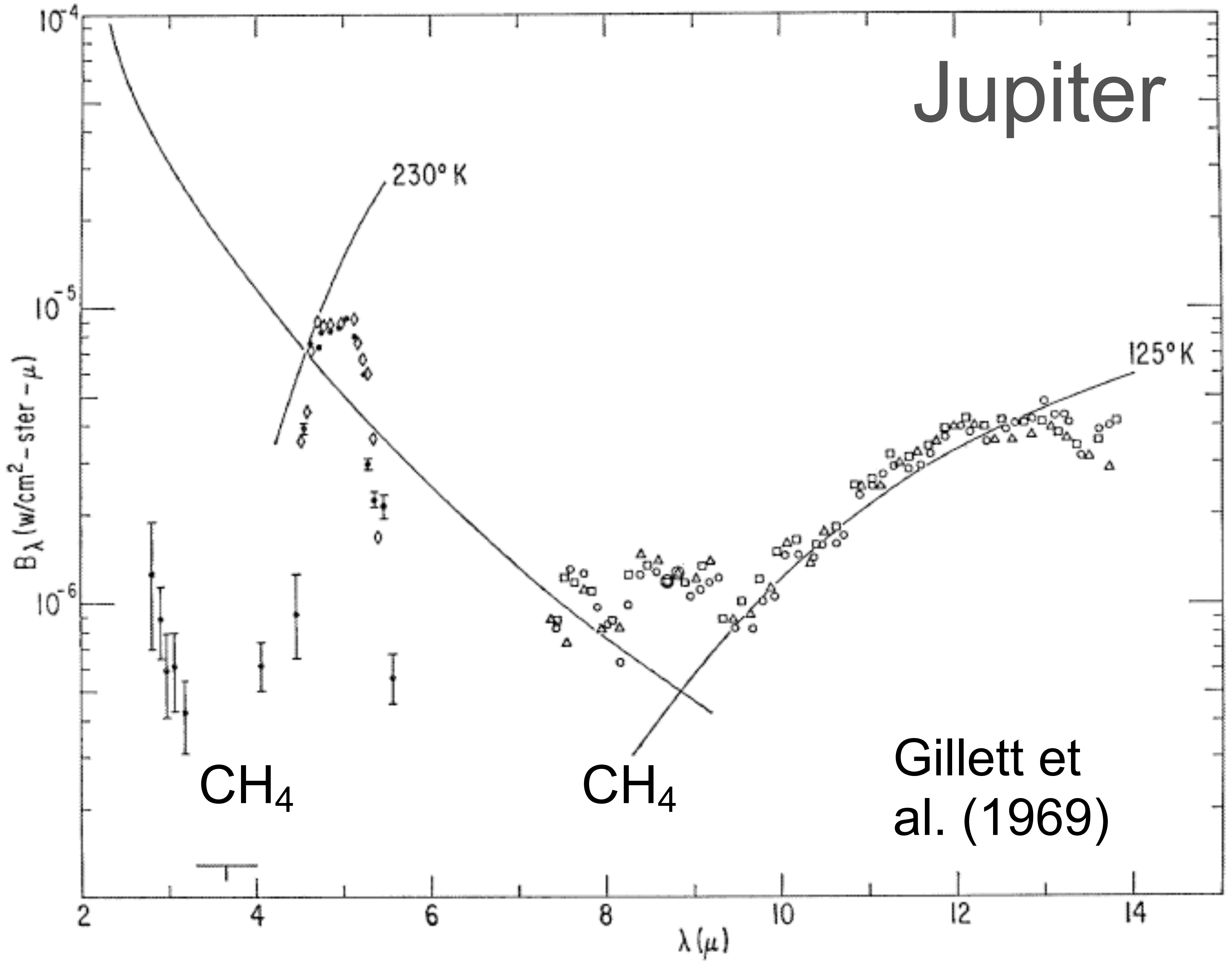
Methods for Characterizing the Atmospheres of Transiting Planets



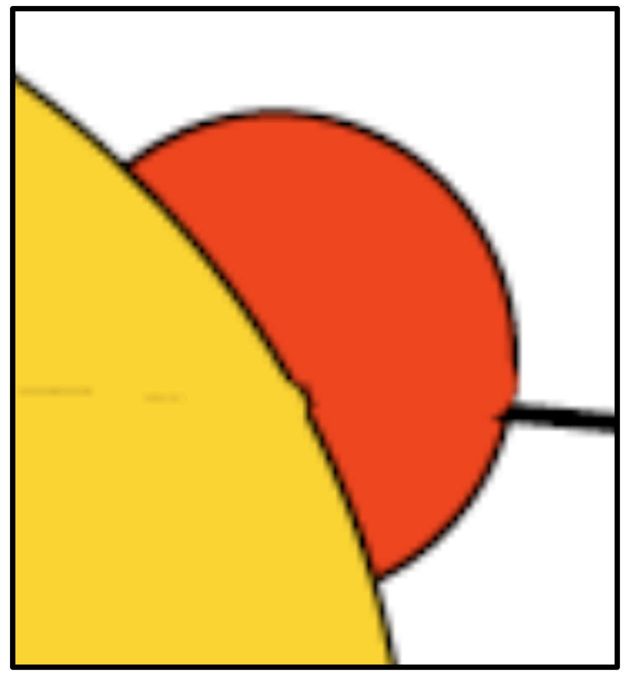
Direct Imaging



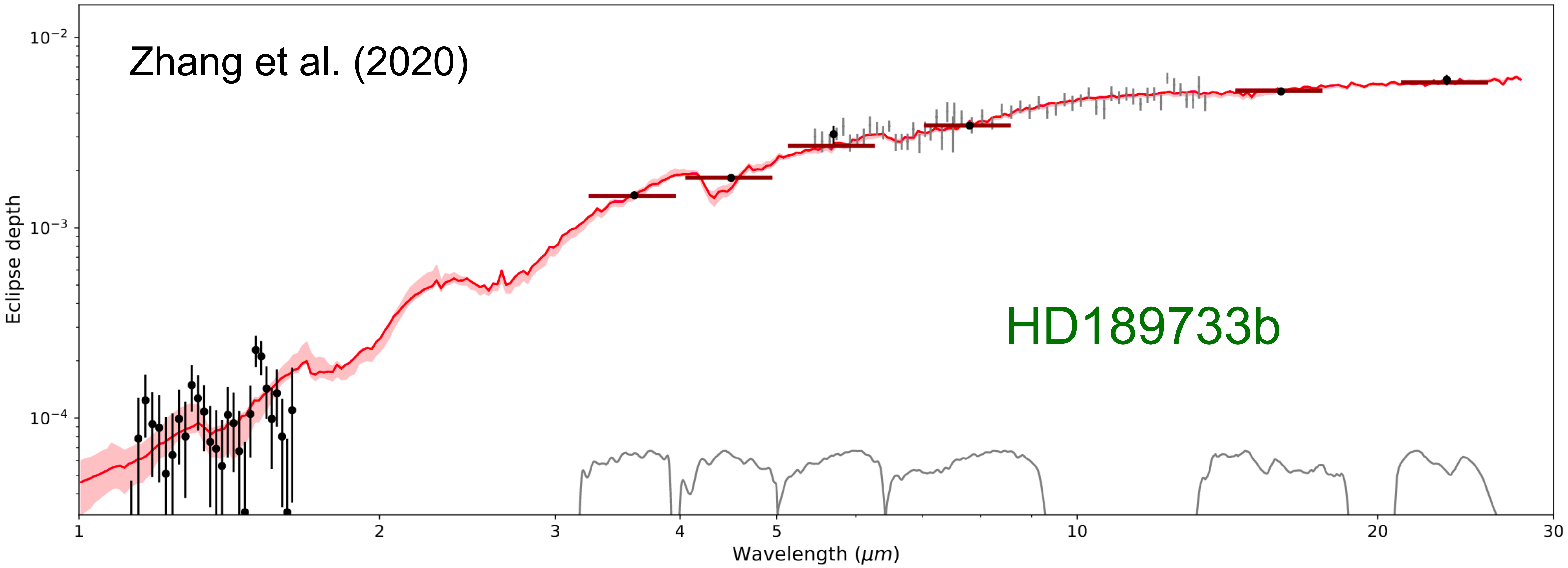
Spectroscopy of thermal infrared light emitted by the planets

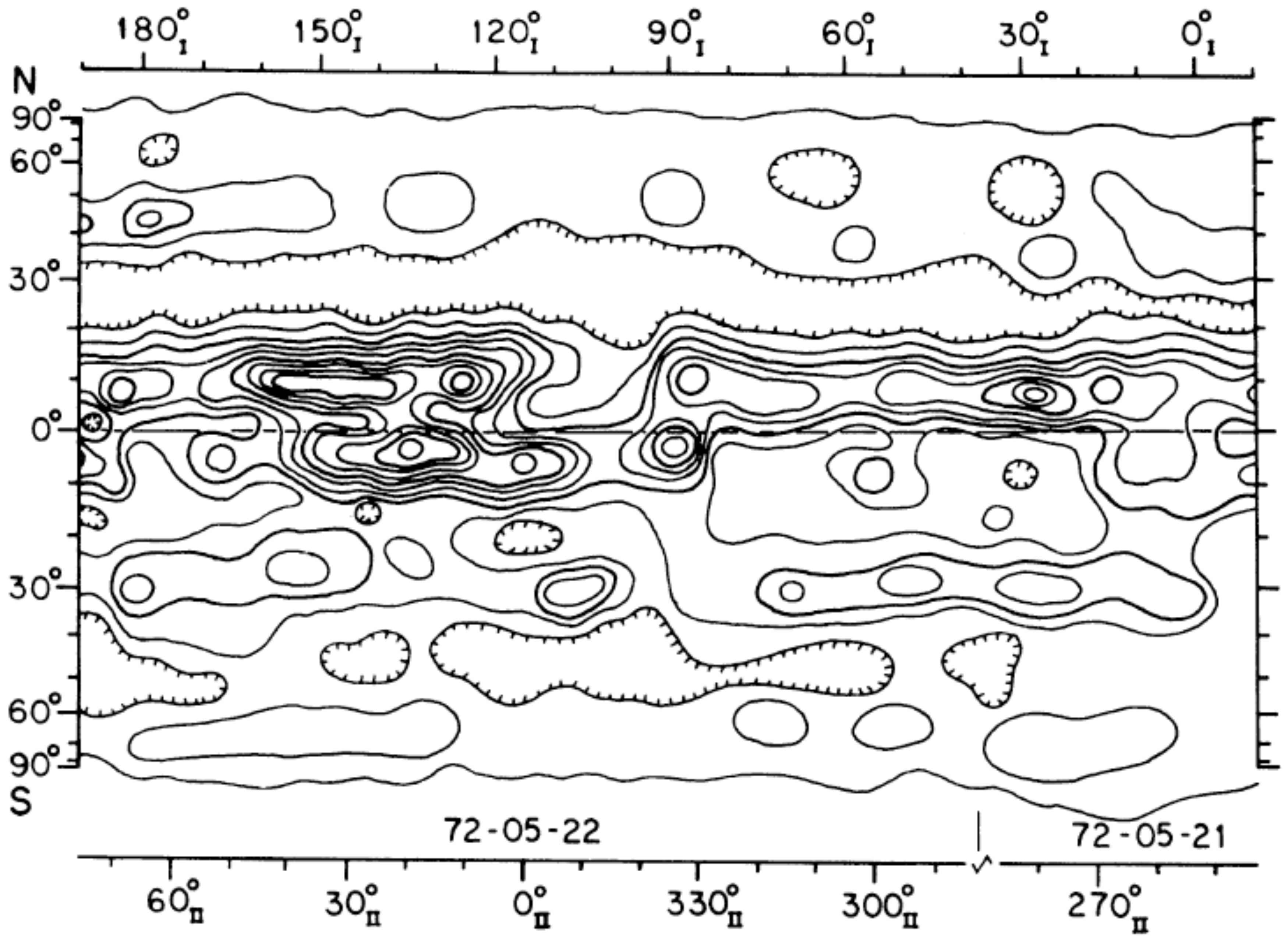


- Jupiter, 1969
- HD 189733b, ~2008



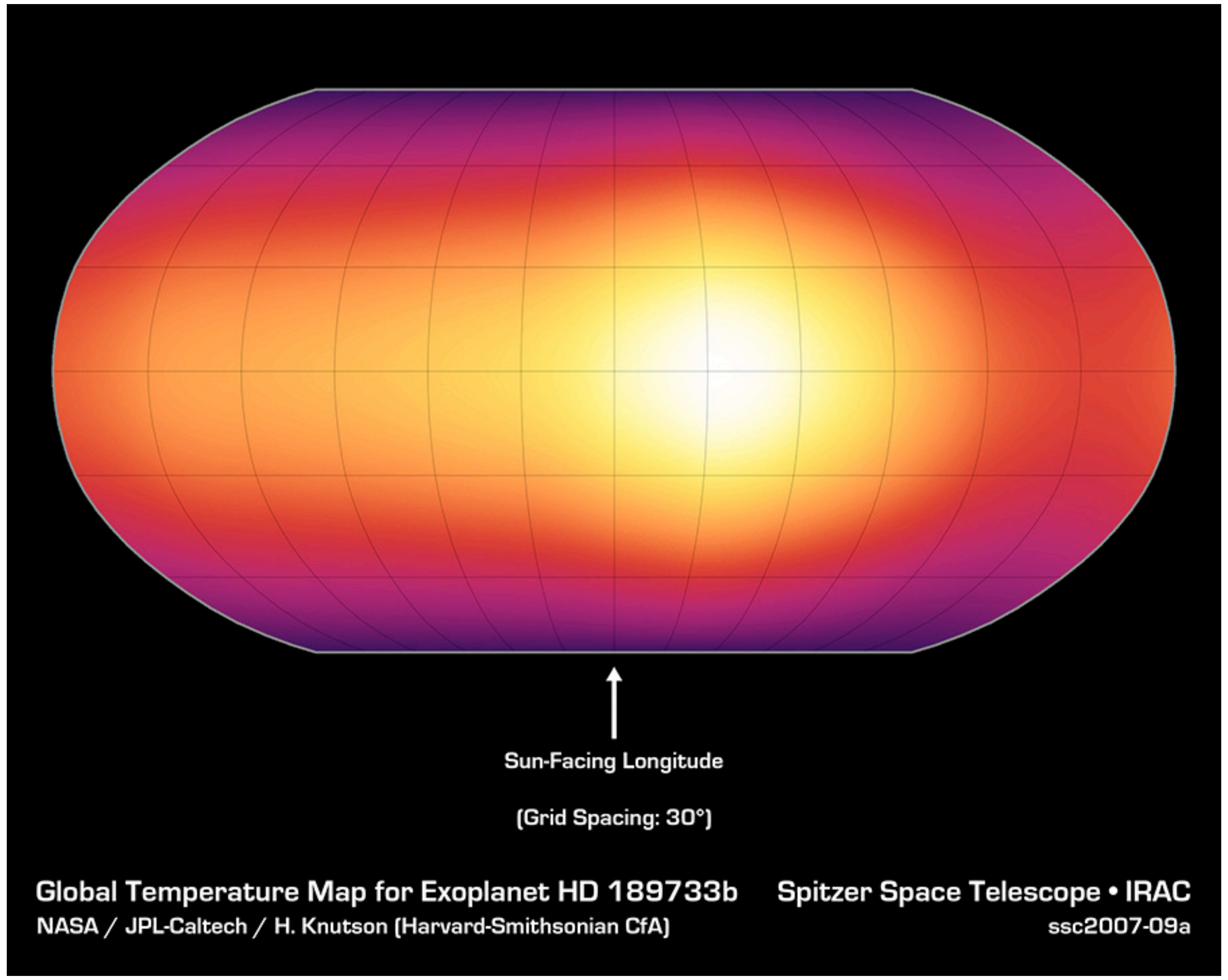
- Exoplanet atmospheres is running **40-50 years** behind solar system atmospheres



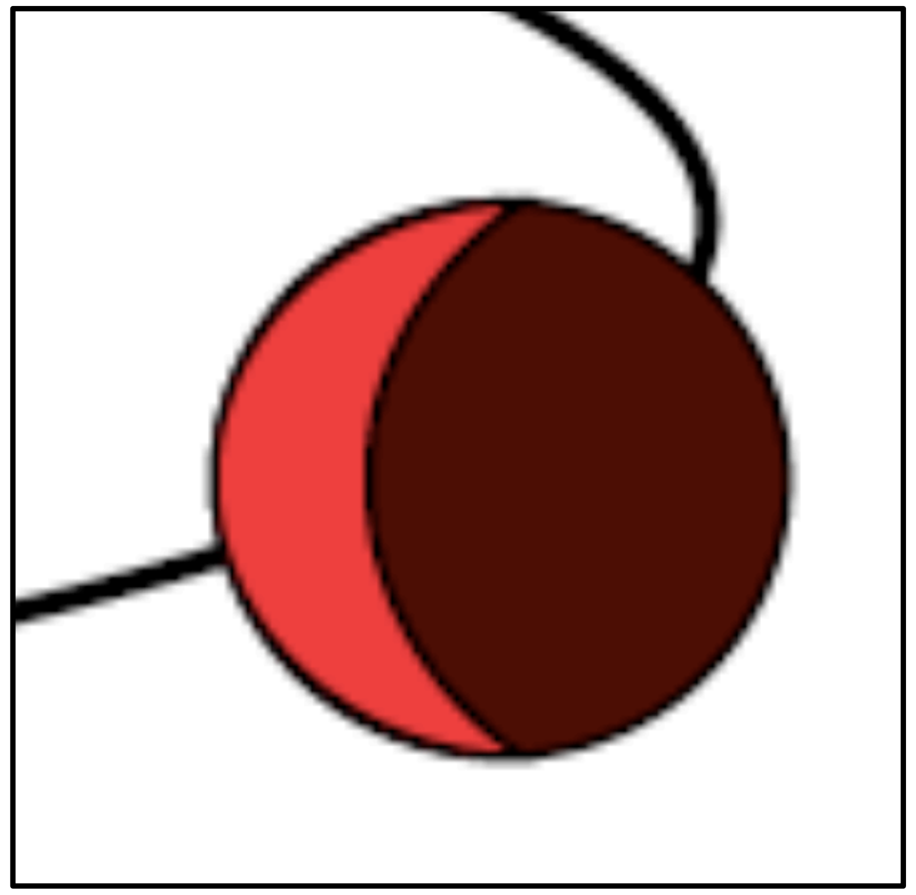


Infrared Brightness Maps in Thermal Emission

- Jupiter, 1972
Key et al., 5 μm

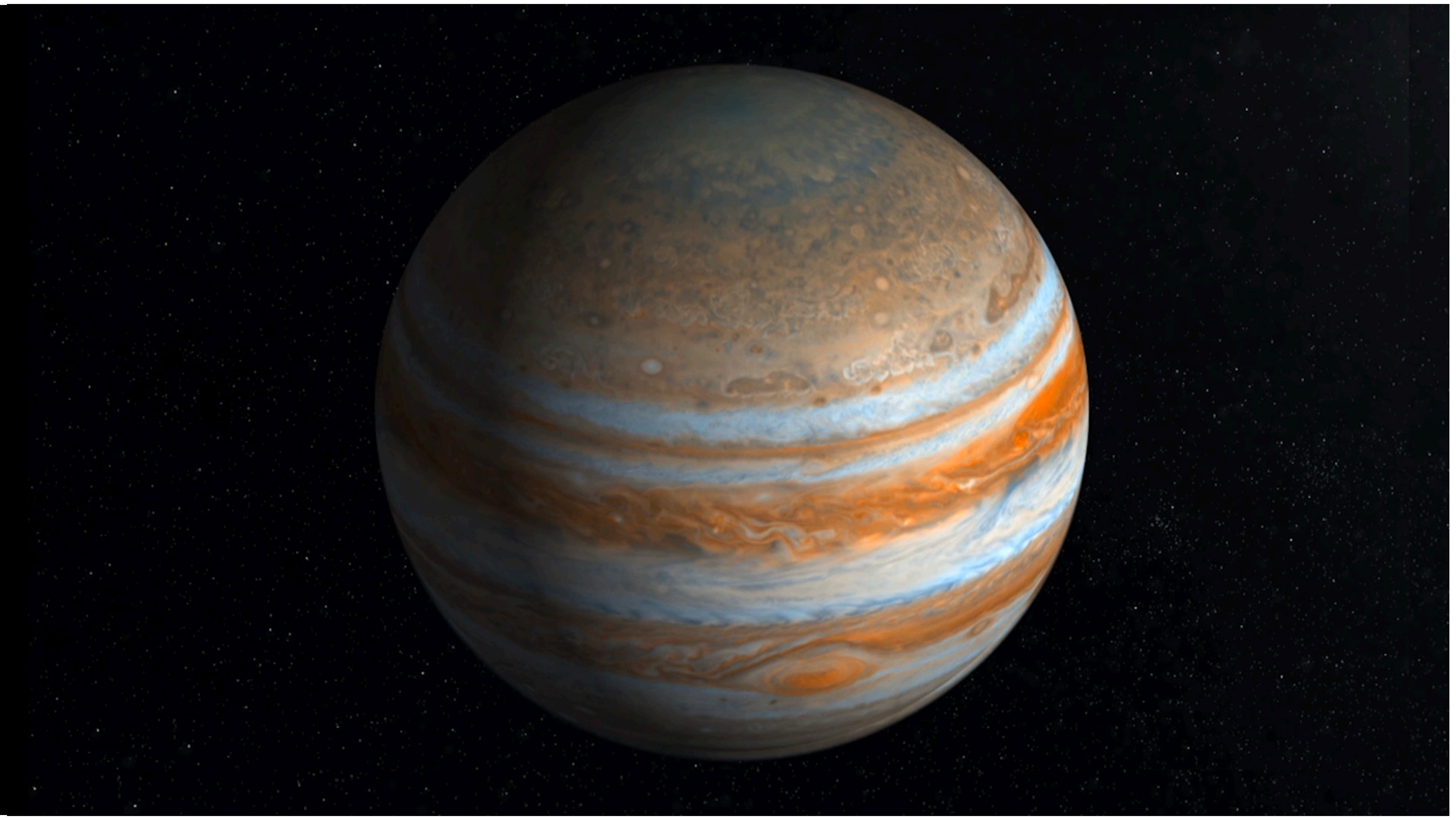


- HD 189733b, 2007
Knutson et al., 8 μm



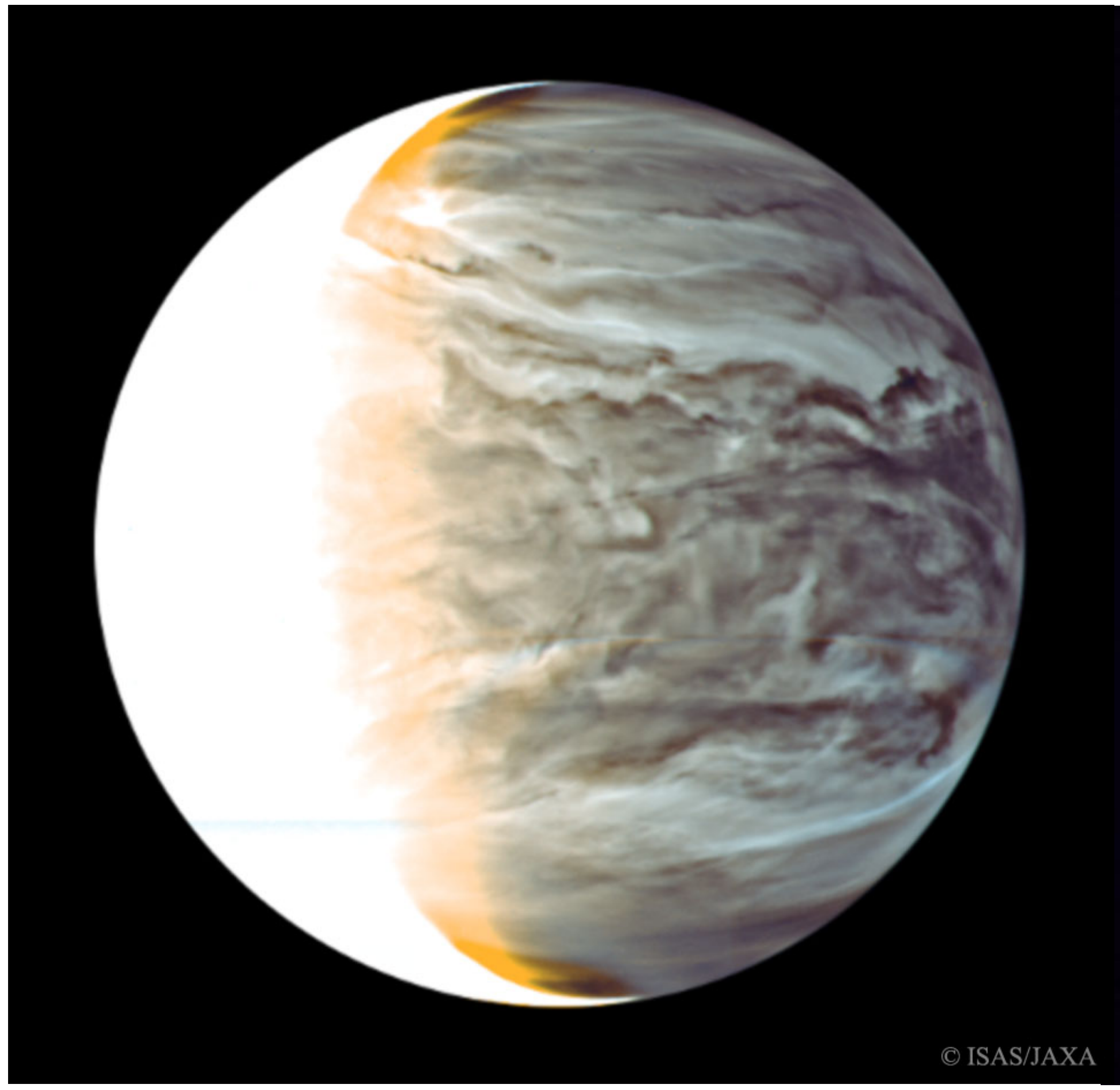
Planets Can Be Categorized

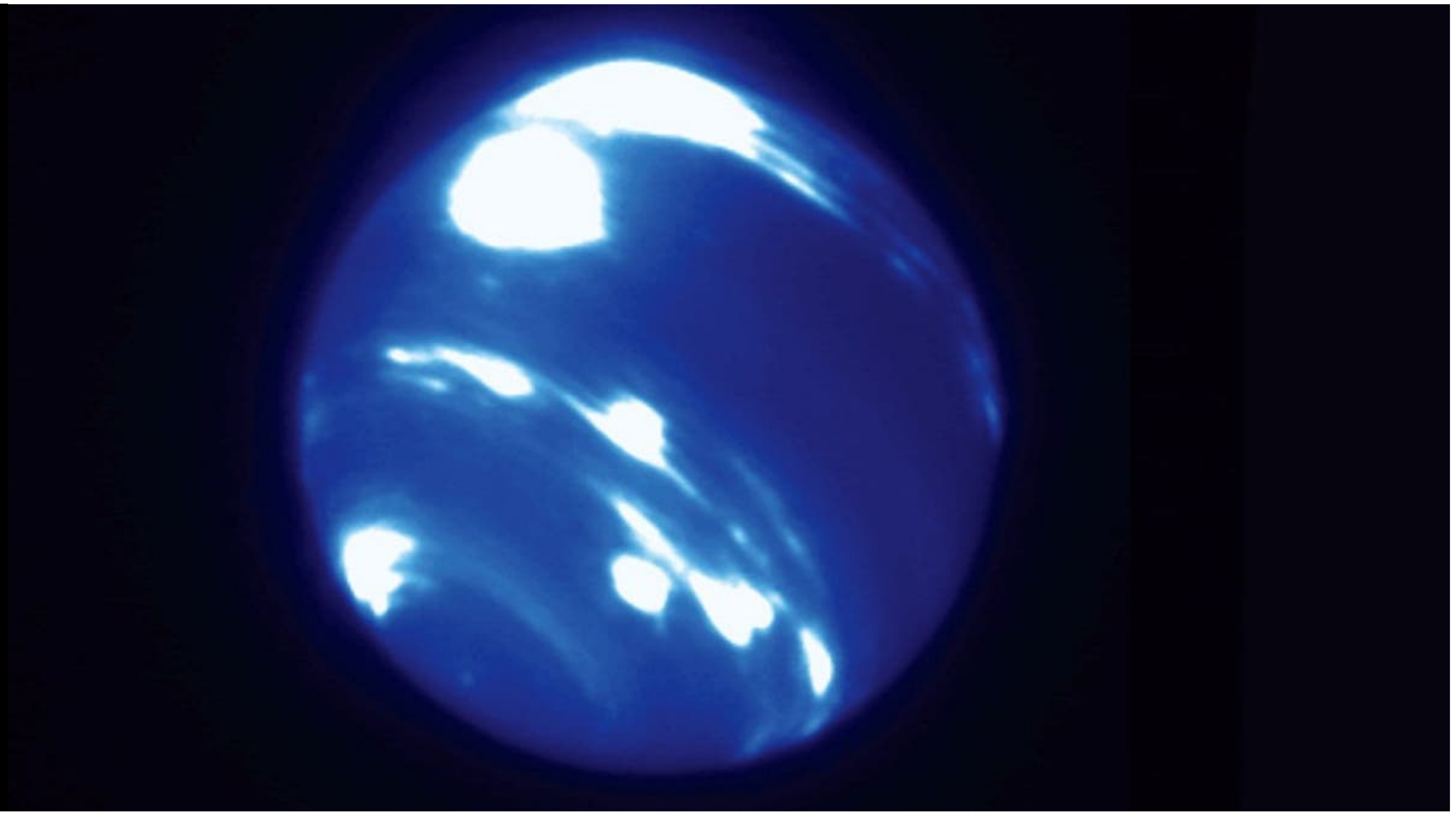
- Planets can generally be grouped (*we think*) based on where their atmospheres came from
  - "**Primary**": Accreted from the protoplanetary disk
    - Jupiter, Saturn, Uranus, Neptune, similar exoplanets
    - Atmosphere can be most of planet's total mass
  - "**Secondary**": Outgassed from the planet's interior
    - Venus, Earth, Mars, Titan, similar exoplanets



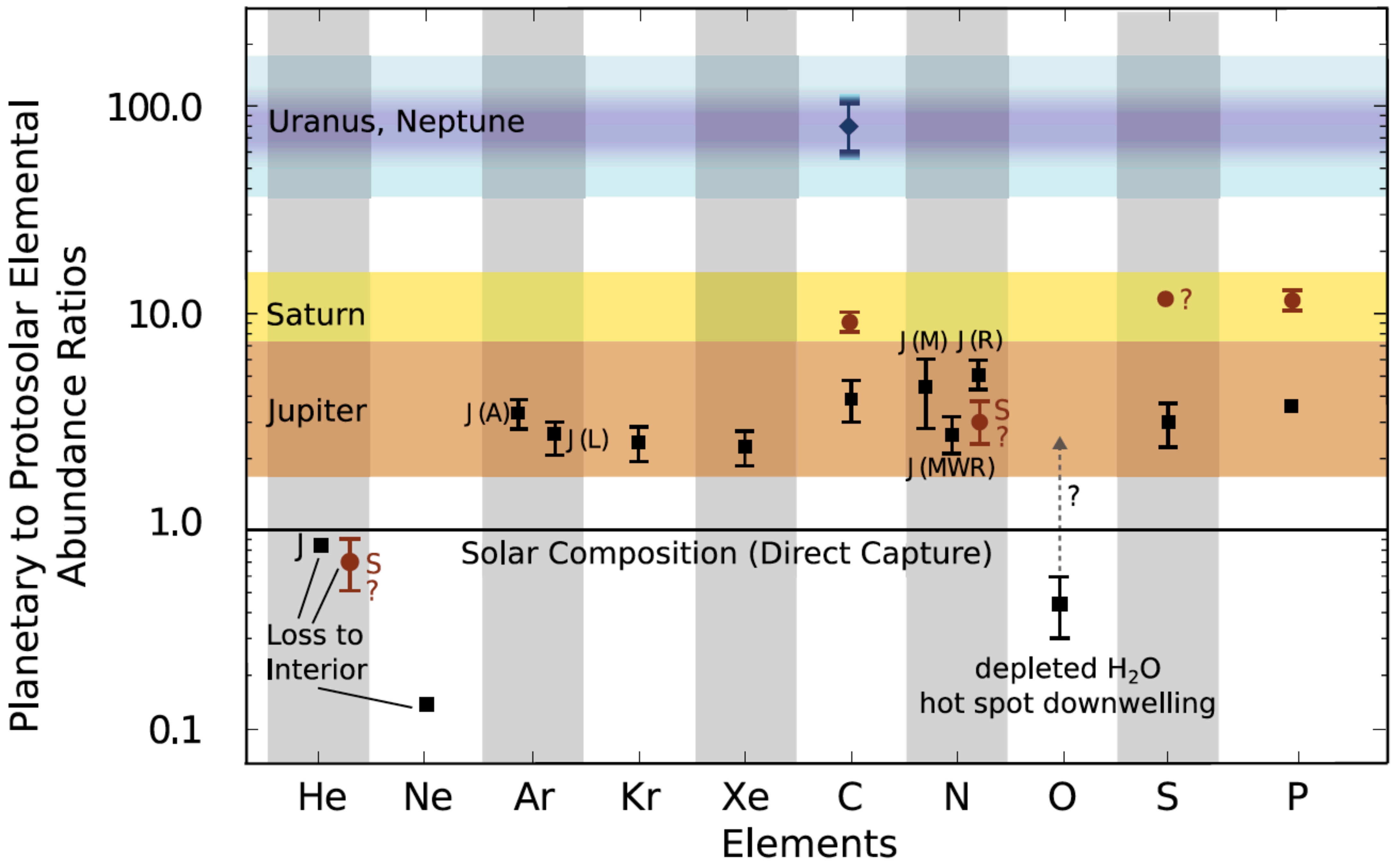
Two Aspects of Studying Atmospheres

- **Understand Atmospheric Physics (and Chemistry)**
  - Absorption and Emission of Radiation
  - Circulation: Advection of Energy
- **Connect to Planetary Origins**
  - Atomic and Molecular Abundances
  - Connect to Formation Location and/or Stellar Abundances

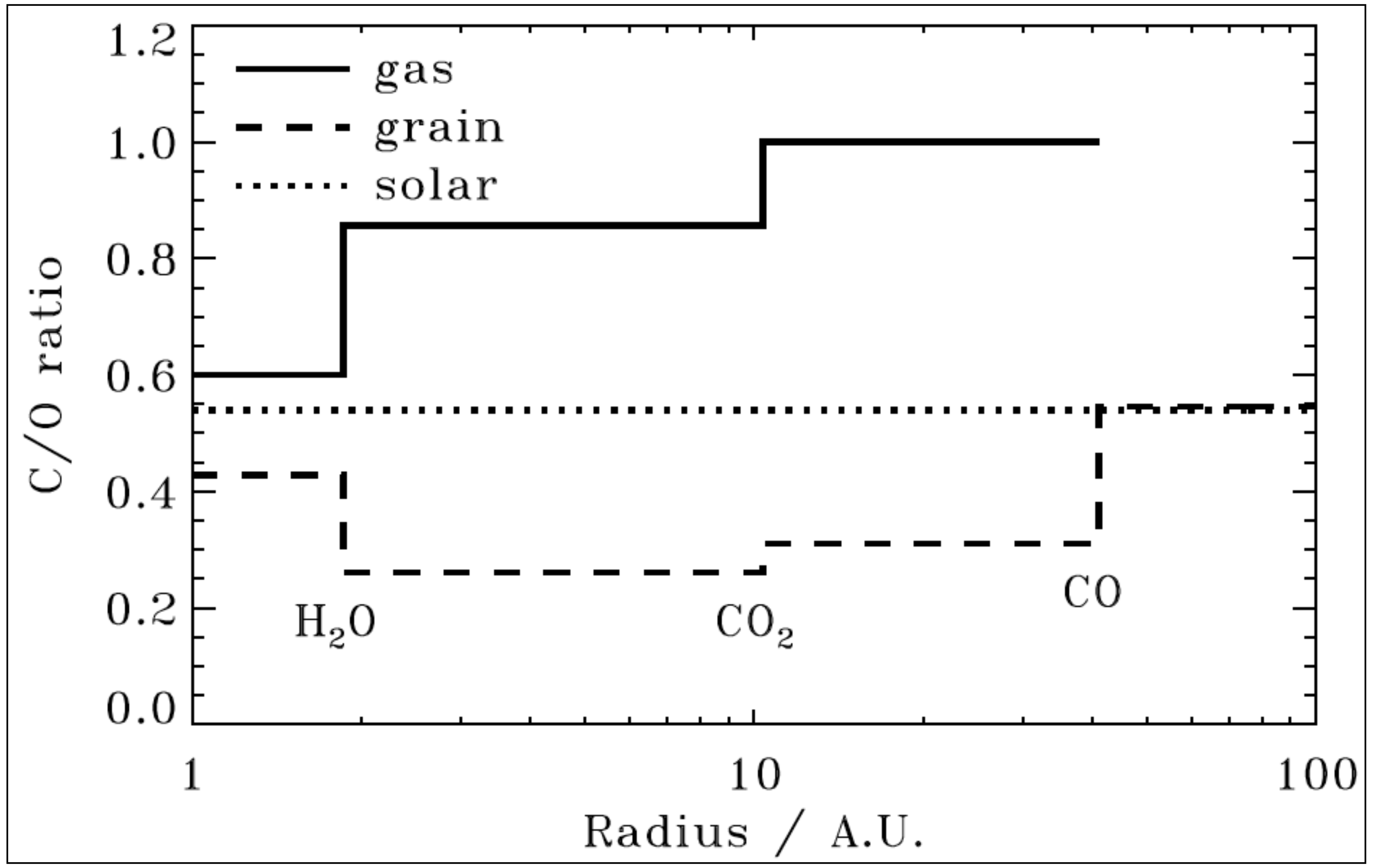




Connecting to Origins for Giant Planets

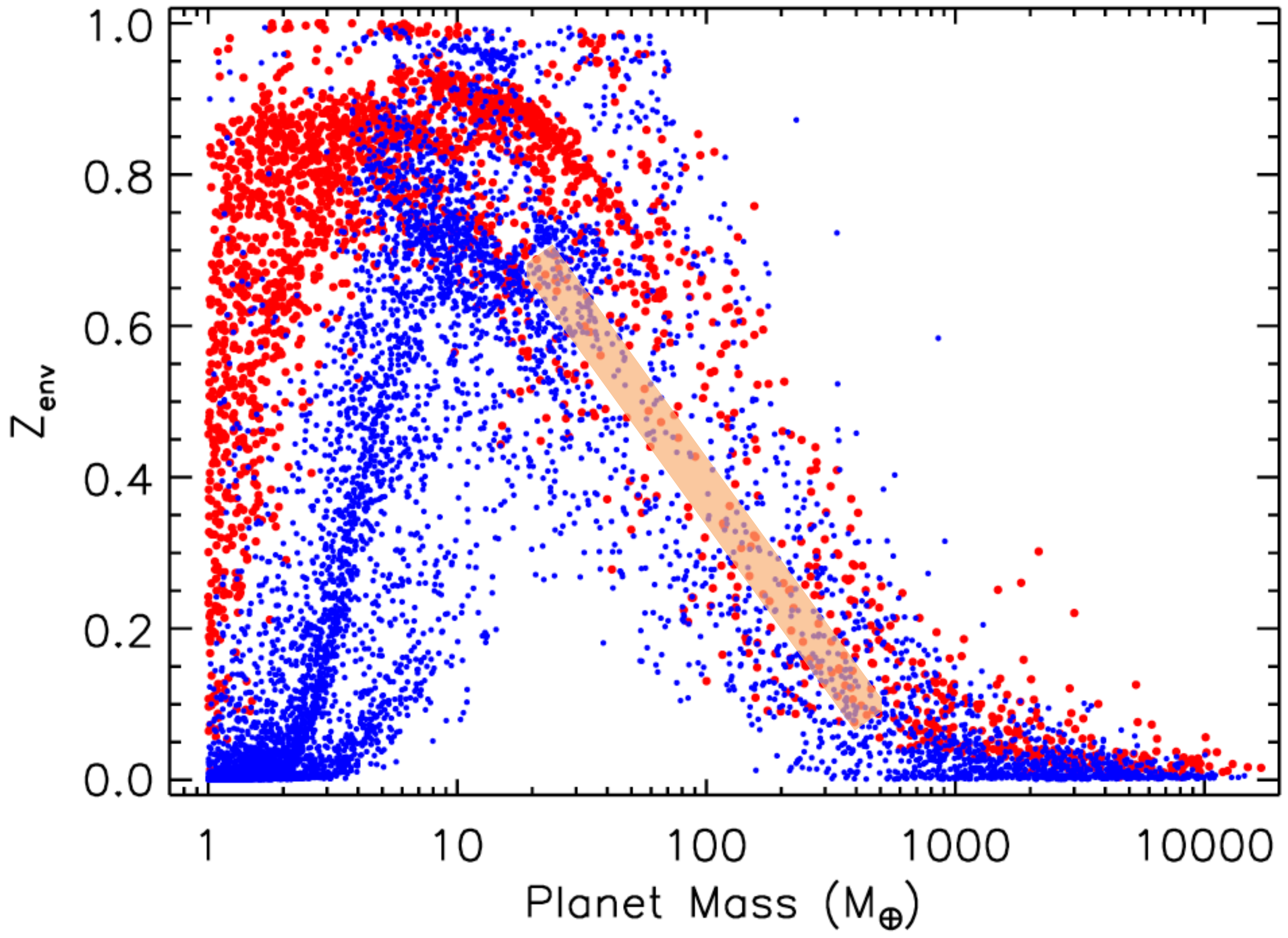


Connection to the Solar System (Atreya et al. 2020)



Giant planet C/O ratio

Oberg et al. (2011)



Giant planet metal-enrichment (Fortney et al. 2013)

Flavors of Models

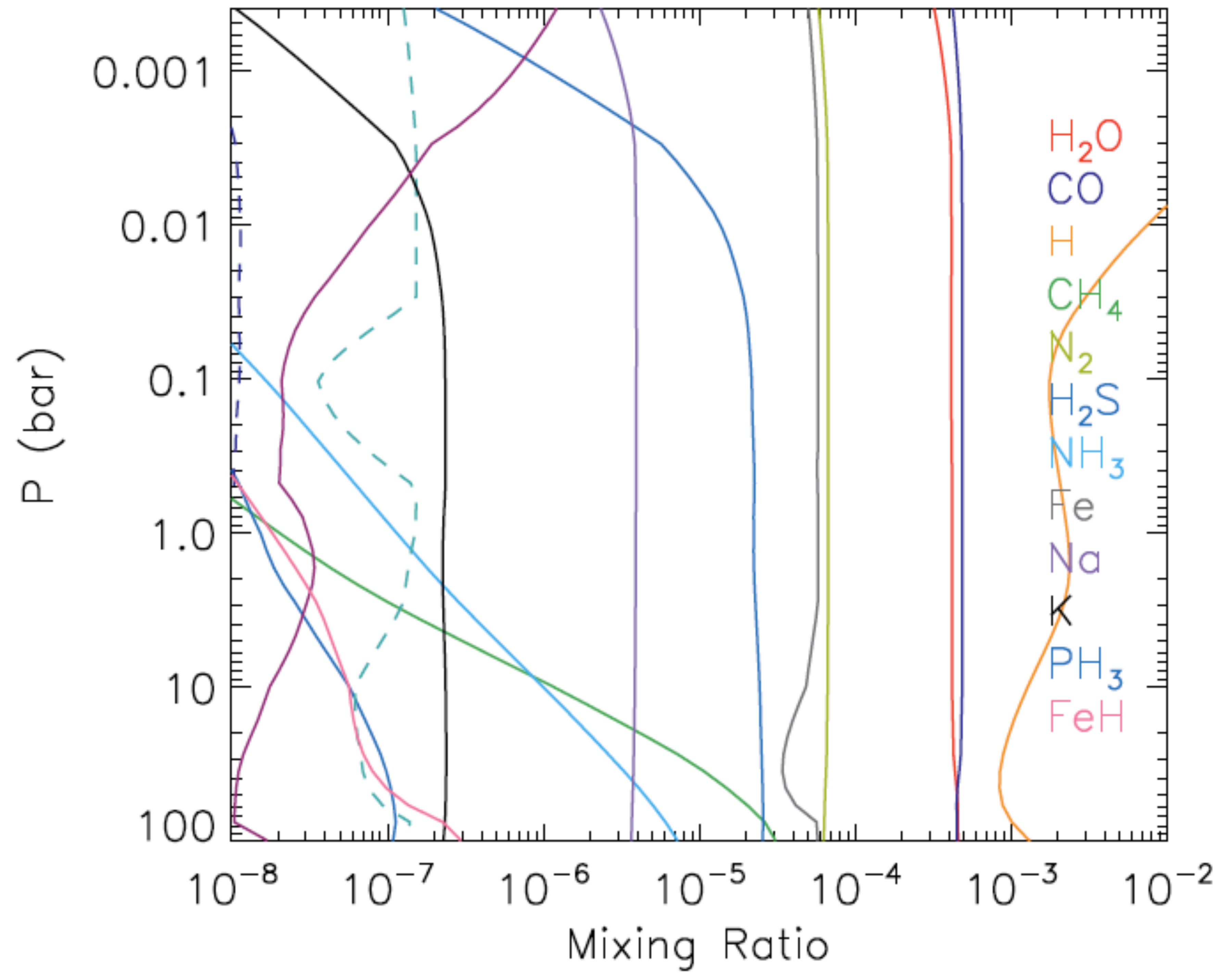
- **1D Radiative/ Convective Equilibrium (RCE)**
- Most akin to classical "stellar atmosphere modeling"
- Specify all the physics and chemistry and iterate to the "solution"
- Compute large grids over T_{eff} (or T_{eq}), gravity, abundances, cloud parameters

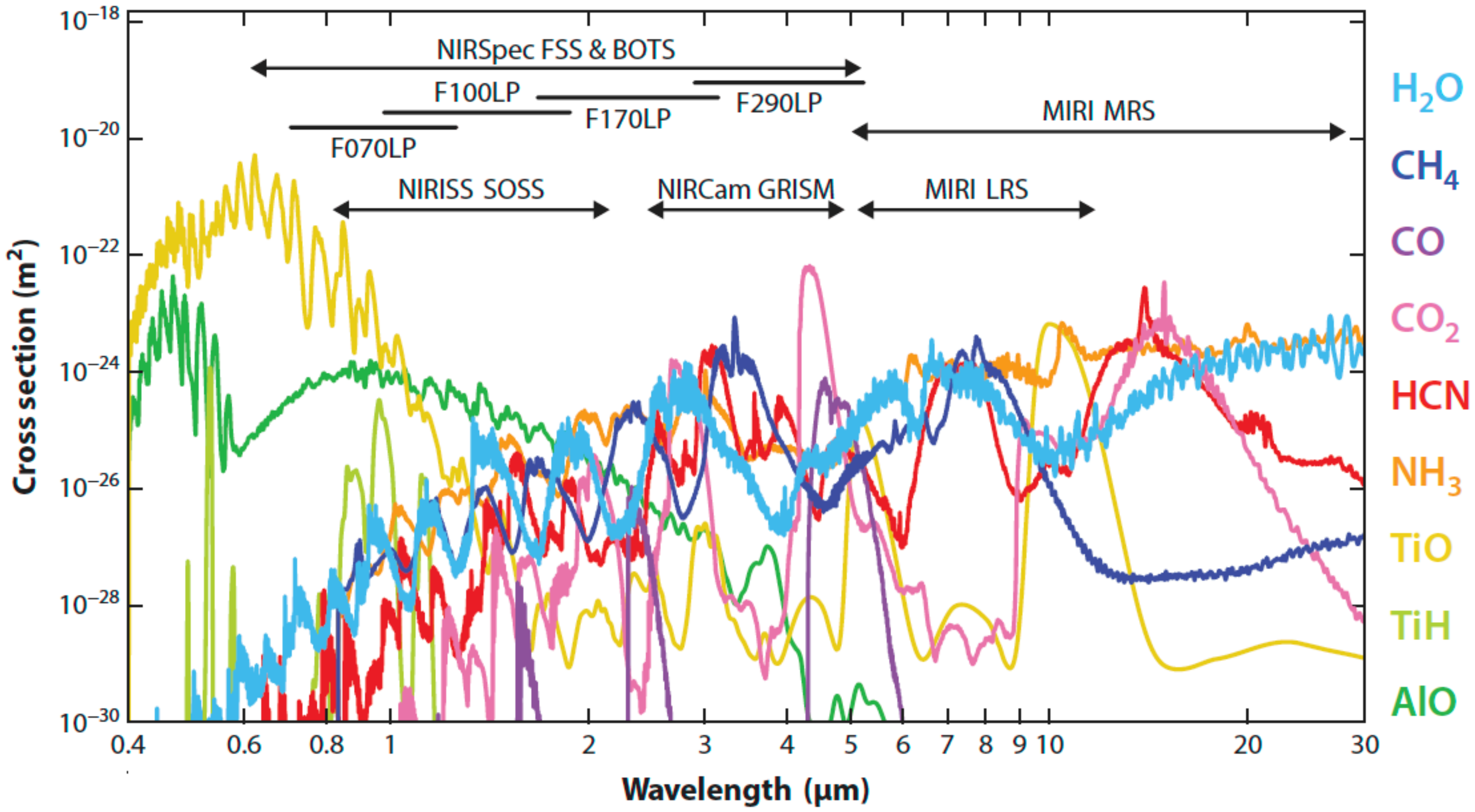
- **1D Inverse Models ("Retrieval")**
- Bayesian data-driven framework to yield constraints on temperature structure + abundances
- "Millions of models"
- Builds on Earth science methods but was rediscovered by astrophysicists (sigh)

- **3D Dynamical Models**
- Radiation + Hydrodynamics
- "GCM": General (or Global) Circulation Model
- Essential, since irradiated and/or cloudy atmospheres are inherently 3D
- Rad-tran and chemistry simplified vs. 1D RCE

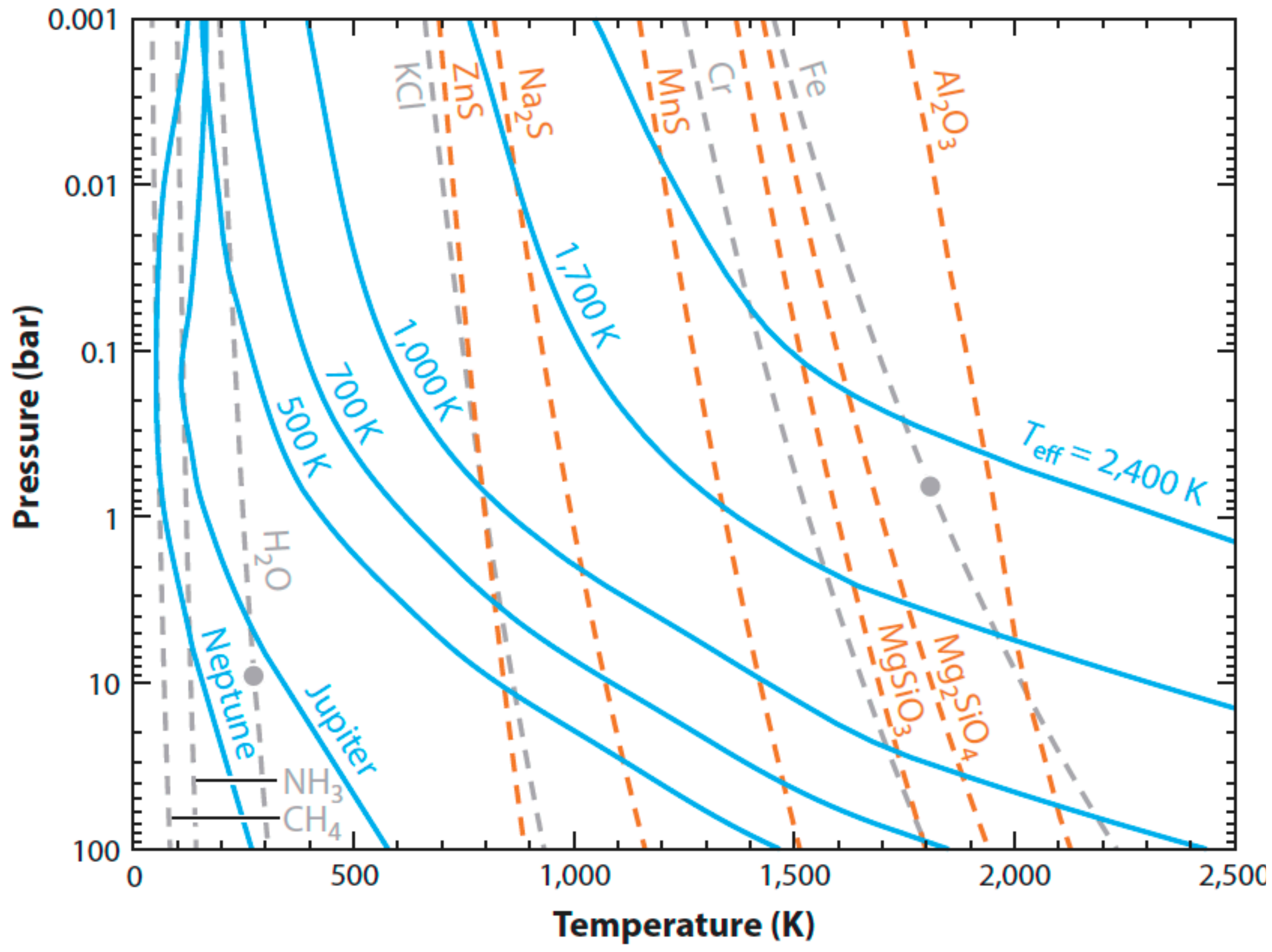
Making a 1D RCE Model

- Abundances
- Chemistry
- Opacities
- Incident stellar energy
- Intrinsic energy
- Radiation/Convection
- Atmospheric pressure-Temperature profile
- Spectrum

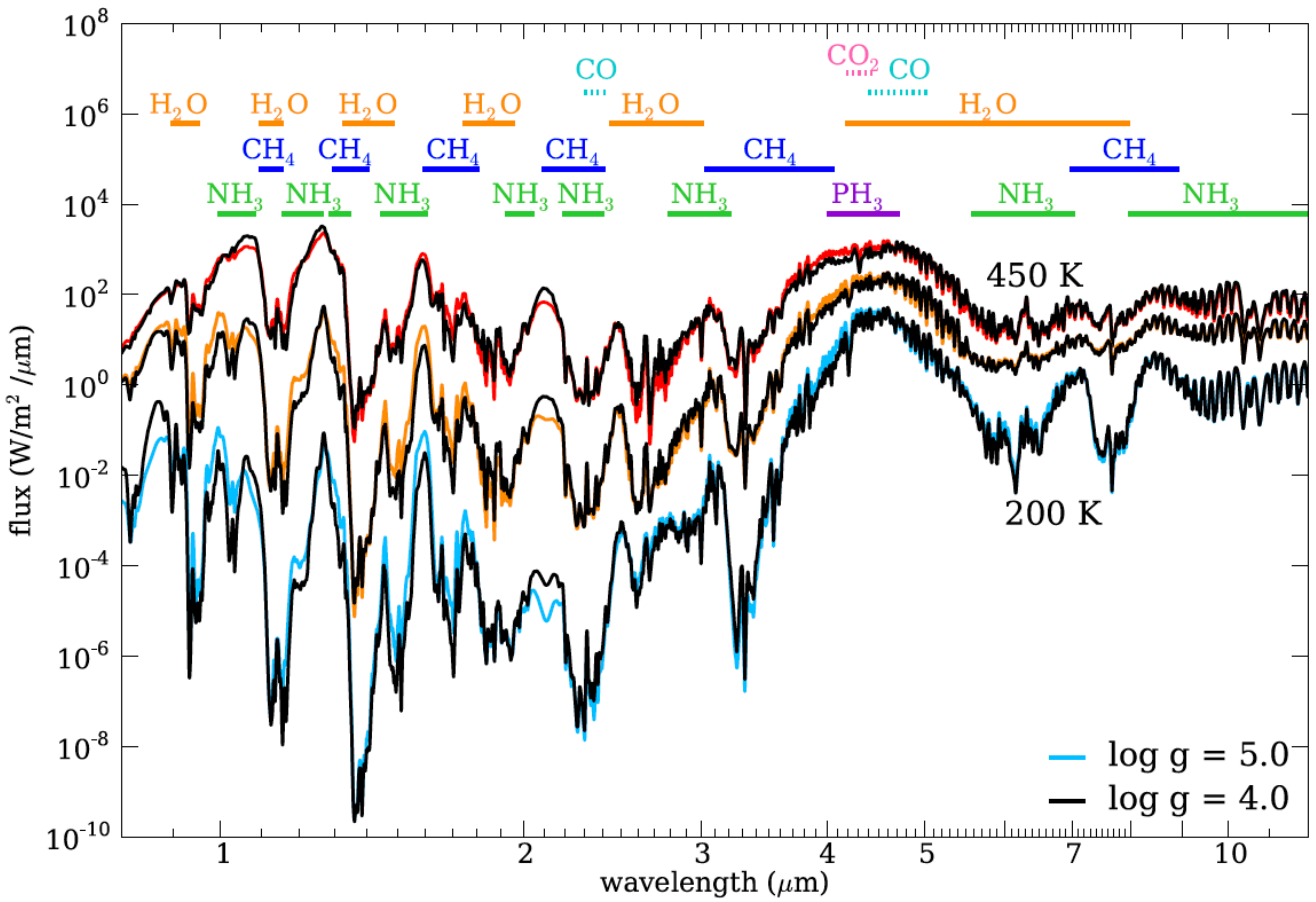




1D RCE Model Allow for Predictions and Explorations of Parameter Space



Pressure-Temperature profiles from Marley & Robinson (2015)



Emission spectra from Morley et al. (2014)

Fitting a Spectrum Via Retrieval

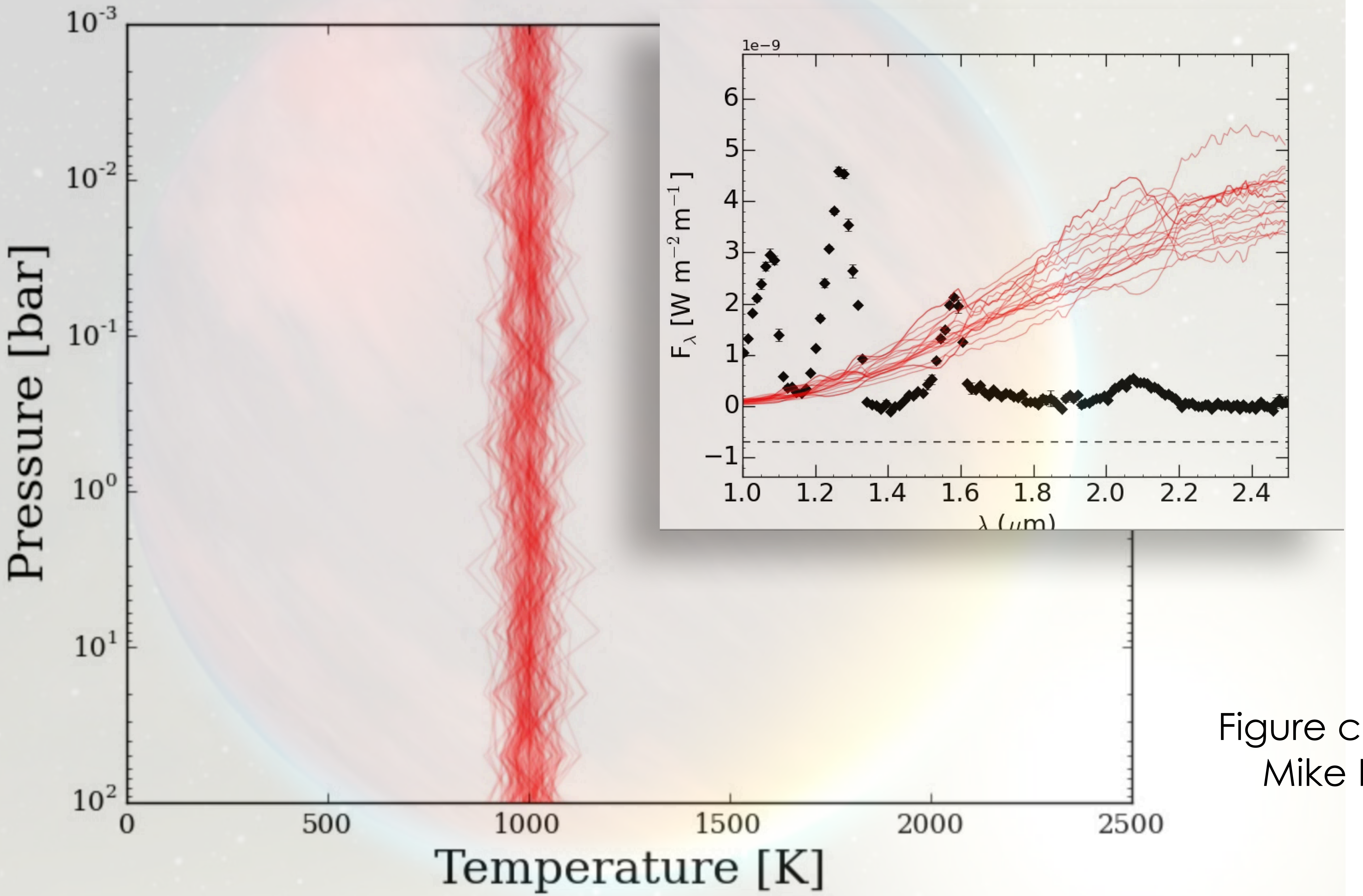
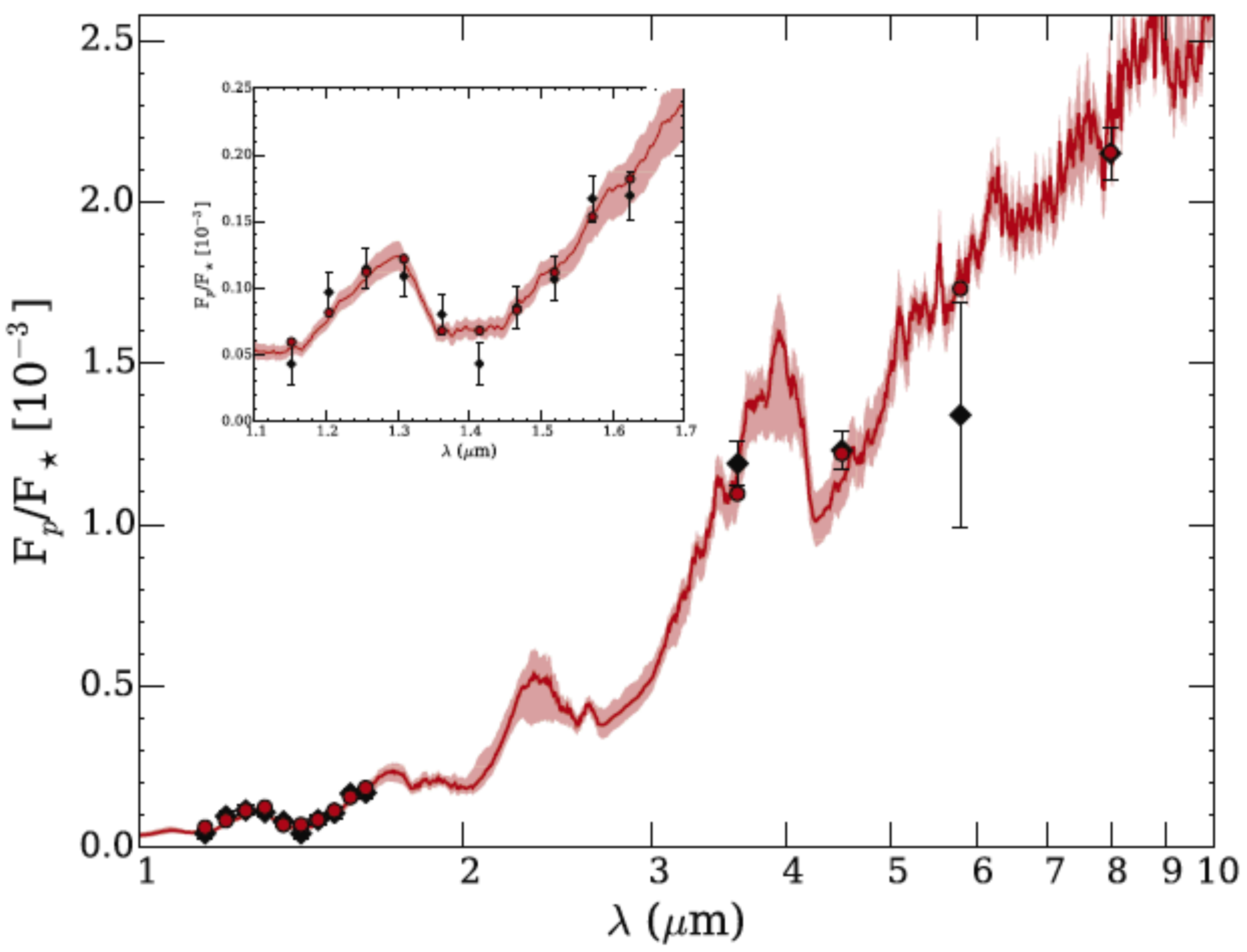
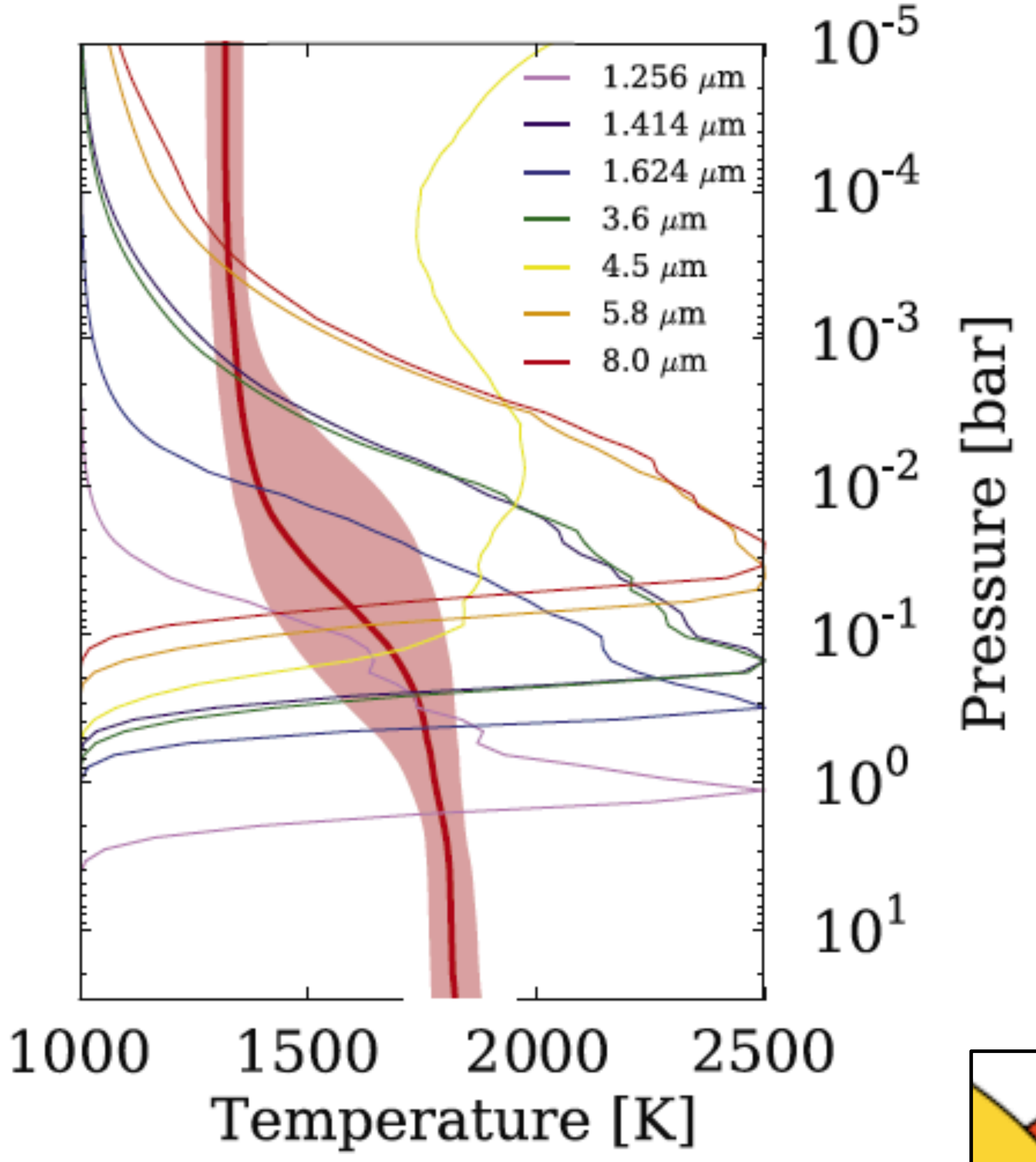


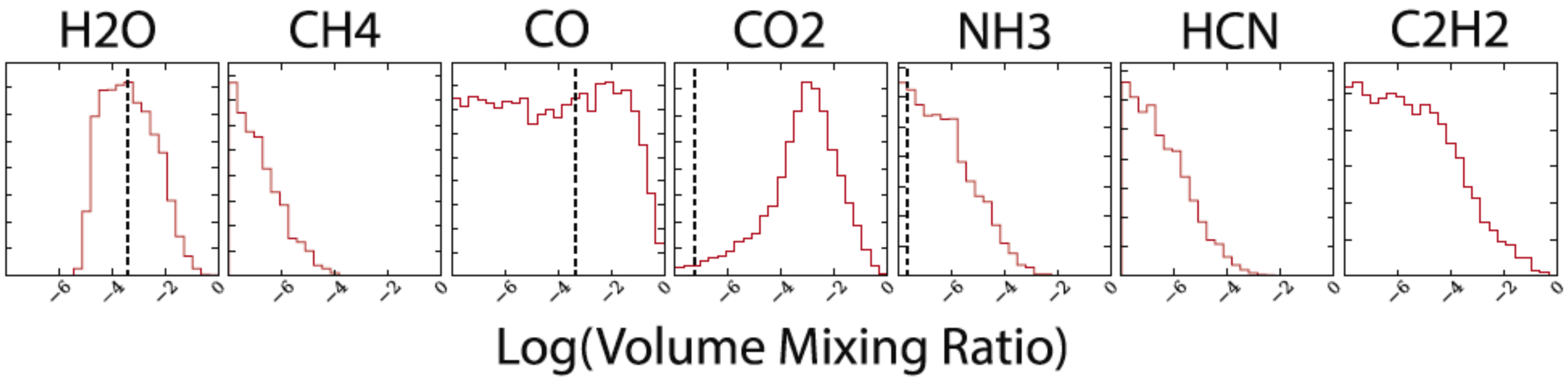
Figure courtesy of
Mike Line (ASU)

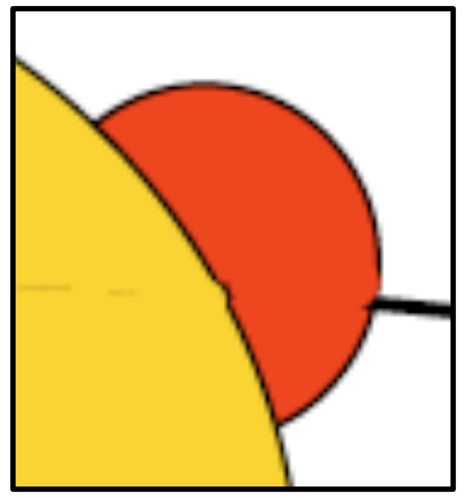
Typical Hot Jupiter Retrieval Outcome





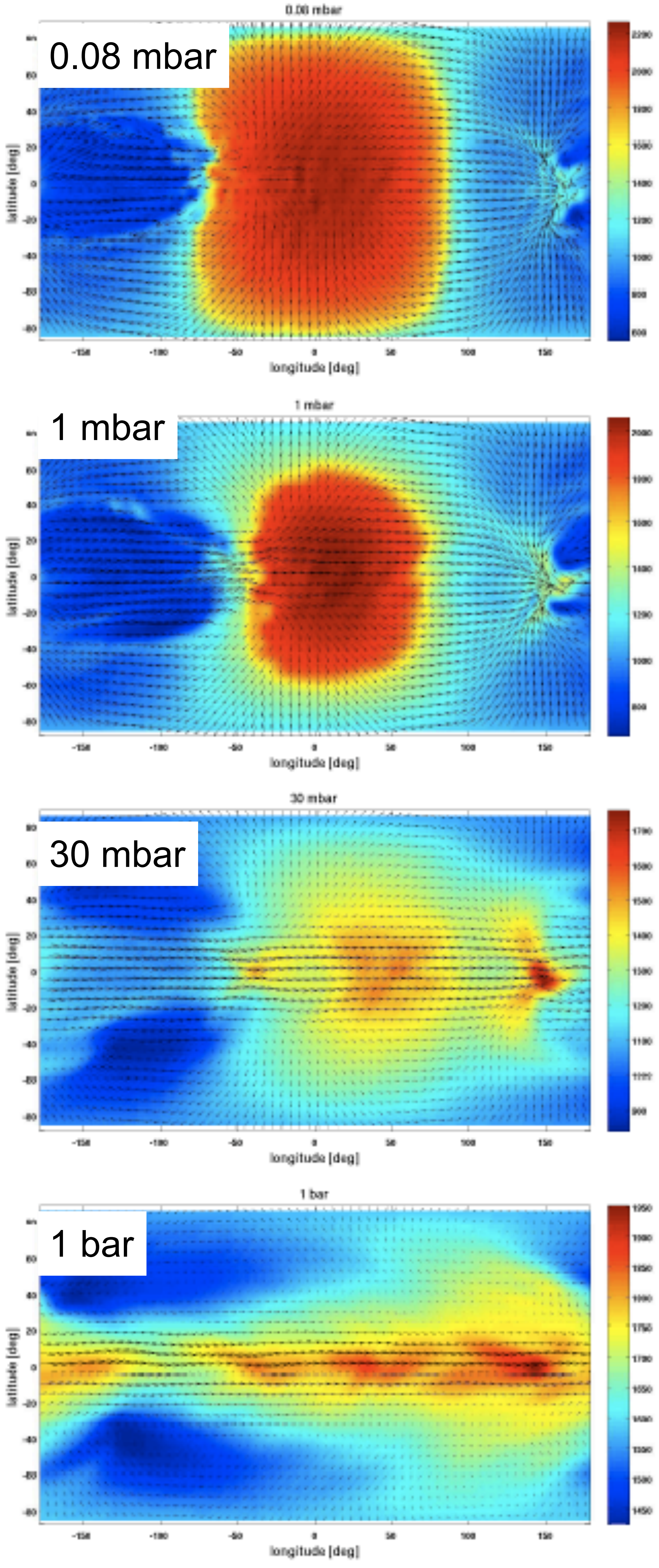
hot Jupiter
HD 209458b
Line et al.
(2016)





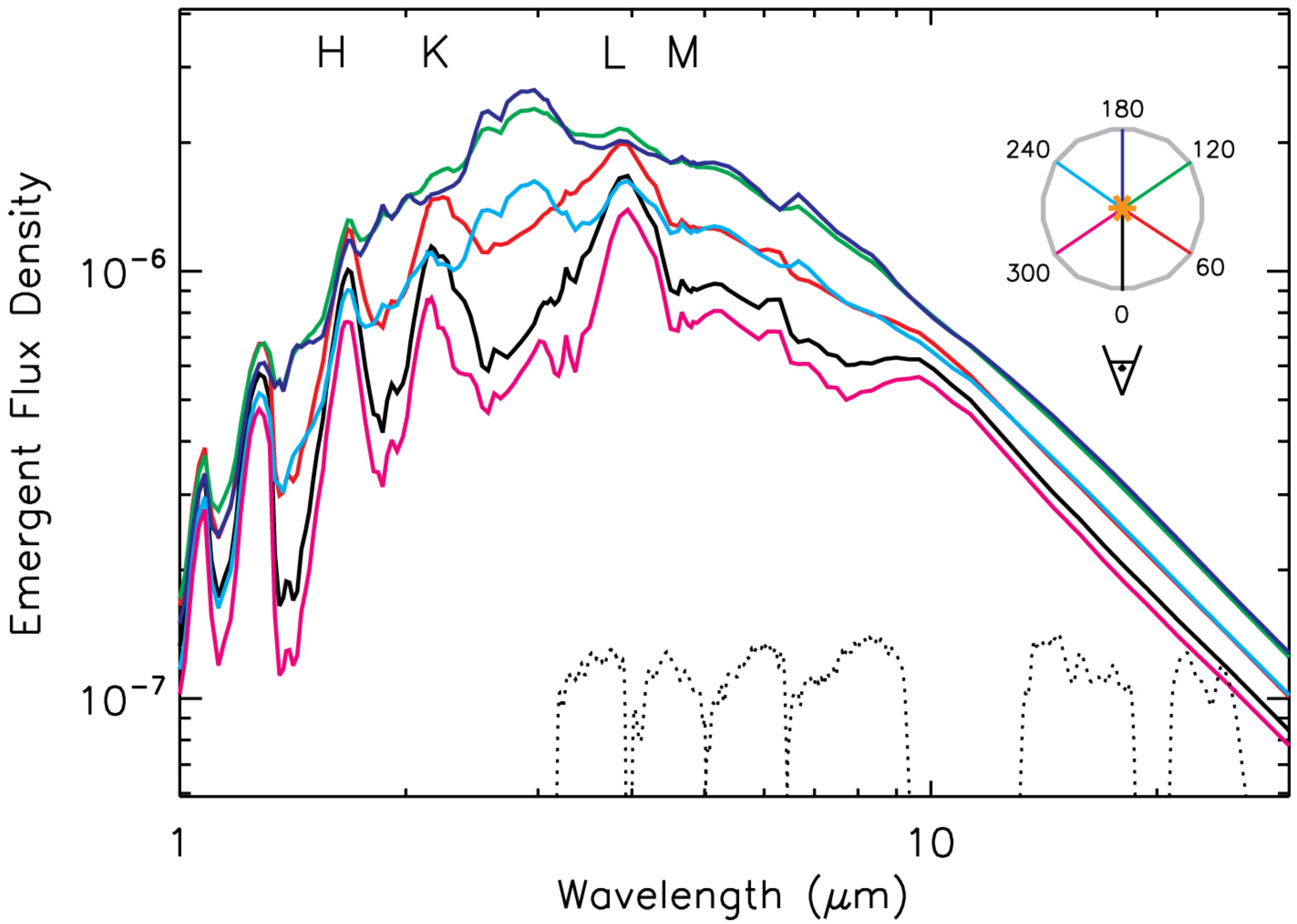
3D GCM Models

- This is a tricky business
- Unlike the solar system, you can't "see" the dynamics
- Dynamics be inferred from time-series photometry or spectroscopy

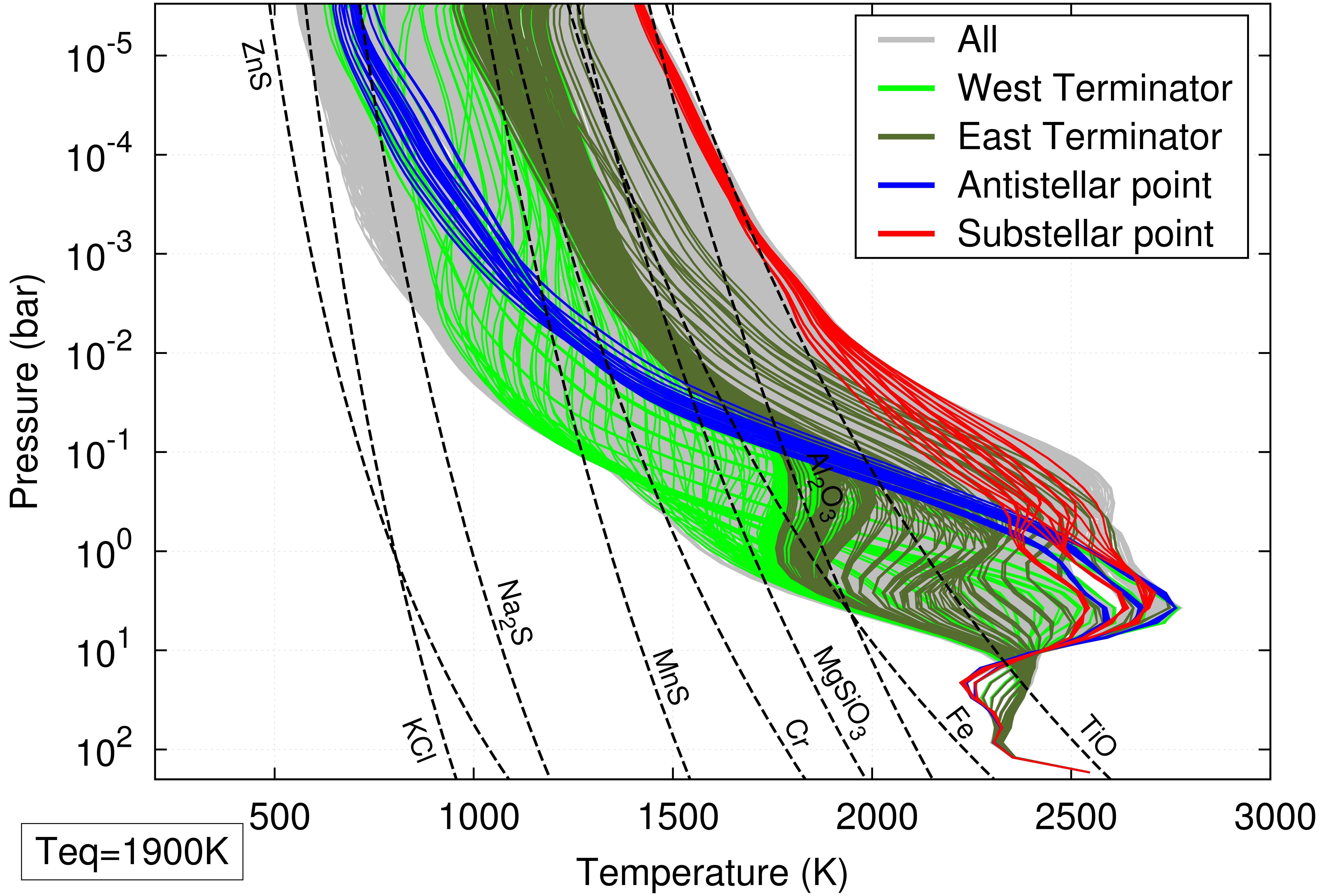


HD 209458b

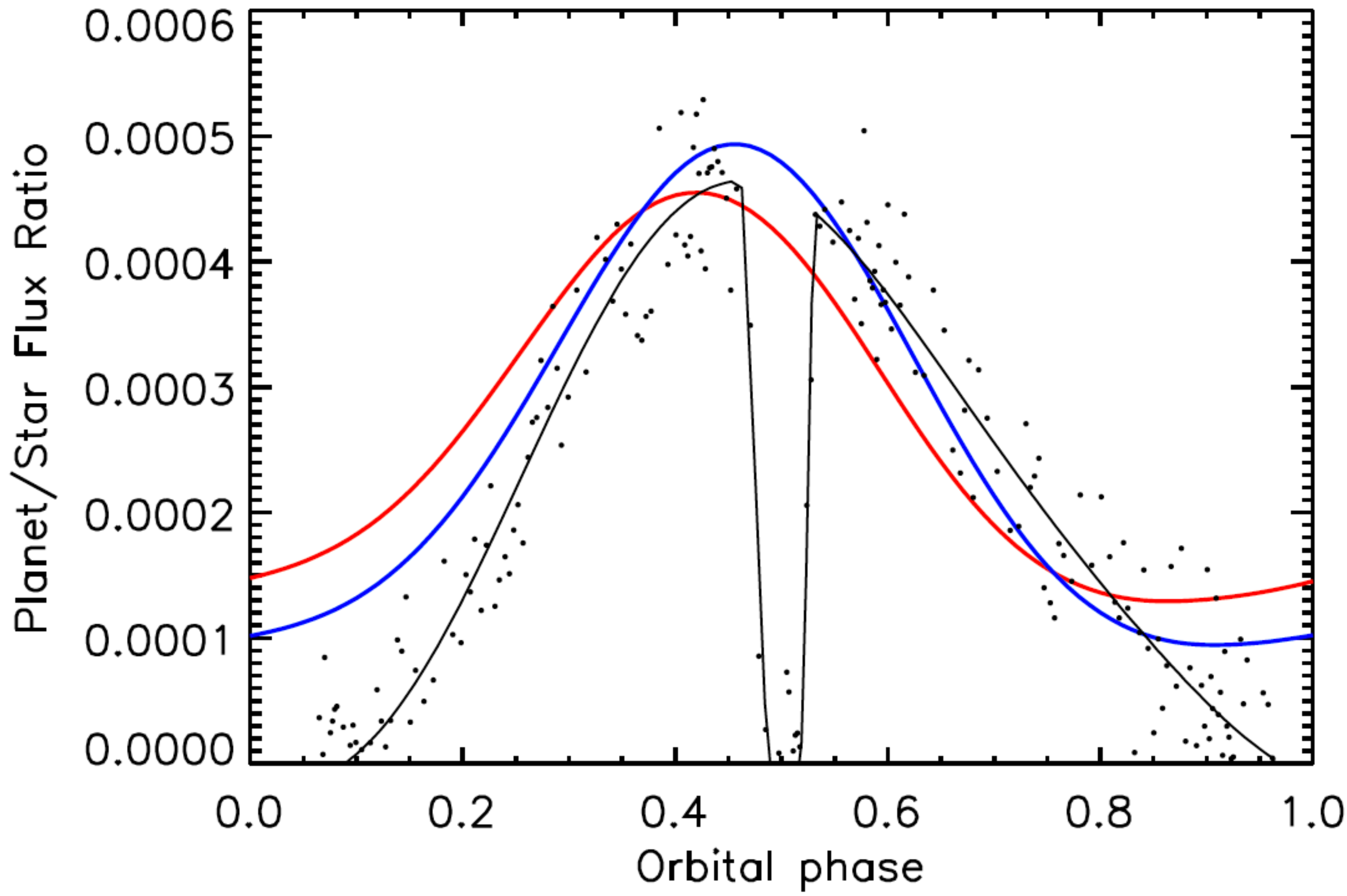
Showman, Fortney, et al. (2009)



Diverse Atmospheres Across Day to Night

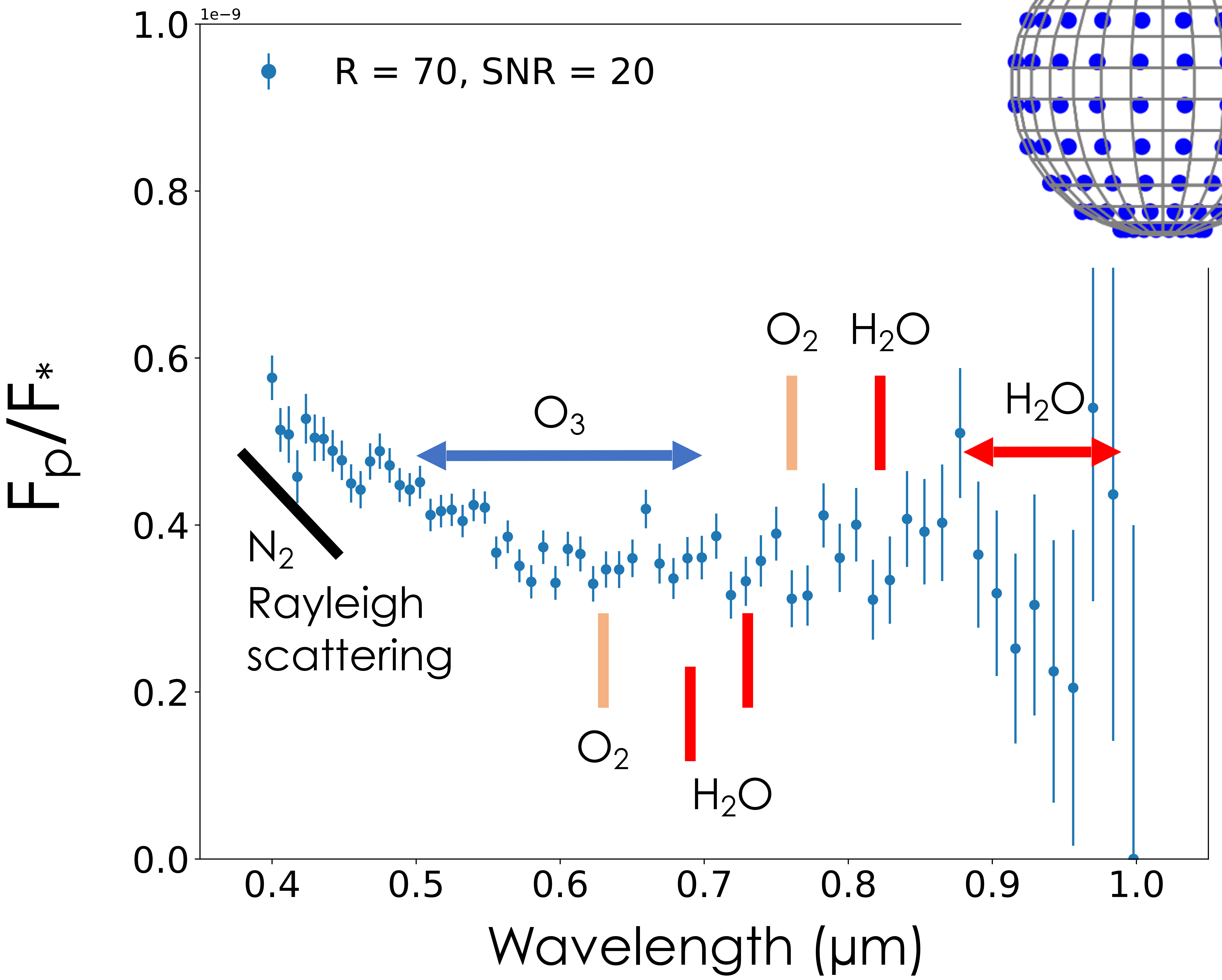


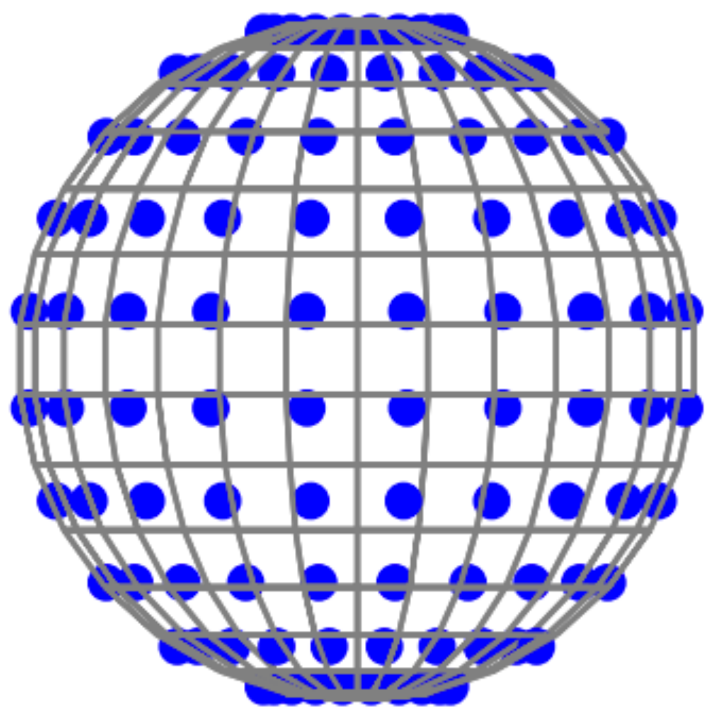
Parmentier et al. (2016)

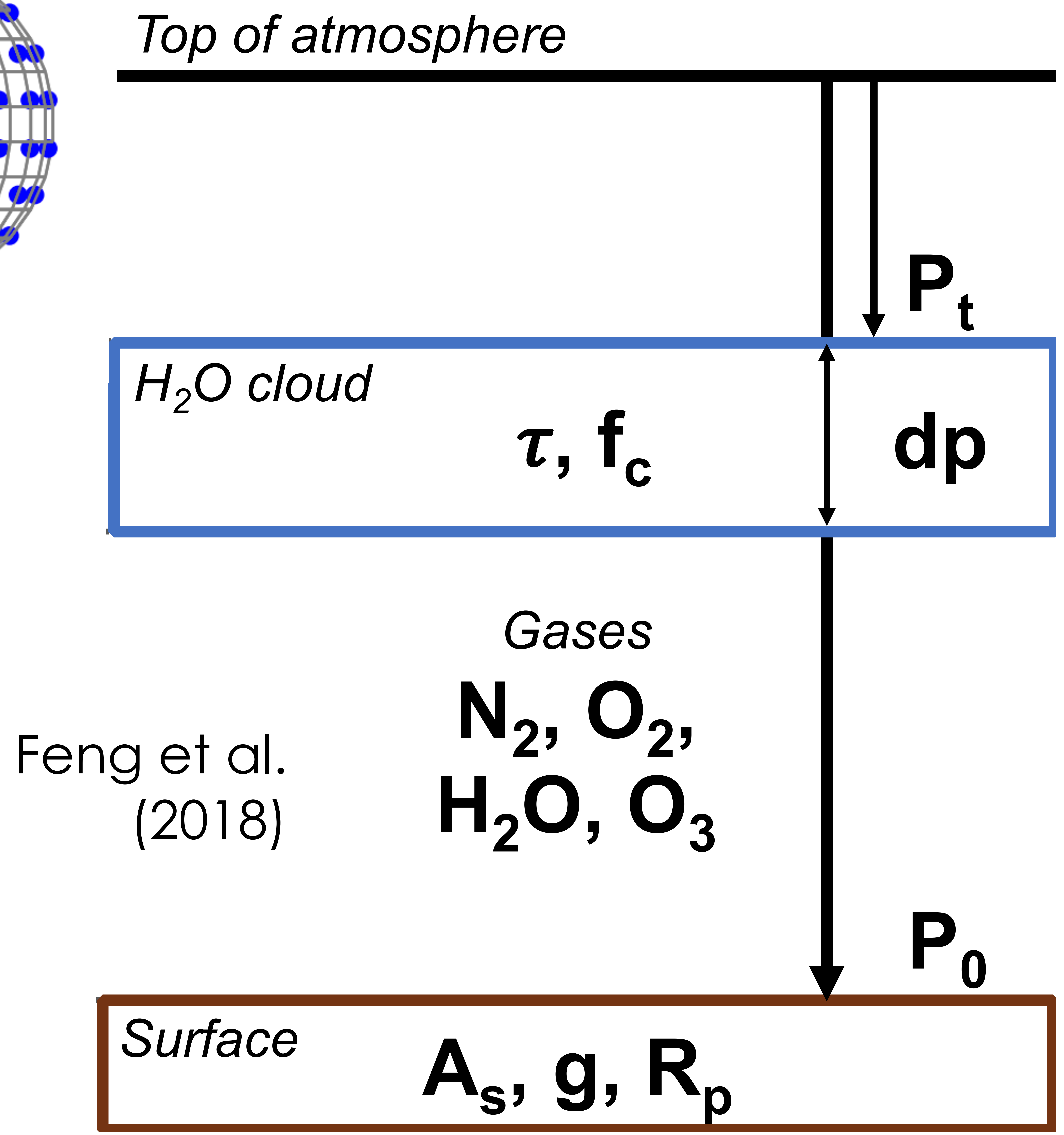


Kataria et al. (2015), WASP-43b

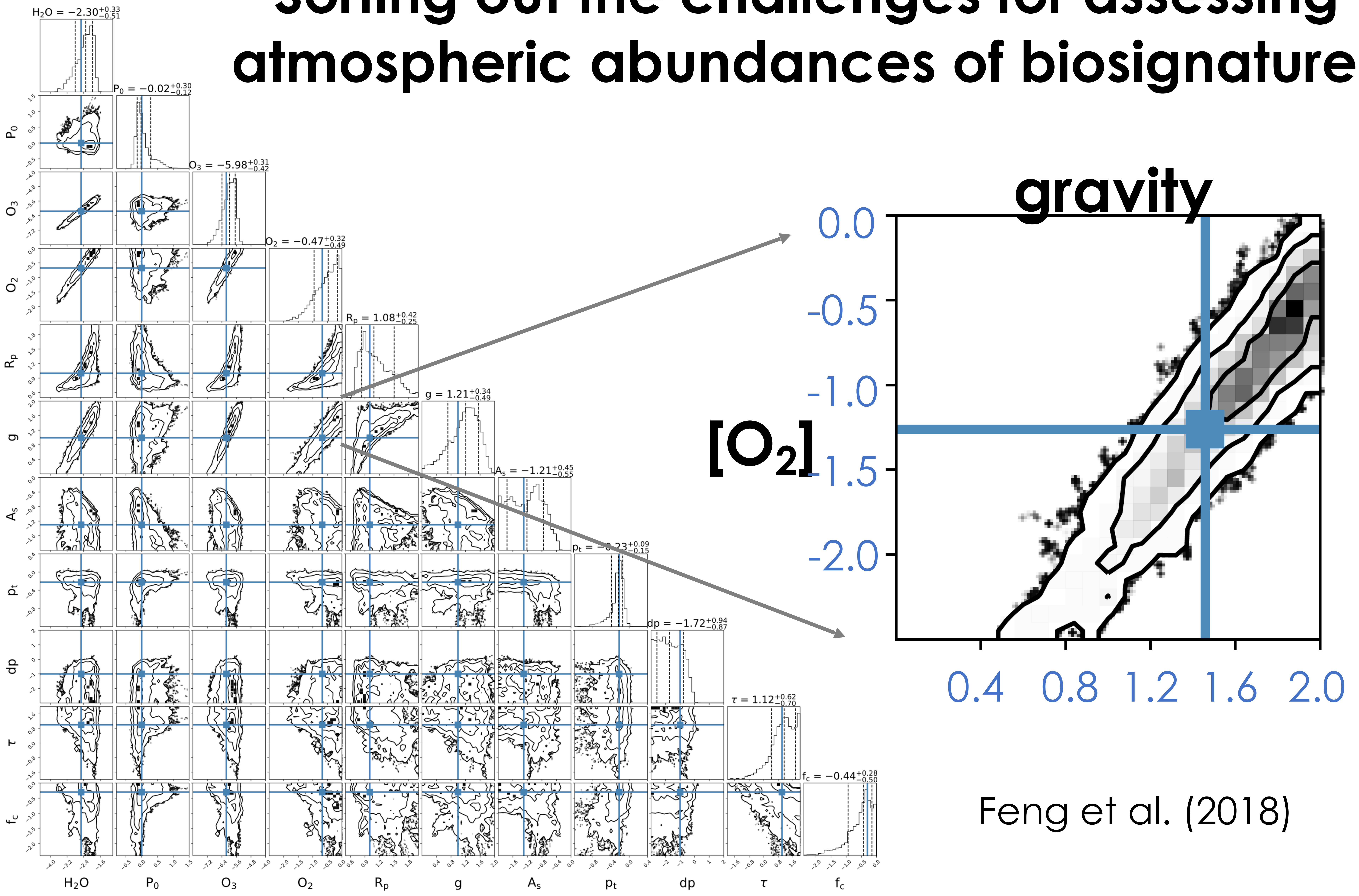
Looking ahead: Reflection spectra of Exo-earths







Sorting out the challenges for assessing atmospheric abundances of biosignatures



Feng et al. (2018)

Current Challenges for Models

- Umm…well…sometimes it isn't clear what observations to trust
- Clouds
  - Condensation, coagulation, sedimentation, transport, vaporization, in 1D or 3D
  - Not a solved problem for the Earth
- Incomplete molecular opacities at high temperatures and high resolution
  - Important role for lab astro
- Phase space for small planets is phenomenally larger in terms of possible chemical abundances

- We've spent considerable time and effort on assessing the known unknowns
- What about the *unknown* unknowns?

We've spent several decades mastering stellar atmospheres. Many more decades will be needed for exoplanet atmospheres