MODELING EXOPLANET ATMOSPHERES

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PLANETARY MODELS AND DATA: A SYMBIOTIC RELATIONSHIP

The importance of collecting and maintaining databases of good water resources data continue to be emphasised whenever hydrologists meet. However, the reality is that the shortcomings of the quality, quantity and coverage of data are discussed only at the time such data is required for an important project and nothing further is done about it. As it is not possible to gather long time series of data within a limited project timetable, consultants such as we have to make use of our verbal and analytical ingenuity to create some useable data out of what is available.

Mathematical models of hydrological systems are used as predictive tools in planning and less often in system operation and flood forecasting. Such models are usually as good as the basic data on which they are based. Good models have undergone a rigorous procedure of calibration and verification. It is usual that the initial process of setting up and calibration of a model requires the collection of data from a network large number of stations, usually installed specially for this purpose, a network more detailed than one would have for routine operation. If such a model is then verified using a new set of data then it is safe to use it for various planning and operational purposes.

"Data and models: a symbiotic relationship." R. Galappatti and A. J. Ranwala, Conference Papers from International Water Management Institute

OUTLINE

- Basic inputs for atmospheric models
- Modeling circulation
- Modeling composition
- Modeling clouds
- Looking forward

What types of models do we use? What do observations tell us?

Atmospheric Circulation: Important Scales

Temporal

$$\tau_{advect} \sim \frac{a}{U}$$

$$\tau_{rad} \sim \frac{\Delta p}{g} \frac{c_p}{4\sigma T^3}$$

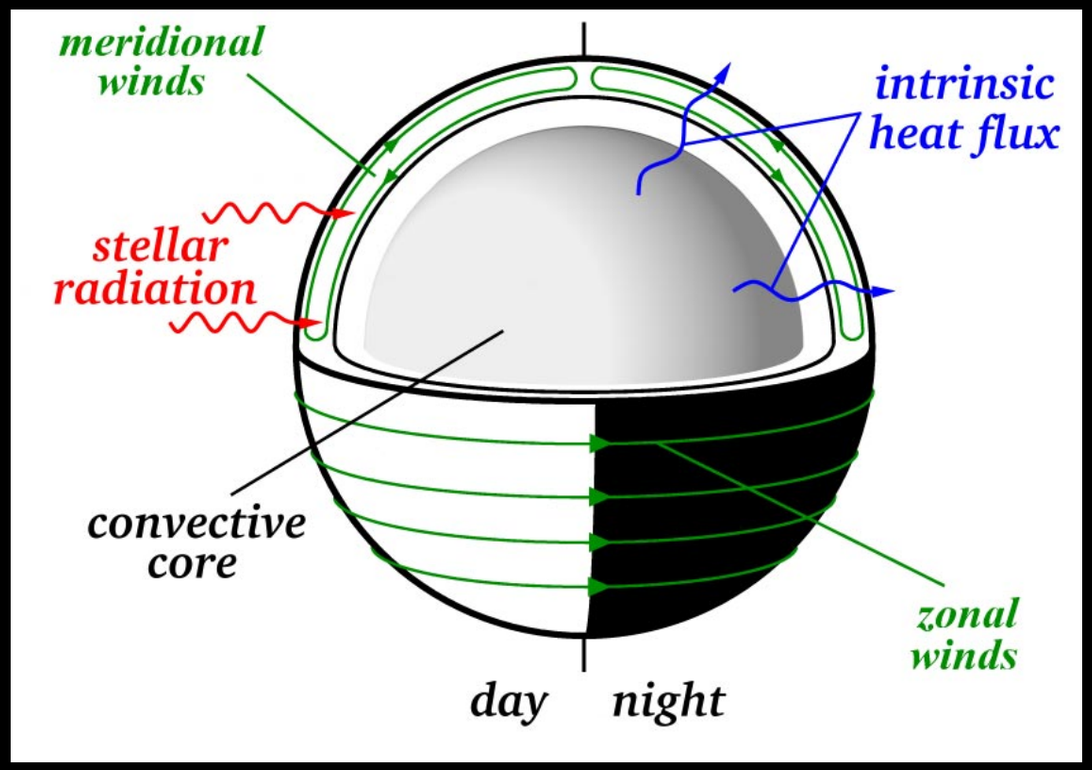
Spatial

$$Ro \equiv \frac{U}{fL}$$

$$L_D = \frac{NH}{f}$$

$$L_\beta = \pi \left(\frac{U}{\beta}\right)^{1/2}$$

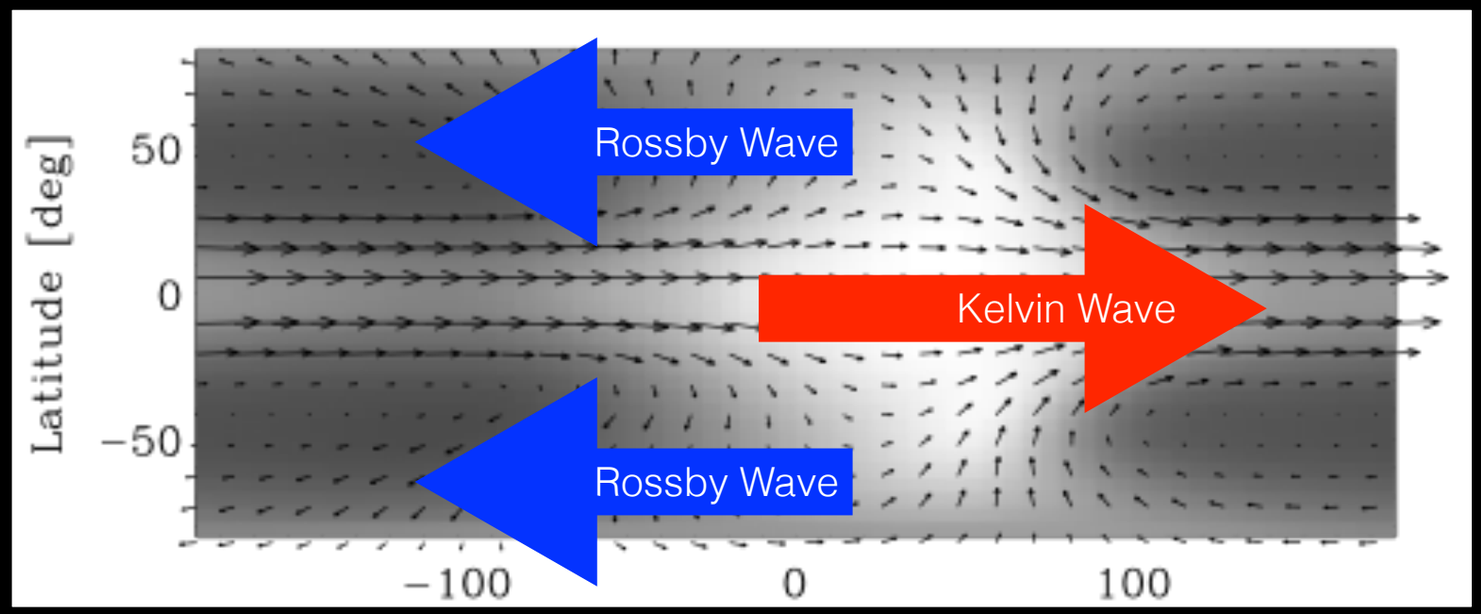
MODELING CIRCULATION: THEORETICAL PREDICTIONS



$$\tau_{advect} \sim \frac{a}{U}$$

$$\tau_{rad} \sim \frac{\Delta p}{g} \frac{c_p}{4\sigma T^3}$$

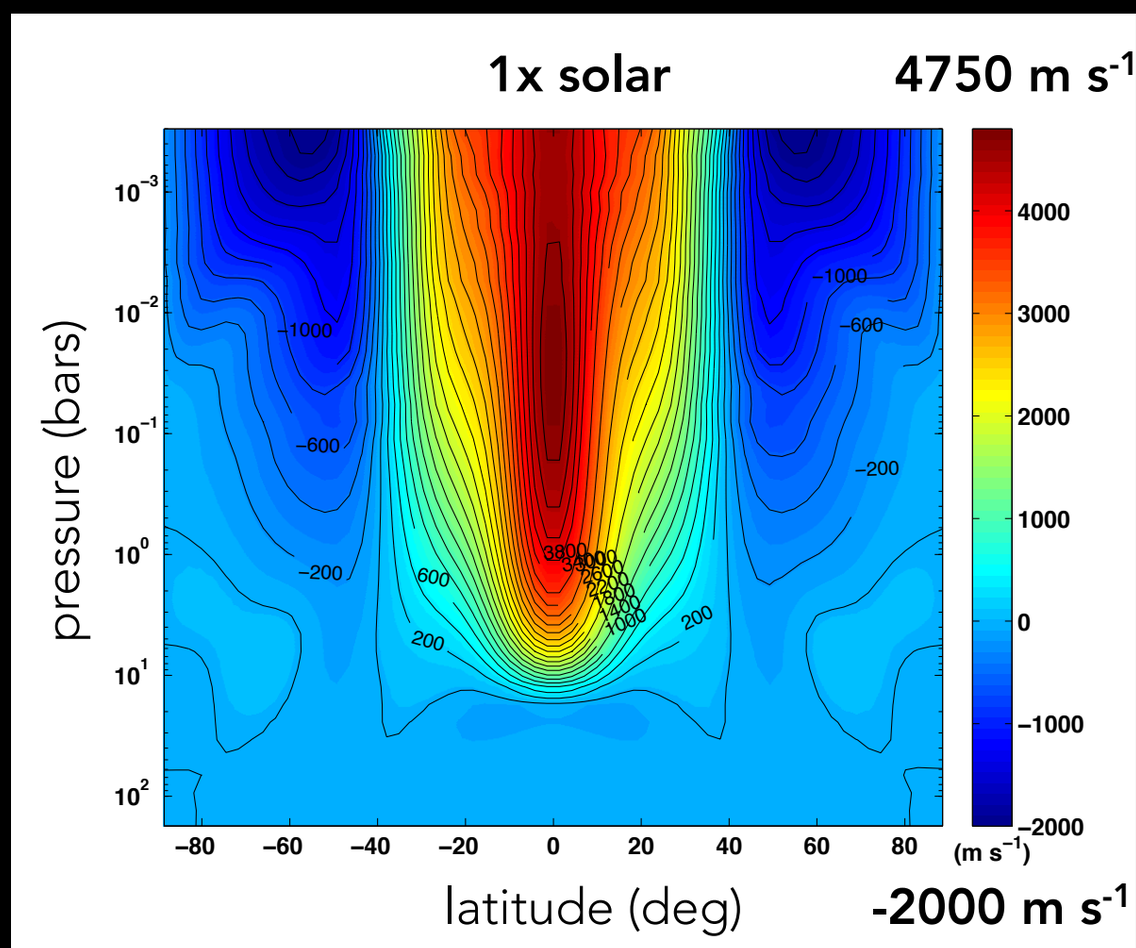
$$N_{jet} = \left(\frac{2\Omega a}{U}\right)^{1/2}$$

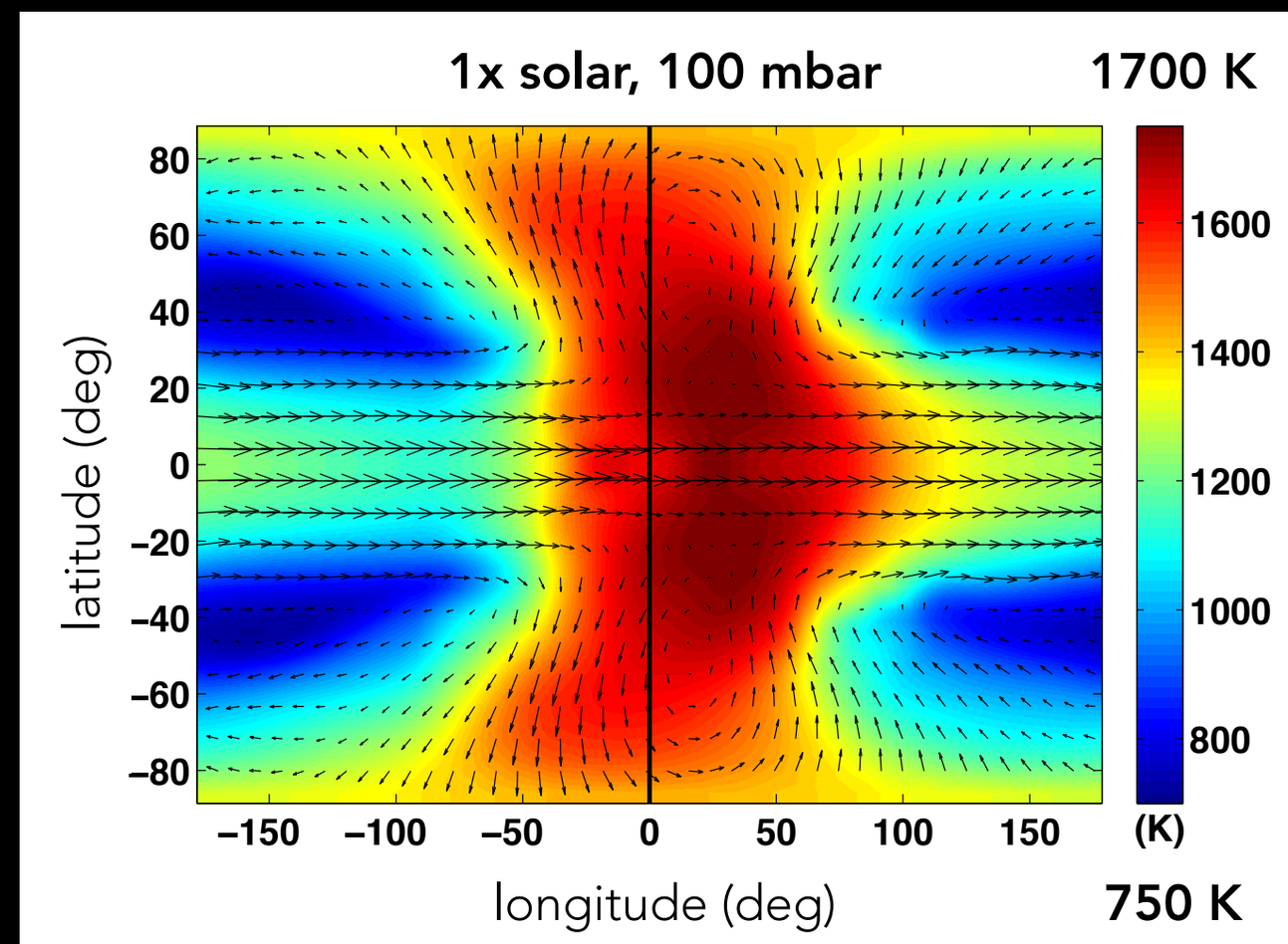


Showman & Guillot (2002)

HOT JUPITER CIRCULATION REGIME: THE CASE OF WASP 43

- Equatorial eastward superrotation
- Hotspot shifted eastward from substellar point
- Large temperature contrast from dayside to nightside (in this case ~600 K) - recirculation efficiency of ~0.6



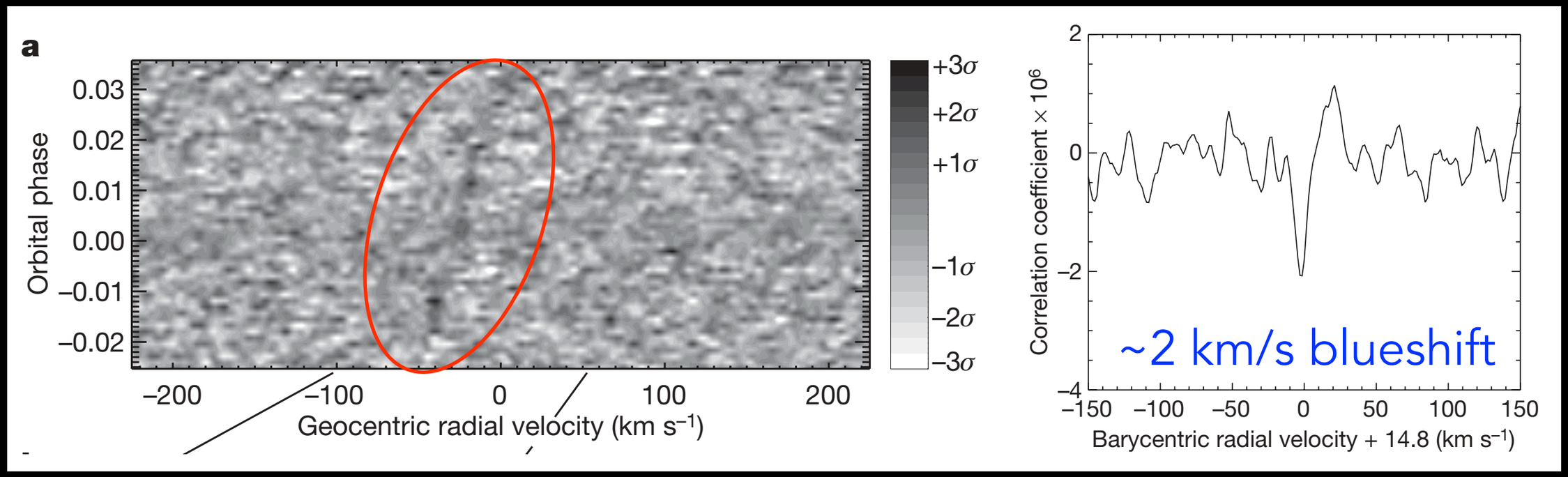


Kataria et al. 2015, ApJ, 801, 86

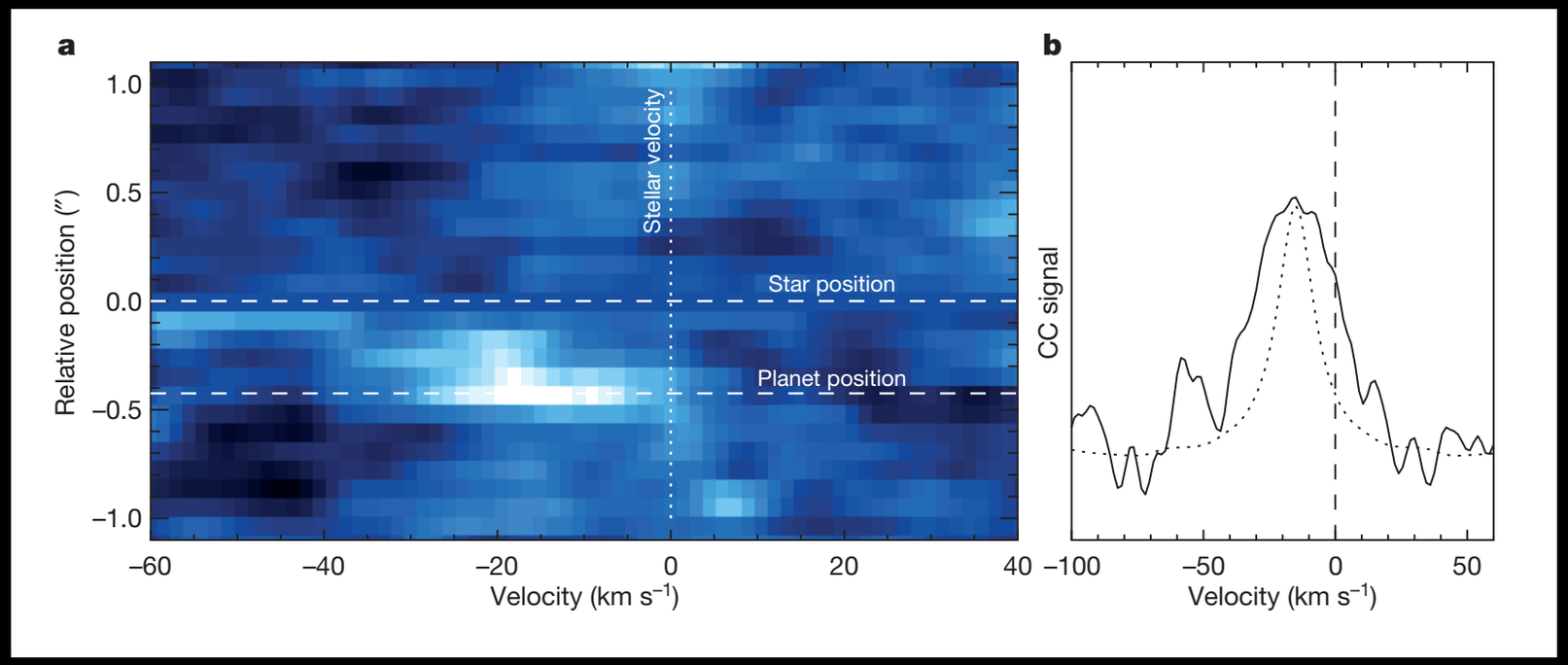
HOW CAN OBSERVATIONS CONSTRAIN THE DYNAMICS?

MEASURING WINDS AND ROTATION IN HOT JUPITERS

HD 209458b



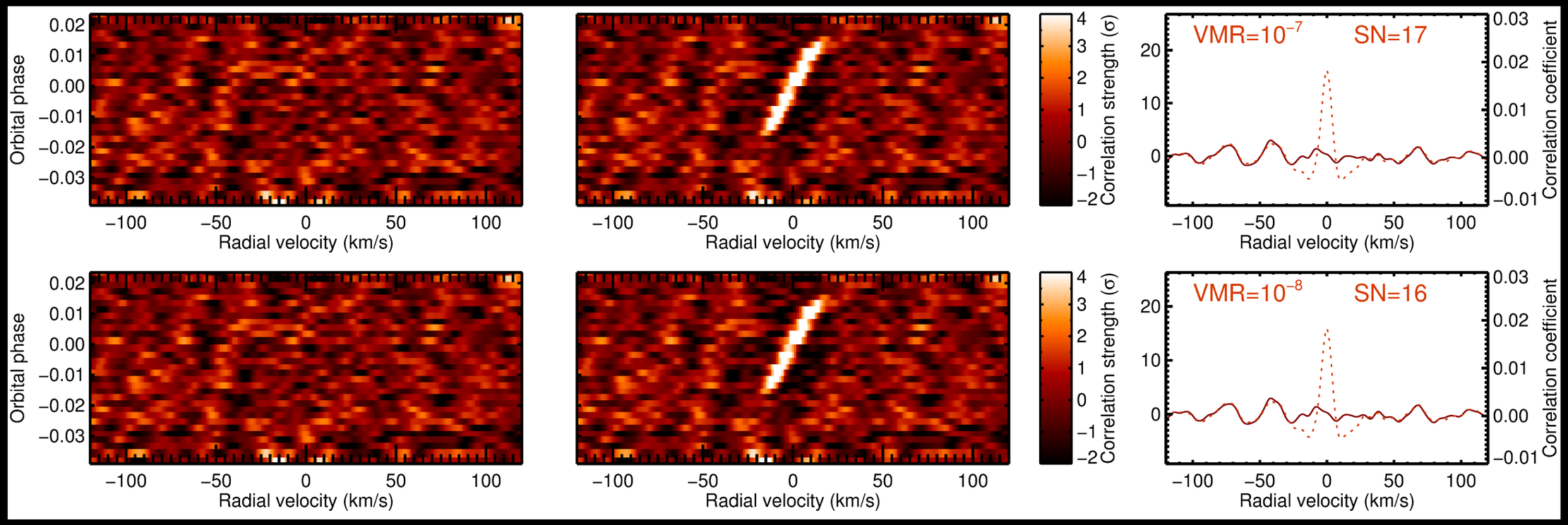
Beta Pictoris b



Snellen et al. 2010,2014

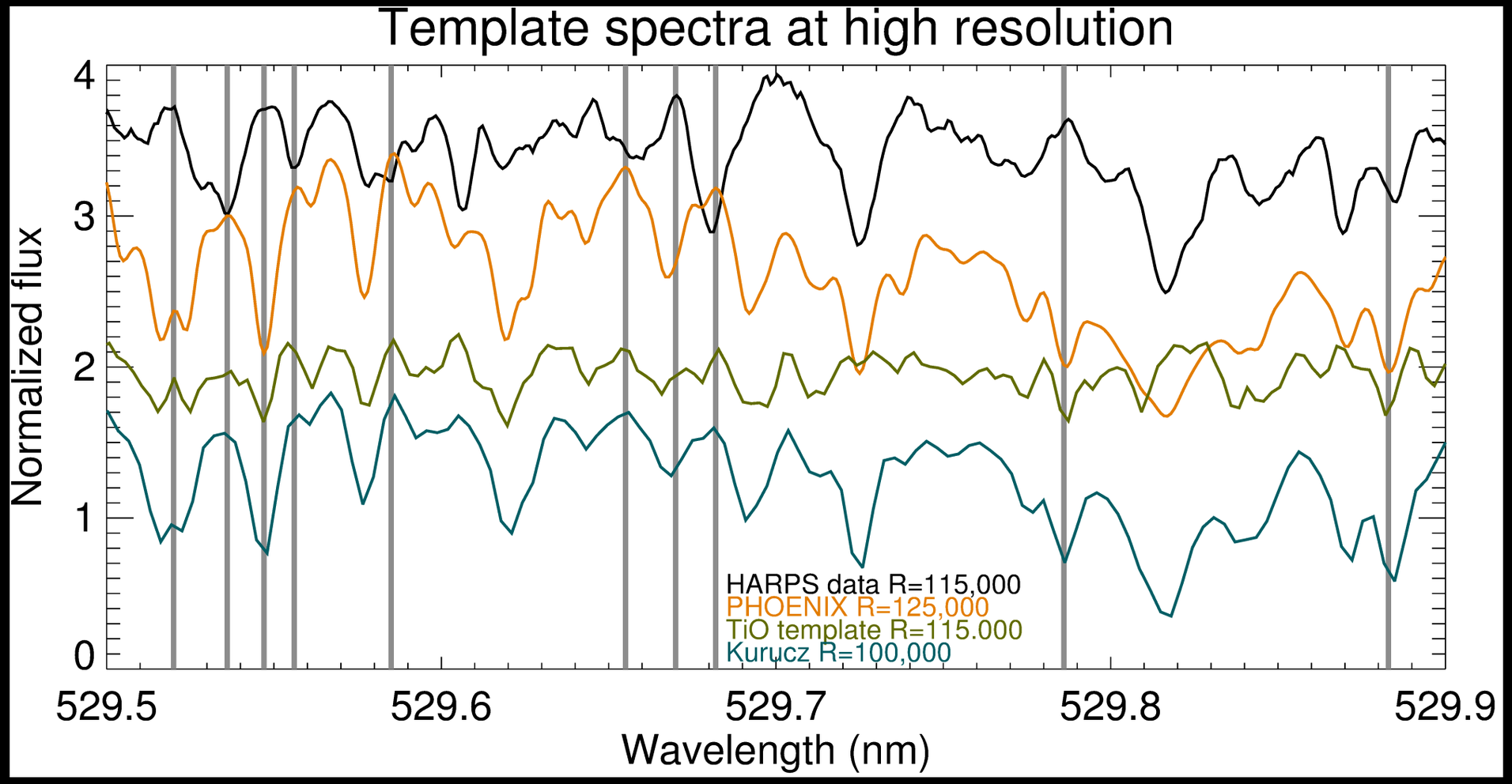
CAVEAT: YOU ARE ONLY AS GOOD AS YOUR LINE LISTS

Searching for TiO in HD 209458b



Hoeijmakers et al. 2015

CAVEAT: YOU'RE ONLY AS GOOD AS YOUR LINE LISTS



Need more accurate line lists!

Hoeijmakers et al. 2015

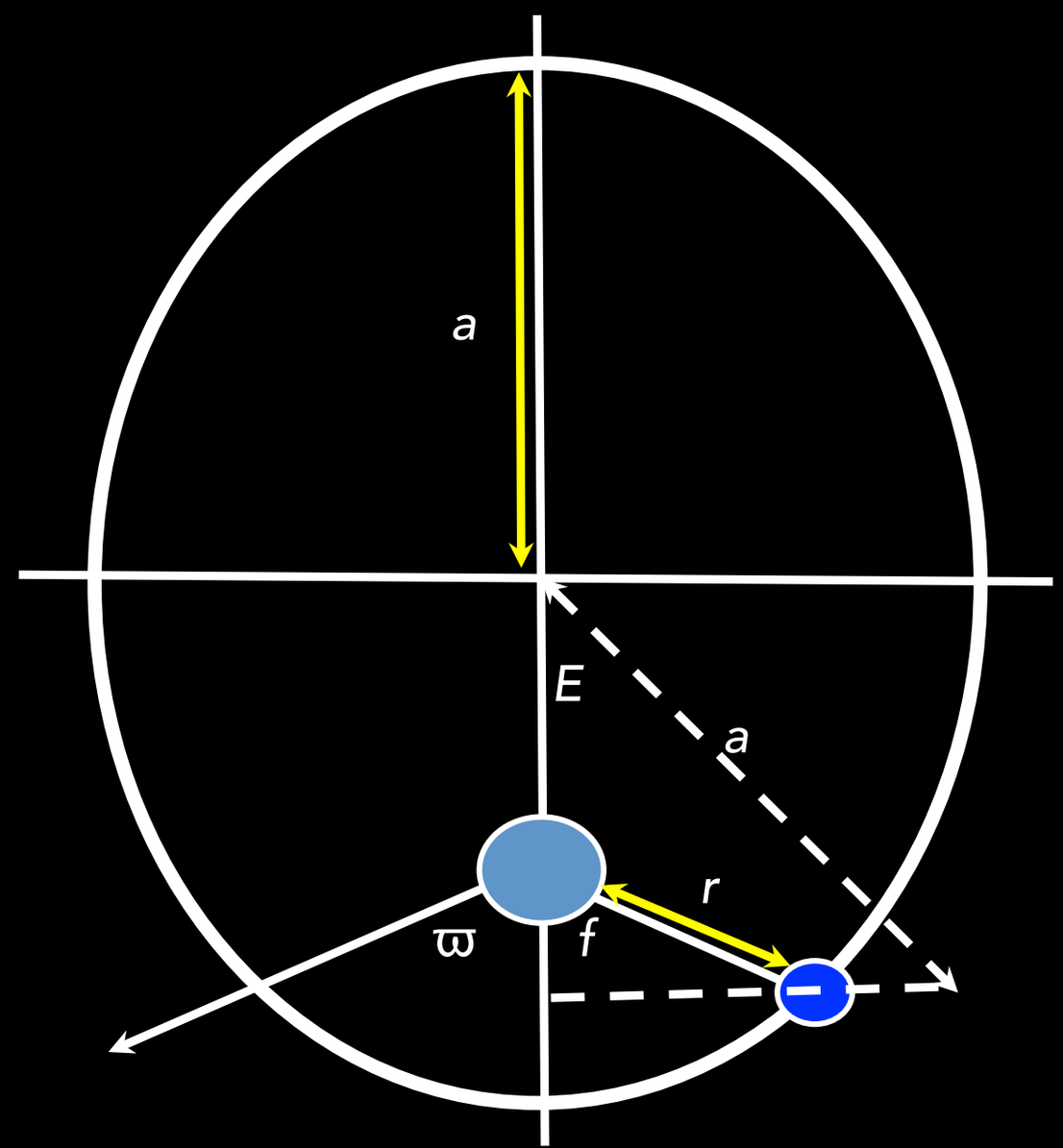
MODELING ECCENTRIC EXOPLANETS

- Distance varies with time

$$r(t) = a(1 - 2\cos E(t))$$

$$M(t) = E(t) - e\sin E(t)$$

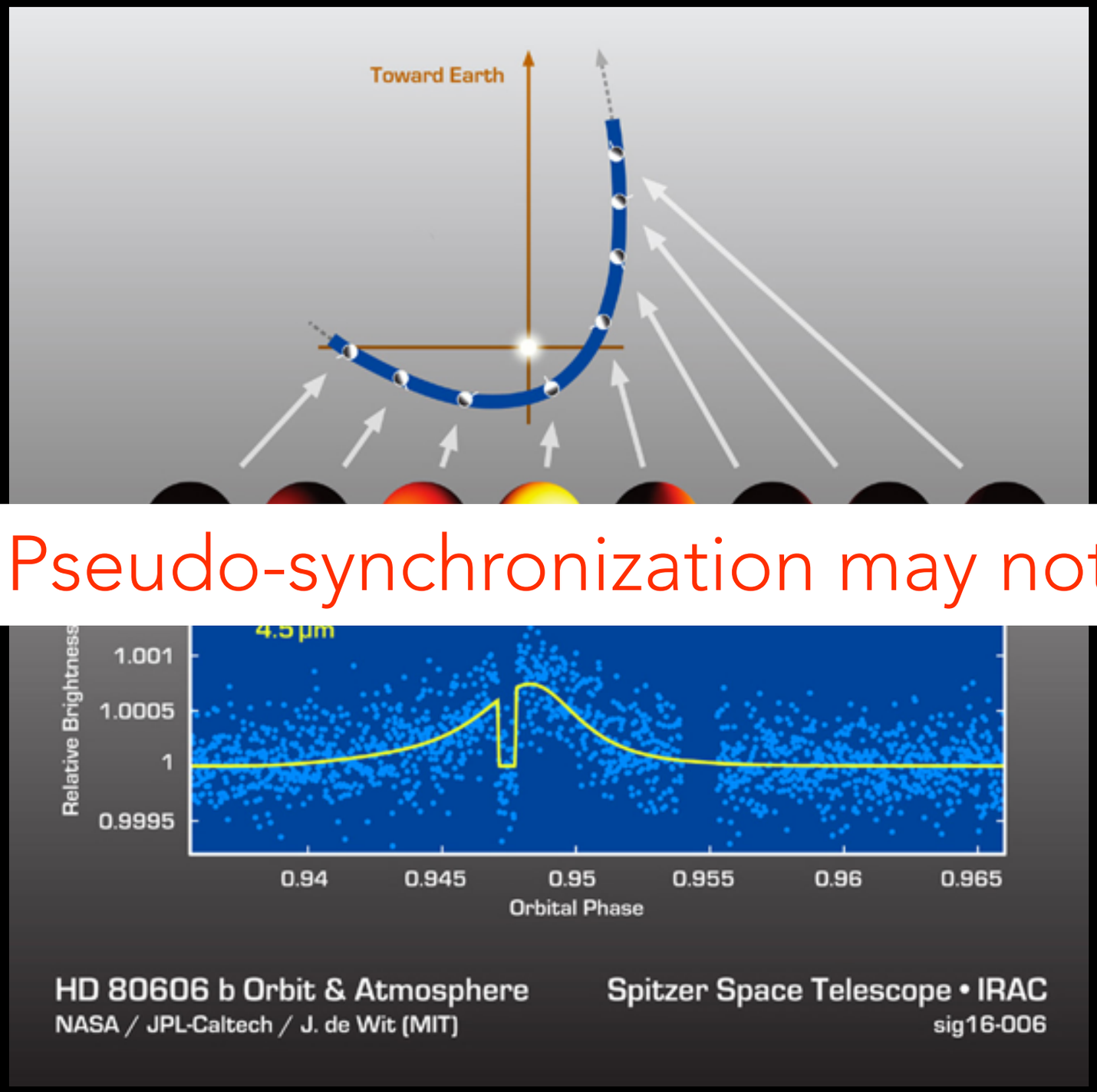
$$M(t) = n(t - \tau)$$



- Planetary rotation is likely non-synchronous
  - Use Hut (1981) formulation

$$P_{rot} = P_{orb}\frac{(1 + 3e^2 + \frac{3}{8}e^4)(1 - e^2)^{3/2}}{1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6}$$

CONSTRAINTS ON RADIATIVE/ DYNAMICAL TIMESCALES



Observations:

$$\tau_{rad} = \sim 4.04 \text{ hr at } 4.5\ \mu\text{m}$$
$$\sim 1.28 \text{ hr at } 8.0\ \mu\text{m}$$

$$T_{rot} = \sim 93 \text{ hr}$$

Pseudo-synchronization may not be a good assumption!

GCM predictions:

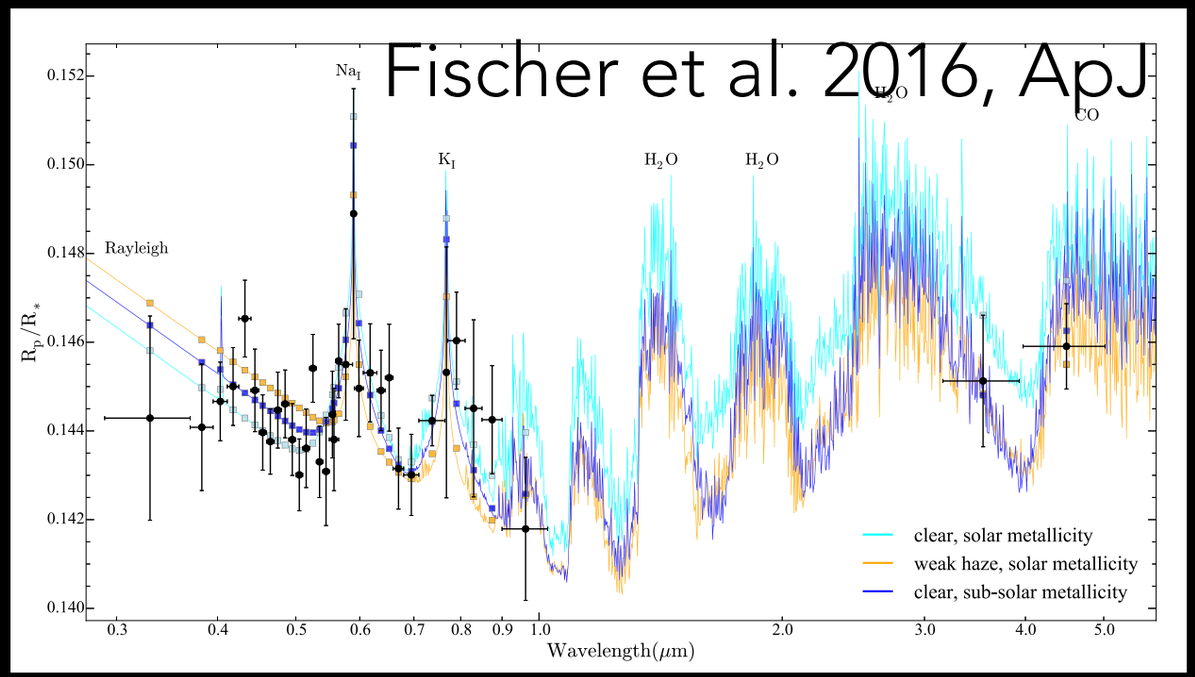
$$\tau_{rad} = \sim 5 \text{ hr}$$

$$T_{rot} = \sim 40 \text{ hr}$$

MODELING COMPOSITION

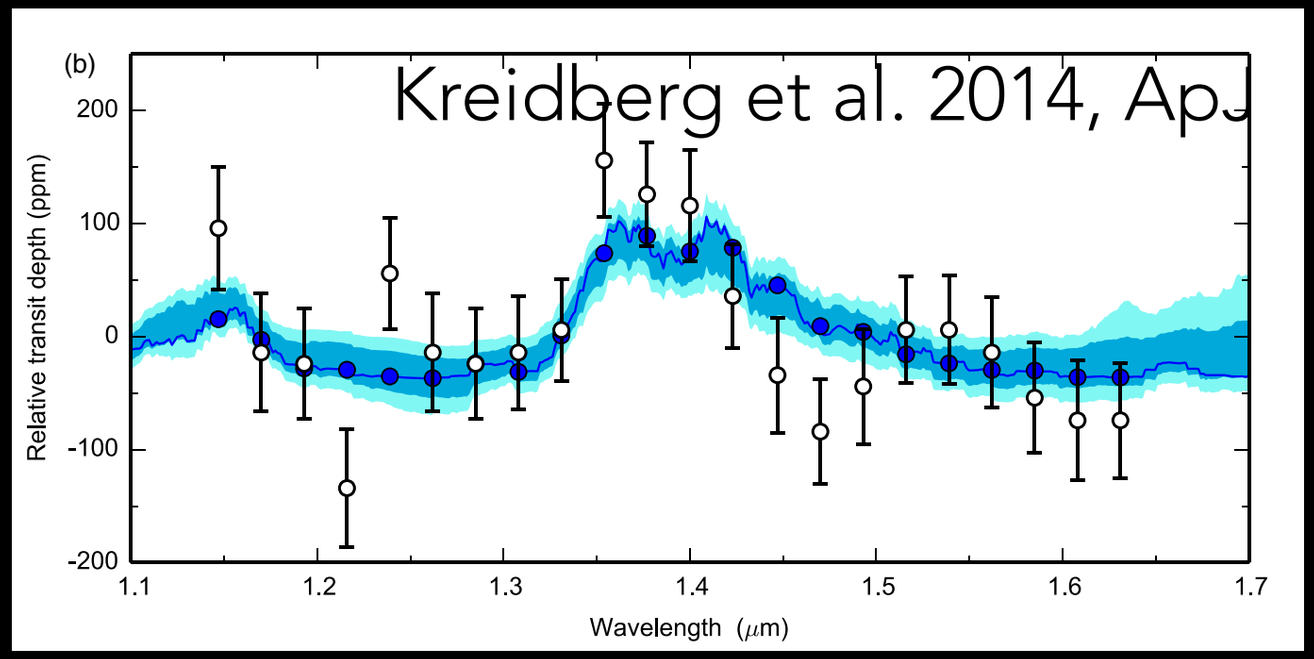
Forward models

Ex) WASP-39b



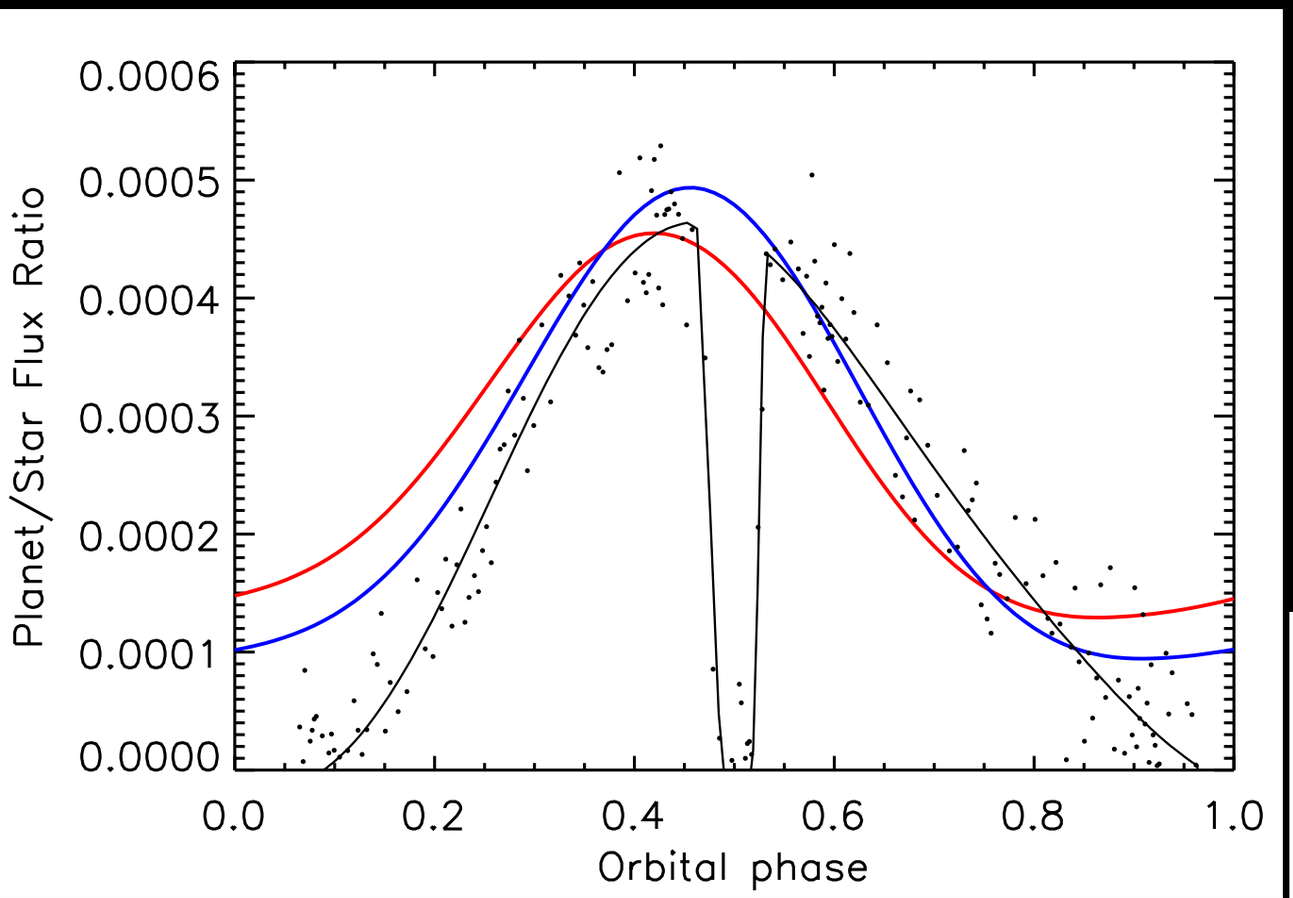
Retrievals

Ex) WASP-43b



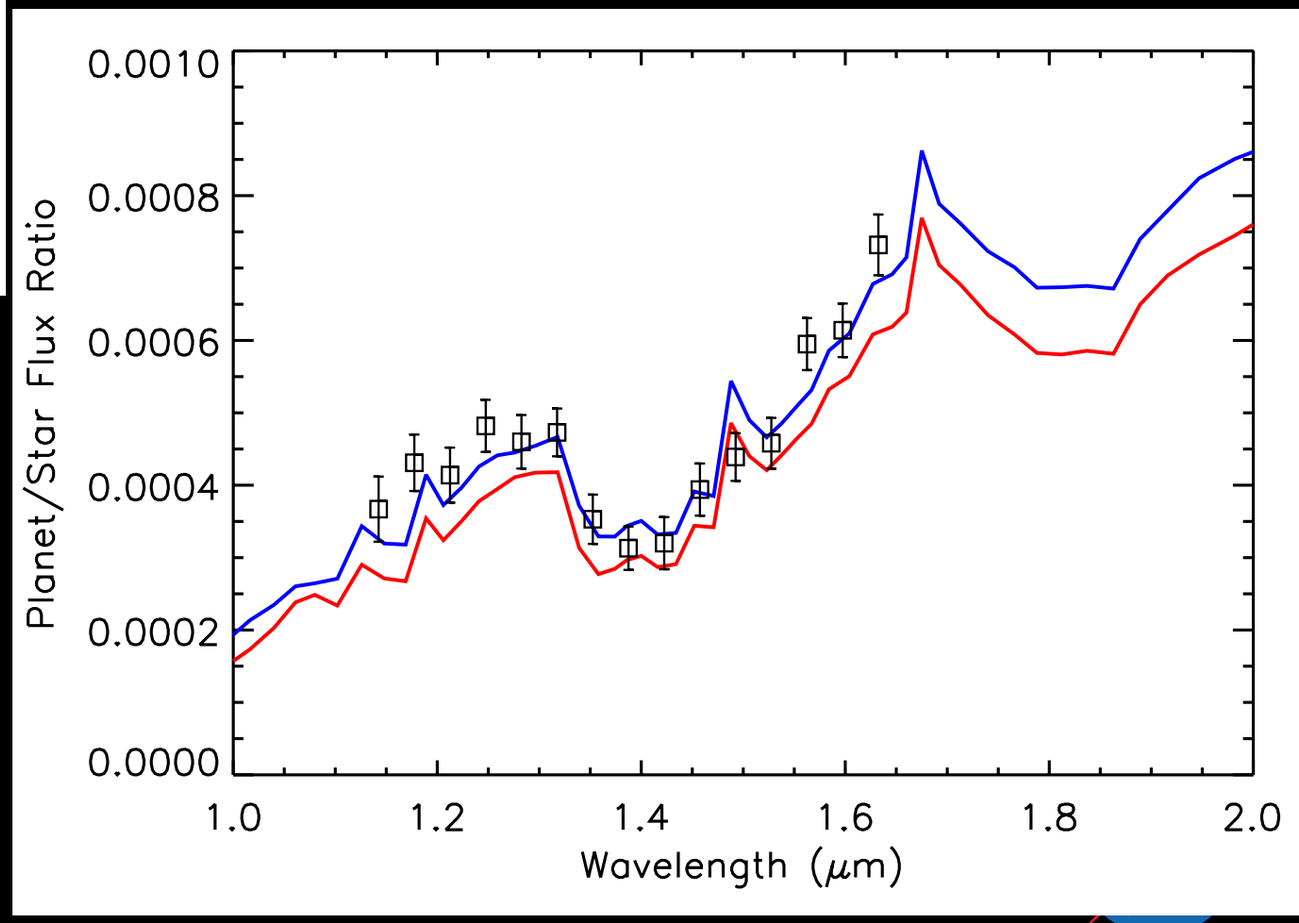
COMPARING GCMs TO SPECTROPHOTOMETRIC DATA: WFC3 OBSERVATIONS OF WASP-43B

Kataria et al. 2015



WHITE LIGHT PHASE CURVE

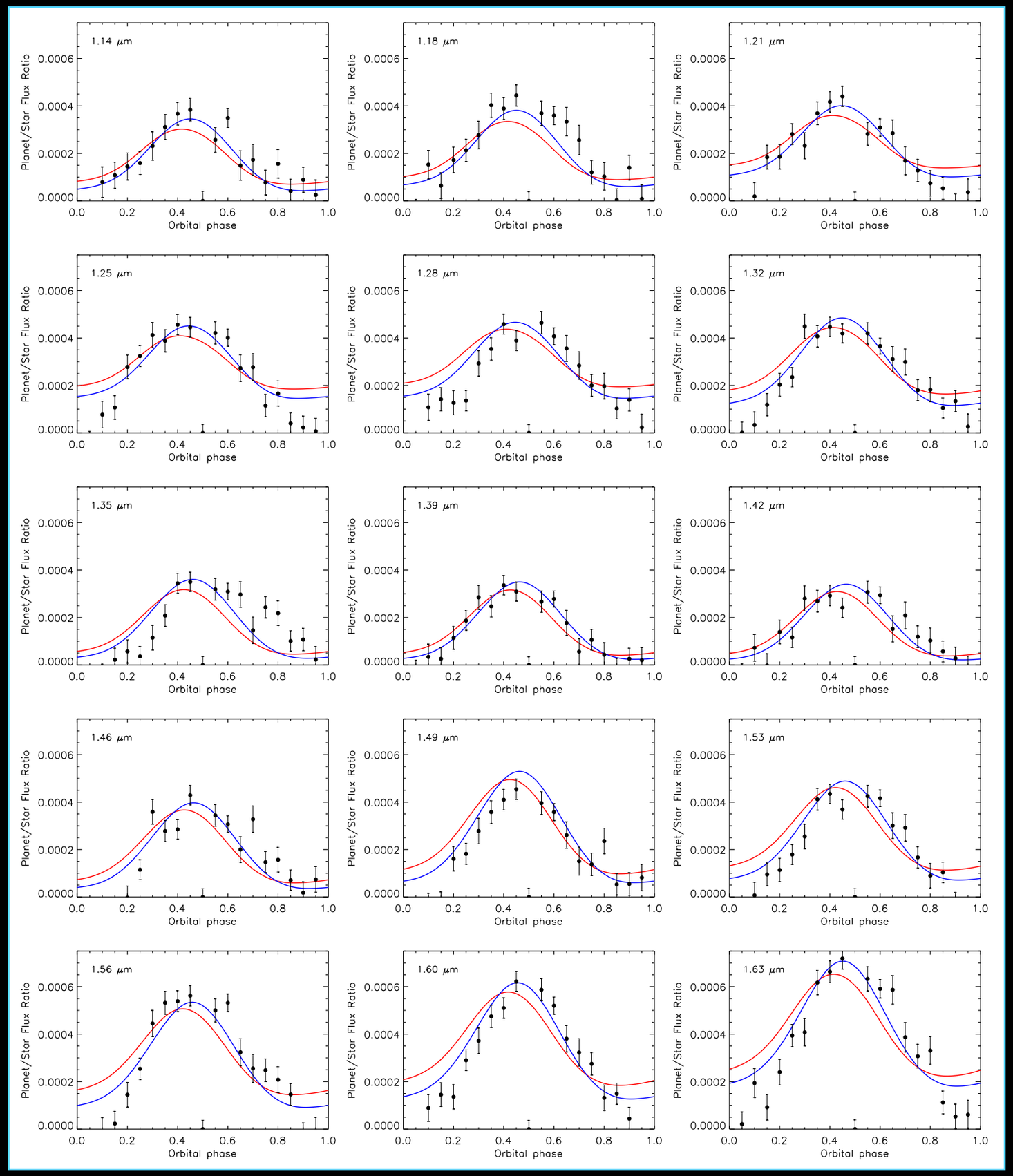
DAYSIDE EMISSION SPECTRUM



COMPARISON TO HST WFC3 OBSERVATIONS

SPECTROPHOTOMETRIC LIGHTCURVES

Red: 1x solar model
Blue: 5x solar model

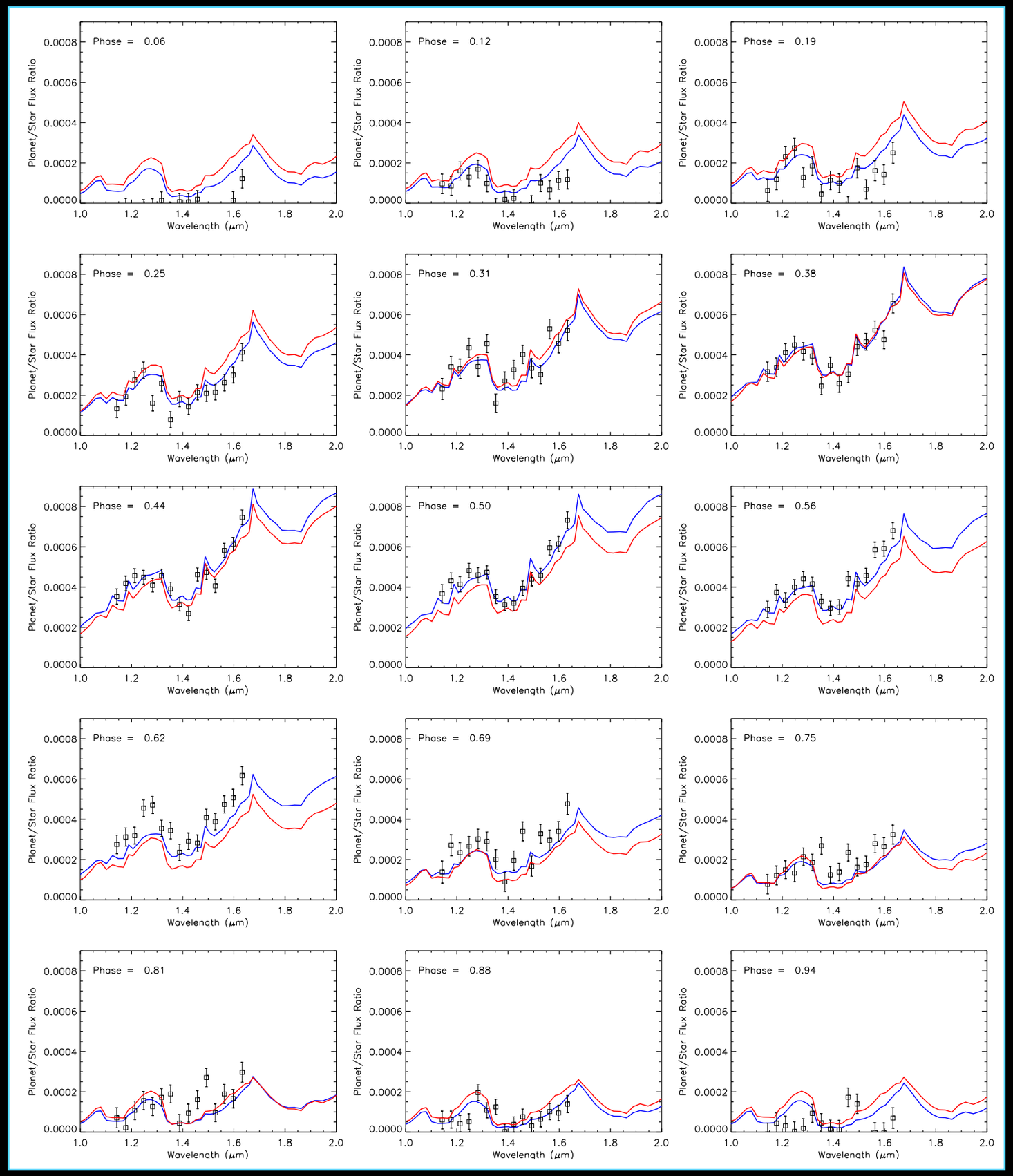


Kataria et al. 2015

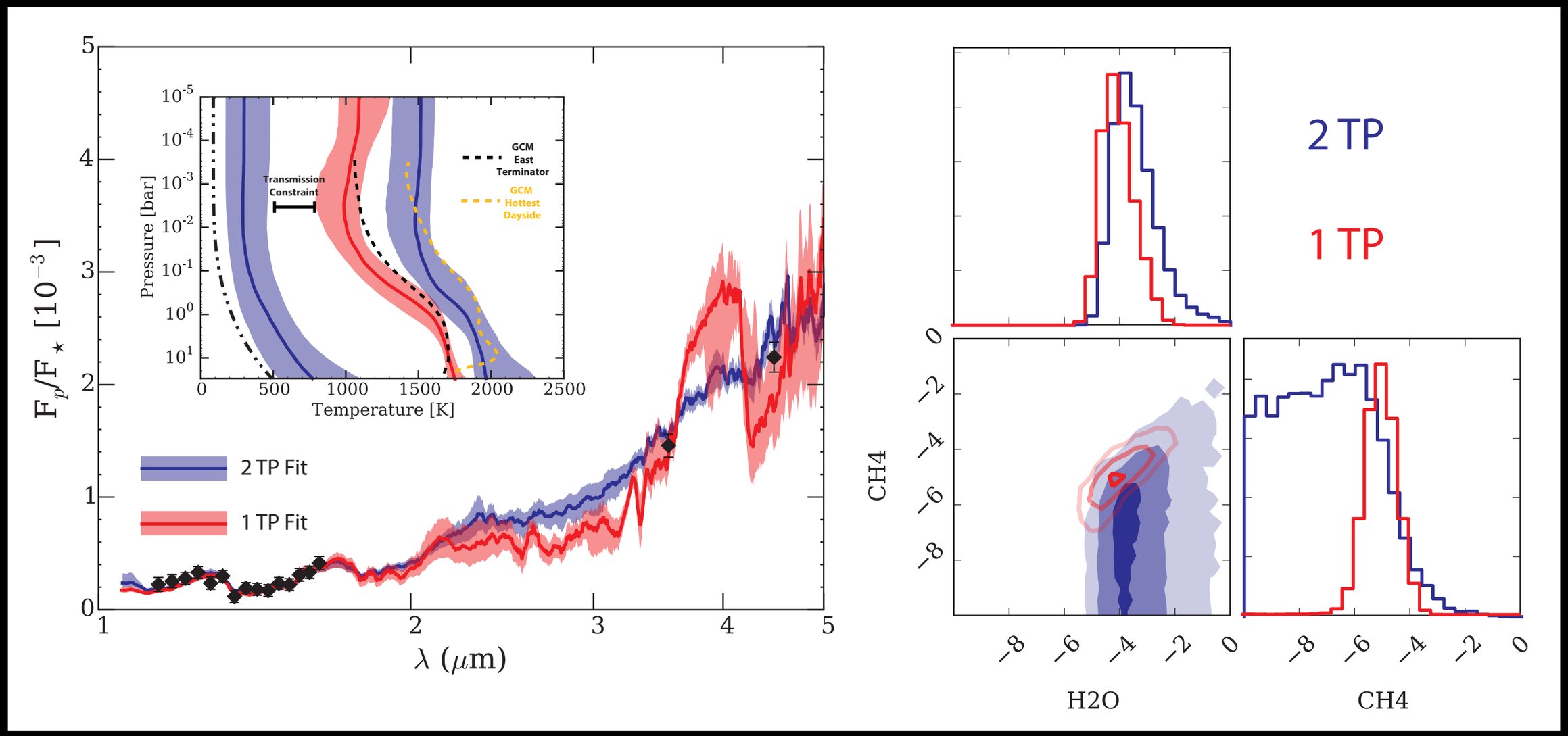
COMPARISON TO HST WFC3 OBSERVATIONS

EMISSION SPECTRA

Red: 1x solar model
Blue: 5x solar model



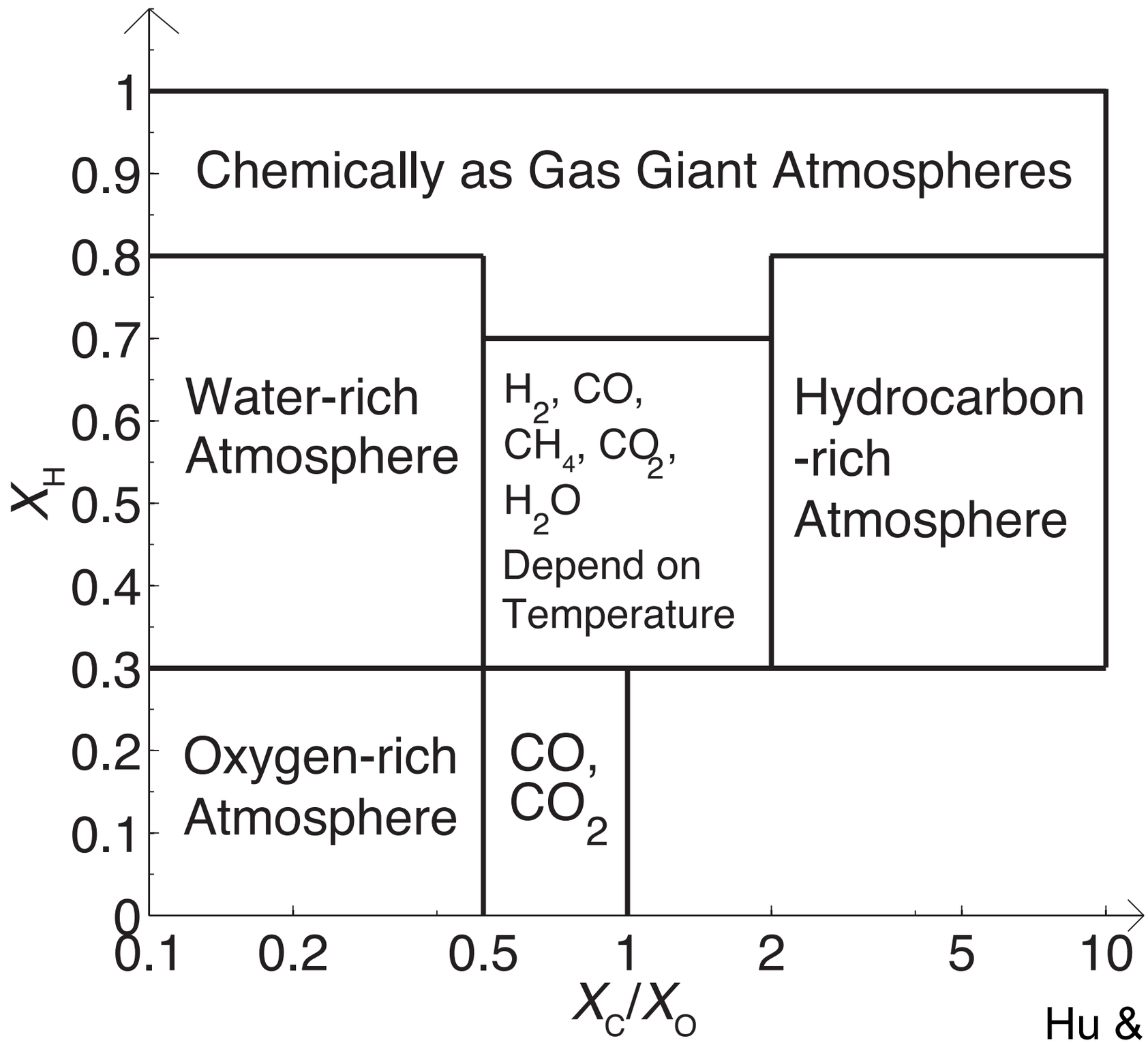
Kataria et al. 2015



Feng et al. 2016

CHARACTERIZING SUPER EARTHS

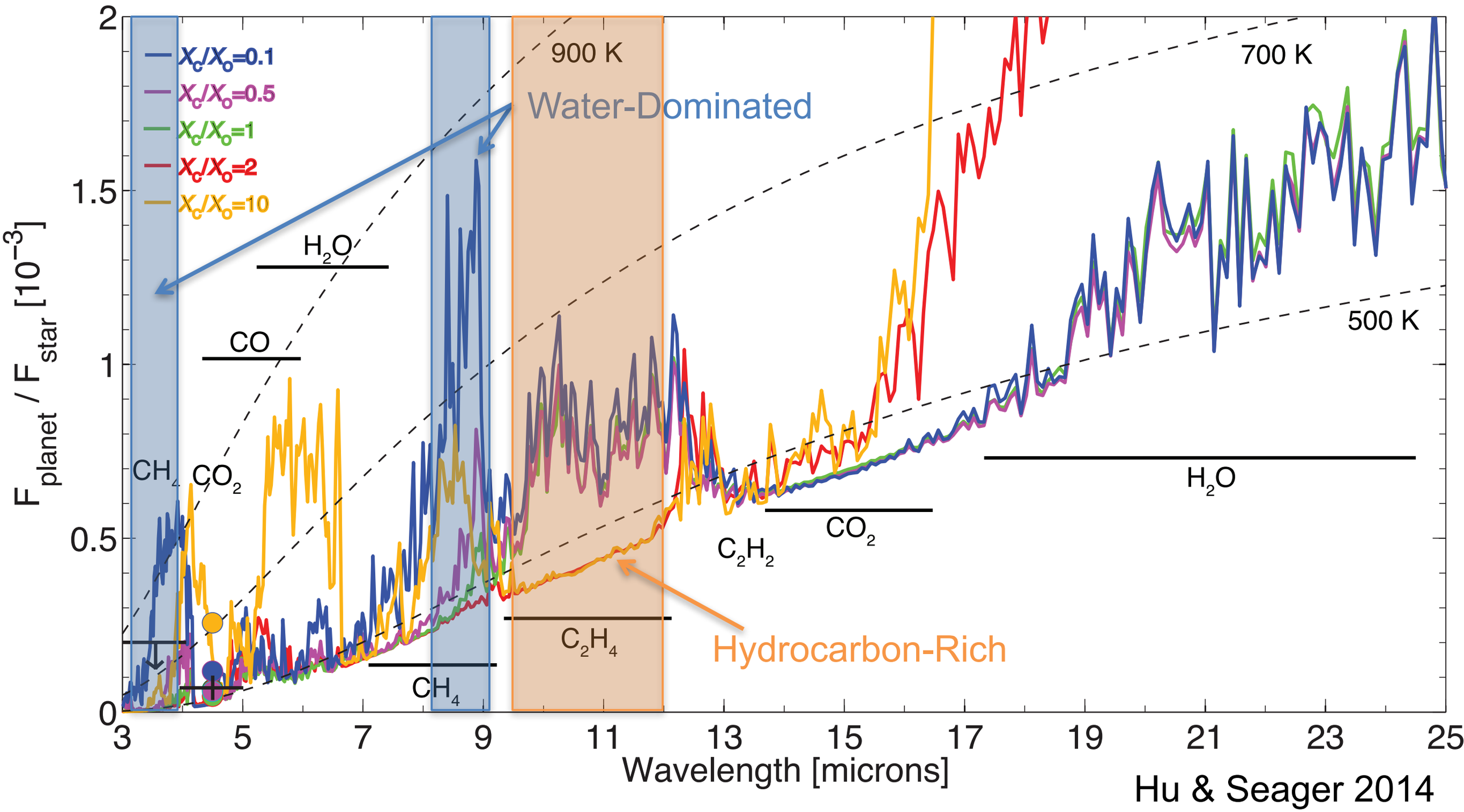
Classification of Super-Earth Atmospheres



Hu & Seager 2014

Emission spectra

- Emission spectra will distinguish types of super-Earth atmospheres

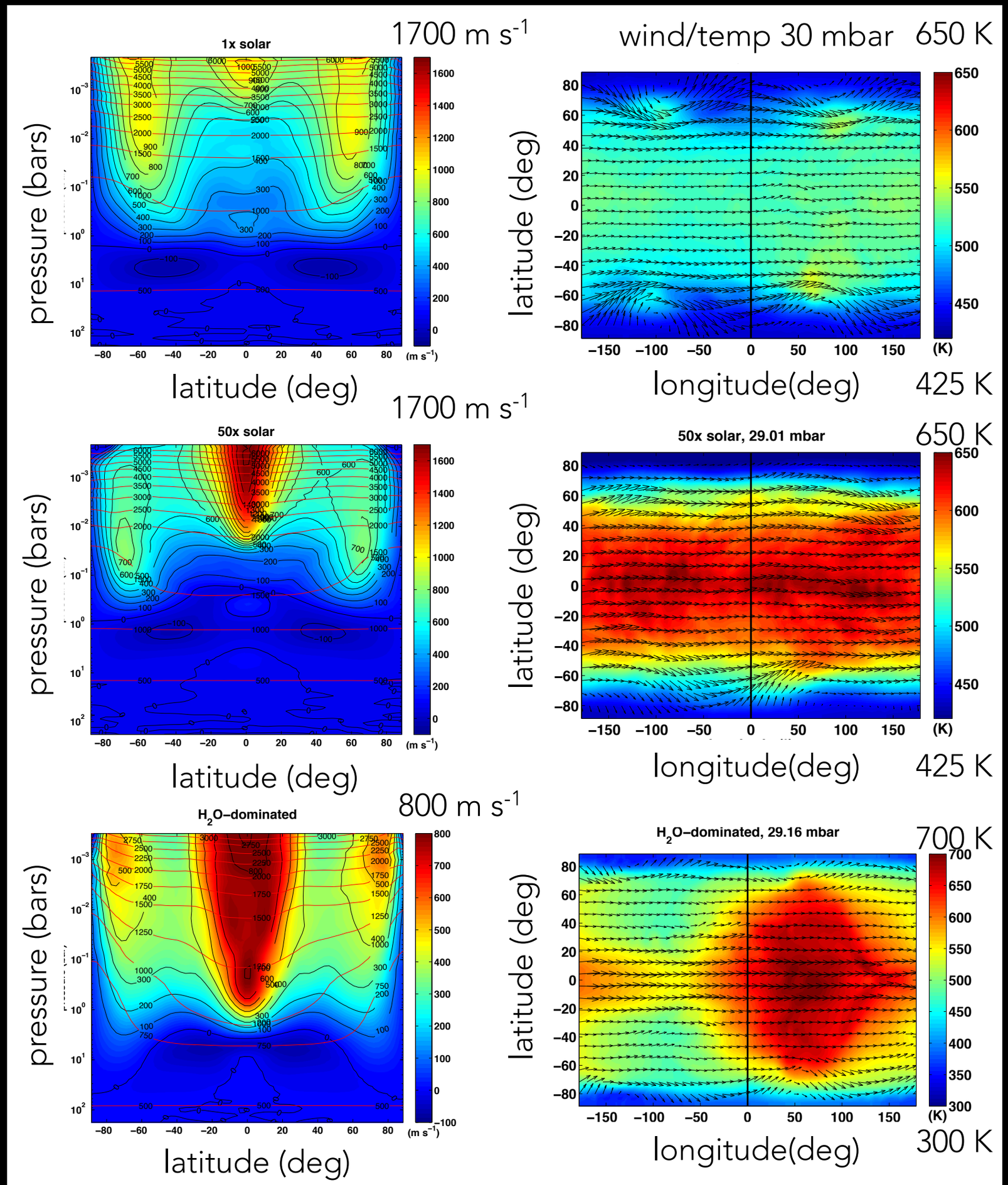


Hu & Seager 2014

1x solar

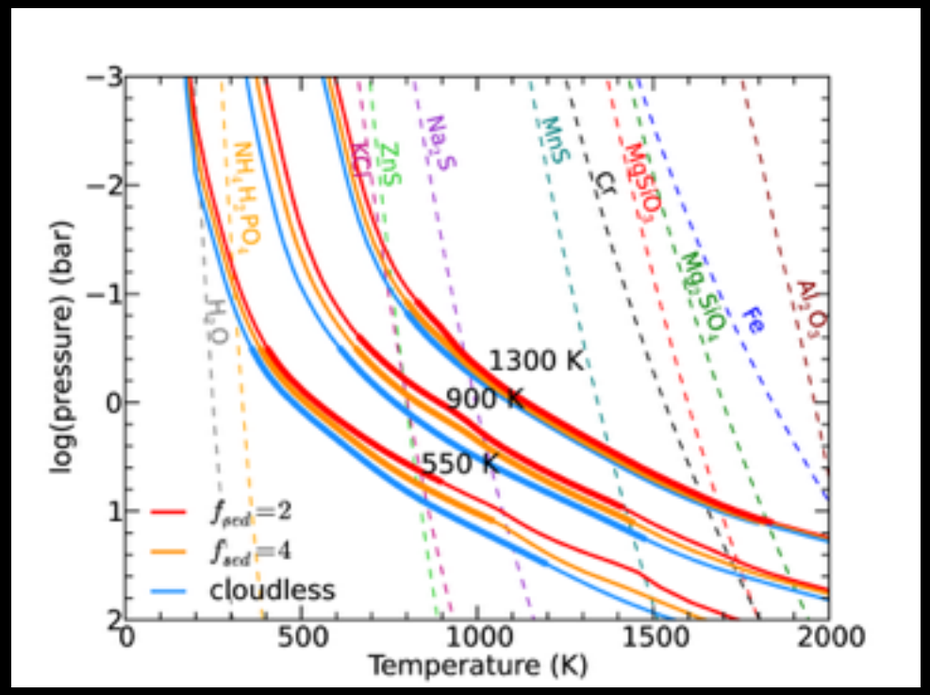
50x solar

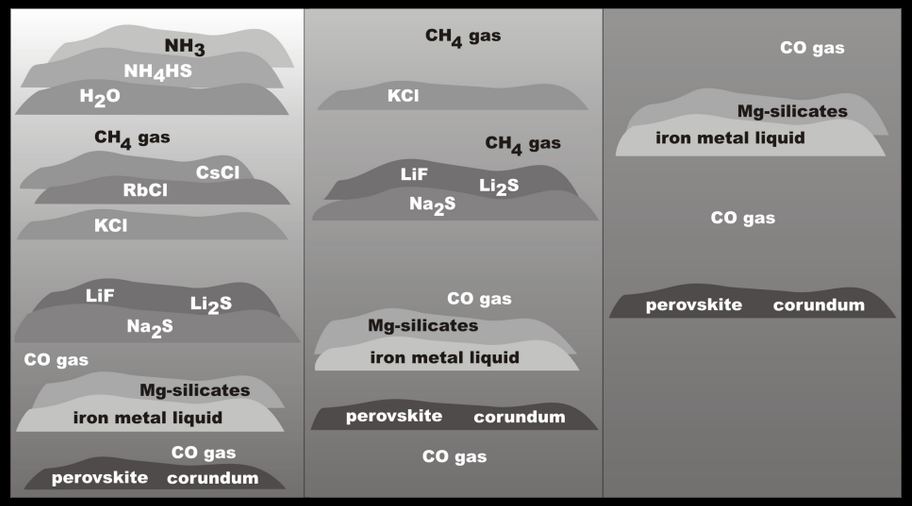
H_2O-dominated



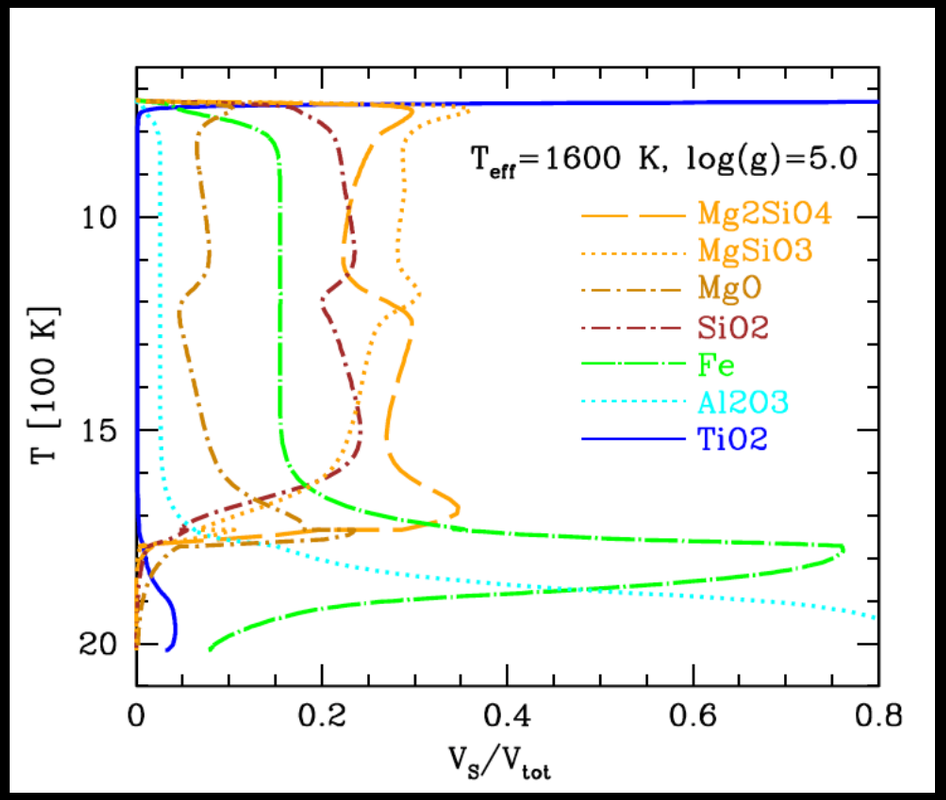
Kataria et al. (2014), ApJ,785,92

MODELING CLOUDS



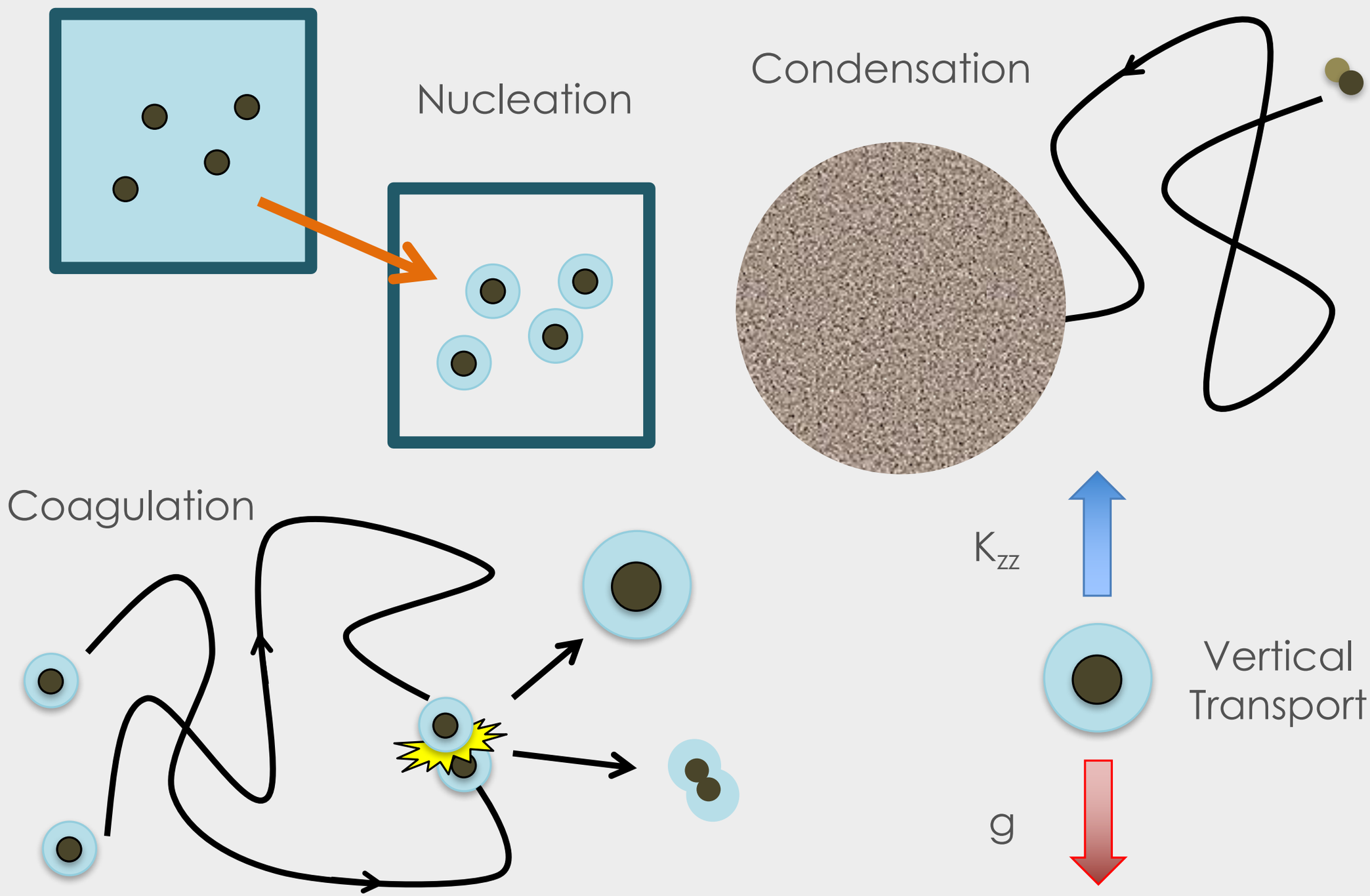


Ackerman & Marley (2001)



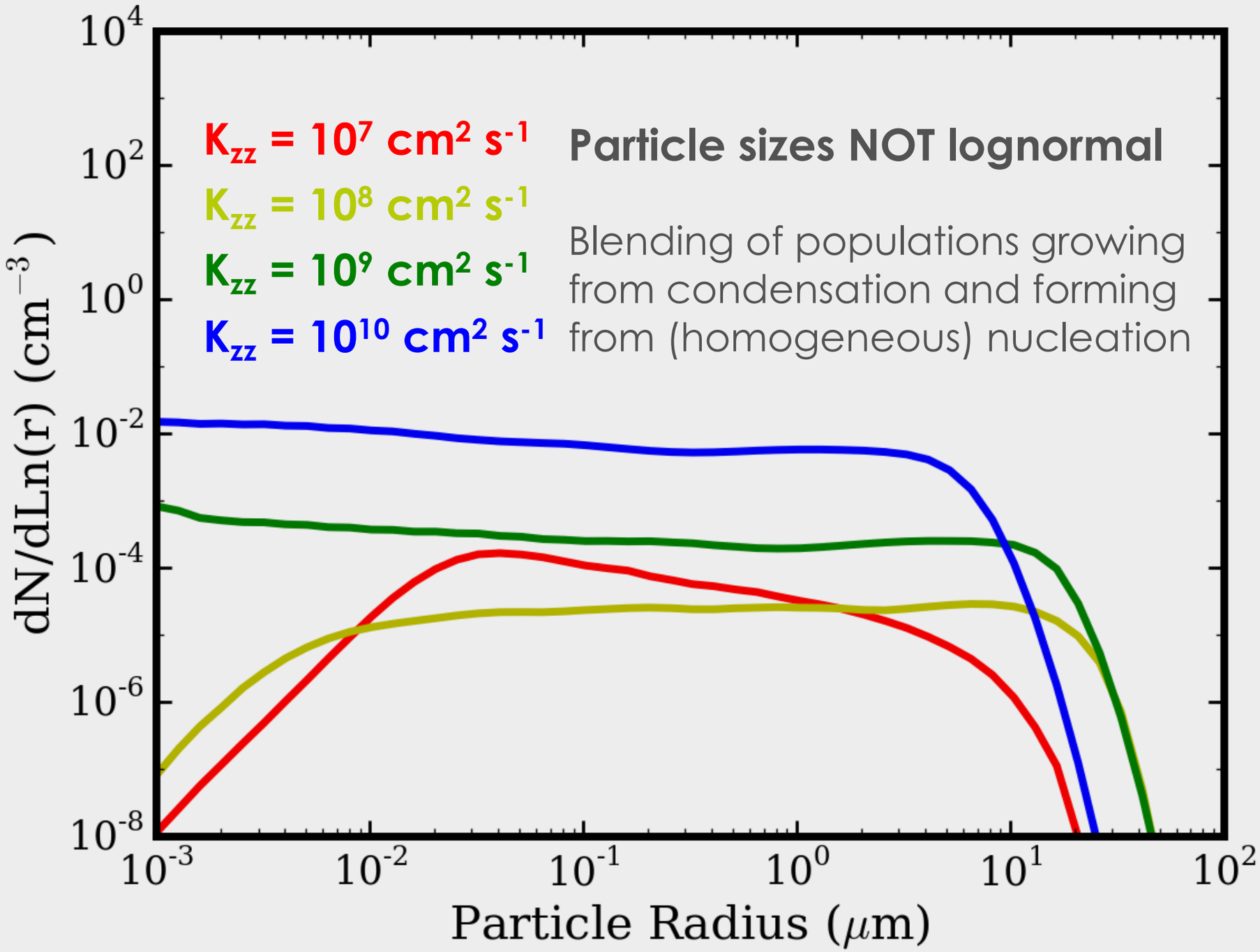
Helling et al. 2008

Cloud Microphysics



Slide from P. Gao

GJ 1214 b: KCl Clouds vs. K_{zz}

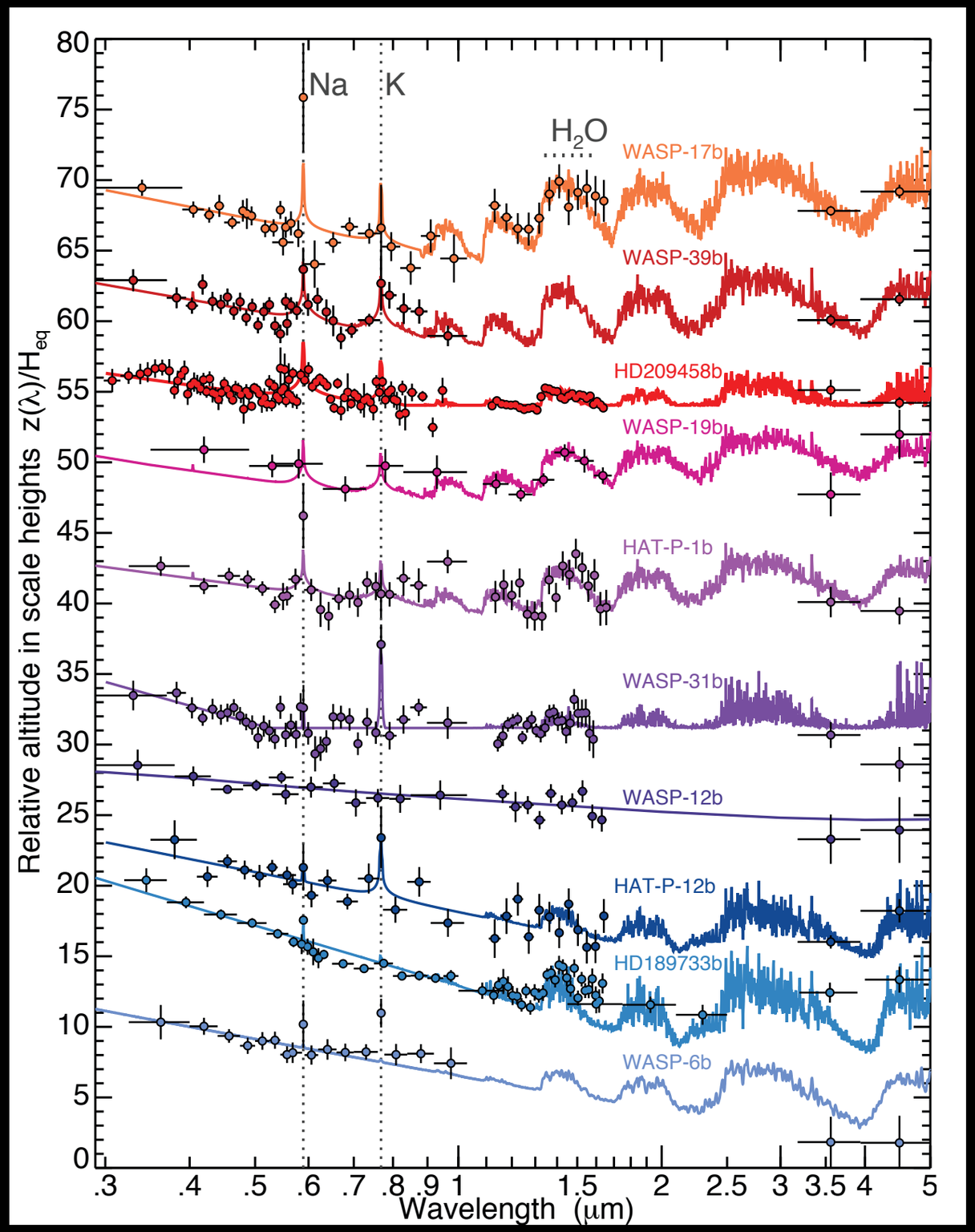


Particle sizes NOT lognormal

Blending of populations growing from condensation and forming from (homogeneous) nucleation

Slide from P. Gao

WHAT DO OBSERVATIONS TELL US?

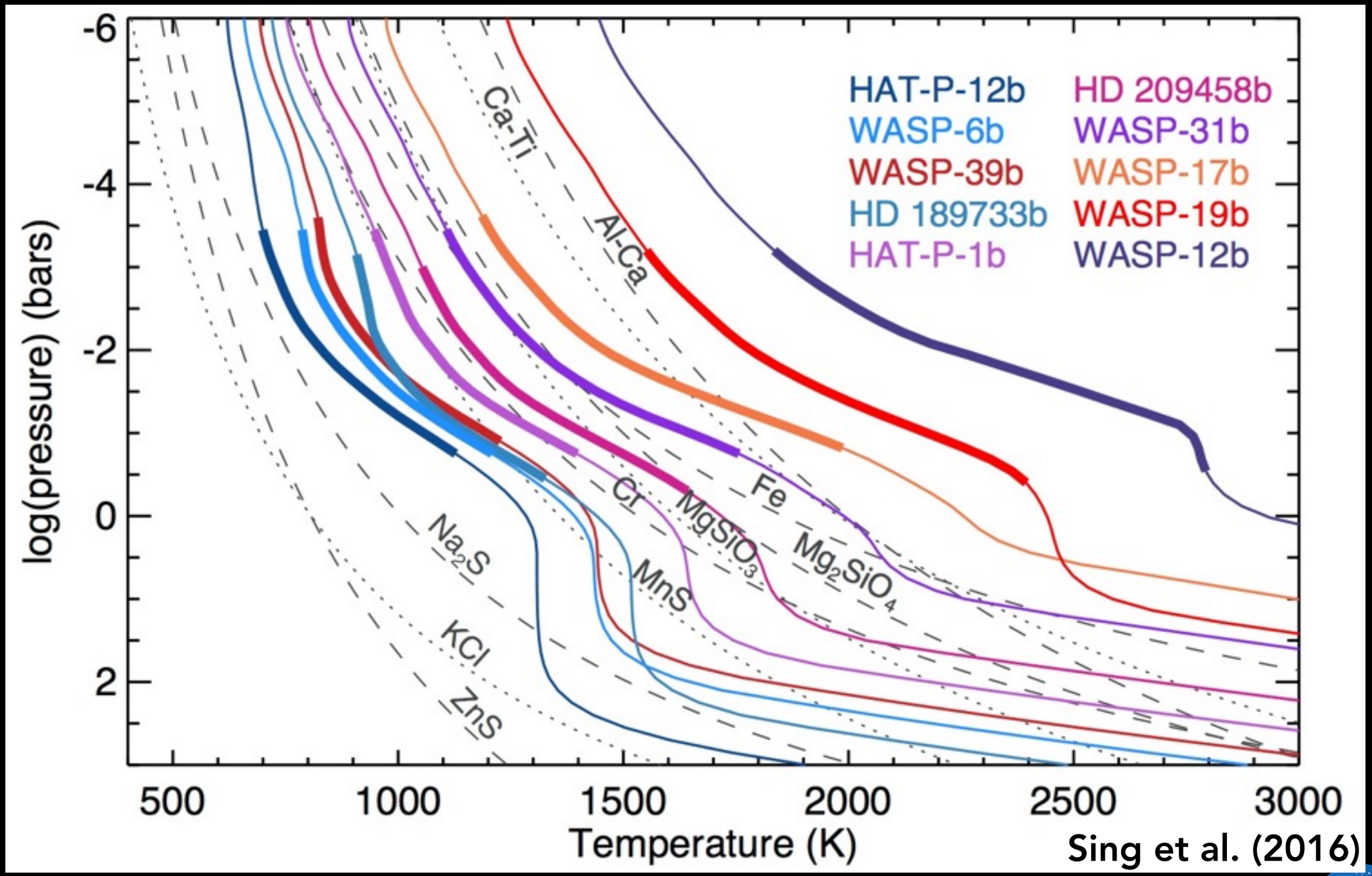


10 hot Jupiters observed in transmission with HST STIS/ WFC3 and Spitzer

Observed diversity in atmospheres over a range of planetary properties

Sing, Fortney, Nikolov, Wakeford, **Kataria** et al. 2016, *Nature*

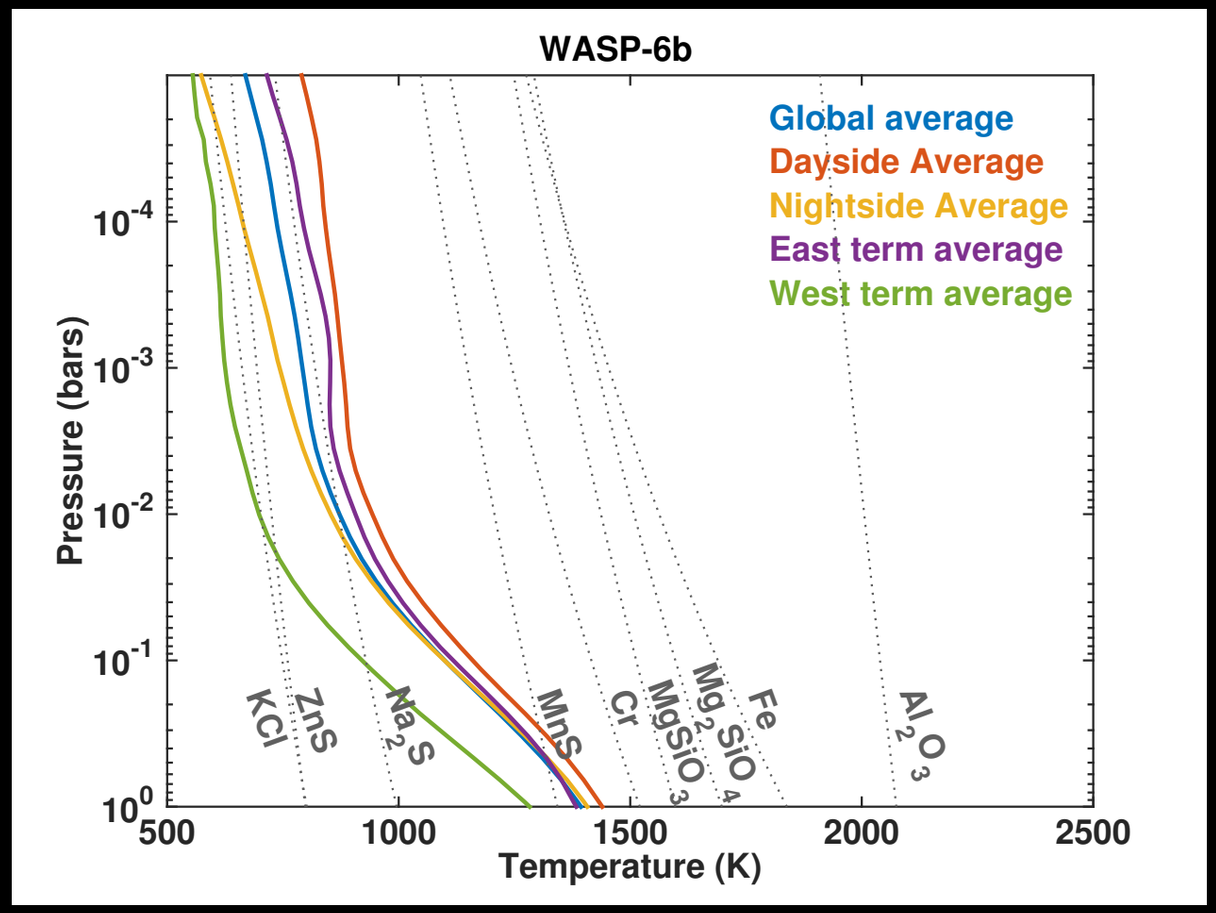
DISENTANGLING CLOUDS



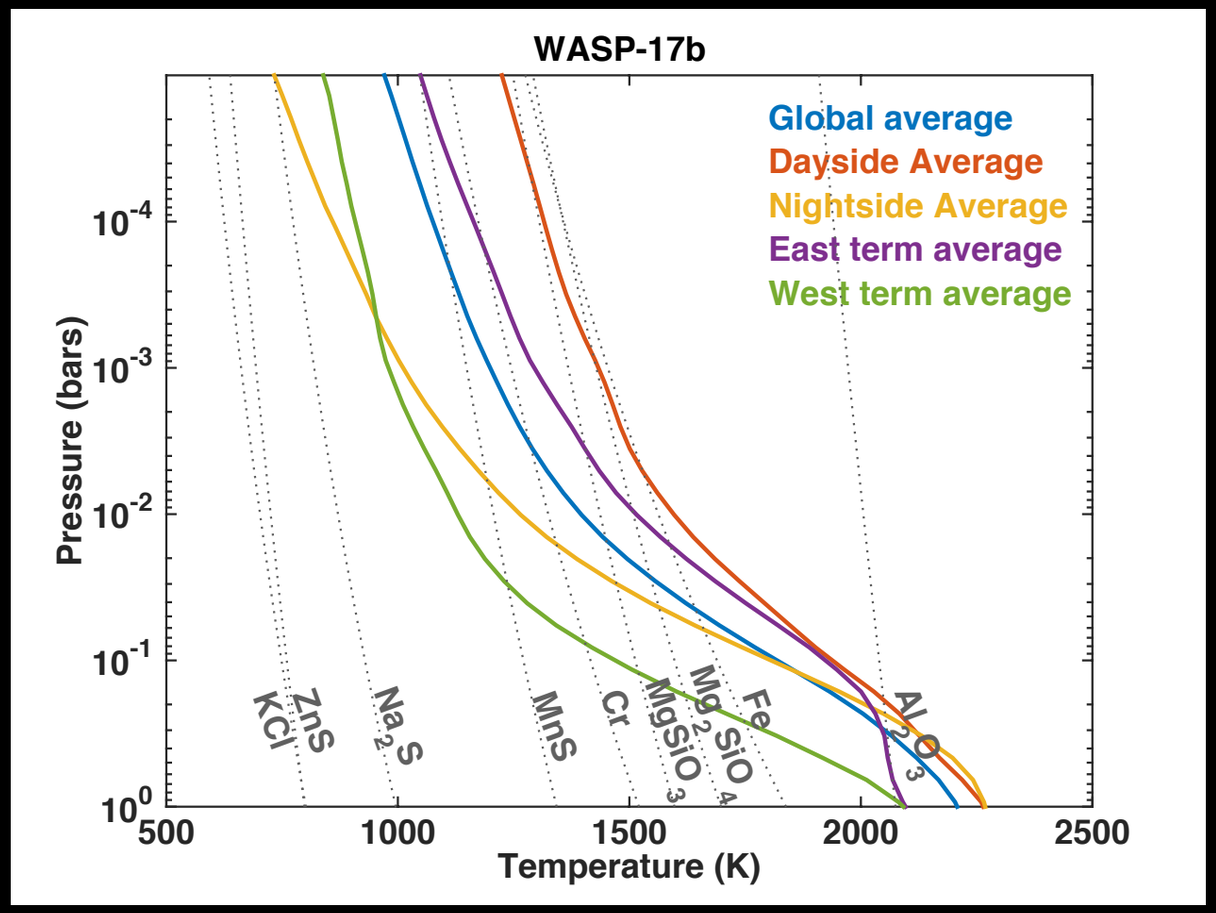
Three-dimensional temperature structure must be considered

LOCALIZED CLOUDS?

WASP-6b: cloudy

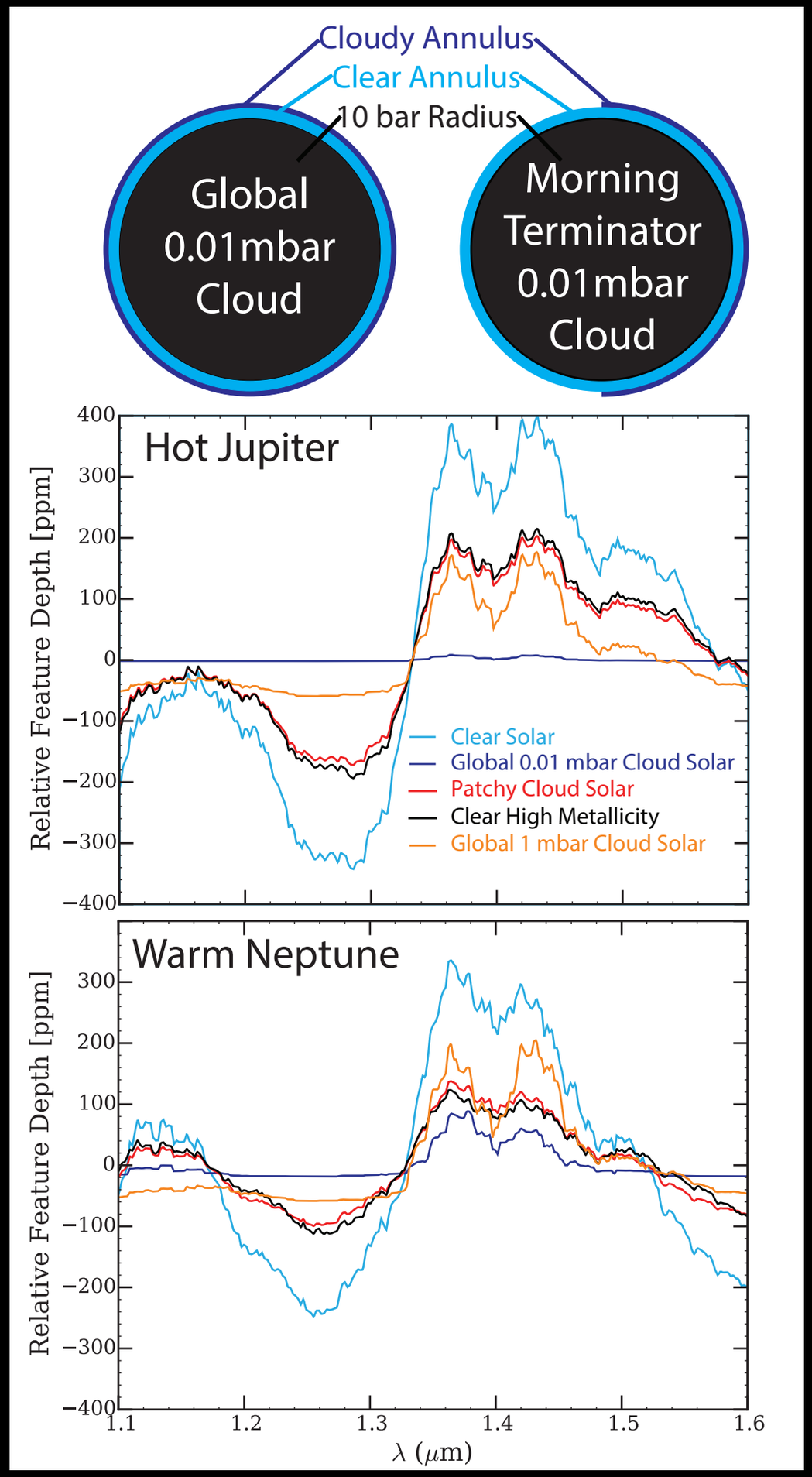


WASP-17b: clear



Kataria et al. 2016, *ApJ*

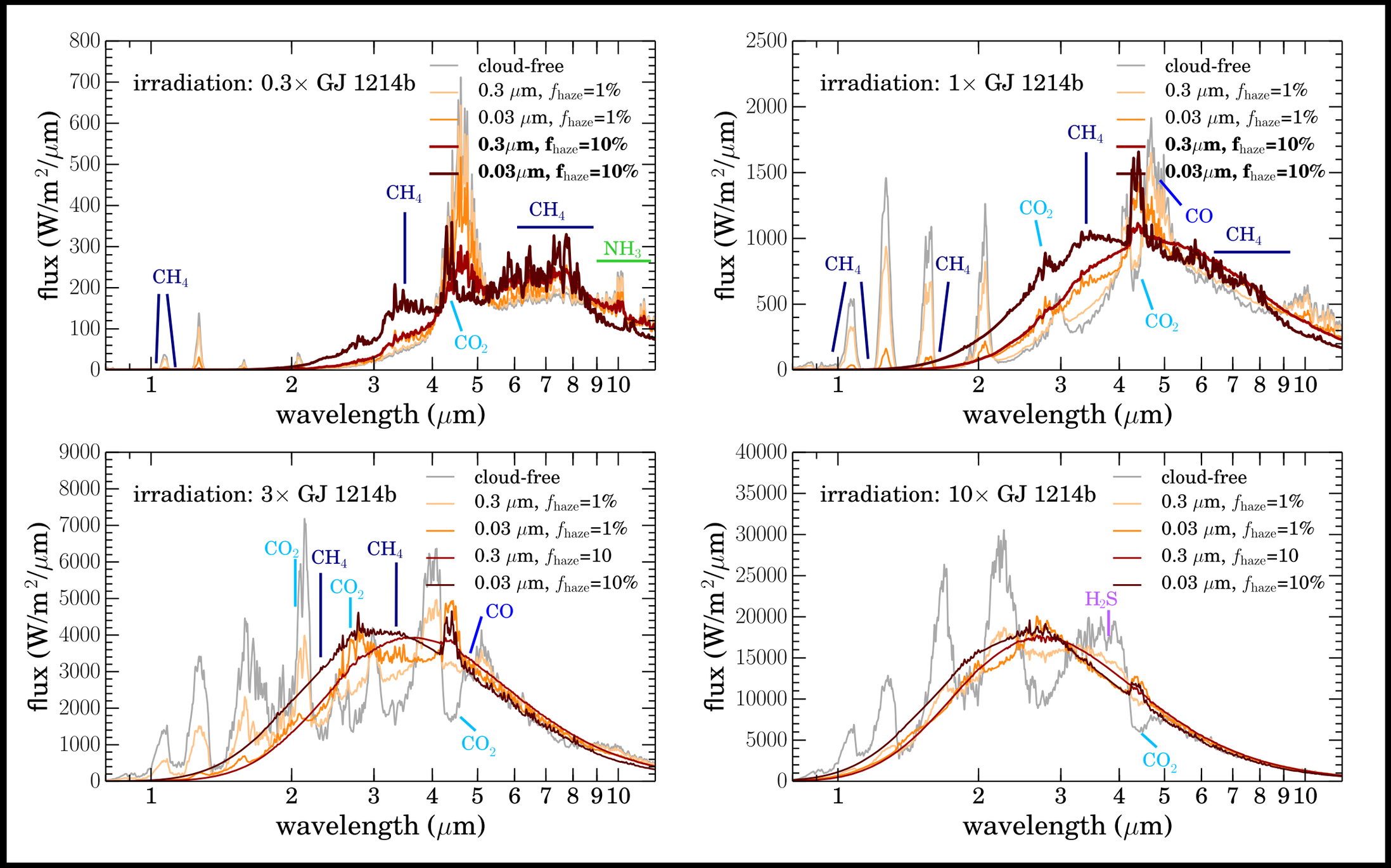
Line and Parmentier (2016)



Need for broader wavelength coverage

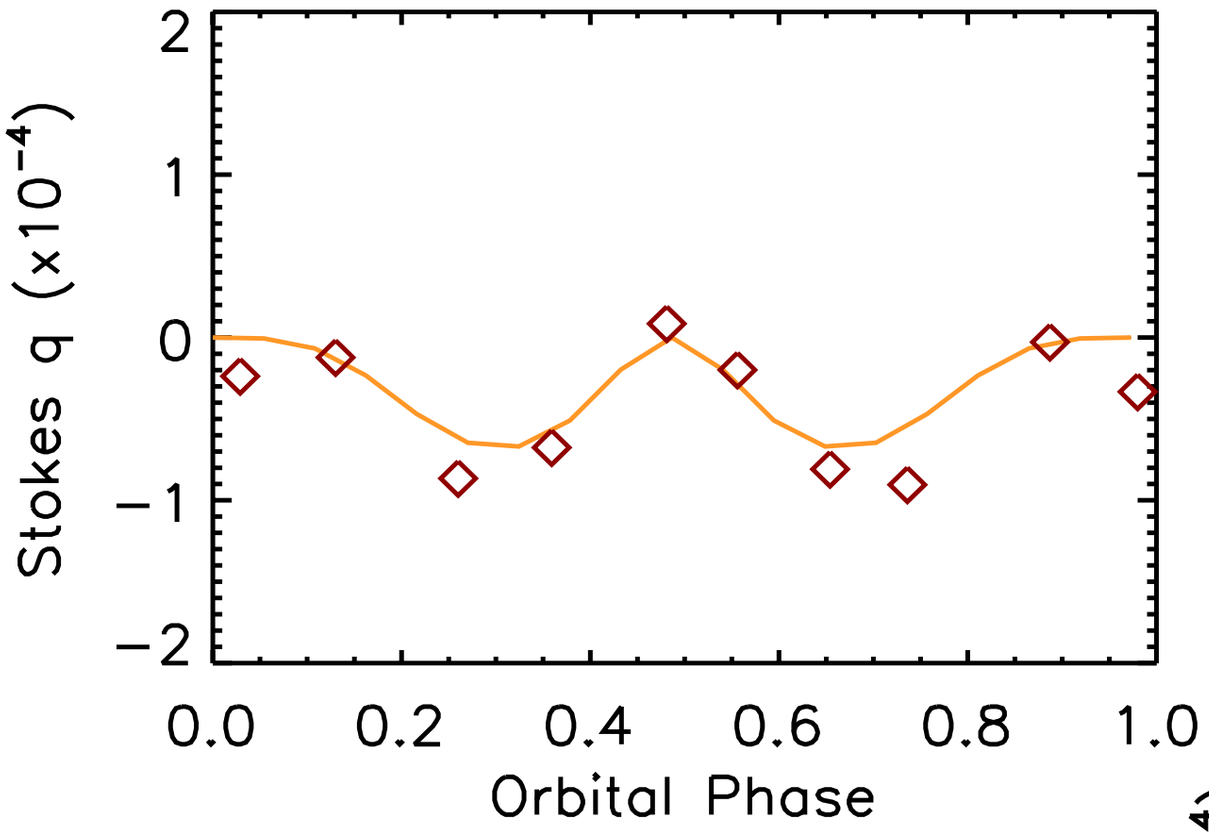
➡ Need for JWST

HAZY SUPER EARTHS IN EMISSION



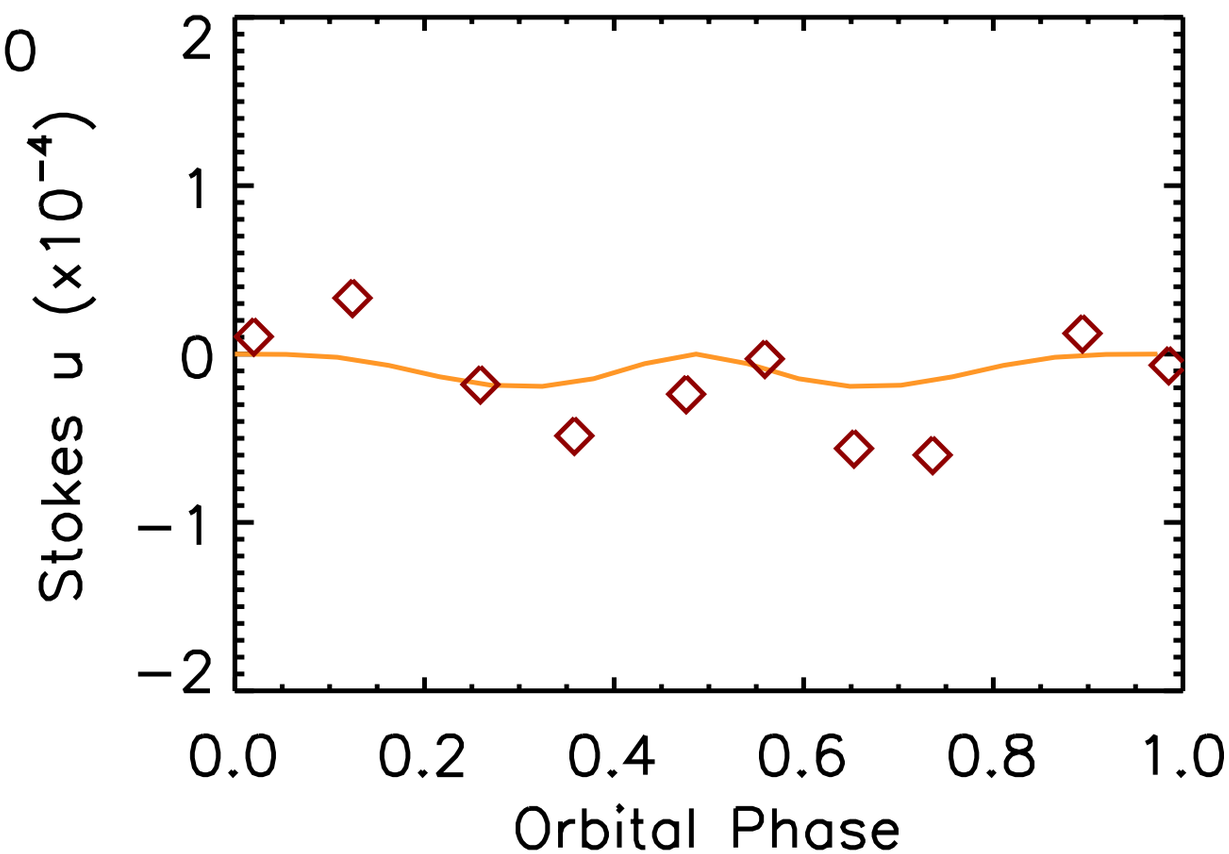
Morley et al. 2015, ApJ

Model Output: Maximum Polarization



Rayleigh atmosphere
Geometric albedo 0.56

Inconsistent with the albedos of Evans et al (2013)

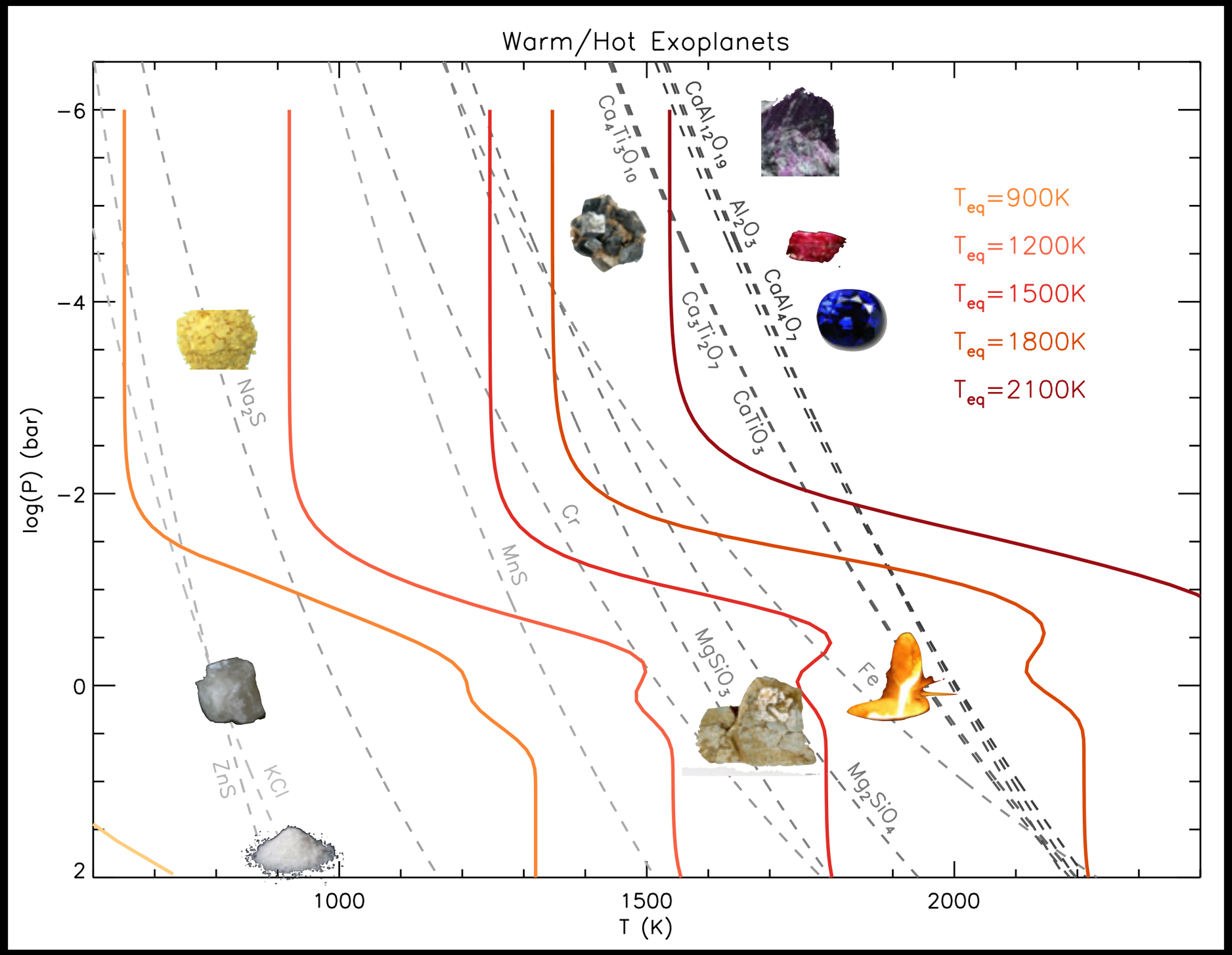


Model

Observations
Berdyugina et al
(2011)

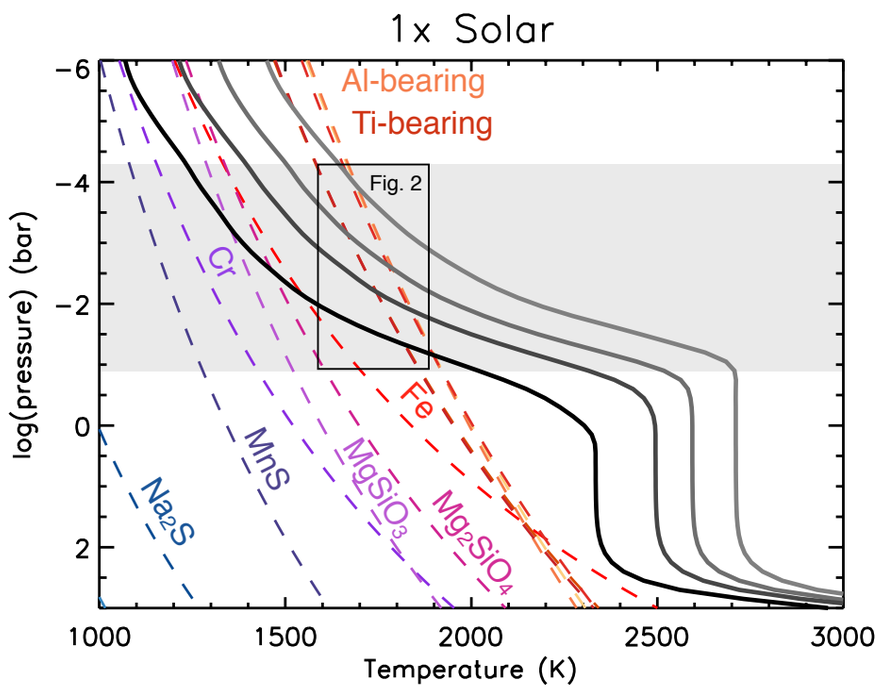
Slide from P. Kopparla

ULTRA HOT JUPITERS



Wakeford et al. 2016, MNRAS, under review

CLOUD MASS



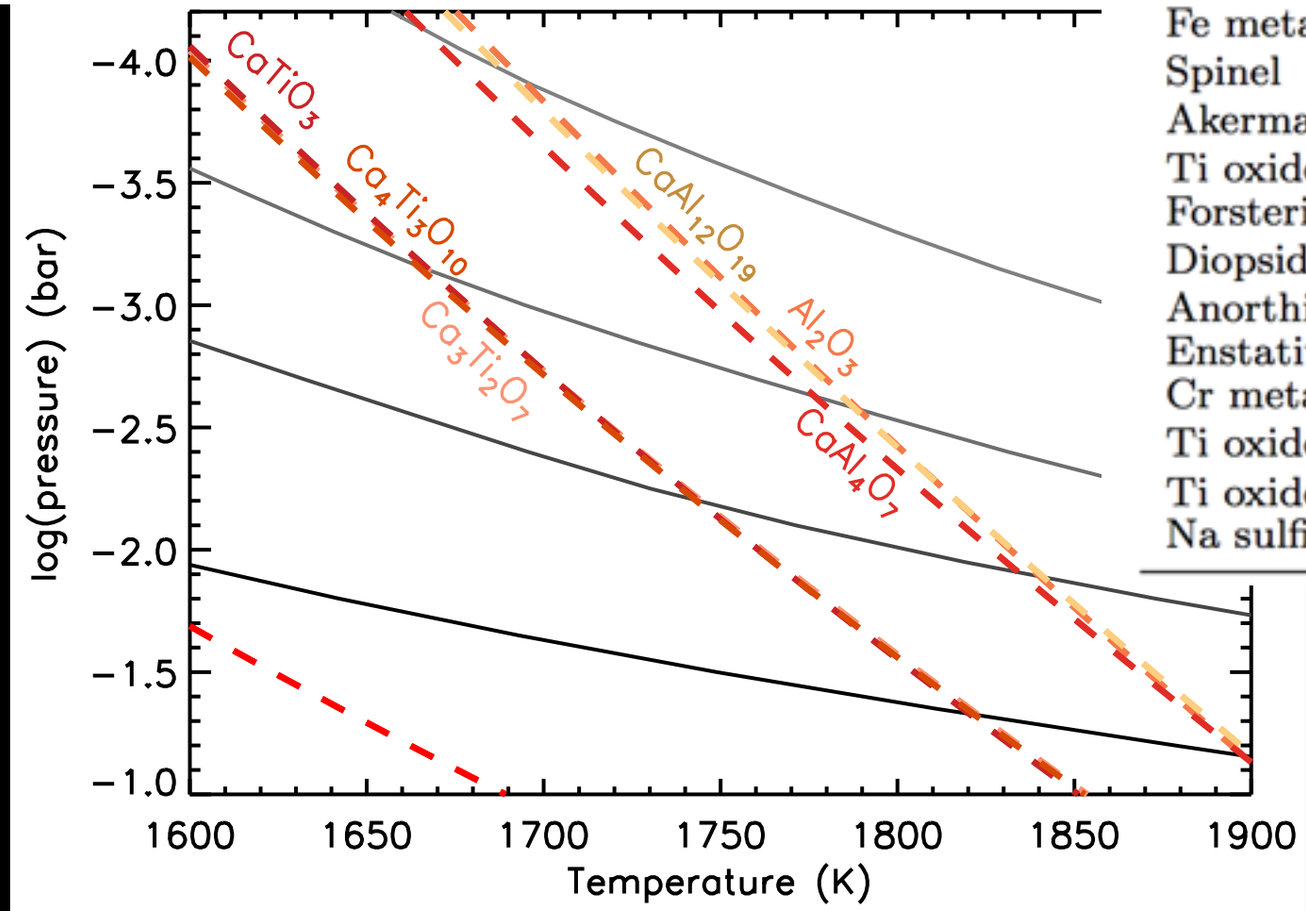
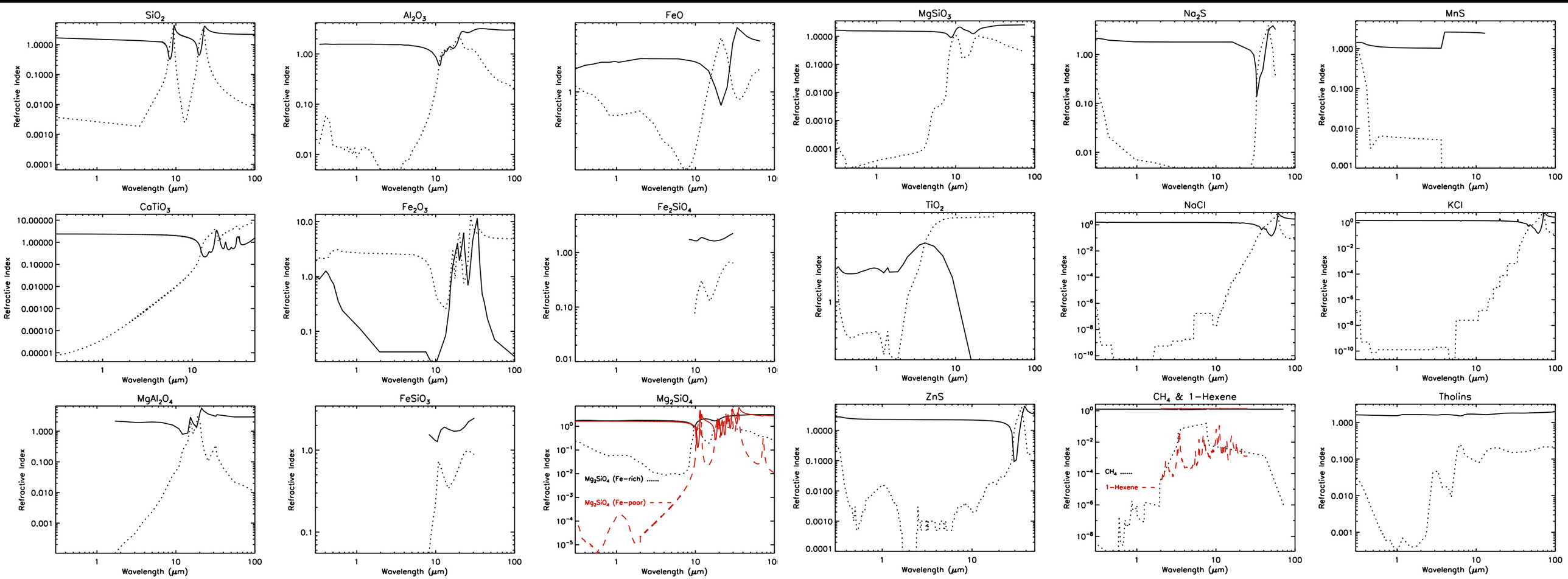


TABLE 1
RELATIVE CLOUD MASSES AND CONDENSATION TEMPERATURES FOR $P_T = 0.1$ BAR AND [Fe/H] = 0.0

Name	Formula	Relative Cloud Mass	Condensation Temperature (K)
Hibonite	$CaAl_{12}O_{19}$	2091	1914^a
Corundum	Al_2O_3	1915	1911^a
Ca titanate	$Ca_4Ti_3O_{10}$	170	1854^a
Grossite	$CaAl_4O_7$	2442	$1848^b(1912^a)$
Ca titanate	$Ca_3Ti_2O_7$	180	$1818^b(1852^a)$
Gehlenite	$Ca_2Al_2SiO_7$	3678	1796^b
Perovskite	$CaTiO_3$	149	$1707^a(1851)$
Fe metal	Fe	21032	1682^a
Spinel	$MgAl_2O_4$	2673	1663^b
Akermanite	$Ca_2Mg_2Si_2O_7$	3657	1626^b
Ti oxide	Ti_3O_5	82	1610^b
Forsterite	Mg_2SiO_4	32180	1592^a
Diopside	$CaMgSi_2O_6$	5809	1560^b
Anorthite	$CaAl_2Si_2O_8$	5227	1513^b
Enstatite	$MgSiO_3$	44585	1508
Cr metal	Cr	303	1411^a
Ti oxide	Ti_4O_7	83	1290^b
Ti oxide	Ti_2O_3	79	$<1000^b$
Na sulfide	Na_2S	$\equiv 1000$	925^a

Wakeford et al. 2016, MNRAS, under review

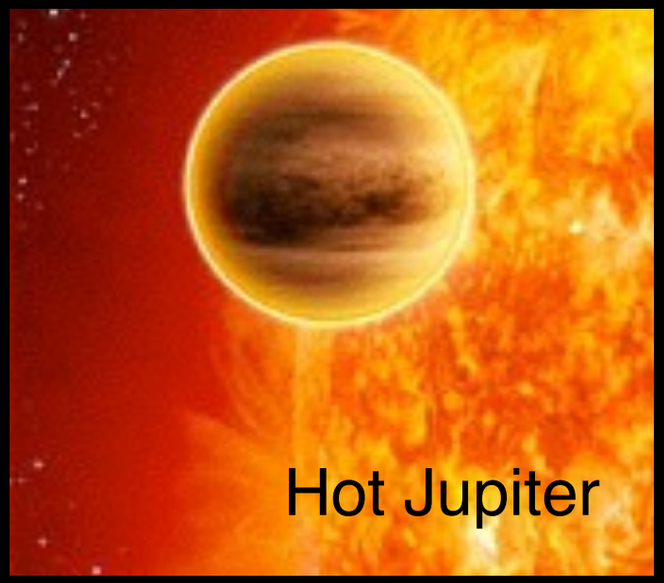
CONDENSATE OPTICAL PROPERTIES



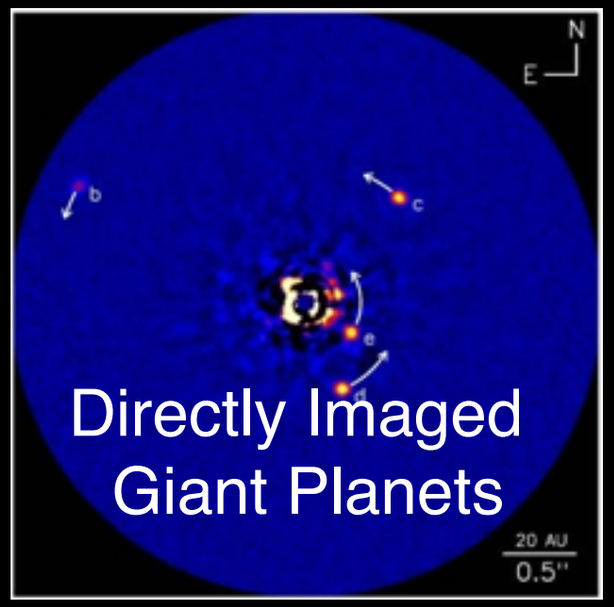
We NEED more lab data!

Wakeford & Sing, 2015, A&A

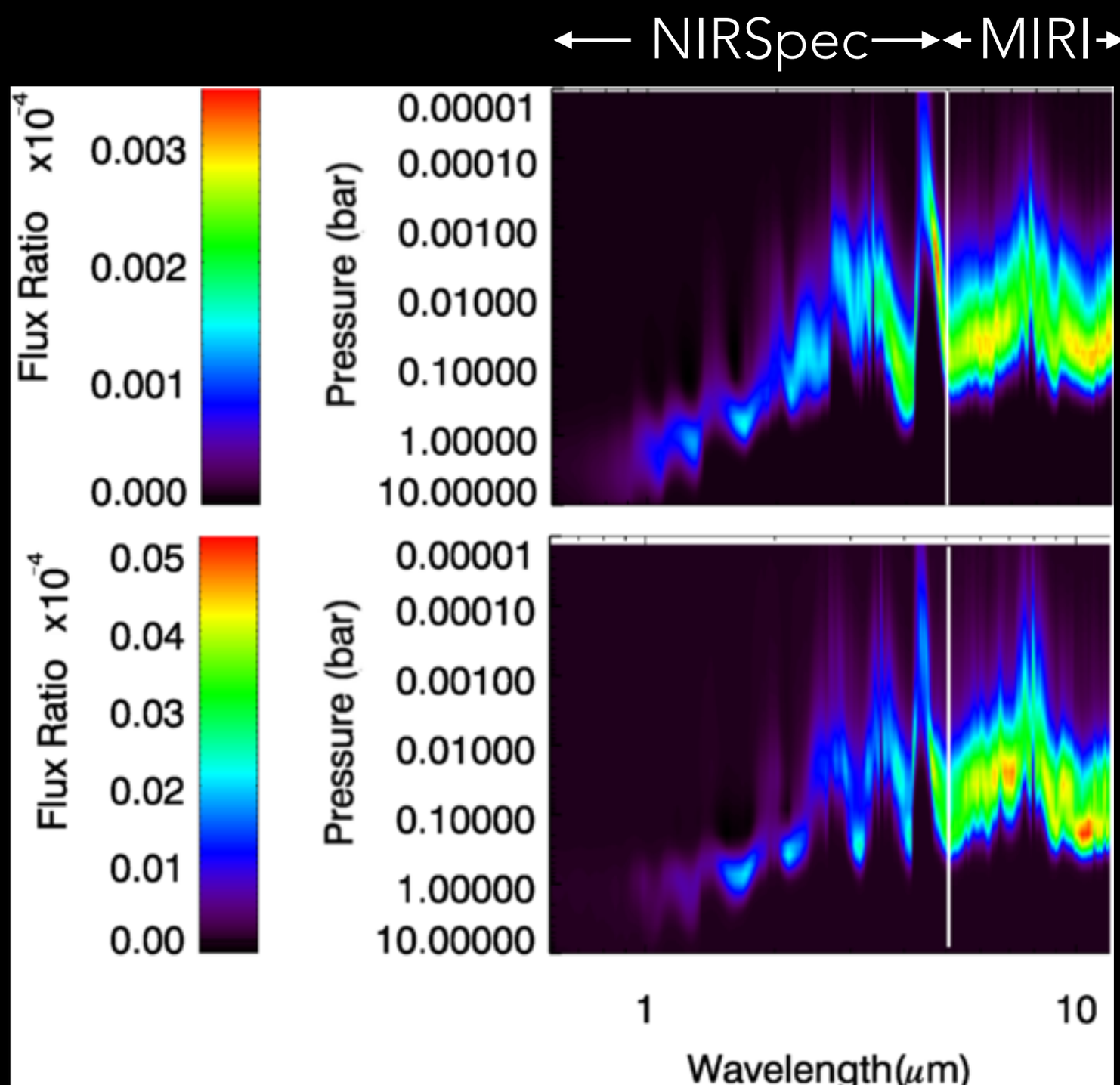
THE FUTURE OF EXOPLANET DETECTION, OBSERVATIONS AND CHARACTERIZATION



Forecast Complexity



TRANSIT SPECTROSCOPY IN THE AGE OF JWST



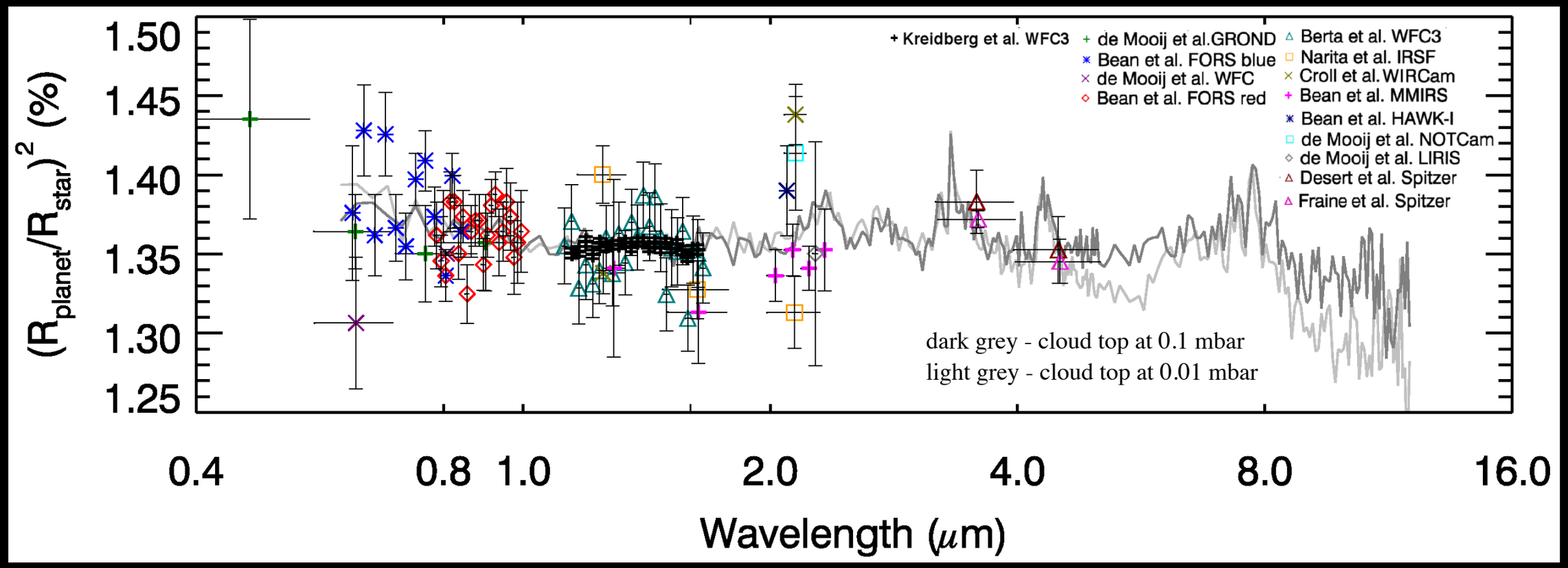
hot Jupiter orbiting Sun-like star

hot Neptune orbiting M dwarf

Barstow et al. (2015)

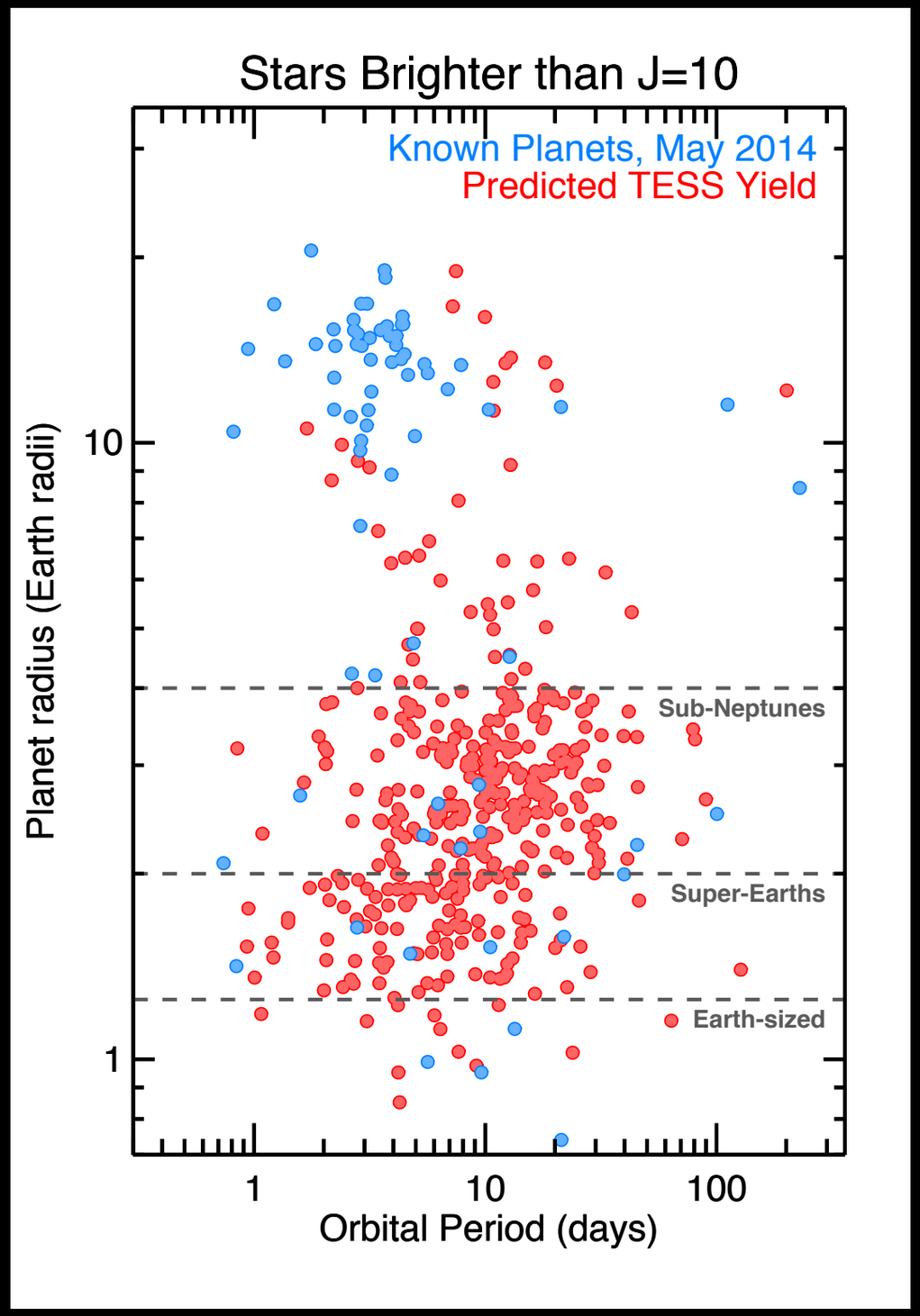
TRANSMISSION SPECTROSCOPY OF SUPER EARTHS WITH JWST

Barstow et al. 2015

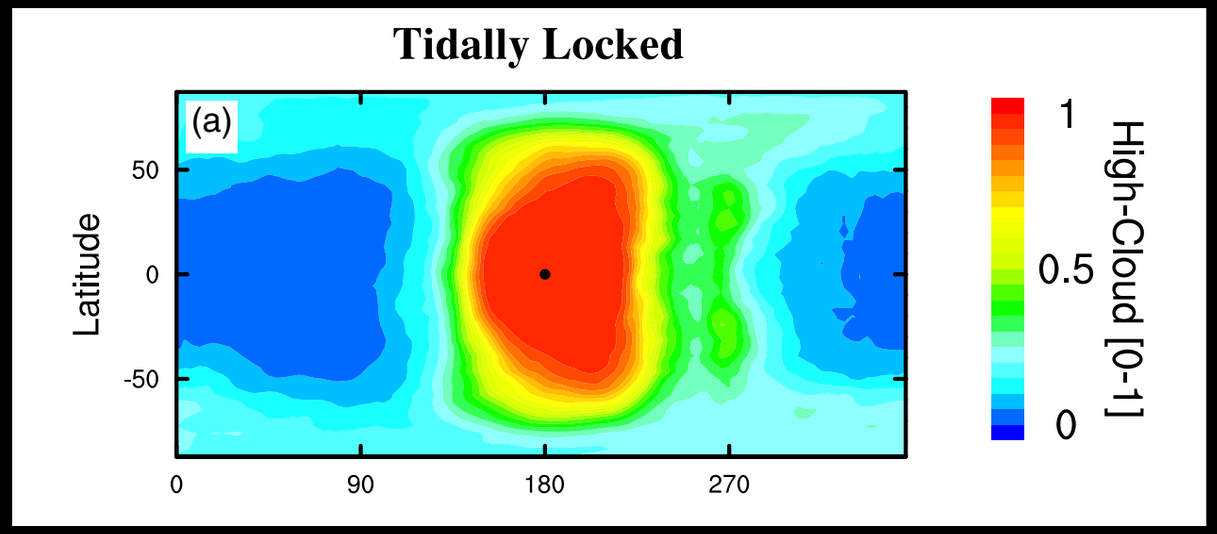


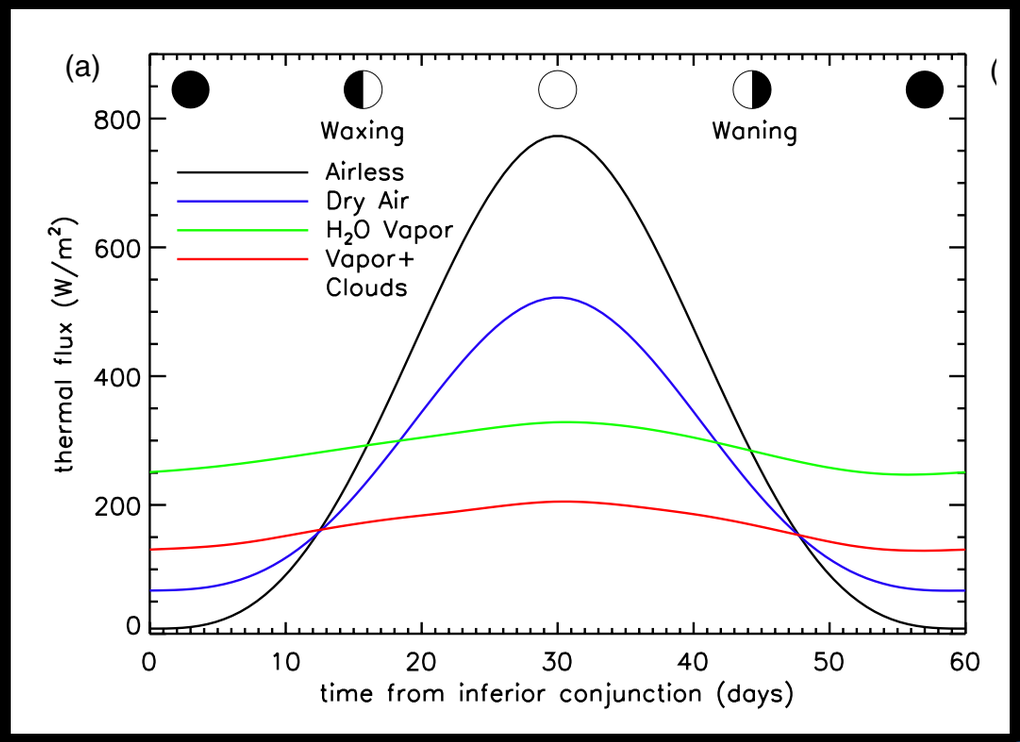
Potential to measure broad-band phase curves for GJ 1214b and a number of super Earths

ATMOSPHERIC CIRCULATION IN THE ERA OF TESS AND JWST



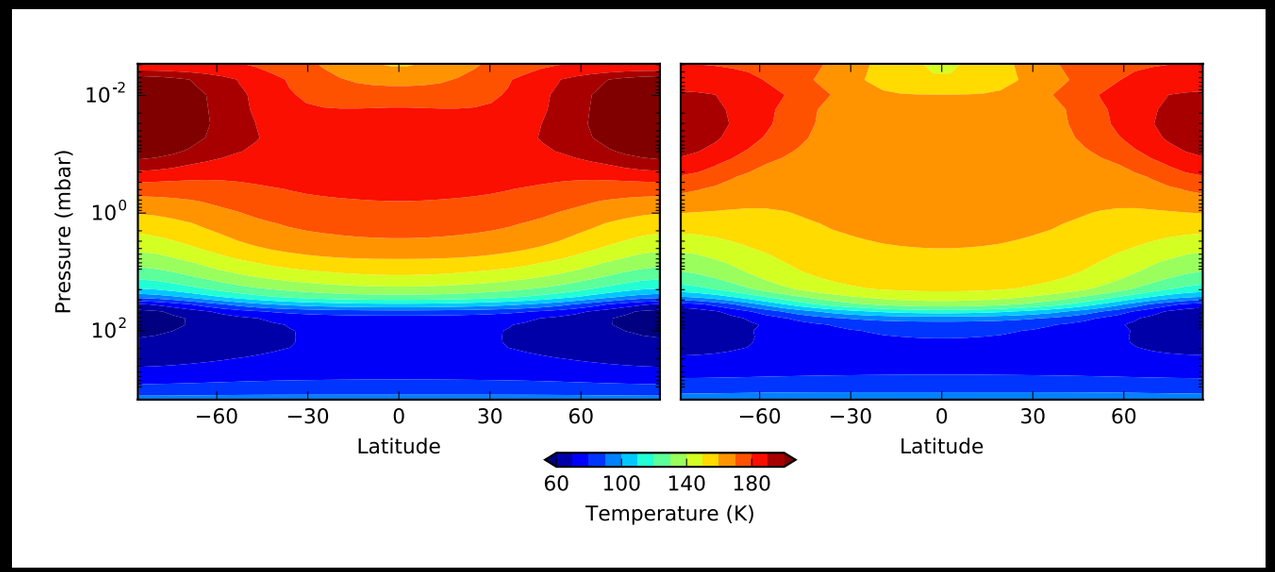
Ricker et al. (2014)

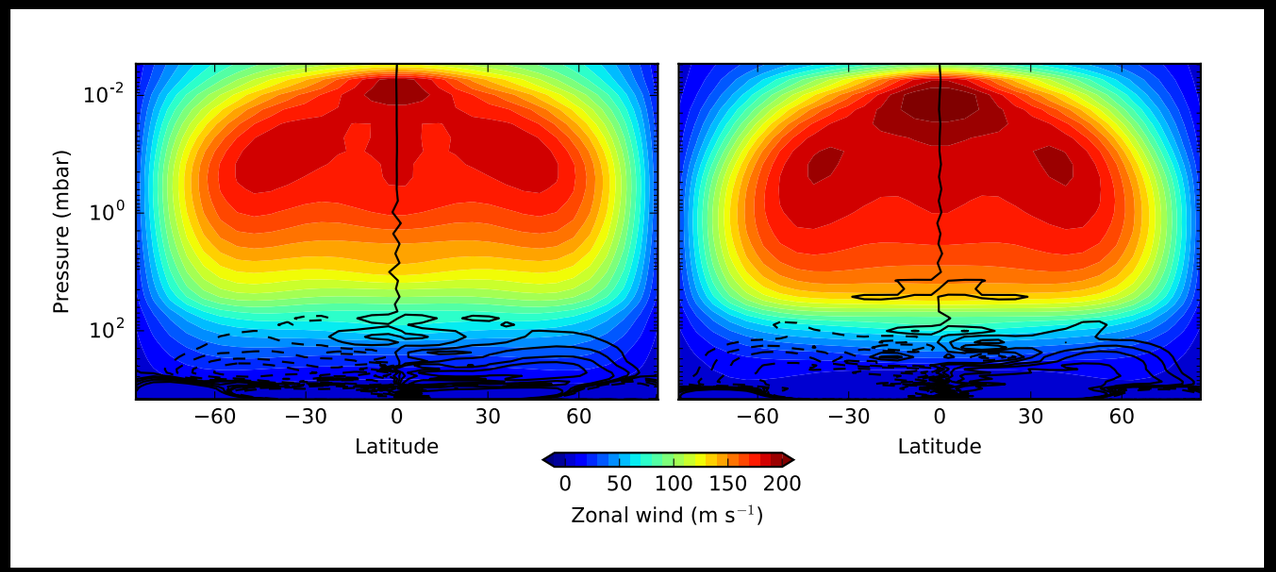


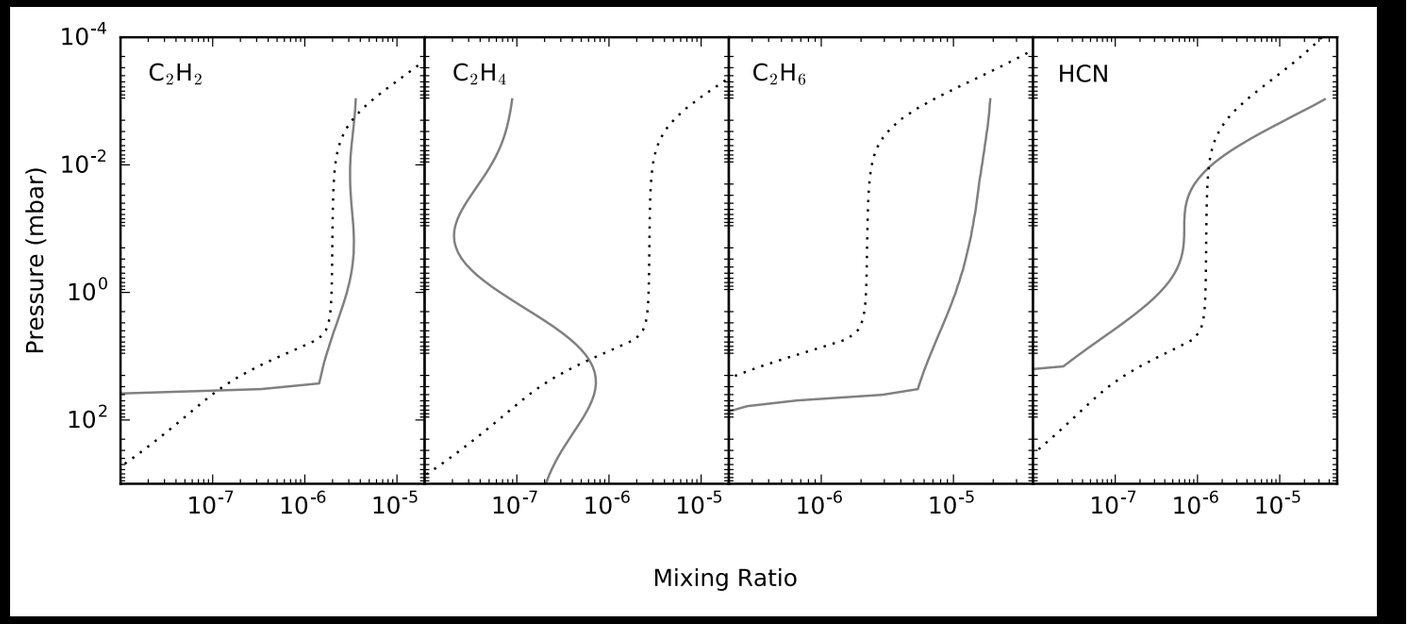


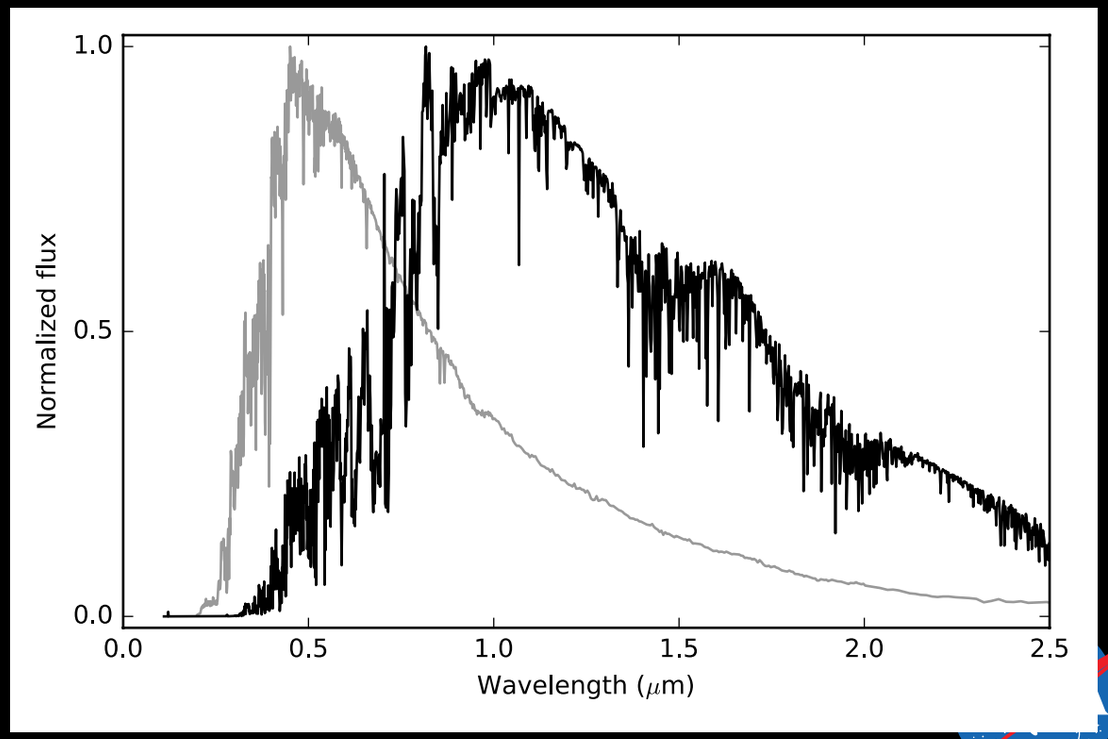
Yang et al. (2013)

CIRCULATION AND CHEMISTRY OF TITAN-LIKE EXOPLANETS





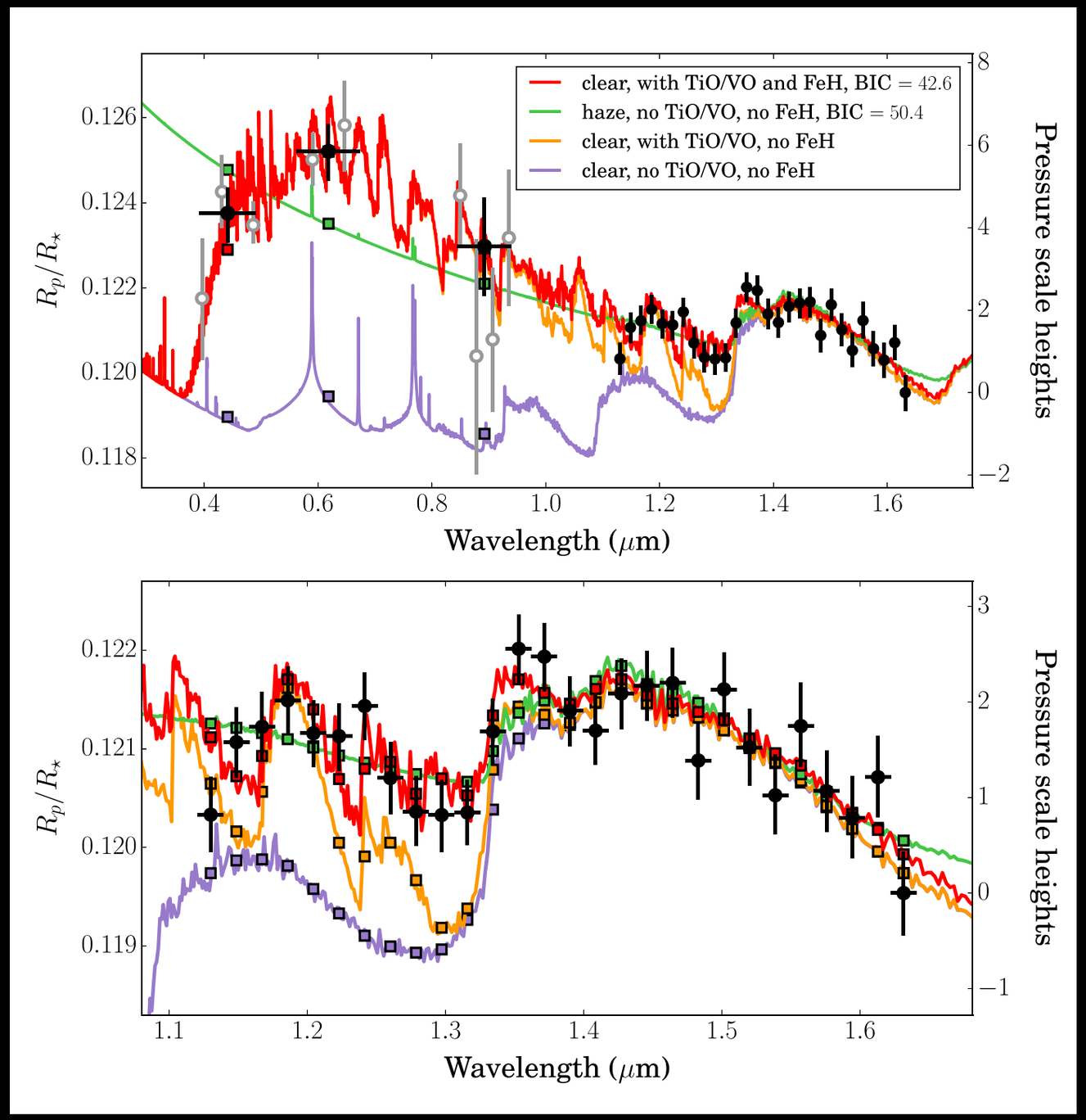




Lora, Kataria, et al. in prep

TESTING COLD TRAPPING WITH WASP-121B

Evans et al. 2016, ApJ



CONCLUSIONS

- Atmospheric models can be used to constrain a wide range of observational data
  - More sophistication necessary as new and innovative observational techniques are developed
- There are still many outstanding questions to be answered
  - How does disequilibrium chemistry play a role in the circulation?
  - Where and how does magnetic drag play a role?
  - What is the nature of exoplanet clouds?

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