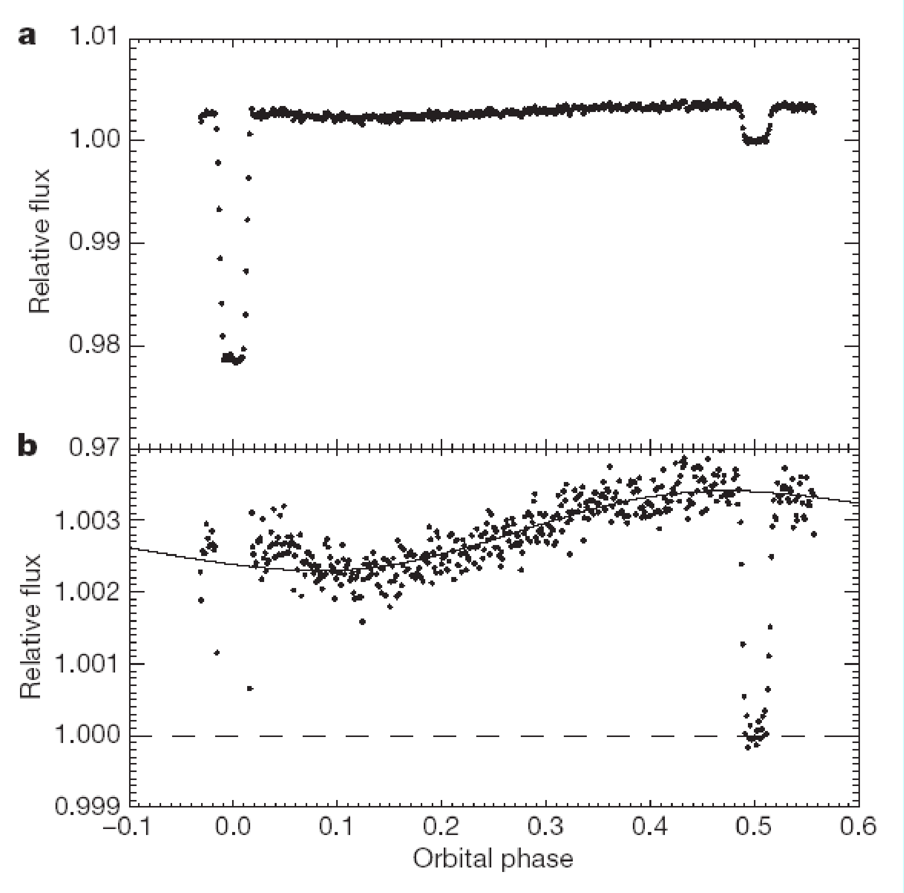
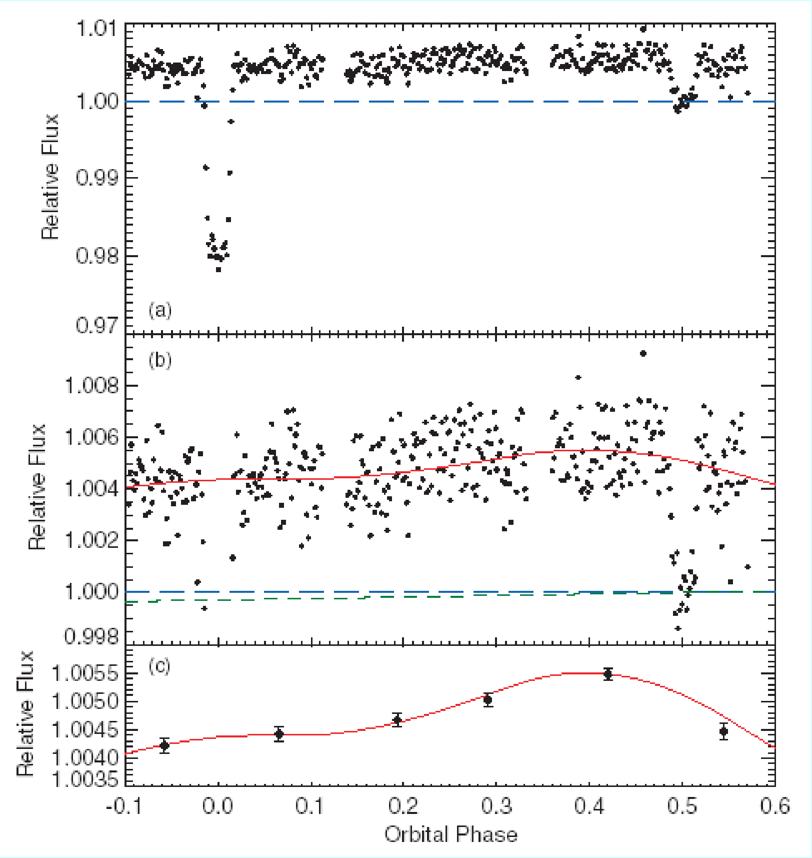
Atmospheric Dynamics of Exoplanets: Status and Opportunities

Adam Showman
University of Arizona

Collaborators: Jonathan Fortney, Lorenzo Polvani, Yuan Lian, Mark Marley, Nikole Lewis, Daniel Perez-Becker, Yohai Kaspi

Spitzer light curves for HD 189733b

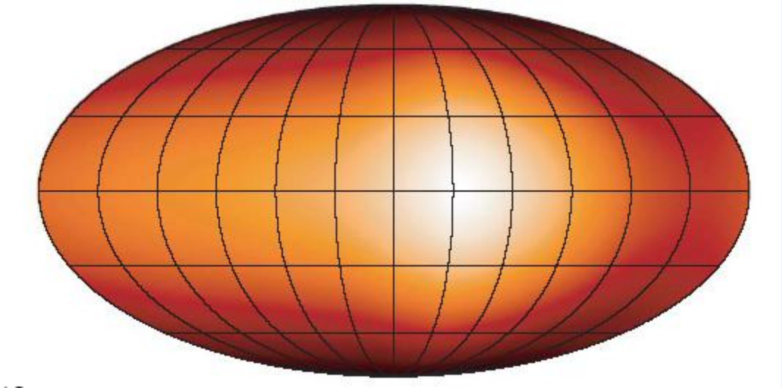




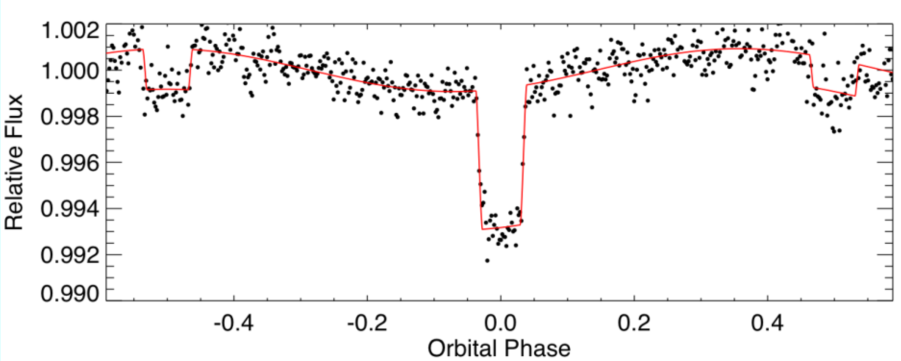
Knutson et al. (2007, 2009)

8 μm

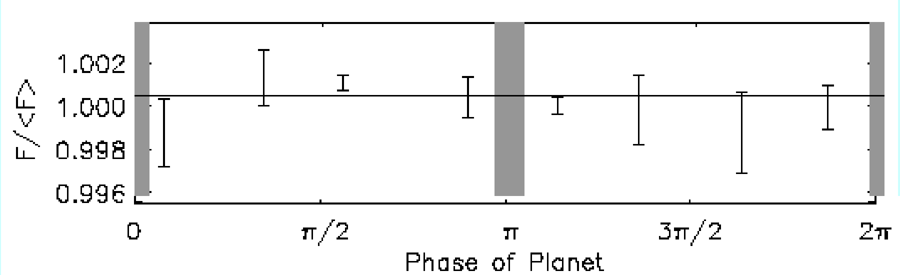
24 μm



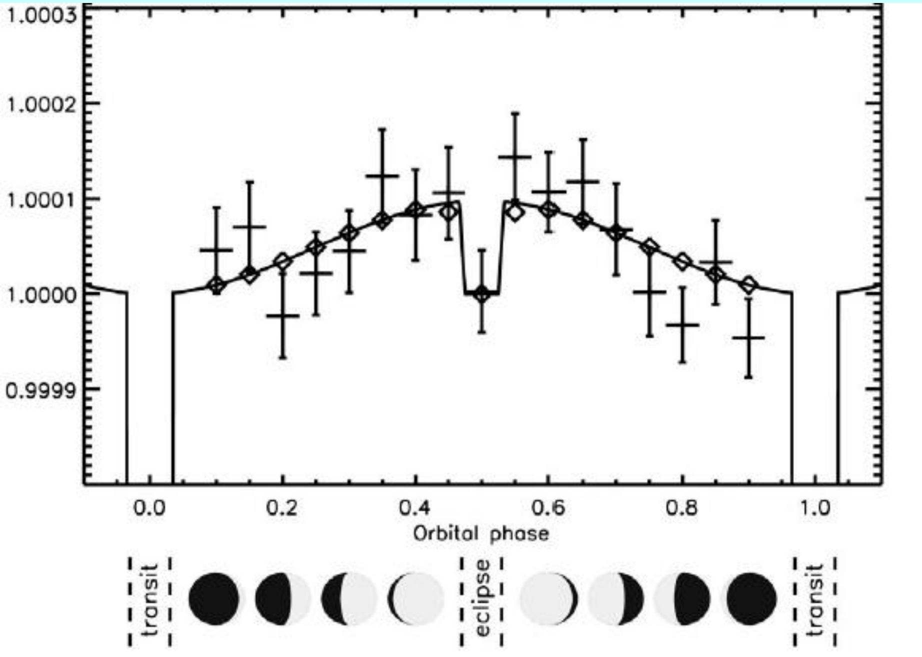
Lightcurves for hot Jupiters



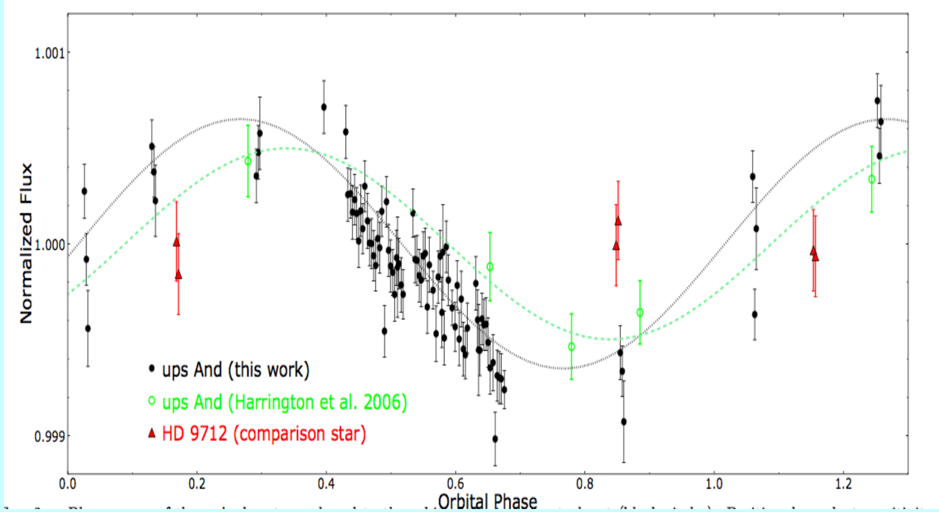
HAT-P-7b (Knutson et al., unpublished; Borucki et al. 2009)



HD209458b (Cowan et al. 2007)

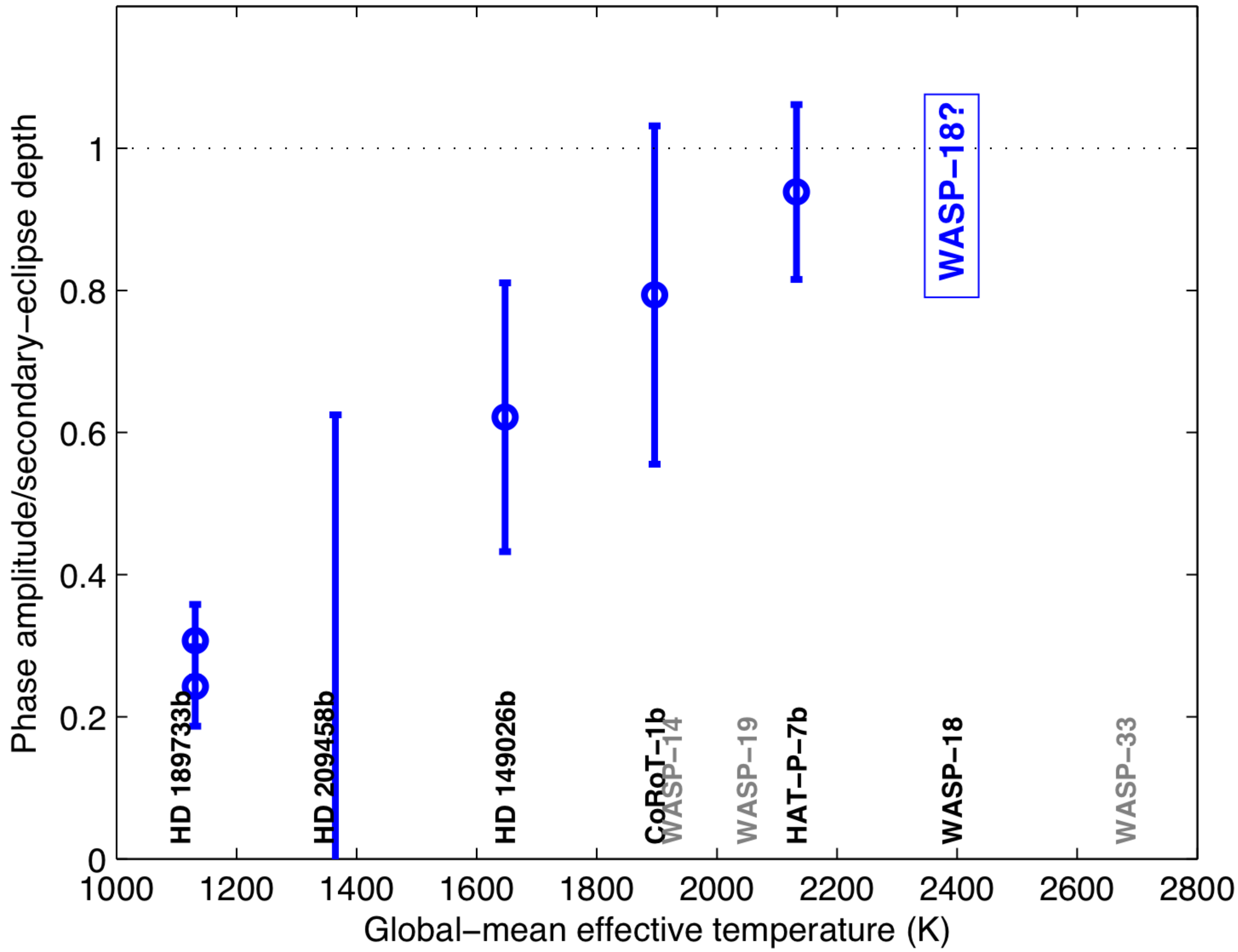


CoRoT-1b (Snellen et al. 2009)

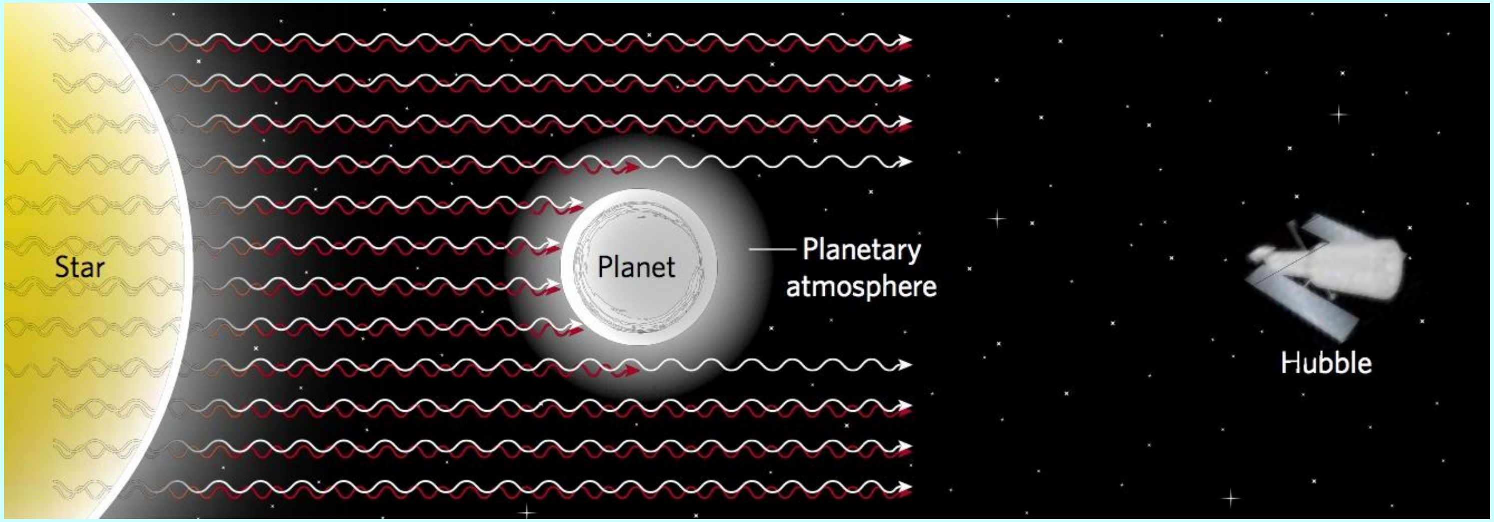


Ups And b (Crossfield et al. 2010)

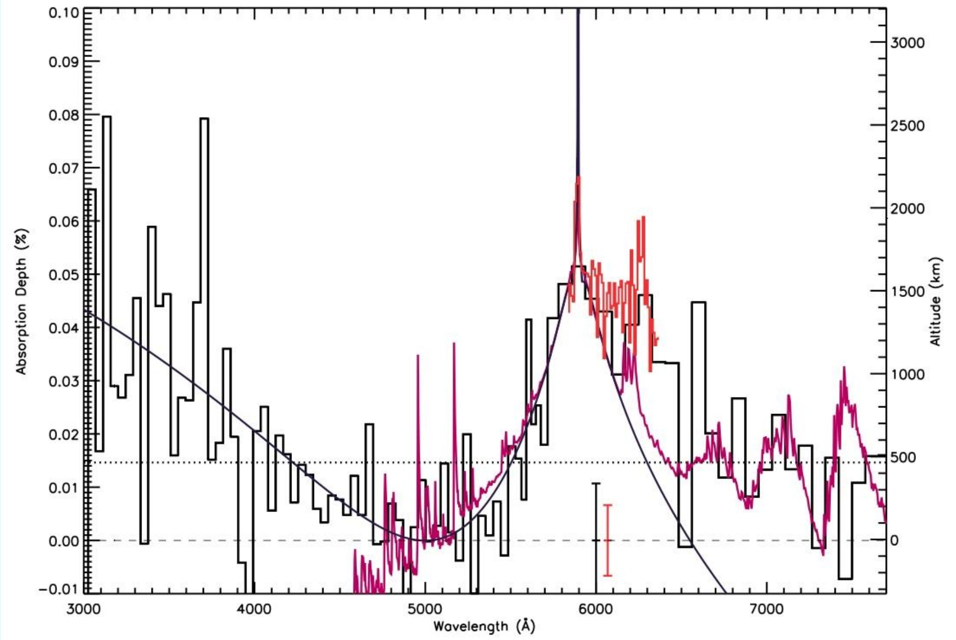
Dependence of day-night flux contrast on effective temperature

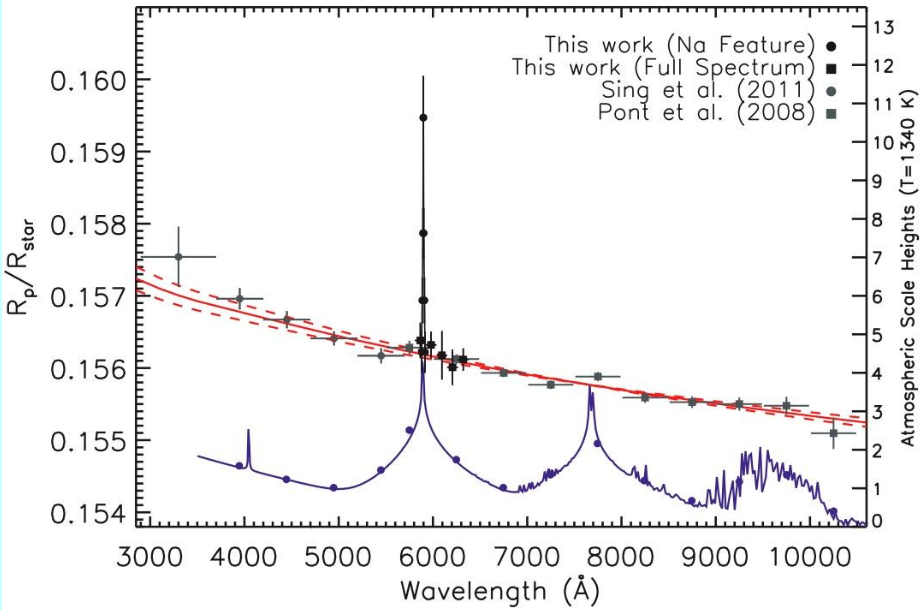


Exoplanet characterization: Transit spectroscopy



Showman (2008)

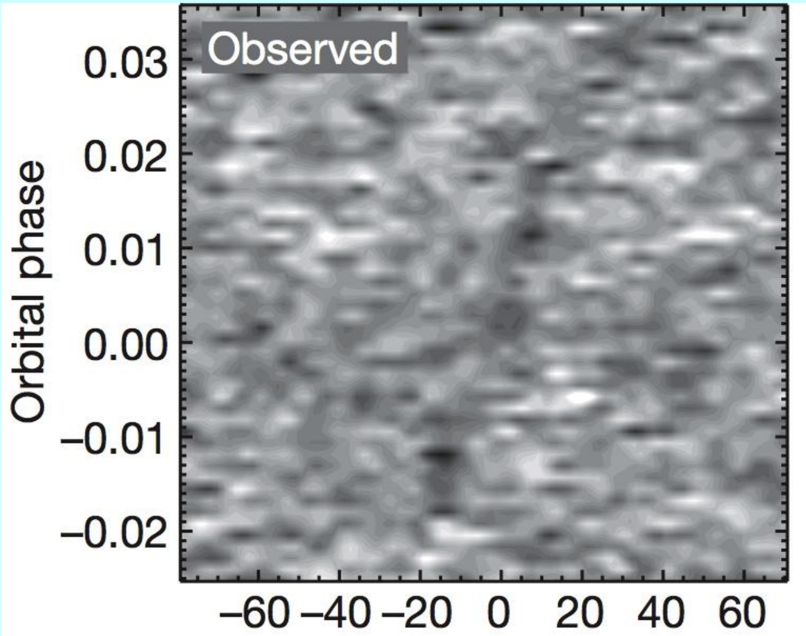


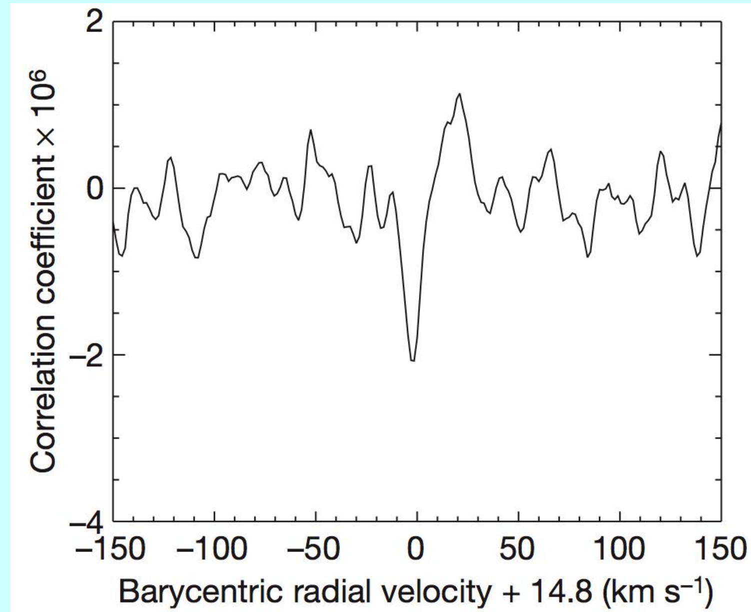


Sing et al. (2008, 2009), Vidal-Madjar et al. (2011), Huitson et al. (2012),Gibson et al. (2012), Barman (2007), Tinetti et al. (2007), Swain et al. (2008),…..

Doppler detection of winds on HD 209458b?

- Snellen et al. (2010, Nature) obtained high-resolution 2 μm spectra of HD 209458b during transit with the CRIRES spectrograph on the VLT

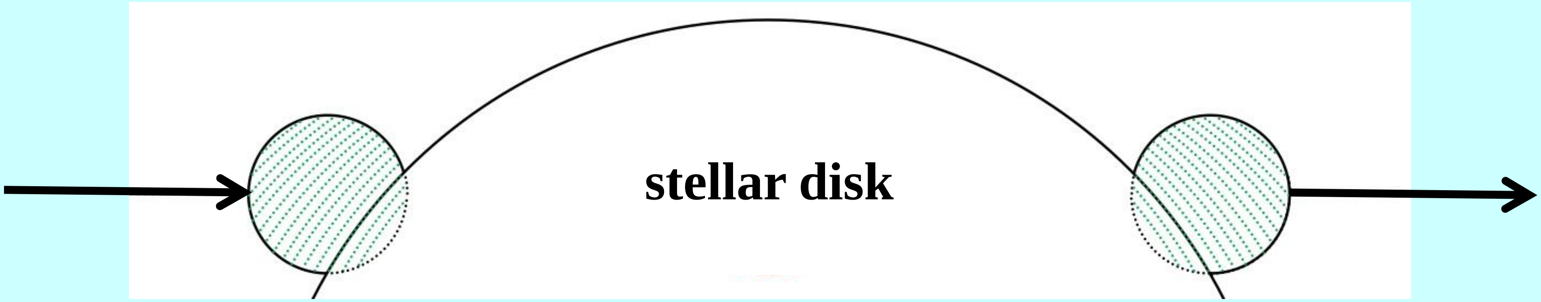


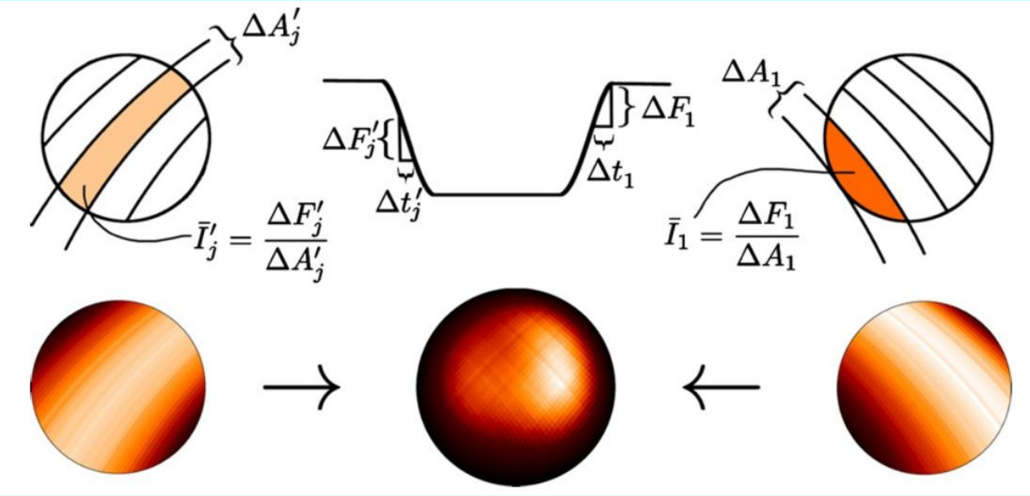


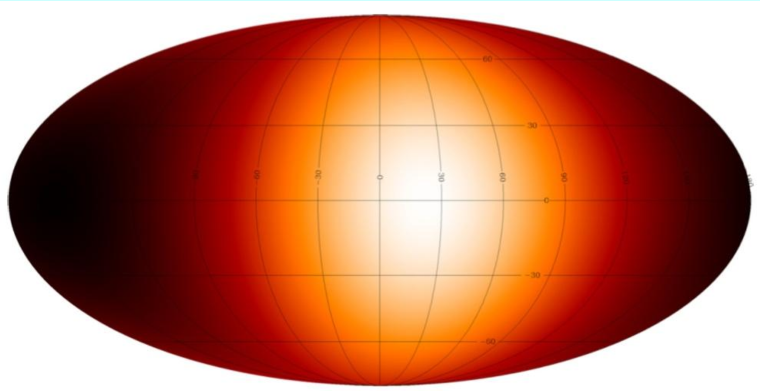
- Tentative detection of ~2 km/sec blueshift in CO lines during transit of HD 209458b

- Interpreted as winds flowing from day to night at high altitude (~0.01-0.1 mbar)

Eclipse mapping







Majeau et al. (2012), de Wit et al. (2012)

Motivating questions

- **What are the fundamental dynamics of this novel, highly irradiated circulation regime?**

- **What is the temperature distribution of exoplanets? What are mechanisms for controlling the day-night temperature contrast on hot Jupiters? What is the mechanism for displacing the hottest regions on HD 189733b?**

- **What are the fundamental wind regimes? Are there regime transitions, and if so, what causes them? What is the connection to dynamical regimes of solar-system planets?**

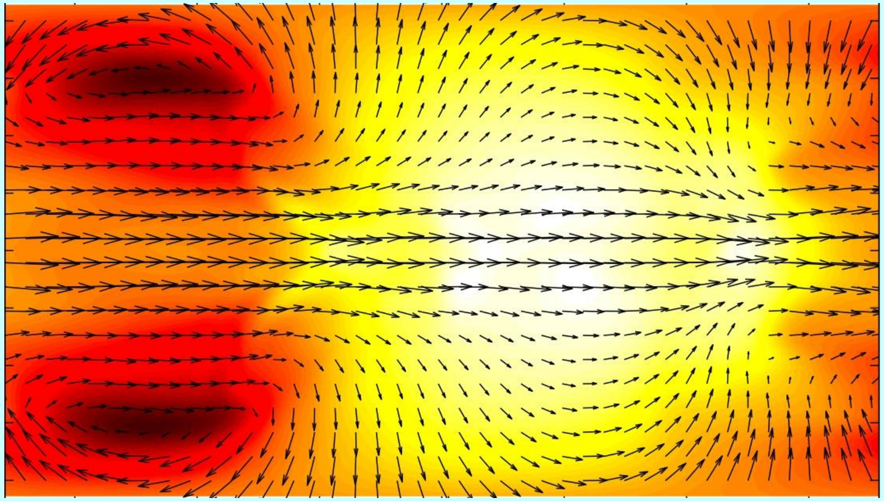
- **How does the circulation interact with the interior? Does it affect the evolution and radius?**

- **What processes control mixing in hot-Jupiter atmospheres? To what extent can chemistry *affect* and/or *probe* the dynamics?**

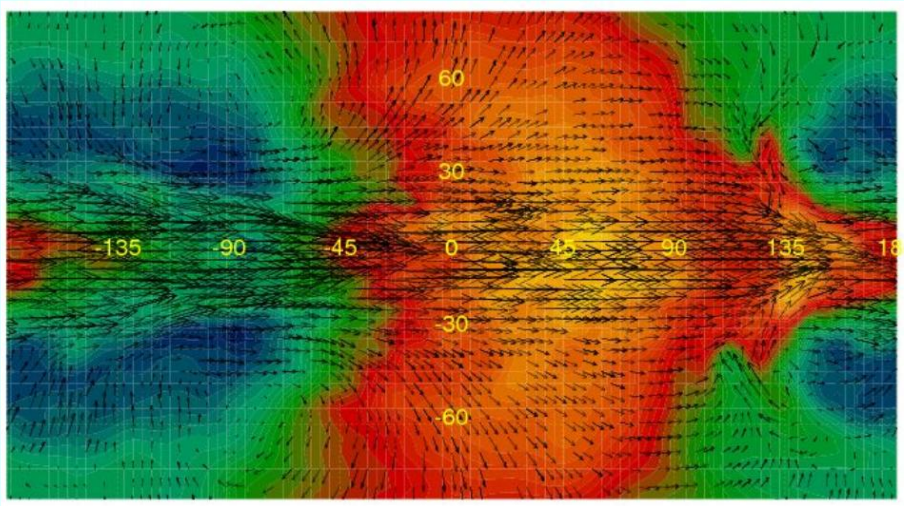
- **What is the atmospheric state and climate of terrestrial exoplanets? How does circulation help control habitability on these worlds?**

Spectroscopy, lightcurves, eclipse mapping, Doppler measurements, etc--both from the ground and space—can address these questions

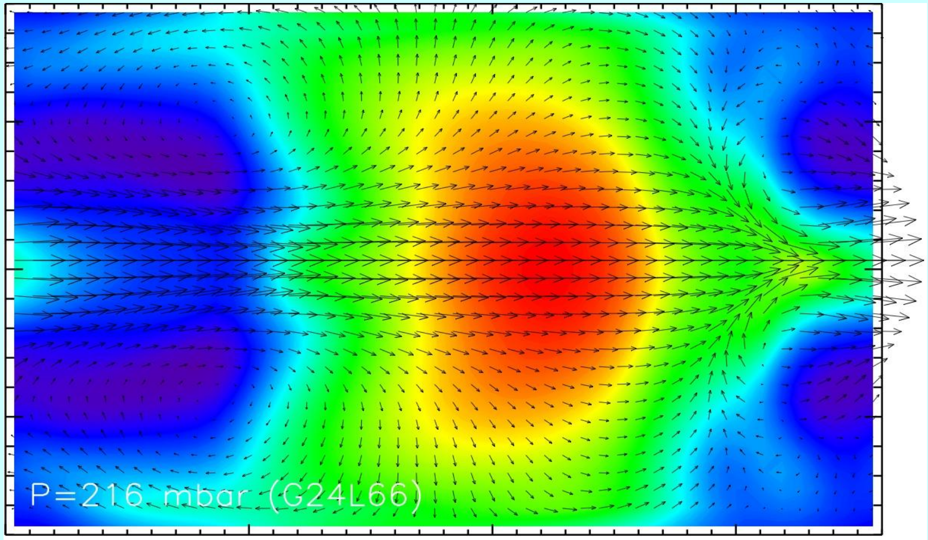
Hot Jupiter circulation models typically predict several broad, fast jets including equatorial superrotation



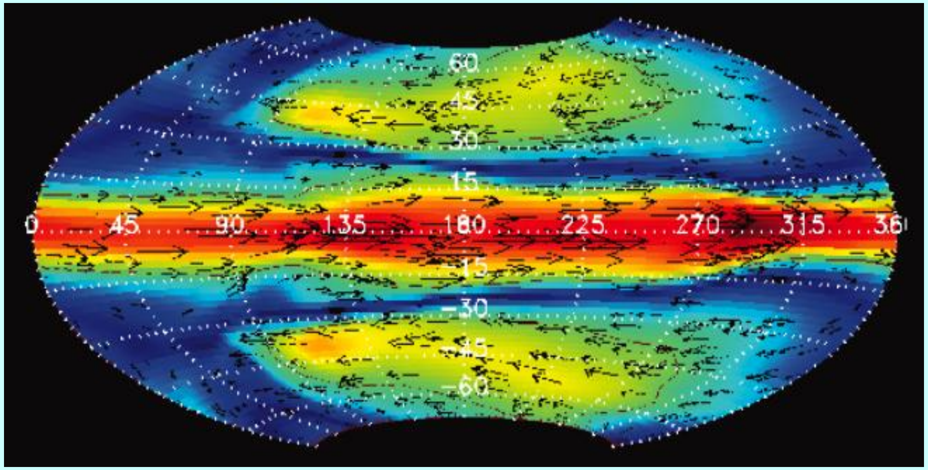
Showman et al. (2009)



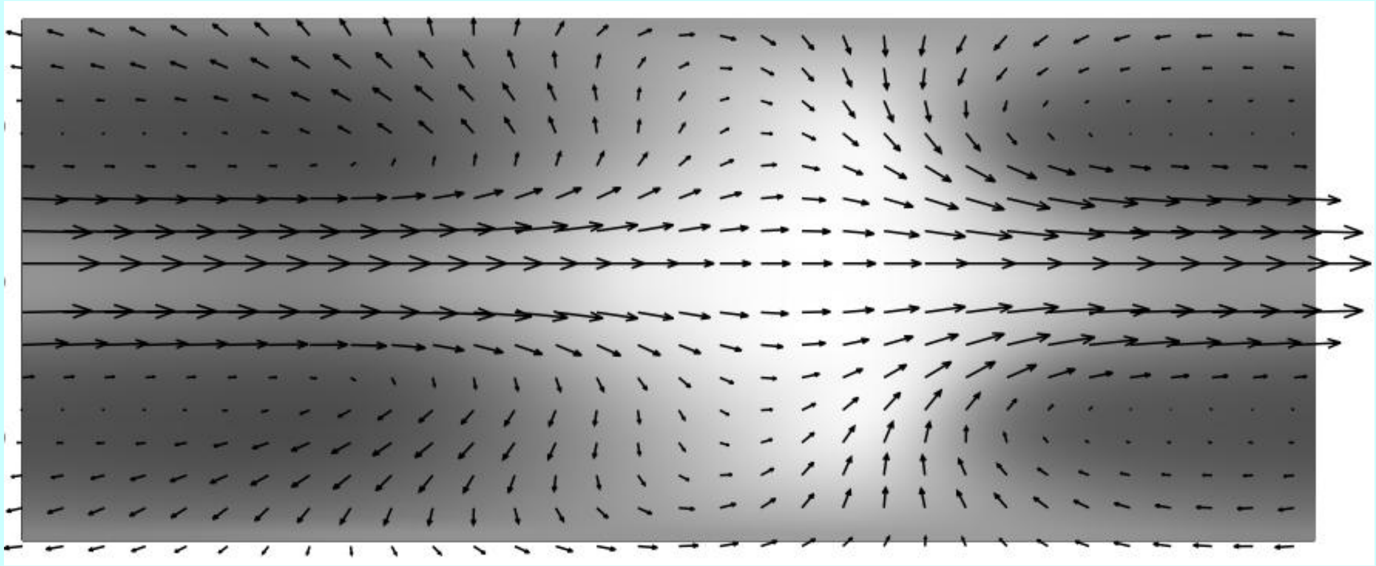
Rauscher & Menou (2010)



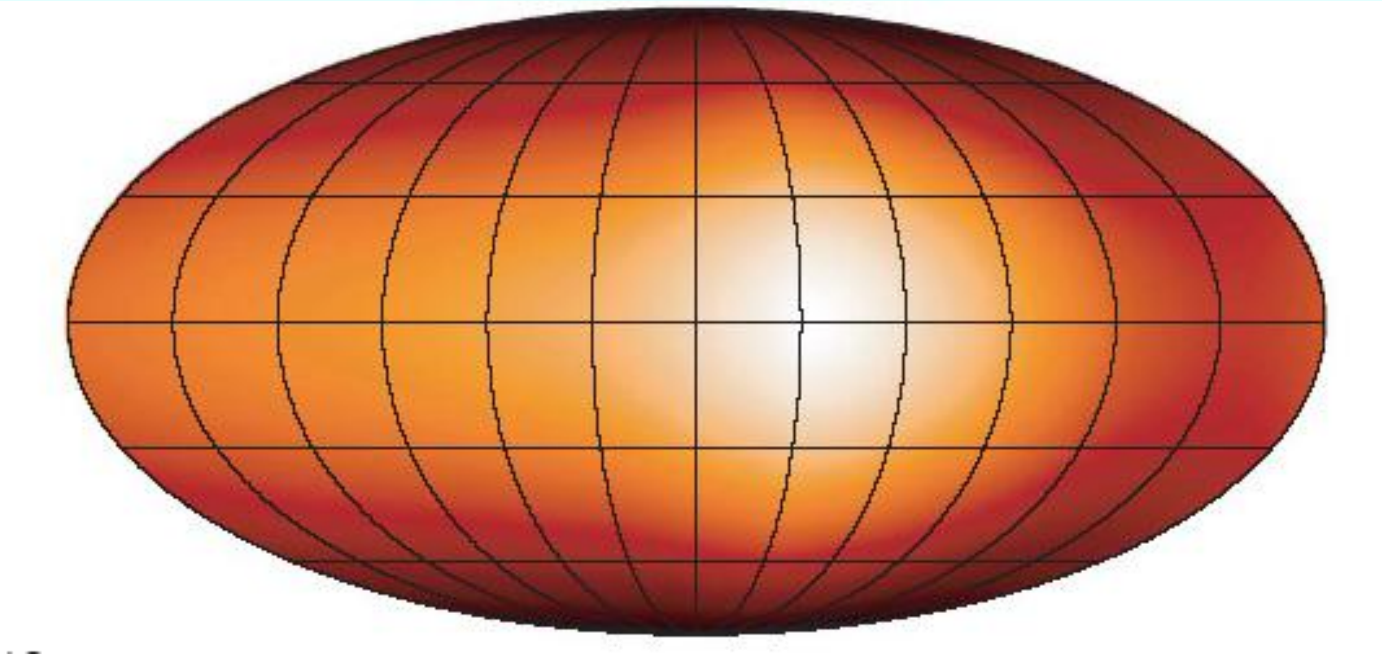
Heng et al. (2010)



Dobbs-Dixon & Lin (2008)

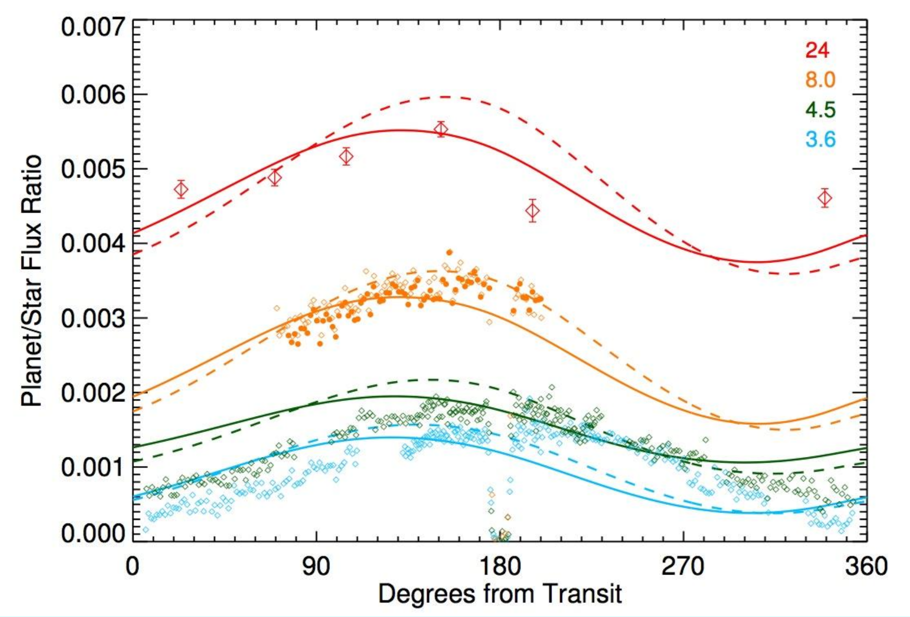


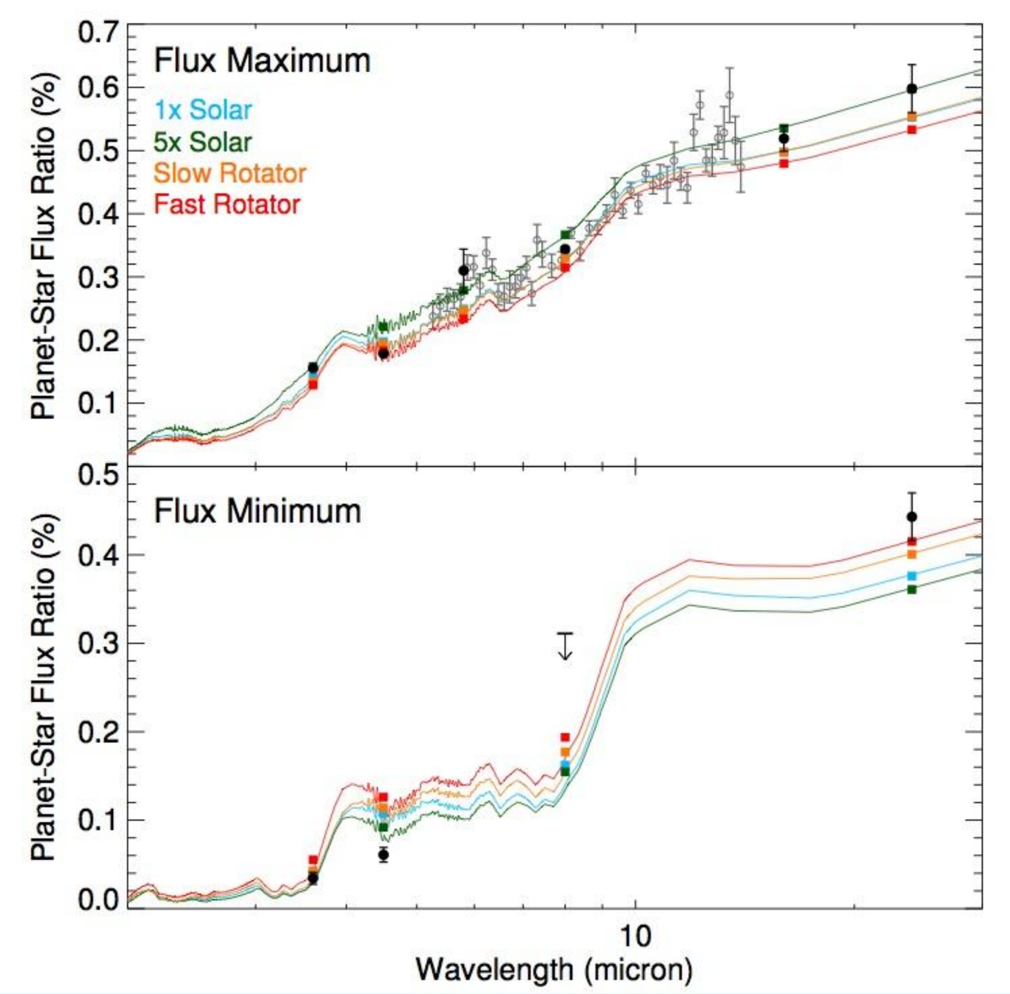
Showman & Guillot (2002)



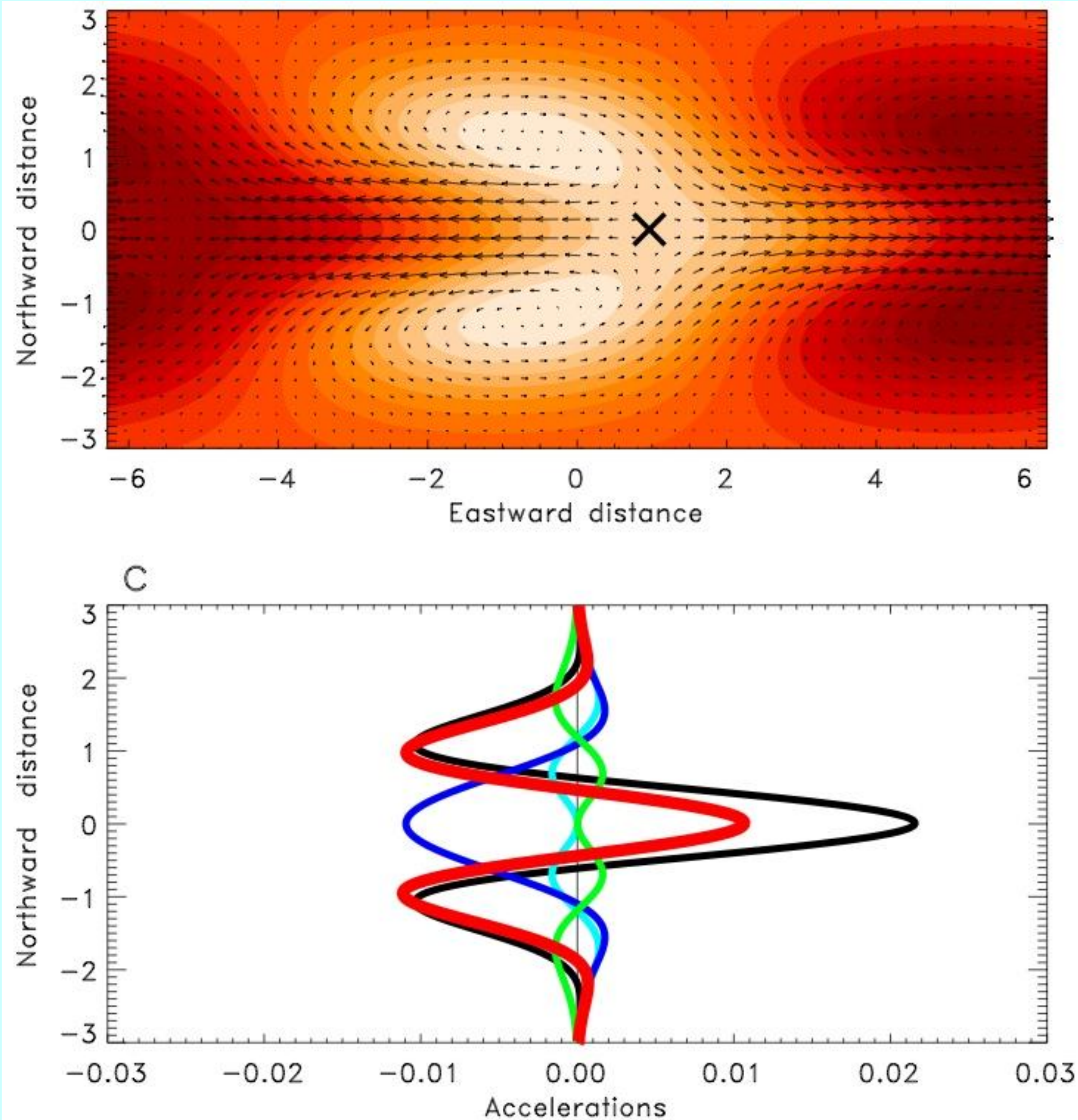
Knutson et al. (2007)

Data-model comparisons





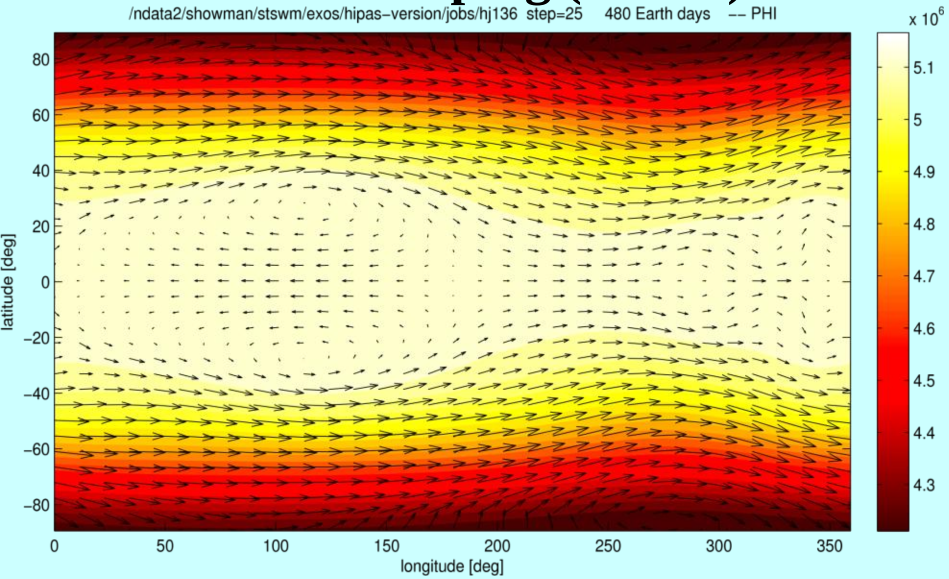
Knutson et al. (2012), Showman et al. (2009)



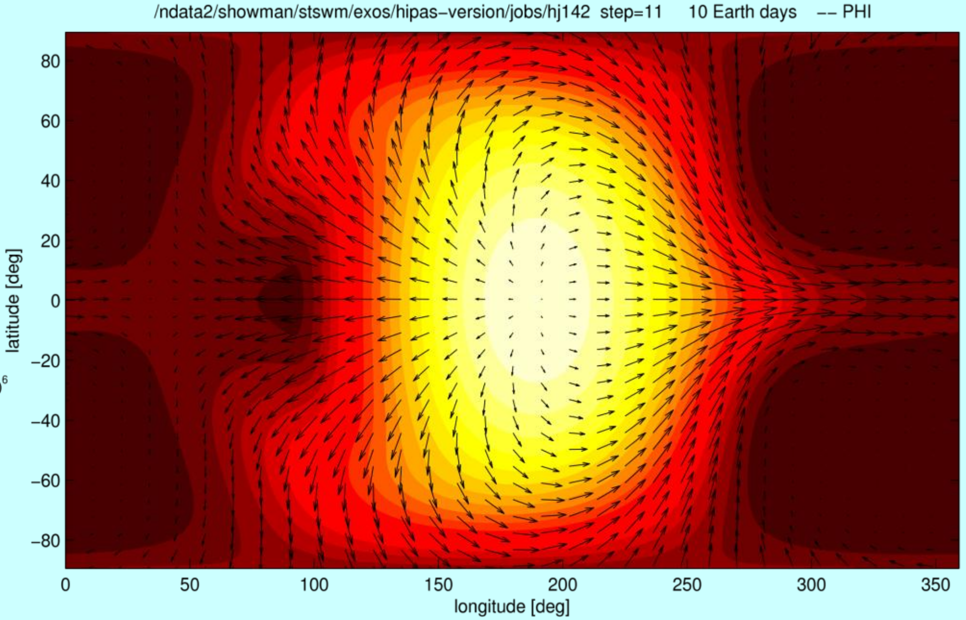
Showman & Polvani (2011), *ApJ* 738, 71

From Warm to Very Hot Jupiters

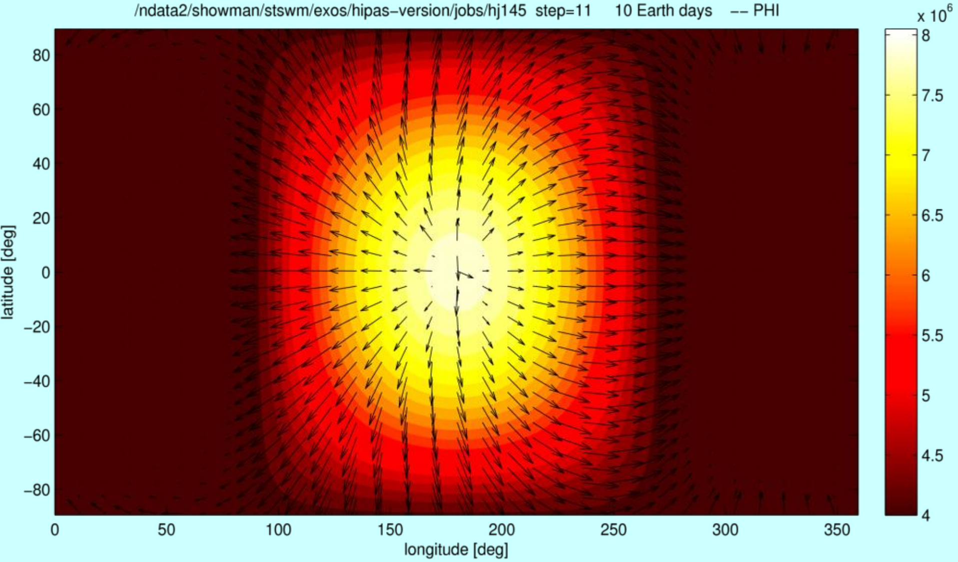
Weak damping (Warm)



Medium damping (Hot)

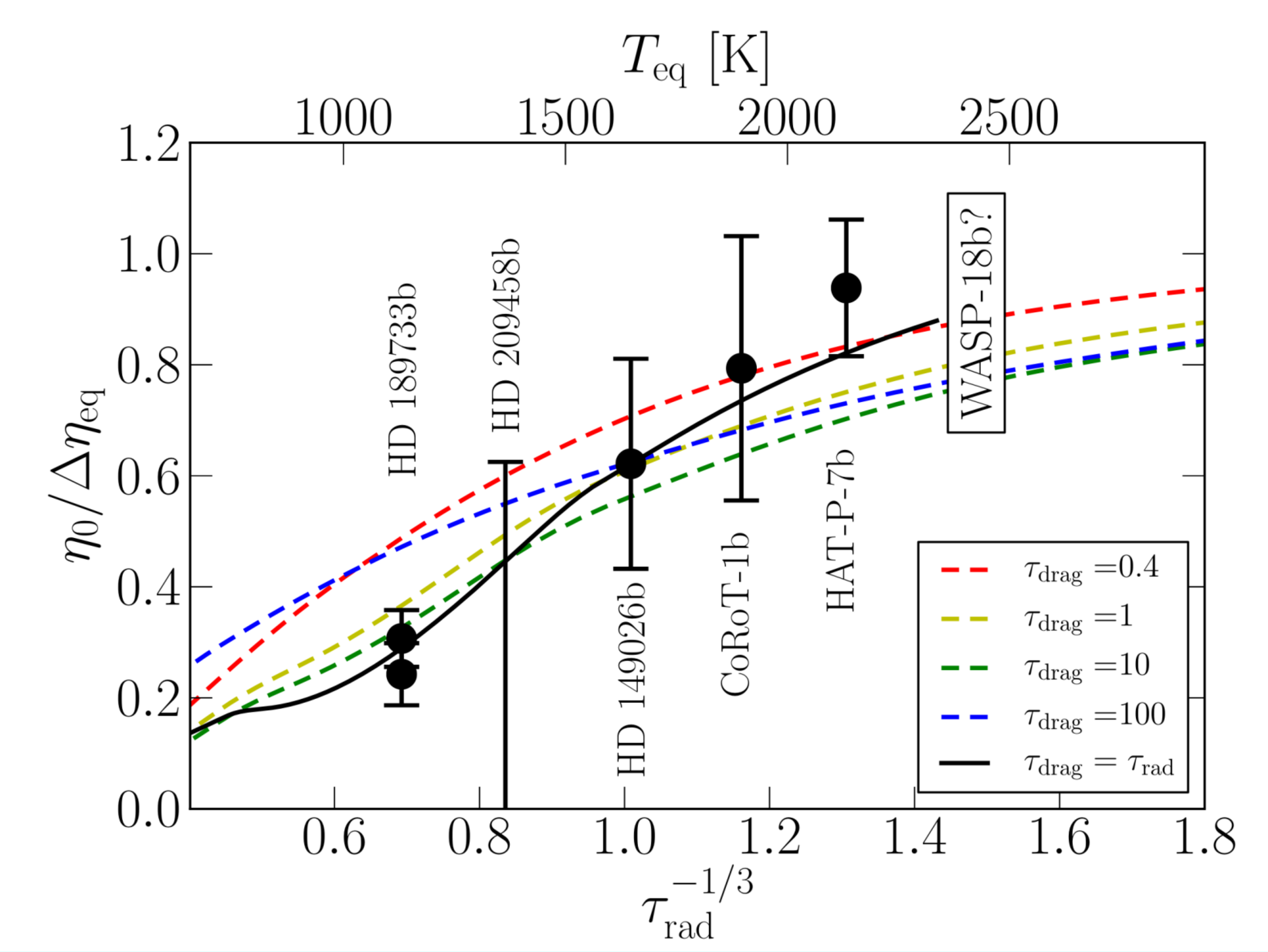


Strong damping (Very Hot)

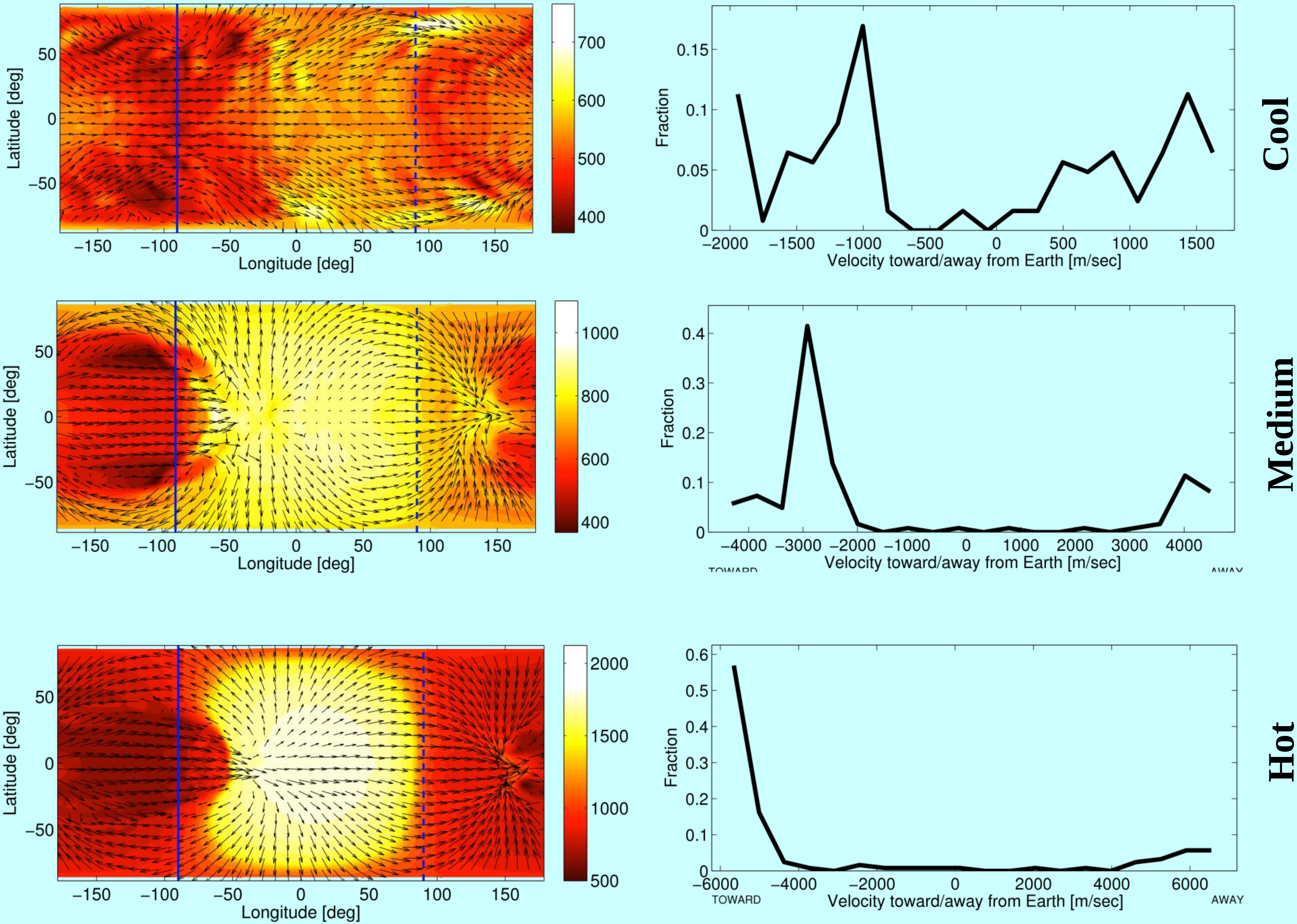


Showman et al. (2013), Perna et al. (2012)

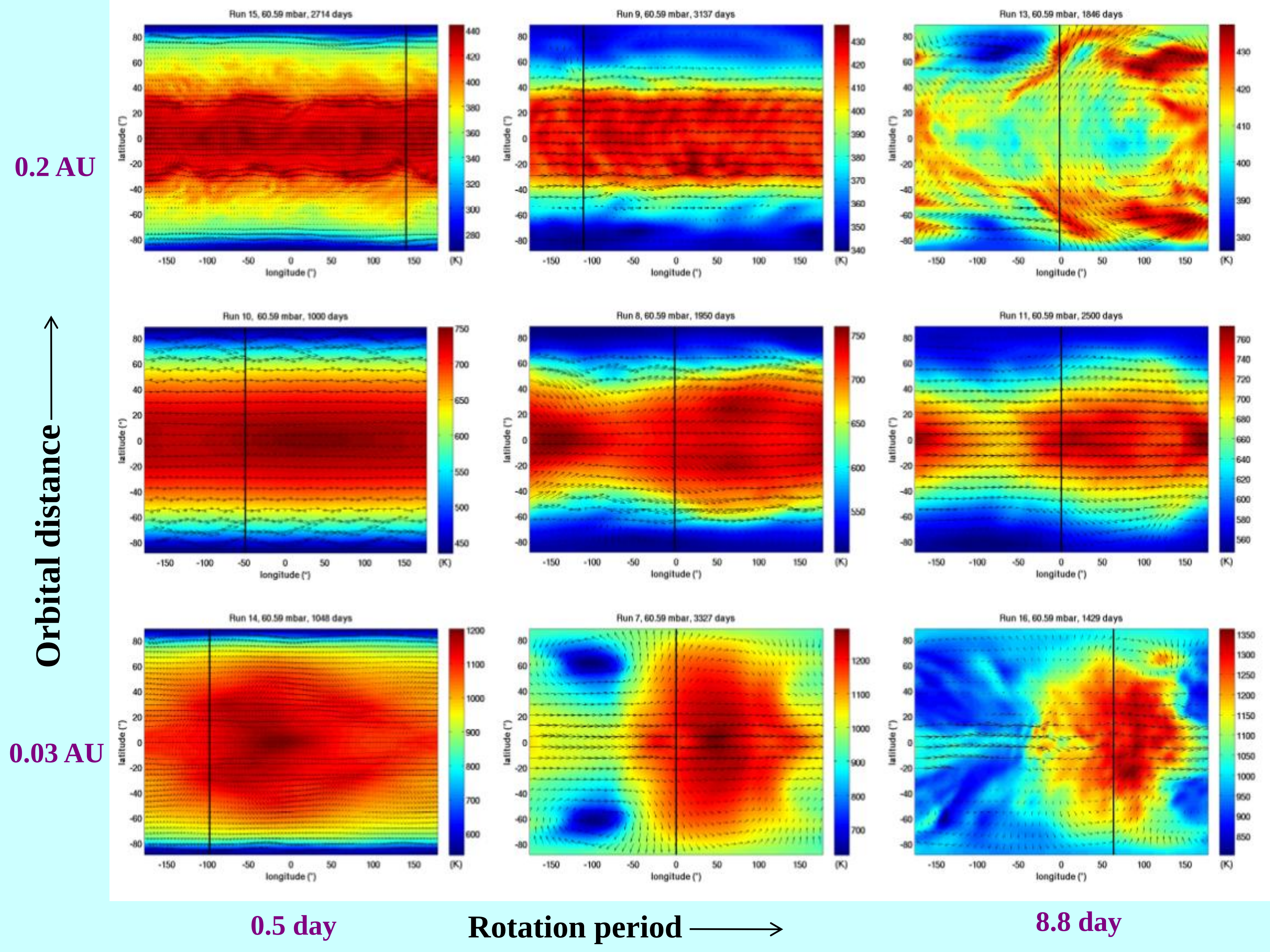
The model explains the emerging observational trend



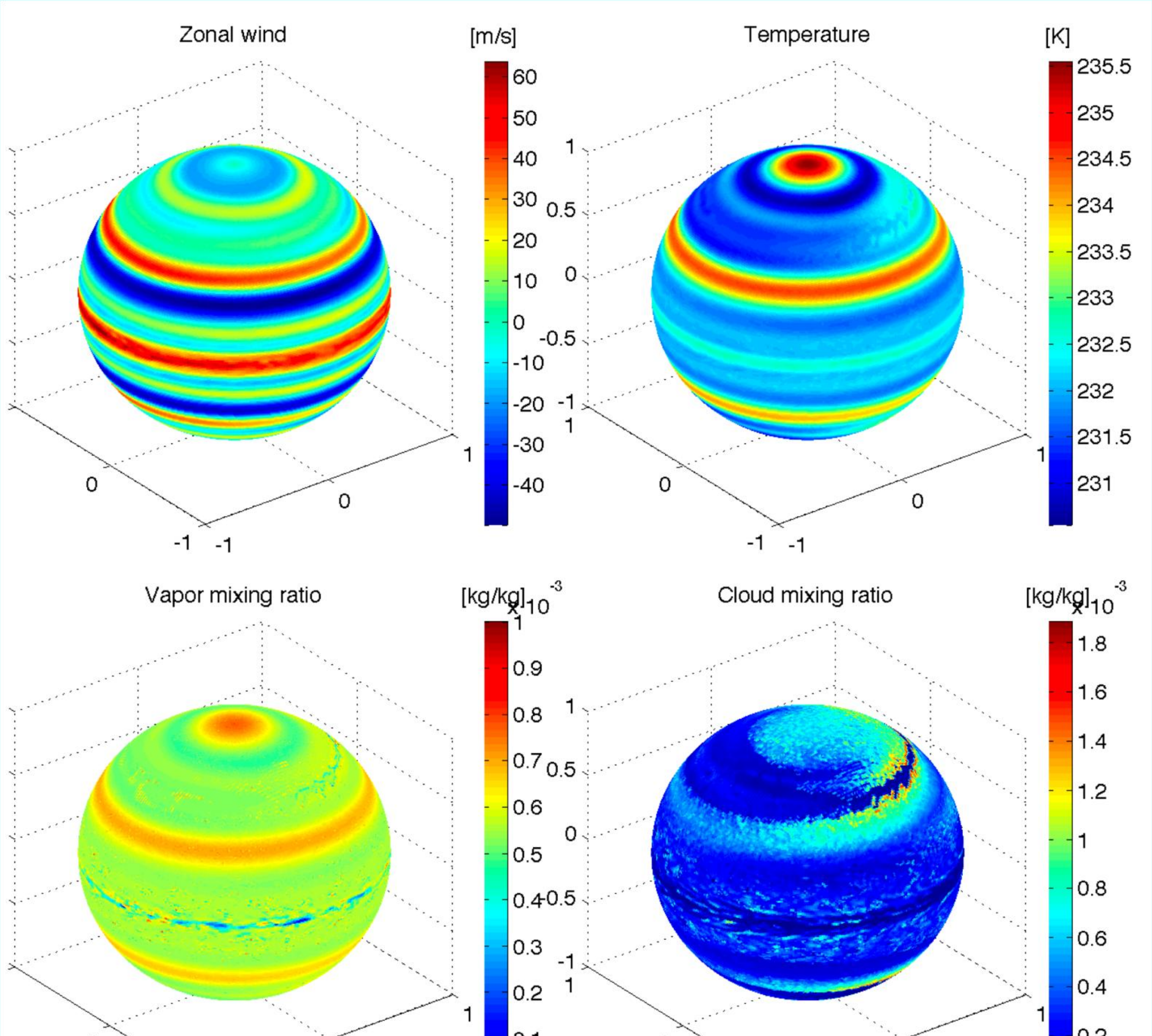
Perez-Becker & Showman (in prep)



Showman et al. (2013)


Run 15, 60.59 mbar, 2714 days
Run 9, 60.59 mbar, 3137 days
Run 13, 60.59 mbar, 1846 days
Run 10, 60.59 mbar, 1000 days
Run 8, 60.59 mbar, 1950 days
Run 11, 60.59 mbar, 2500 days
Run 14, 60.59 mbar, 1048 days
Run 7, 60.59 mbar, 3327 days
Run 16, 60.59 mbar, 1429 days
latitude (°)
longitude (°)
(K)
0.2 AU
Orbital distance
0.03 AU
0.5 day
Rotation period
8.8 day

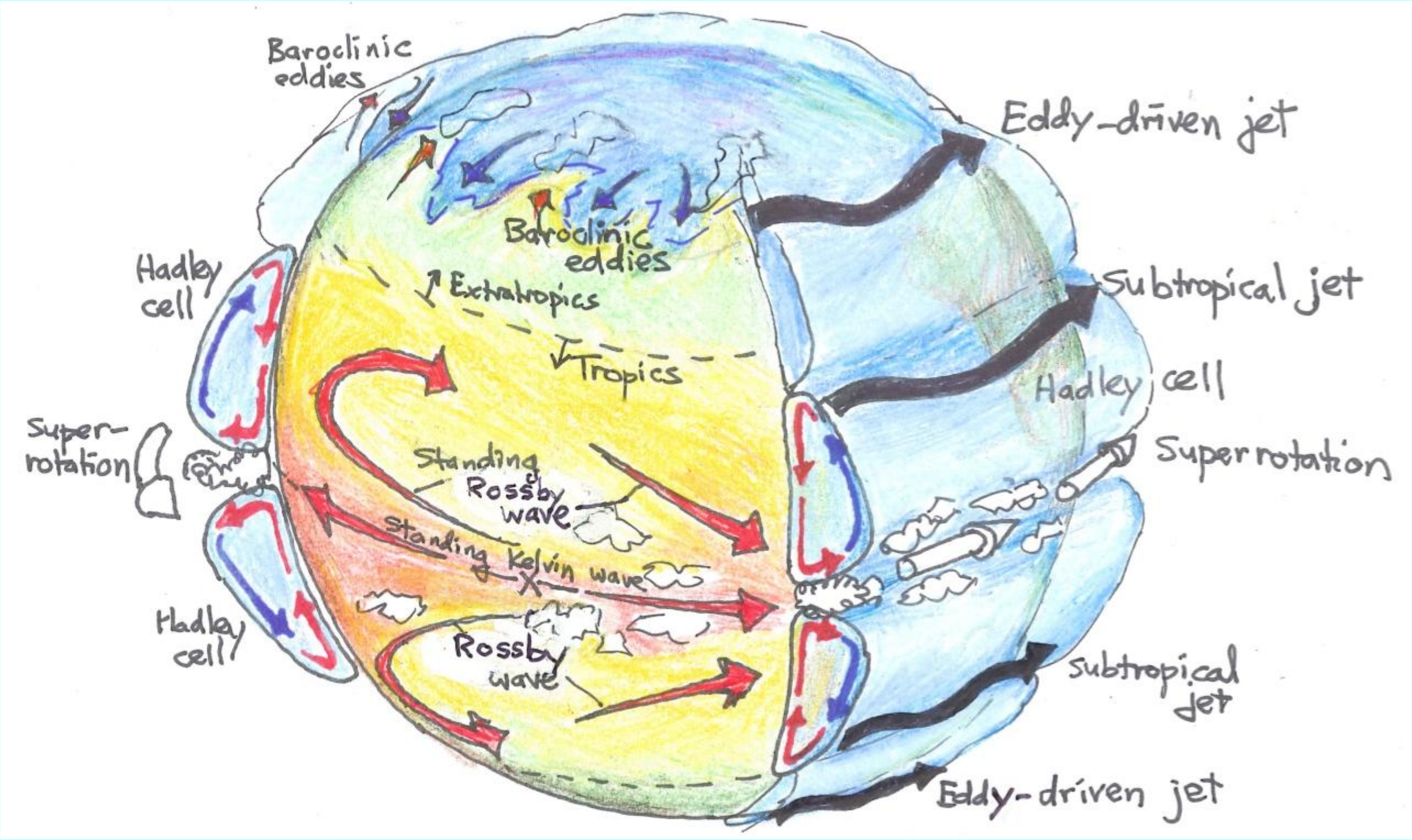
Jupiter models including hydrological cycle and water clouds



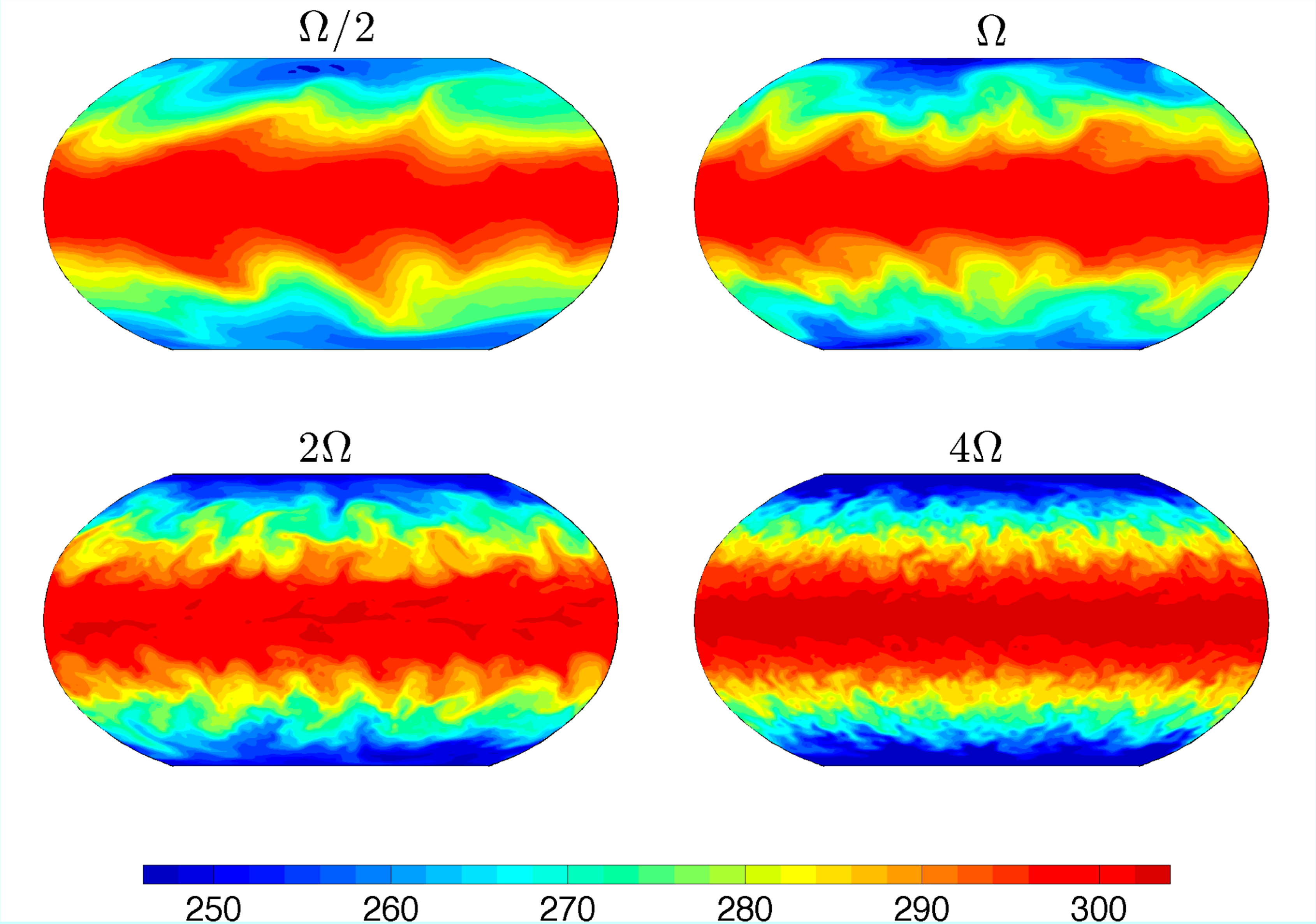
Lian & Showman (AGU poster)

What about smaller planets?

Atmospheric circulation of a generic terrestrial exoplanet



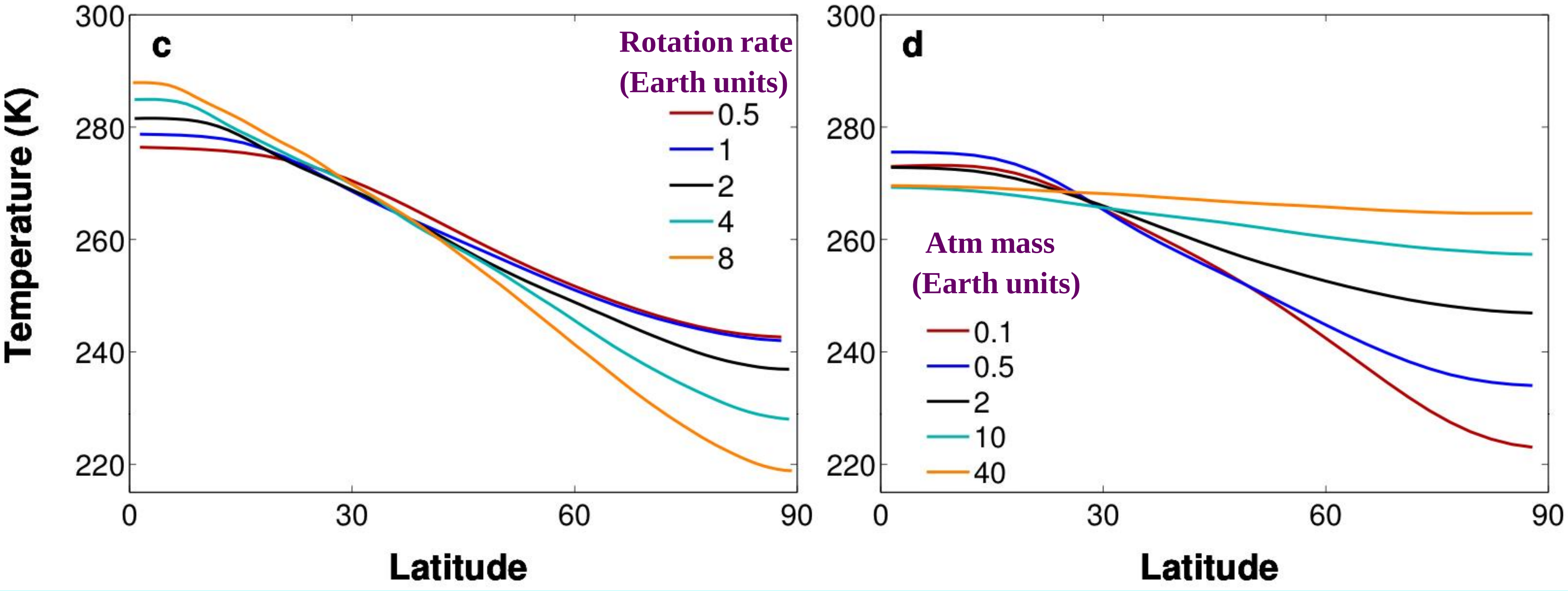
Temperature structure of Earth-like terrestrial planets at different rotation rates



Kaspi & Showman

Latitudinal temperature profiles of Earth-like exoplanets

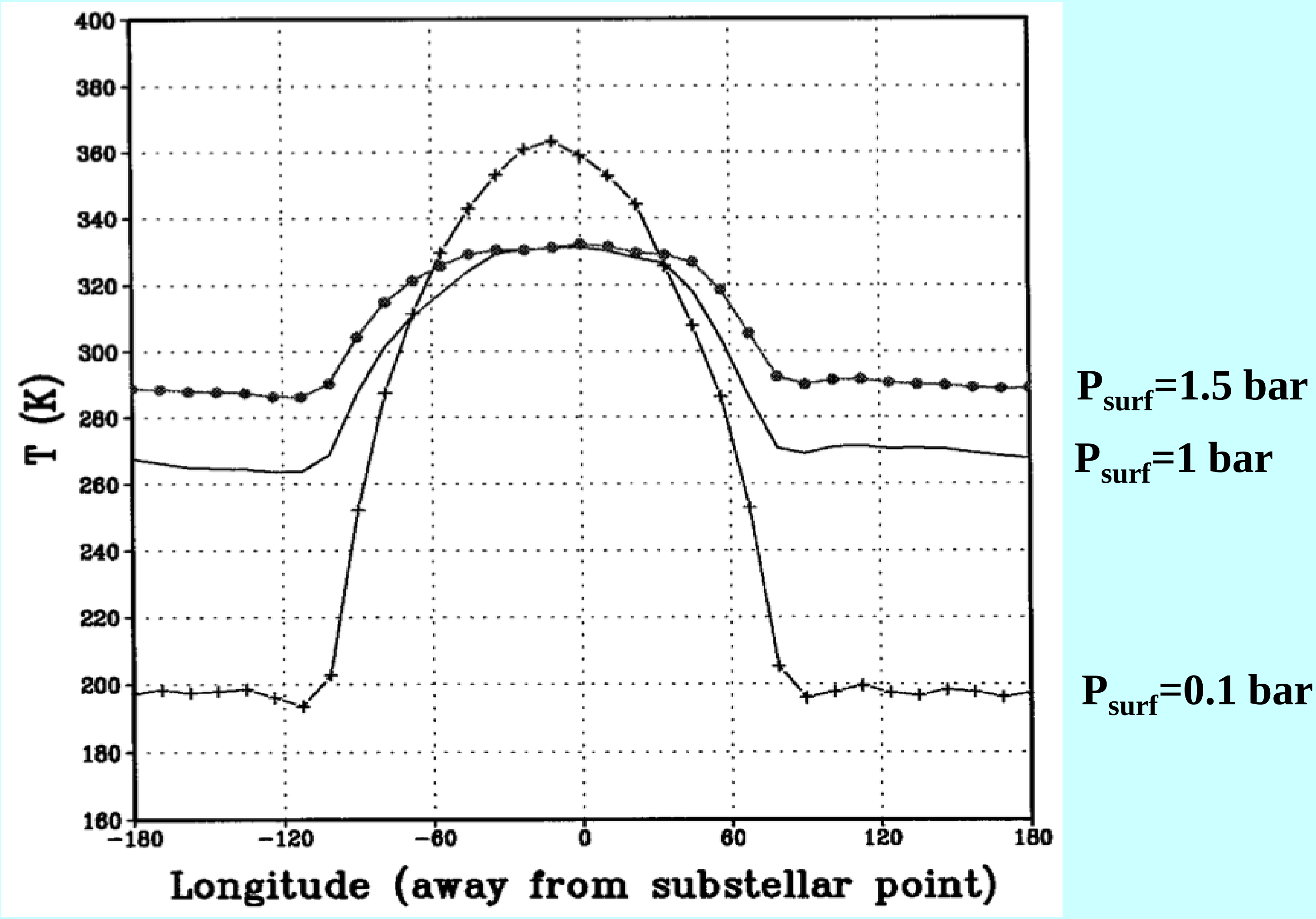
Varying rotation rate | **Varying atmospheric mass**



Earth-like planets with faster rotation and/or smaller atmospheric mass exhibit larger equator-pole temperature differences

Kaspi & Showman

Day-night temperature pattern on synchronously locked terrestrial exoplanets



Joshi et al. (1997); see also Merlis & Schneider (2010), Heng & Vogt (2011), Wordsworth et al. (2011), Leconte et al. (2013)

Implications of circulation for habitability of terrestrial exoplanets

- **Circulation controls the spatial patterns of temperature/humidity, and the existence and 3D distribution of clouds**

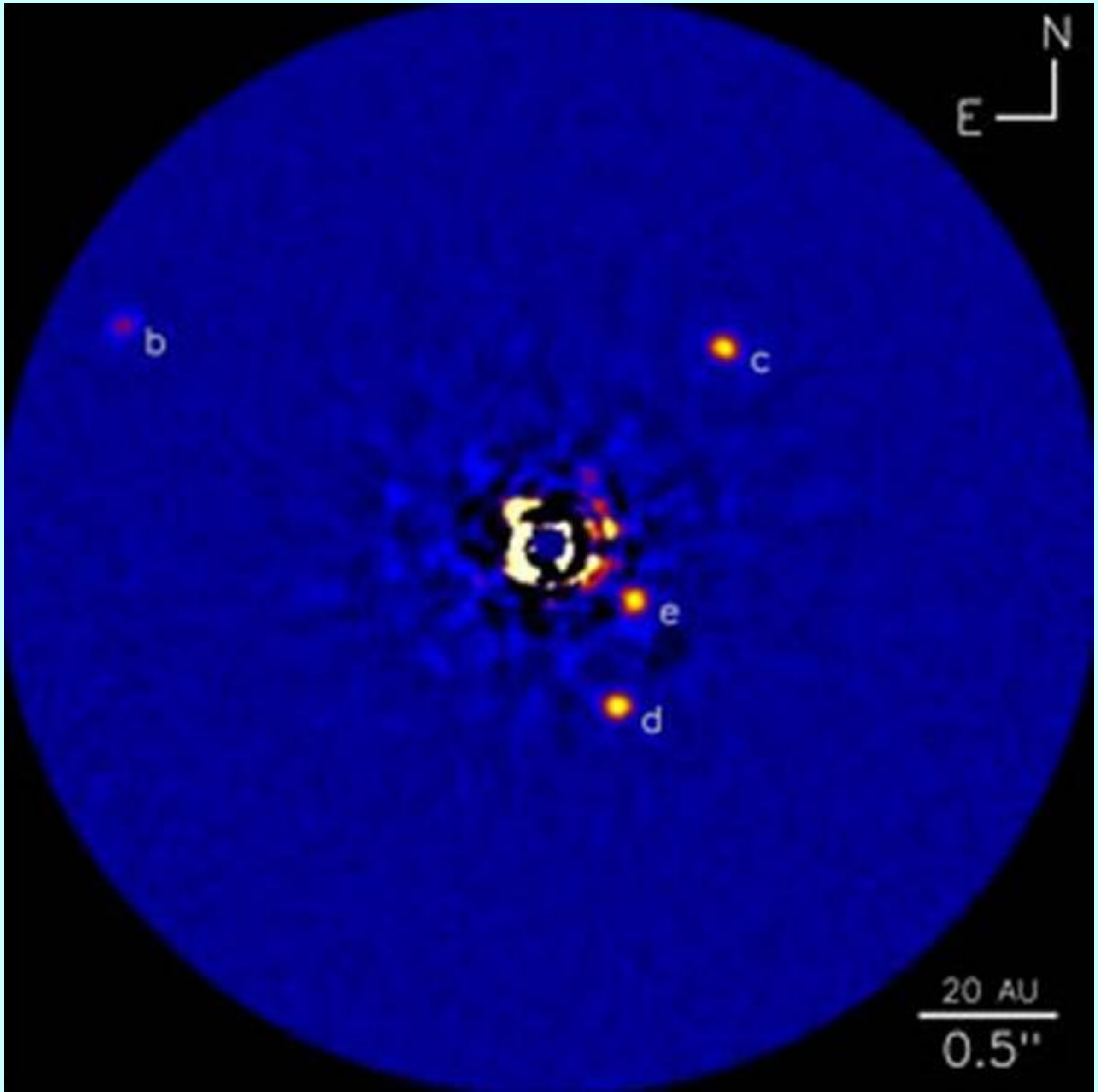
- **Susceptibility to atmospheric collapse or transitions to Snowball-Earth state depend on day-night and equator-pole temperature differences.**

- **Atmospheres may only be stable at surface pressures exceeding a critical value (~0.1 bar under Earth-like insolation)**

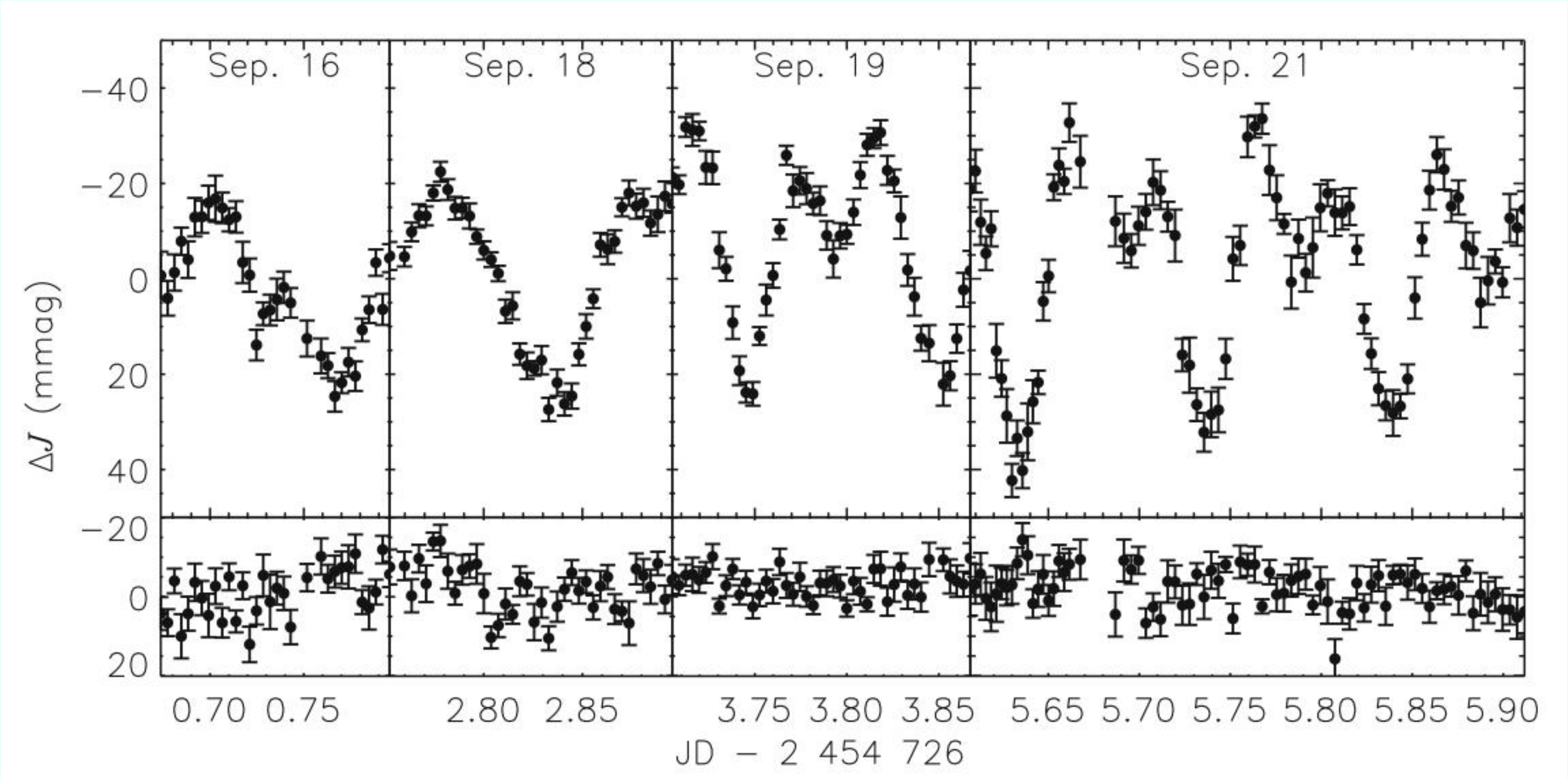
- **Cloud and humidity patterns help control albedo and greenhouse effect, hence mean surface temperature**

- **Cloud patterns, mean relative humidity, and existence/absence of local dry regions affect the transition to runaway greenhouse**

A new frontier: directly imaged planets and brown dwarfs



T2.5 brown dwarf SIMP 0136 shows weather variability



Artigau et al. (2009); see also Radigan et al. (2012), Buenzli et al. (2012), and many upcoming papers by Apai, Metchev, Radigan, Flateau, ….

Weather on brown dwarfs and directly imaged giant planets

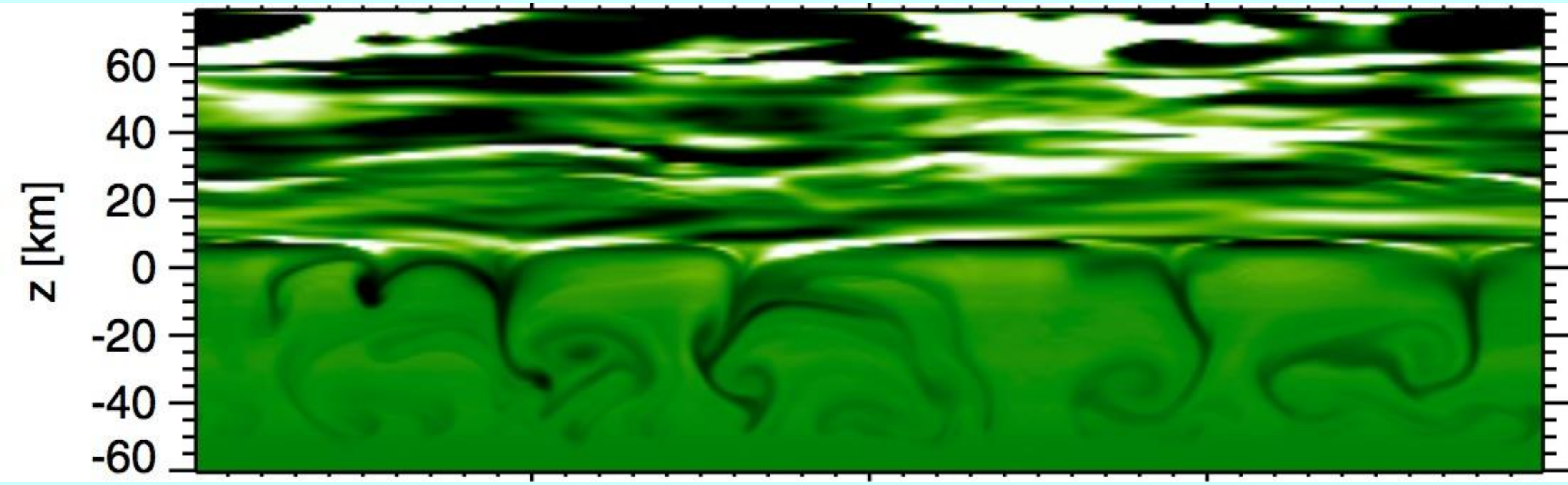
Evidence:

- Clouds
- Disequilibrium chemistry (quenching of CO, CH_4, NH_3)
- Lightcurve variability (cloudy and cloud-free patches rotating in and out of view)

Dynamical regime:

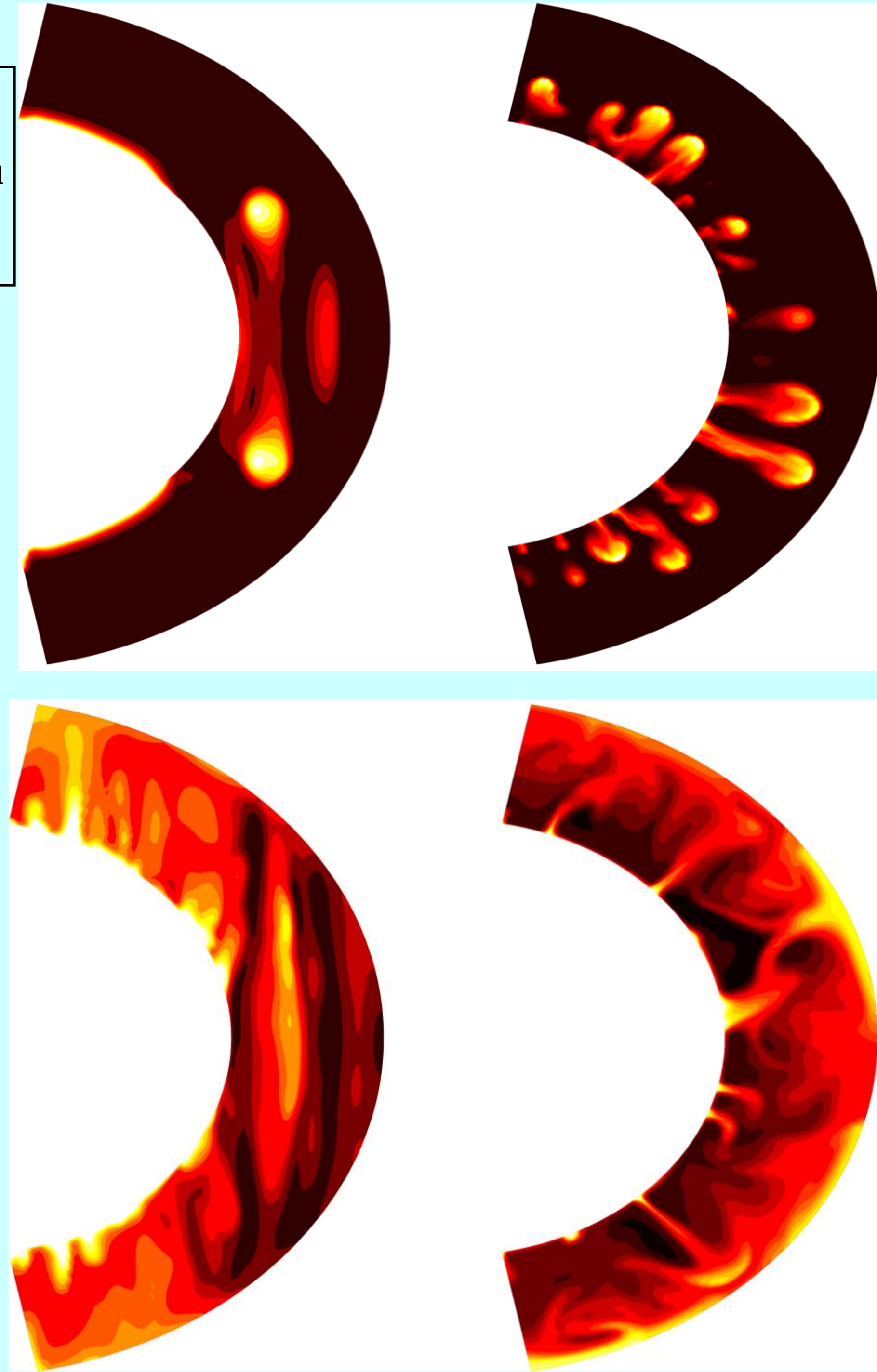
- Rapid rotation (P ~ 2-12 hours) implies rotational domination
- Vigorously convecting interior underlies stably stratified atmosphere
- No external irradiation $\Longrightarrow$ no imposed horizontal gradients in heating or temperature (unlike solar system planets or transiting exoplanets)
- Wave generation will play a key role

Convection in a brown dwarf drives atmospheric waves



Freytag et al. (2010)

Convection will be dominated by rotation at large scales

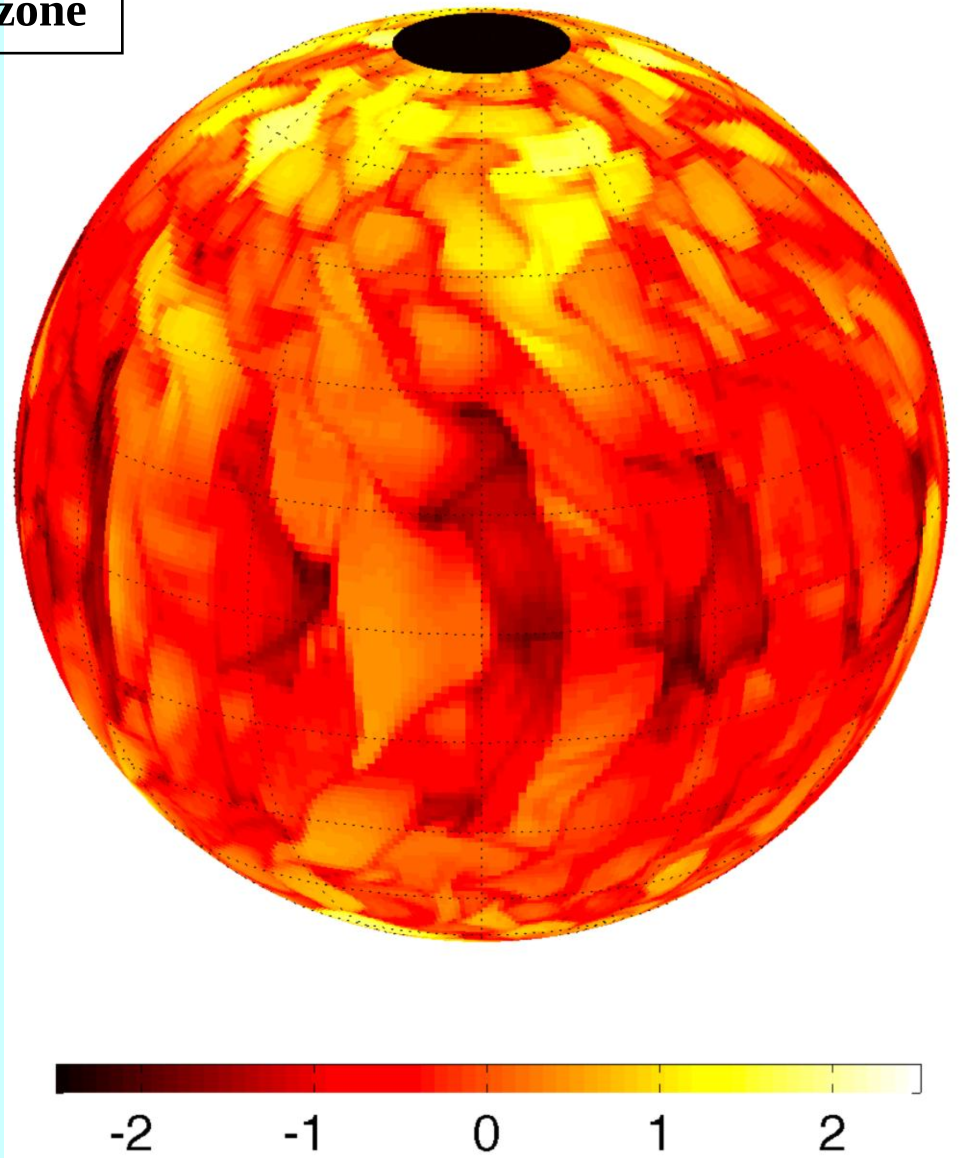


Rapidly rotating model

Slowly rotating model

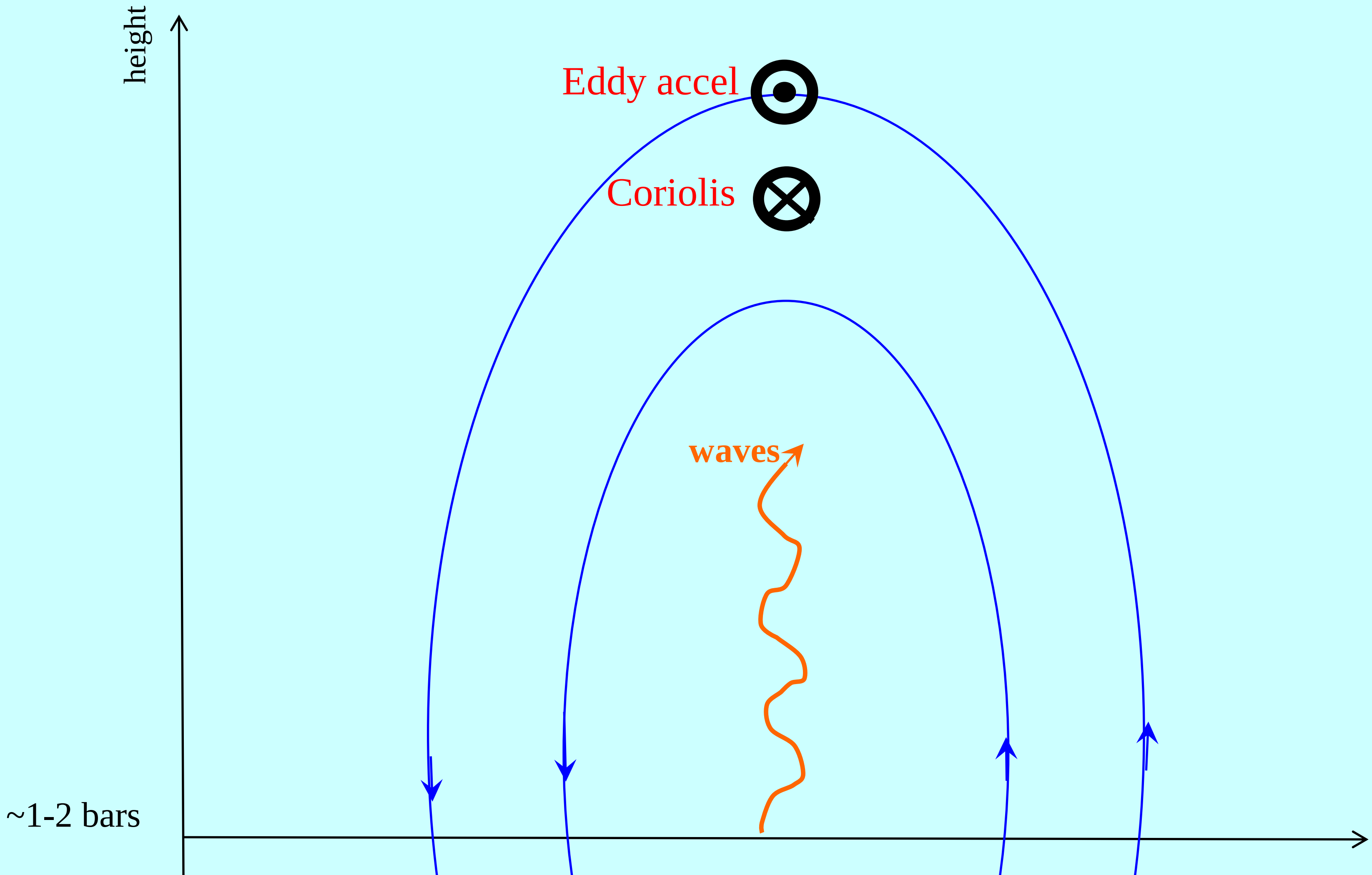
Showman & Kaspi (arXiv 1210:7573)

Temperature perturbations near top of convection zone

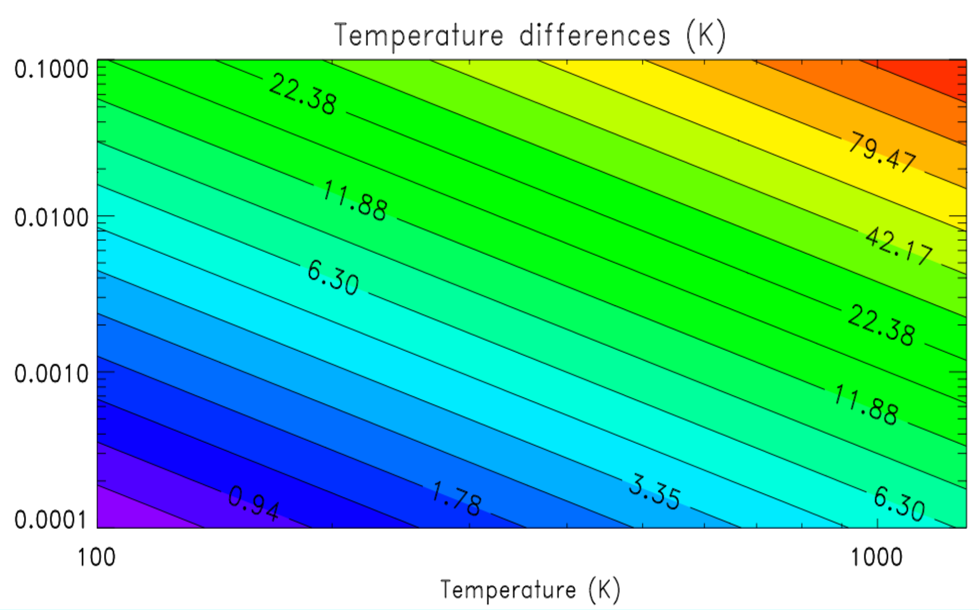


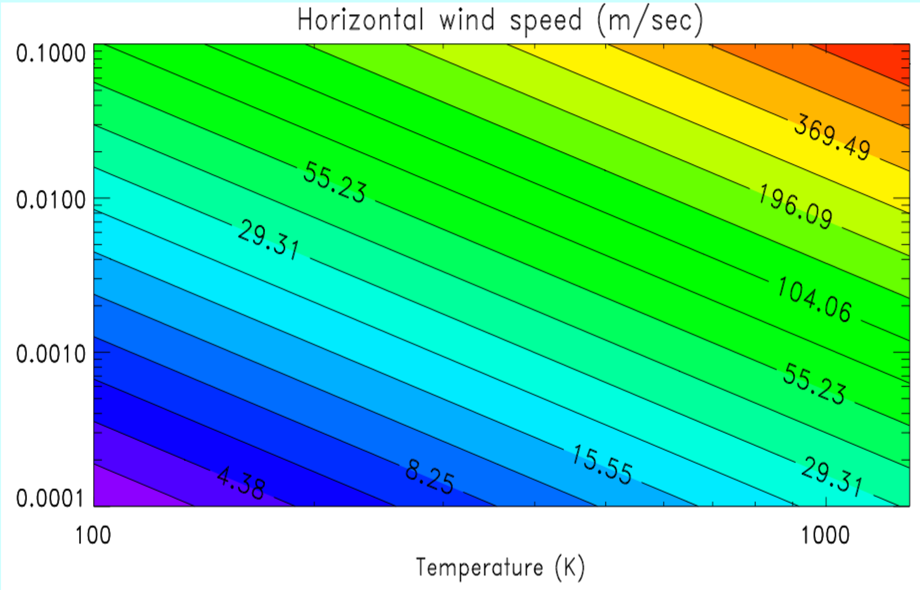
Showman & Kaspi (arXiv 1210:7573)

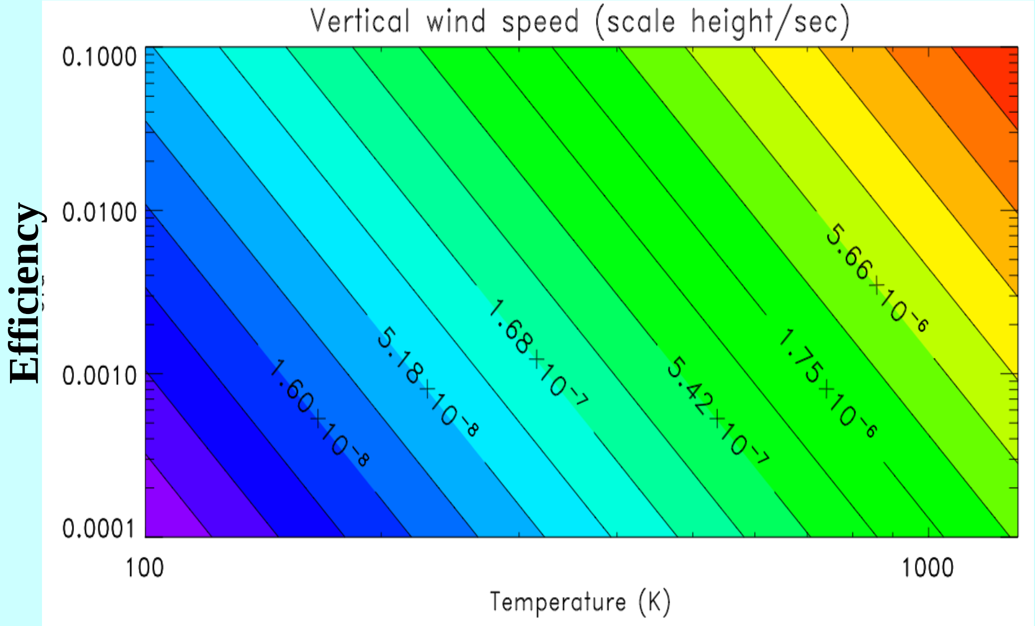
Wave-driven atmospheric circulation on directly imaged EGPs and brown dwarfs



Wave-driven atmospheric circulation causes spatially coherent vertical motions and horizontal temperature differences, helping to explain cloud patchiness and chemical disequilibrium







Showman & Kaspi (arXiv 1210:7573)

Conclusions

A wealth of techniques are being used to characterize the atmospheres of hot Jupiters and directly imaged EGPs, and these will be applied to smaller and smaller planets over the coming decade. These observations yield constraints on atmospheric composition, day-night temperature differences, vertical temperature profiles, hot spot offsets, hazes, and wind speeds/geometry.

Highly irradiated exoplanets occupy a unique regime of atmospheric circulation that does not exist in our solar system. The slow rotation and day-night thermal forcing lead to just a few broad jet streams, typically including equatorial superrotation, explaining the eastward offset of the hot spot on HD 189733b. Regime transitions from small to large day-night temperature difference, and from banded to day-night airflow patterns, are predicted and help to explain current observational trends.

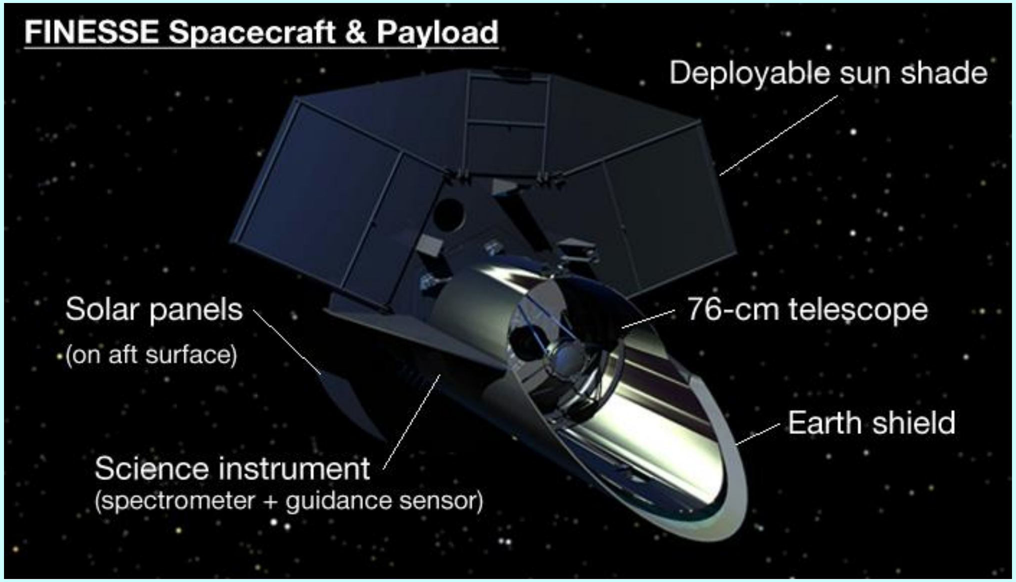
More distant EGPs will not generally be tidally locked, and atmospheric circulation models demonstrate a continuum of behaviors between hot Jupiters and the giant planets of our solar system.

Terrestrial exoplanets will exhibit many of the same dynamical processes as EGPs, but modified by a surface. Current GCMs suggest that horizontal temperature differences and climate feedbacks—hence habitability—depend significantly on planetary rotation rate, atmospheric mass, and other properties.

Brown dwarfs and directly imaged EGPs will exhibit active interior convection, generating atmospheric waves that should drive an active atmospheric circulation, which helps to explain cloud patchiness and chemical disequilibrium observed on these objects.

The need for a dedicated exoplanet characterization mission

FINESSE



EChO