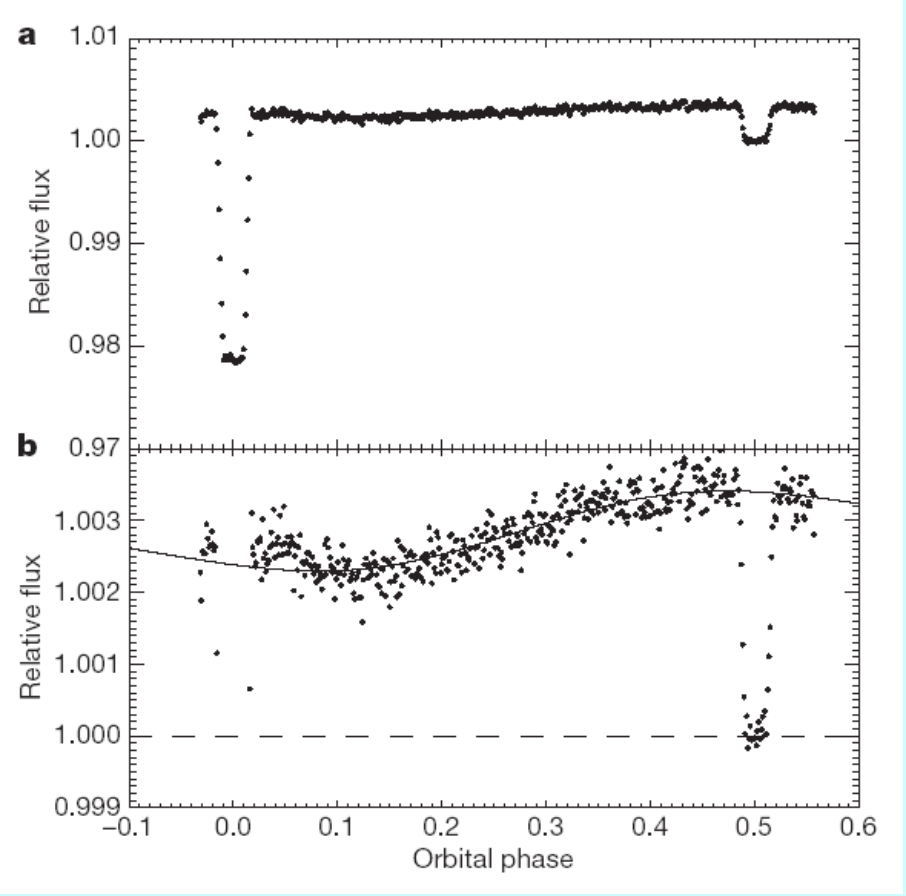
Atmospheric Dynamics of Exoplanets: Status and Opportunities

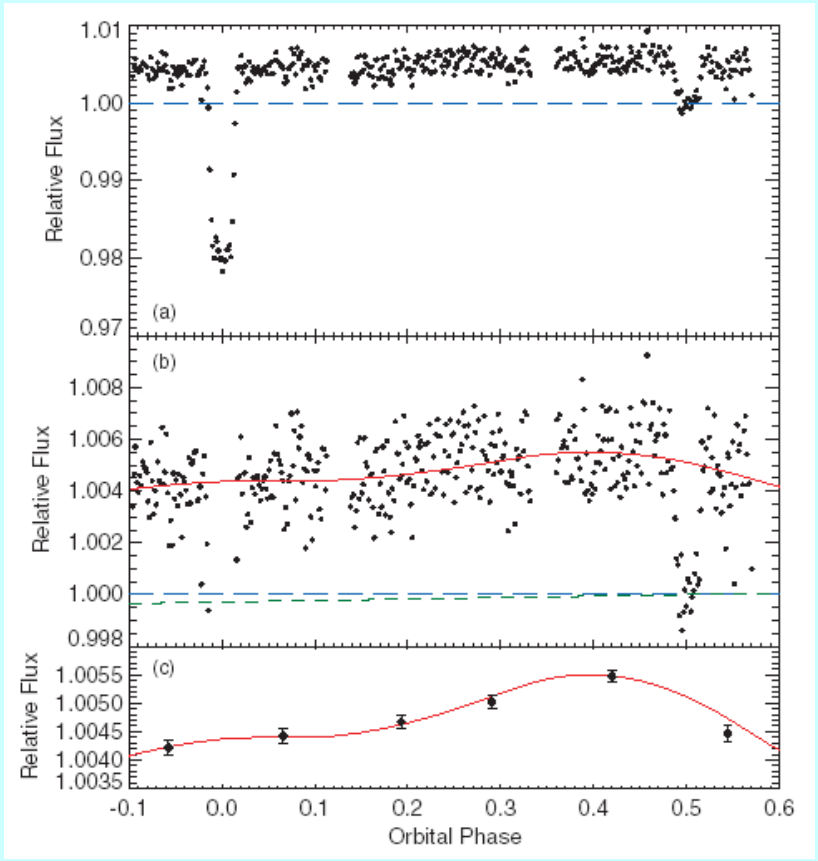
Adam Showman
University of Arizona

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

Spitzer light curves for HD 189733b

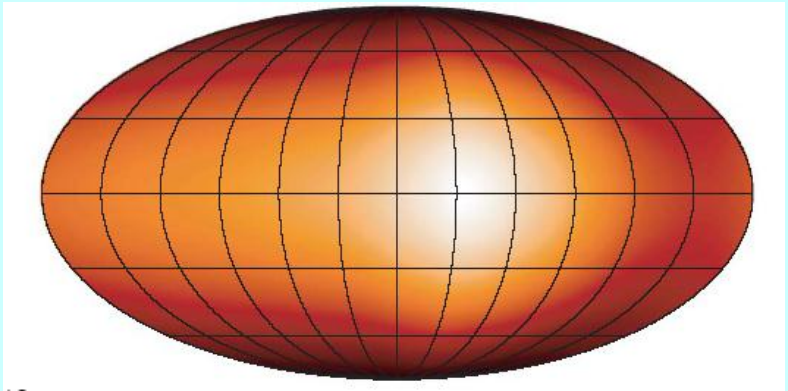


8 μm

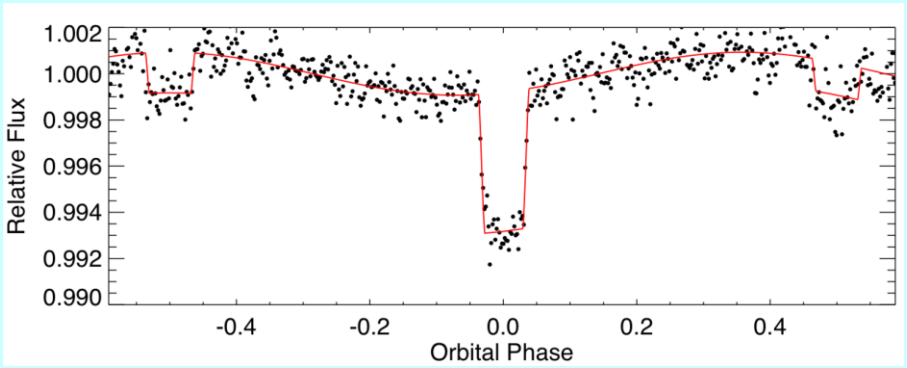


24 μm

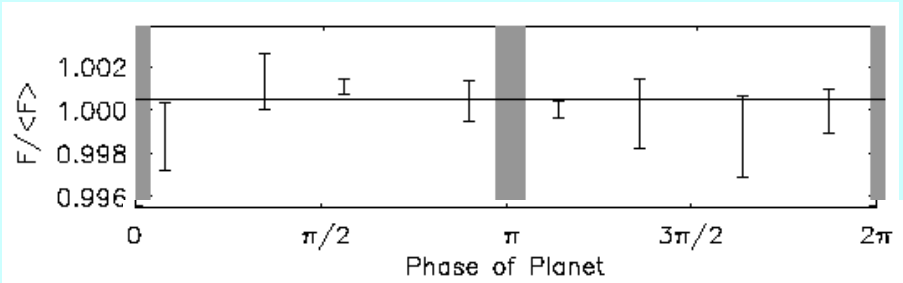
Knutson et al. (2007, 2009)



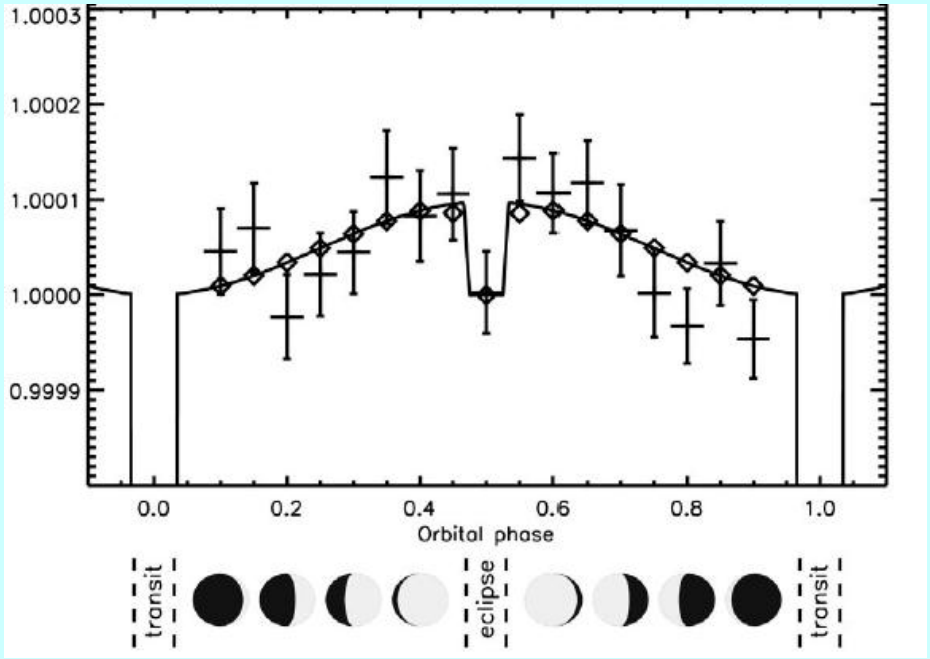
Lightcurves for hot Jupiters



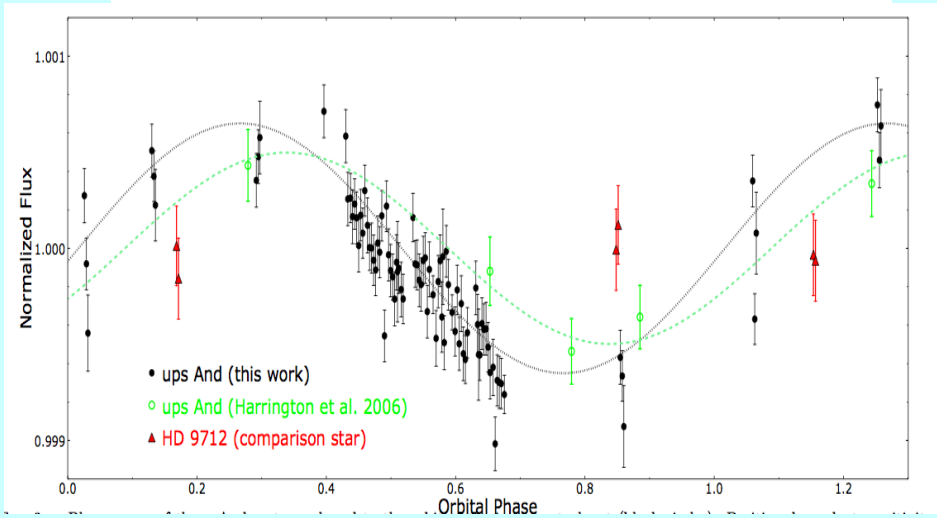
HAT-P-7b (Knutson et al., unpublished; Borucki et al. 2009)



HD209458b (Cowan et al. 2007)

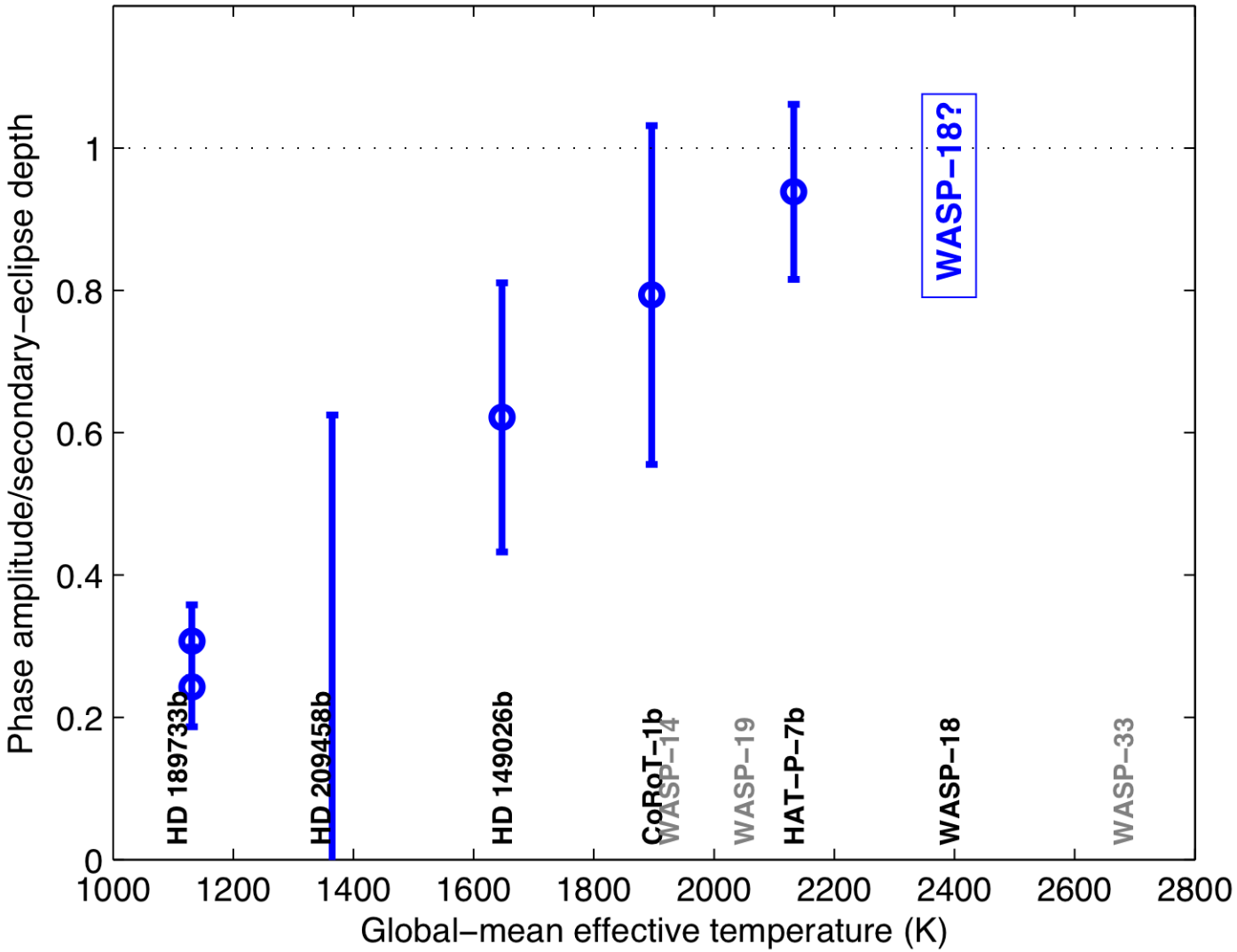


CoRoT-1b (Snellen et al. 2009)



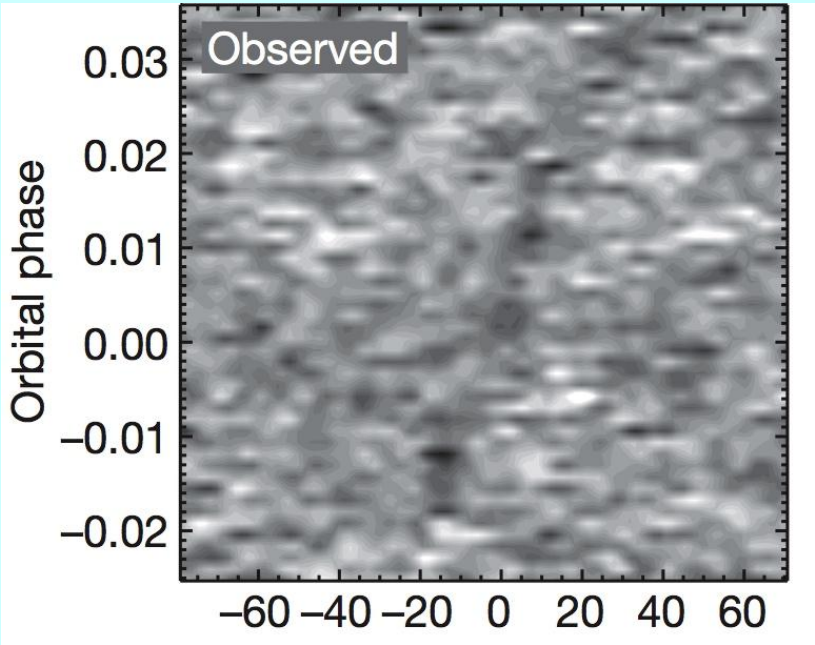
Ups And b (Crossfield et al. 2010)

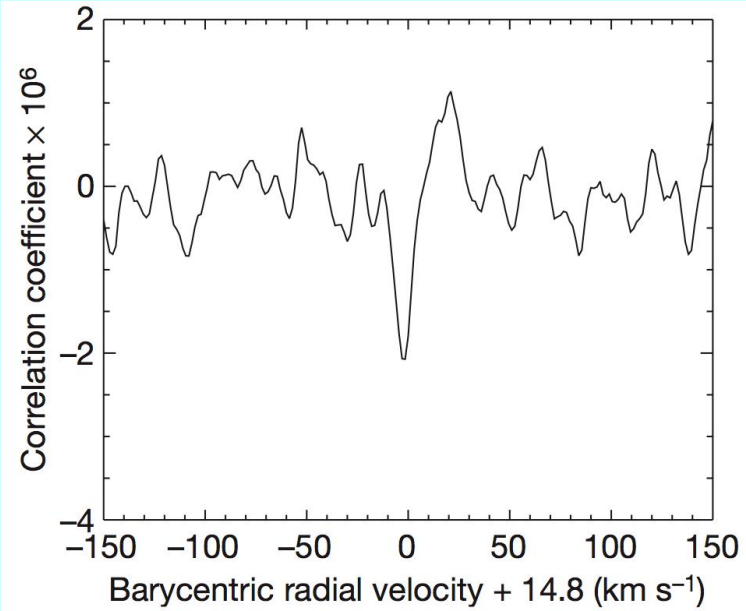
Dependence of day-night flux contrast on effective temperature



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**

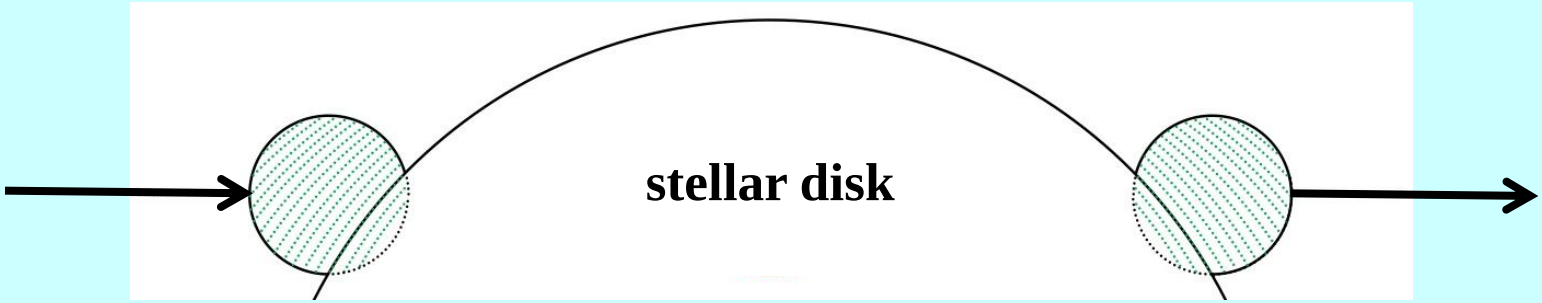


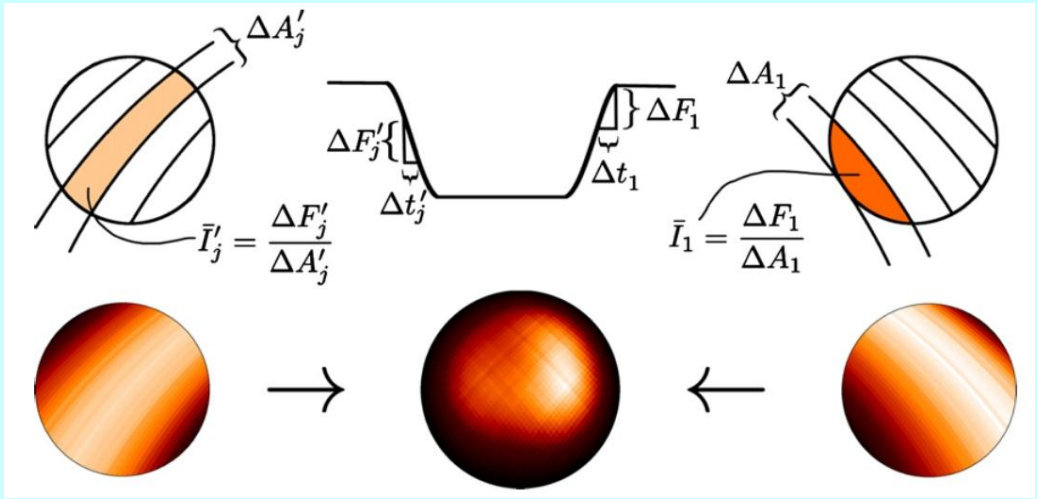


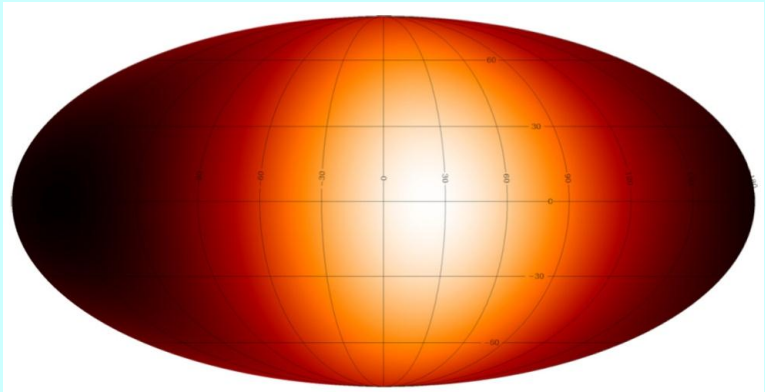
- **Tentative detection of ~2 km/sec blueshift in CO lines during transit of HD 209458b**

- **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?**

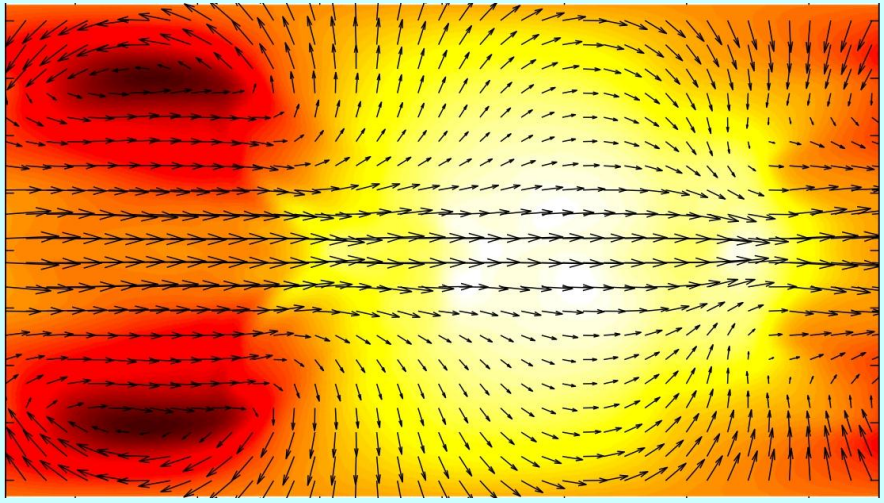
- **How does the circulation interact with the interior? Does it affect the evolution and radius?**

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

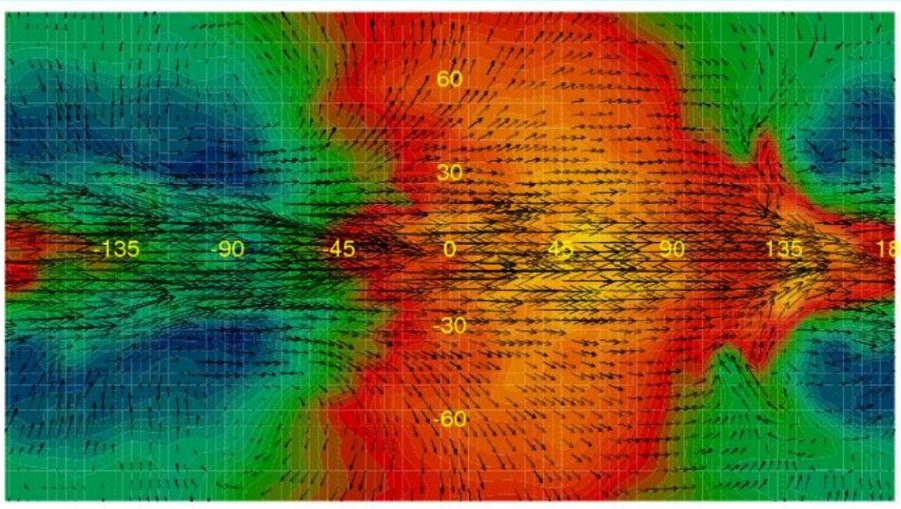
- **What is the atmospheric state and climate of terrestrial exoplanets? How does circulation help control habitability on these worlds?**

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

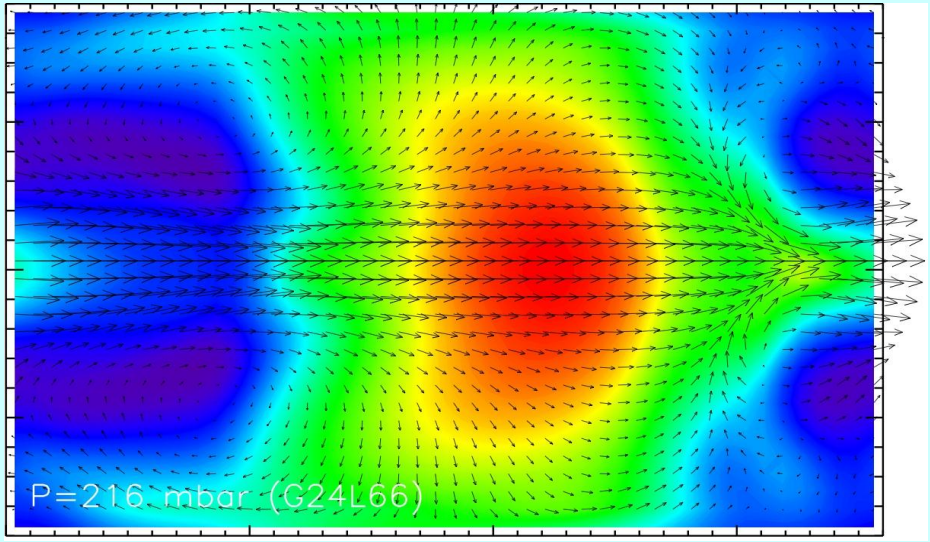
Hot Jupiter circulation models typically predict several broad, fast jets including equatorial superrotation



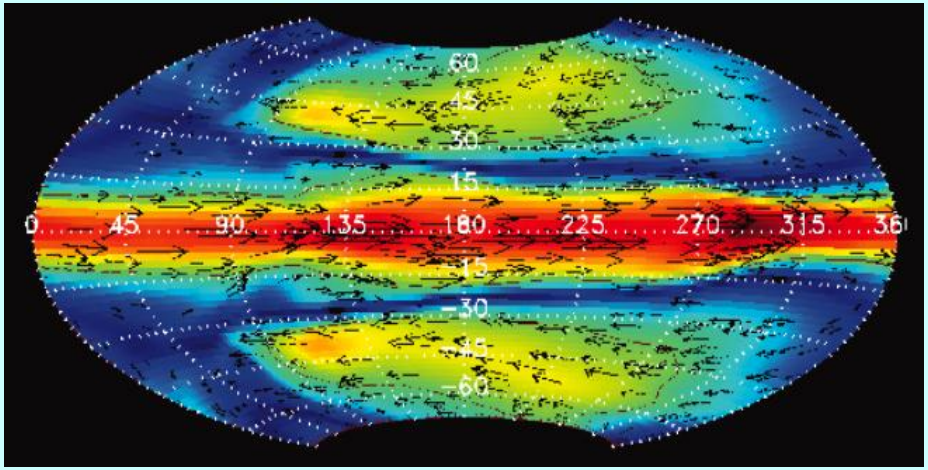
Showman et al. (2009)



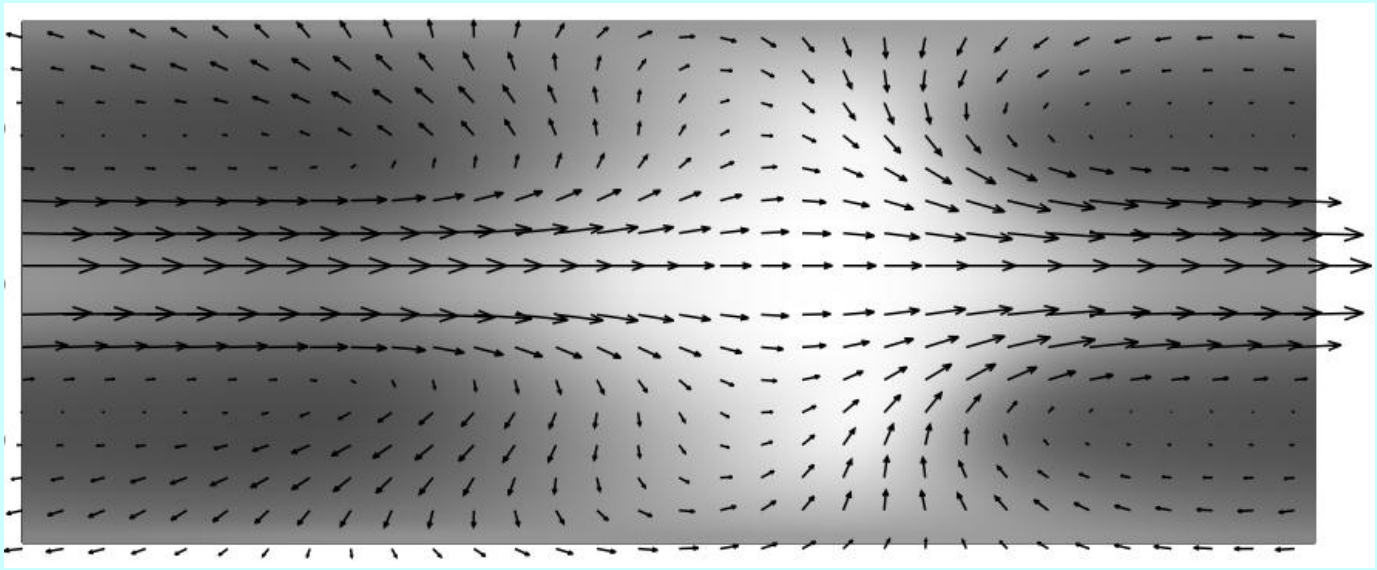
Rauscher & Menou (2010)



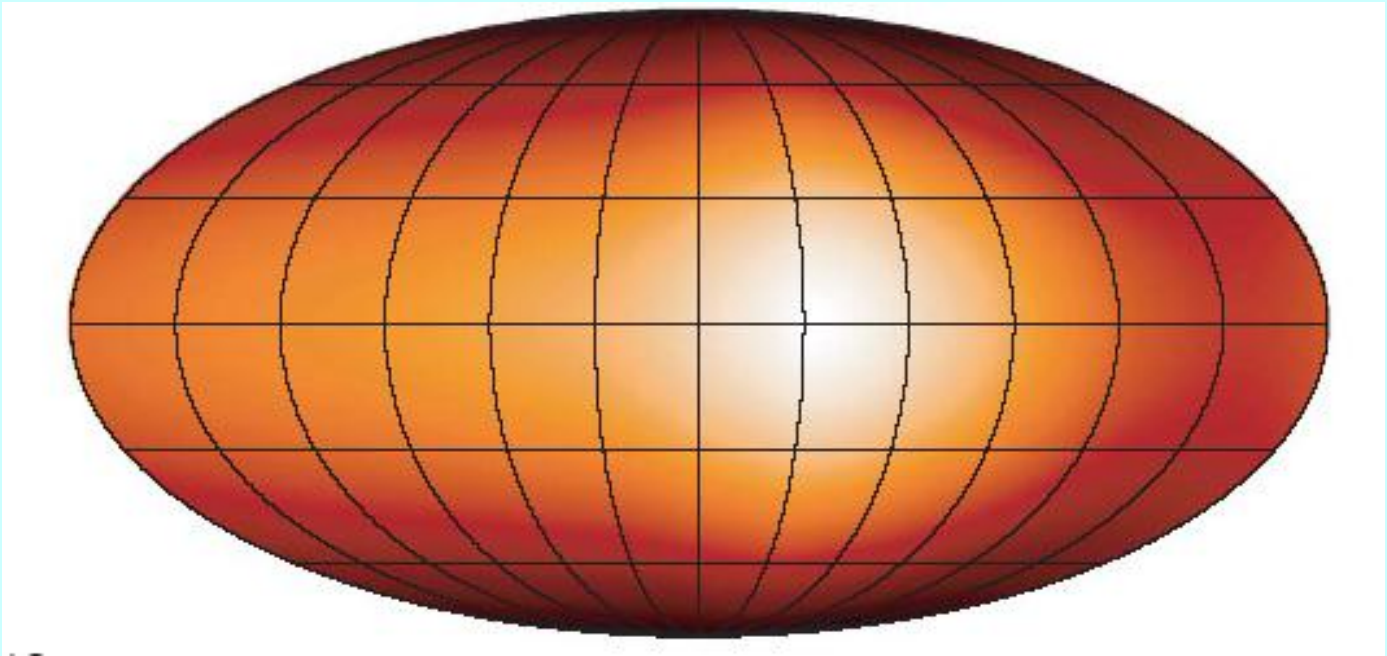
Heng et al. (2010)



Dobbs-Dixon & Lin (2008)

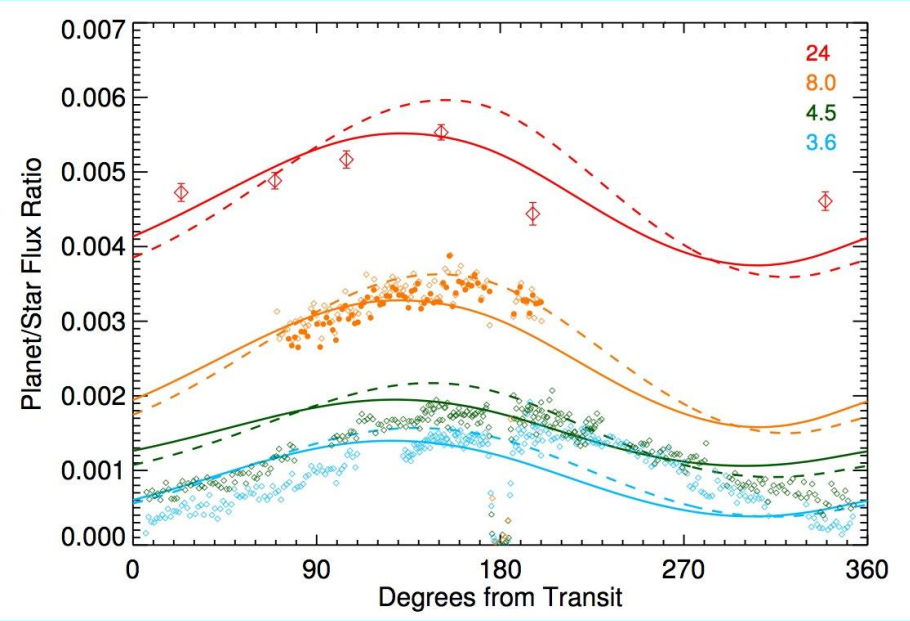


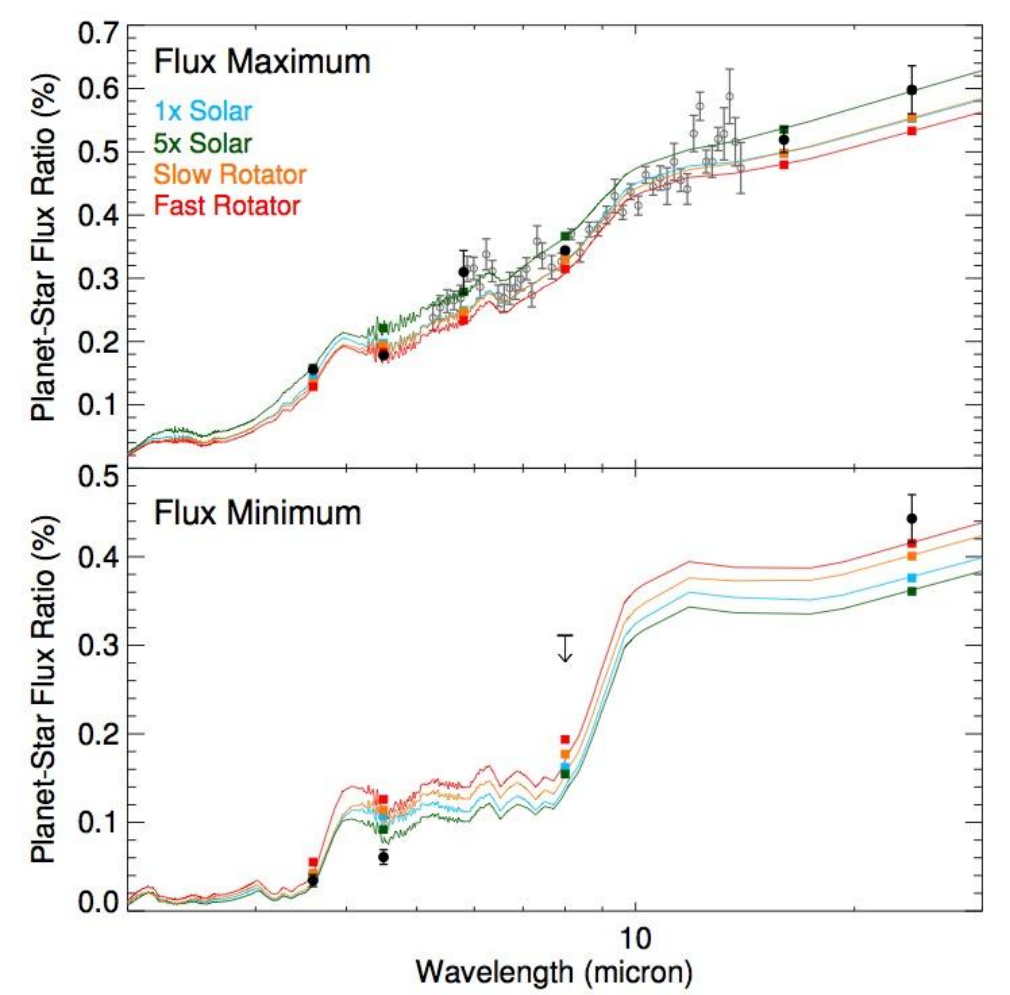
Showman & Guillot (2002)



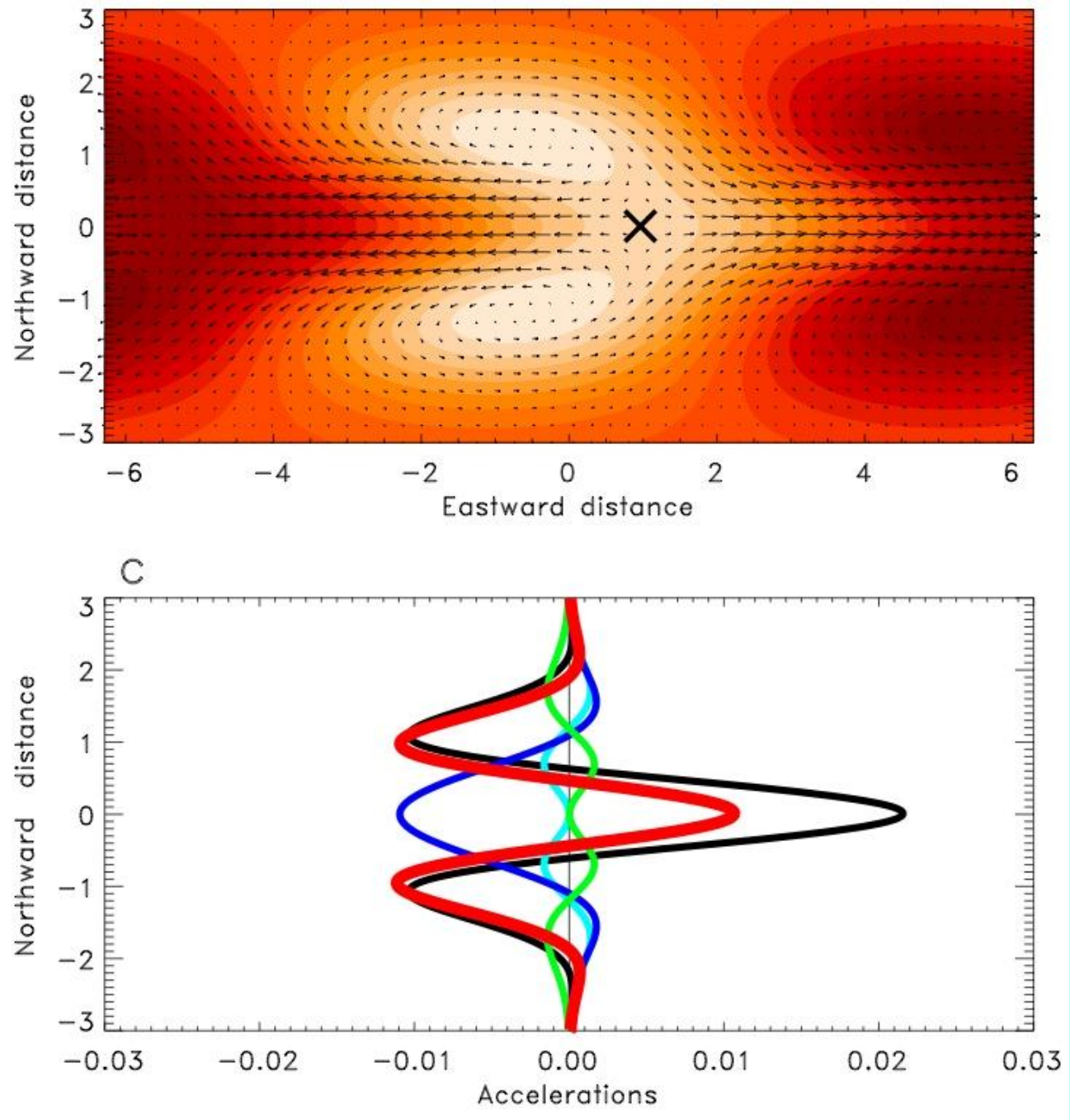
Knutson et al. (2007)

Data-model comparisons



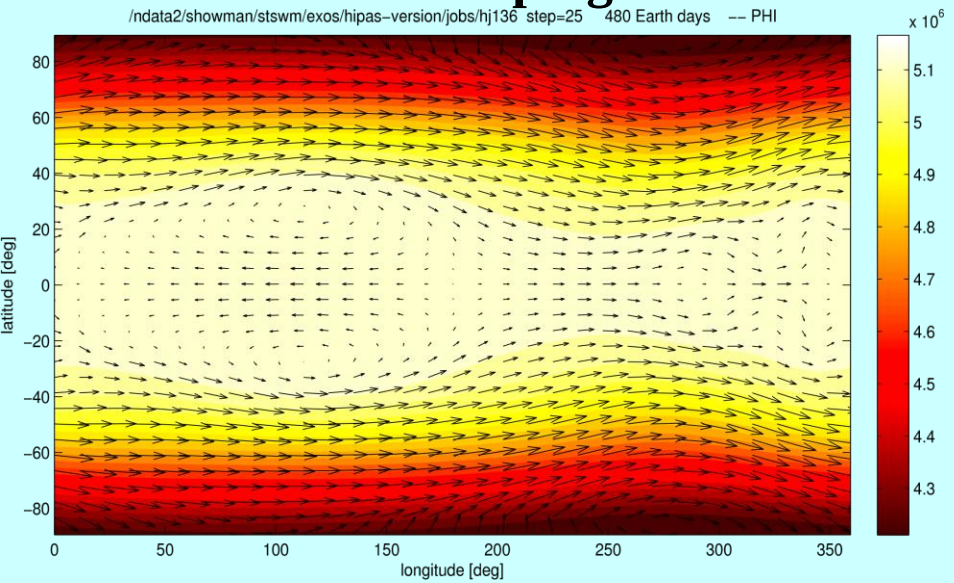


Knutson et al. (2012), Showman et al. (2009)

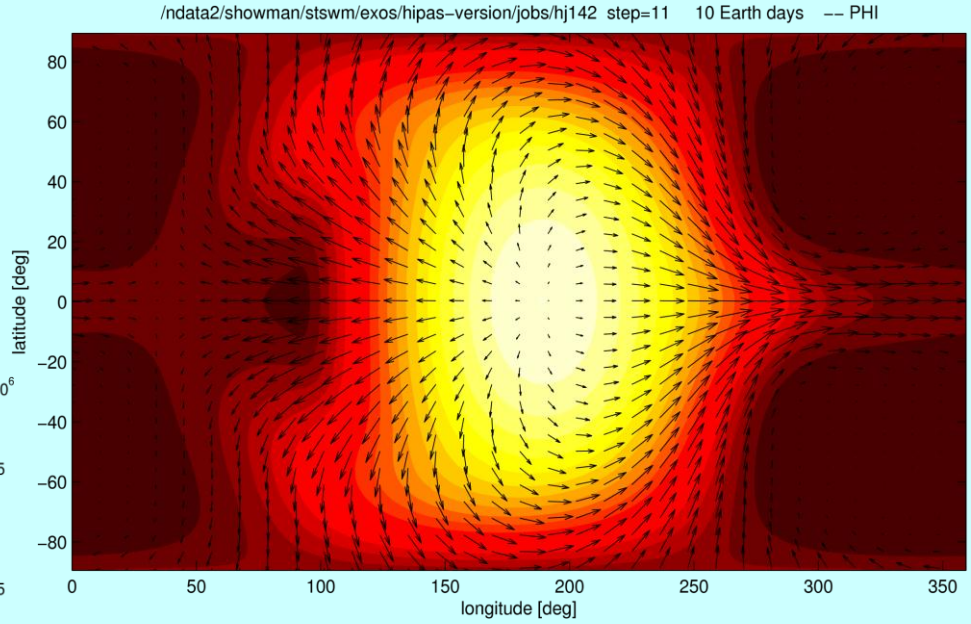


Showman & Polvani (2011), *ApJ* 738, 71

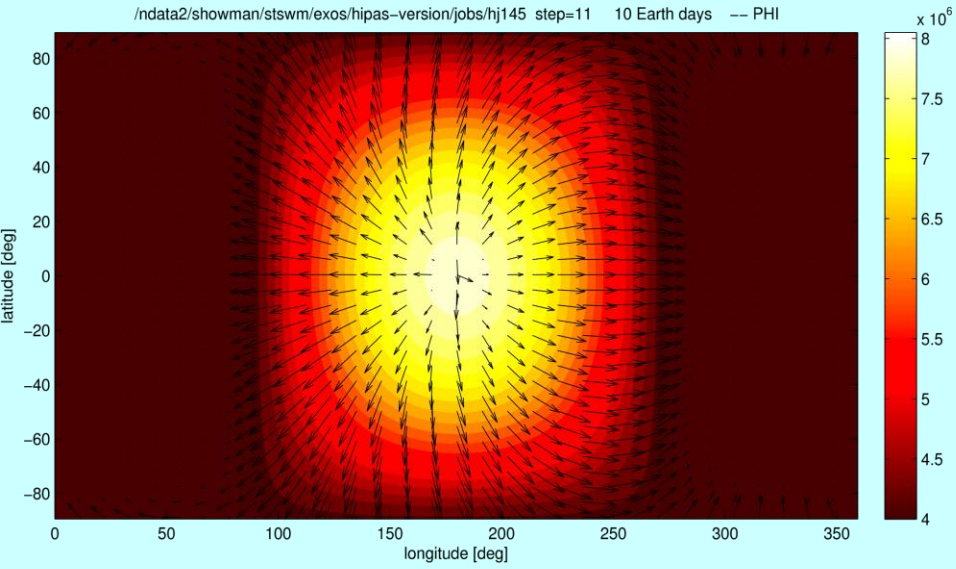
Weak damping



Moderate damping

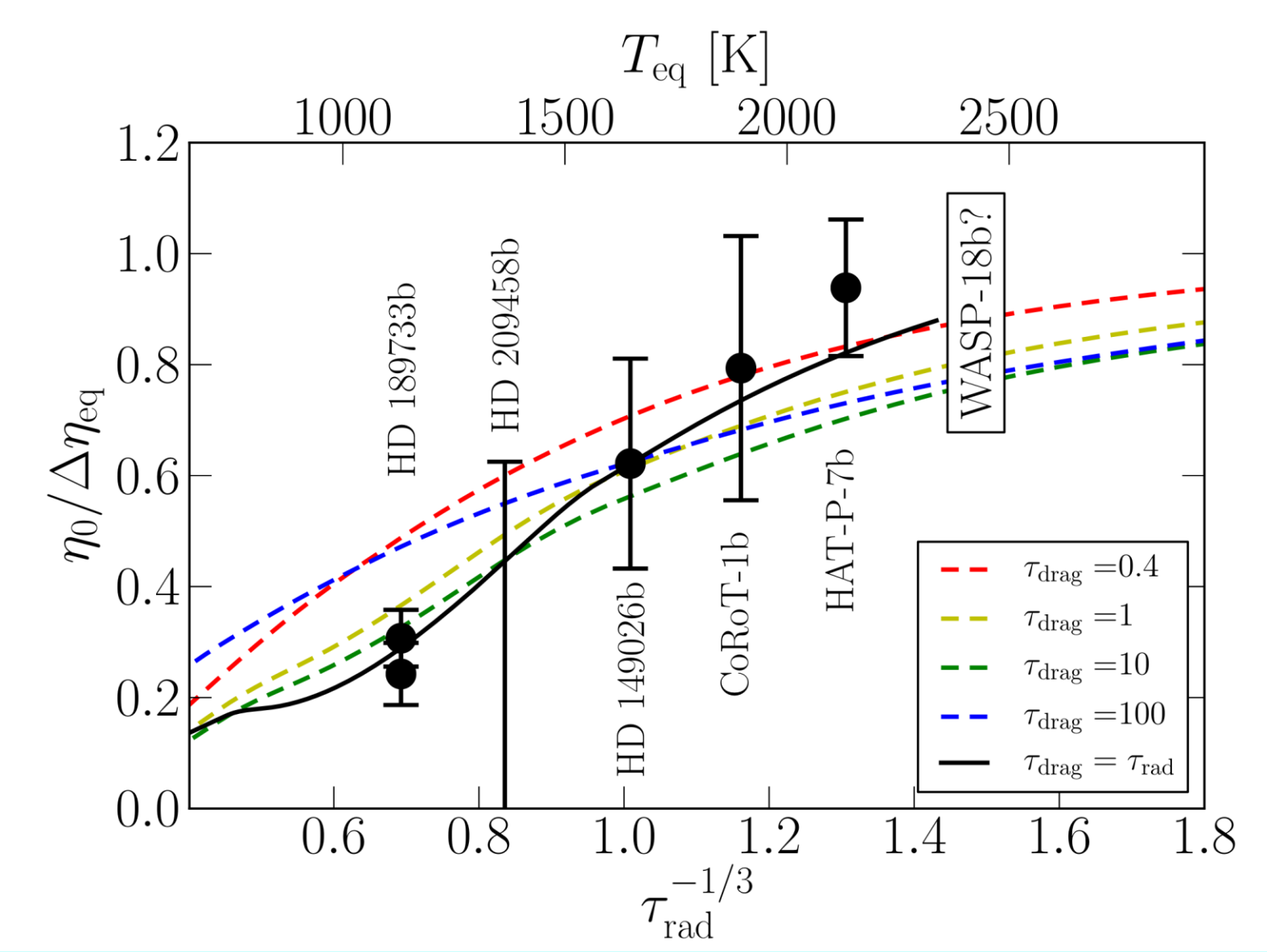


Strong damping

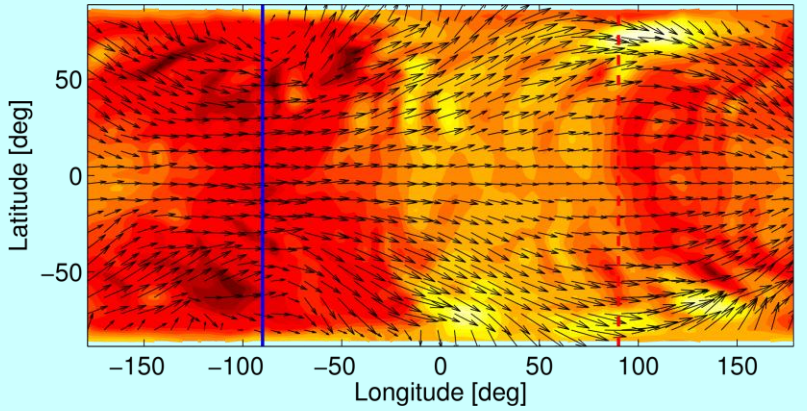


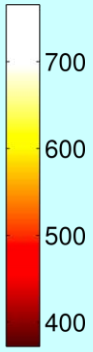
Showman et al. (2012), see also Perna et al. (2012)

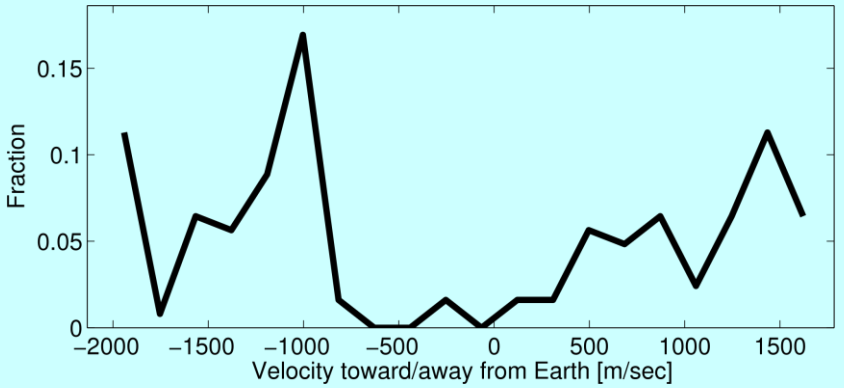
The model explains the emerging observational trend



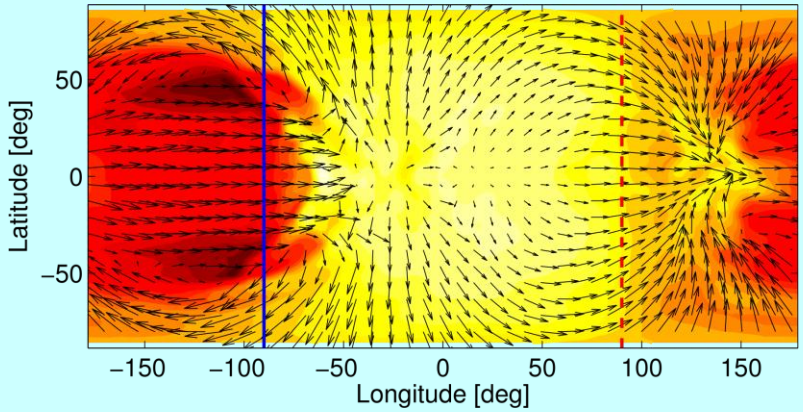
Perez-Becker & Showman (in prep)

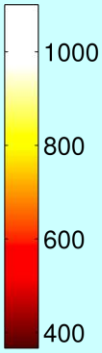


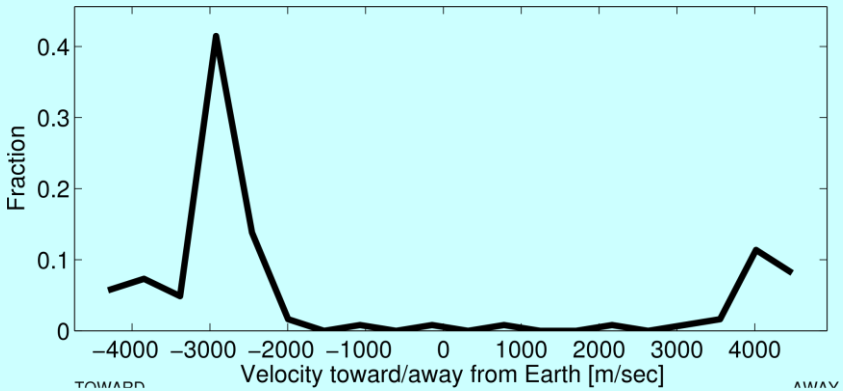




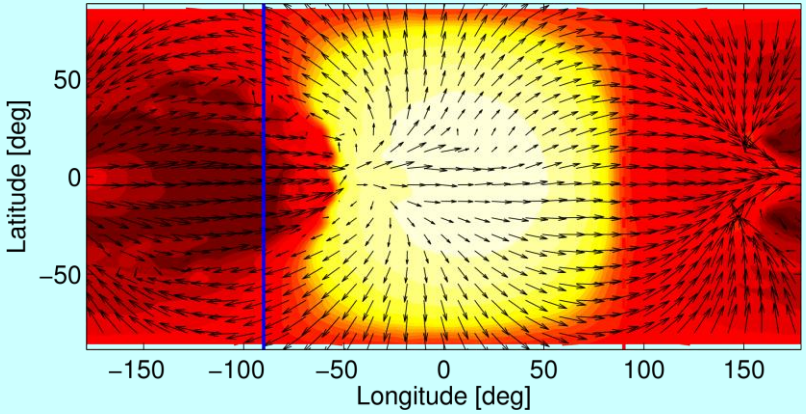
Cool

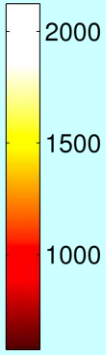


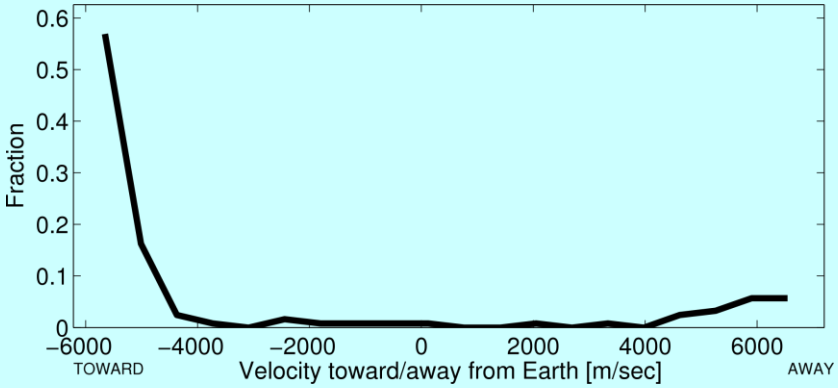




Medium



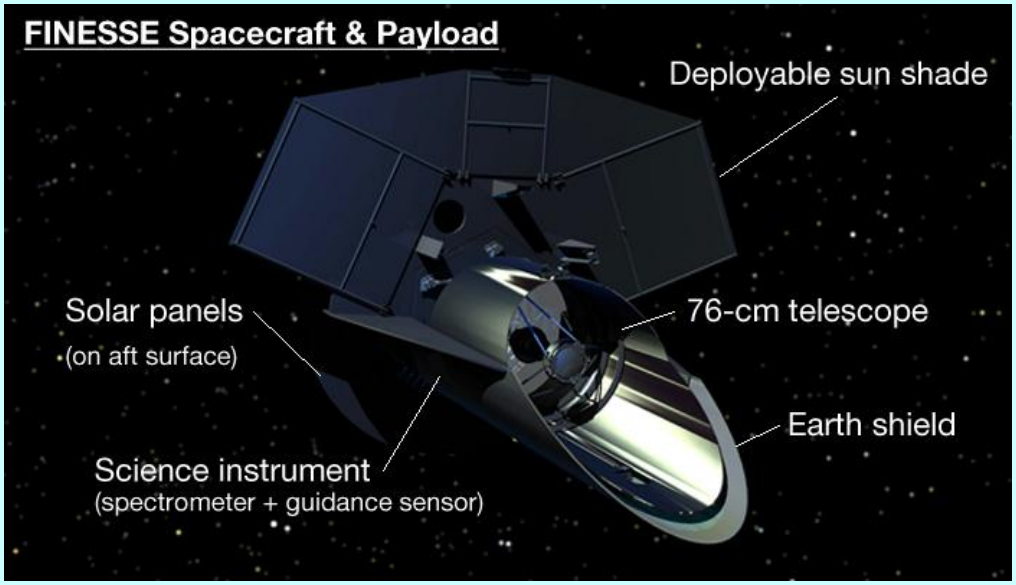




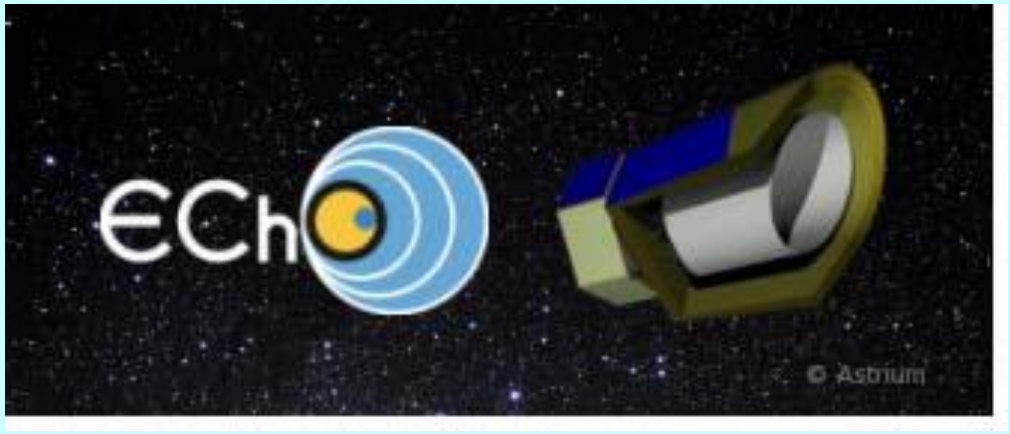
Hot

The need for a dedicated exoplanet characterization mission

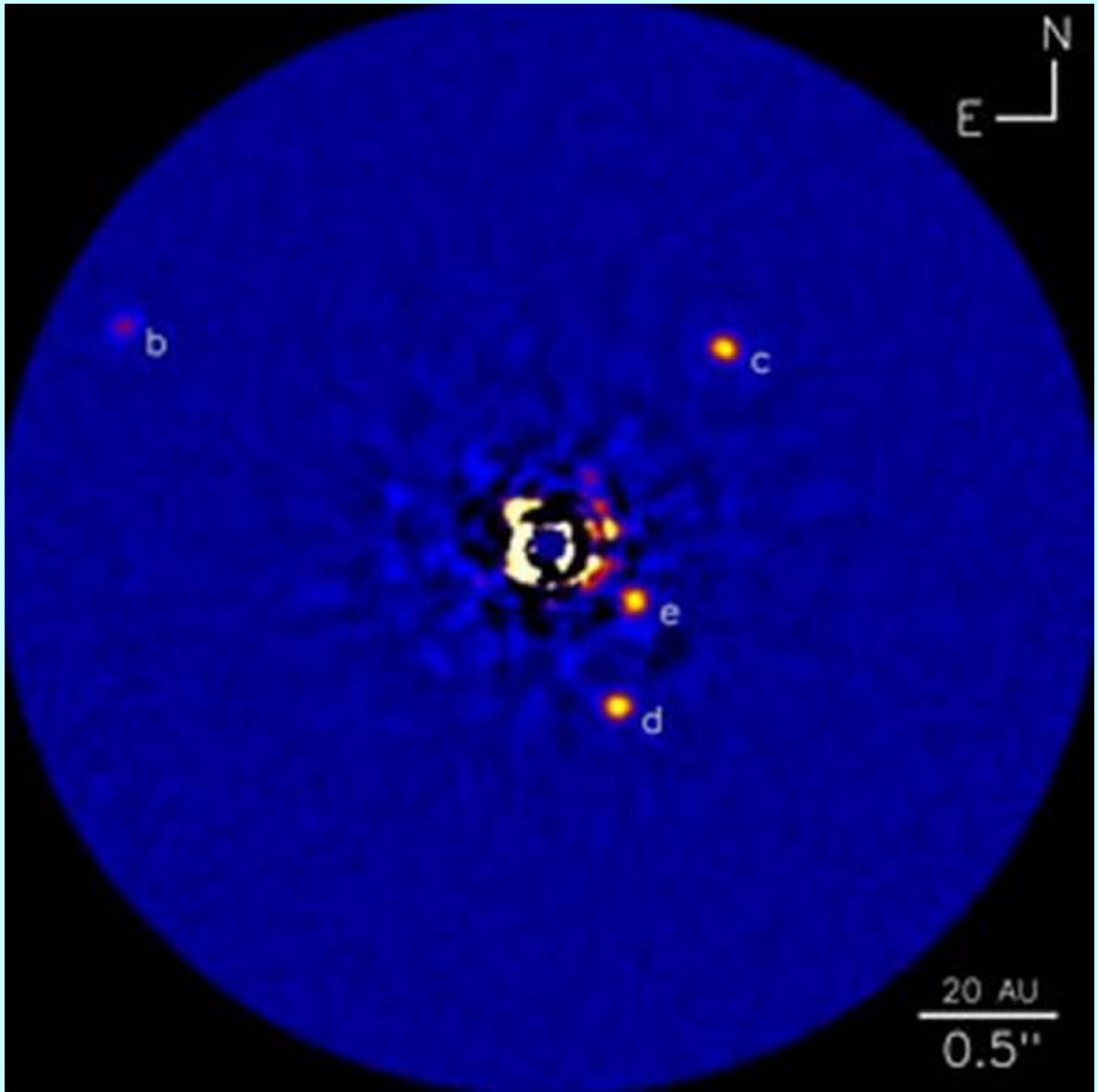
FINESSE



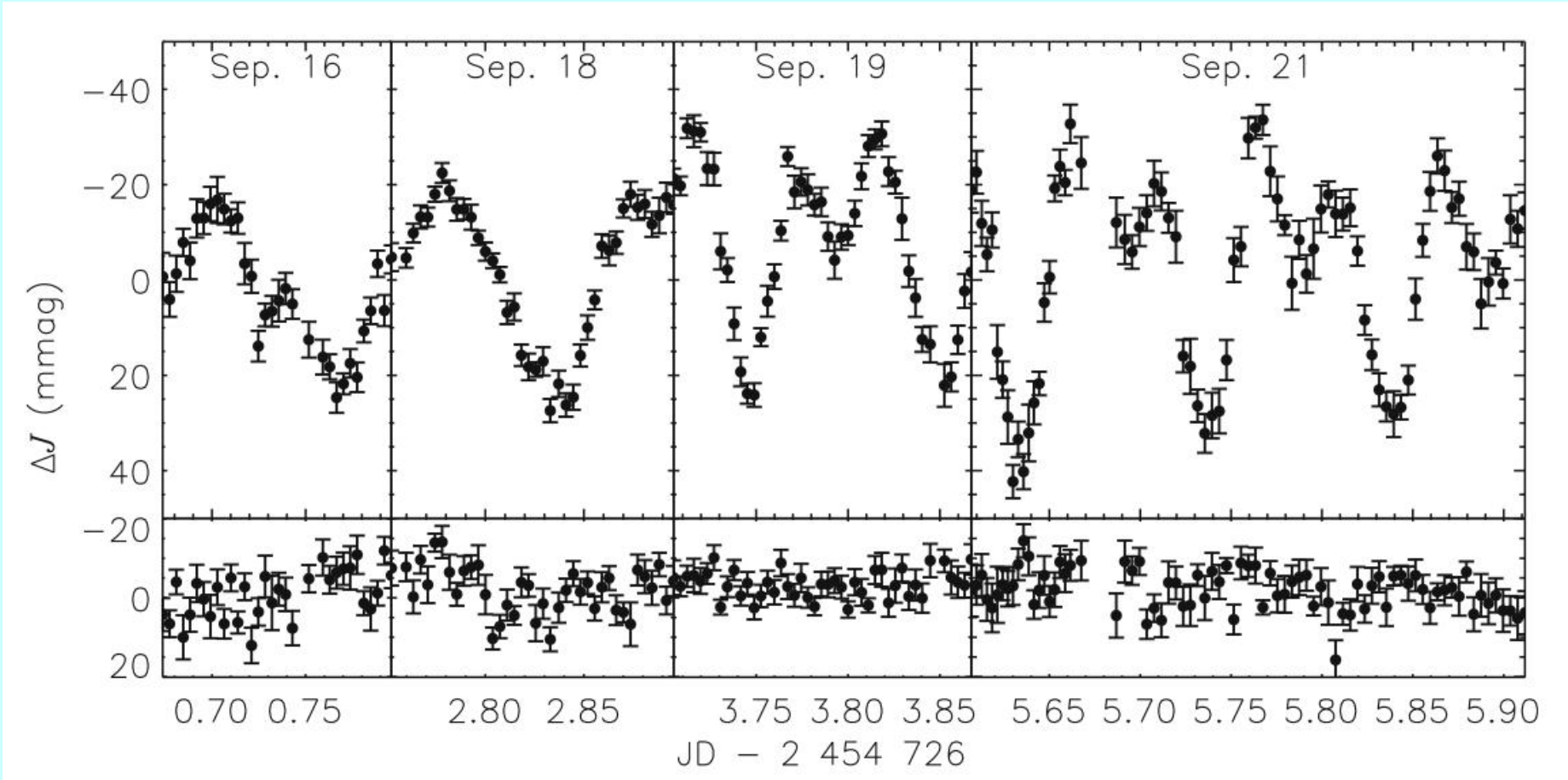
EChO



A new frontier: directly imaged planets and brown dwarfs



T2.5 brown dwarf SIMP 0136 shows weather variability



Artigau et al. (2009)

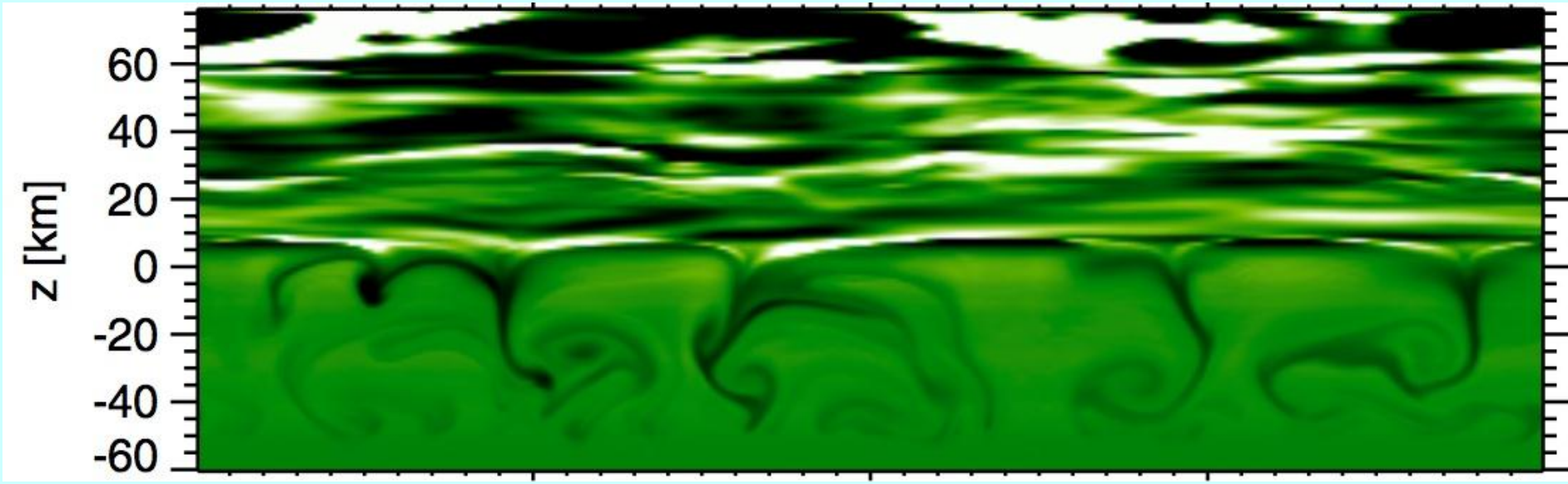
Weather on brown dwarfs and directly imaged giant planets

Evidence:

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

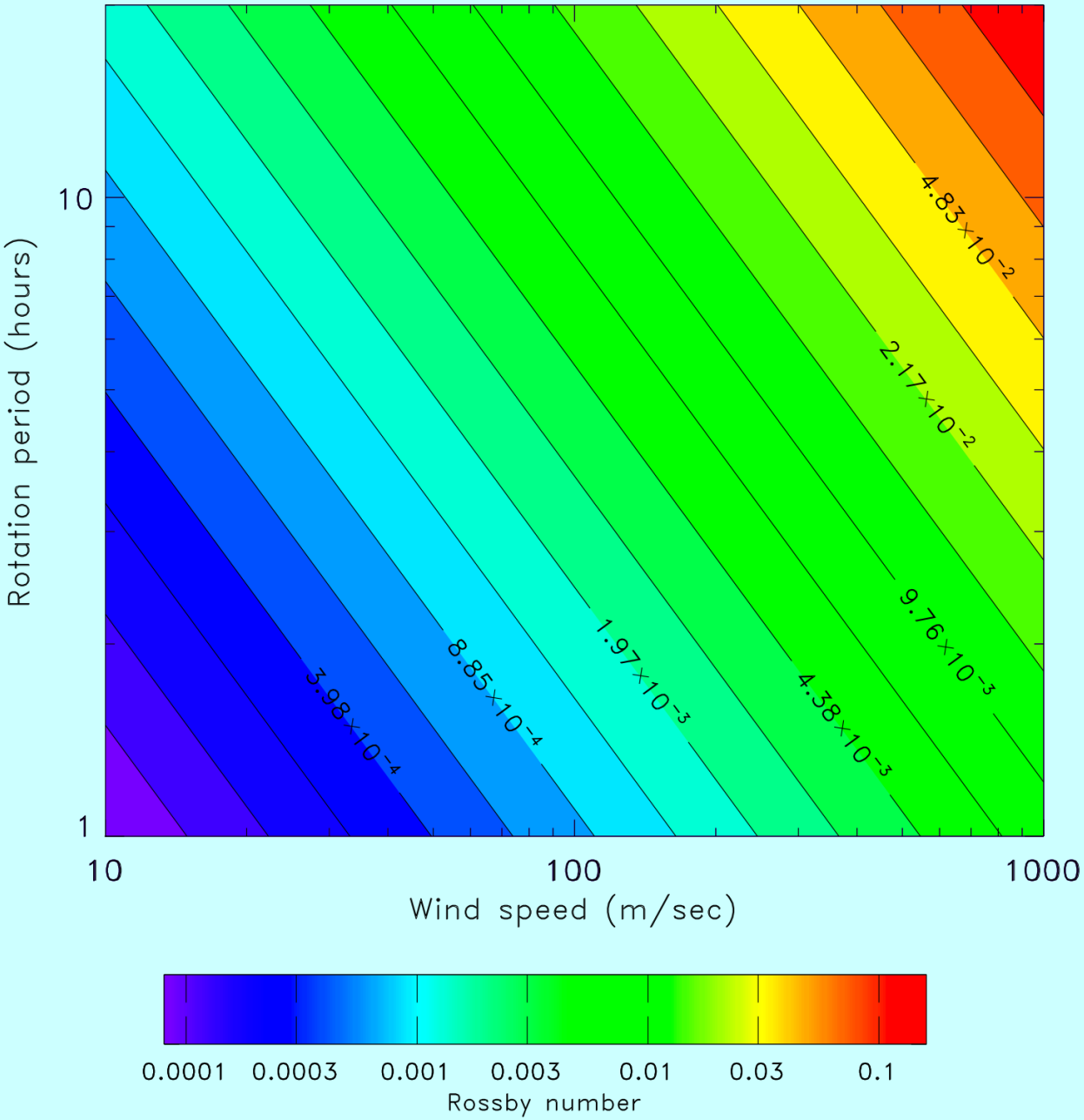
Dynamical regime:

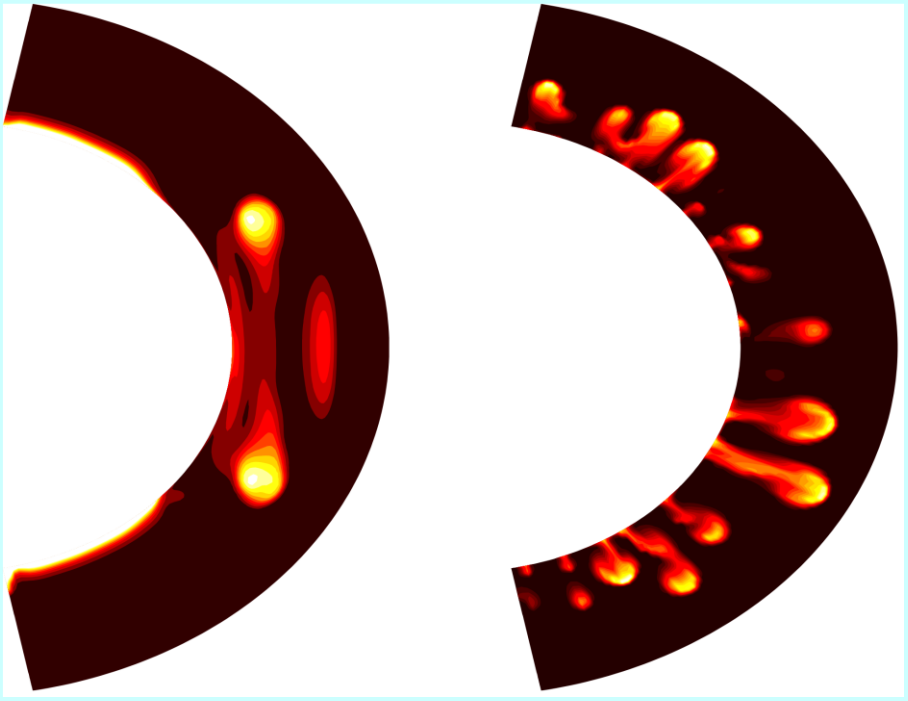
- **Rapid rotation (P ~ 2-12 hours) implies rotational domination**
- **Vigorously convecting interior underlies stably stratified atmosphere**
- **No external irradiation $\Longrightarrow$ no imposed horizontal gradients in heating or temperature (unlike solar system planets or transiting exoplanets)**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

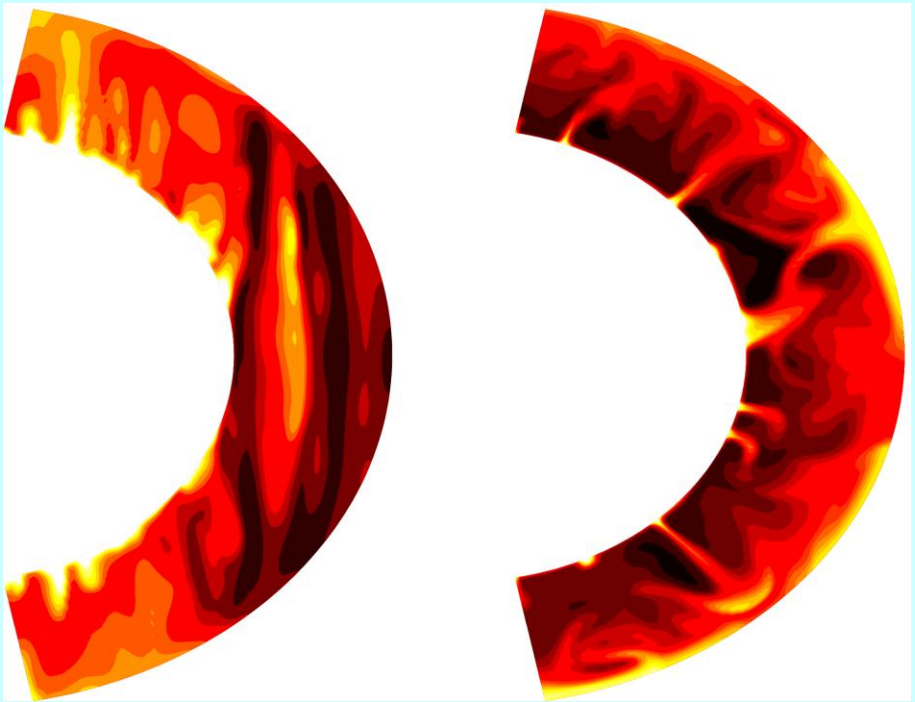


Freytag et al. (2010)

Rossby numbers



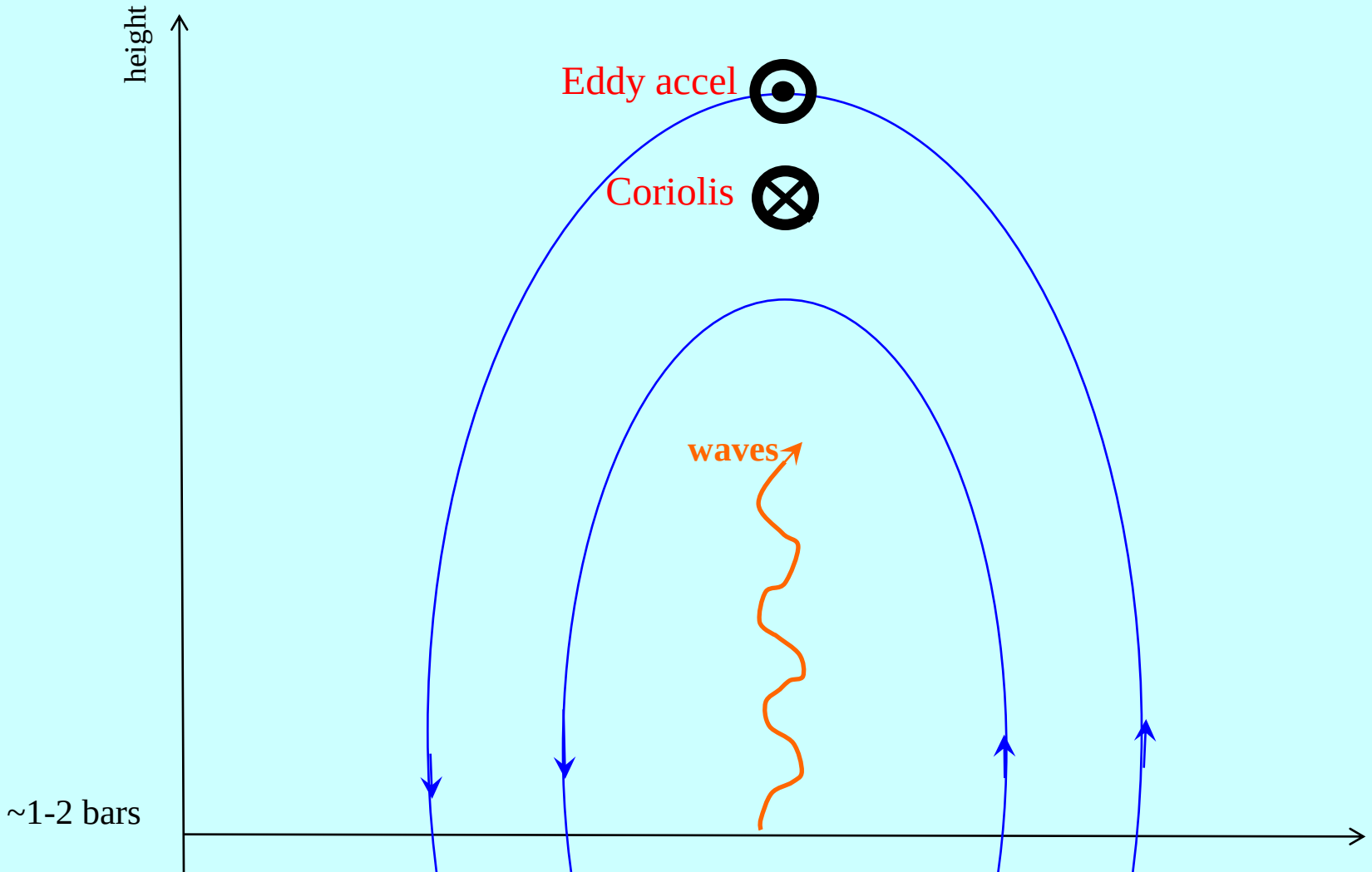


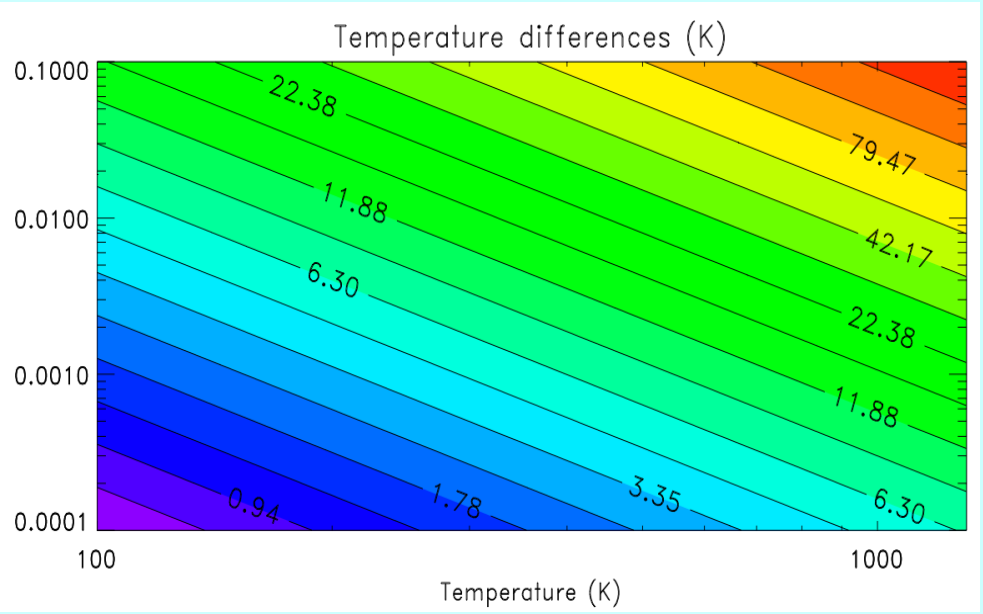


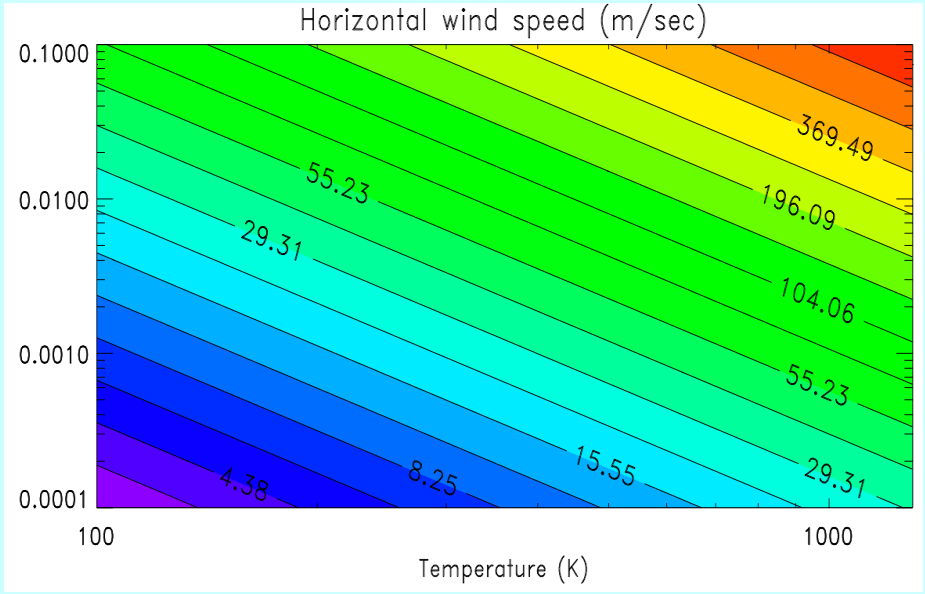
Showman & Kaspi (in prep)

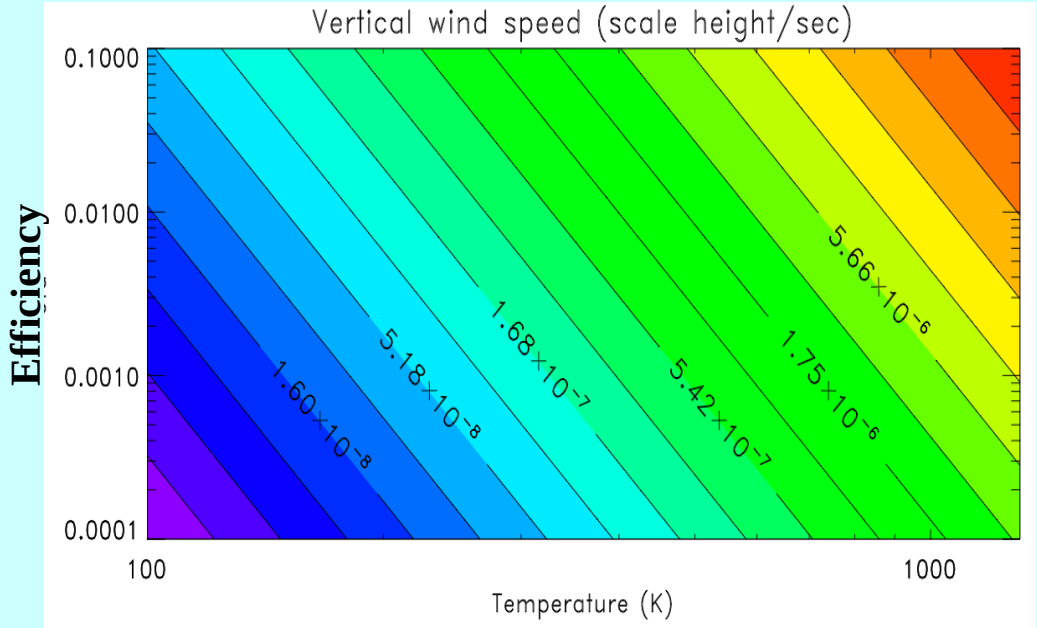
Showman & Kaspi (in prep)

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









Showman & Kaspi (in prep)

Conclusions

Hot Jupiters occupy a dynamically unique regime of atmospheric circulation that does not exist in our Solar System. The intense day-night radiative forcing produces wind speeds >1 km/sec and temperature contrasts of ~200-1000 K. The winds can distort the temperature pattern in a complex manner, with important implications for lightcurves and spectra.

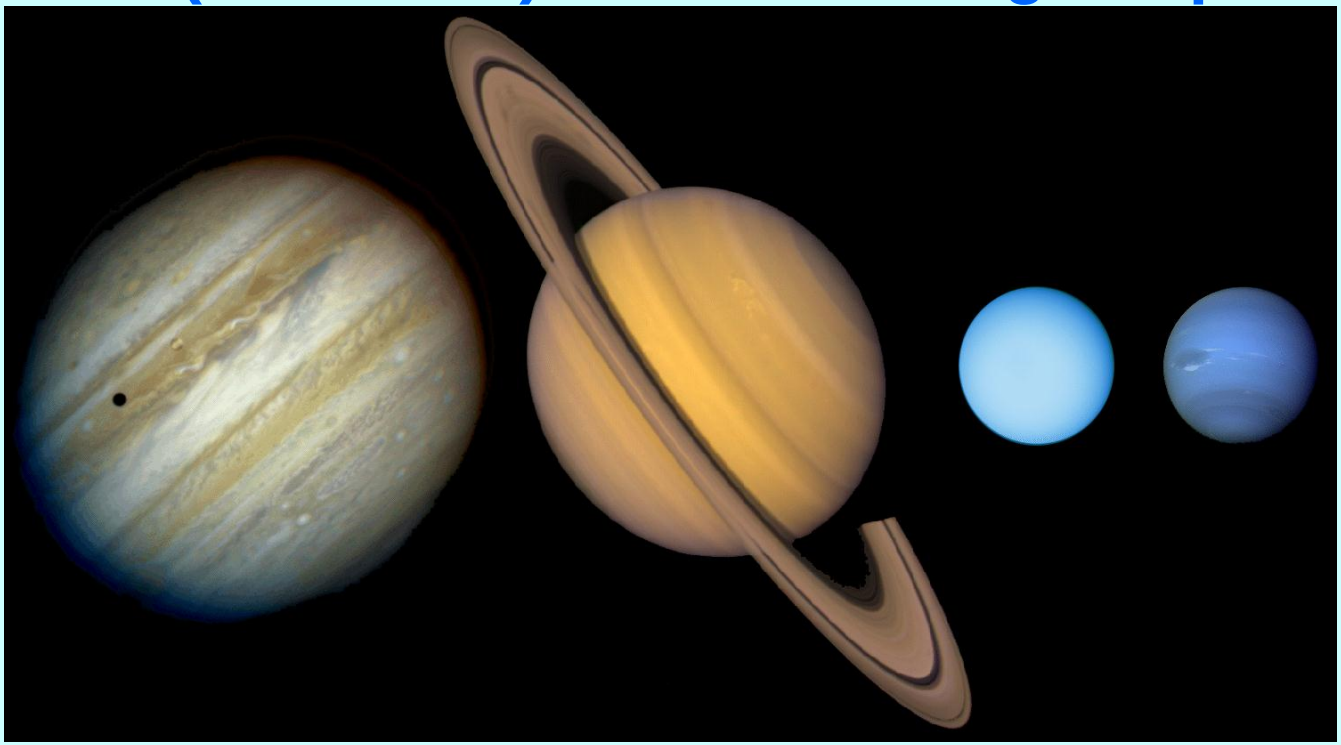
The radiative forcing generates equatorial superrotation that can displace the hottest regions to the east of the substellar point, explaining the observed offset on HD 189733b. The superrotation results from up-gradient momentum transport due to standing Rossby and Kelvin waves triggered by the longitudinal (day-night) heating variations.

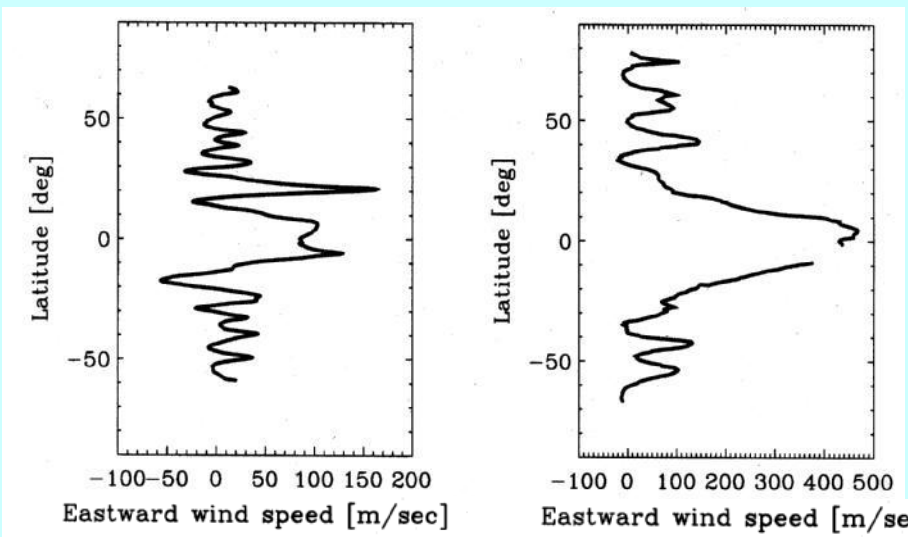
Our theory predicts a regime transition: Modest irradiation/friction allows the waves to adjust the thermal structure and leads to small day-night temperature differences, but strong irradiation/friction damps the waves and leads to large day-night temperature differences. This explains the trend emerging in IR lightcurves and secondary eclipses.

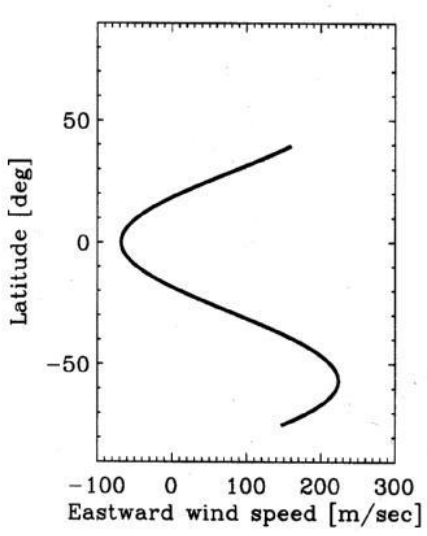
The same regime transition predicts a transition in wind pattern with implications for direct Doppler detection of atmospheric winds.

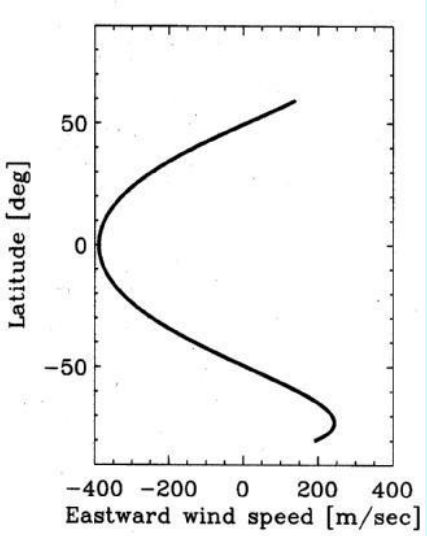
Many questions remain: Does the atmospheric circulation help explain the inflated radii of hot Jupiters? What is the atmospheric circulation of directly imaged planets and brown dwarfs? Stay tuned!

Zonal (east-west) winds on the giant planets







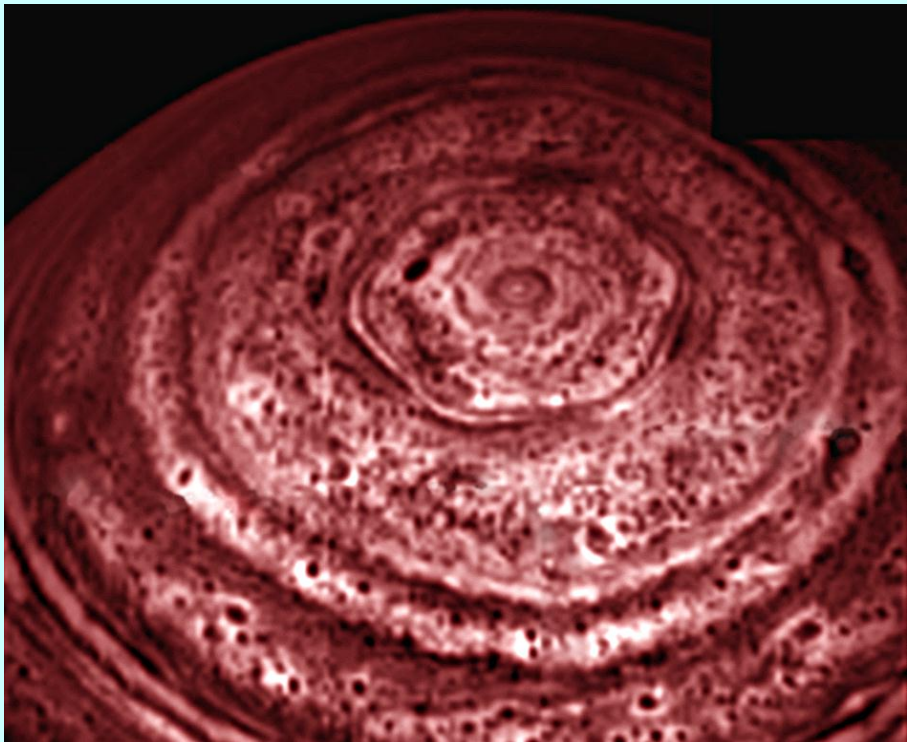


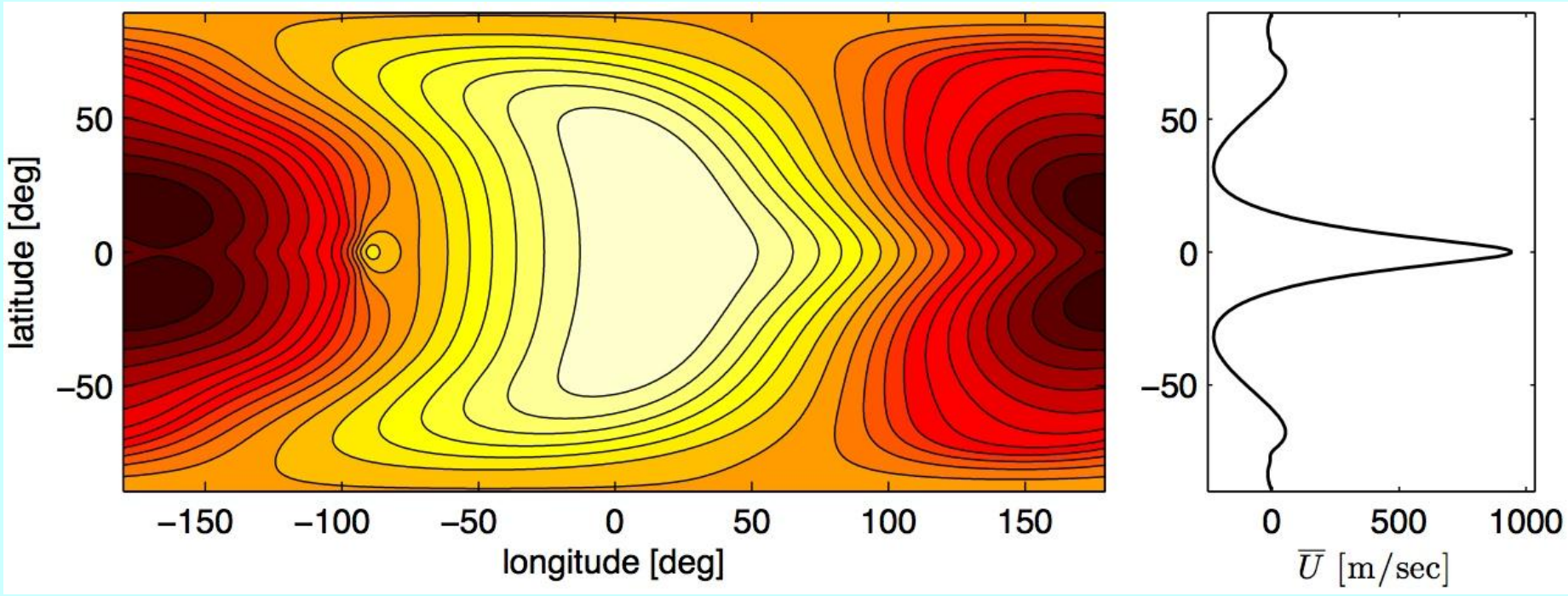
What controls the size and shape of flow structures?

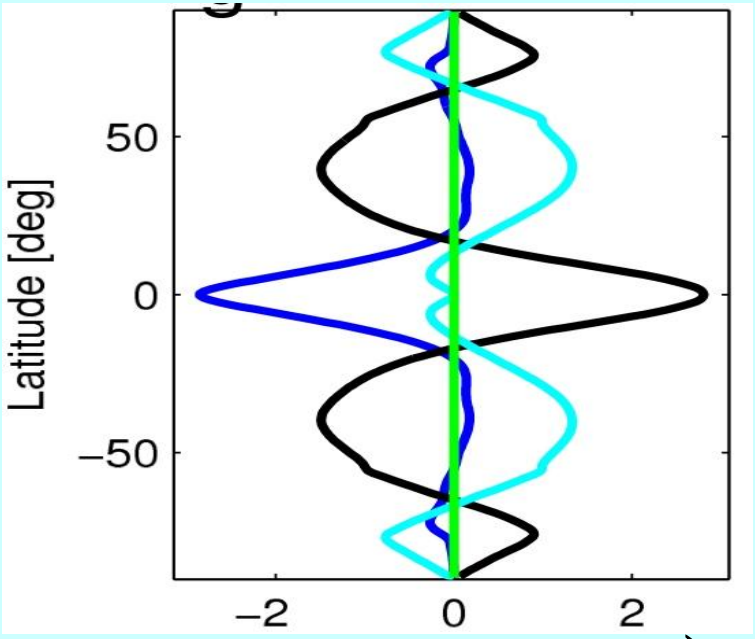
- **Rhines length**, $(U/\beta)^{1/2}$, is the scale at which planetary rotation causes east-west elongation (jets).
- **Deformation radius**, c/Ω, is a natural scale of vortex formation and flow instability

On Jupiter/Saturn, these lengths are << planetary radius

On most hot Jupiters, they are close to planetary radius. Jets and vortices should therefore be global in scale.



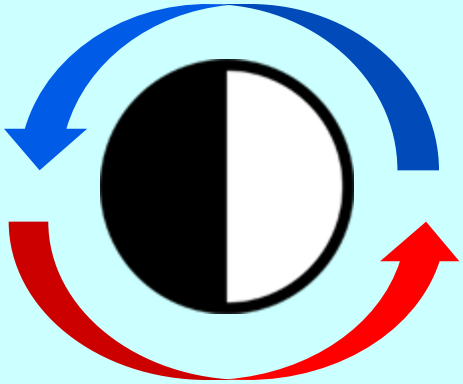




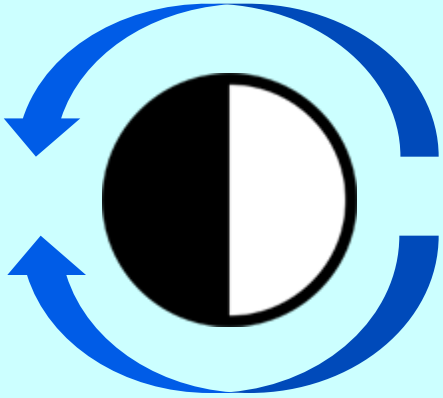
Showman & Polvani (2011)

The two regimes also lead to distinct Doppler predictions

- **At weak-to-moderate stellar fluxes and friction, standing planetary waves induce zonal jets. This causes bimodal blue and redshifted velocity peaks:**



- **Extreme stellar fluxes and/or friction damp the planetary waves, inhibiting zonal jet formation and leading to predominant day-night flow at high altitude. This causes a predominant blueshifted velocity peak:**

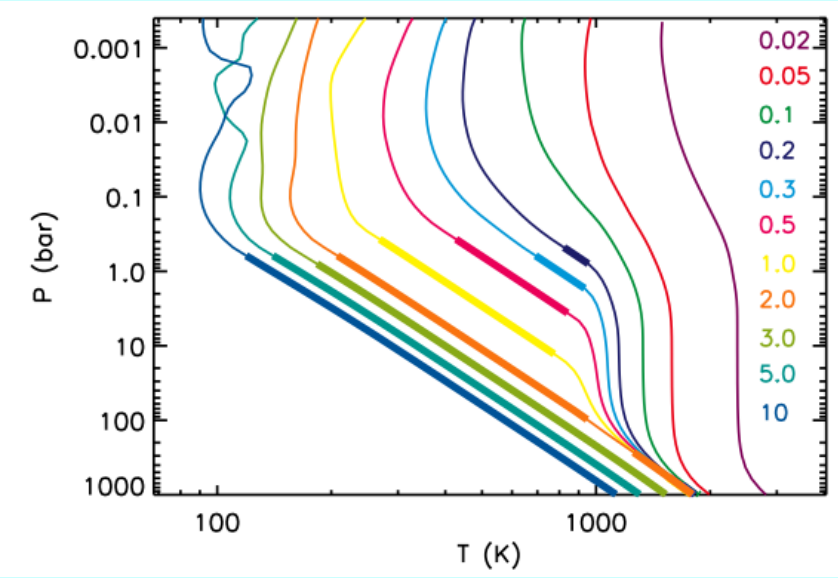


Dynamical regime of hot Jupiters

- **Circulation driven by global-scale heating contrast: ~10^5 W/m^2 of stellar heating on dayside and IR cooling on nightside**

- **Rotation expected to be synchronous with the 1-10 day orbital periods; Coriolis forces important but not dominant**

- **Weather occurs in a statically stable radiative zone extending to ~100-1000 bar**



Fortney et al. (2007)

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?** ***[spectroscopy, lightcurves, eclipse mapping]***

- **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?** ***[Doppler, lightcurves, eclipse mapping]***

- **How does the circulation interact with the interior? Does it affect the evolution and radius?** ***[Radii statistics, constraints on circulation, composition, magnetic fields]***

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

- **What is the atmospheric state and climate of terrestrial exoplanets? How does circulation help control habitability on these worlds?** ***[Spectroscopy, lightcurves,…]***