Atmospheric Circulation of hot Jupiters

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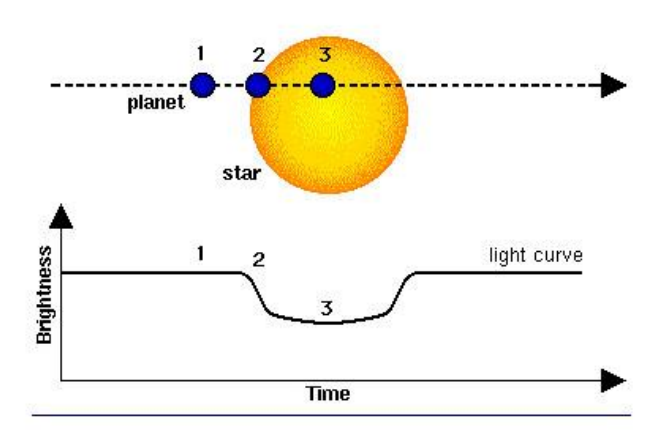
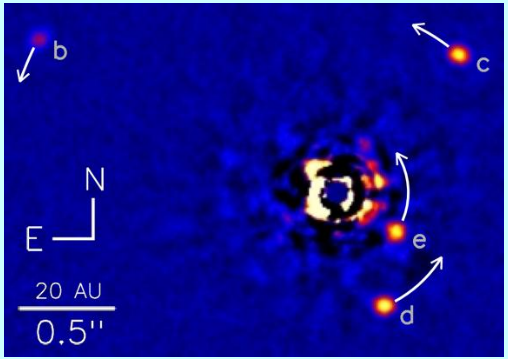
Exoplanets: an exploding new field

- **Over 3500 known extrasolar planets**
- **Nearly 700 planets have been detected with the "Doppler" method**
- **Nearly 2700 planets have been detected with "transit" method (plus many Kepler candidates):**

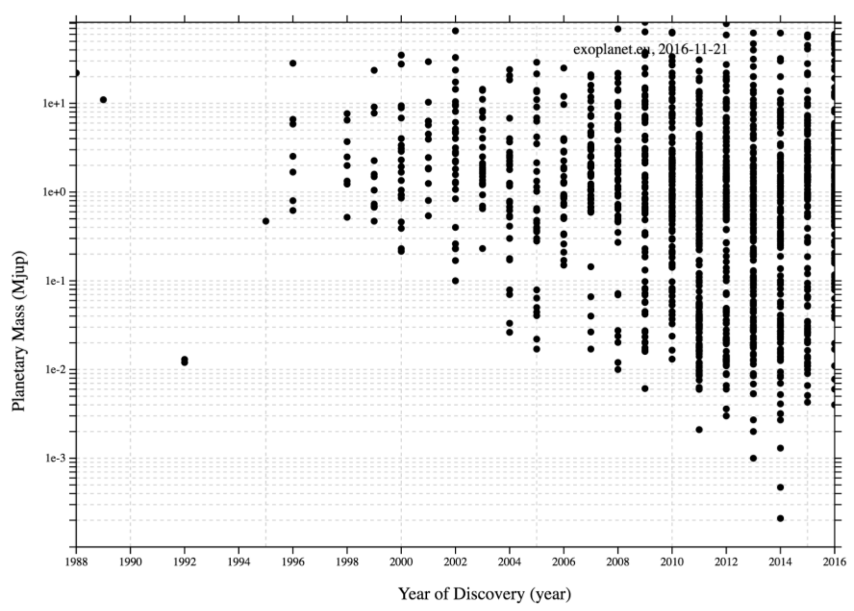


Together, these give the planetary mass, radius, and orbital properties.

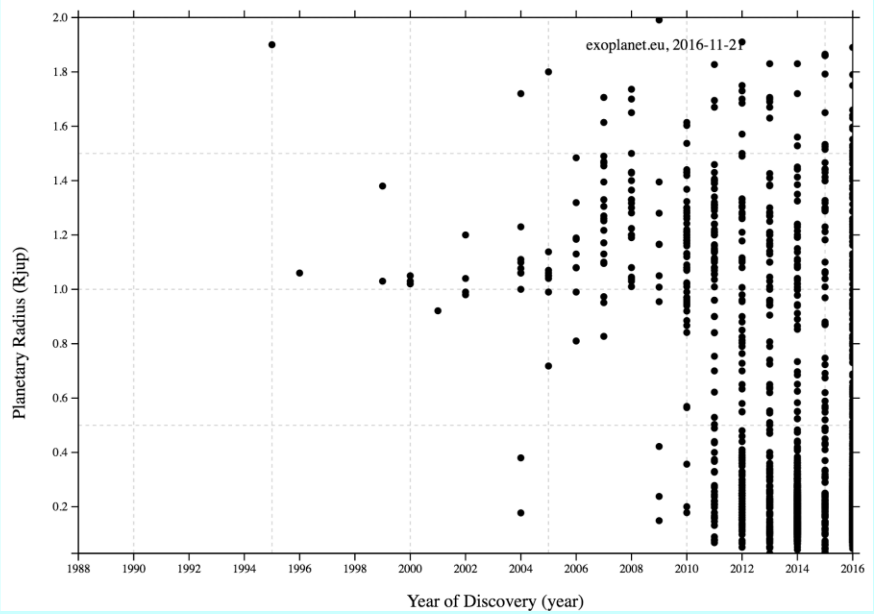
- **~50 planets discovered by direct imaging:**



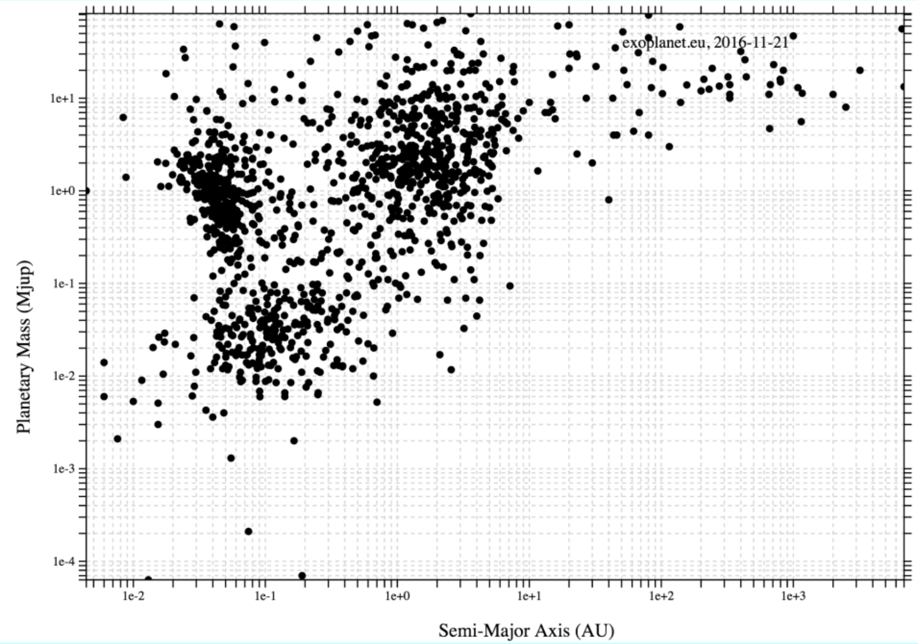
Planet mass vs. year of discovery



Planet radius vs. year of discovery

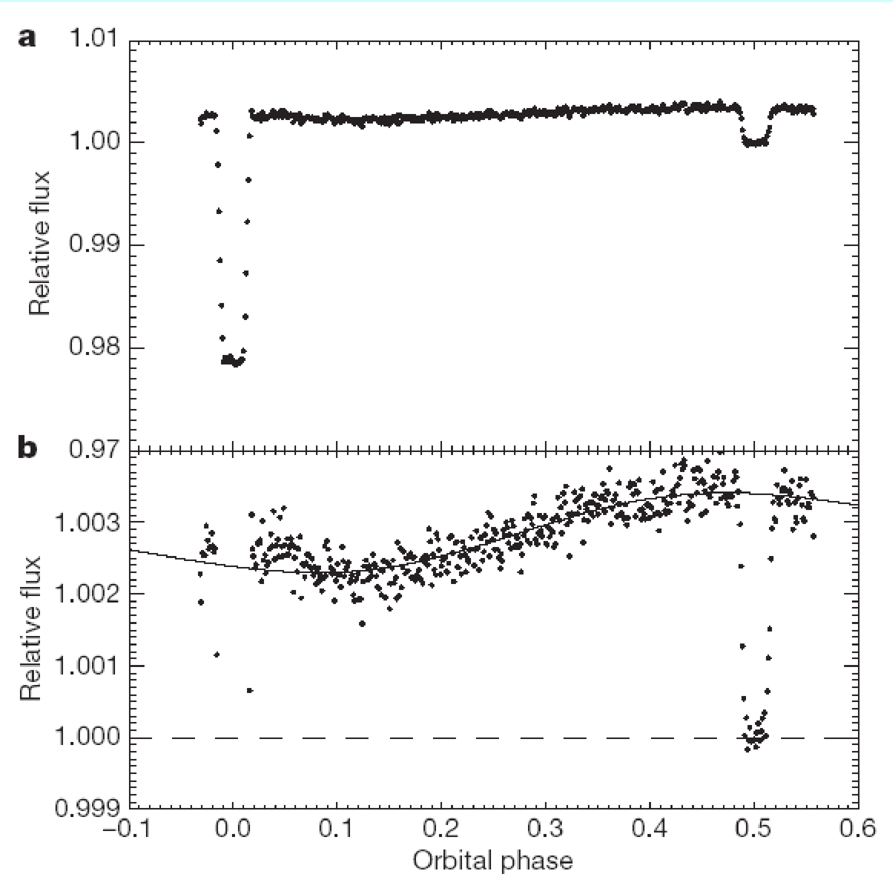


Planet mass vs. semi-major axis

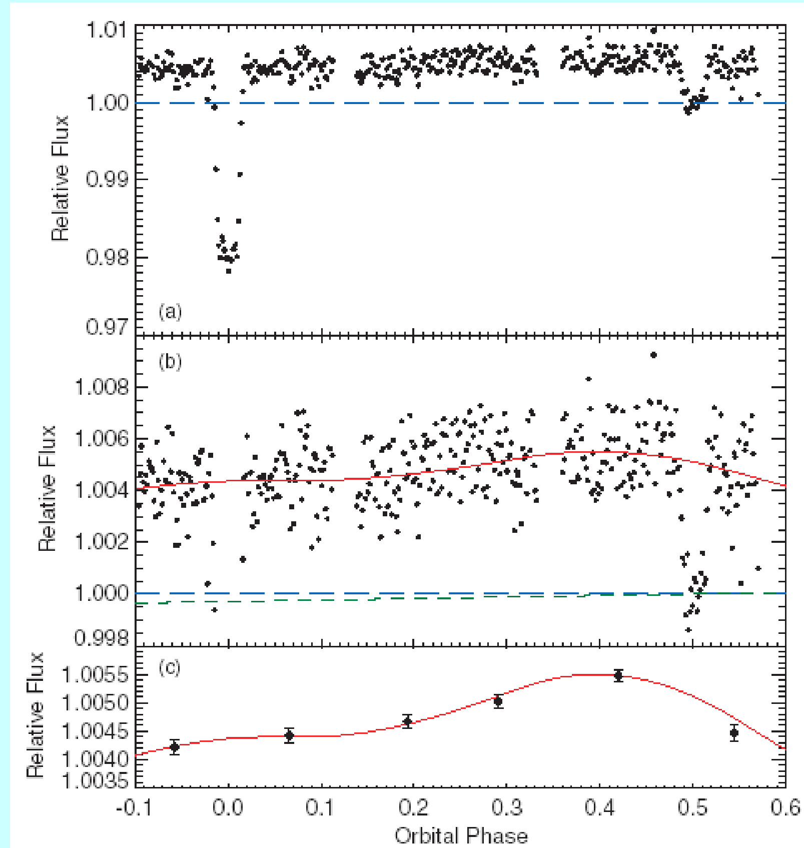


exoplanet.eu

Hot Jupiters: Spitzer light curves for HD 189733b

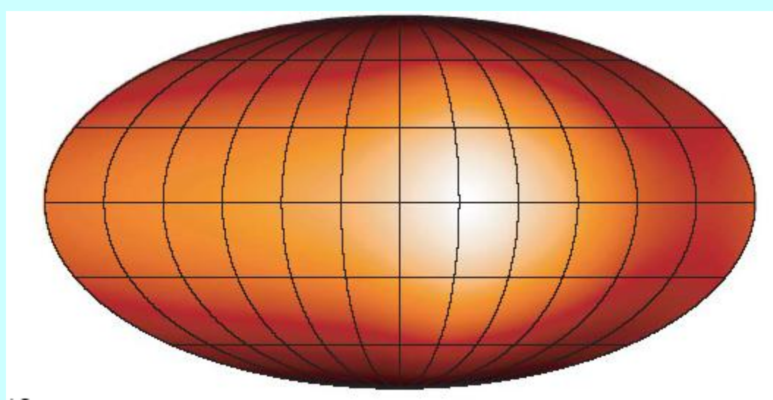


8 μm

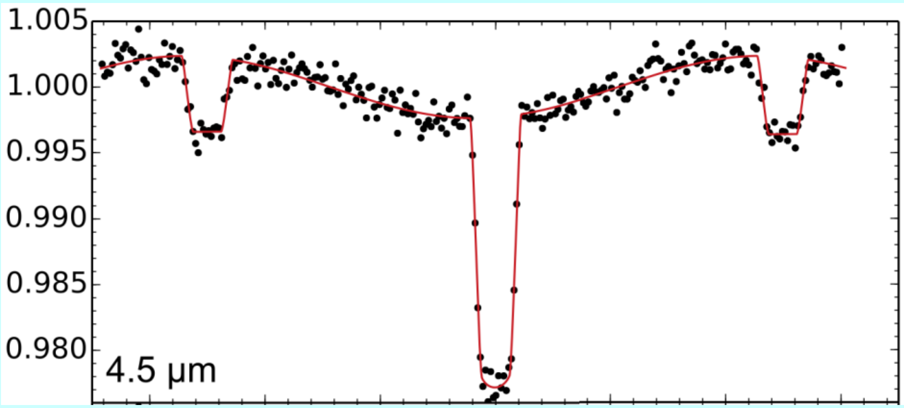


24 μm

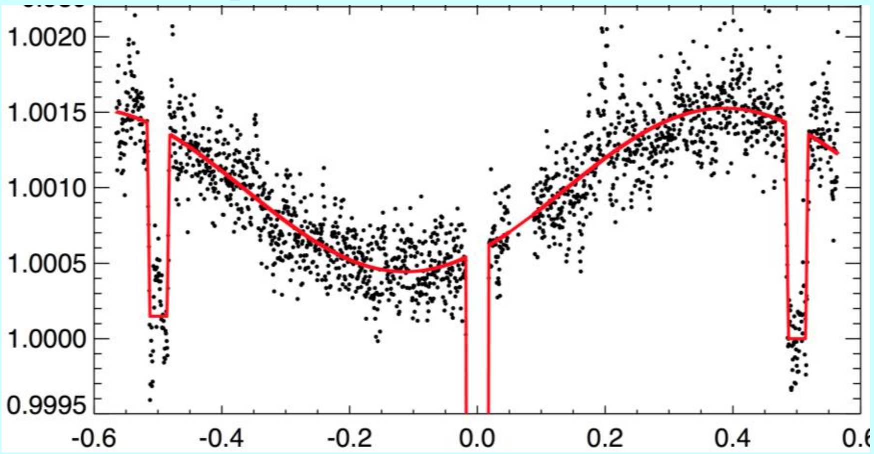
Knutson et al. (2007, 2009)



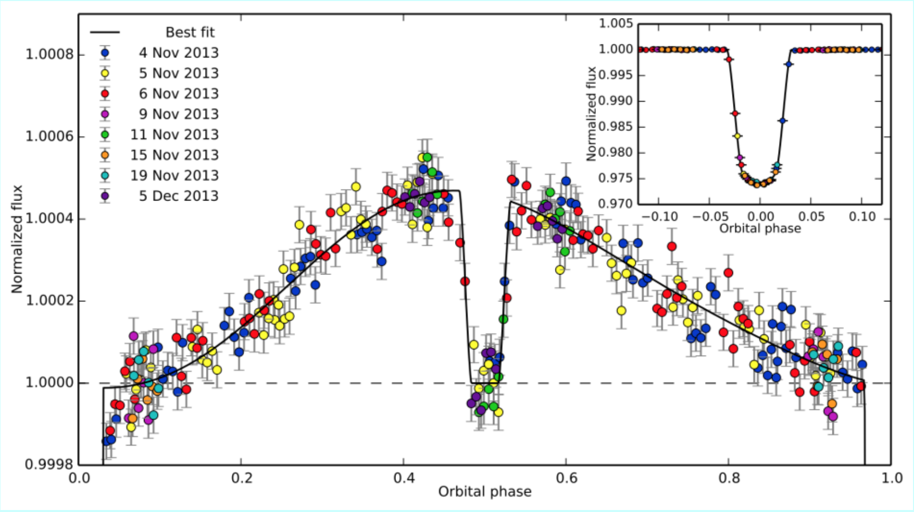
Lightcurves for hot Jupiters



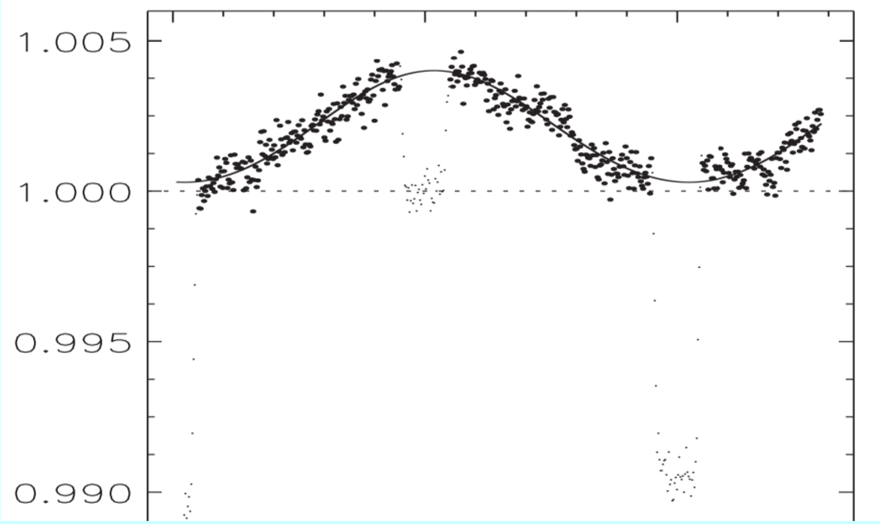
WASP-19b (Wong et al. 2016)



HD209458b (Zellem et al. 2014)

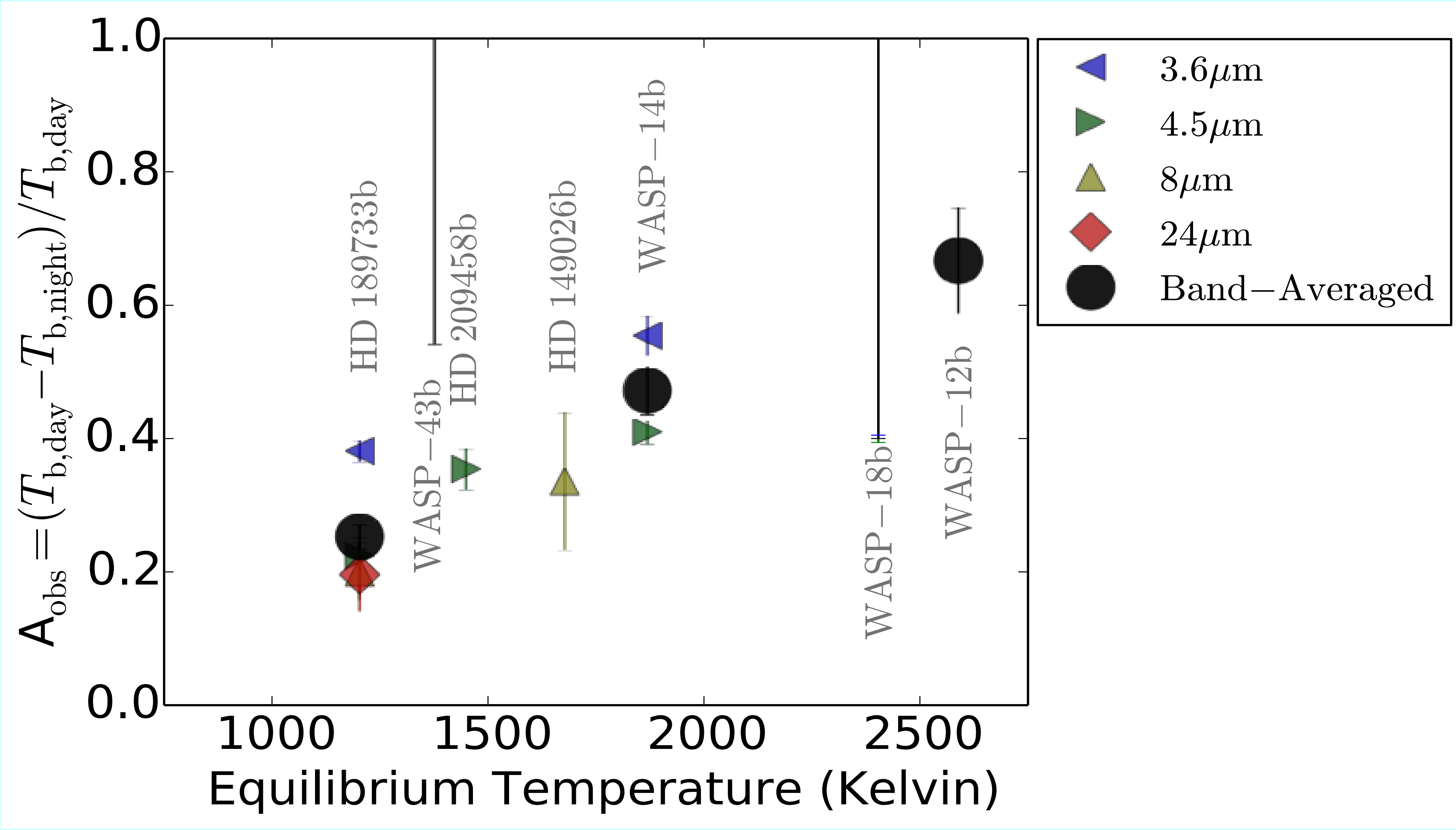


WASP-43b (Stevenson et al. 2014)



WASP-18b (Maxted et al. 2013)

Dependence of day-night flux contrast on effective temperature



Komacek et al. (2017)

Motivating questions

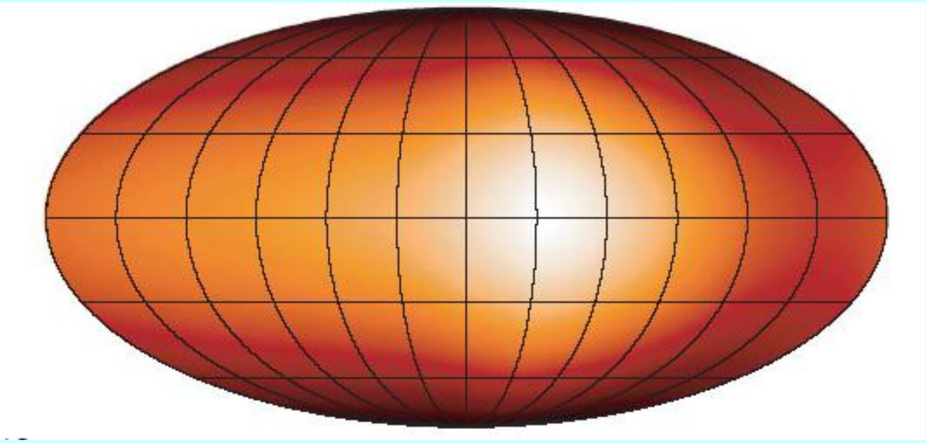
- **What are the fundamental dynamics of the highly irradiated "hot Jupiter" circulation regime? Can we explain lightcurves of specific hot Jupiters? What is the mechanism for displacing the hottest regions to the east?**

- **What are mechanisms for controlling the day-night temperature contrast on hot Jupiters? Can we explain the increasing trend of day-night flux contrast with incident stellar flux?**

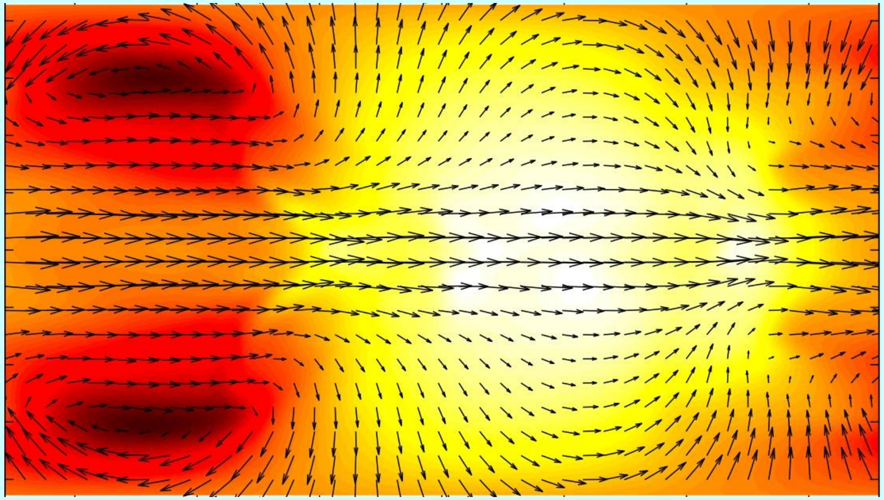
- **What controls the cloudiness of hot Jupiters?**

- **How do circulation regime---and observables---of hot Jupiters vary with parameters like incident stellar flux and rotation rate?**

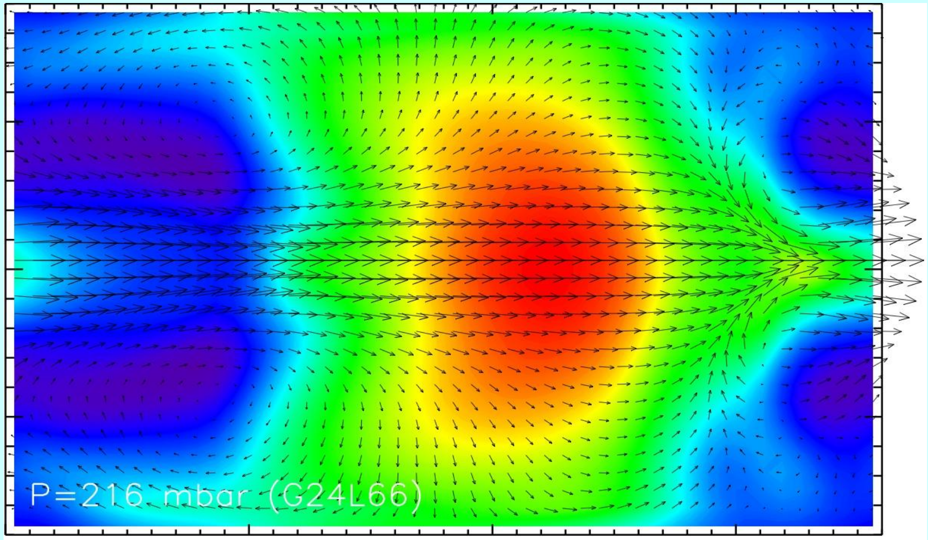
Hot Jupiter circulation models typically predict several broad, fast jets including equatorial superrotation



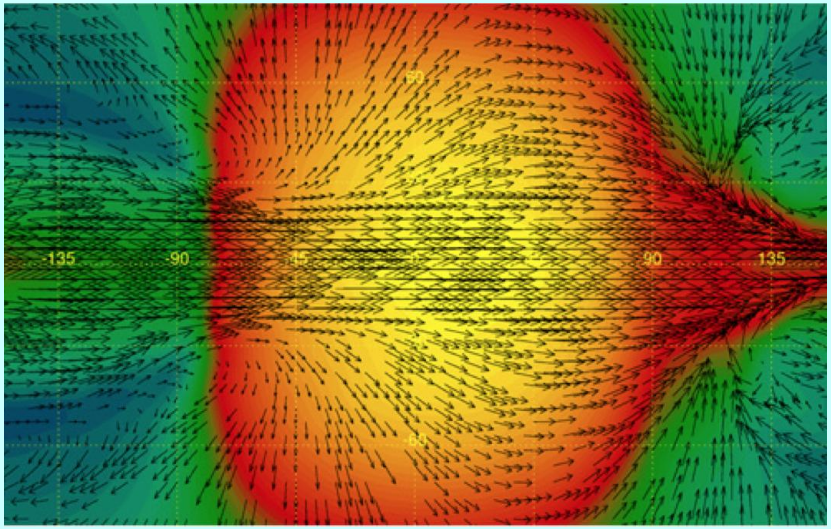
Knutson et al. (2007)



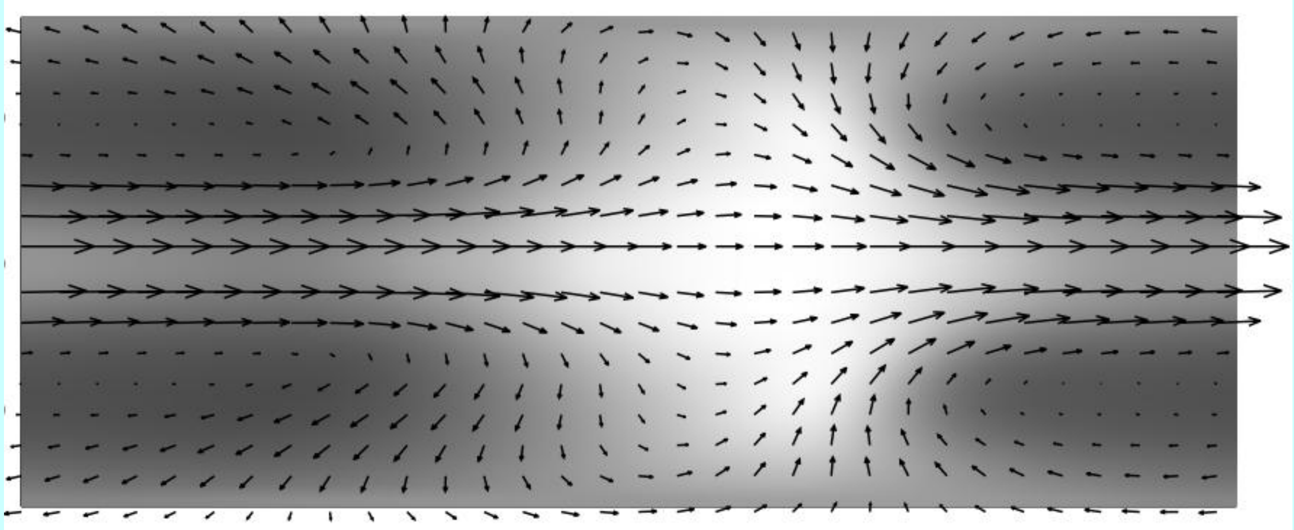
Showman et al. (2009)



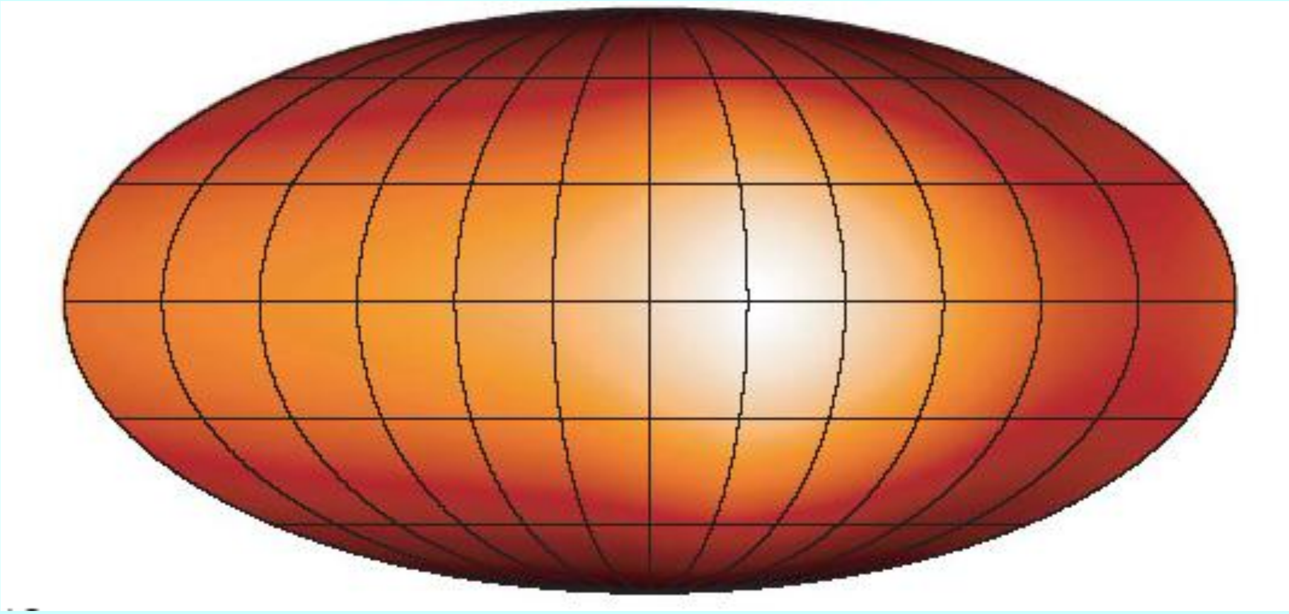
Heng et al. (2011)



Rauscher & Menou (2012)



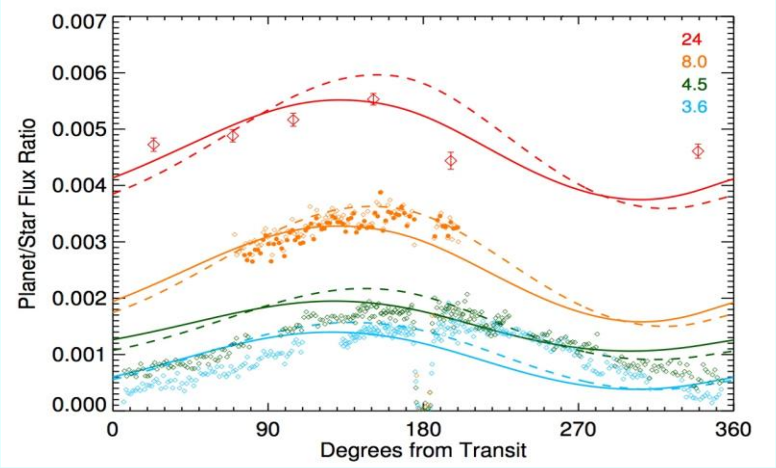
Showman & Guillot (2002)

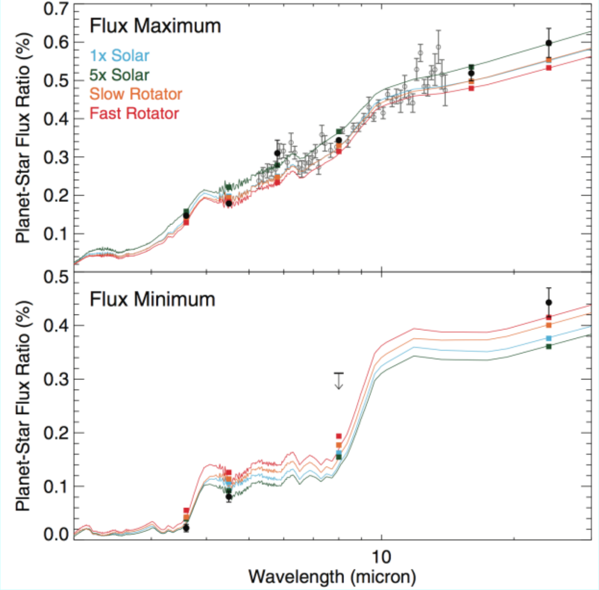


Knutson et al. (2007)

Comparisons of data to GCMs

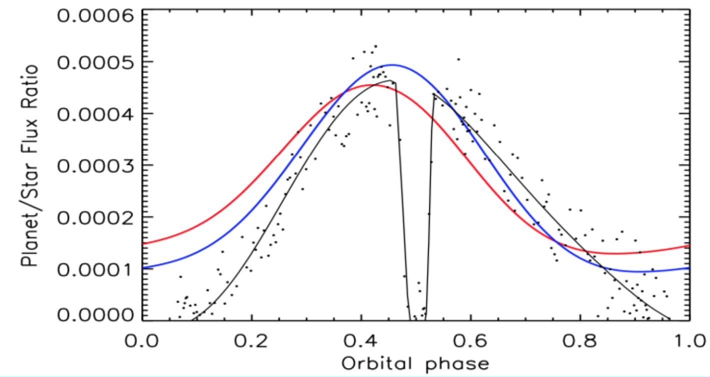
HD 189733b

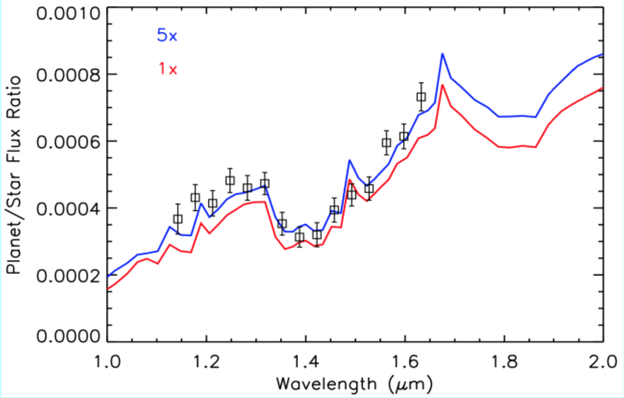




Showman et al. (2009), Knutson et al. (2012)

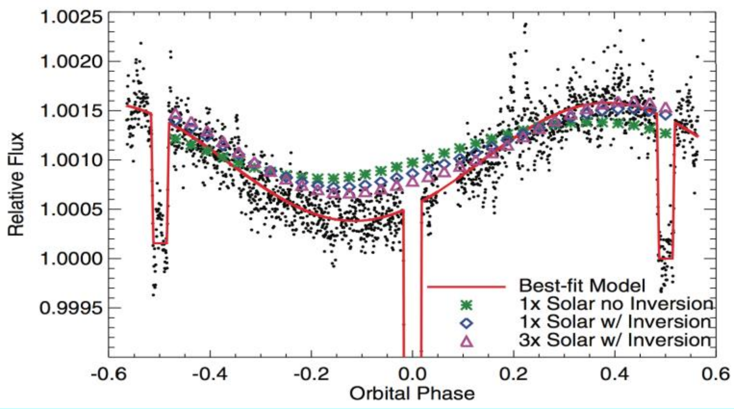
WASP-43b

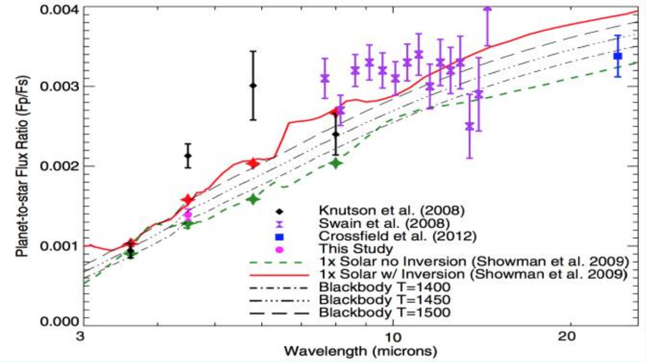




Kataria et al. (2015)

HD 209458b





Showman et al. (2009), Zellem et al. (2014)

What causes the equatorial superrotation?

Hide's theorem: **Superrotating equatorial jets (corresponding to local maxima of angular momentum) cannot result from axisymmetric circulations (e.g., angular-momentum conserving Hadley cells).**

Such jets must instead result from up-gradient momentum transport by waves and/or turbulence

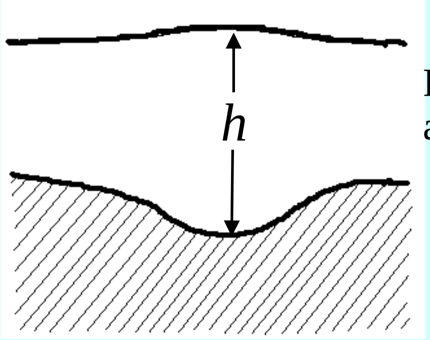
This is a fairly common phenomenon in turbulence… the question is, in the present context, what is the specific mechanism?

Simple models to isolate superrotation mechanism

- **To capture the mechanism in the simplest possible context, adopt the shallow-water equations for a single fluid layer:**

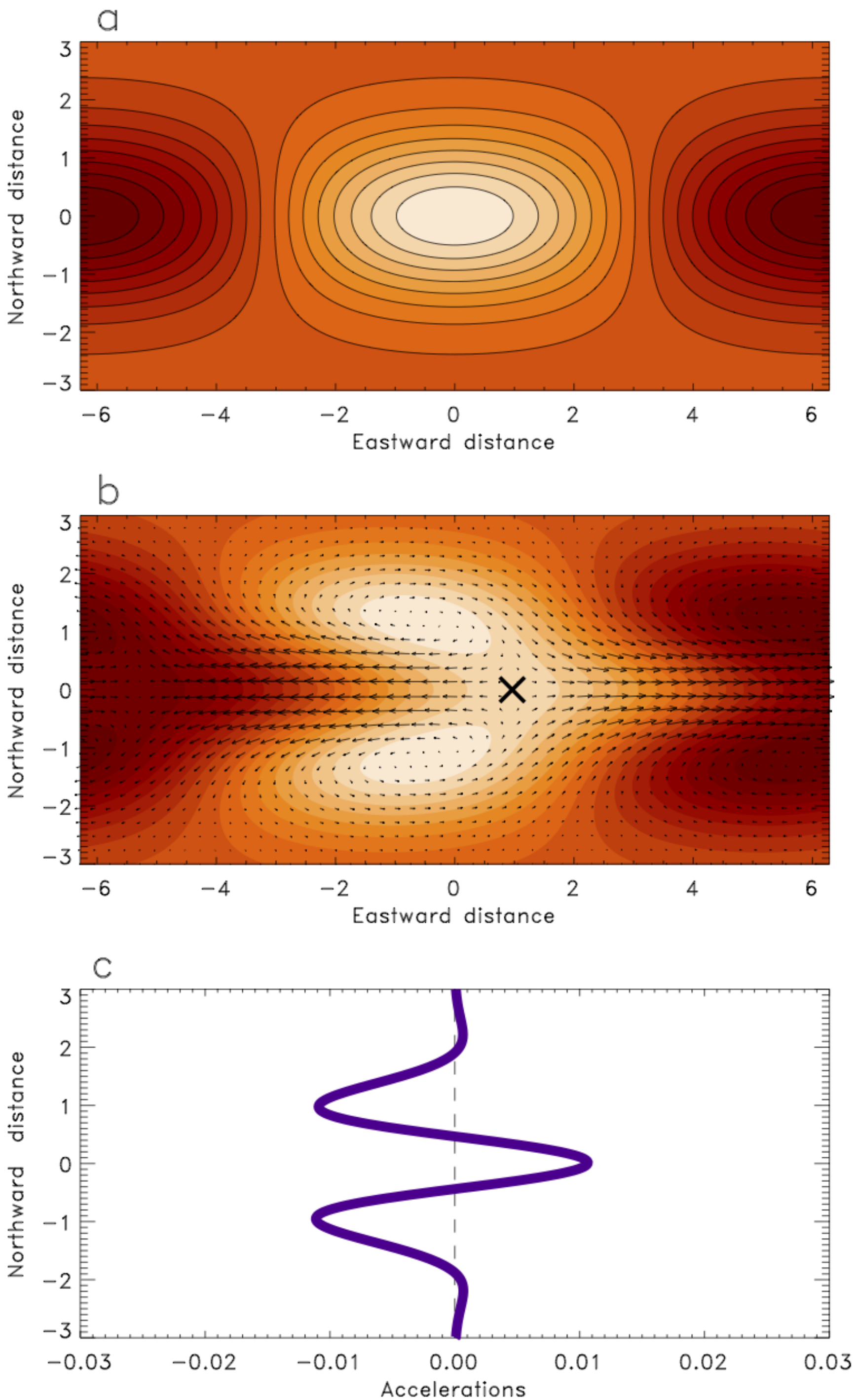
$$\frac{d\vec{v}}{dt} + g\nabla h + fk \times \vec{v} = -\frac{\vec{v}}{\tau_{drag}} - \vec{v}\frac{Q_h}{h}\delta$$

$$\frac{\partial h}{\partial t} + \nabla \cdot (h\vec{v}) = \frac{h_{eq} - h}{\tau_{rad}} \equiv Q_h$$



where $(h_{eq}-h)/\tau_{rad}$ represents thermal forcing/damping, $-v/\tau_{drag}$ represents drag, and where $\delta=1$ when $Q_h>0$ and $\delta=0$ otherwise

- **First consider linear, steady analytic solutions and then consider full nonlinear solutions on a sphere.**

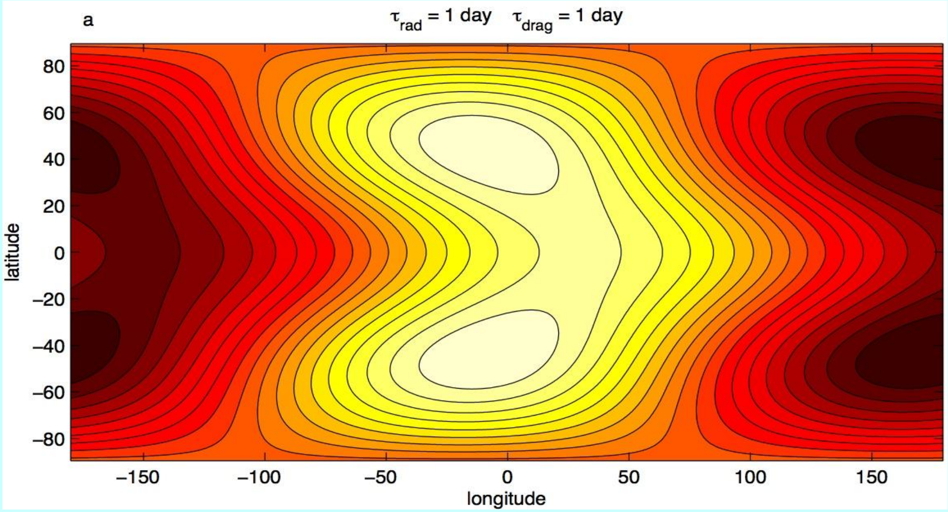


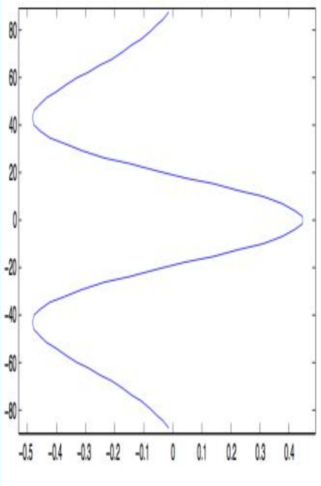
Linear analytic calculation

The day/night thermal forcing induces standing planetary-scale (Rossby and Kelvin) waves, which transport momentum to the equator. This induces superrotation.

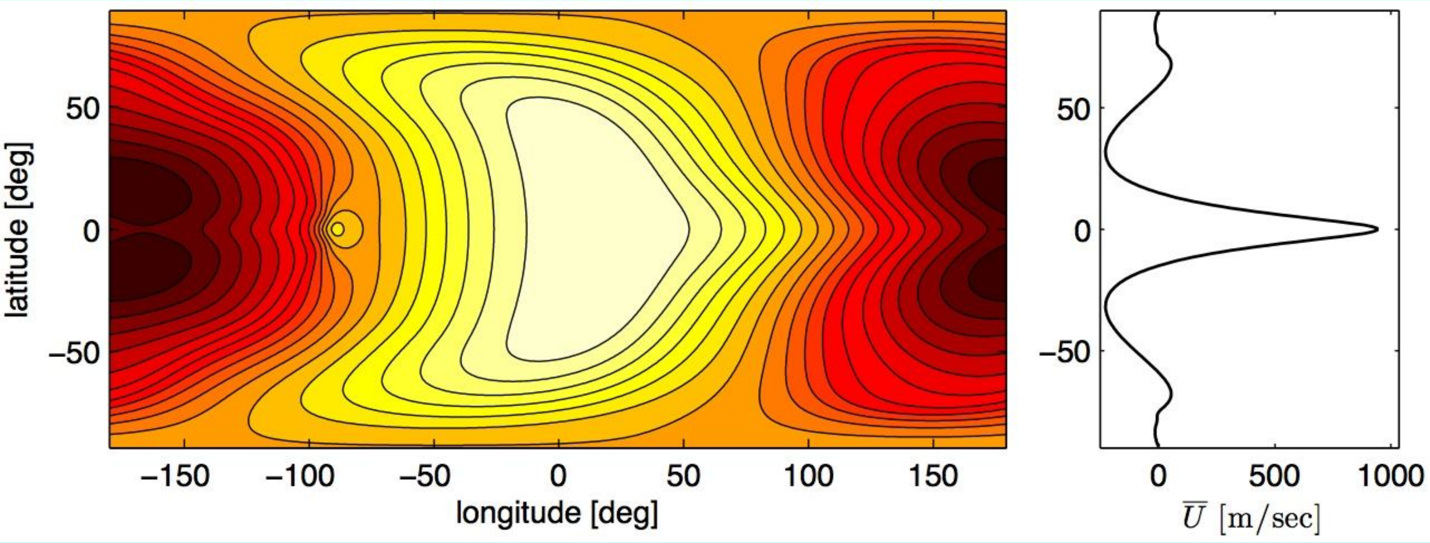
Showman & Polvani (2011), *ApJ* 738, 71

Full nonlinear numerical solutions on a sphere





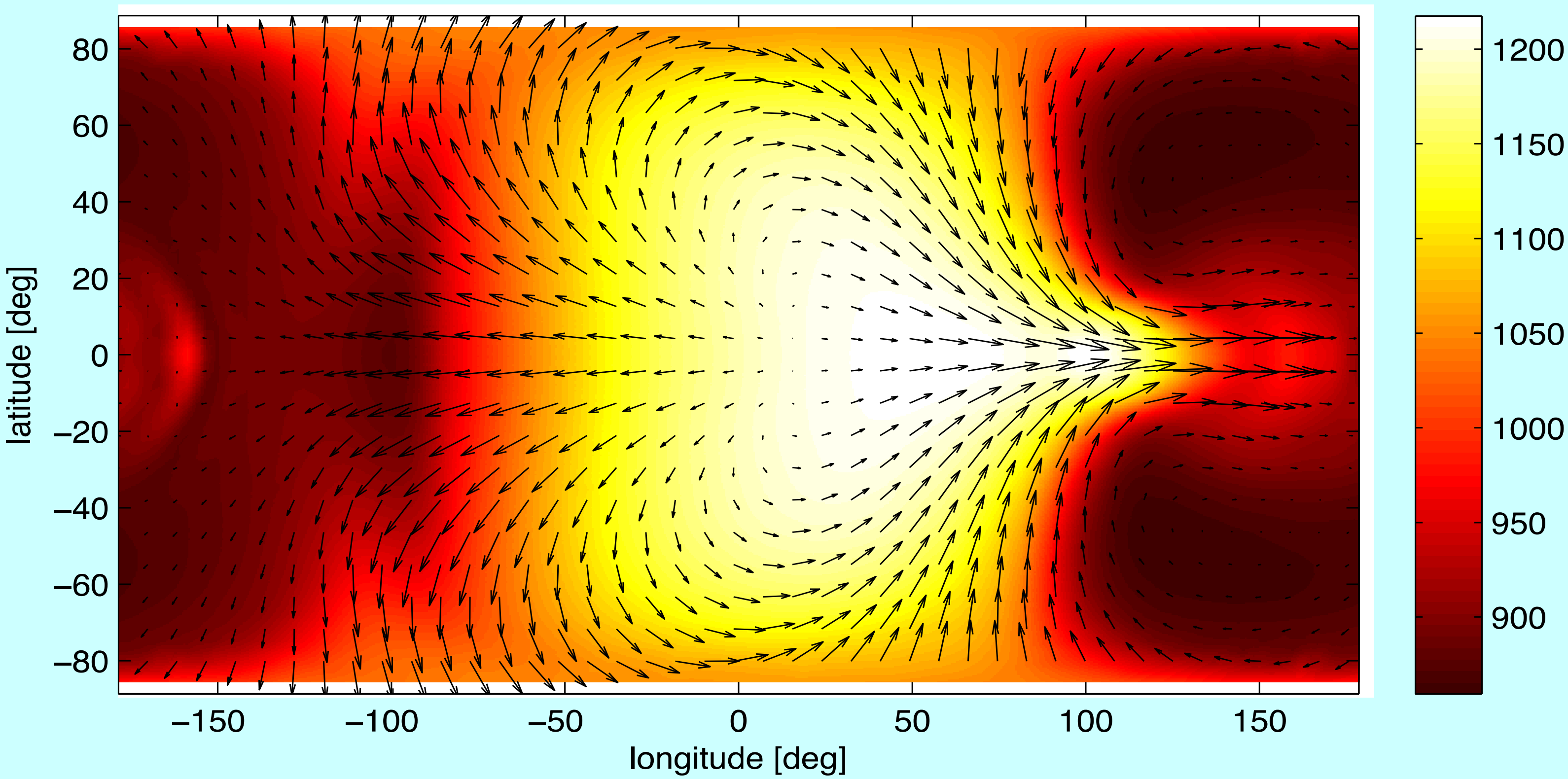
Low amplitude (~linear)



High amplitude (non-linear)

Showman & Polvani (2011)

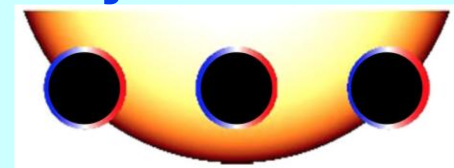
This Rossby/Kelvin wave pattern is clearly evident in spin-up phase of 3D hot Jupiter simulations

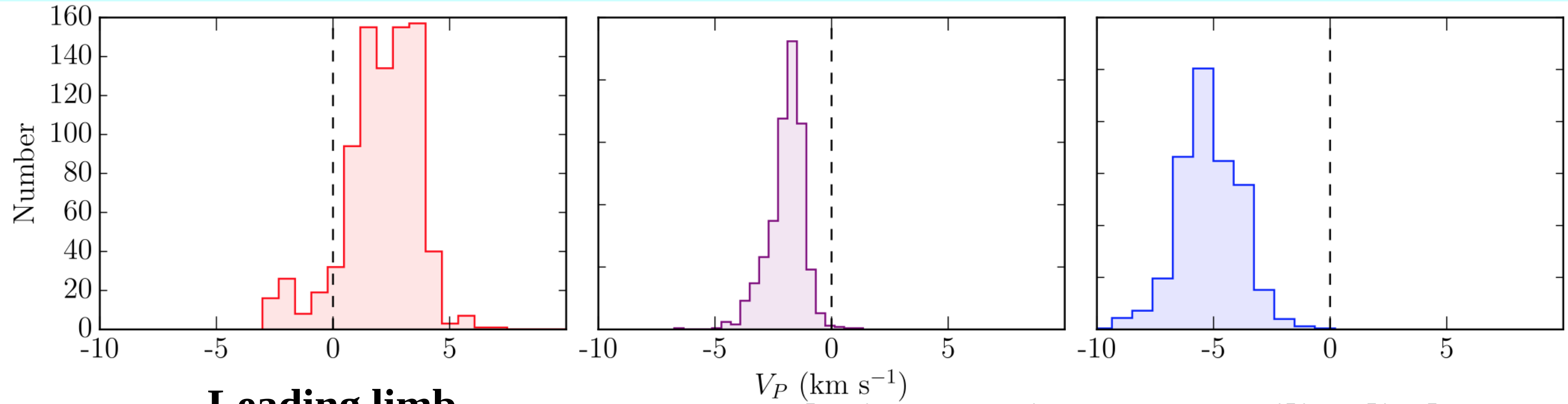


Showman & Polvani (2011)

Doppler detection of equatorial jet

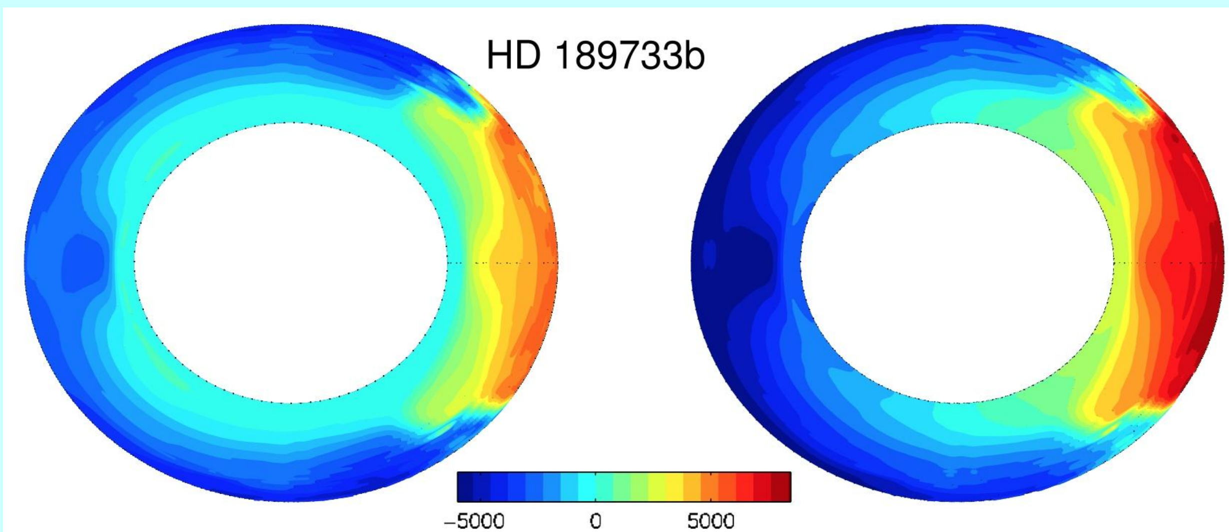
A direct detection of the equatorial jet has recently been made, and is consistent with GCM predictions.





Leading limb **Average during transit** **Trailing limb**

Louden & Wheatley (2015)



Showman et al. (2013a)

Toward predictive theories of the circulation

- **GCM simulations are useful but by themselves do not imply understanding**

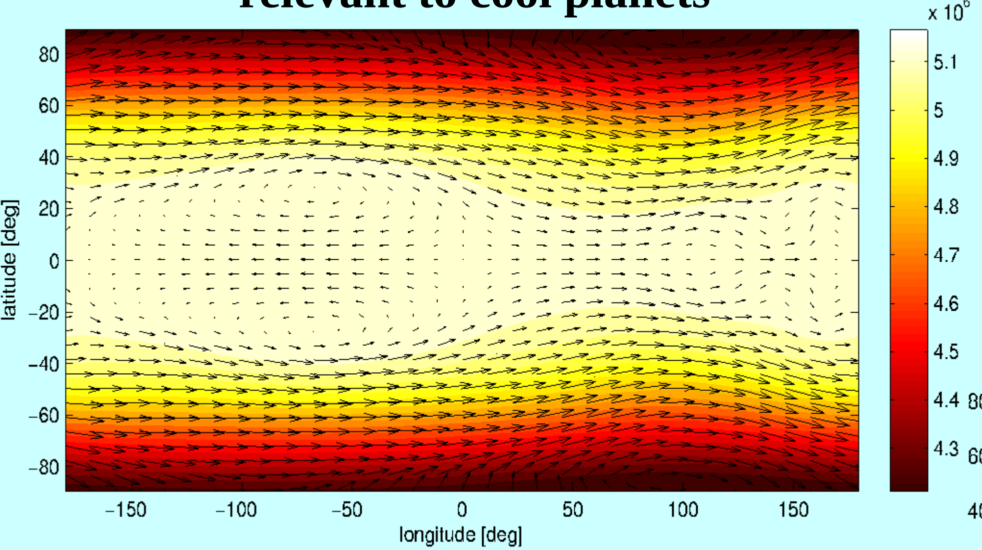
- **The ultimate goal is to *understand* the mechanisms and obtain a *predictive* theory for the day-night temperature differences, vertical mixing rates, and other aspects of the circulation.**

It is commonly assumed that day-night temperature differences are small if $\tau_{rad} >> \tau_{advect}$ and temperature differences are large if $\tau_{rad} << \tau_{advect}$.

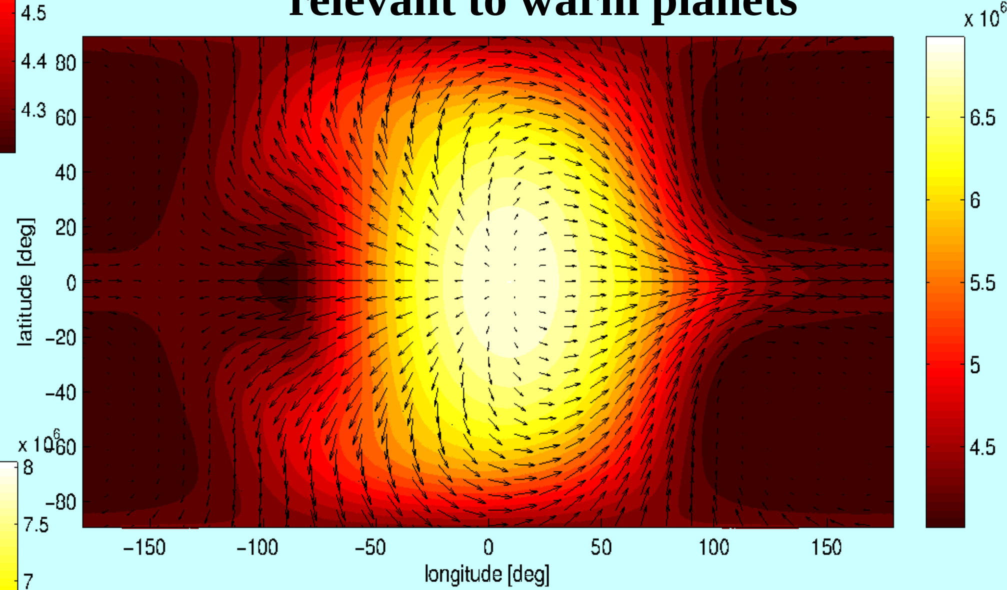
- **Problems: This is not predictive, since τ_{advect} depends on the flow. It also neglects a role for other important timescales in the problem, including wave, frictional, and rotational timescales. These almost certainly matter.**

From Warm to Very Hot Jupiters

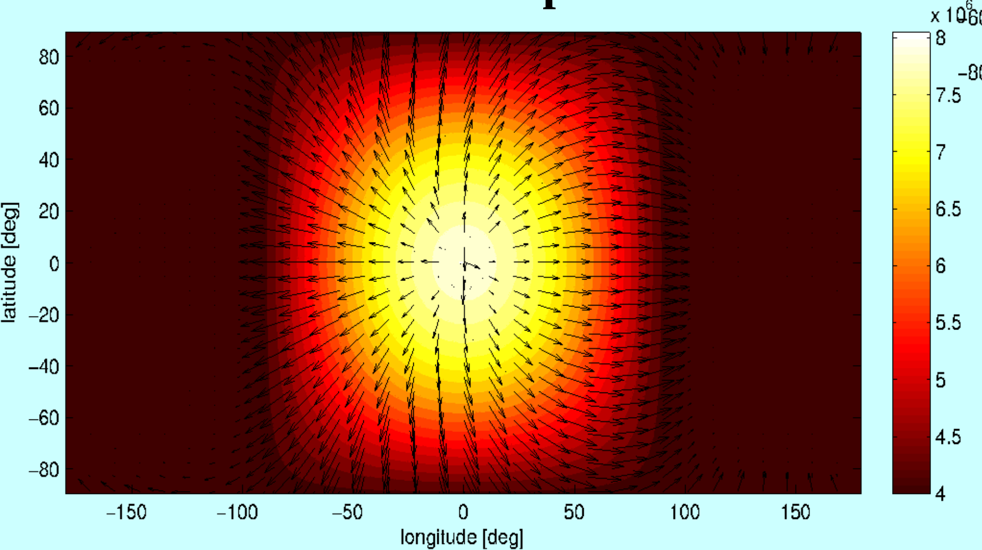
Weak damping (τ_{rad} = 10 days), relevant to cool planets



Moderate damping (τ_{rad} = 1 day), relevant to warm planets

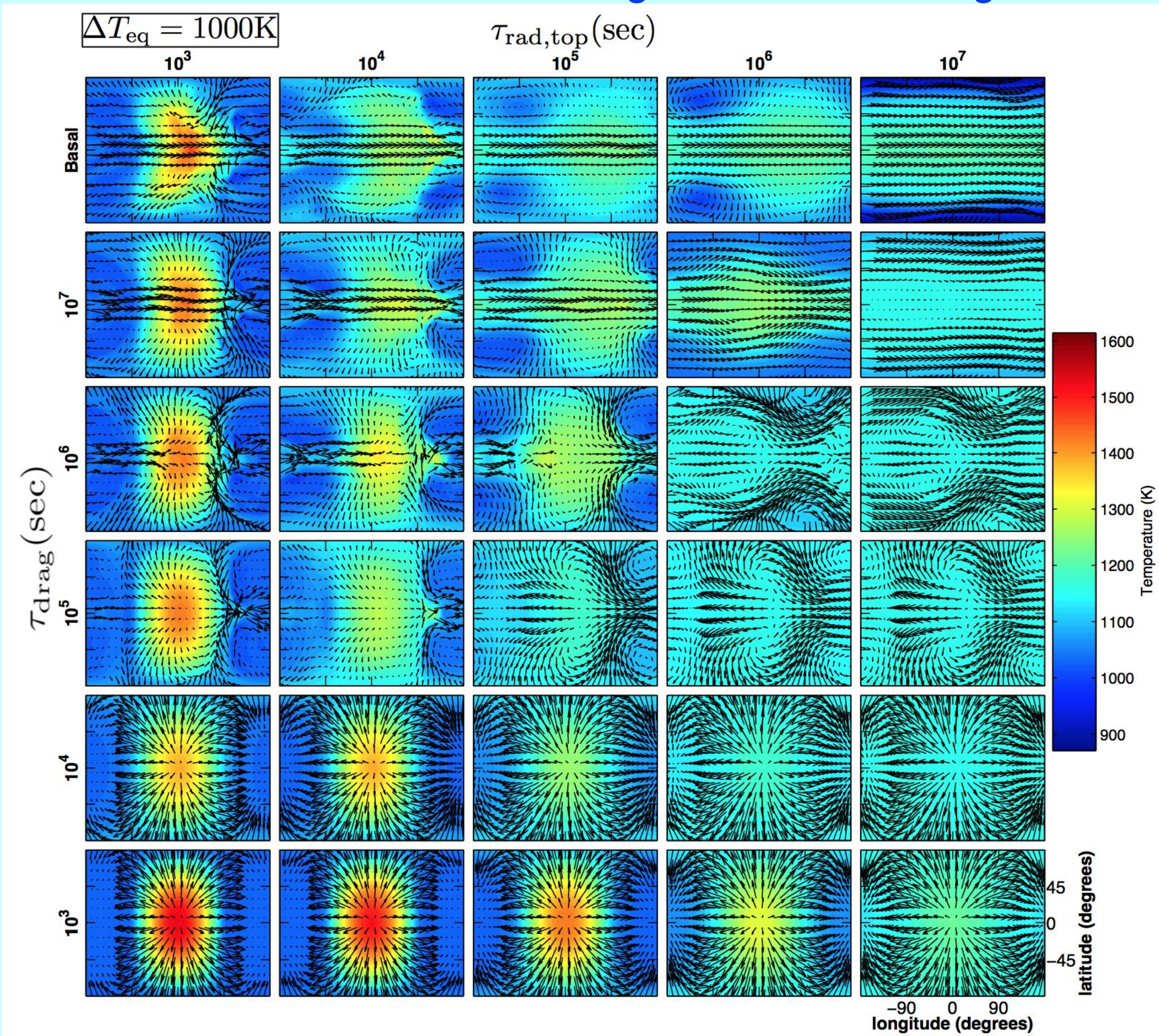


Strong damping (τ_{rad} = 0.1 days), relevant to hot planets



Showman et al. (2013a)

Hot-Jupiter circulation in idealized GCM simulations as a function of radiative time constant and strength of frictional drag

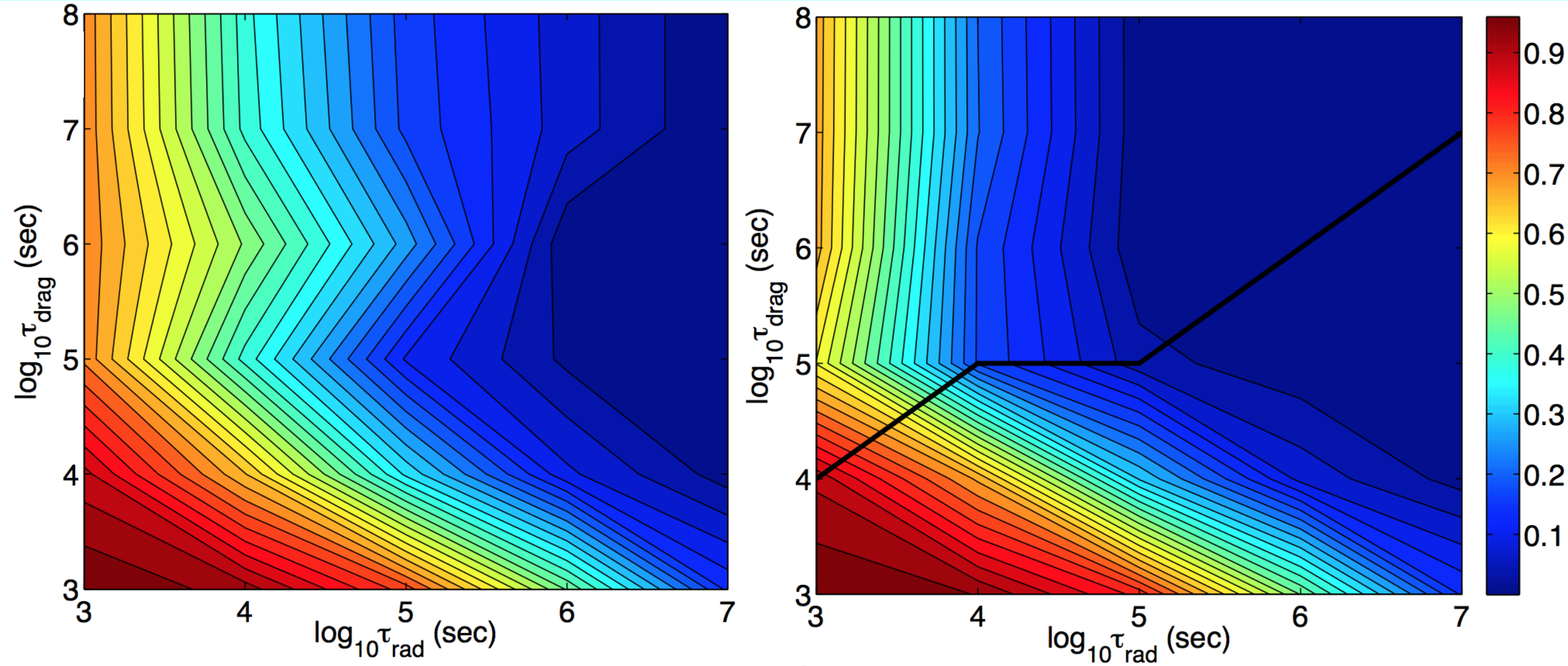


Komacek & Showman (2016); see also Perez-Becker & Showman (2013)

Theory for day-night temperature contrast

Day-night thermal contrast from three-dimensional GCM simulations

Day-night thermal contrast from a fully predictive theory with zero free parameters and no tuning

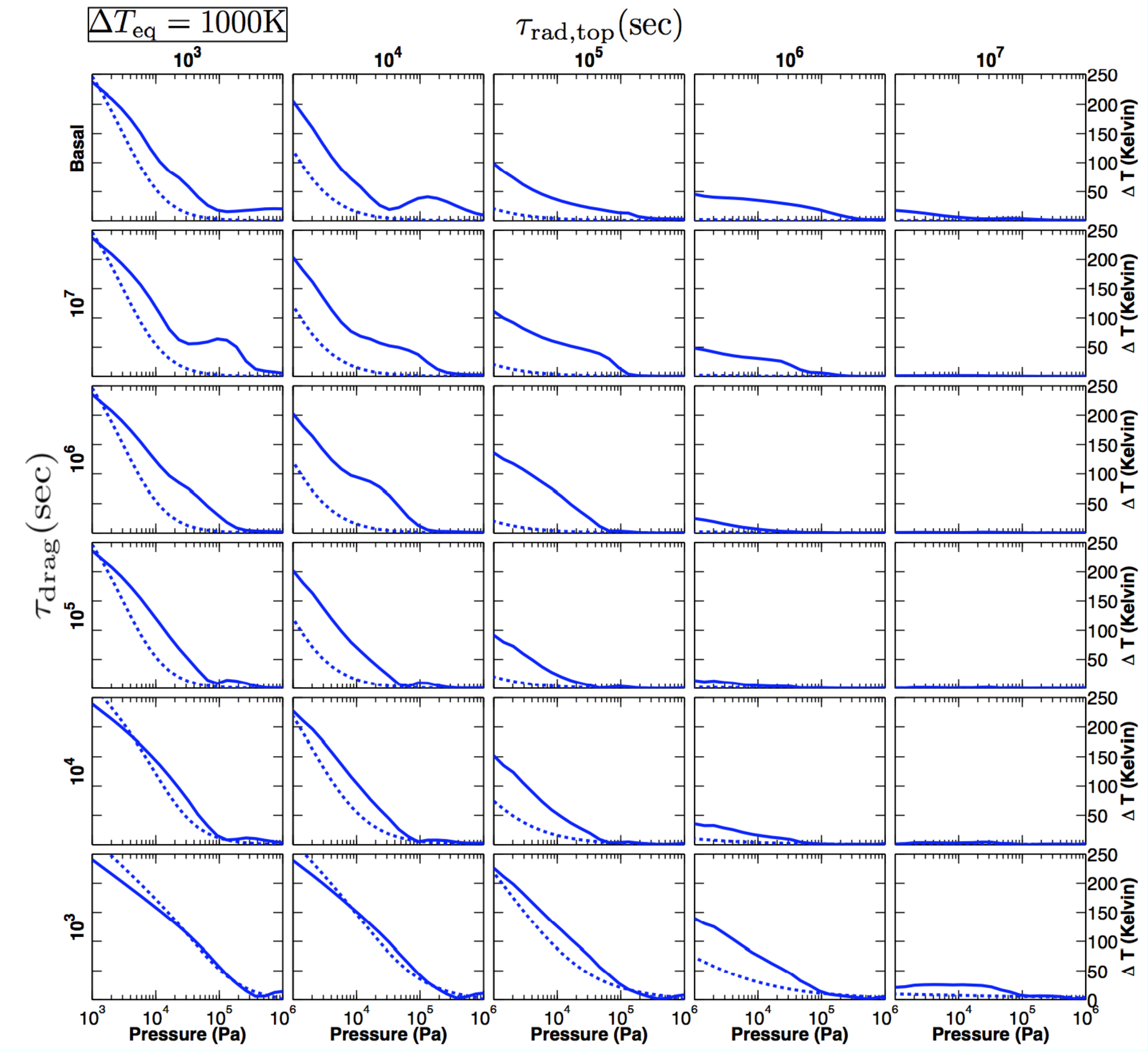


Komacek & Showman (2016); see also Perez-Becker & Showman (2013)

The theory matches the simulation results well over a multi-order-of-magnitude parameter space in the radiative and frictional time constants.

The theory shows that the transition between regimes is generally controlled by wave adjustment (and the resulting vertical advection) rather than horizontal advection timescales.

Day-night temperature differences vs pressure



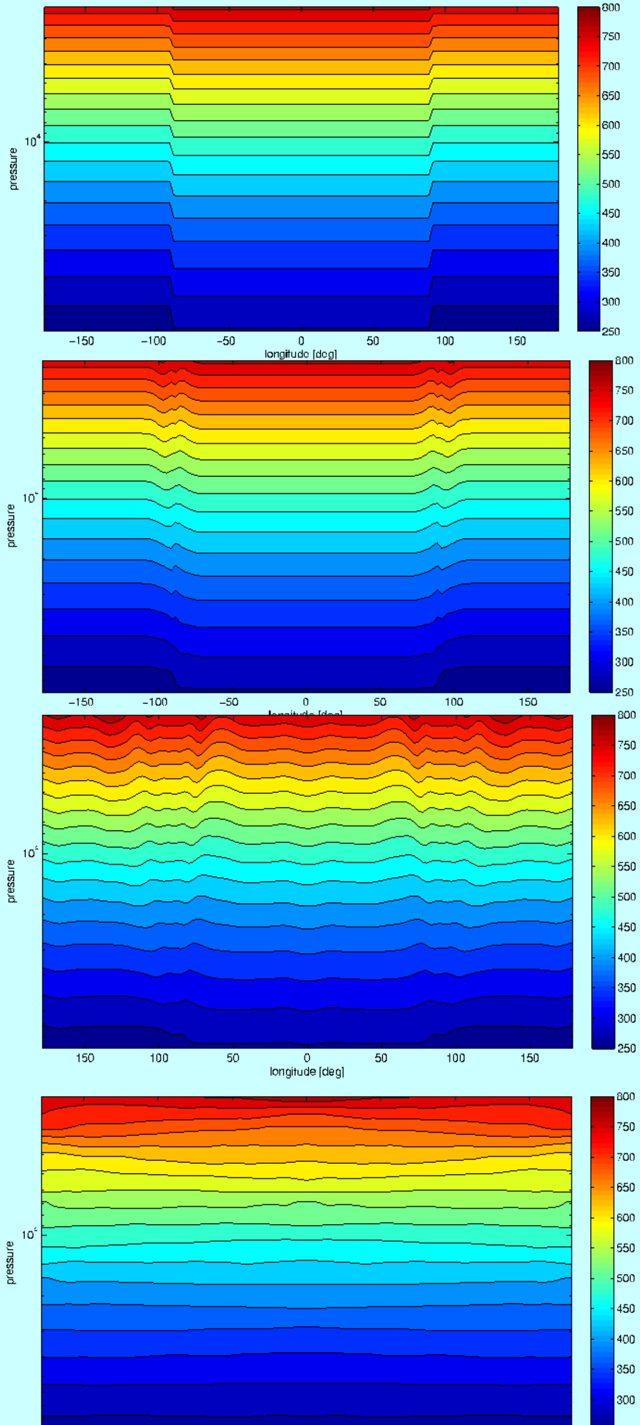
Komacek & Showman (2016)

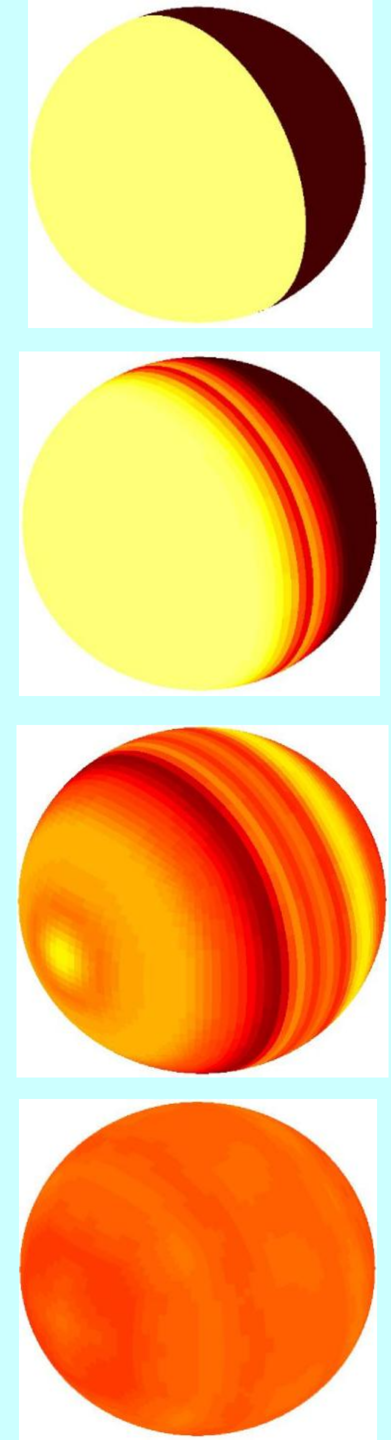
Curves:
Solid=GCM
Dotted=theory

Wave adjustment process

Waves adjust isentropes up or down in an attempt to flatten them. This erases horizontal temperature differences.

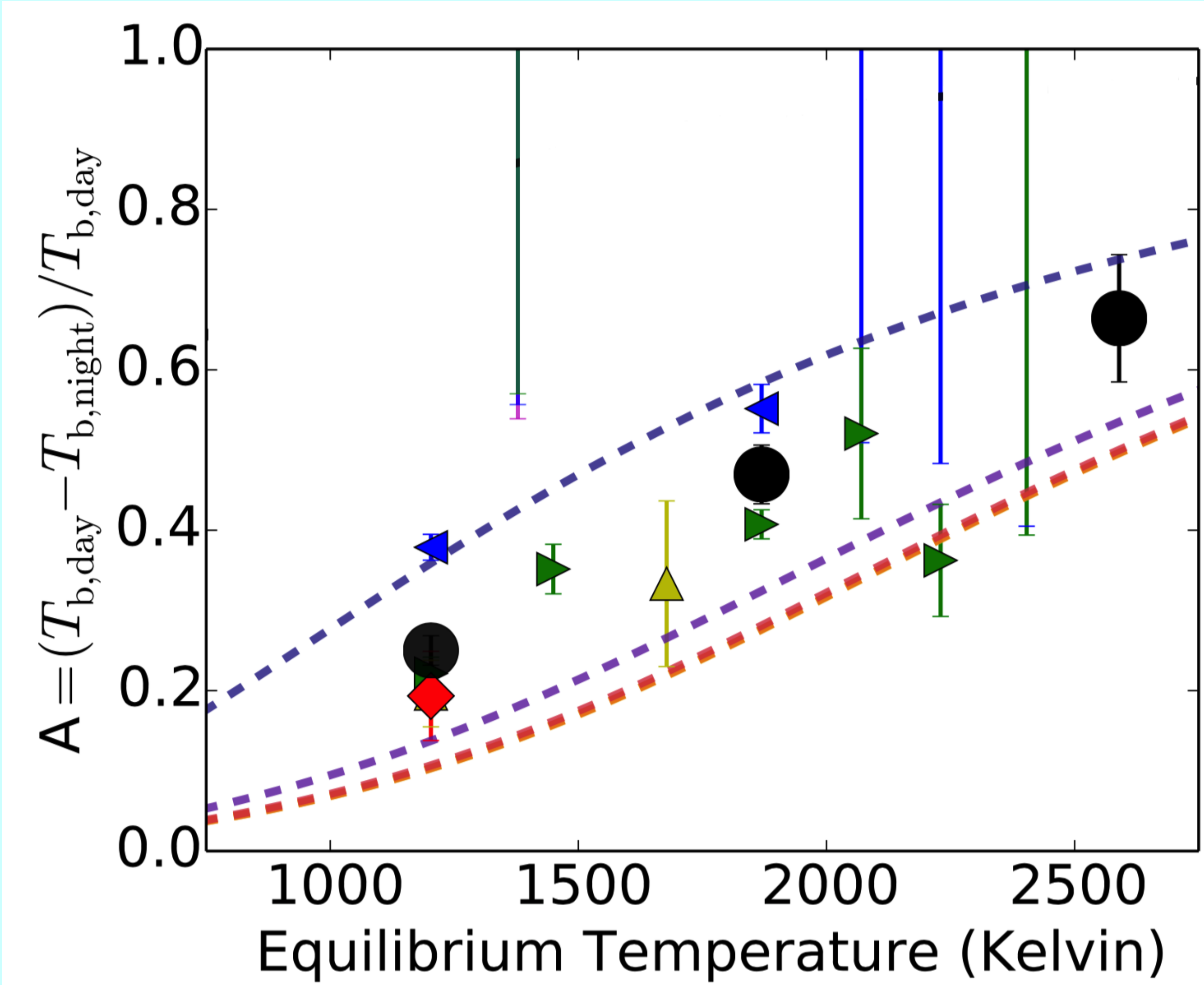
This is a key mechanism for maintaining the small longitudinal temperature differences in Earth's tropics: the "weak temperature gradient" or WTG regime.





Showman et al. (2013b), "Atmospheric circulation of terrestrial exoplanets," submitted to *Comparative Climatology of TerrestrialPlanets*, Univ. Arizona Press (to be published)

The model explains the emerging observational trend



Komacek et al. (2017), Perez-Becker & Showman (2013)

What about objects cooler than "classical" hot Jupiters?

- **Despite the focus on hot Jupiters, known EGPs populate a continuum from ~0.03-0.05 AU to > 1 AU**

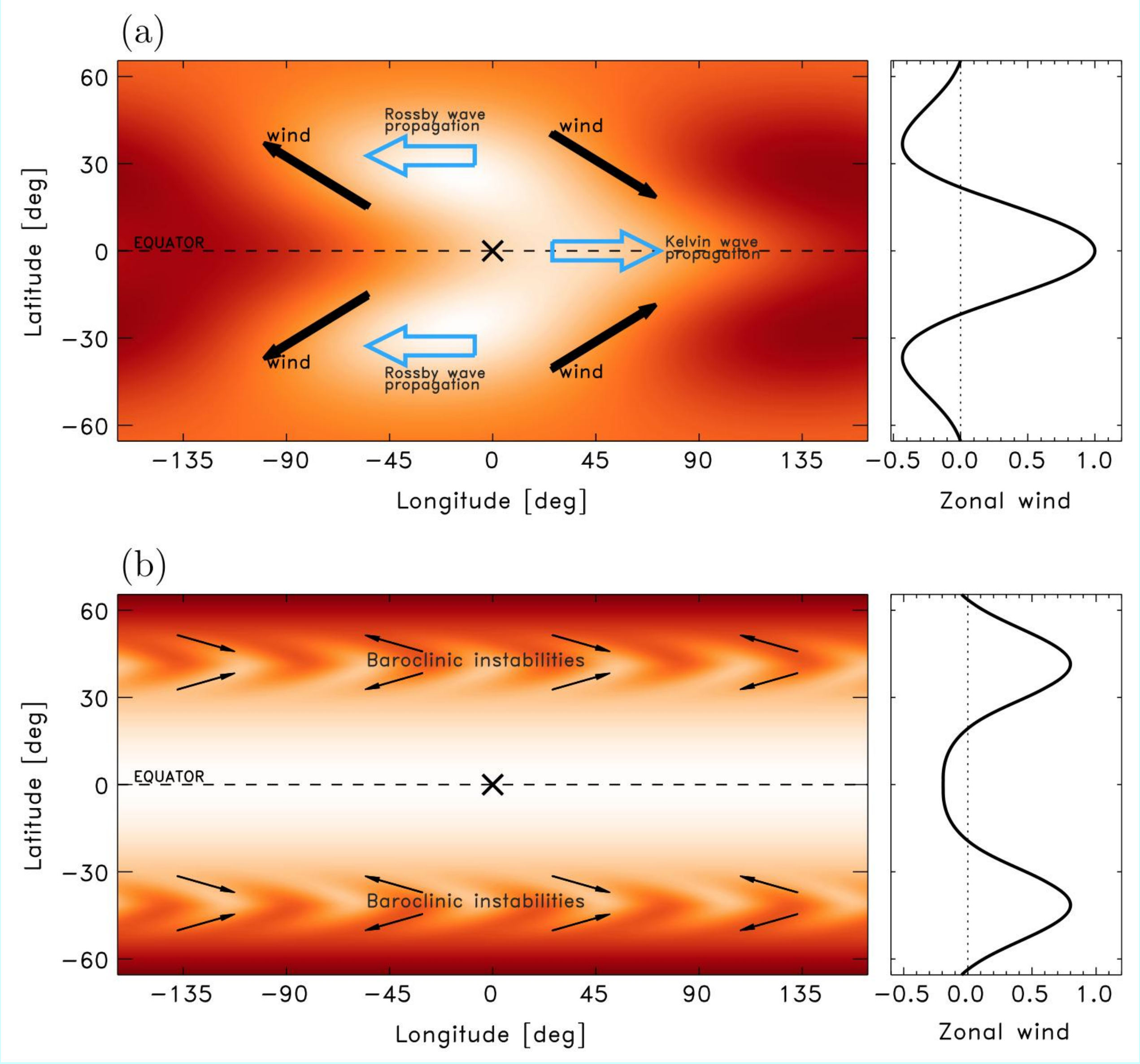
- **Such "warm" Jupiters will rotate non-synchronously:**

$$t_{\rm spindown} \approx 10^6 \left(\frac{Q}{10^5}\right)\left(\frac{a_{\rm orb}}{0.05\,{\rm AU}}\right)^6 {\rm yr}$$

- **Fundamental questions also exist about how the circulation on hot Jupiters relates to that on Jupiter, Earth, and brown dwarfs**

All of this motivates an investigation of how hot Jupiter circulation regimes--and observables--vary with incident stellar flux and rotation rate

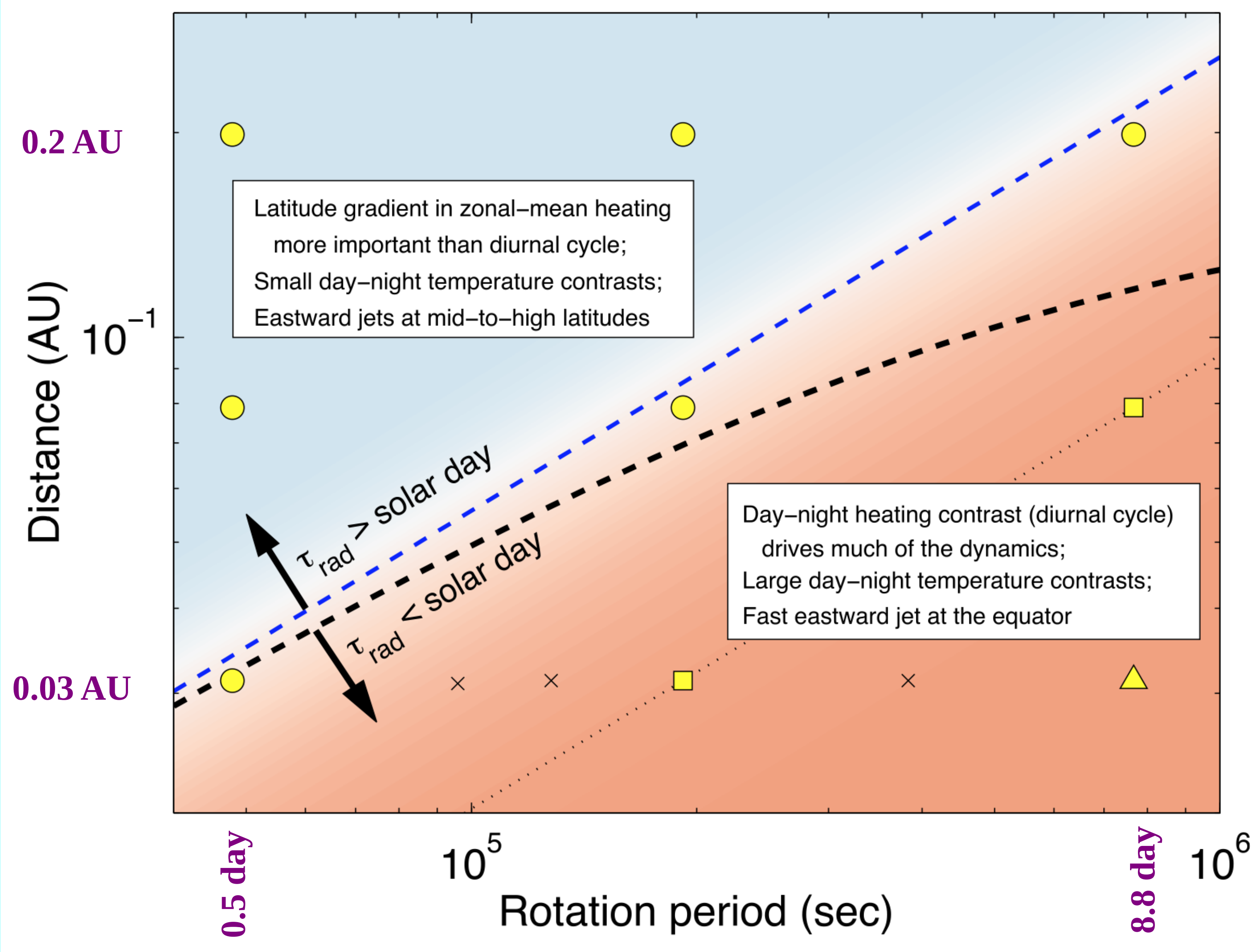
A regime shift from hot to warm Jupiters?



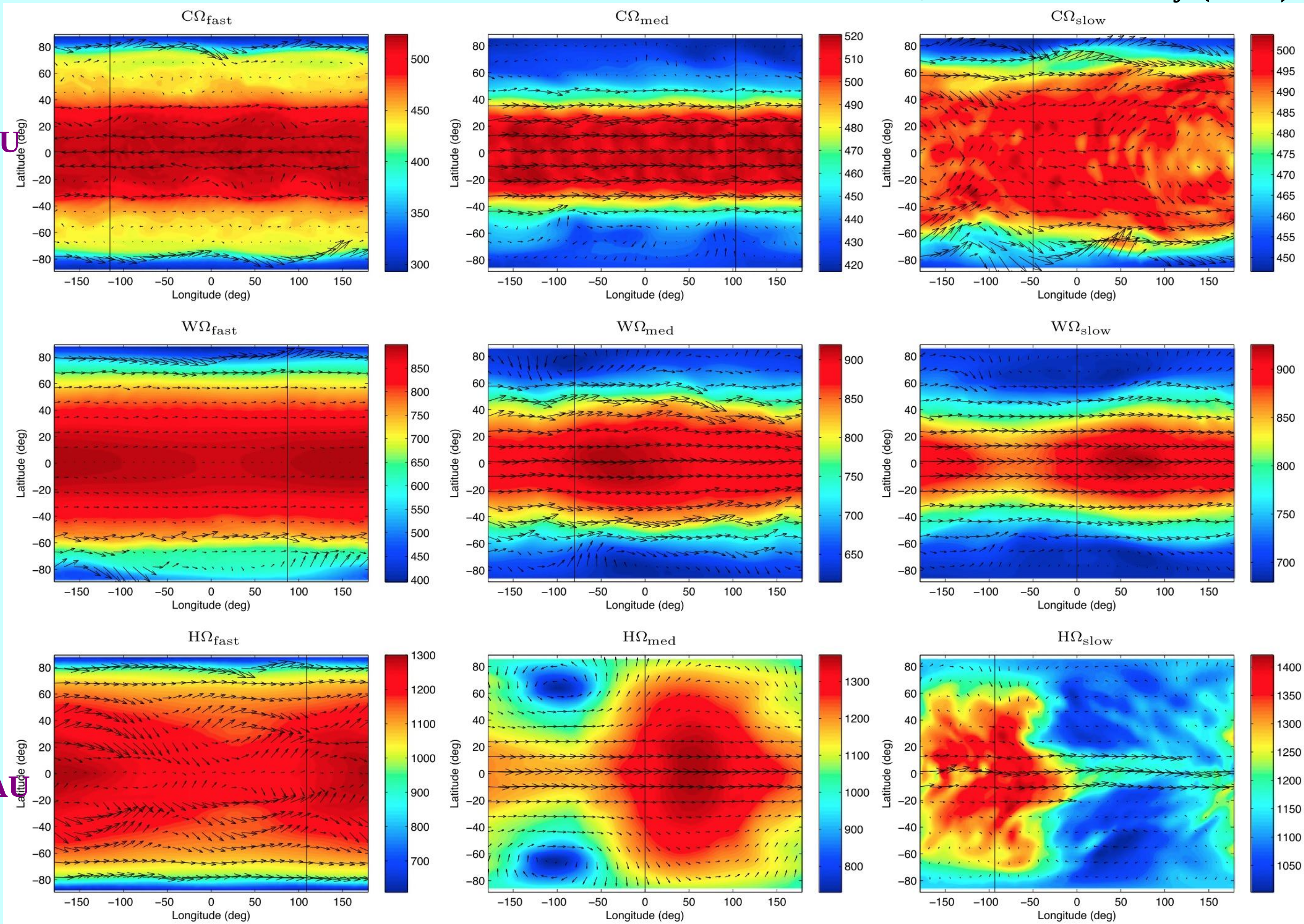
Showman, Lewis & Fortney (2015)

Showman, Lewis & Fortney (2015)

Predicted regimes



Showman, Lewis & Fortney (2015)



0.2 AU

0.03 AU

Orbital distance

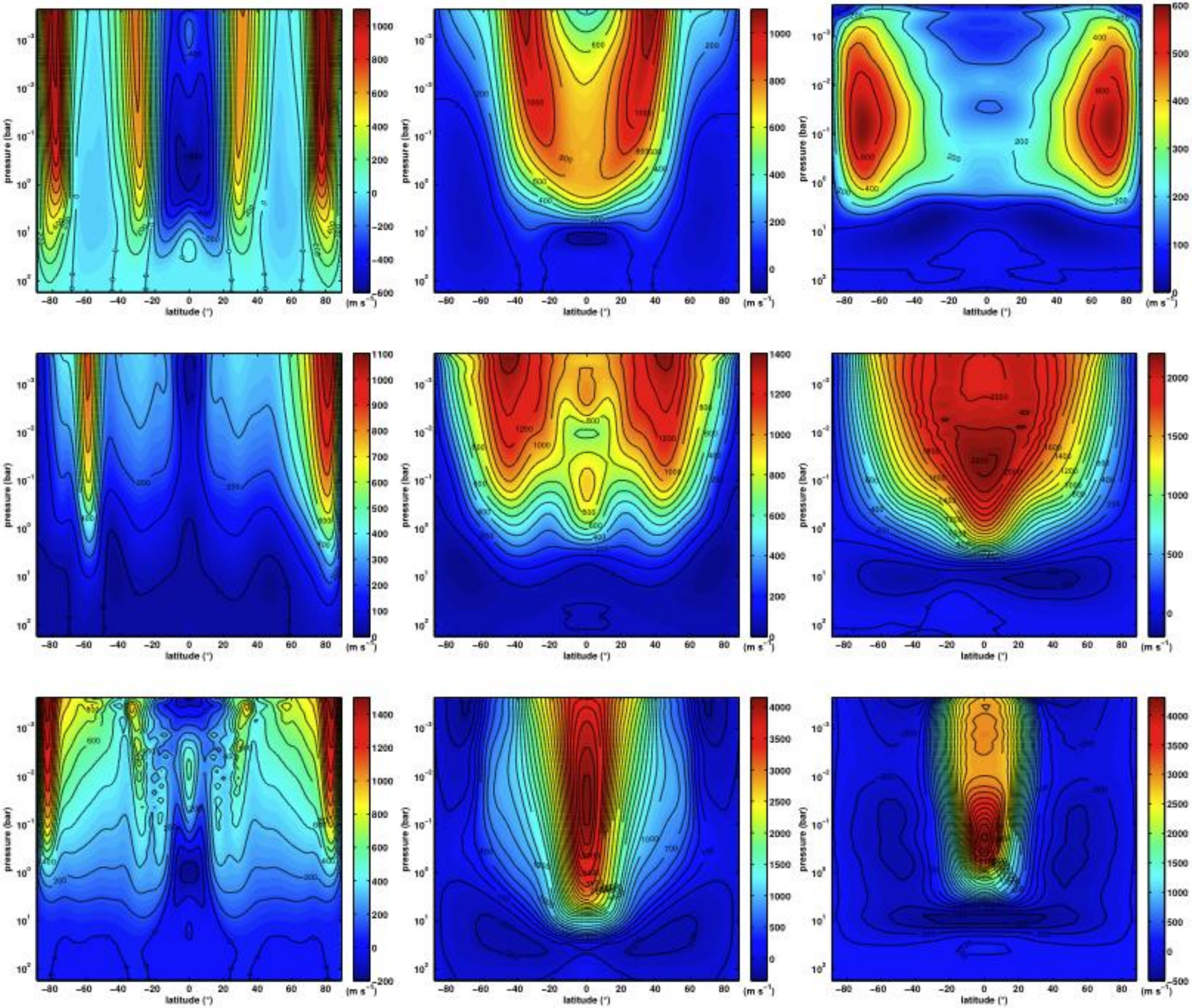
0.5 day

8.8 day

Rotation period

0.2 AU

Orbital distance ⟶



0.03 AU

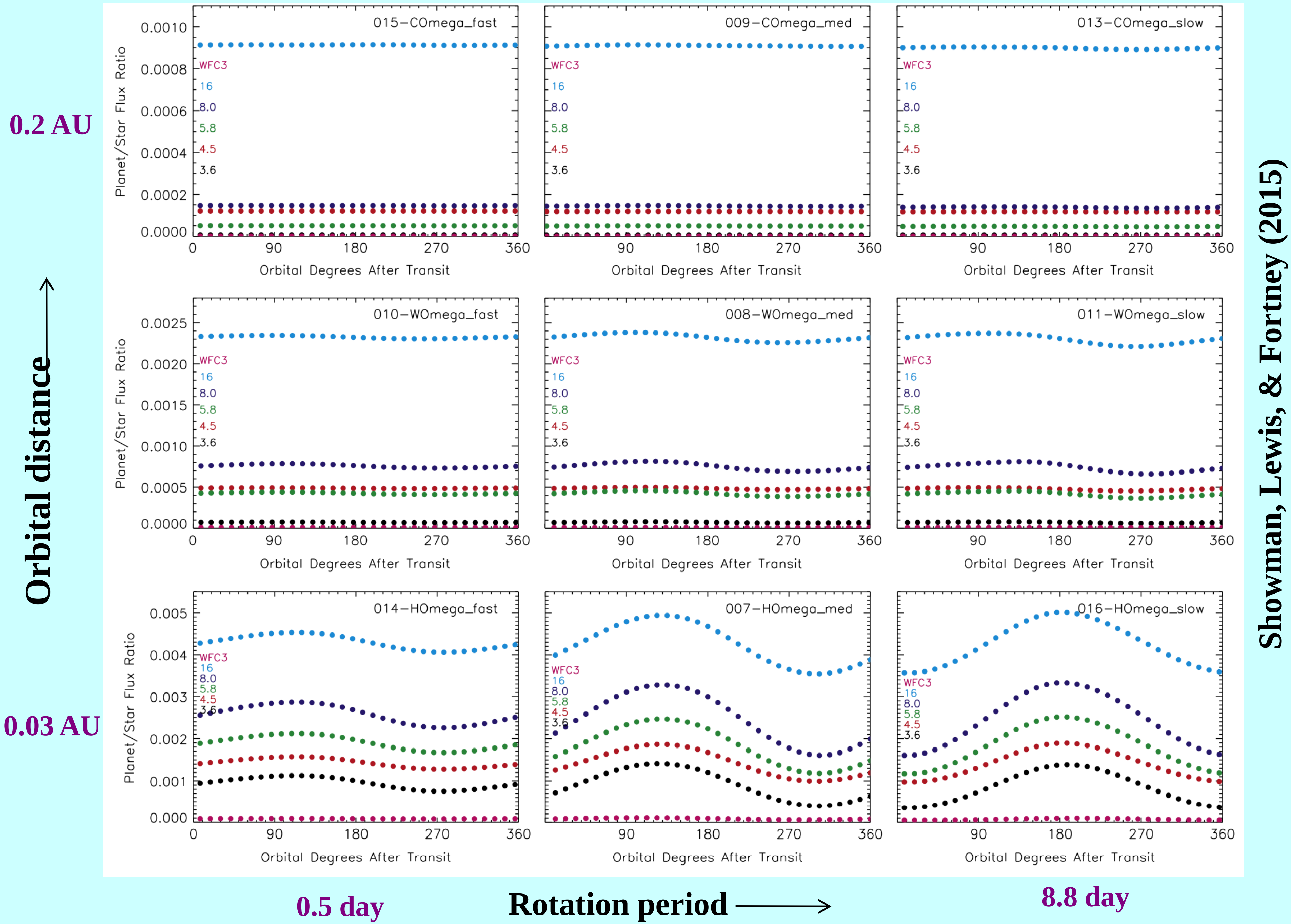
Showman, Lewis, & Fortney (2015)

0.5 day

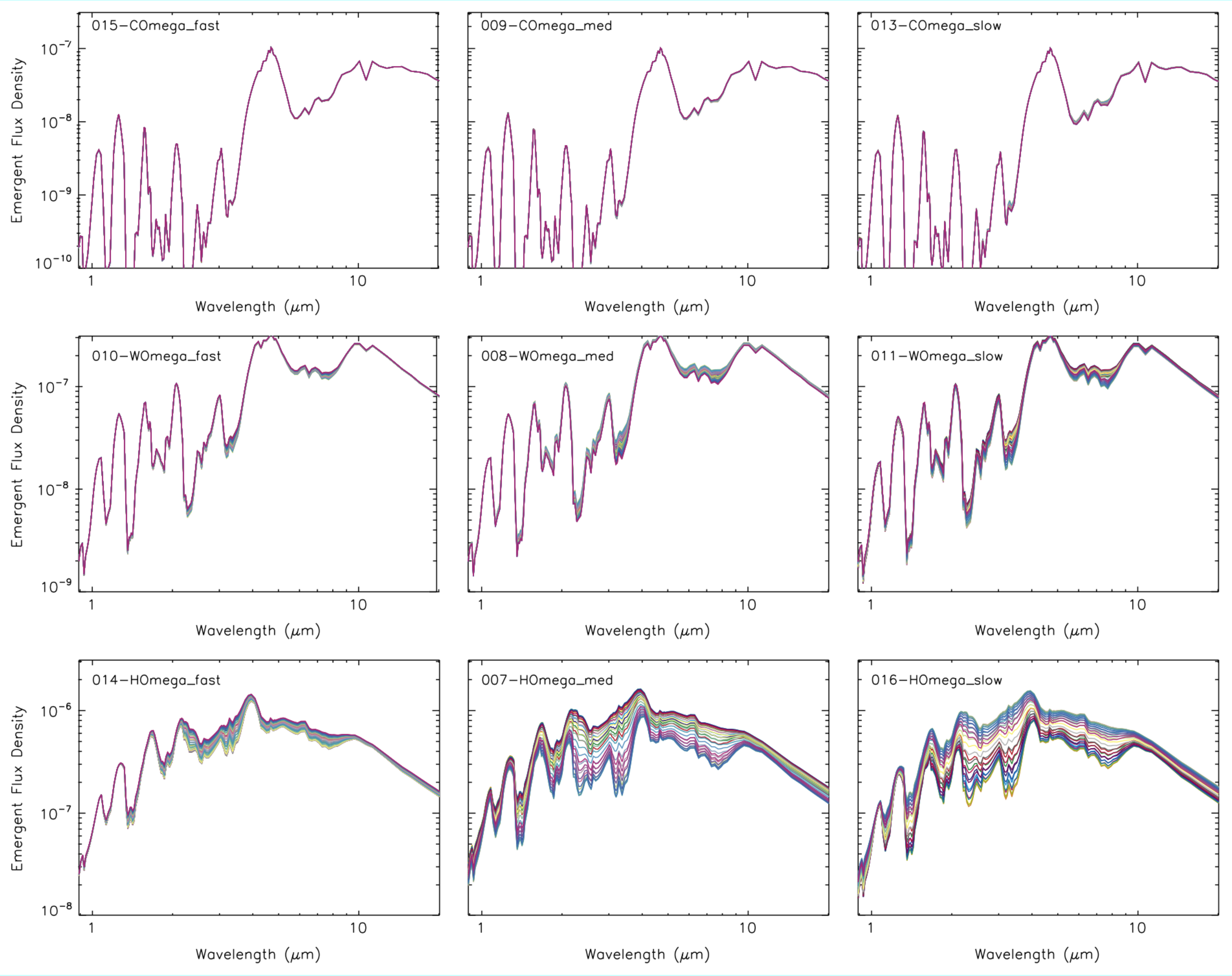
Rotation period ⟶

8.8 day

Observational predictions: IR light curves



Observational predictions: IR spectra



Dynamical themes

- **The typical hot Jupiter is in the "all tropics" regime where equatorial (e.g., Kelvin and Rossby) waves adjust the temperature structure in the longitude direction, and meridional ("Hadley") circulations adjust it in latitude.**

- **Breakdown of the wave adjustment allows large day-night temperature differences on particularly close-in hot Jupiters.**

- **Standing equatorial (Kelvin and Rossby) waves triggered by the day-night thermal forcing transport momentum to the equator, causing equatorial superrotation.**

- **Rapidly rotating EGPs will have both tropics and an extratropics, with heat transport at high latitudes controlled by baroclinic instabilities, with large equator-pole temperature differences and zonal-mean winds peaking in midlatitudes. Lightcurves may allow constraints on rotation rates for non-synchronously rotating planets.**

Approach to constructing a theory

Thermodynamic energy equation:

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + w\frac{N^2 H^2}{R} = \frac{T_{\mathrm{eq}} - T}{\tau_{\mathrm{rad}}}$$

Approach to constructing a theory

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$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + w \frac{N^2 H^2}{R} = \frac{T_{\rm eq} - T}{\tau_{\rm rad}}$$

$$\Rightarrow \max\left[\frac{U\,\Delta T}{L}, W\frac{N^2 H^2}{R}\right] \approx \frac{\Delta T_{\rm eq} - \Delta T}{\tau_{\rm rad}}$$

Here, variables are:
ΔT=day-night temperature difference
U=horizontal wind speed
W=vertical wind speed

Goal: solve analytically for ΔT, U, and W as a function of control parameters ($\tau_{\rm rad}$, $\tau_{\rm drag}$, rotation rate, planetary radius, etc)

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Here, variables are:
***ΔT*=day-night temperature difference**
***U*=horizontal wind speed**
***W*=vertical wind speed**

Momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla \mathbf{v} + w\frac{\partial \mathbf{v}}{\partial z} + f\hat{\mathbf{k}}\times\mathbf{v} = -\nabla\Phi - \frac{\mathbf{v}}{\tau_{\rm drag}}.$$

Goal: solve analytically for *ΔT*, *U*, and *W* as a function of control parameters (τ_{rad}, τ_{drag}, rotation rate, planetary radius, etc)

Approach to constructing a theory

Thermodynamic energy equation:

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + w\frac{N^2 H^2}{R} = \frac{T_{\rm eq} - T}{\tau_{\rm rad}}$$

$$\Rightarrow \max\left[\frac{U\,\Delta T}{L}, W\frac{N^2H^2}{R}\right] \approx \frac{\Delta T_{\rm eq} - \Delta T}{\tau_{\rm rad}}$$

Here, variables are:
***ΔT*=day-night temperature difference**
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***W*=vertical wind speed**

Momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + w\frac{\partial \mathbf{v}}{\partial z} + f\hat{\mathbf{k}} \times \mathbf{v} = -\nabla\Phi - \frac{\mathbf{v}}{\tau_{\rm drag}}.$$

$$\Rightarrow \max\left[\frac{U^2}{L}, \frac{UW}{H}, fU, \frac{U}{\tau_{\rm drag}}\right] \approx \nabla\Phi$$

Goal: solve analytically for *ΔT*, *U*, and *W* as a function of control parameters ($\tau_{\rm rad}$, $\tau_{\rm drag}$, rotation rate, planetary radius, etc)

Approach to constructing a theory

Thermodynamic energy equation:

$$\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T + w\frac{N^2 H^2}{R} = \frac{T_{\text{eq}} - T}{\tau_{\text{rad}}}$$

$$\Rightarrow \max\left[\frac{U\,\Delta T}{L}, W\frac{N^2 H^2}{R}\right] \approx \frac{\Delta T_{\text{eq}} - \Delta T}{\tau_{\text{rad}}}$$

Here, variables are:
***ΔT*=day-night temperature difference**
***U*=horizontal wind speed**
***W*=vertical wind speed**

Momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} + w\frac{\partial \mathbf{v}}{\partial z} + f\hat{\mathbf{k}} \times \mathbf{v} = -\nabla \Phi - \frac{\mathbf{v}}{\tau_{\text{drag}}}.$$

$$\Rightarrow \max\left[\frac{U^2}{L}, \frac{UW}{H}, fU, \frac{U}{\tau_{\text{drag}}}\right] \approx \nabla \Phi$$

Continuity equation:

$$\Rightarrow \frac{U}{L} \approx \frac{W}{H}$$

Goal: solve analytically for *ΔT*, *U*, and *W* as a function of control parameters (τ_{rad}, τ_{drag}, rotation rate, planetary radius, etc)

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