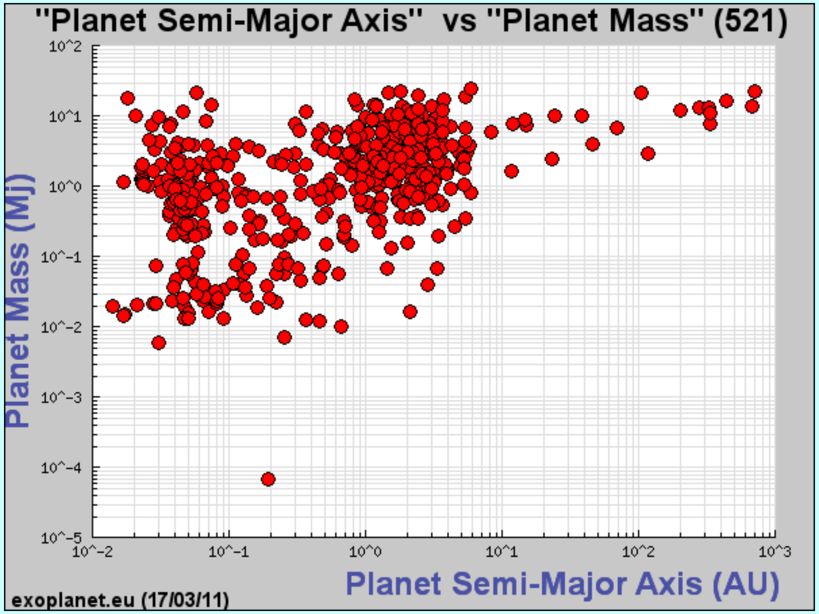
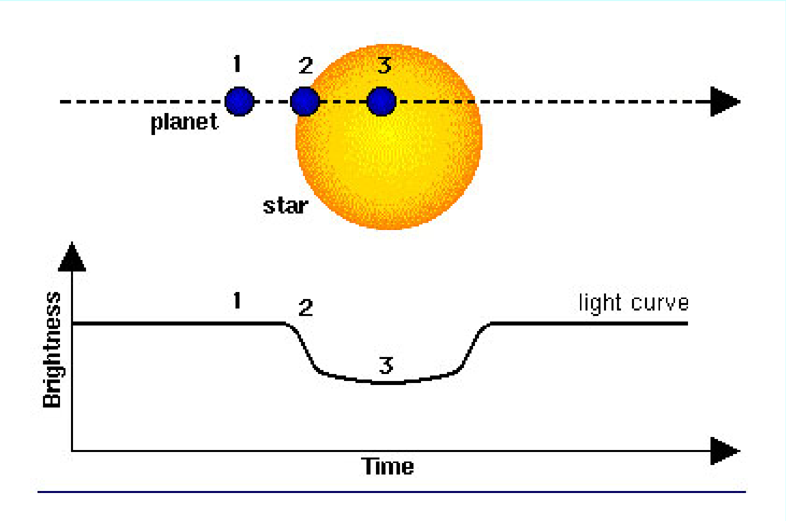
Exoplanets: the Atmospheric Dynamics of hot Jupiters

Adam P. Showman
University of Arizona

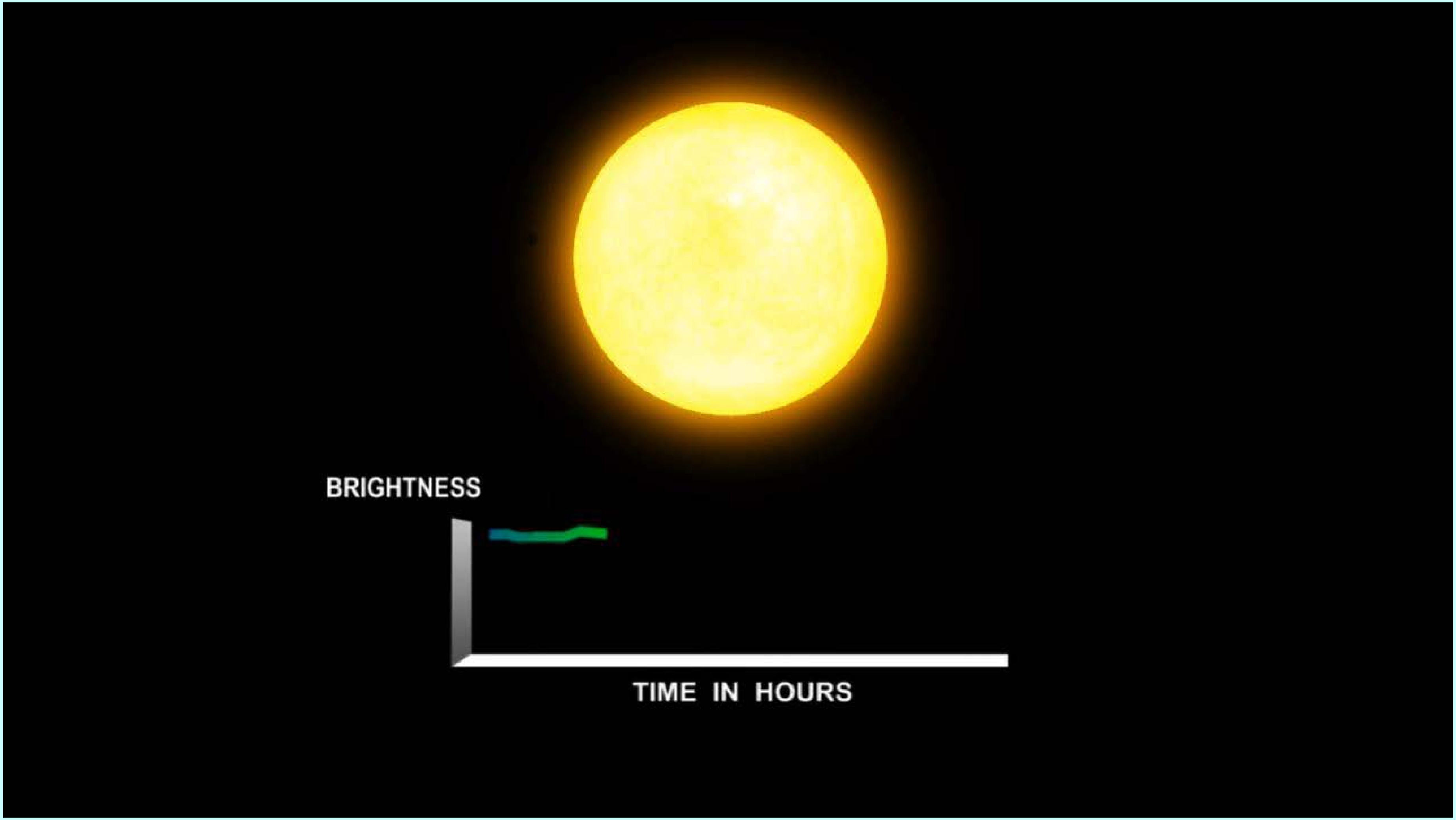
Collaborators: Yuan Lian, Yohai Kaspi, Lorenzo Polvani, Jonathan Fortney, Nikole Lewis, Daniel Perez-Becker, Mark Marley, Heather Knutson

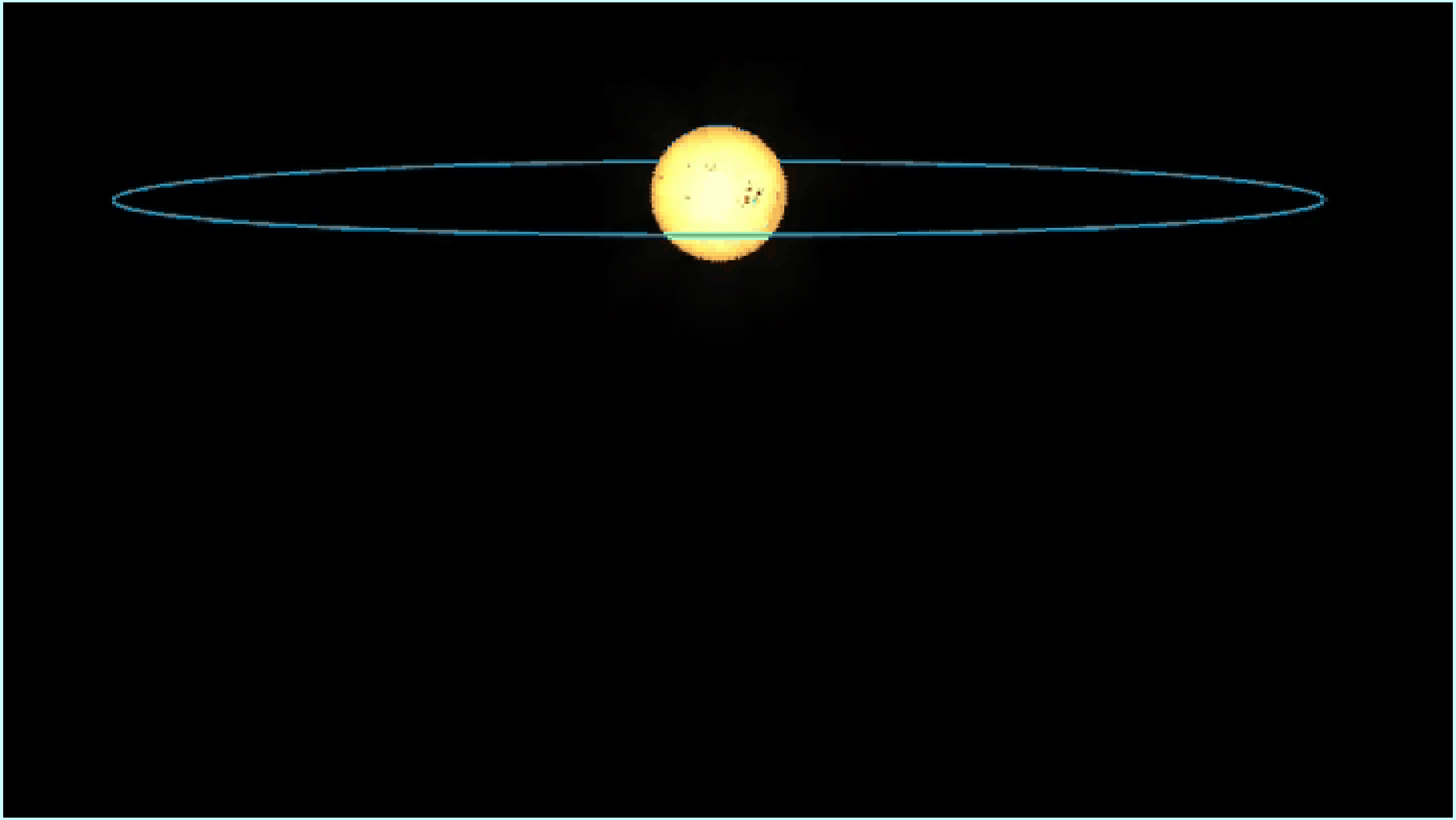
Exoplanets: an exploding new field

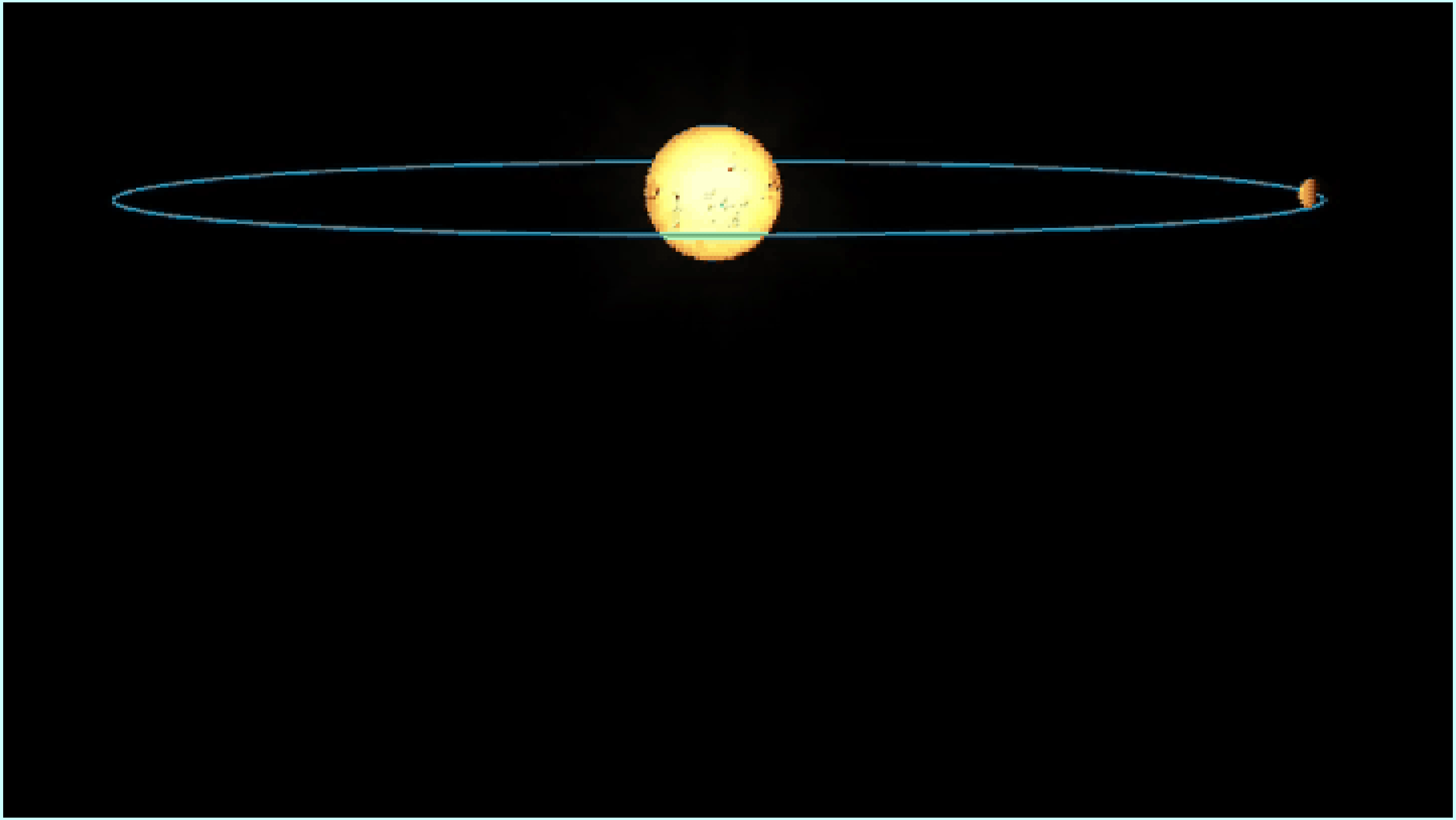




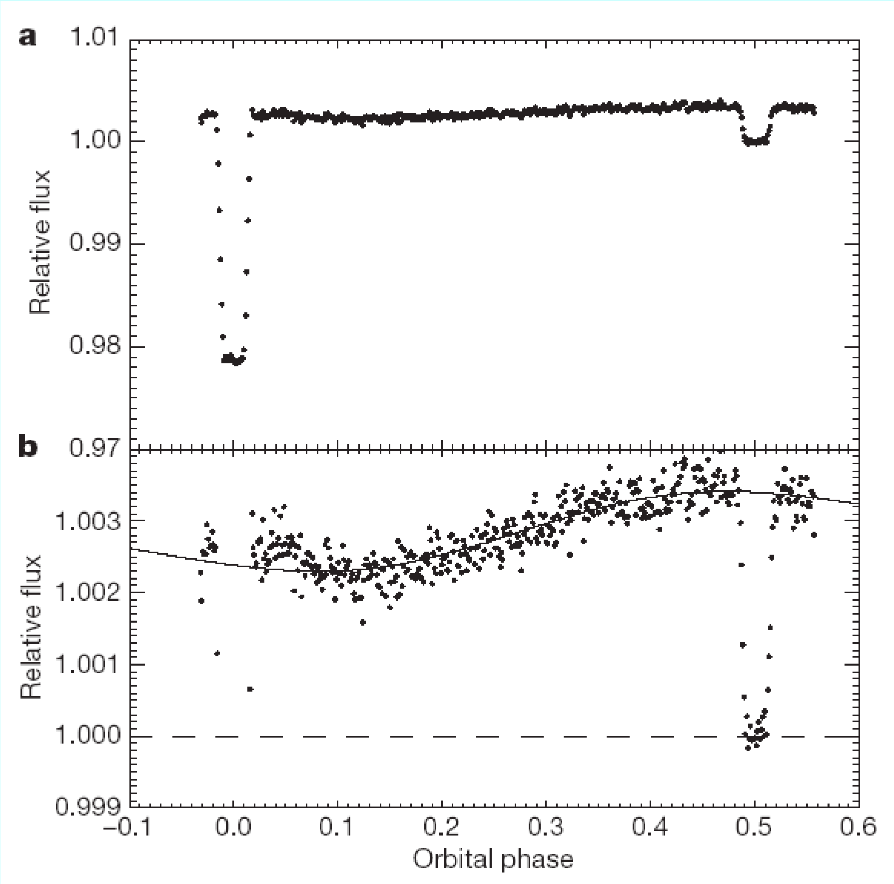
- Almost 900 known extrasolar planets, most discovered with the "Doppler" method (plus ~2300 candidates from the NASA Kepler mission).
- ~300 planets detected with "transit" method (allows characterization)
- Together, these data give mass, radius, mean density, and orbital properties
- Many are Jupiter-mass planets very close to their stars: the "hot Jupiters"


BRIGHTNESS
TIME IN HOURS

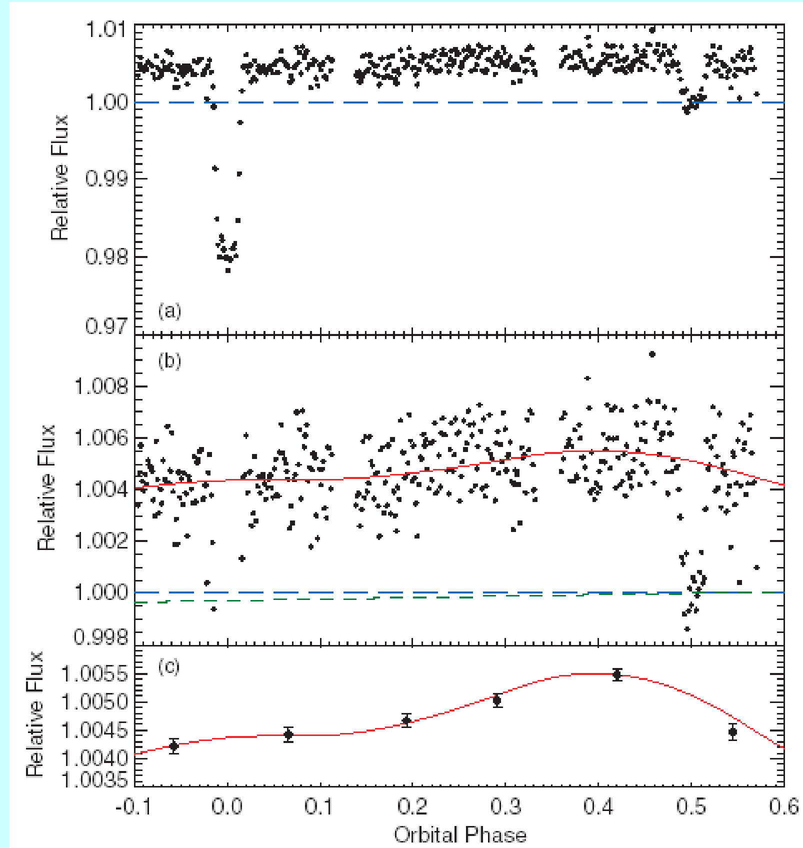




Spitzer light curves for HD 189733b

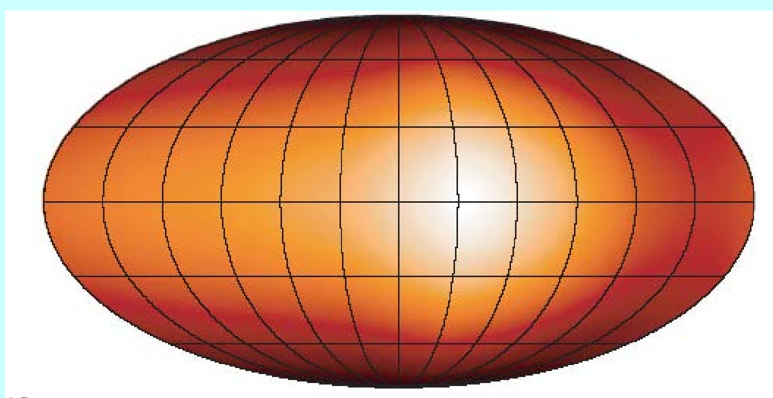


8 μm

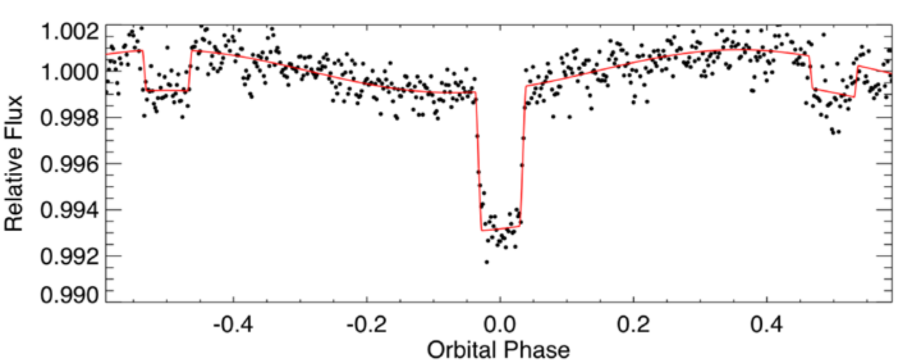


24 μm

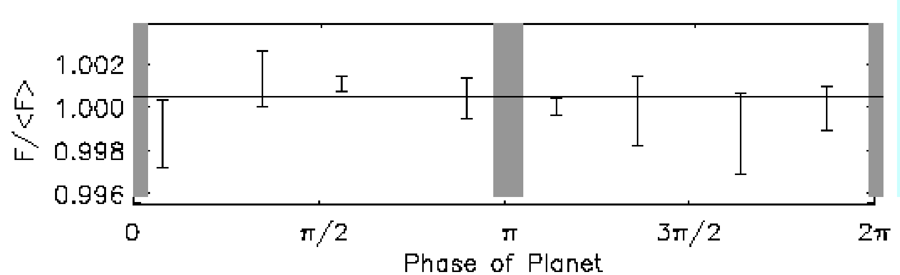
Knutson et al. (2007, 2009)



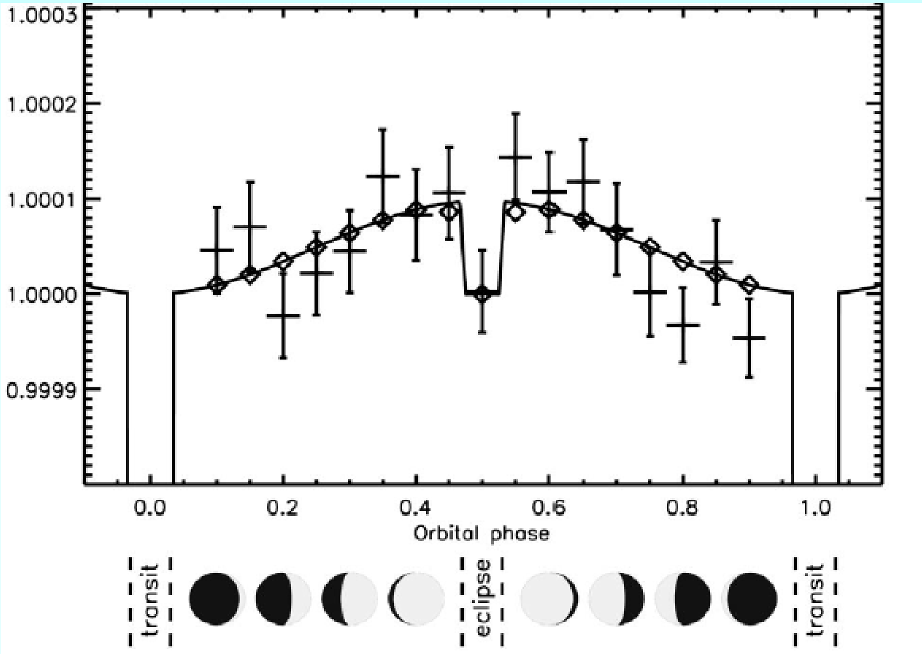
Lightcurves for hot Jupiters



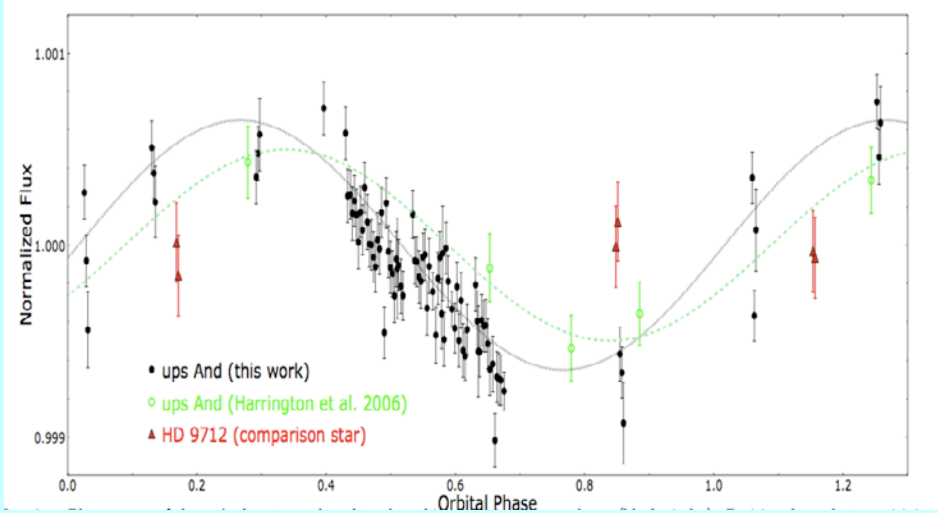
HAT-P-7b (Knutson et al., unpublished; Borucki et al. 2009)



HD209458b (Cowan et al. 2007)

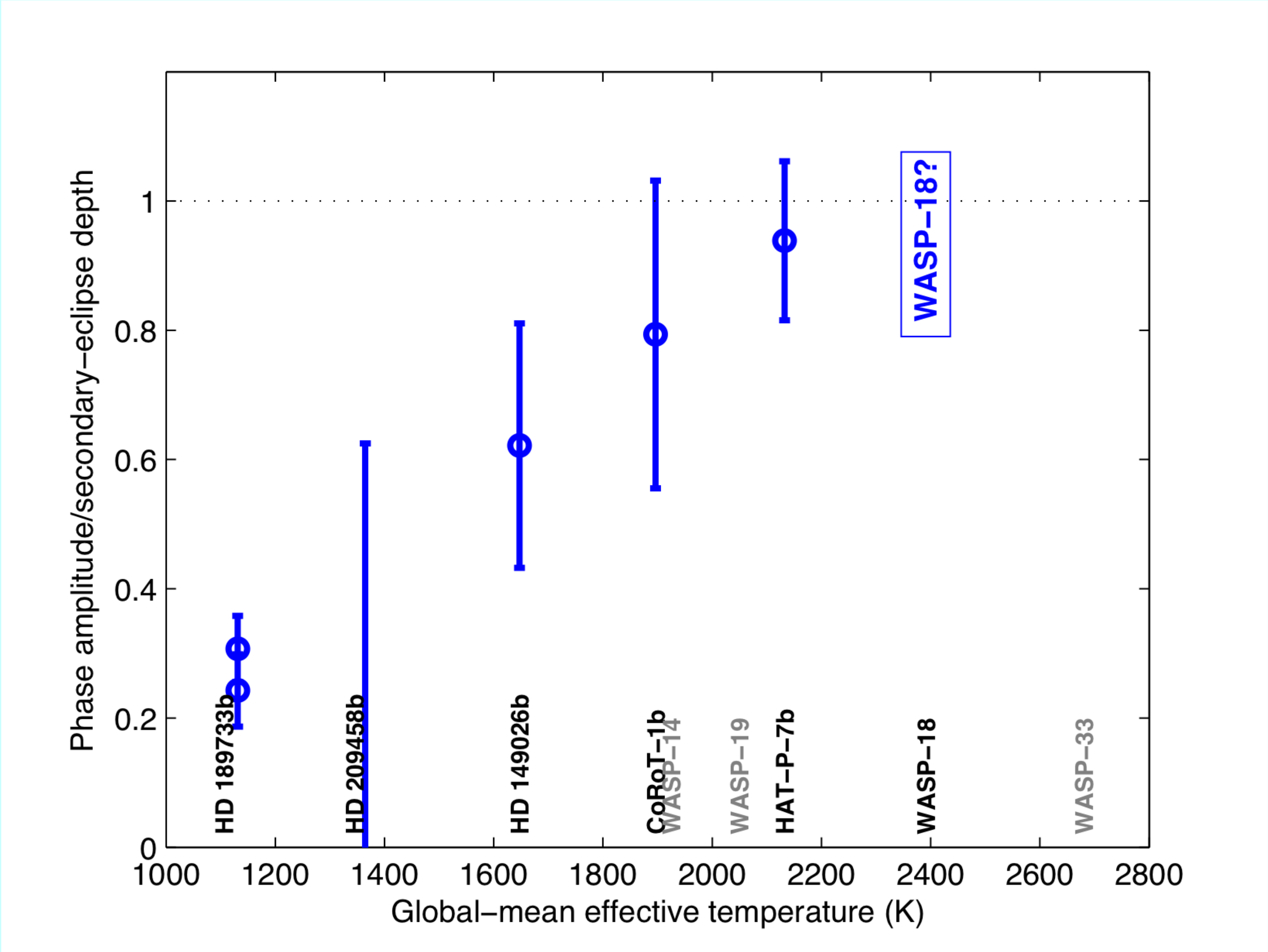


CoRoT-1b (Snellen et al. 2009)



Ups And b (Crossfield et al. 2010)

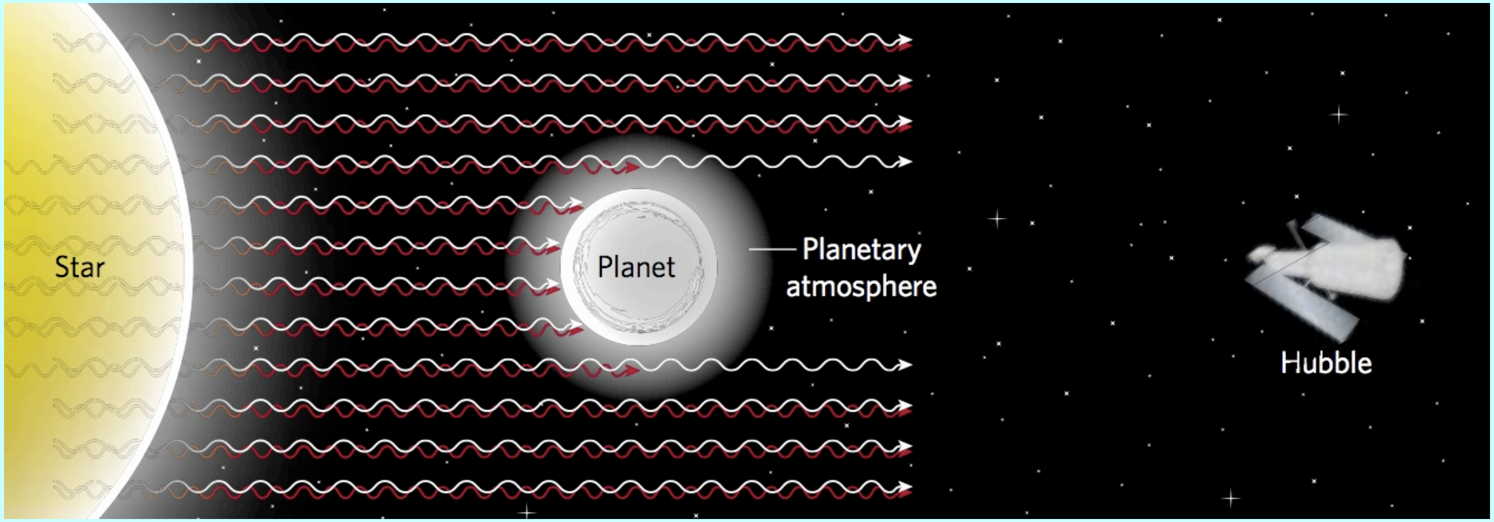
Results from lightcurves: dependence of day-night flux contrast on effective temperature



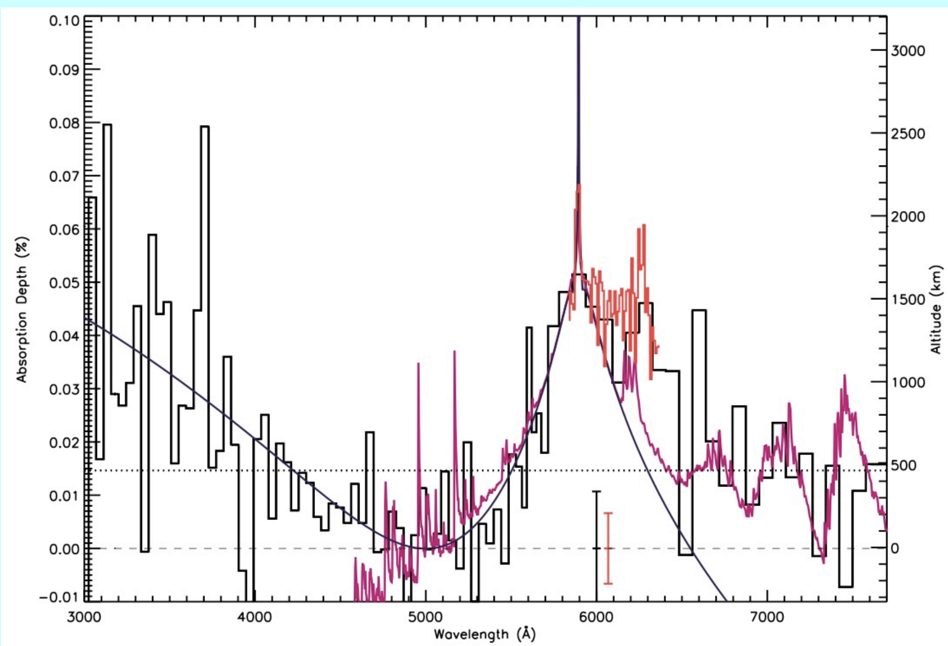
Perez-Becker & Showman (in preparation)

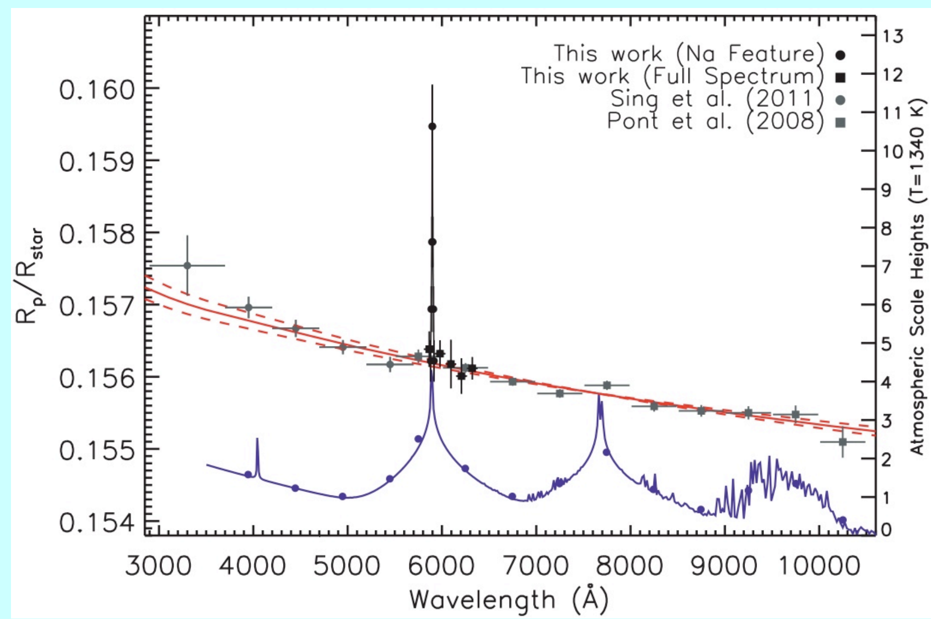
A trend seems to be emerging: more strongly irradiated planets have larger fractional day-night temperature differences at the photosphere

Exoplanet characterization: Transit spectroscopy



Showman (2008)

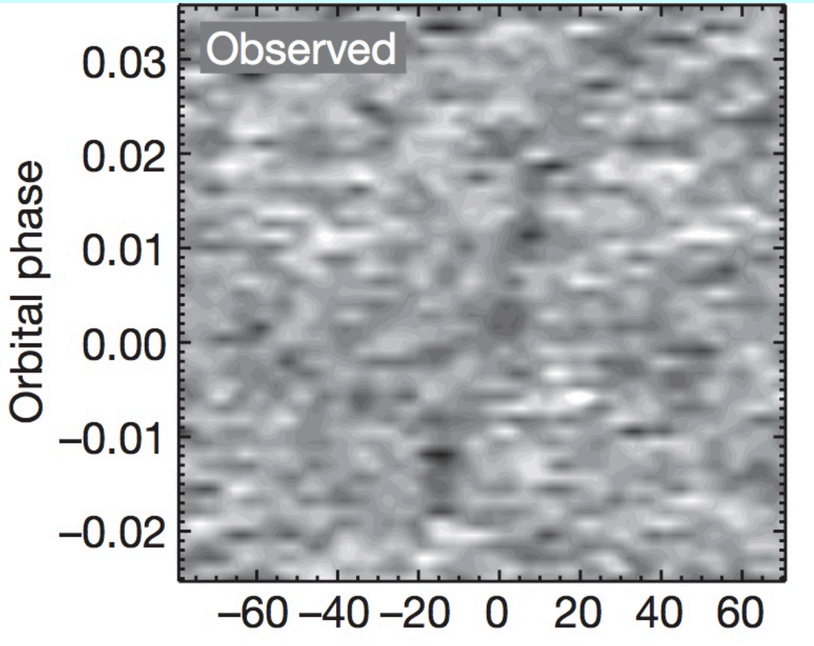


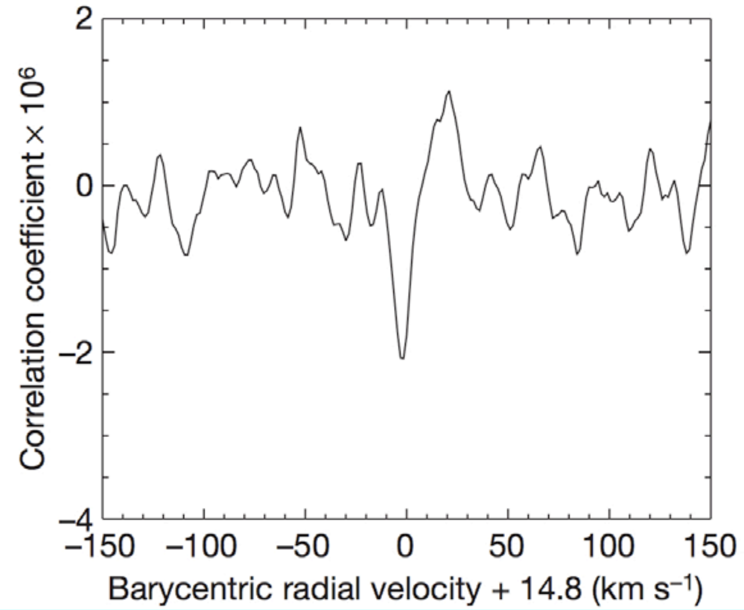


Sing et al. (2008, 2009), Vidal-Madjar et al. (2011), Huitson et al. (2012),Gibson et al. (2012), Barman (2007), Tinetti et al. (2007), Swain et al. (2008),…..

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)**

Motivating questions

- **What are the fundamental dynamics of this novel, highly irradiated circulation regime? Can we explain lightcurves of specific hot Jupiters? What is the mechanism for displacing the hottest regions on HD 189733b?**

- **Can we explain the Doppler measurements of HD 209458b? What are the expected Doppler signatures, and what can we learn from the measurement?**

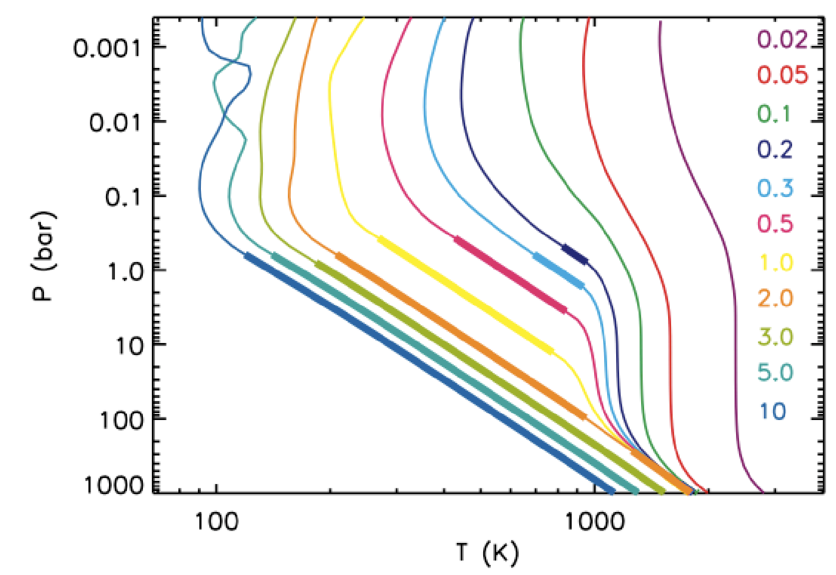
- **What are mechanisms for controlling the day-night temperature contrast on hot Jupiters? Can we explain the increasing trend of day-night flux contrast with incident stellar flux?**

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

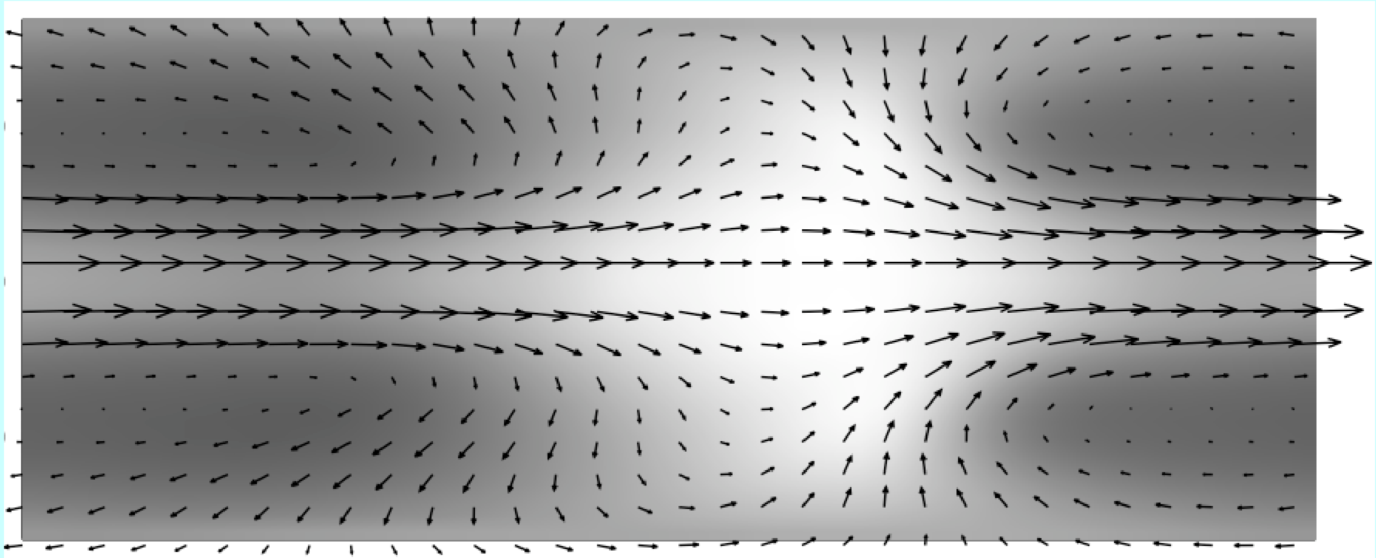
- Weather occurs in a statically stable radiative zone extending to ~100-1000 bar



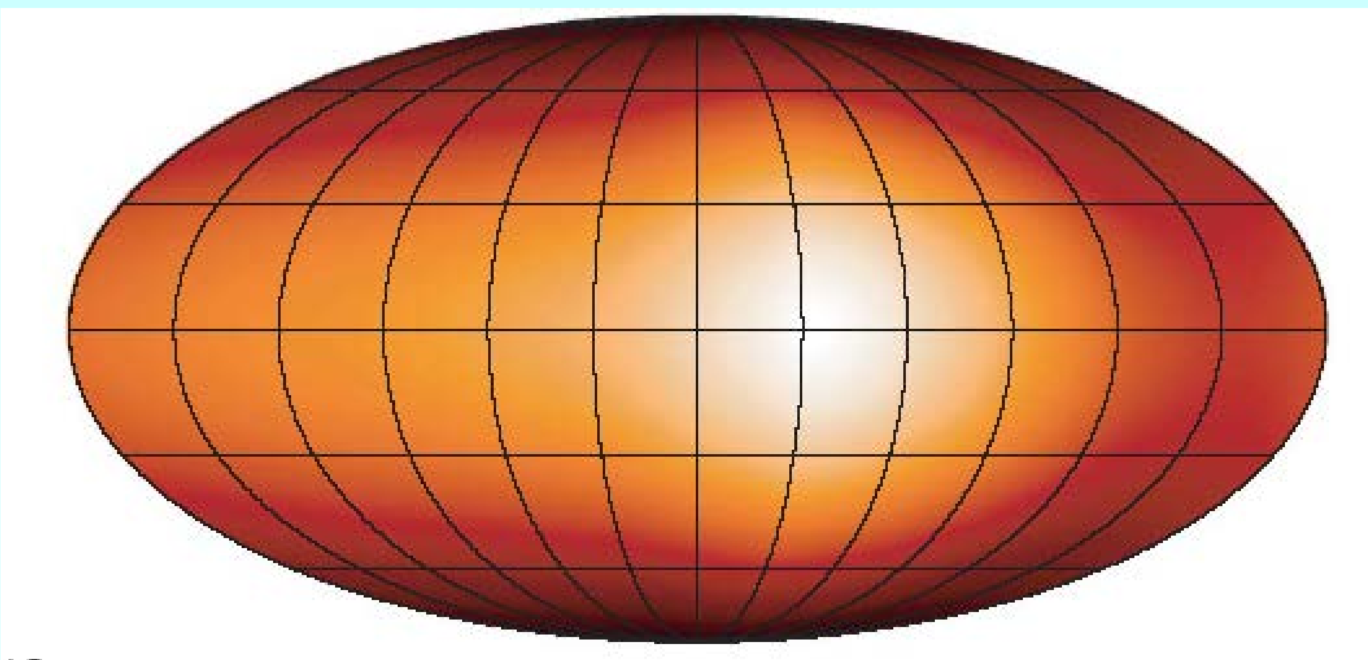
Fortney et al. (2007)

- Rossby deformation radius typically comparable to a planetary radius

- Simple scaling suggests fast wind speeds, e.g., u~2 km/sec, implying Rossby numbers Ro ~ 1.

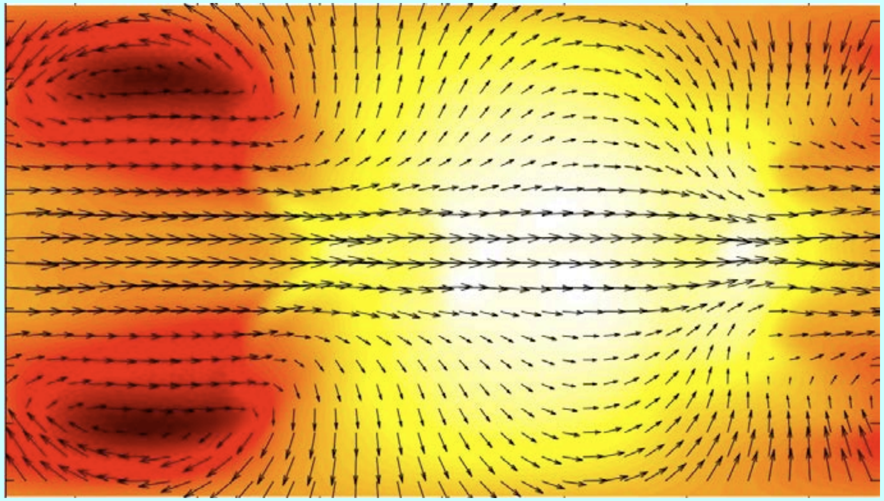


Showman & Guillot (2002)

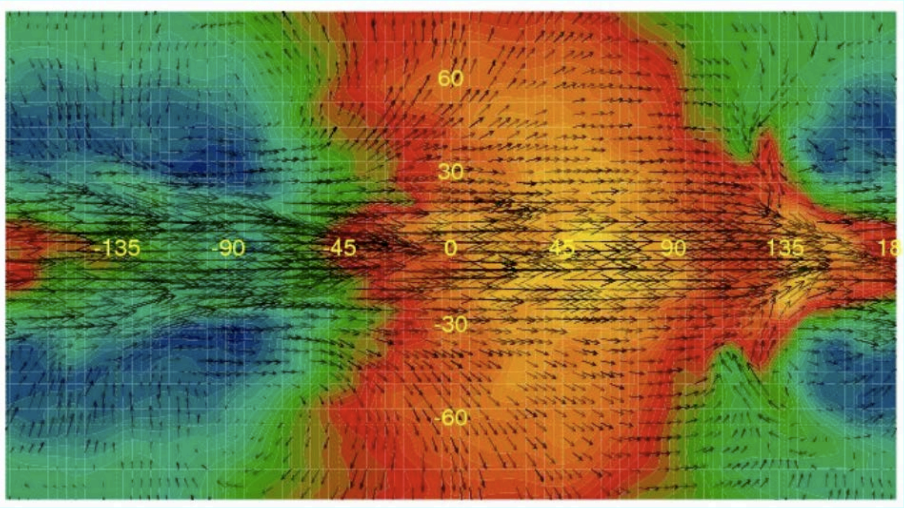


Knutson et al. (2007)

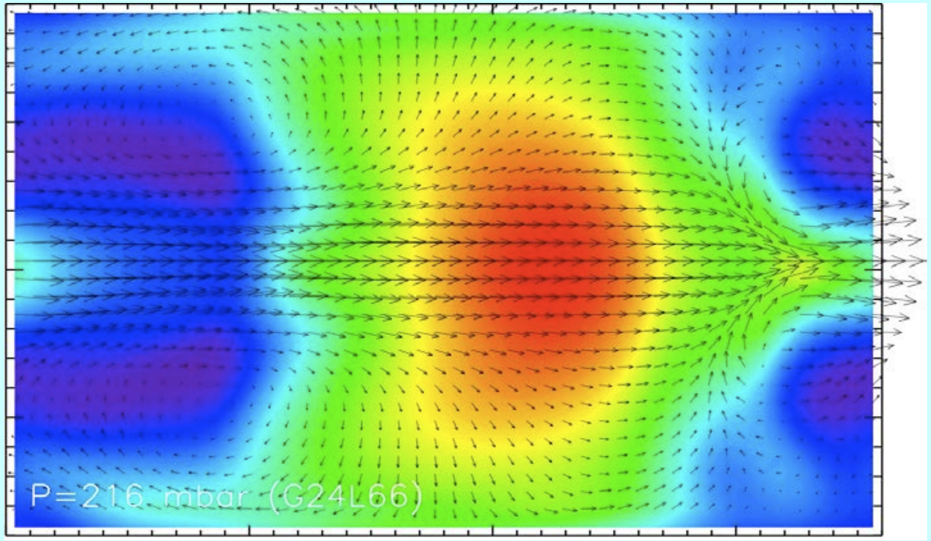
Hot Jupiter circulation models typically predict several broad, fast jets, often including equatorial superrotation



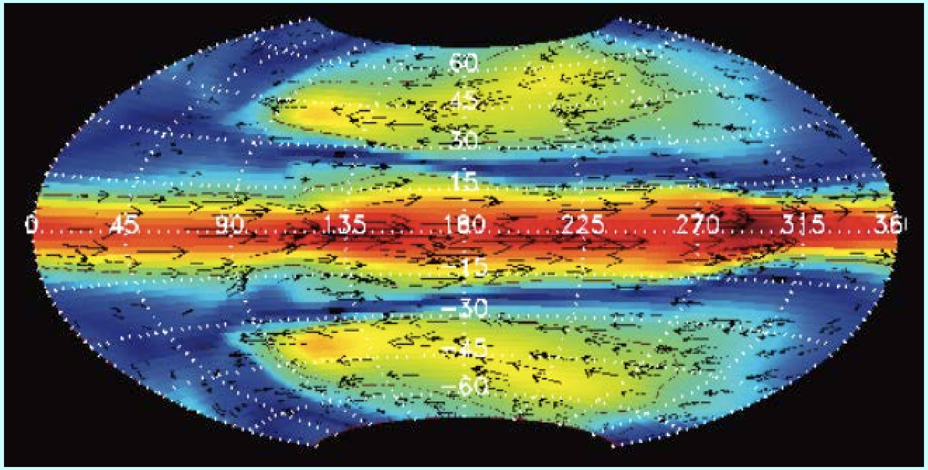
Showman et al. (2009)



Rauscher & Menou (2010)

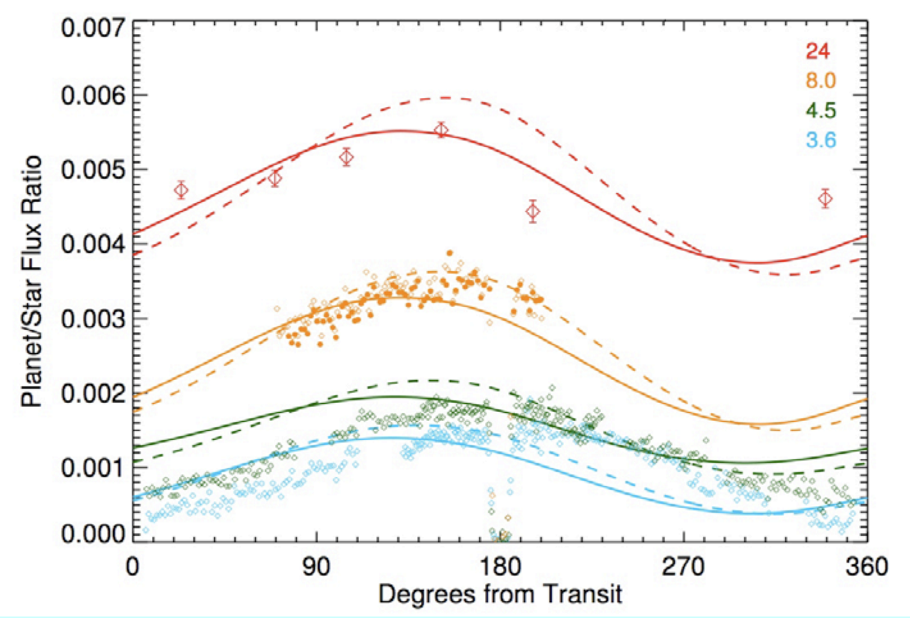


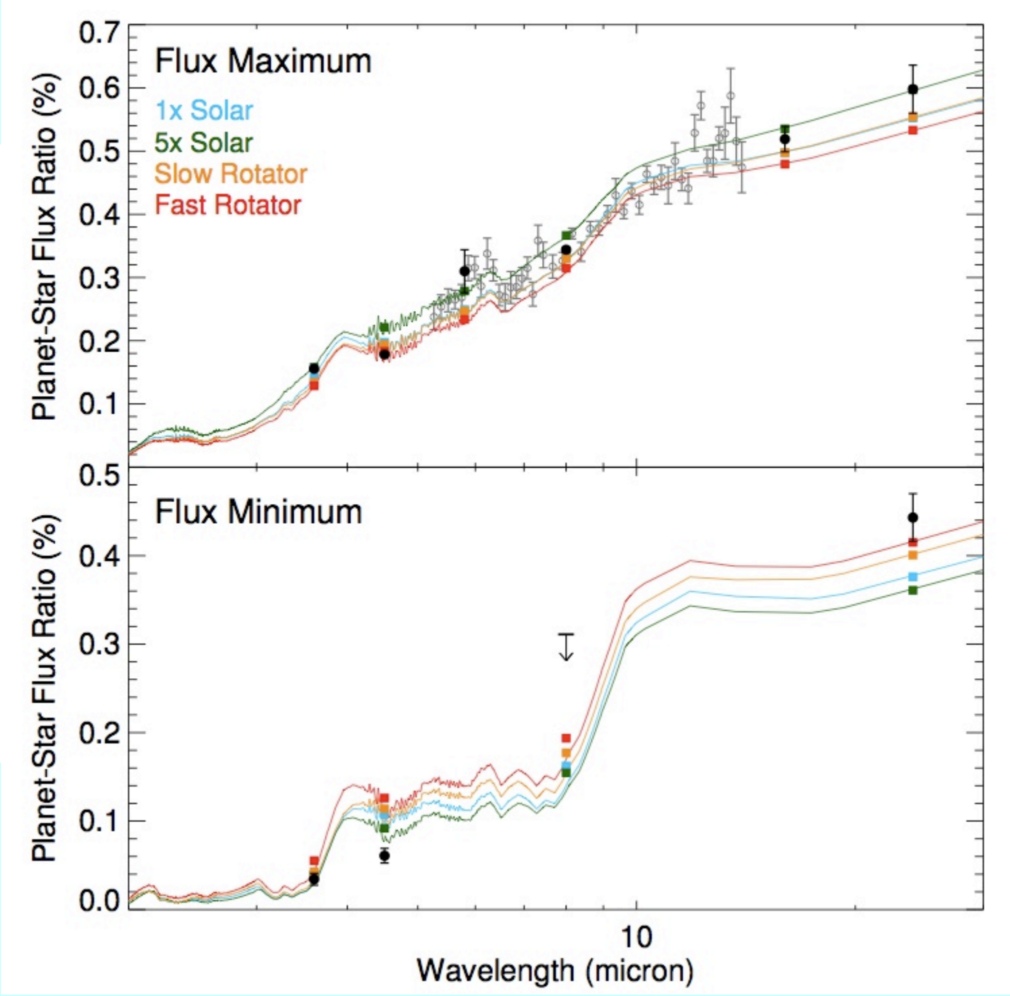
Heng et al. (2010)



Dobbs-Dixon & Lin (2008)

Data-model comparisons





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

Let’s focus on three topics for hot Jupiters

- **What is the mechanism for the equatorial superrotation?**

- **How should the day-night temperature difference and wind regime vary from hot to very hot Jupiters? Can we explain the emerging observational trend from lightcurves? What are implications for Doppler detections of atmospheric winds?**

- **How should dynamics vary for exoplanets more distant from their stars? What is the continuum between hot Jupiters and Jupiter itself?**

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:**

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

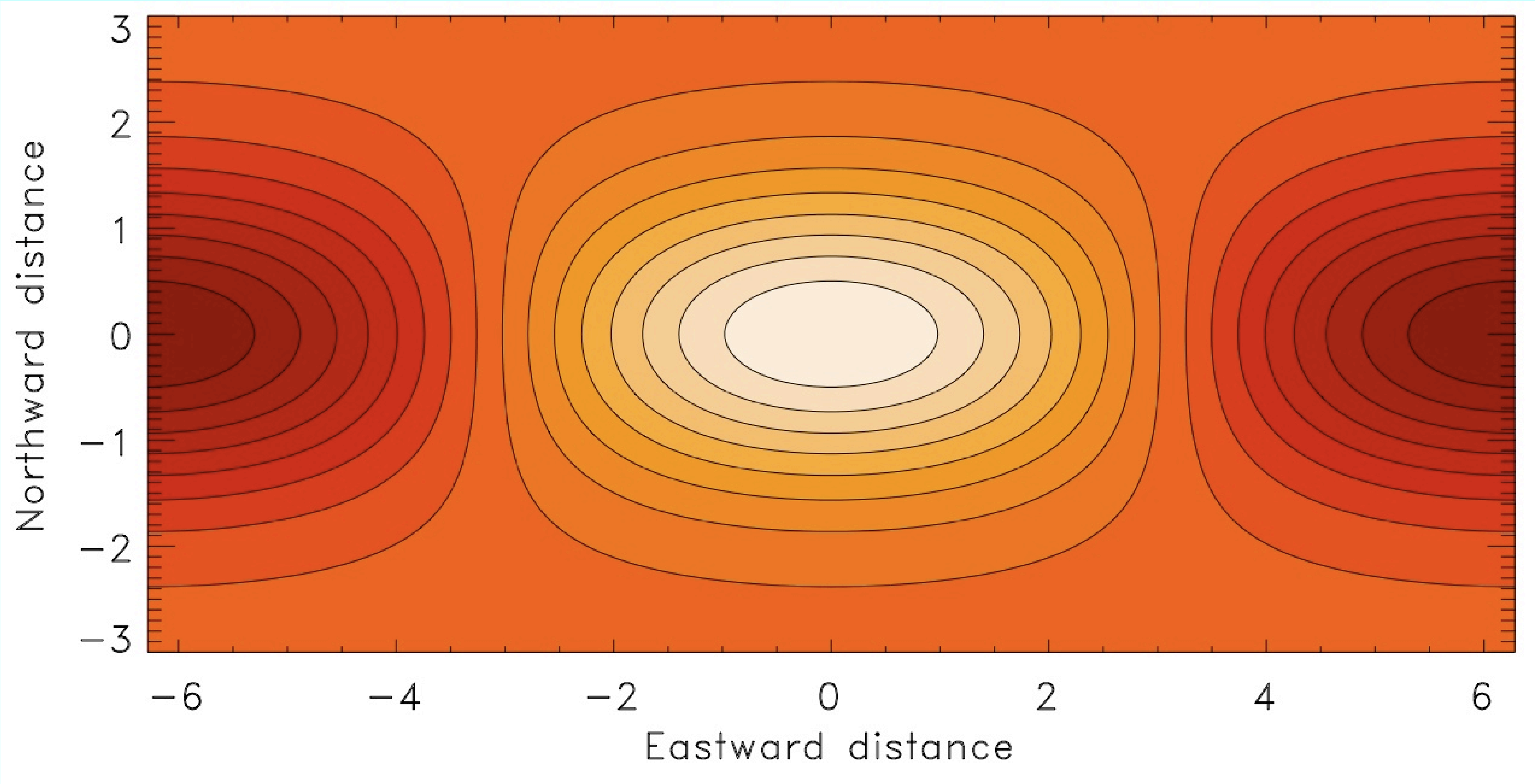
$$\frac{\partial h}{\partial t} + \nabla \cdot (h\vec{v}) = \frac{[h_{eq}(x,y) - h]}{\tau_{rad}} \equiv Q_h$$

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.**

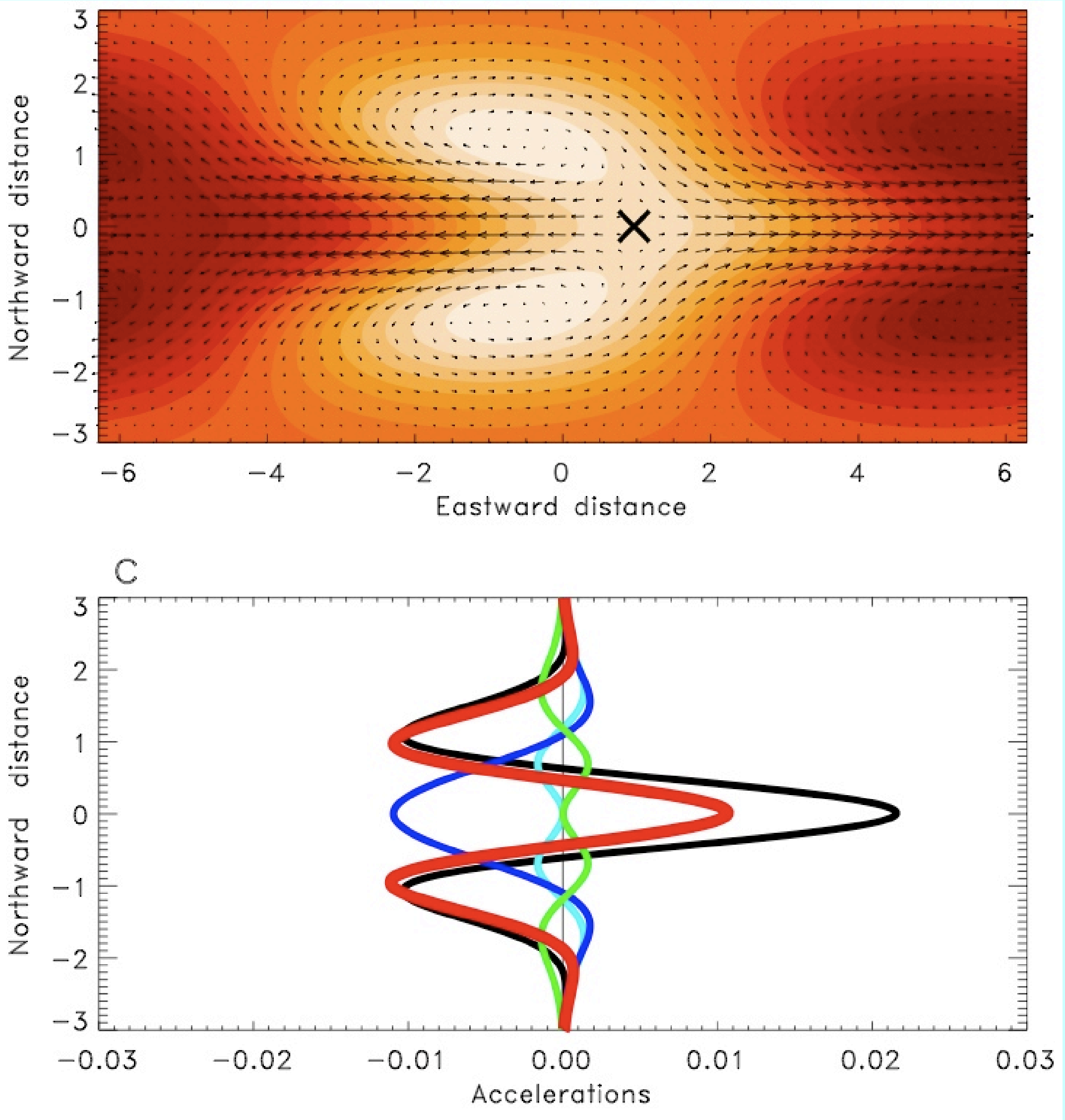
Showman & Polvani (2011, Astrophysical Journal, 738, 71)

Forcing



Showman & Polvani (2011)

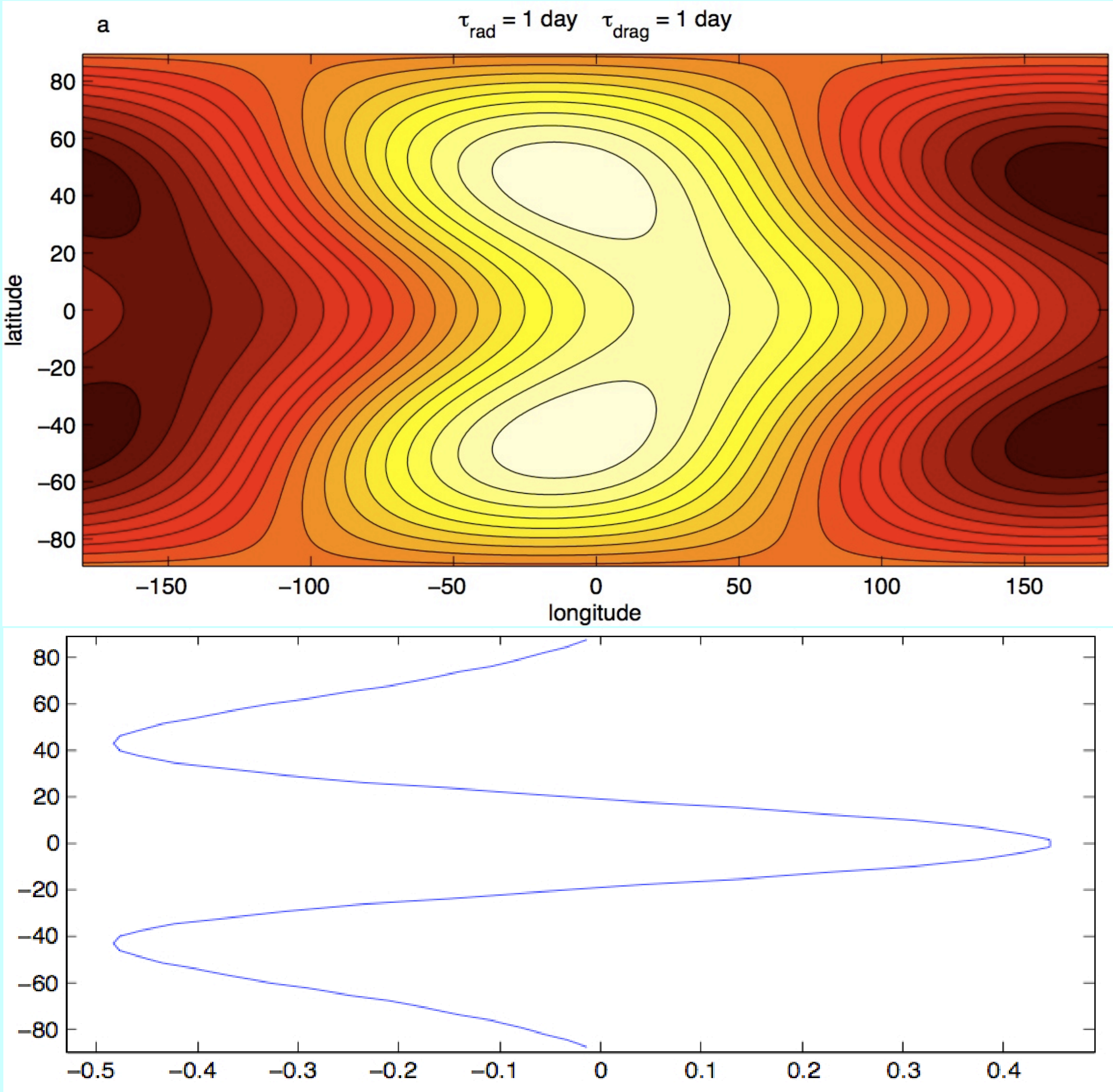
Analytical solution of standing, steady wave response to day-night thermal forcing



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

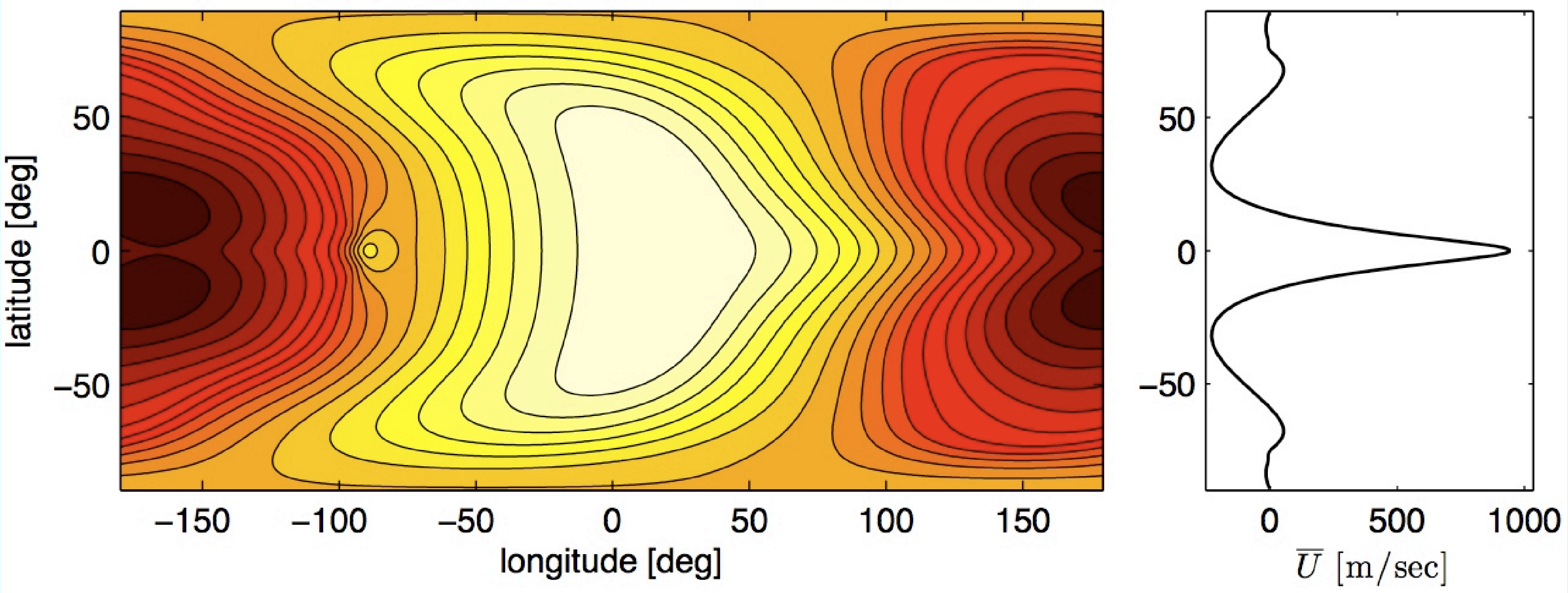
- The response corresponds to standing, equatorially trapped Kelvin and Rossby waves
- The Kelvin waves propagate to east, Rossby waves to west, leading to a chevron pattern with velocities tilted NW-SE (SW-NE) in northern (southern) hemisphere
- This causes an equatorward flux of eddy momentum and drives superrotation

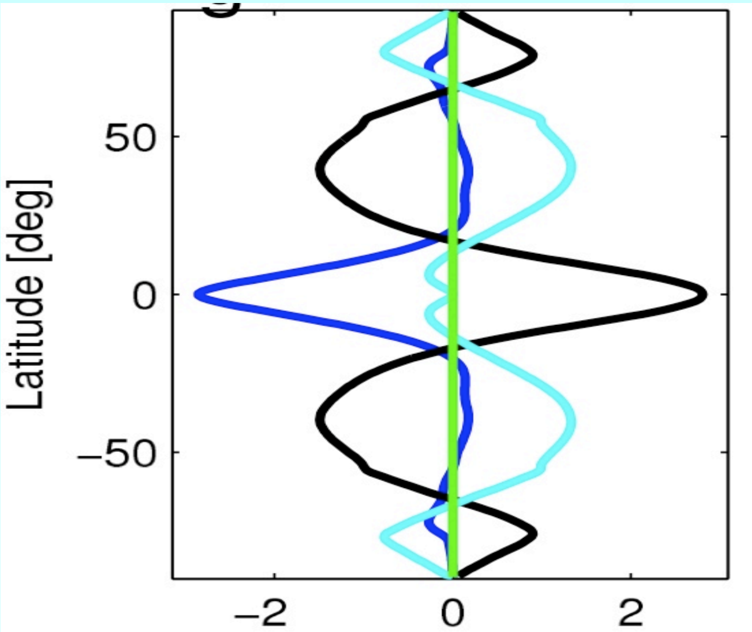
Linear response of shallow-water model to steady day-night forcing in full spherical geometry: the results qualitatively match our analytic β plane solutions



Zonal-mean zonal wind

Showman & Polvani (2011)





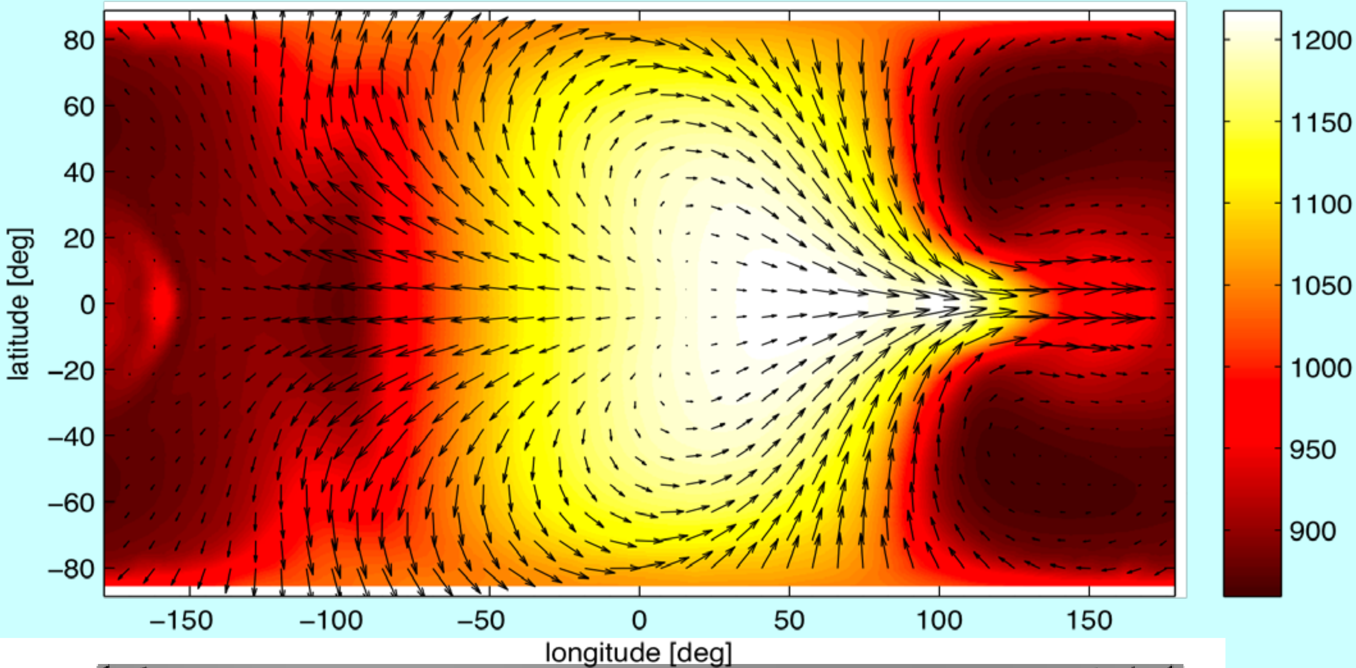
Acceleration (10^{-3} m/sec^2)

At high amplitude, non-linearities affect the solution, but the results are qualitatively similer.

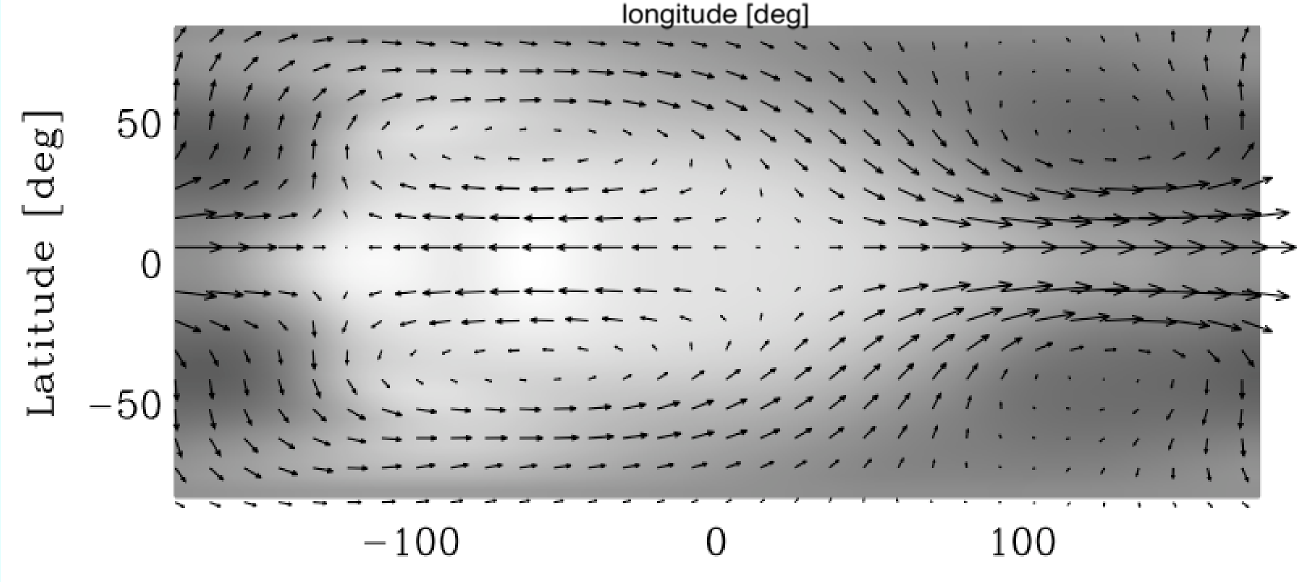
Standing Kelvin and Rossby waves drive a fast equatorial superrotation.

Showman & Polvani (2011)

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



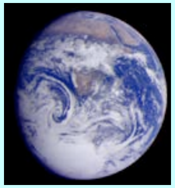
Showman & Polvani (2011)

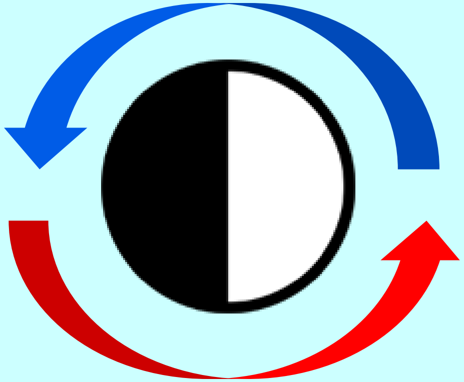


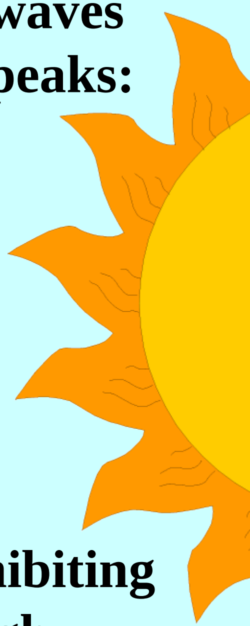
Showman & Guillot (2002)

This dynamical theory predicts two regimes

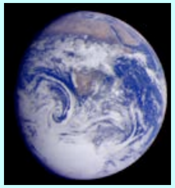
- **At weak-to-moderate stellar fluxes and friction, standing planetary waves induce zonal jets. This causes bimodal blue and redshifted velocity peaks:**

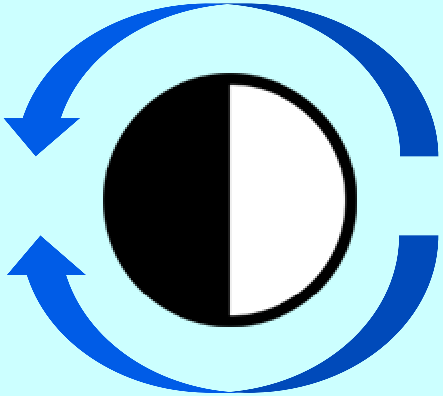


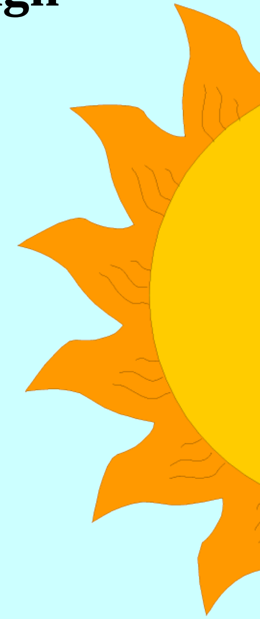




- **Extreme stellar fluxes and/or friction damp the planetary waves, inhibiting zonal jet formation and leading to predominant day-night flow at high altitude. This causes a predominant blueshifted velocity peak:**







Showman et al. (2013), Astrophysical Journal, 762, 24

Transition between regimes should occur when damping timescales are comparable to wave propagation time across a hemisphere:

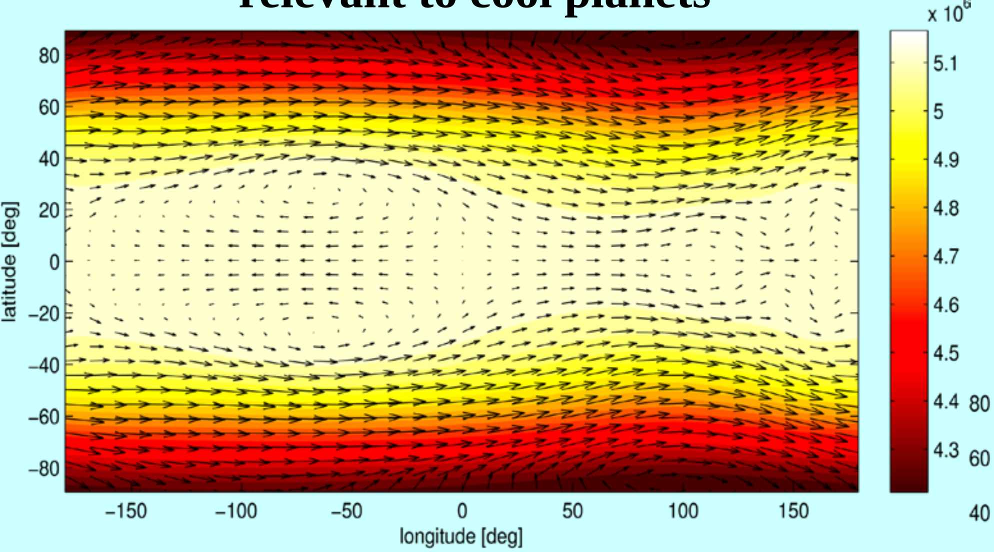
Kelvin wave propagation speed $\sim NH$

Propagation time across hemisphere $\sim \dfrac{a}{NH} \sim 10^5 \text{ sec}$

We now test the theory, first with idealized models, then with full 3D circulation models with realistic, non-grey radiative transfer

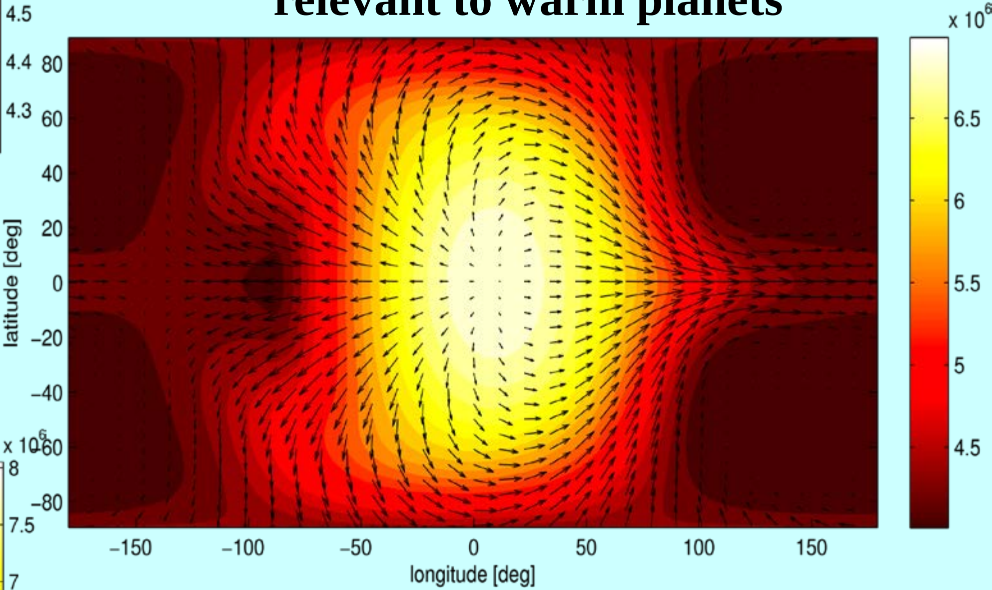
Showman et al. (2013)

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

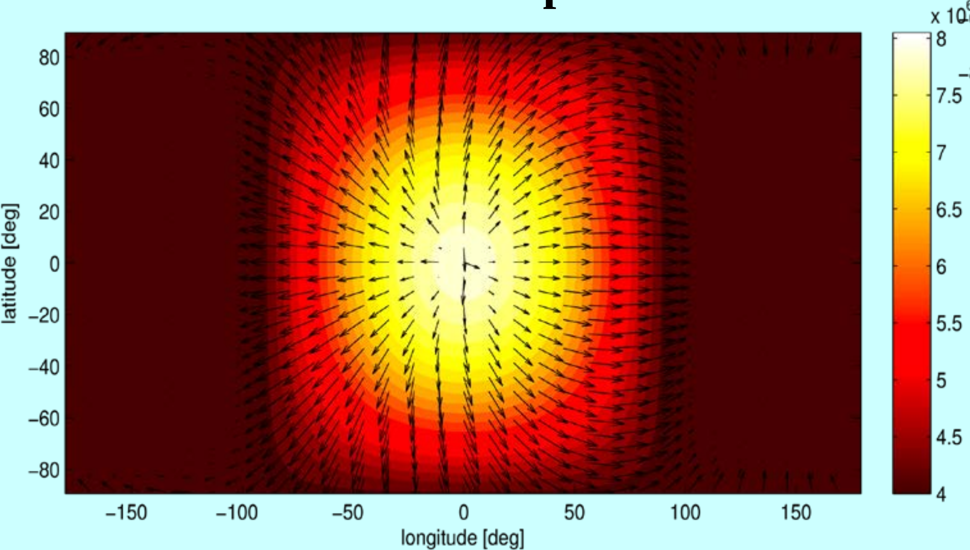


Fully nonlinear shallow-water models on the sphere.

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

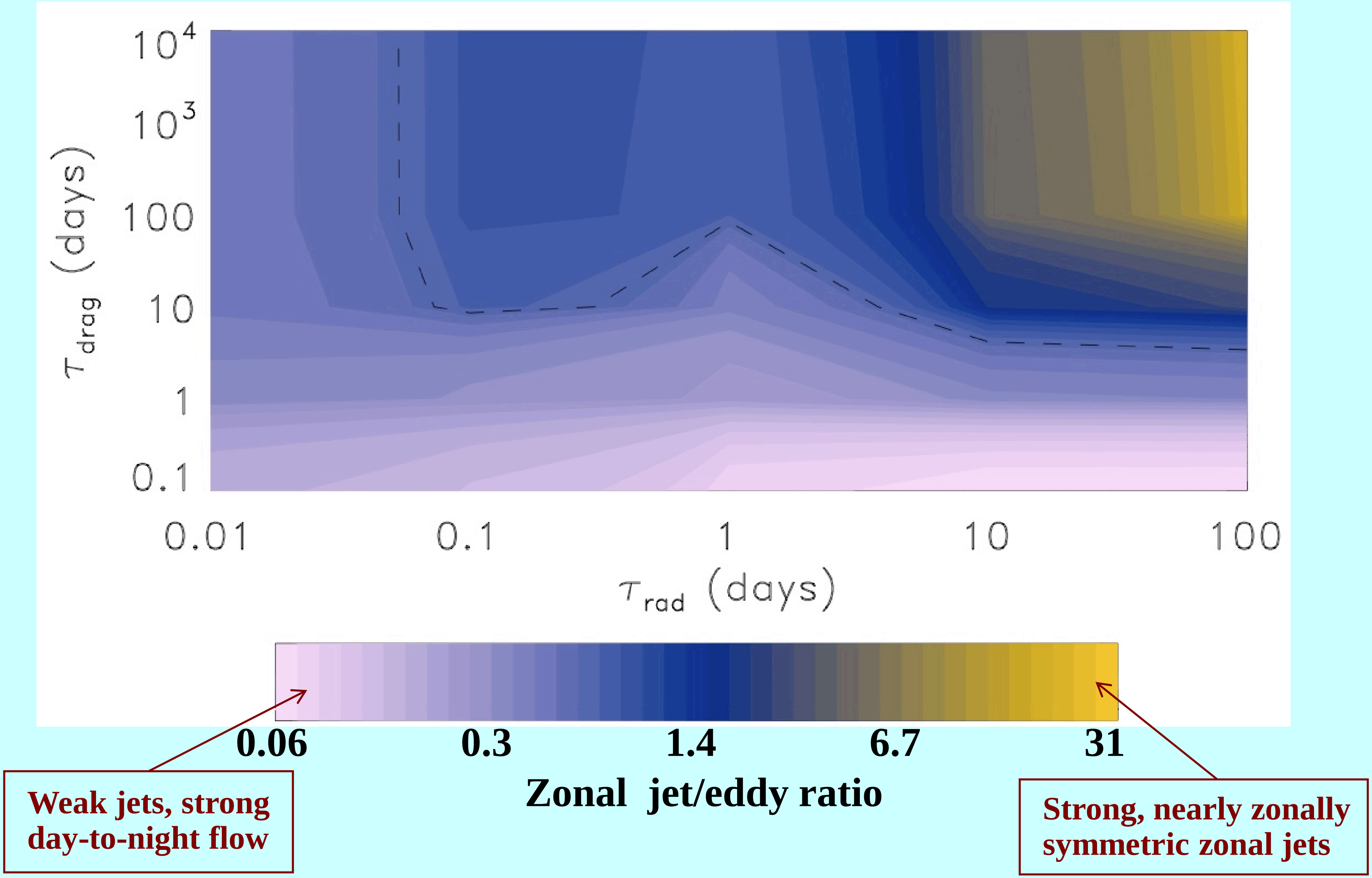


Strong damping (τ_{rad} = 0.1 days), relevant to hot planets



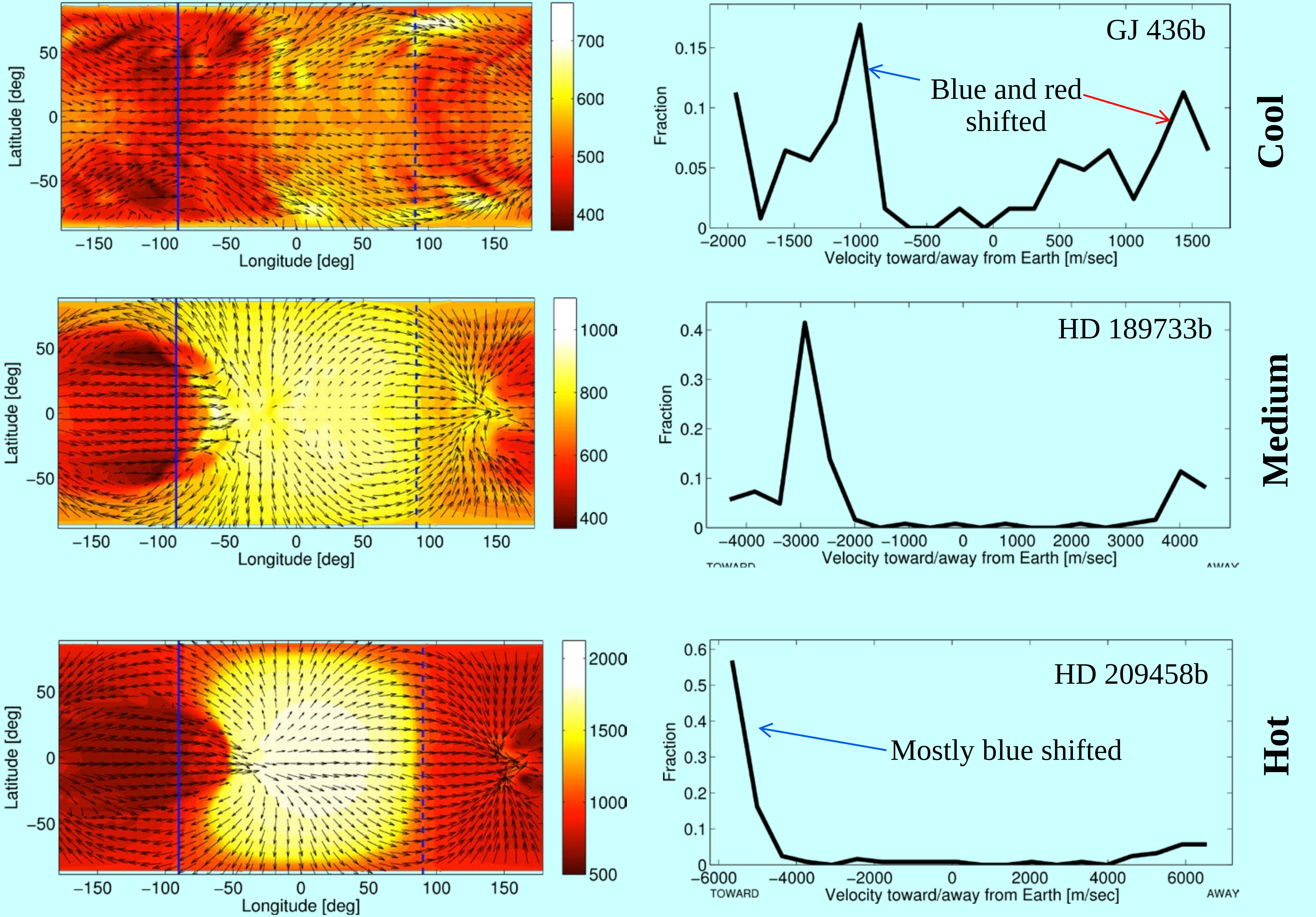
Showman et al. (2013)

Dependence of flow regime on radiative and drag time constants



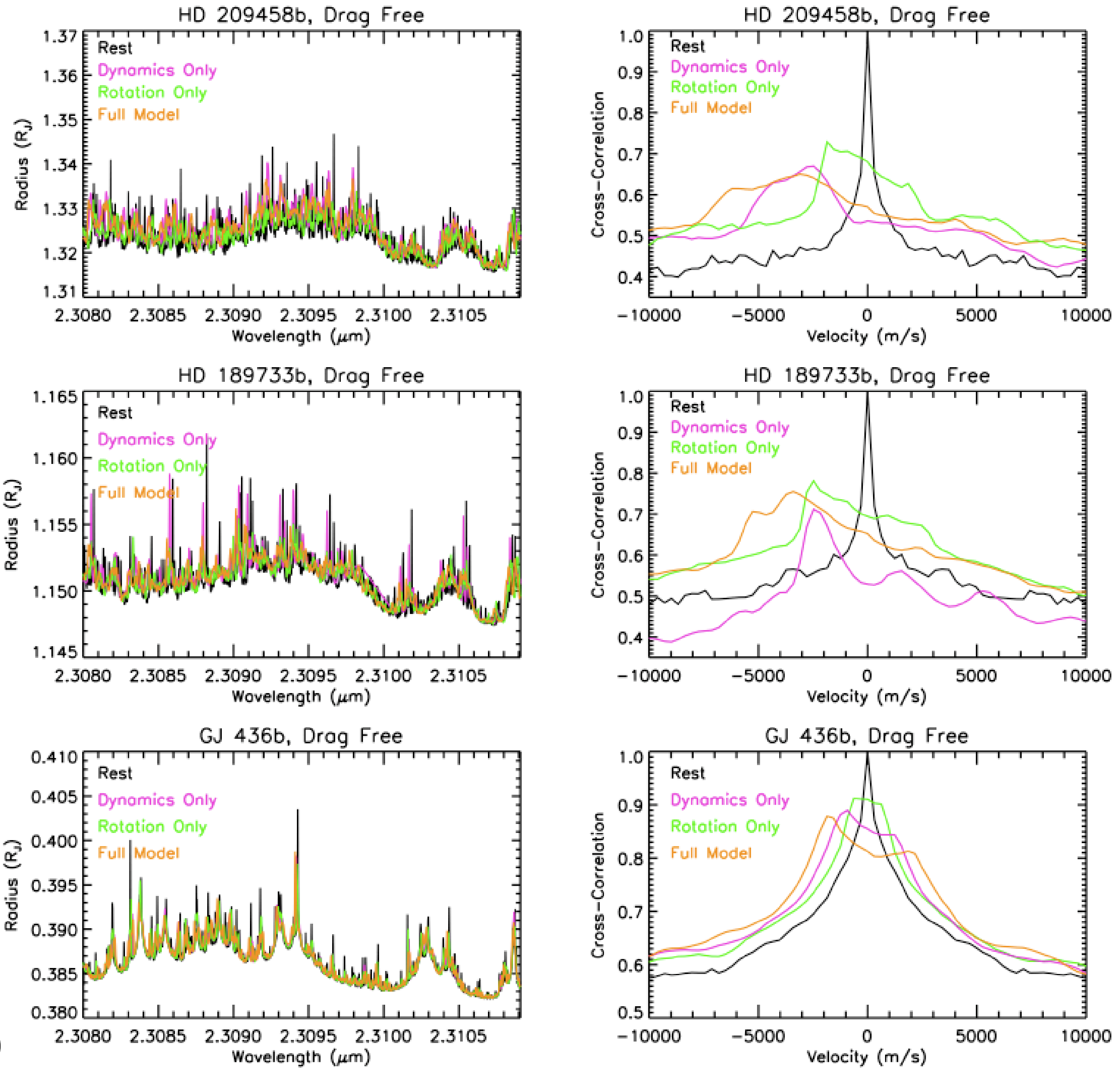
Showman et al. (2013)

A similar transition occurs in full 3D models with realistic non-grey radiative transfer:



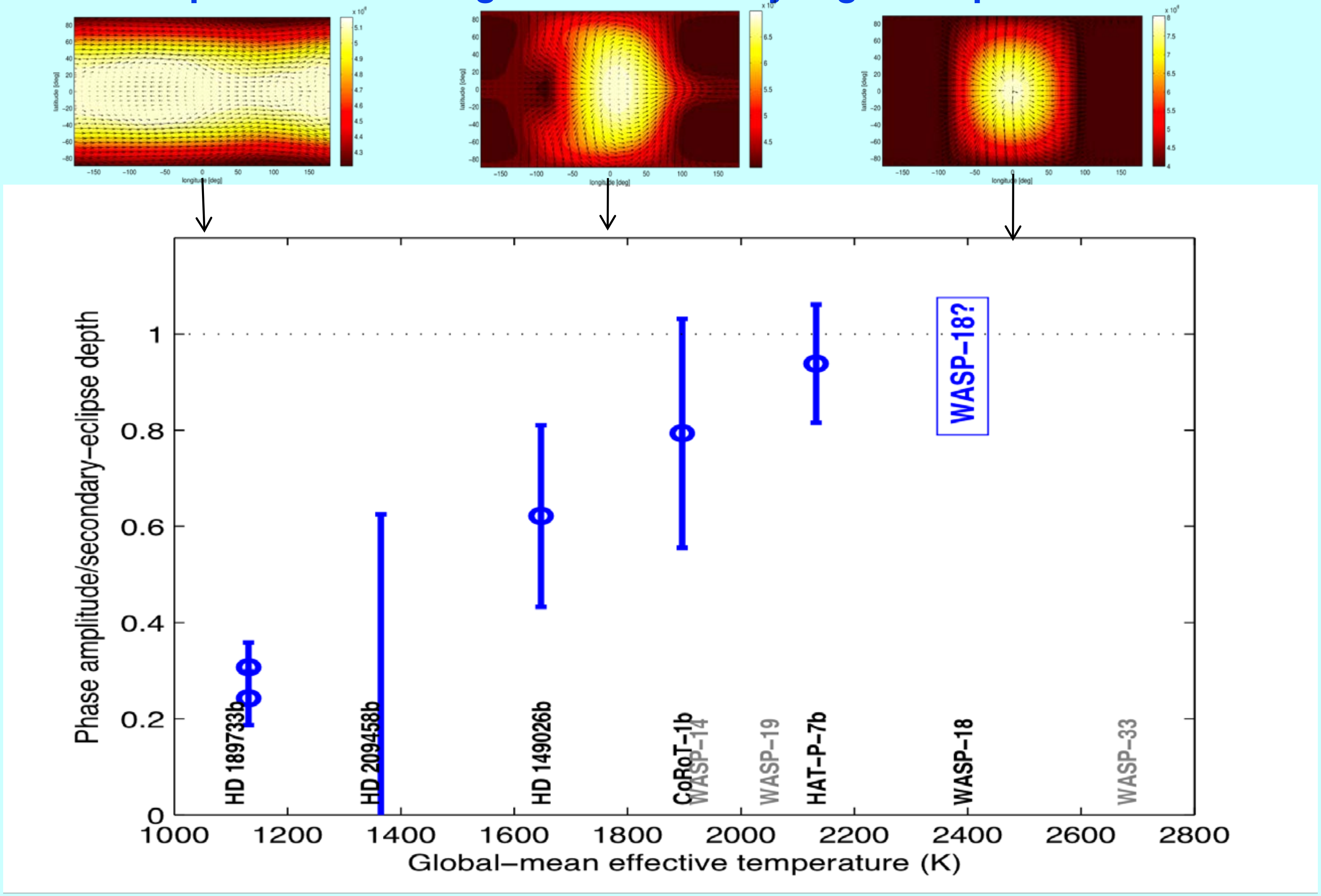
Showman et al. (2013)

Detailed radiative transfer analysis of these 3D models confirms this picture.



Showman et al. (2013)

The same shallow-water models also qualitatively explain the observation that hotter planets have larger fractional day-night temperature differences:



Let's now use this as a model system to understand the mechanisms that control the day-night temperature difference on synchronously rotating exoplanets

What controls the day-night temperature difference on a synchronously rotating planet?

Most previous authors have assumed that

Temperature differences are small if $\tau_{rad} >> \tau_{advect}$ and

Temperature differences are large if $\tau_{rad} << \tau_{advect}$,

where τ_{rad} is the radiative time constant and τ_{advect} is horizontal advection time from day to night.

Perez-Becker & Showman (in preparation)

There are several problems with this as an explanation:

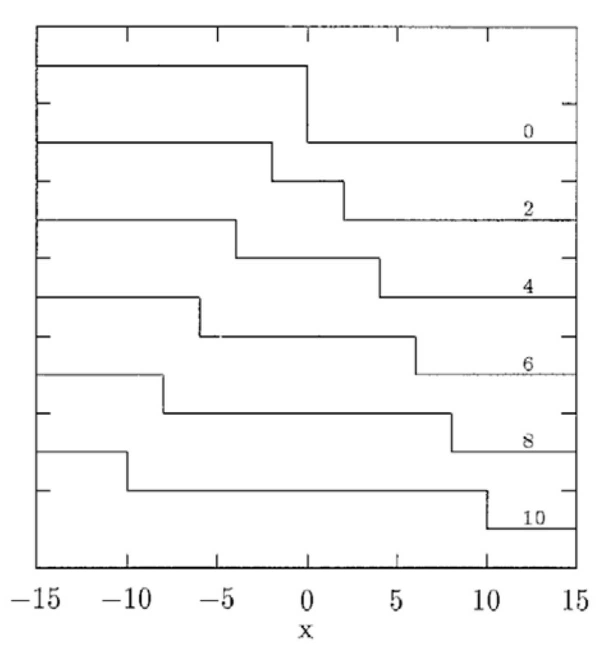
- **It is not predictive, since τ_{advect} depends on the flow. You can't even evaluate the criterion under given external forcing conditions unless you already have a theory for the flow itself. No such theory has ever been presented.**

- **While attractive, this timescale comparison neglects any role for other important timescales, including timescales for wave propagation, frictional drag, and planetary rotation. These almost certainly matter.**

- **More generally, we seek not just a criterion for the transition between regimes but a predictive theory for the day-night temperature difference itself, valid across the full parameter space.**

Background: wave adjustment as a regulator of thermal structure

- **Shallow-water solutions of the “dam break” problem show how wave adjustment can flatten material surfaces:**



Kuo & Polvani (1997)

- **The waves cause horizontal convergence/divergence that changes the fluid thickness, allowing the topography to be flattened if the waves radiate to infinity**

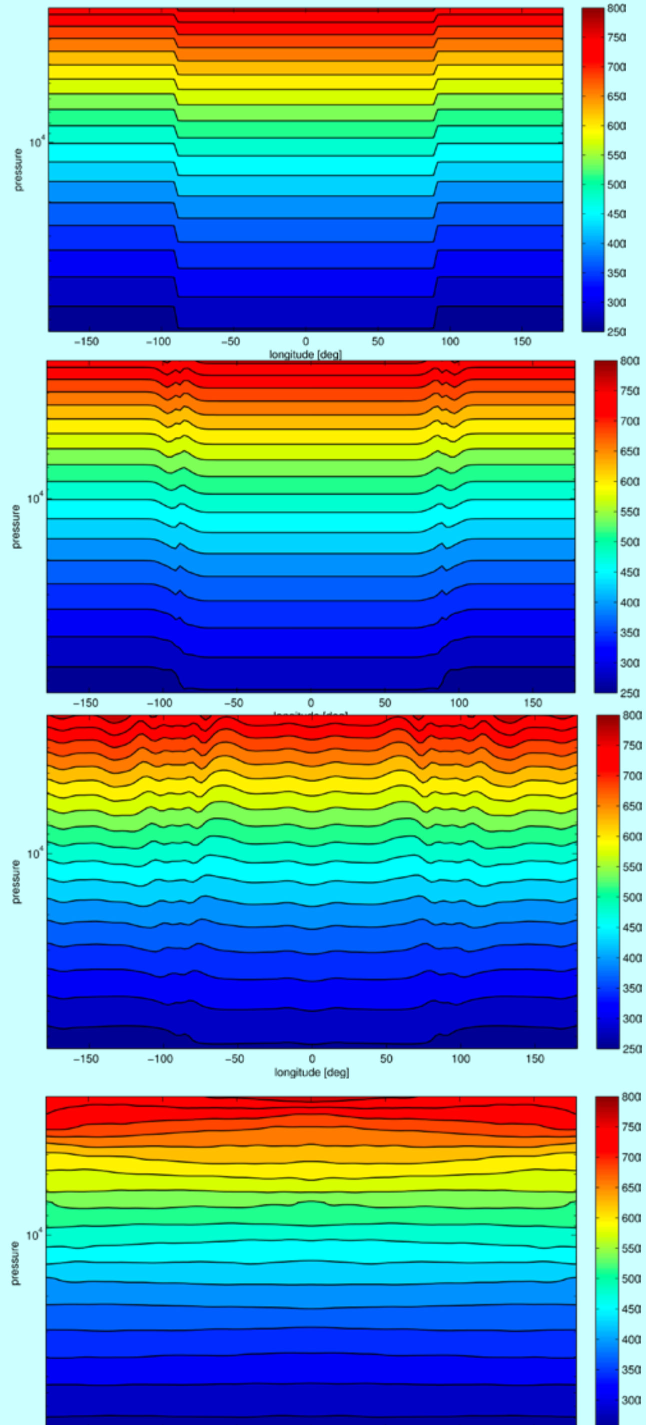
- **The process does not require long distance horizontal advection; fluid columns move horizontally by only a small amount if the initial topographic step is small.**

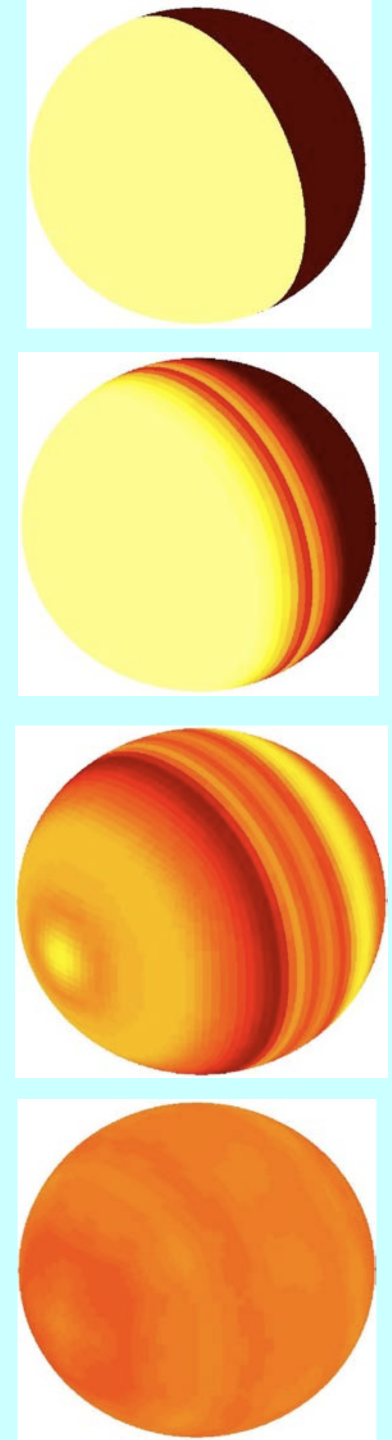
- **The process operates not over a horizontal advection time but rather over the horizontal wave propagation timescale.**

The same wave adjustment process operates in 3D

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

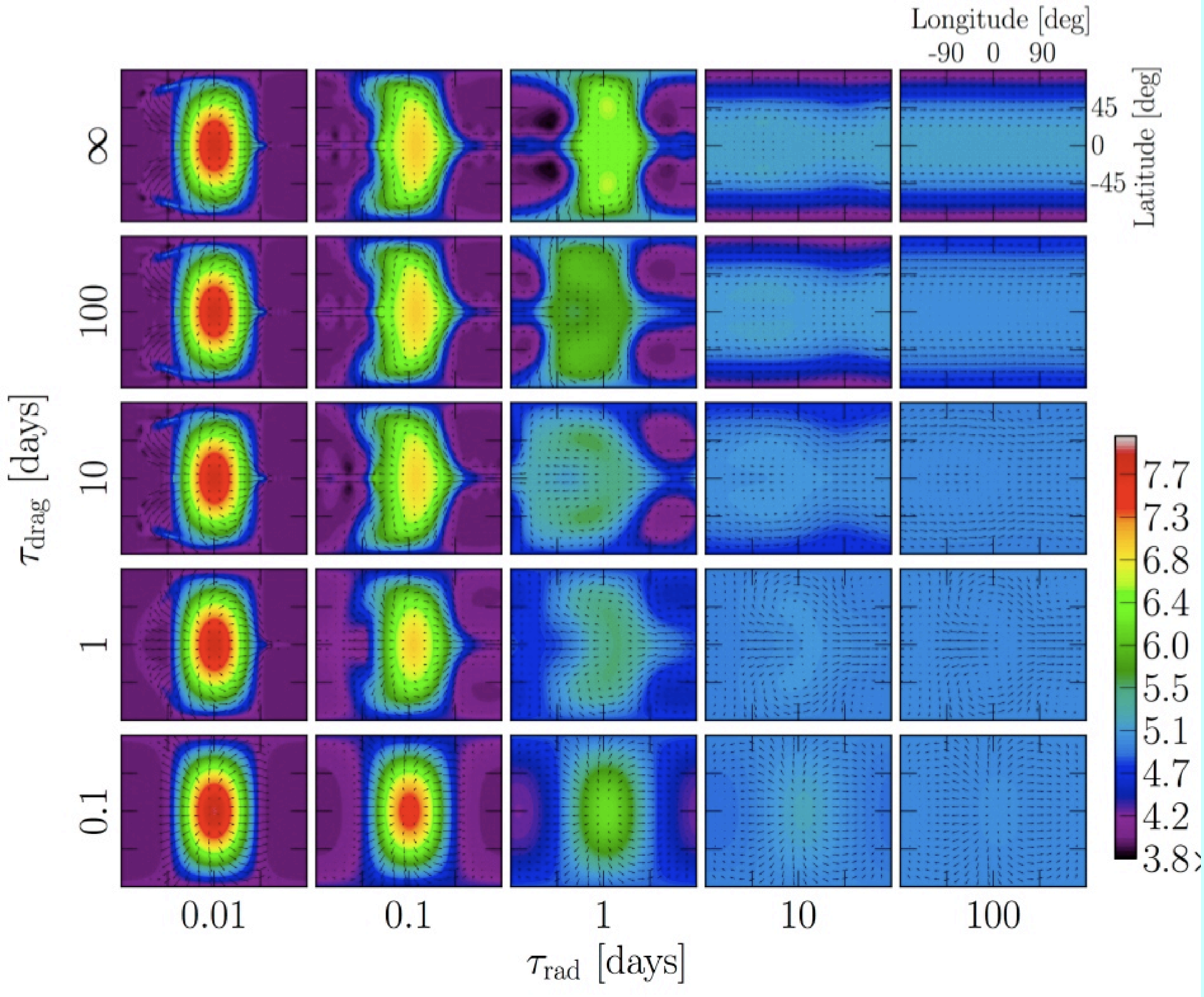
This is a key mechanism for maintaining the small longitudinal temperature differences in Earth's tropics: the "weak temperature gradient" or WTG regime.



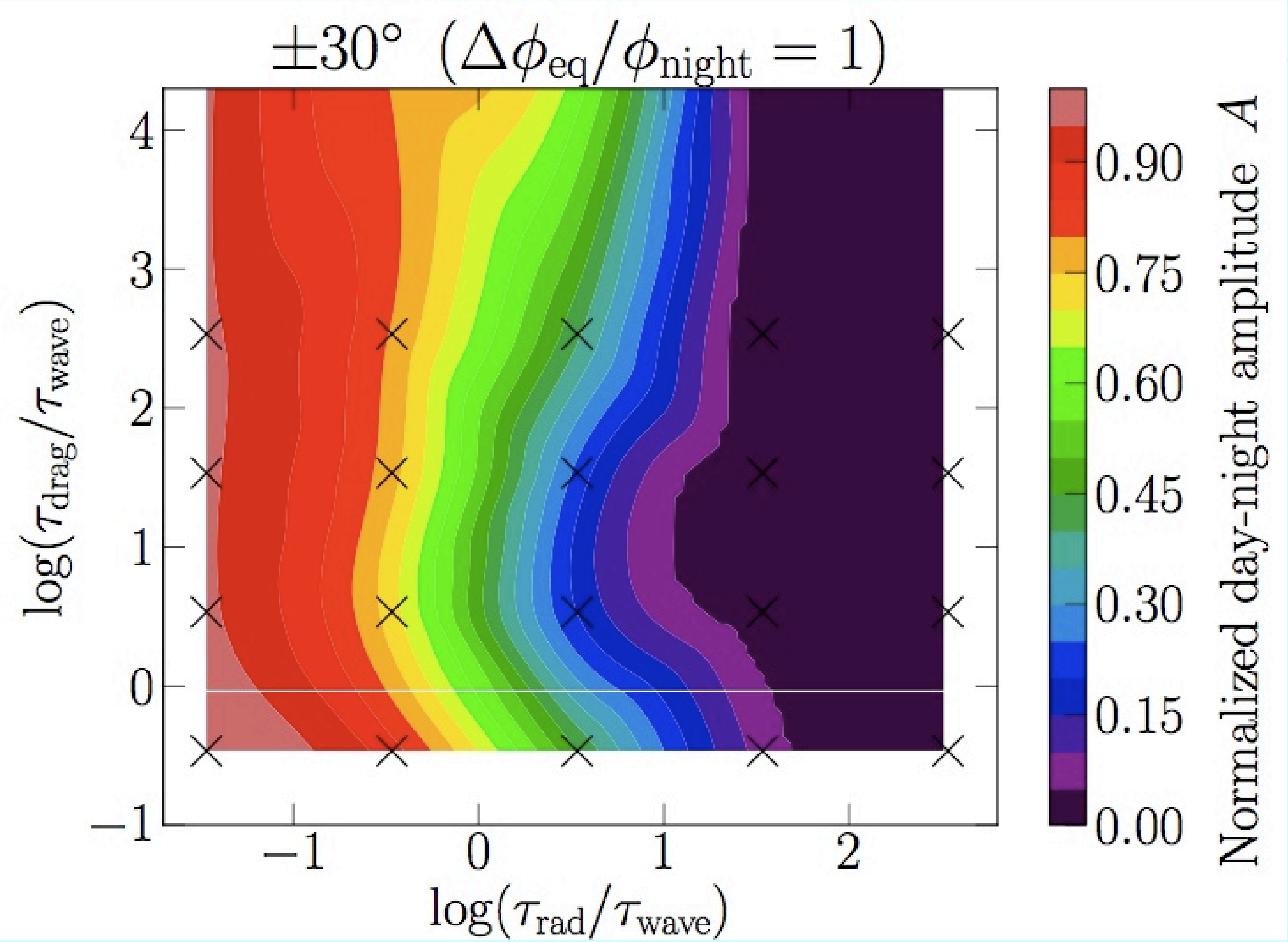


Showman et al. (2013b), "Atmospheric circulation of terrestrial exoplanets," submitted to *Comparative Climatology of TerrestrialPlanets*, Univ. Arizona Press (to be published)

To investigate this question, we ran shallow-water models of synchronously rotating planets over a full grid of τ_{rad} and τ_{drag}, which are external parameters

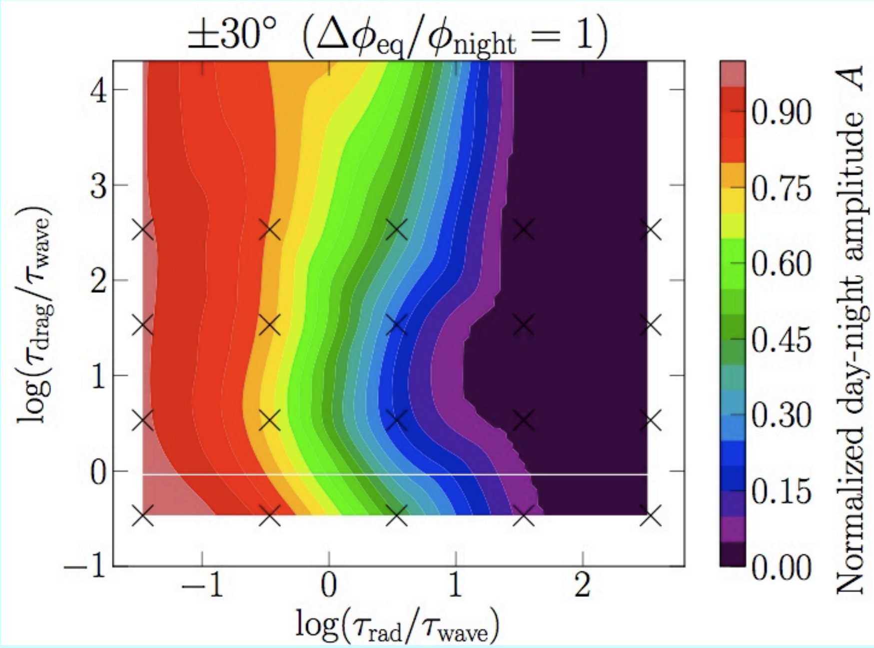


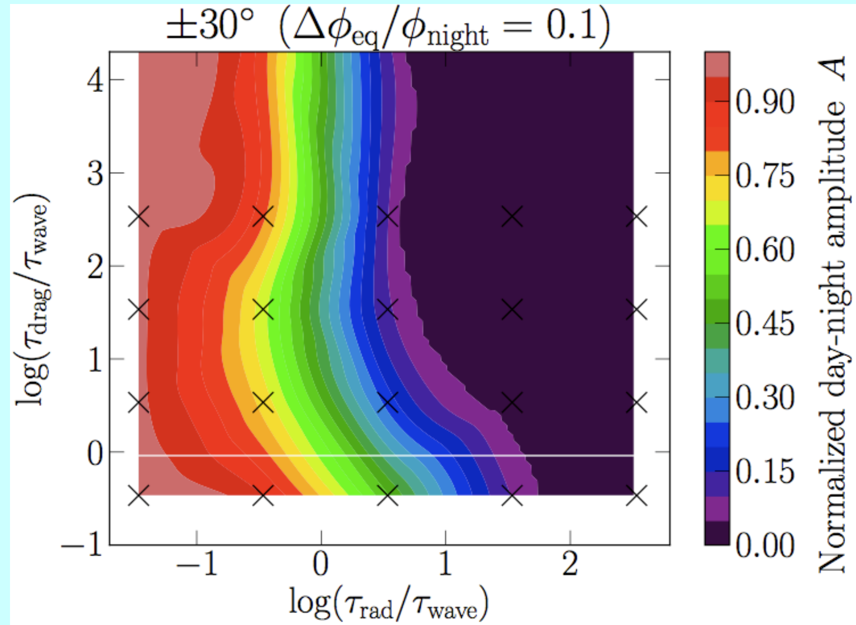
Perez-Becker & Showman (in preparation)

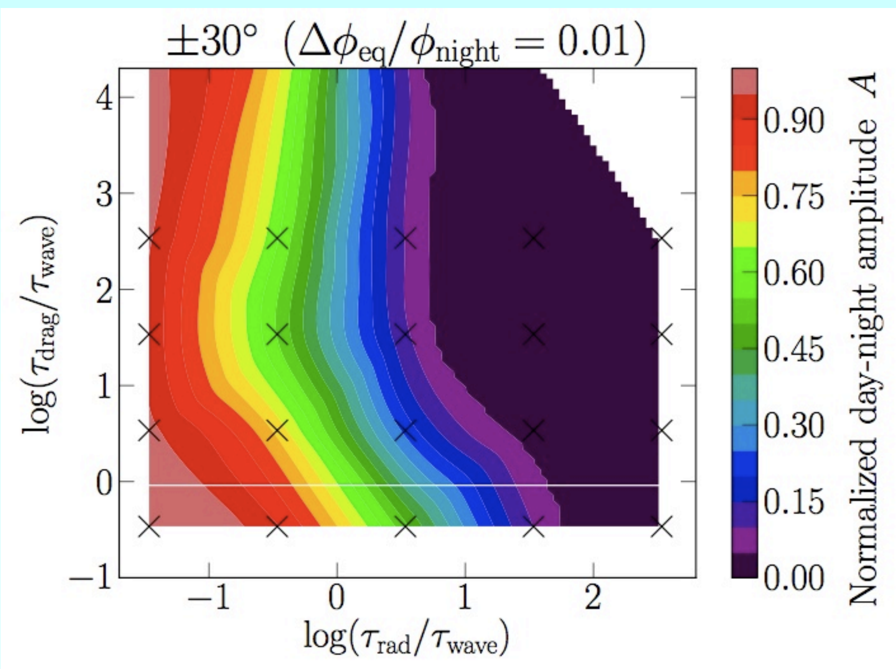


Perez-Becker & Showman (in preparation)

Amplitude dependence

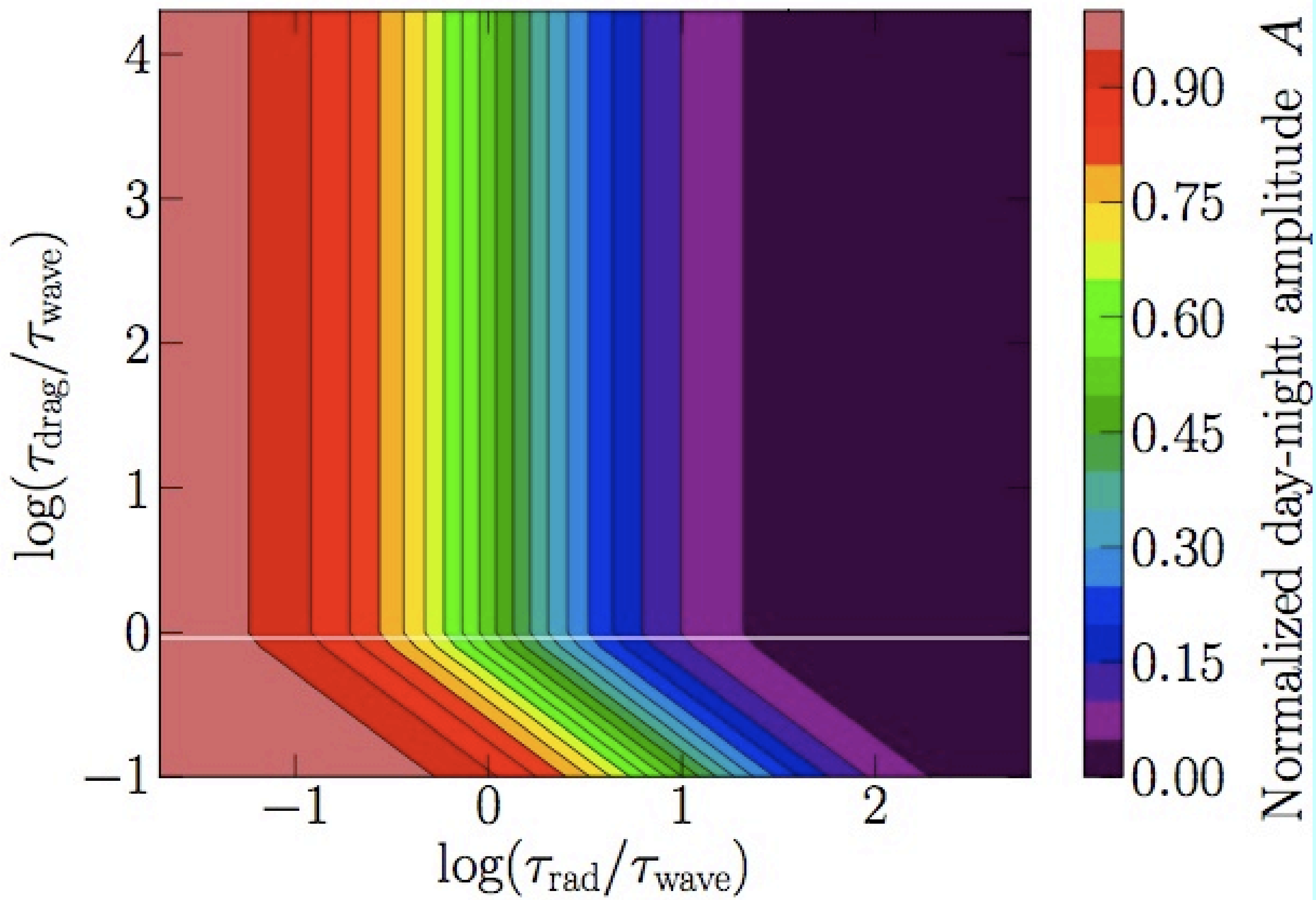






Perez-Becker & Showman (in preparation)

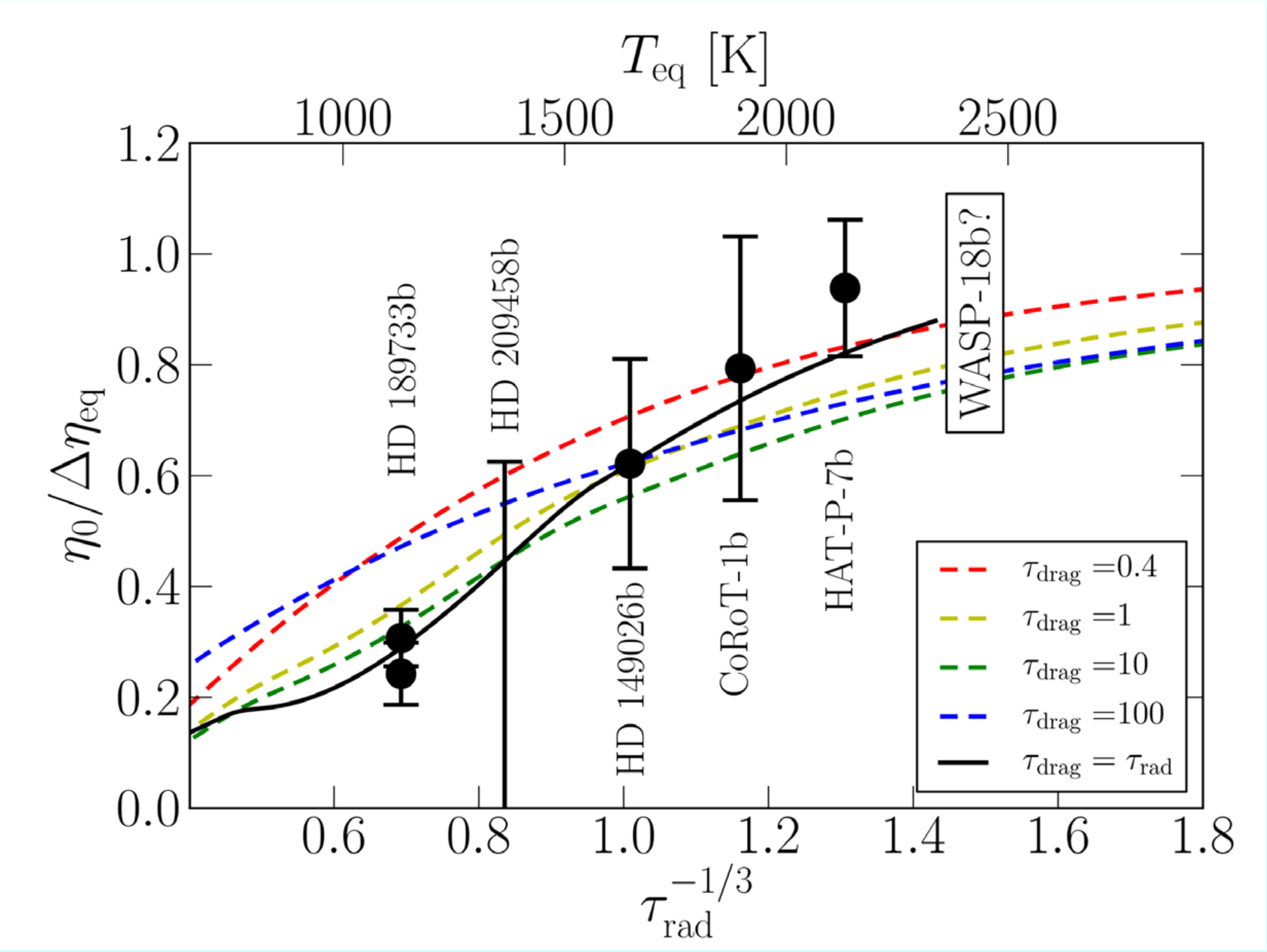
Analytic theory



- **Theory shows that transition occurs at** $\tau_{wave} \approx \sqrt{\tau_{rad}\tau_{drag}}$ **in strong drag limit and** $\tau_{wave} \approx \sqrt{\frac{\tau_{rad}}{\Omega}}$ **in weak drag limit.**

Perez-Becker & Showman (in preparation)

The model explains the emerging observational trend



Perez-Becker & Showman (in prep)

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:**

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

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

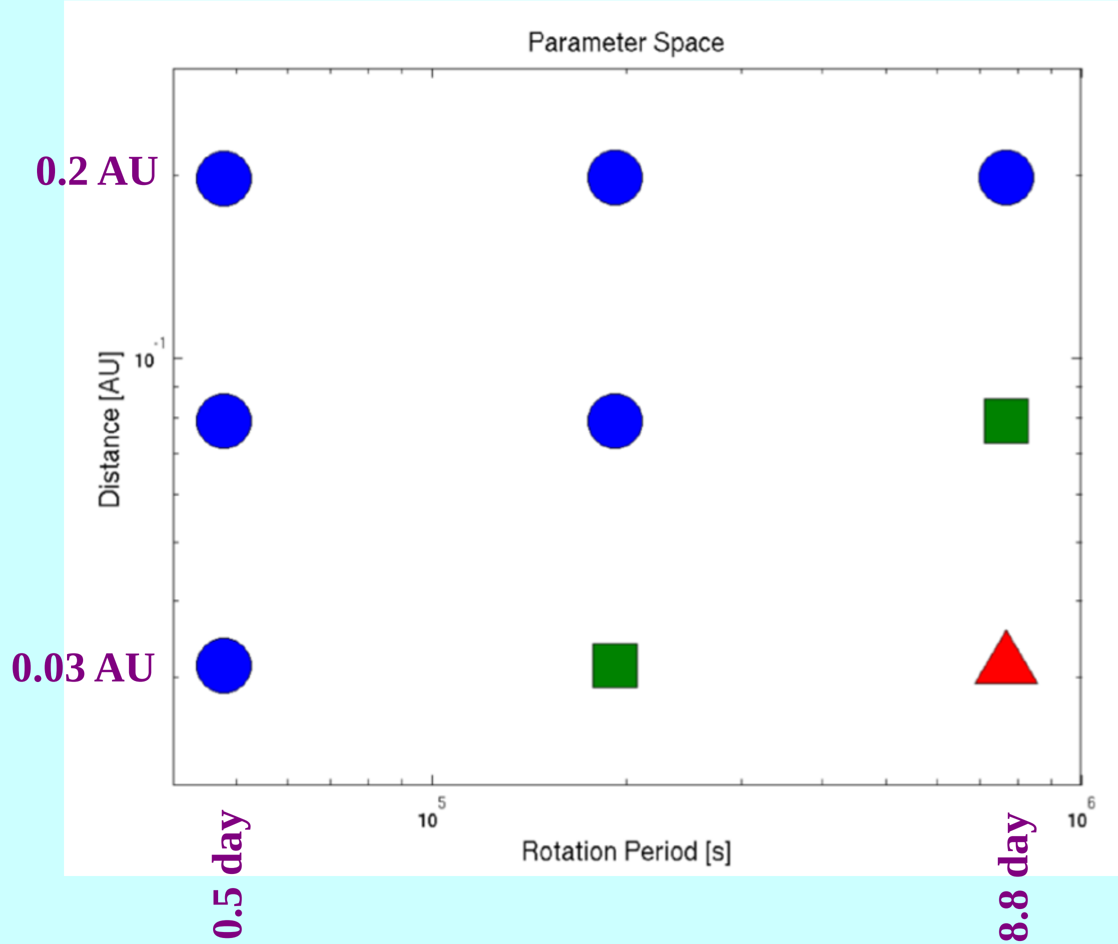
All of this motivates an investigation of how hot Jupiter circulation regimes--and observables--vary with incident stellar flux and rotation rate

Showman, Lewis, Fortney (in prep)

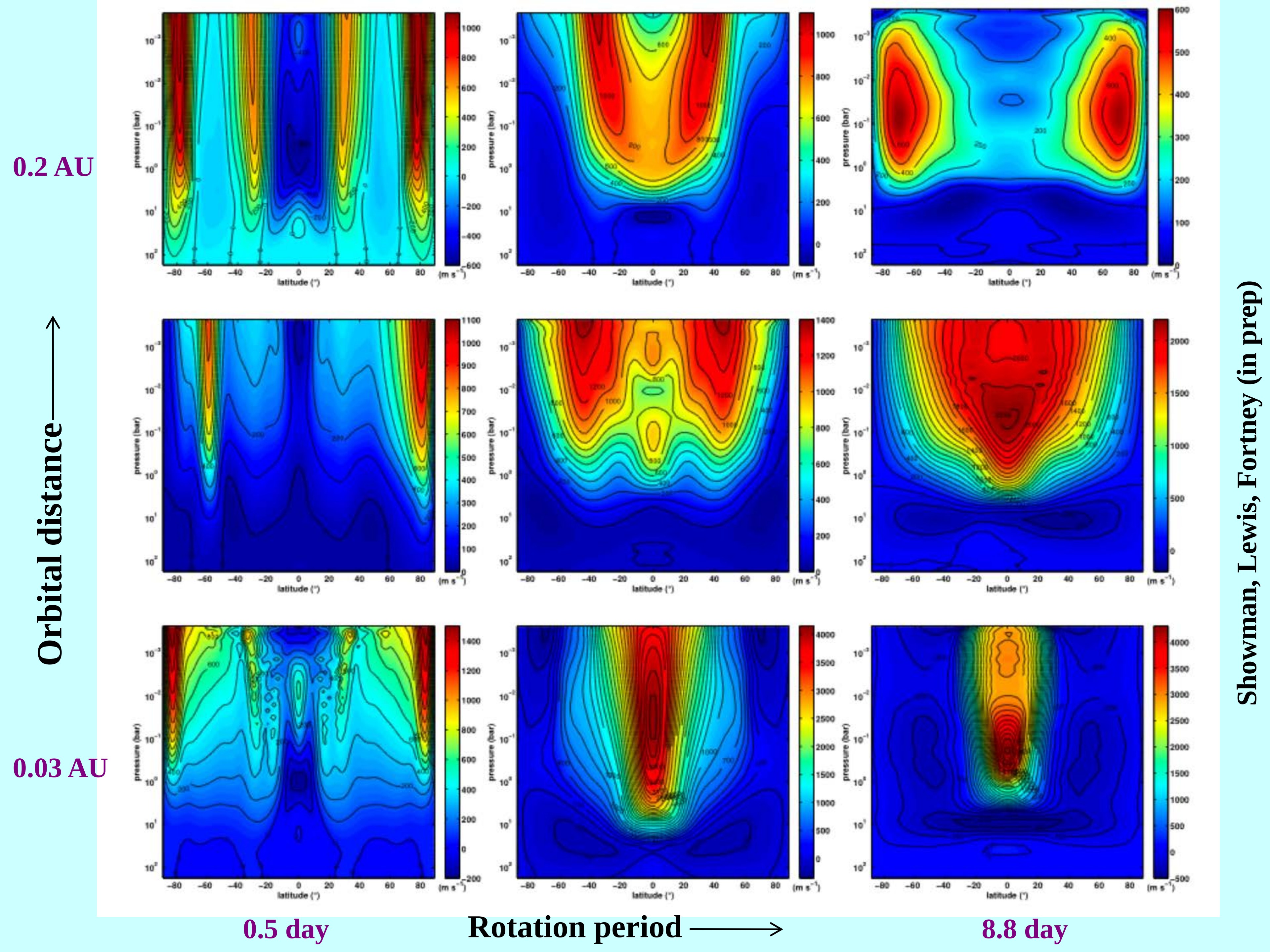
- Explore a regular grid of models varying rotation rate from 0.5 to 8.8 Earth days and orbital semi-major axes from 0.03 -- 0.2 AU

- Allows us to emphasize planets amenable to transit characterization while exploring a factor of 16 in rotation rate and ~40 in incident stellar flux

- Stellar/planetary properties of HD 189733



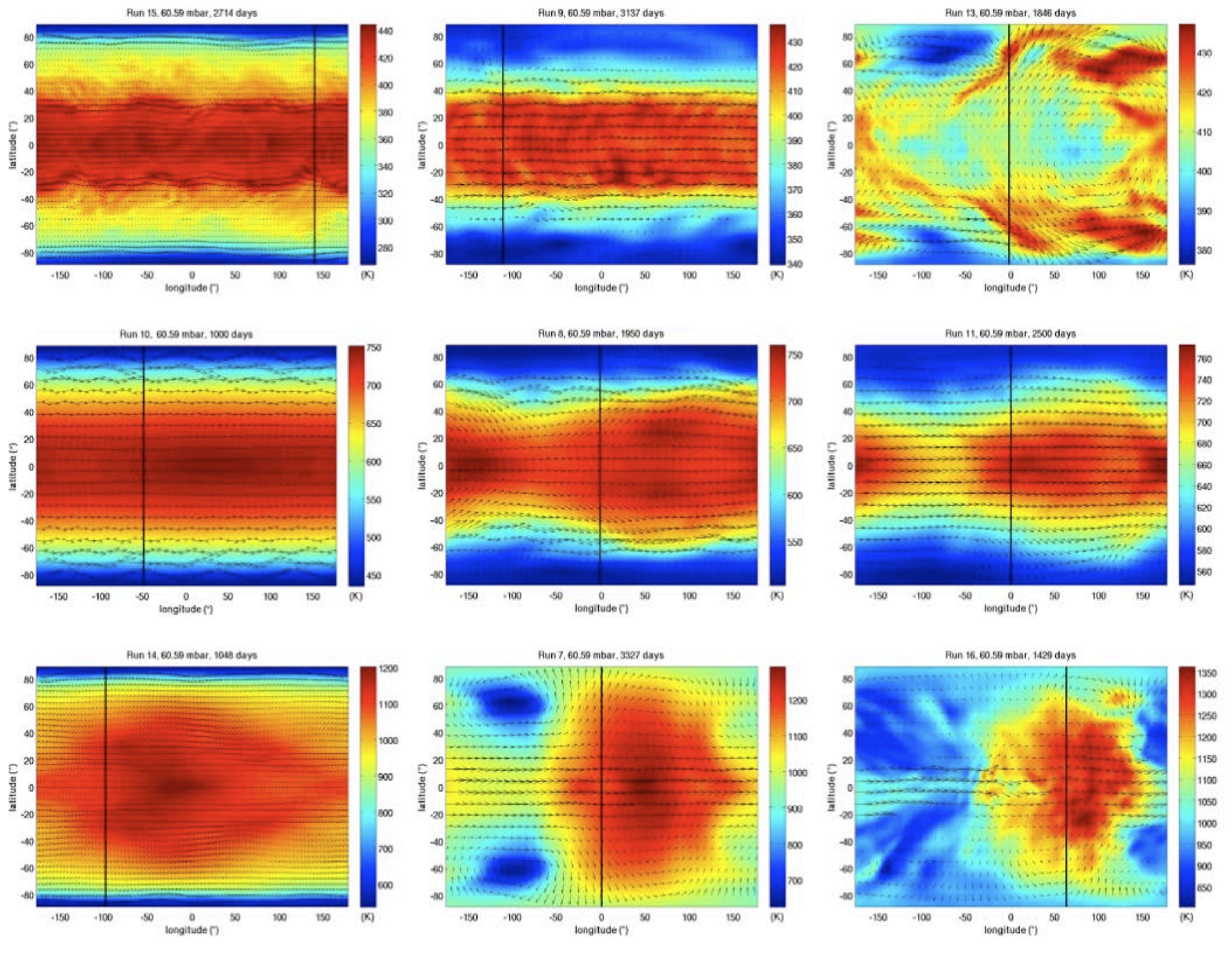
Showman, Lewis, Fortney (in prep)


0.2 AU
0.03 AU
Orbital distance
0.5 day
Rotation period
8.8 day
Showman, Lewis, Fortney (in prep)
pressure (bar)
latitude (°)
(m s⁻¹)

0.2 AU

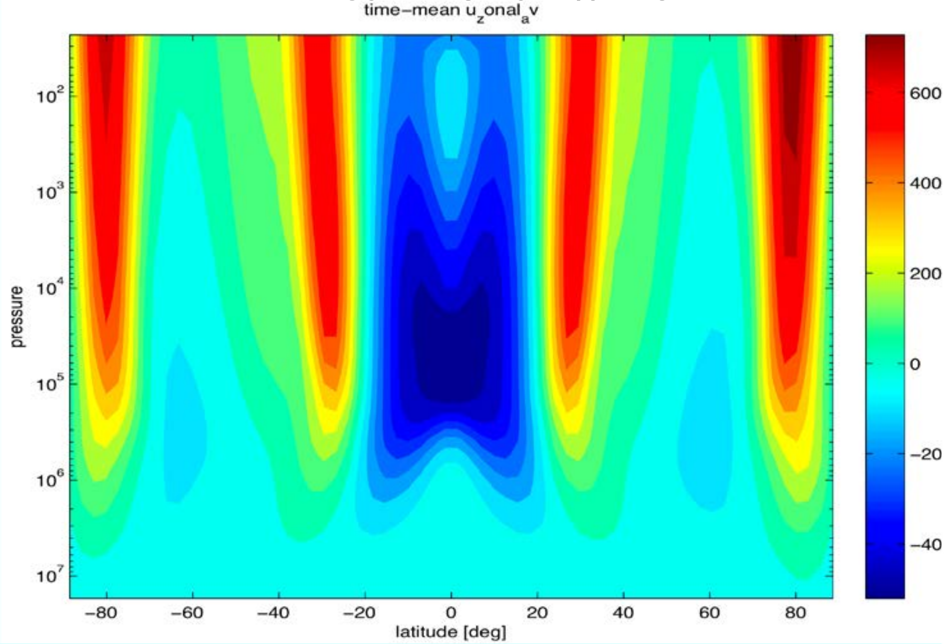
Orbital distance

0.03 AU



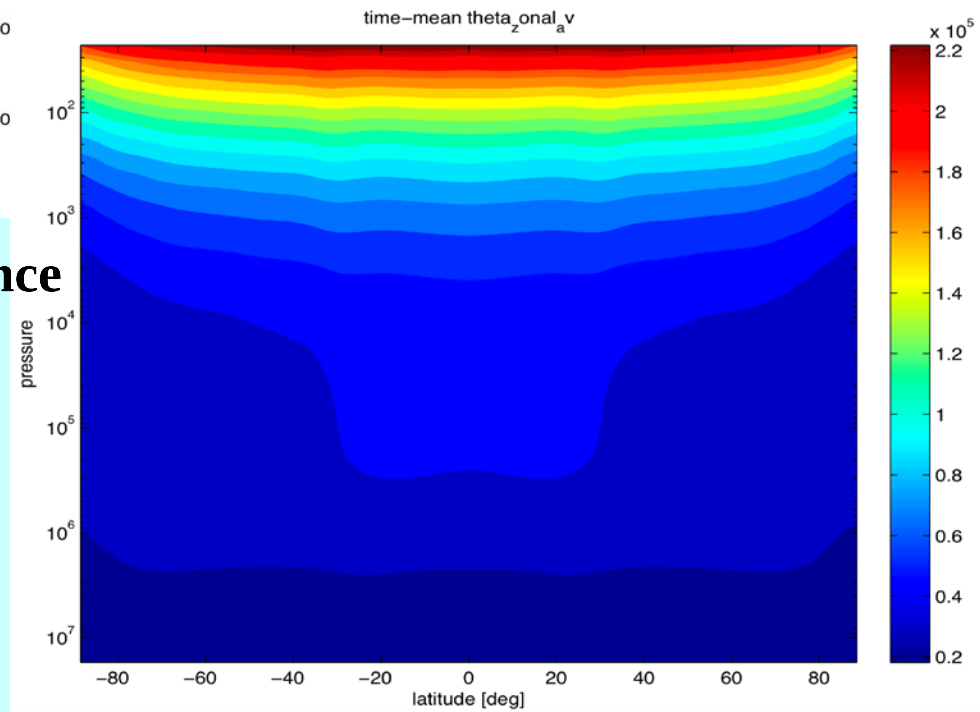
0.5 day **Rotation period** 8.8 day

Mean zonal wind

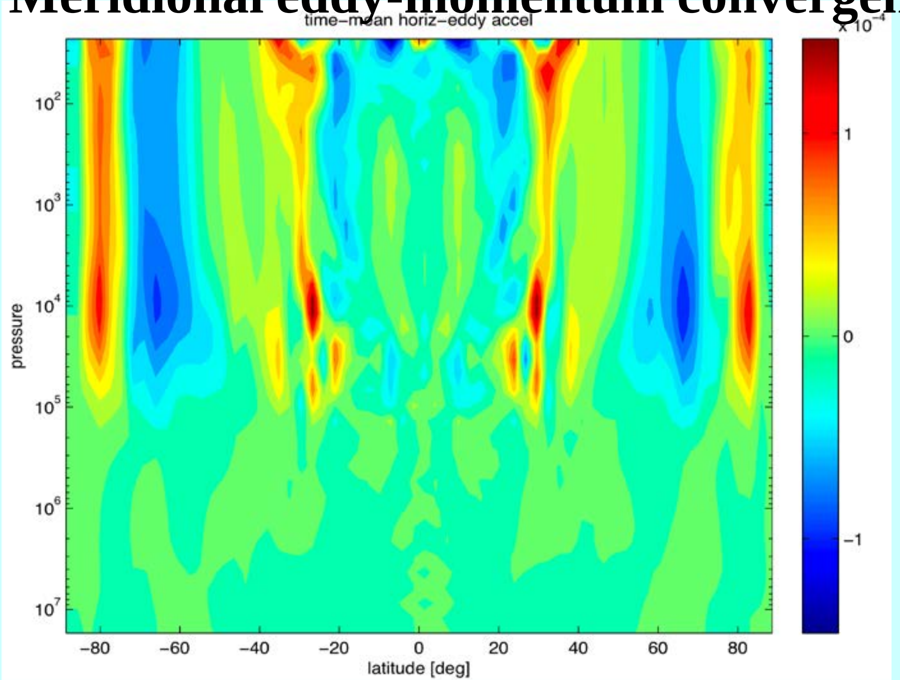


Our least irradiated and most rapidly rotating "warm Jupiter" model: development of multiple jets in each hemisphere due to baroclinic instability!

Potential temperature



Meridional eddy-momentum convergence



Showman, Lewis, Fortney (in prep)

Conclusions: hot Jupiters

- **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 day-night forcing generates planetary-scale waves that pump momentum to the equator, leading to equatorial superrotation that explains the observed hot-spot offset on HD 189733b.**

- **On *very* hot Jupiters, the strong radiation/friction damps these waves, preventing their ability to adjust the thermal structure and leading to large day-night temperature differences. On *warm* Jupiters, radiative damping is weaker, and the waves efficiently mute the longitudinal thermal differences. Our models thus explain the emerging observational trend of increasing fractional day-night temperature difference with incident stellar flux.**

- **The same dynamics predicts a transition in wind regime: from zonally banded flows at weak irradiation to a day-night flow at strong irradiation. This explains the blue-shifted Doppler measurement of HD 209458b and leads to a prediction for future measurements.**

Conclusions II: hot Jupiters

- **At faster rotation rates and weaker stellar fluxes, the day-night heating gradient is less important, and baroclinic instabilities emerge as a dominant player, leading to eastward jets in the mid-latitudes, significant equator-pole temperature differences, and minimal temperature differences in longitude.**

- **Our most rapidly rotating and least irradiated EGP models exhibit multiple eastward jets in each hemisphere—similar to the jets on Jupiter and Saturn—and illuminate the dynamical continuum between highly irradiated EGPs and the weakly irradiated giant planets of our own Solar System.**

Additional papers mentioned during questions and discussion

- **Showman & Polvani (2010, GRL 37, L18811, "The Matsuno-Gill model and equatorial superrotation"): Shows effect of the vertical momentum transport on equatorial superrotation in a 1-1/2 layer shallow-water model with Gill-type forcing**

- **Kataria, Showman, et al. (2013, "Three dimensional atmospheric circulation of hot Jupiters on highly eccentric orbits," Astrophysical Journal, in press)**

- **Liu & Showman (2013, "Atmospheric circulation of hot Jupiters: insensitivity to initial conditions", submitted to Astrophysical Journal)**