Theoretical Perspectives on Giant Planets

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Fundamental motivation: to understand the atmosphere/interior circulation and structure on giant planets, broadly defined.

- **What is the nature of the circulation (zonal jets, vortices, storms, turbulence)? What are the wind speeds, temperature variations, key length scales, and time variability? How do they depend on parameters?**
- **How does the circulation work: what are the dynamical mechanisms controlling it?**
- **What is the role of condensation and clouds? Coupling to atmospheric chemistry?**
- **Can we achieve a unified theory of giant planet atmospheric circulation that explains observations of hot Jupiters, brown dwarfs, and solar system planets?**
- **Does this knowledge provide insights about the circulation and climate of (less easily observed) smaller planets?**

Factors that shape giant planet circulation and structure

External irradiation

Internal (convective) heat flux

Gravity (mass)

Rotation rate

Composition (metallicity, C/O ratio, etc)

Clouds/chemistry

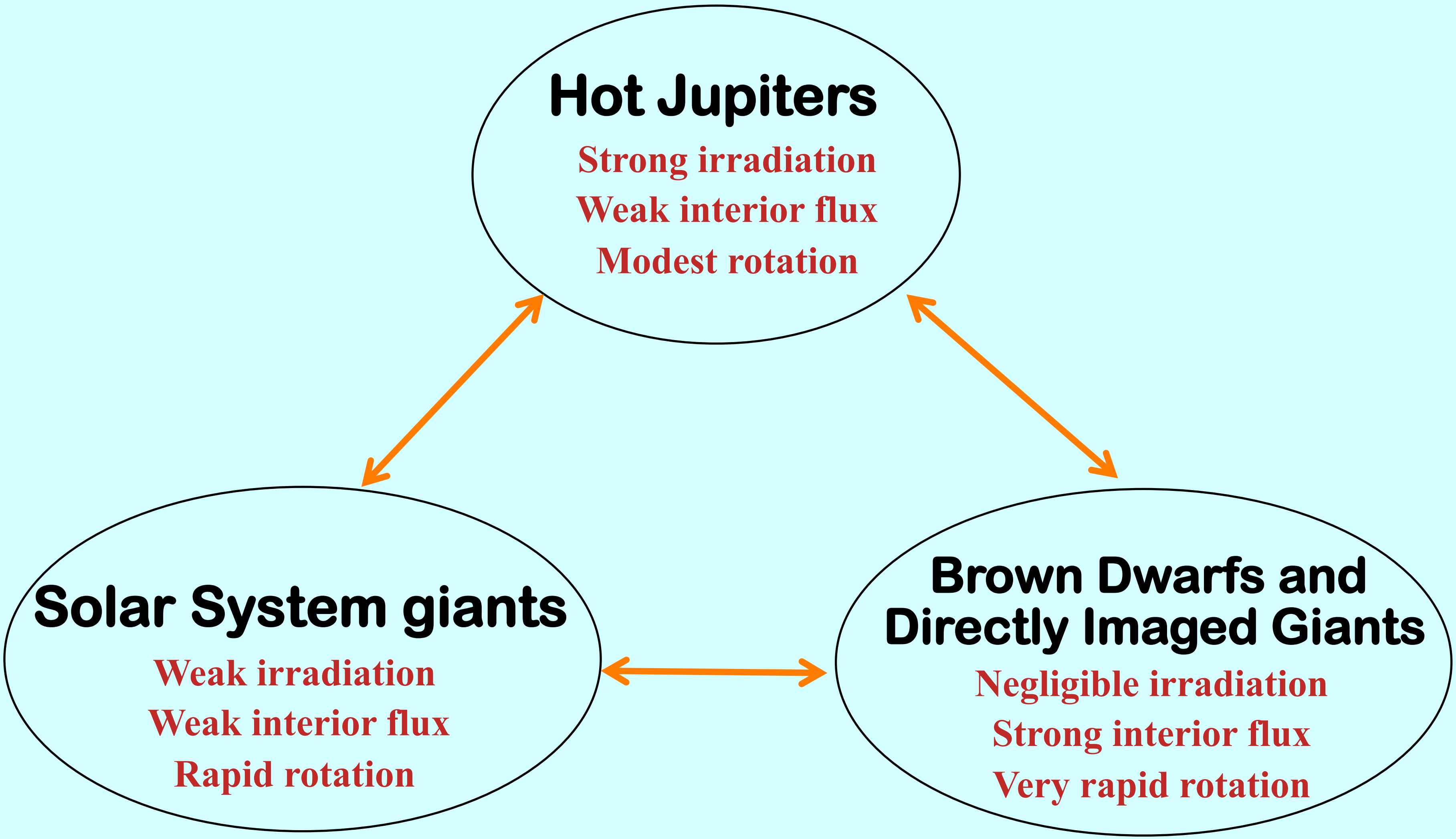
Interaction with interior

History

Factors that can affect giant planet circulation and structure

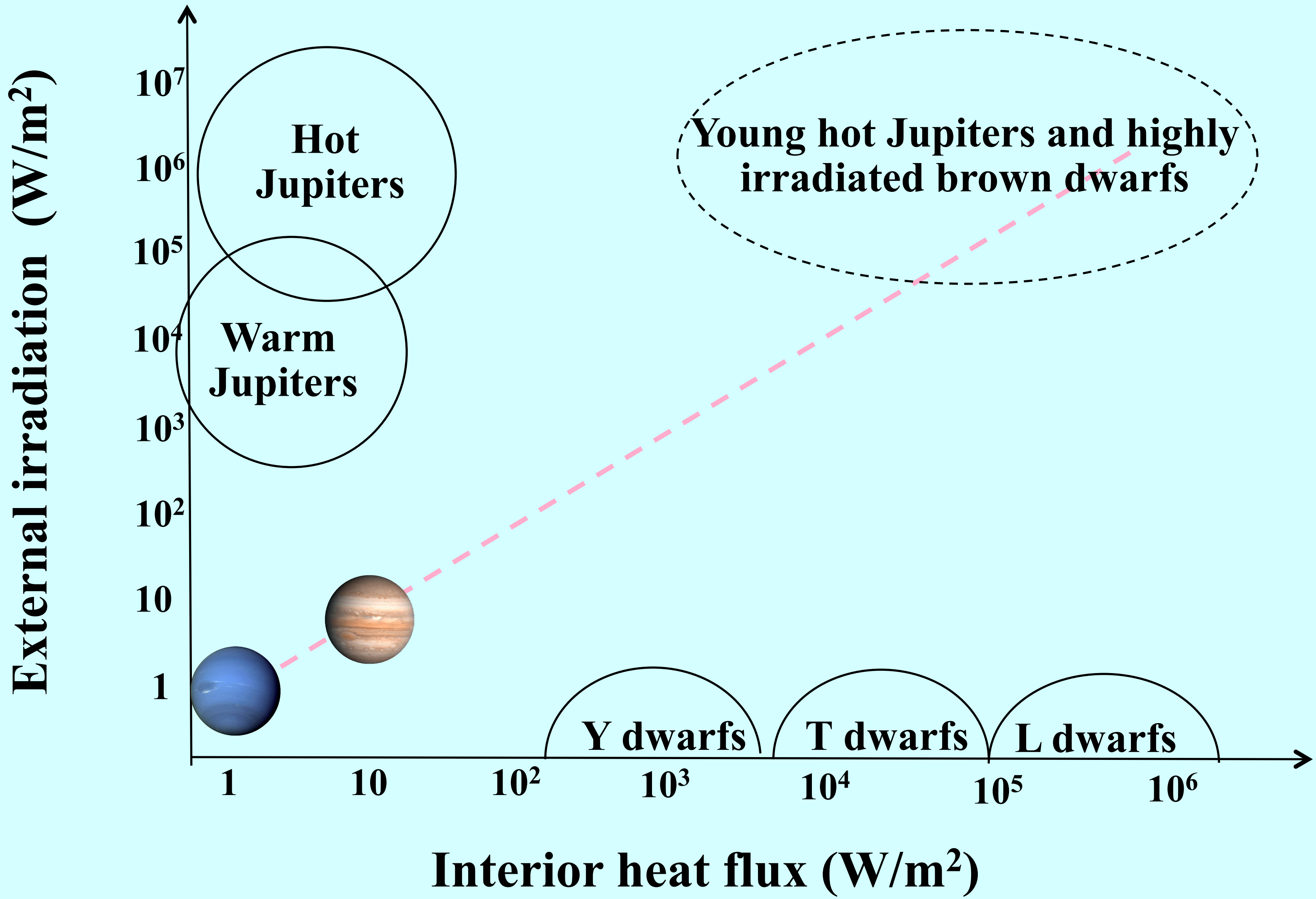
External irradiation	**$\sim 10^7$**
Internal (convective) heat flux	**$\sim 10^6$**
Gravity (mass)	**~100**
Rotation rate	**~100**
Composition (metallicity, C/O ratio, etc)	**~100**
Clouds/chemistry	
Interaction with interior	
History	

Observationally booming subfields yield constraints at the extreme ranges of key parameters

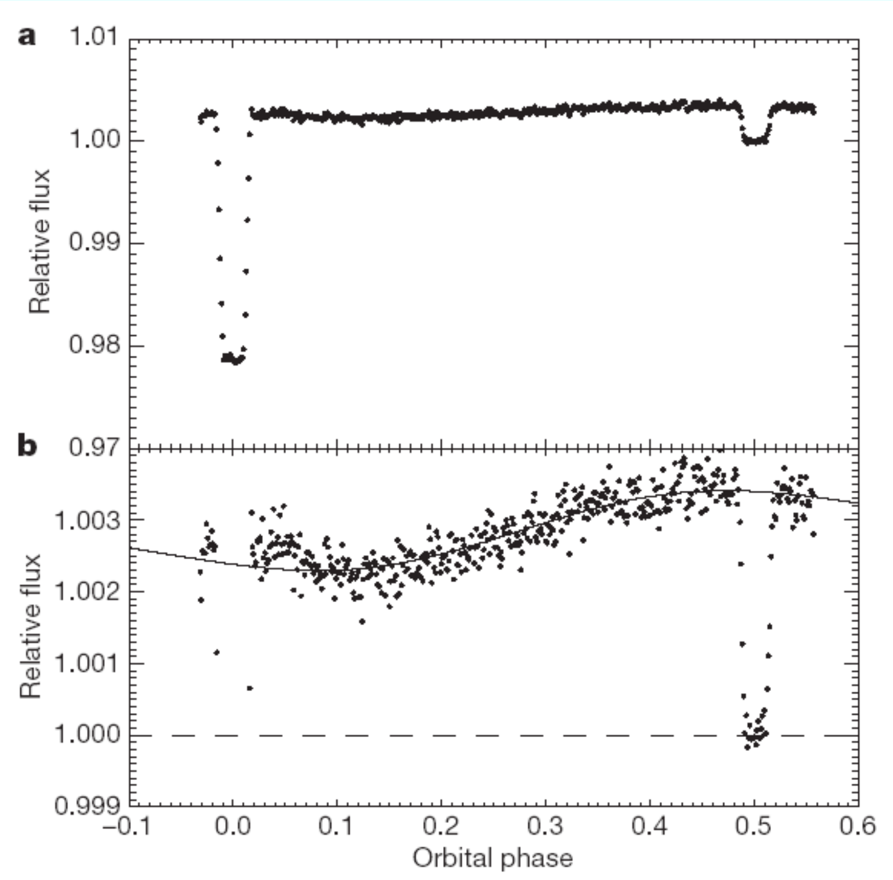


This opens the possibility of synergy between subfields

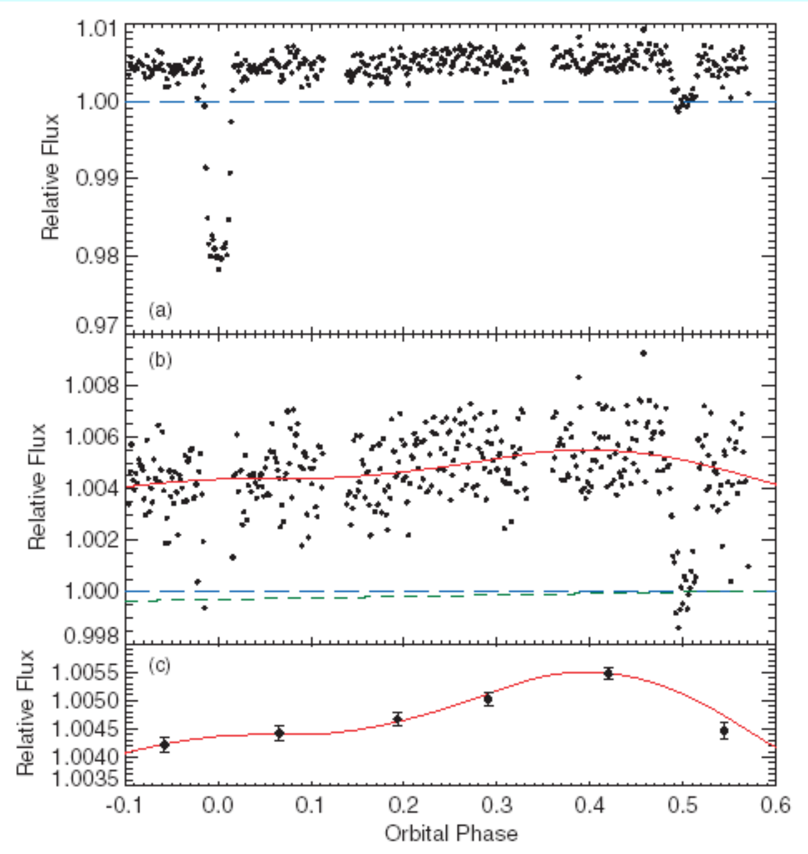
Observational constraints at the corners of a wide parameter space



Hot Jupiters: Spitzer light curves for HD 189733b

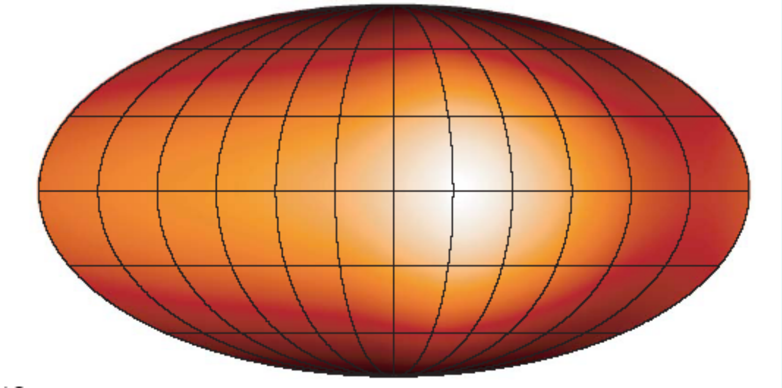


8 μm

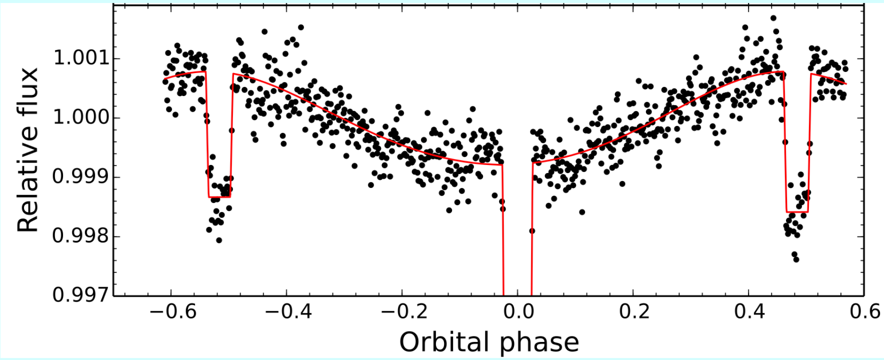


24 μm

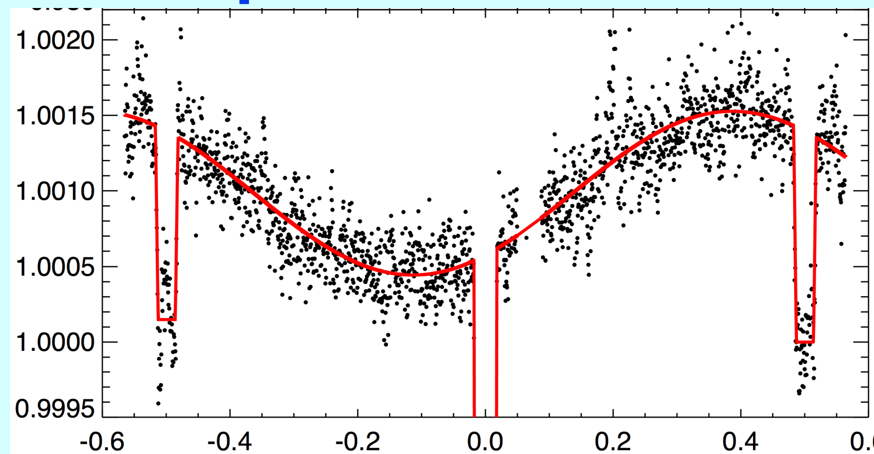
Knutson et al. (2007, 2009)



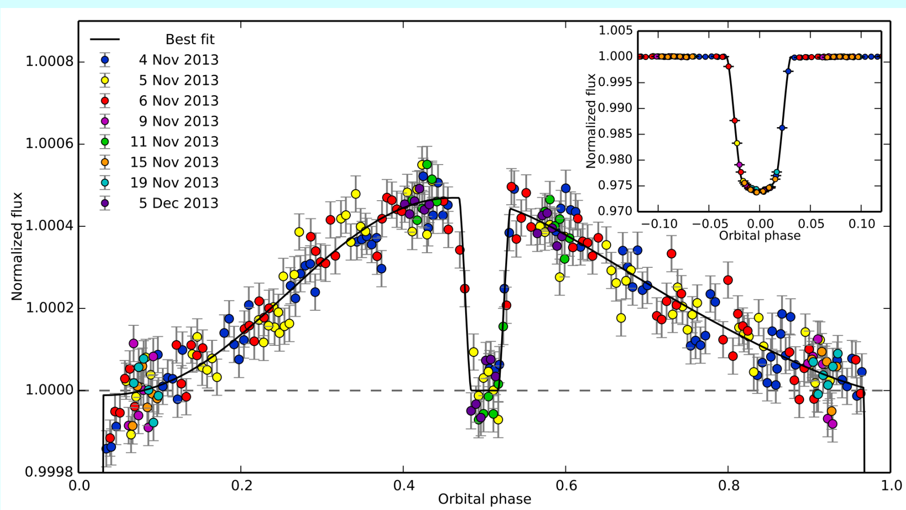
Lightcurves for hot Jupiters



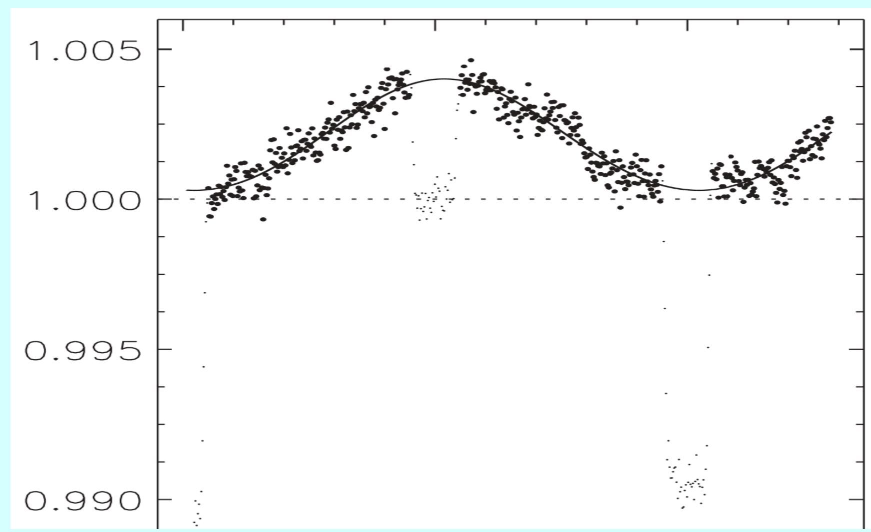
WASP-14b (Wong et al. arXiv 1505.03158)



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

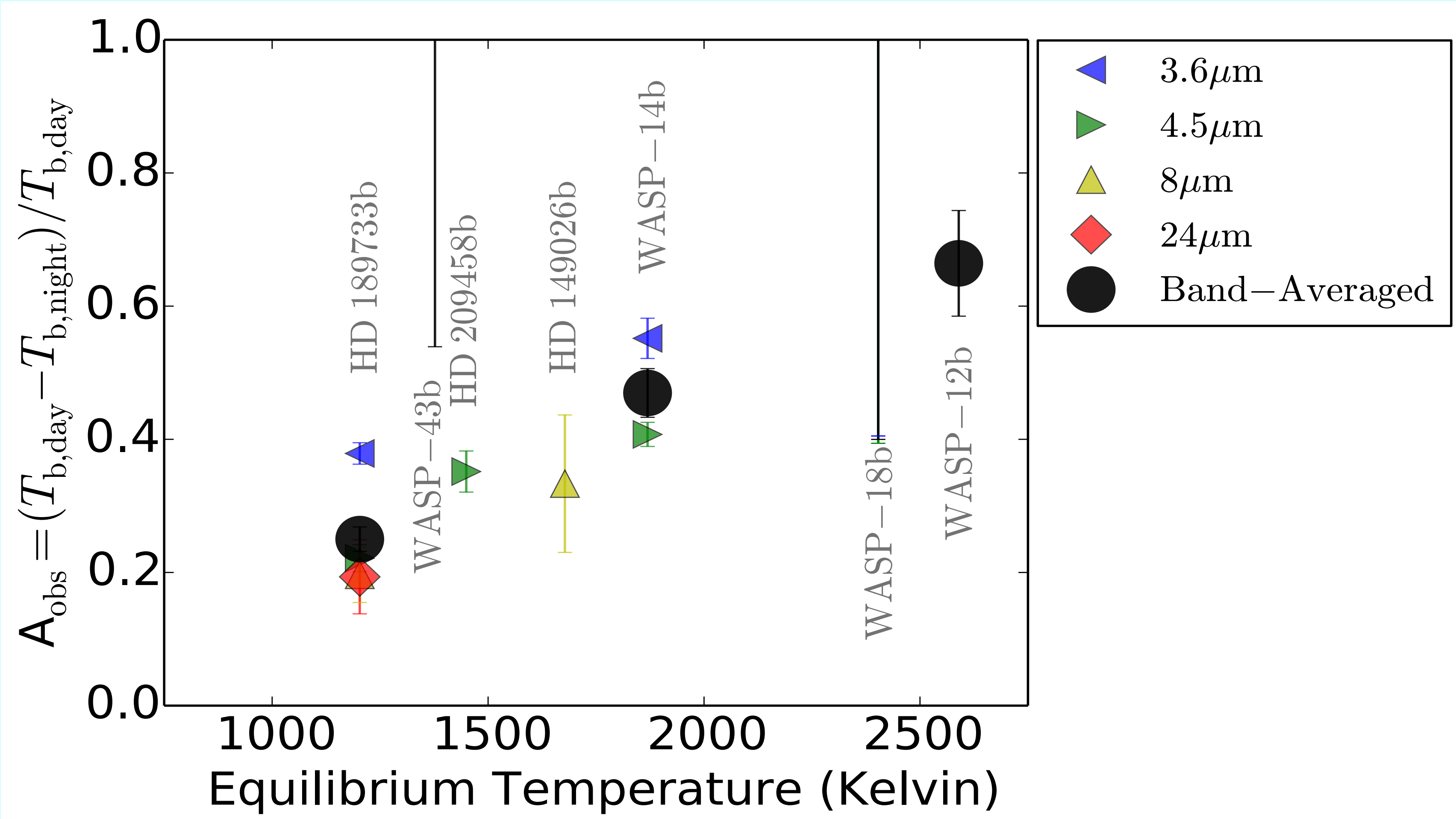


Figure courtesy of Tad Komacek

Motivating questions

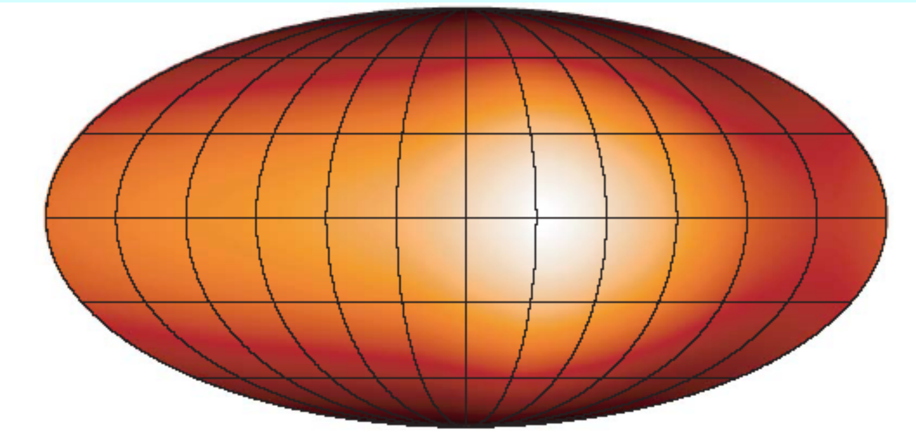
- **What are the fundamental dynamics of the highly irradiated "hot Jupiter" circulation regime? Can we explain lightcurves of specific hot Jupiters? What is the mechanism for displacing the hottest regions to the east?**

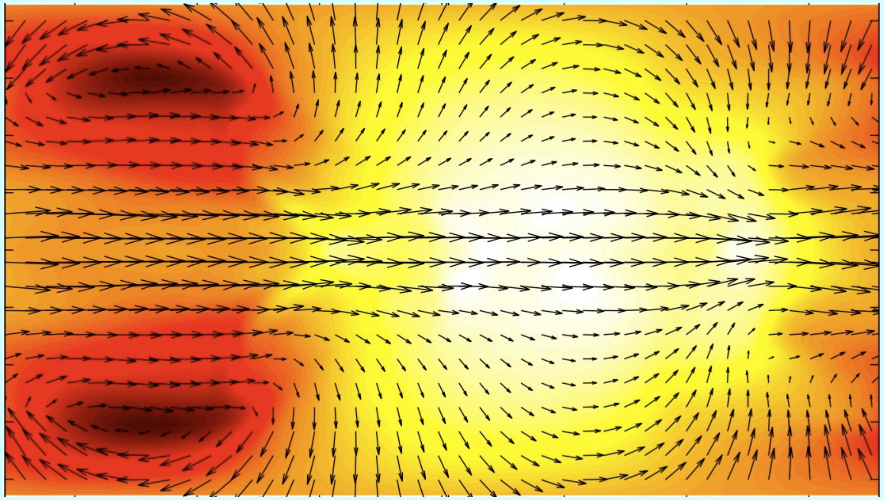
- **What are mechanisms for controlling the day-night temperature contrast on hot Jupiters? Can we explain the increasing trend of day-night flux contrast with incident stellar flux?**

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

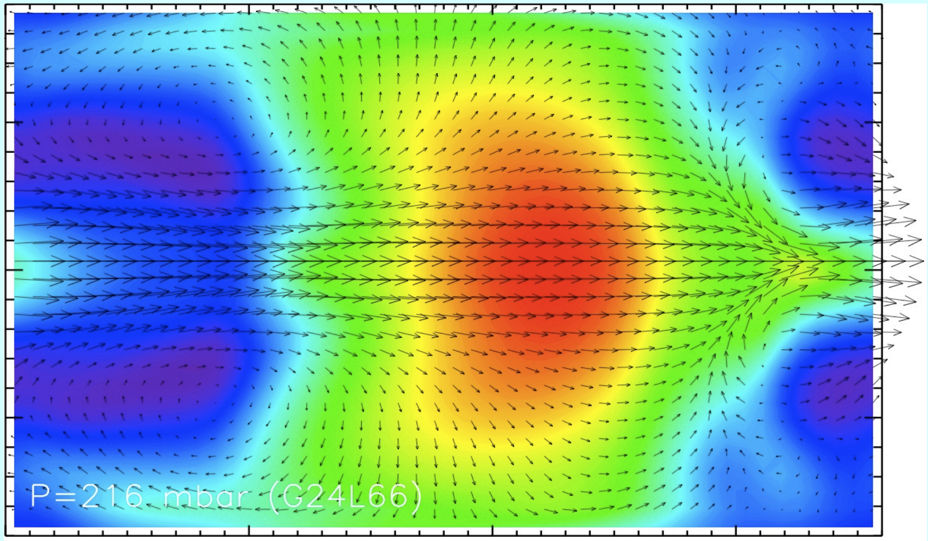
- **How do circulation regime---and observables---of hot Jupiters vary with parameters like incident stellar flux and rotation rate?**

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

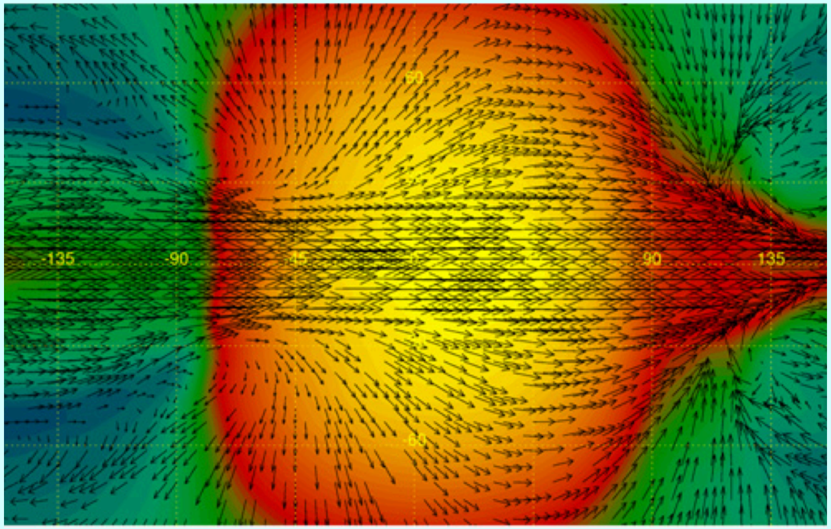




Showman et al. (2009)

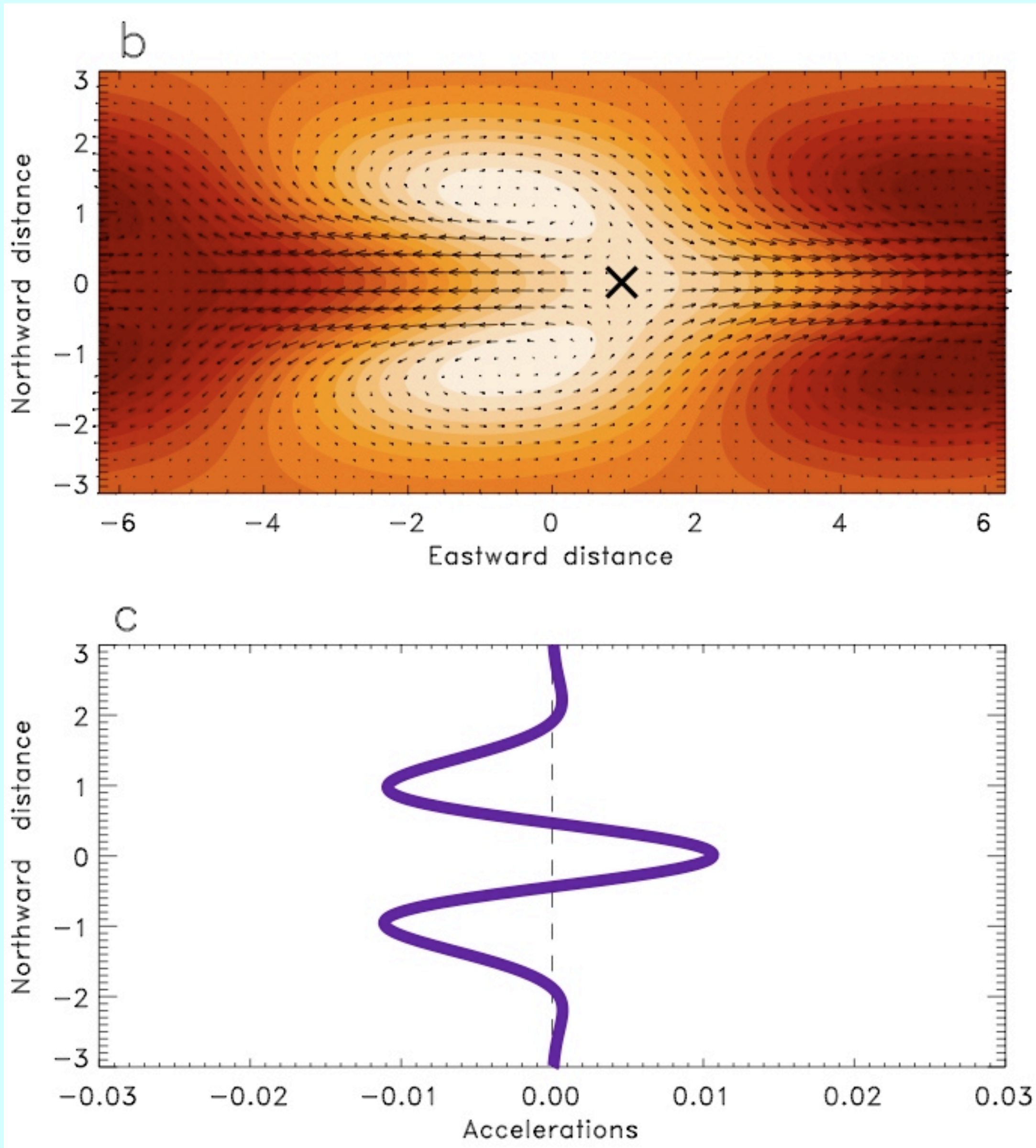


Heng et al. (2010)



Rauscher & Menou (2012)

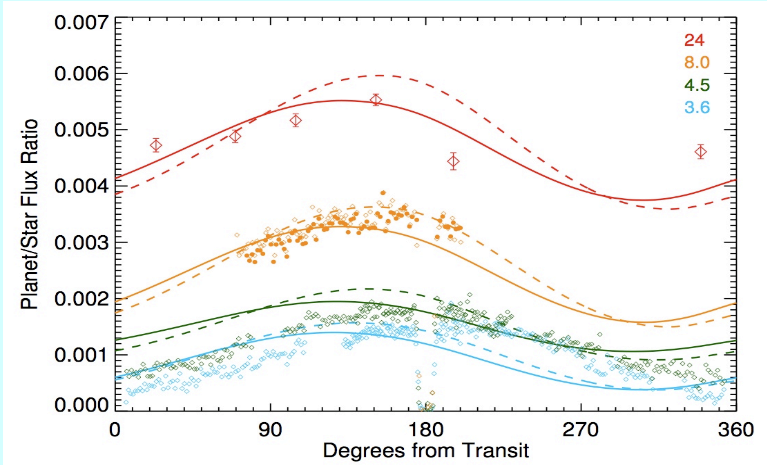
What causes the equatorial jet? The day-night thermal forcing induces planetary-scale waves, which pump momentum to the equator

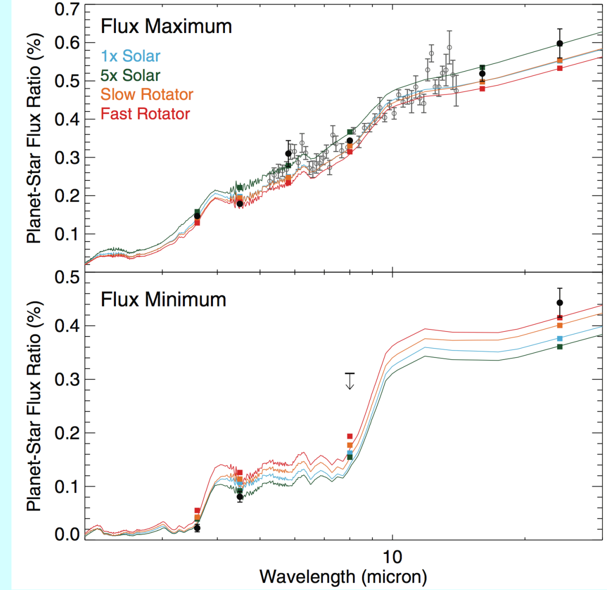


Showman & Polvani (2011), *ApJ* 738, 71

Comparisons of data to GCMs

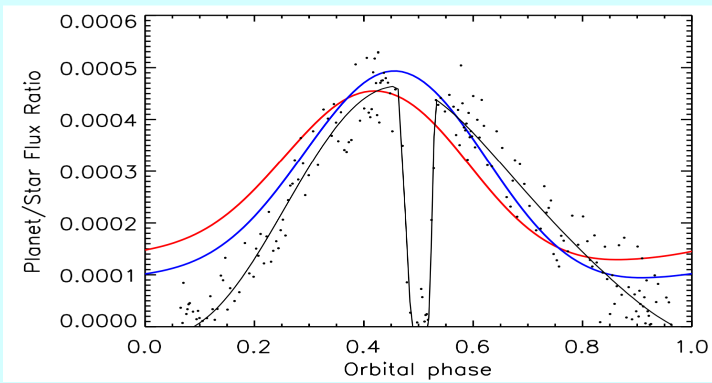
HD 189733b

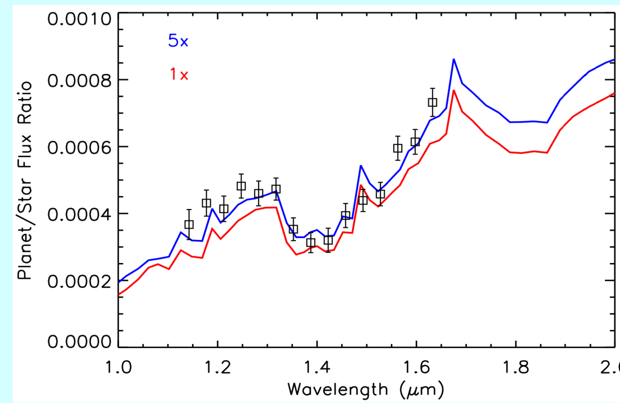




Showman et al. (2009),
Knutson et al. (2012)

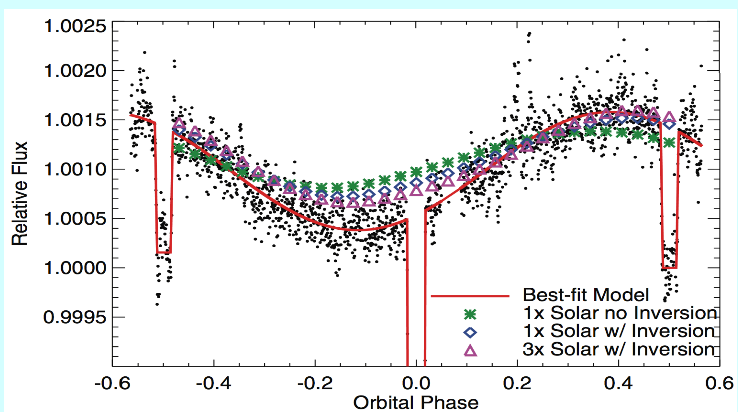
WASP-43b

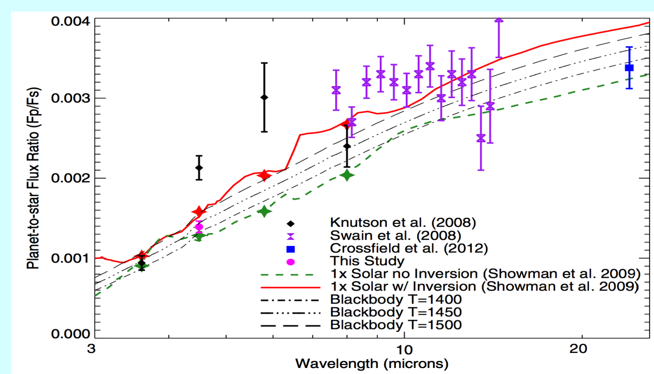




Kataria et al. (2015)

HD 209458b





Toward predictive theories of the circulation

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

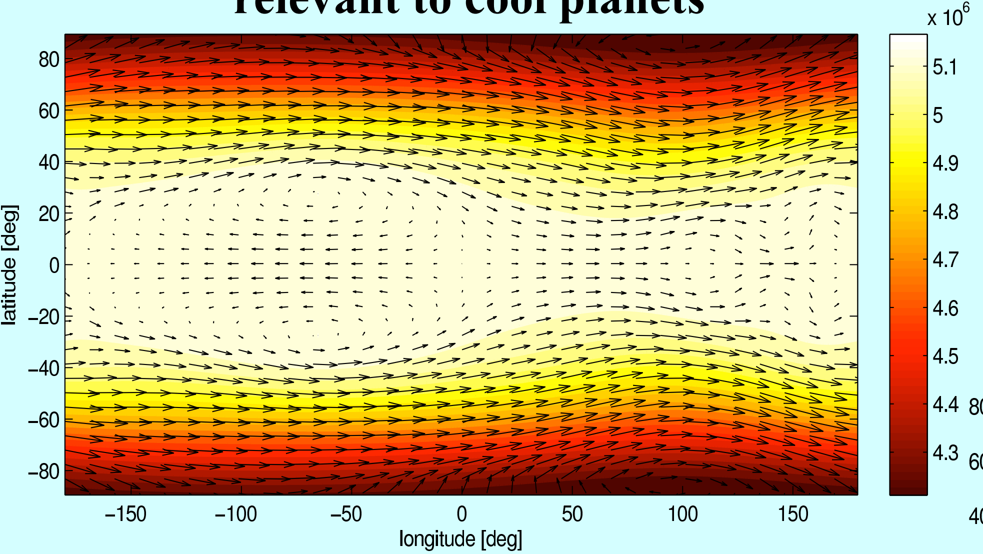
- **The ultimate goal is to *understand* the mechanisms and obtain a *predictive* theory for the day-night temperature differences, vertical mixing rates, and other aspects of the circulation.**

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

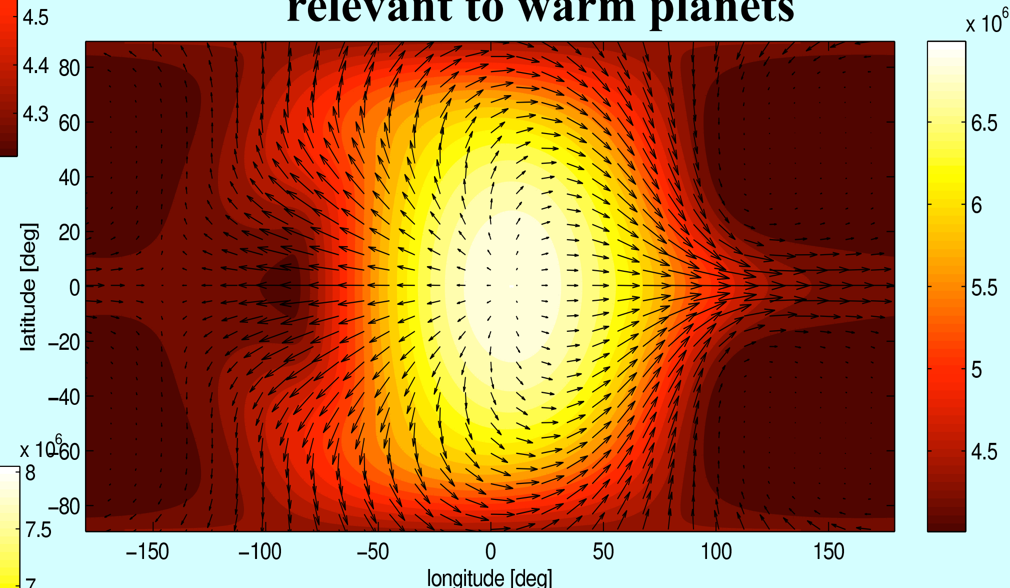
- **Problems: This is not predictive, since τ_{advect} depends on the flow. It also neglects a role for other important timescales in the problem, including wave, frictional, and rotational timescales. These almost certainly matter.**

From Warm to Very Hot Jupiters

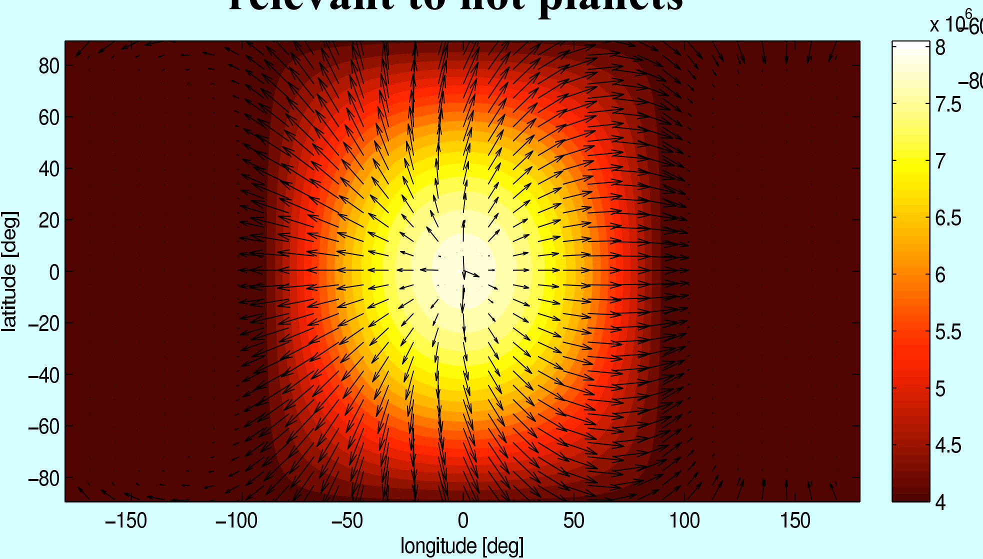
Weak damping (τ_{rad} = 10 days), relevant to cool planets



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

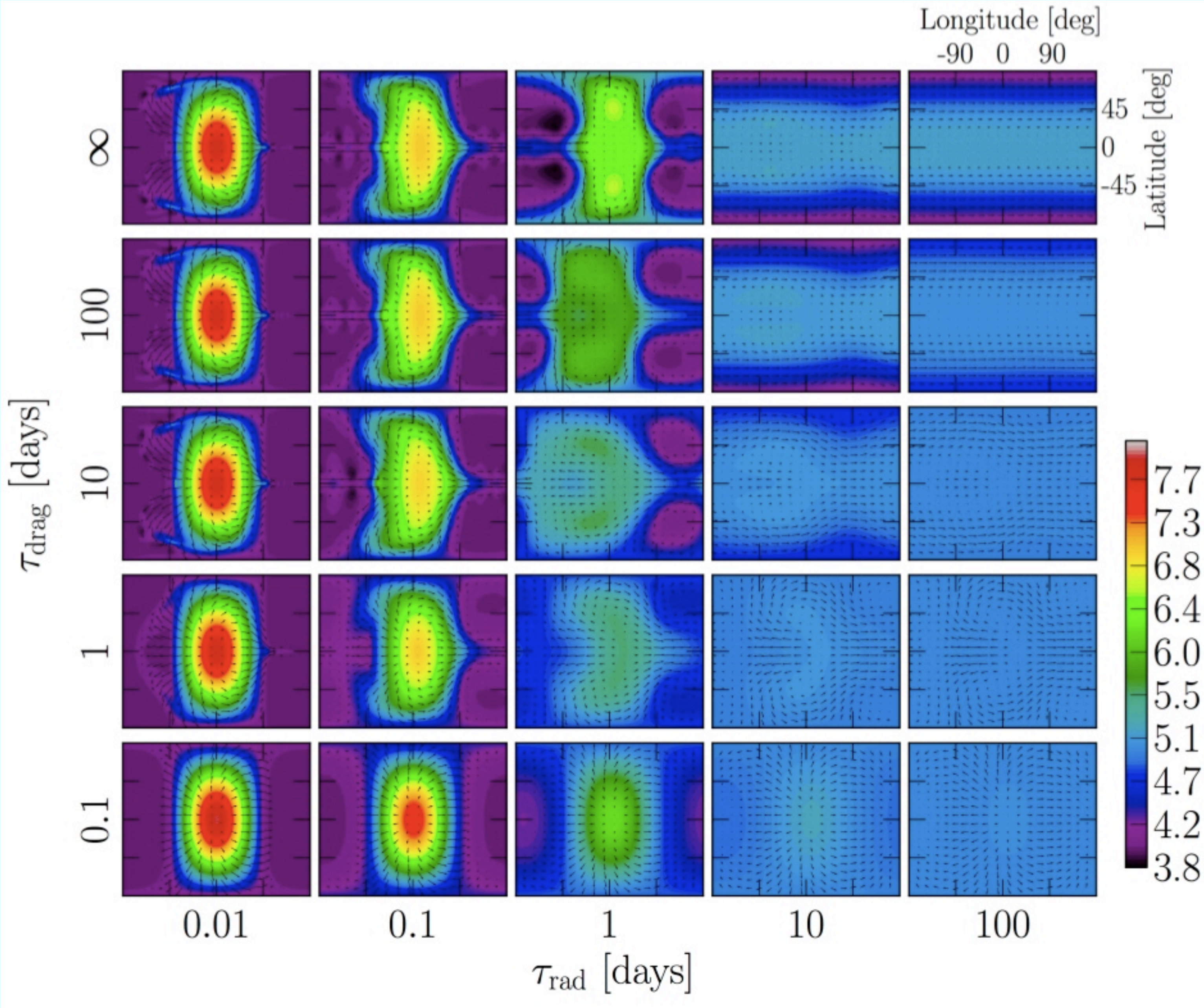


Strong damping (τ_{rad} = 0.1 days), relevant to hot planets



Showman et al. (2013)

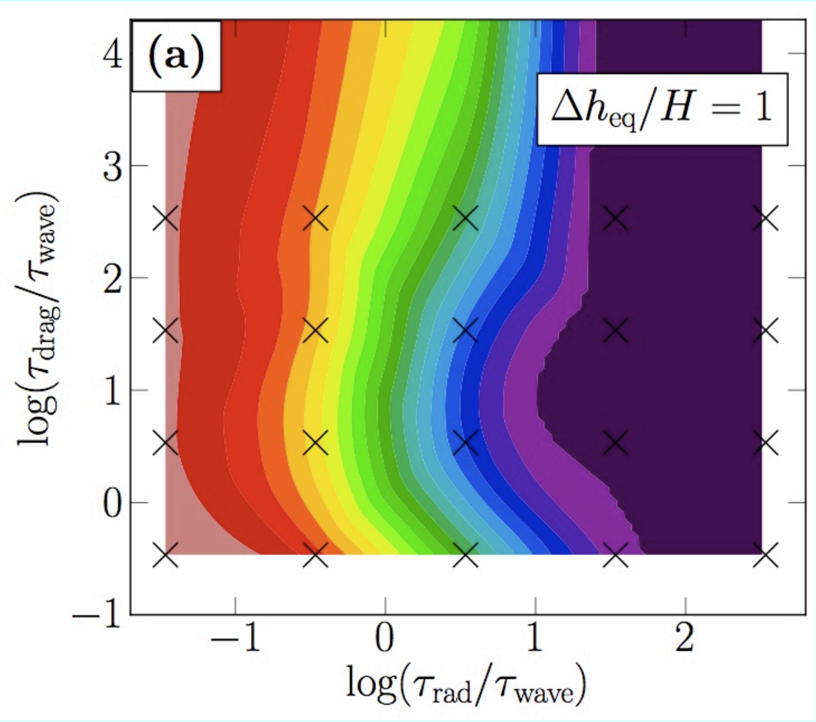
Hot-Jupiter circulation in idealized models as a function of radiative time constant and strength of frictional drag



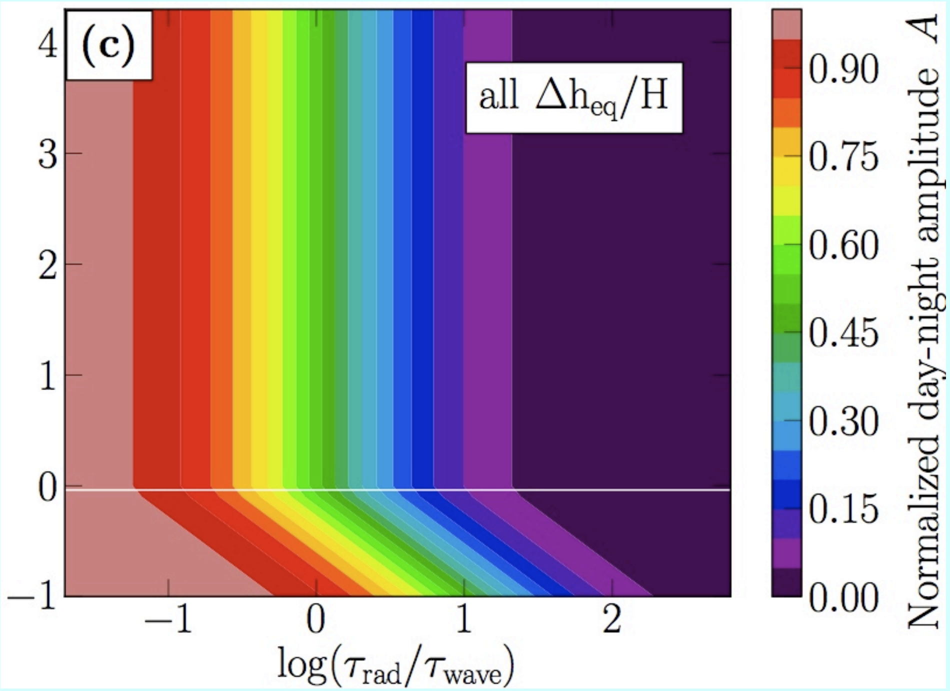
Perez-Becker & Showman (2013)

Theory for day-night temperature contrast

Day-night thermal contrast from atmospheric simulations



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



Perez-Becker & Showman (2013)

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

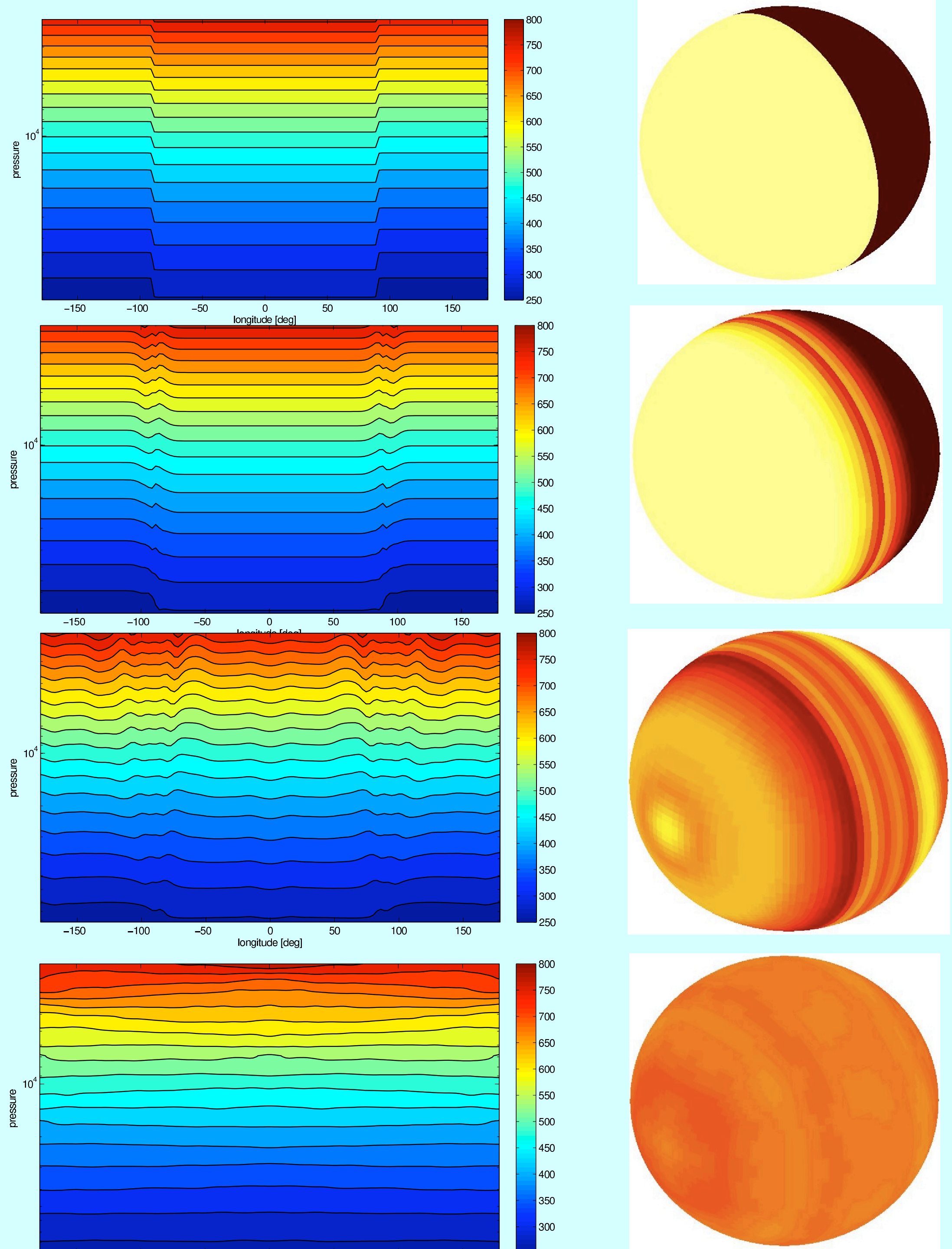
The theory shows that the transition between regimes is generally controlled by wave and vertical advection rather than horizontal advection timescales.

See Tad Komacek talk Friday afternoon

Wave adjustment process

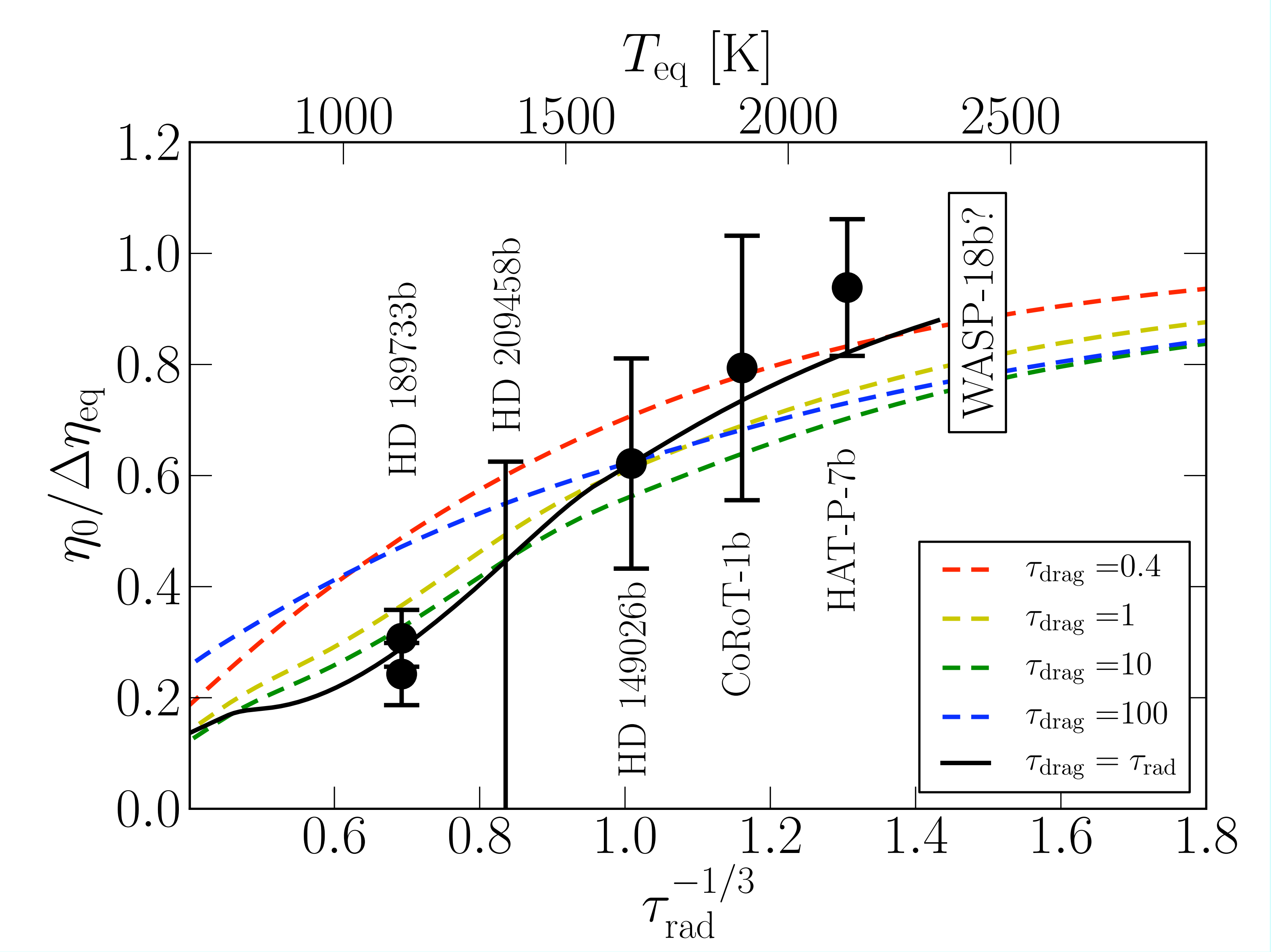
Waves adjust isentropes up or down in an attempt to flatten them. This erases horizontal temperature differences.

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



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**

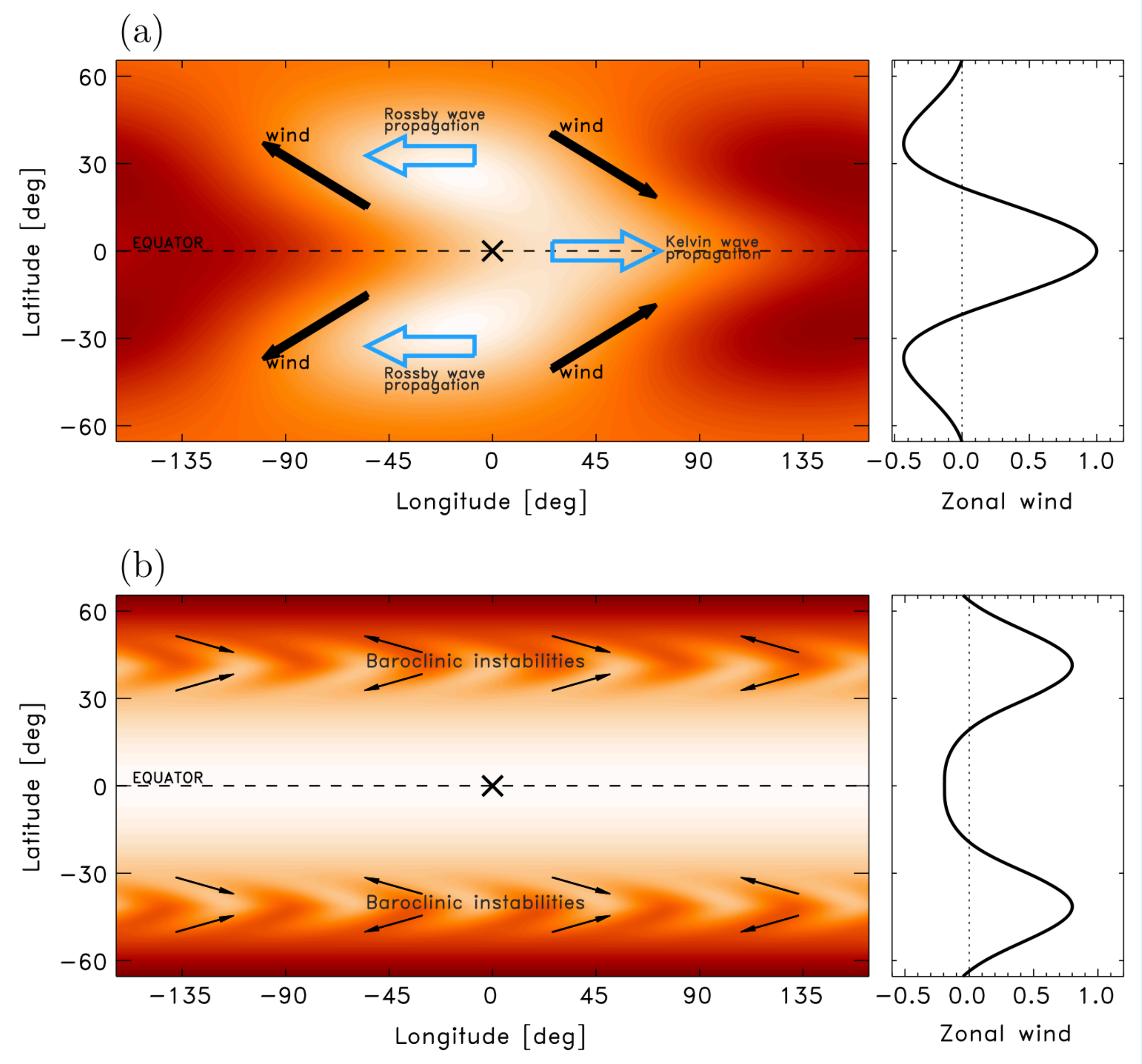
- **Such "warm" Jupiters will rotate non-synchronously:**

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

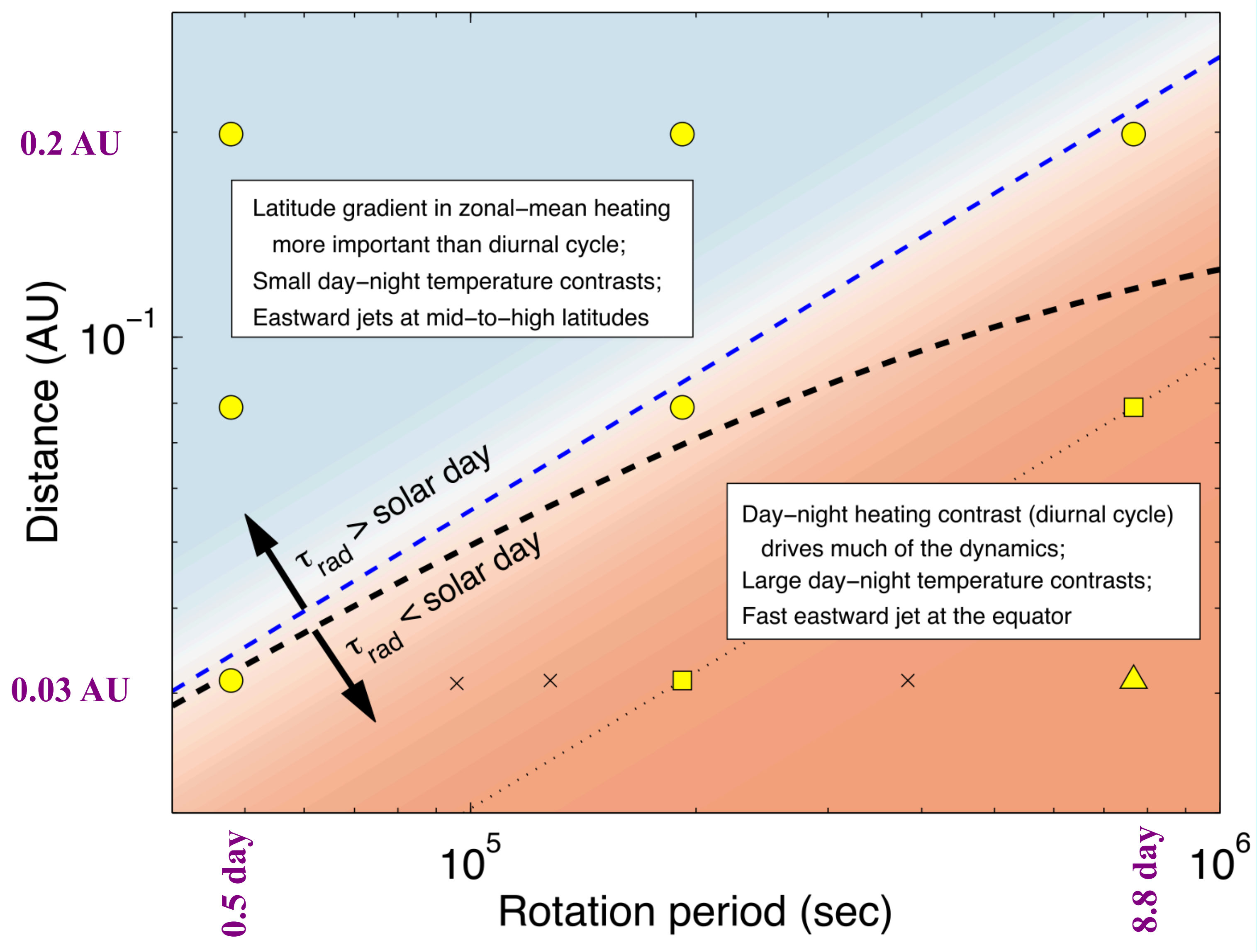
- **Fundamental questions also exist about how the circulation on hot Jupiters relates to that on Jupiter, Earth, and brown dwarfs**

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?



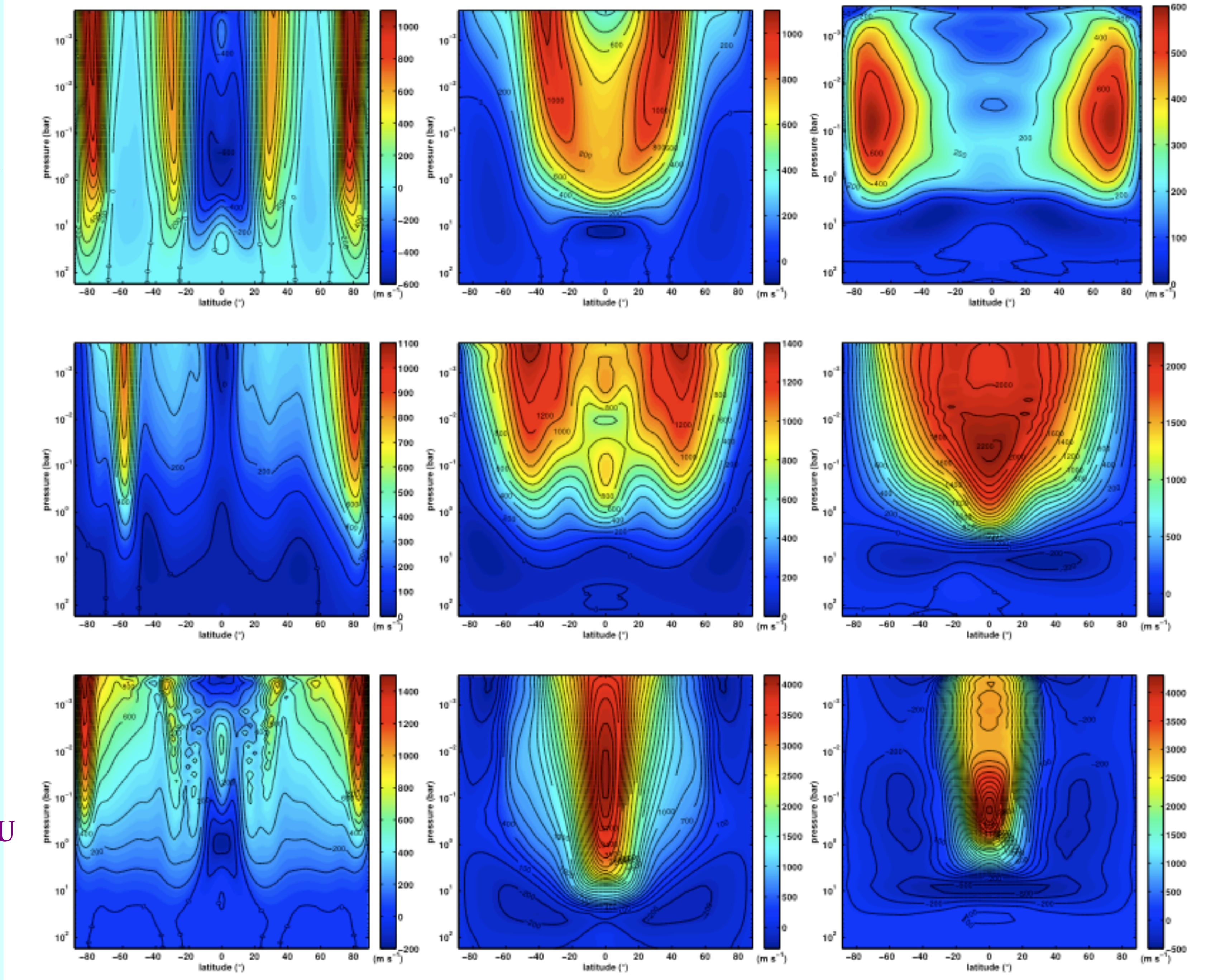
Predicted regimes



0.2 AU

Orbital distance

0.03 AU



0.5 day

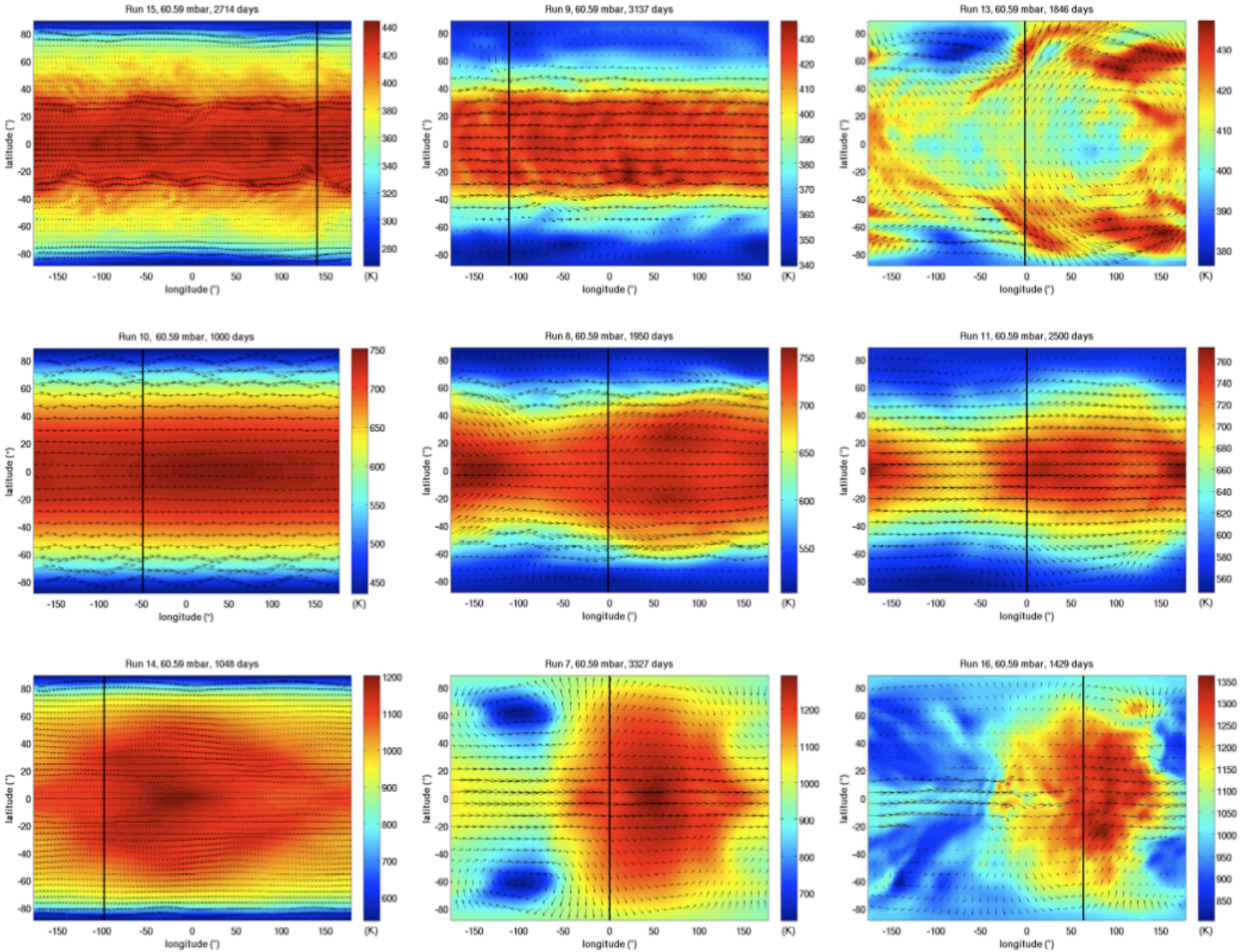
Rotation period

8.8 day

0.2 AU

Orbital distance

0.03 AU



0.5 day

Rotation period

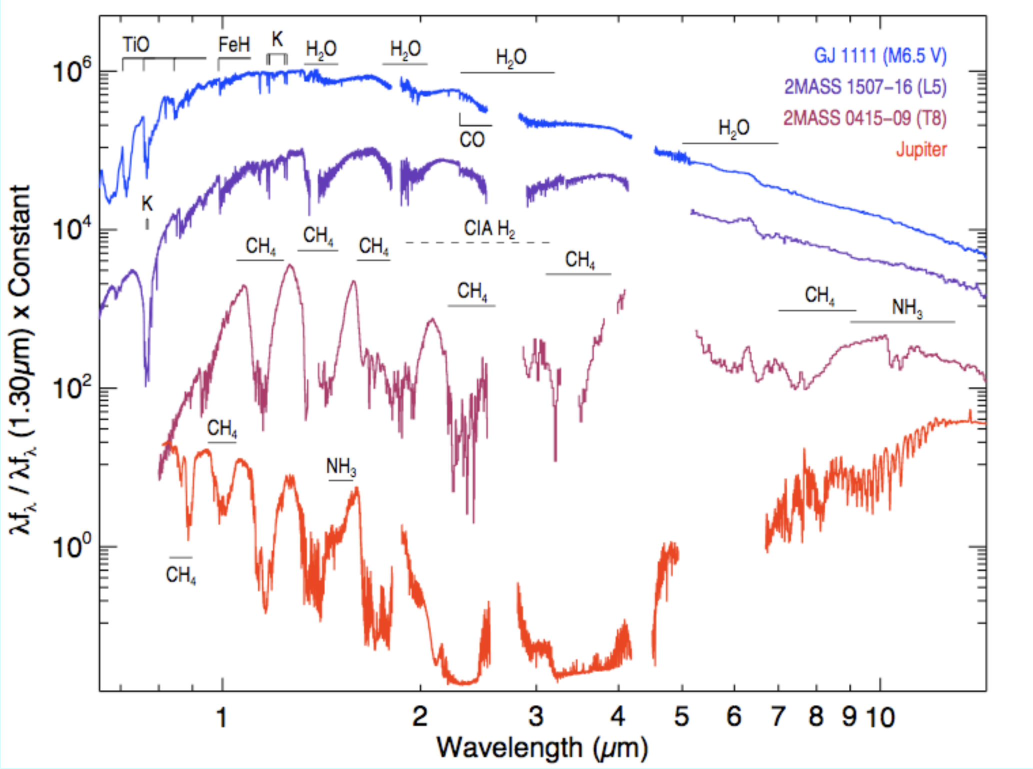
8.8 day

Brown dwarf basics

- **Brown dwarfs are fluid hydrogen objects intermediate in mass between giant planets and stars (~13 to ~80 Jupiter masses)**

- **Since they cannot fuse hydrogen, they cool off over time (like Jupiter). But massive brown dwarfs cool slowly and can still have surface temperatures >1000 K even after many billions of years**

- **~1000 brown dwarfs have been discovered, mostly with high temperature (>700 K) but now including objects as cool as 300-400 K.**



Burgasser et al. (2009)

Weather on brown dwarfs and directly imaged giant planets

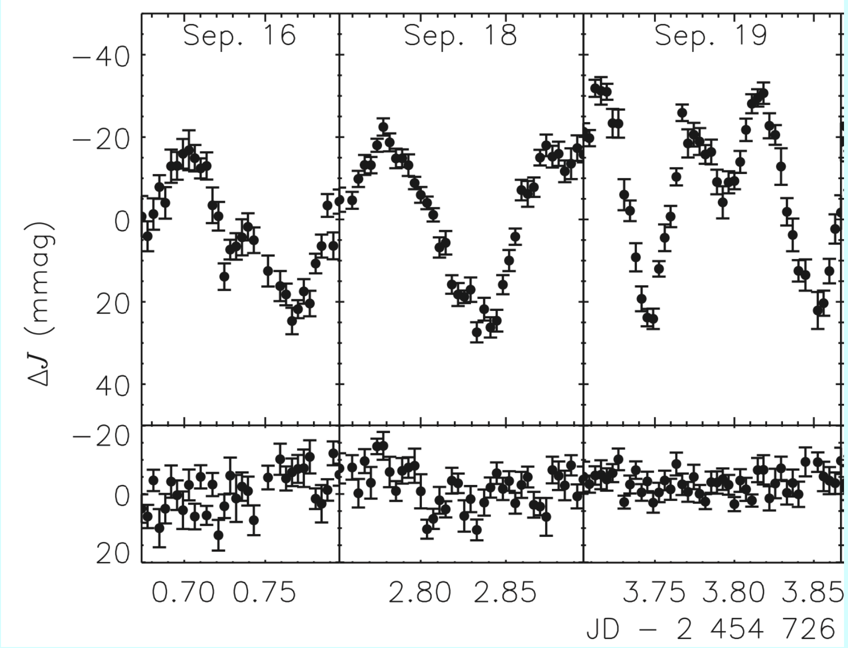
Evidence:

- **Clouds**

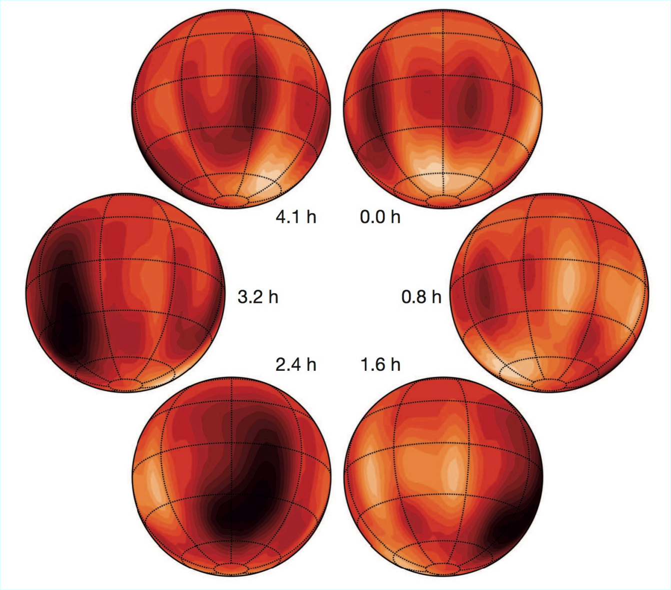
- **Disequilibrium chemistry (quenching of CO, CH_4, NH_3)**

- **Lightcurve variability (cloudy and cloud-free patches rotating in and out of view)**

- **Doppler-imaging maps showing surface patchiness**



Artigau et al. (2009)



Crossfield et al. (2014)

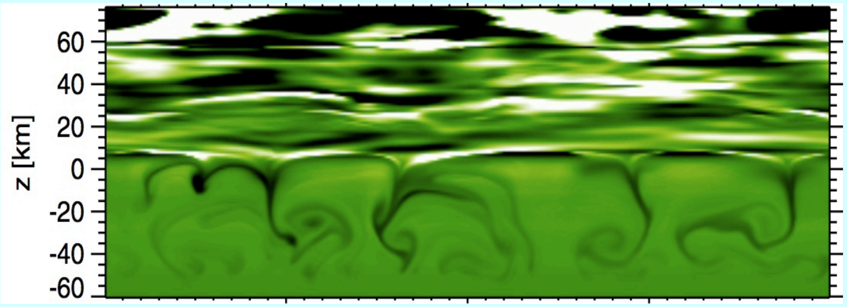
Dynamical Regime and Questions

- Rapid rotation (period ~ 2-12 hours) implies rotational domination
  (Rossby numbers << 1)

- Vigorously convecting interior underlies stably stratified atmosphere

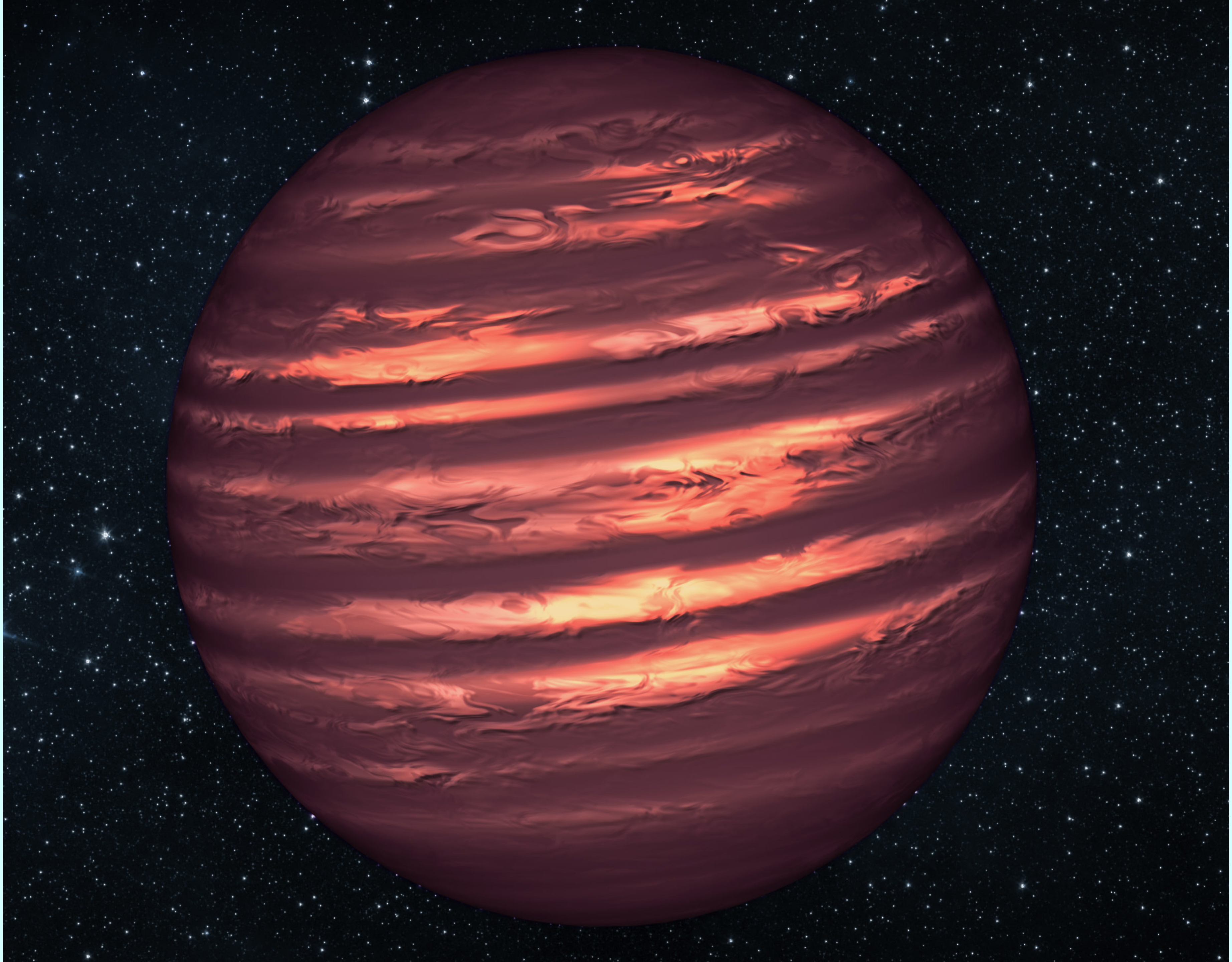
- No external irradiation ⟹ no imposed horizontal gradients in heating or temperature (unlike solar system planets or hot Jupiters)

- Convection will generate atmospheric waves



Freytag et al. (2010)

What is the atmospheric circulation like on brown dwarfs? Are there zonal jets? Large vortices and turbulence? What controls which dominates? And what are the implications for observables?



Goal: determine the 3D atmospheric circulation that results from isotropic convective forcing near the radiative-convective boundary.

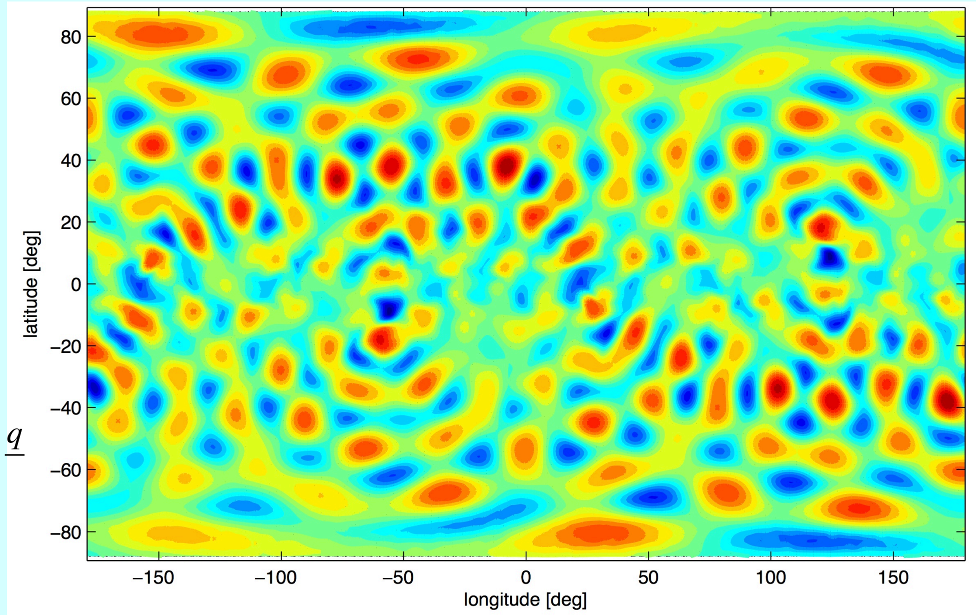
- **Solve global 3D primitive equations in a stratified atmosphere with MITgcm. Domain from 0.01-10 bars.**

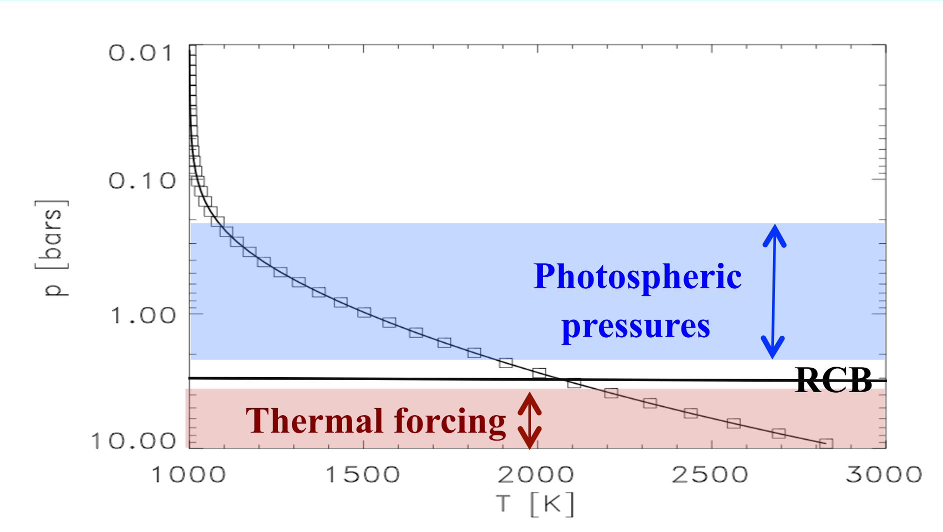
- **Parameterize convection by adding isotropic thermal perurbations to bottom of model.**

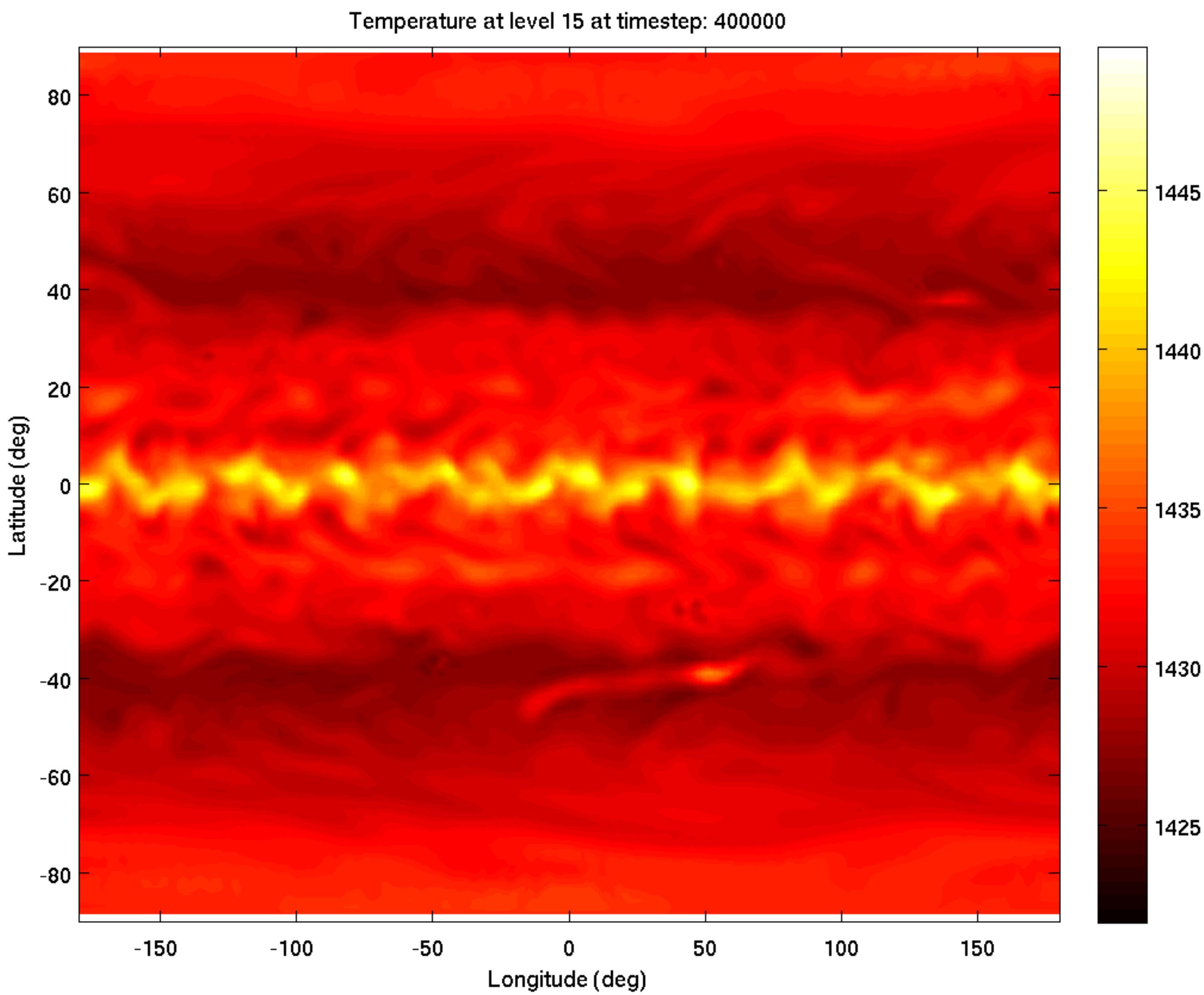
- **Radiation parameterized by Newtonian cooling:**

$$\frac{q}{c_p} = \frac{T_{eq}(p) - T(\lambda,\phi,p,t)}{\tau_{rad}}$$

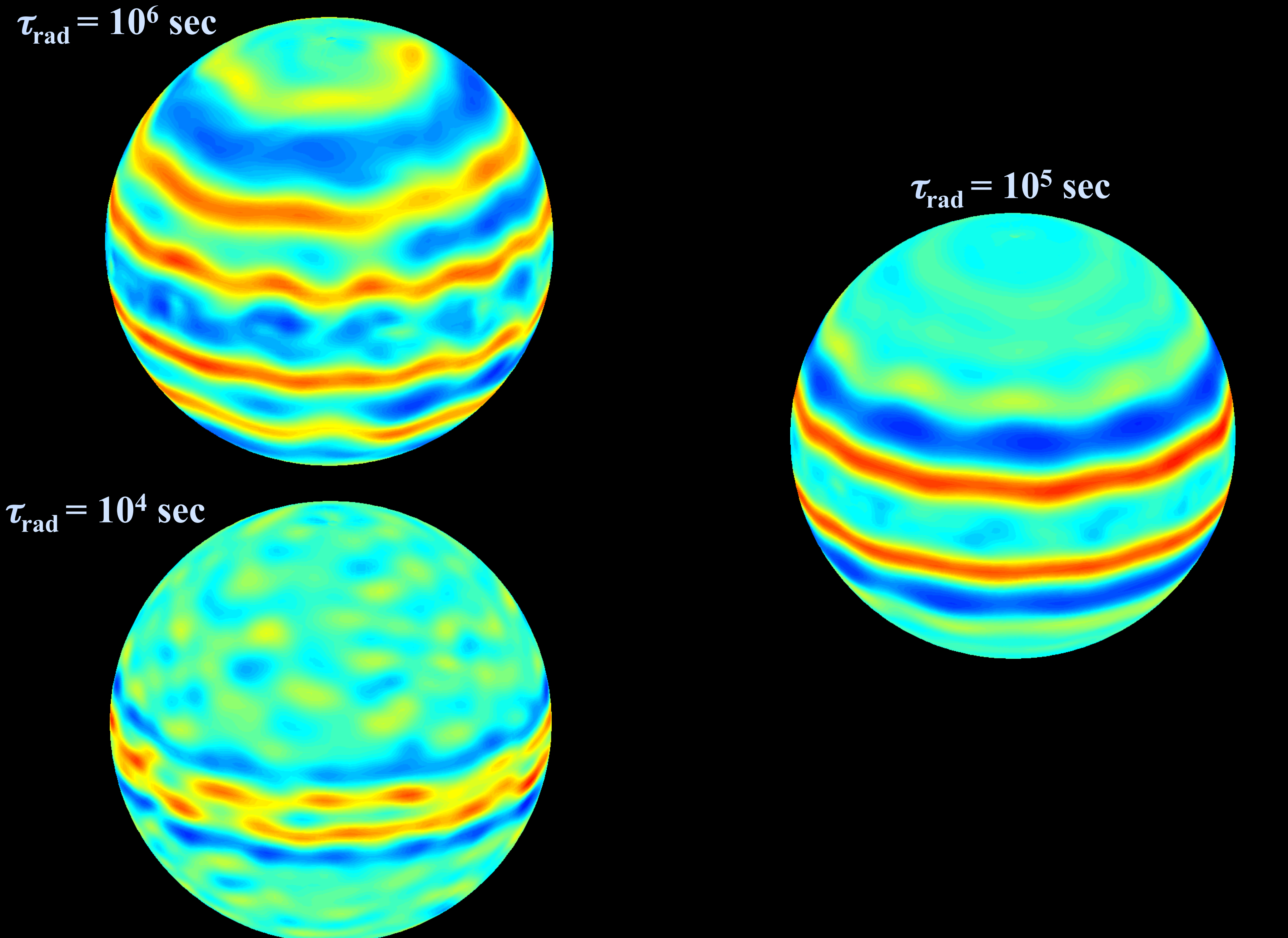
- **Systematically vary τ_{rad} to span the range of brown dwarfs from hot (short τ_{rad}) to cooler (long τ_{rad})**

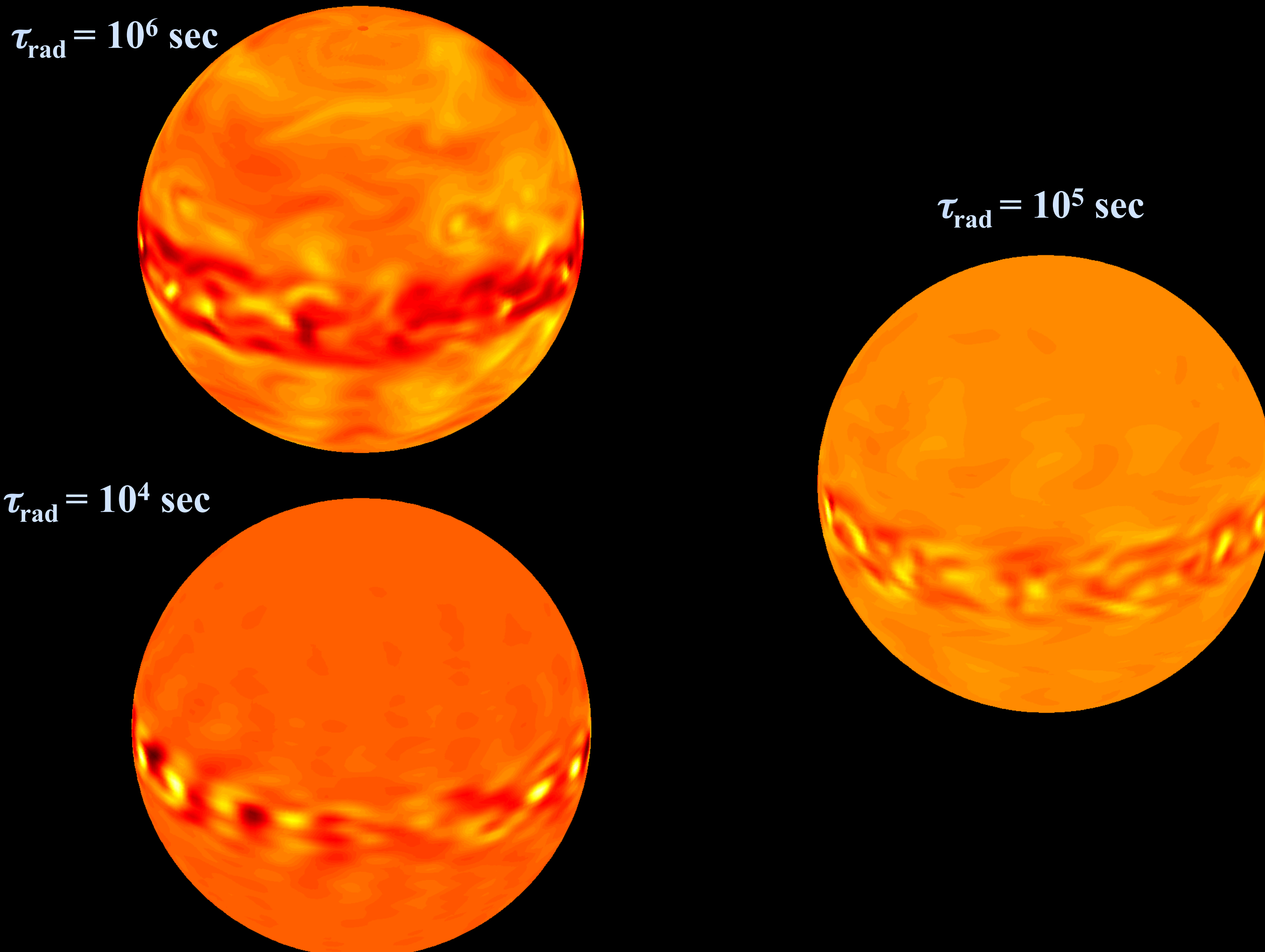






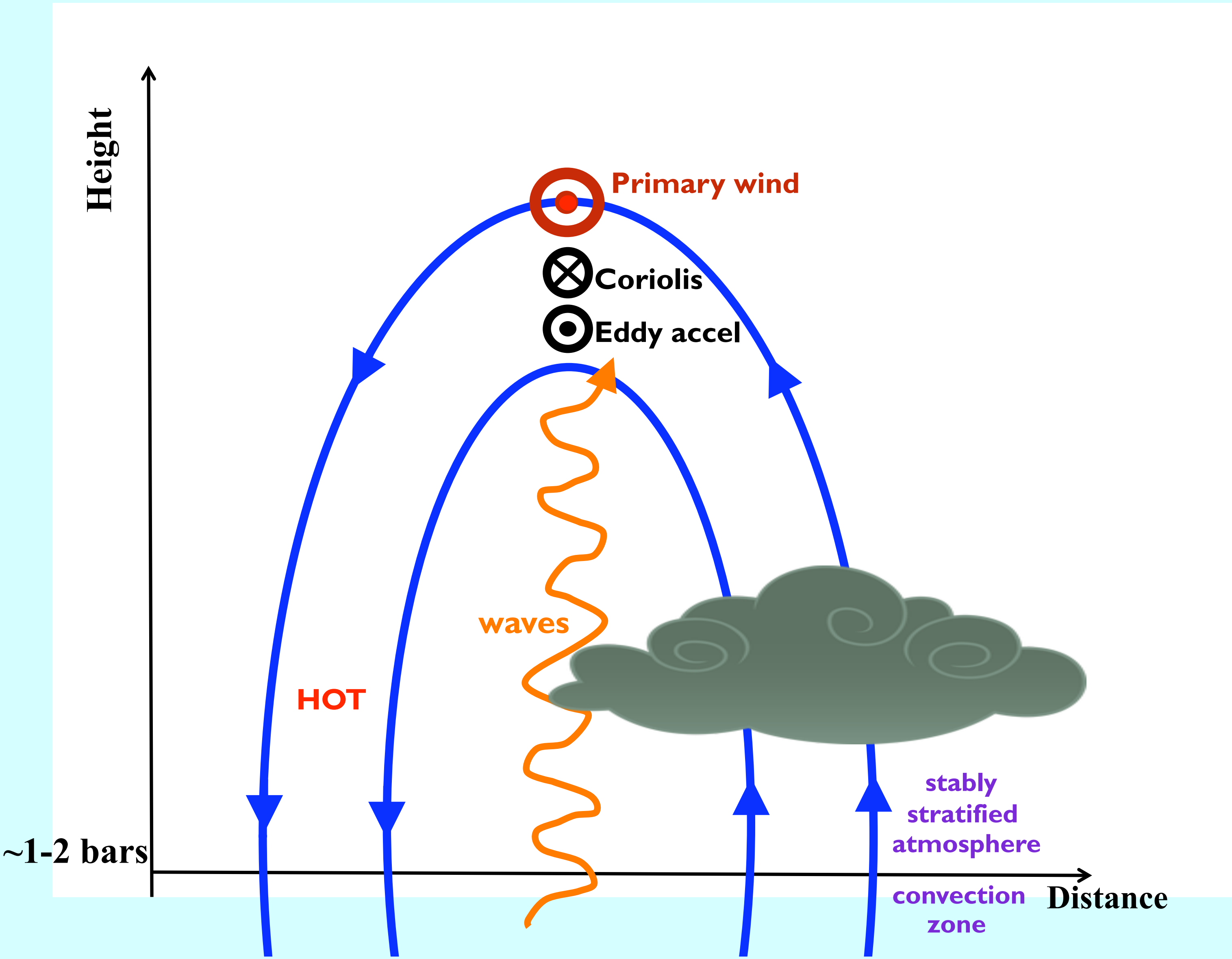
Temperature at level 15 at timestep: 400000
80
60
40
20
0
-20
-40
-60
-80
Latitude (deg)
-150
-100
-50
0
50
100
150
Longitude (deg)
1445
1440
1435
1430
1425


$\tau_{rad} = 10^6$ sec
$\tau_{rad} = 10^5$ sec
$\tau_{rad} = 10^4$ sec



$\tau_{rad} = 10^6$ sec
$\tau_{rad} = 10^5$ sec
$\tau_{rad} = 10^4$ sec

Vertical motion associated with turbulence will lead to patchy clouds



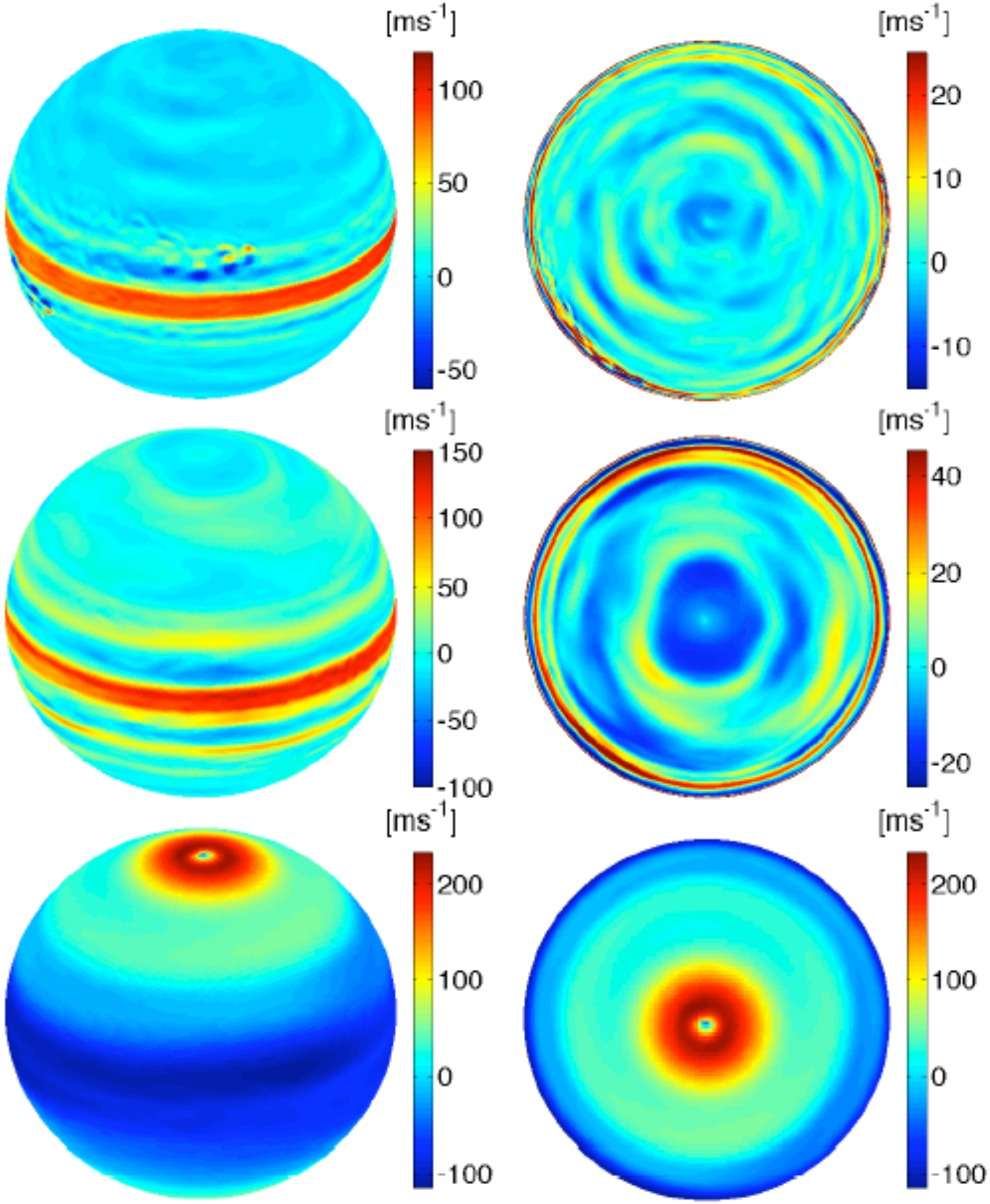
Conclusions

- **Giant planets--broadly defined--span a multi order-of-magnitude range of external irradiation, internal flux, gravity, rotation rate, and composition. Booming observational areas (Solar System giants, hot Jupiters, and brown dwarfs) occupy the corners of this parameter space, providing observational leverage to tie down how circulation broadly depends on these parameters.**

- **Hot Jupiters exhibit large day-night temperature differences and eastward hotspot offsets that can be explained by equatorial superrotation. The superrotation results from the day-night thermal contrast, which triggers planetary-scale waves that transport momentum to the equator. The trend in day-night temperature contrast can be explained by simple dynamical models. Predictive theories of the atmospheric temperature differences are within reach. Clouds are a growth area.**

- **Brown dwarfs show a wealth of observational evidence for weather and dynamics. The rapid rotation will control the atmospheric dynamical regime. The circulation results from a very different mechanism than occurs on highly irradiated planets. Simple theories predict that convective forcing of the atmosphere will lead to turbulence, vortices, and jets that will become modulated by cloud patchiness. Global 3D models are in their infancy.**

Lian & Showman (2010)

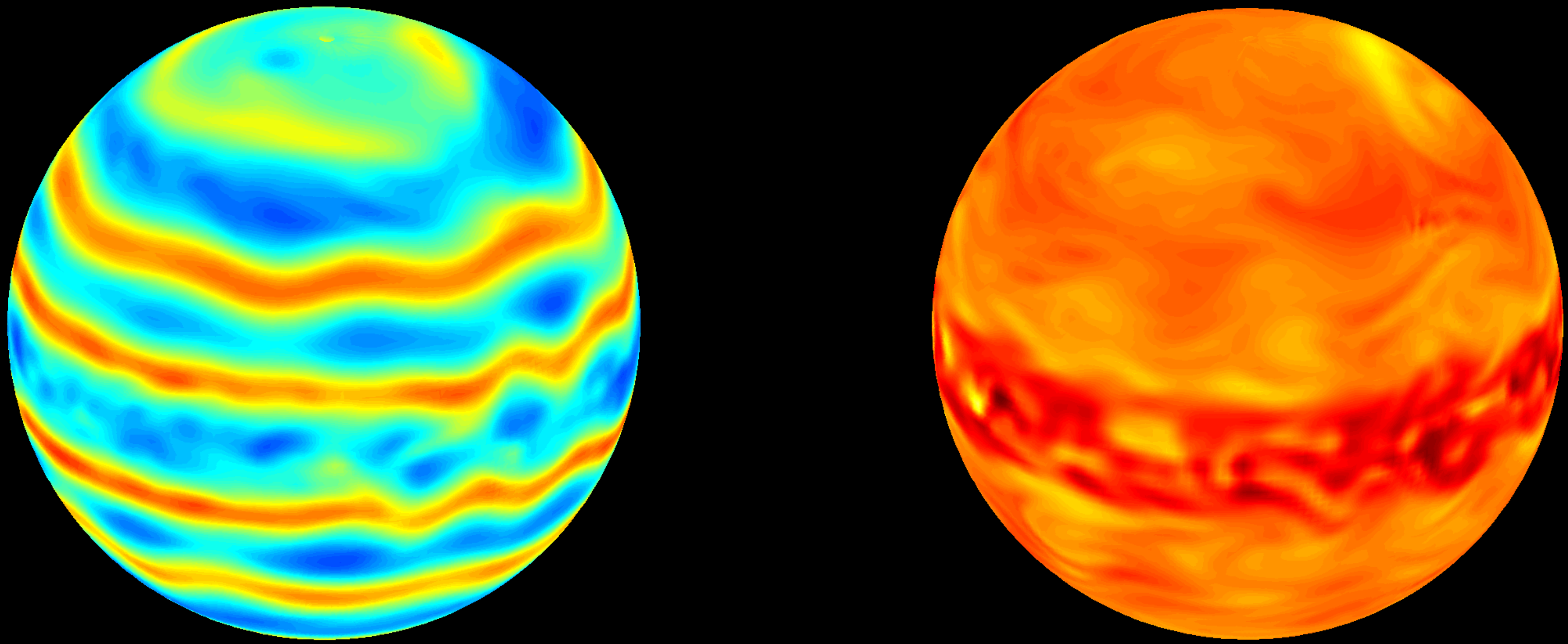


Jupiter

Saturn

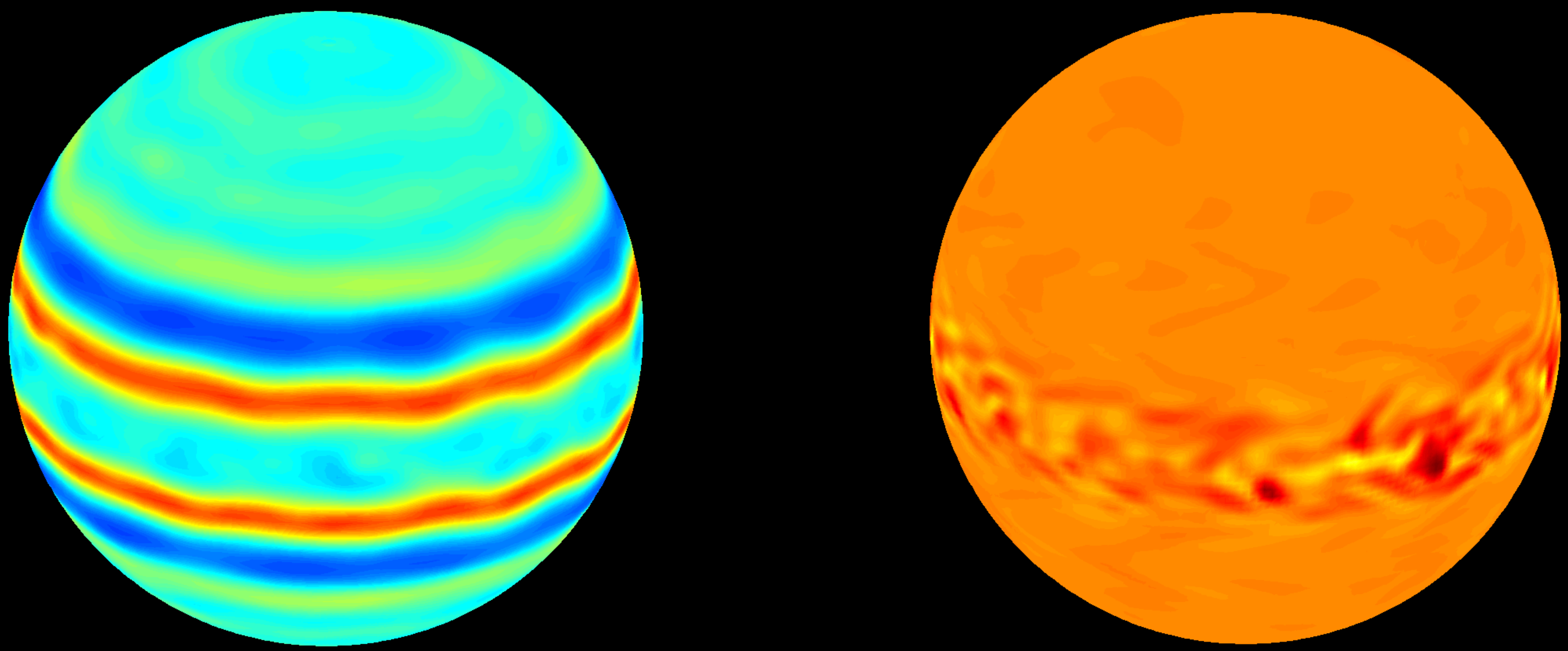
Uranus/Neptune

$\tau_{rad} = 10^6$ sec



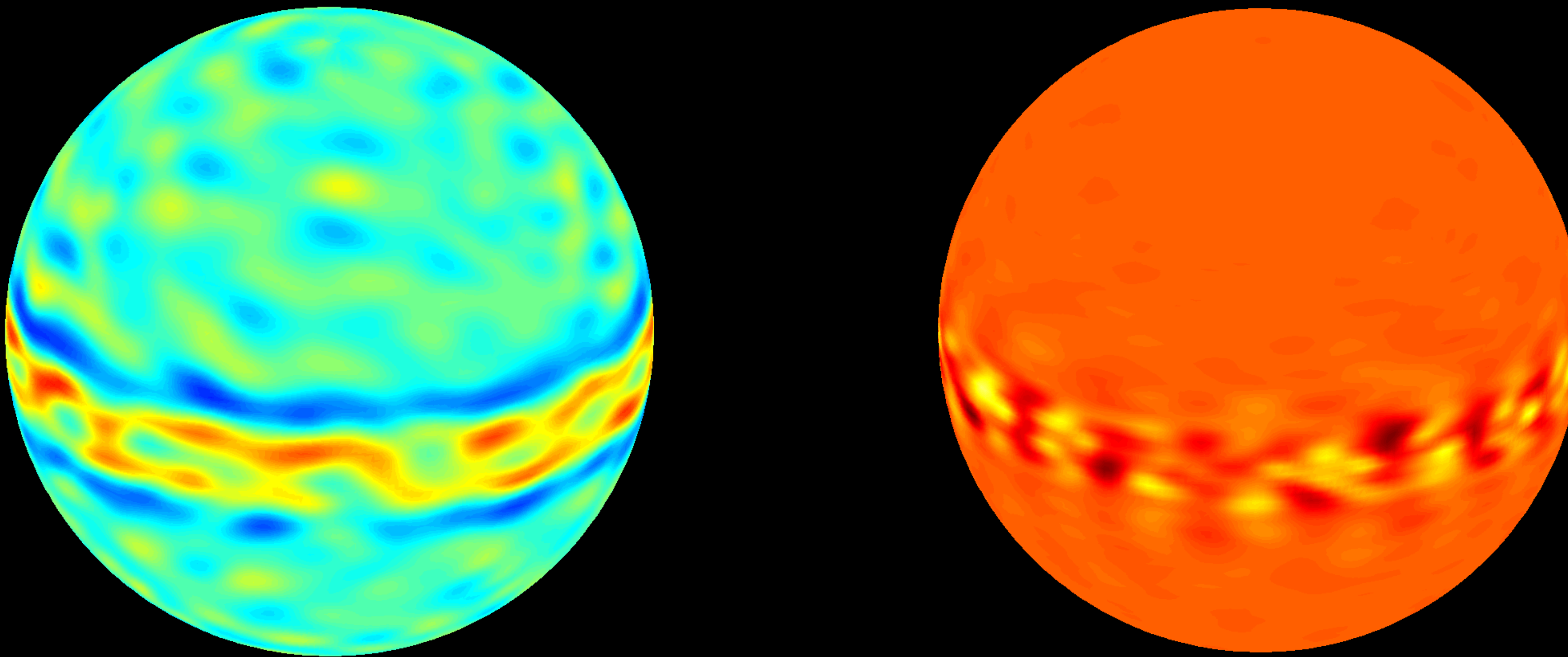
Showman et al. (in prep)

$\tau_{rad} = 10^5$ sec



Showman et al. (in prep)

$\tau_{rad} = 10^4$ sec



Showman et al. (in prep)