Atmospheric Dynamics of Giant Planets Inside and Outside the Solar System

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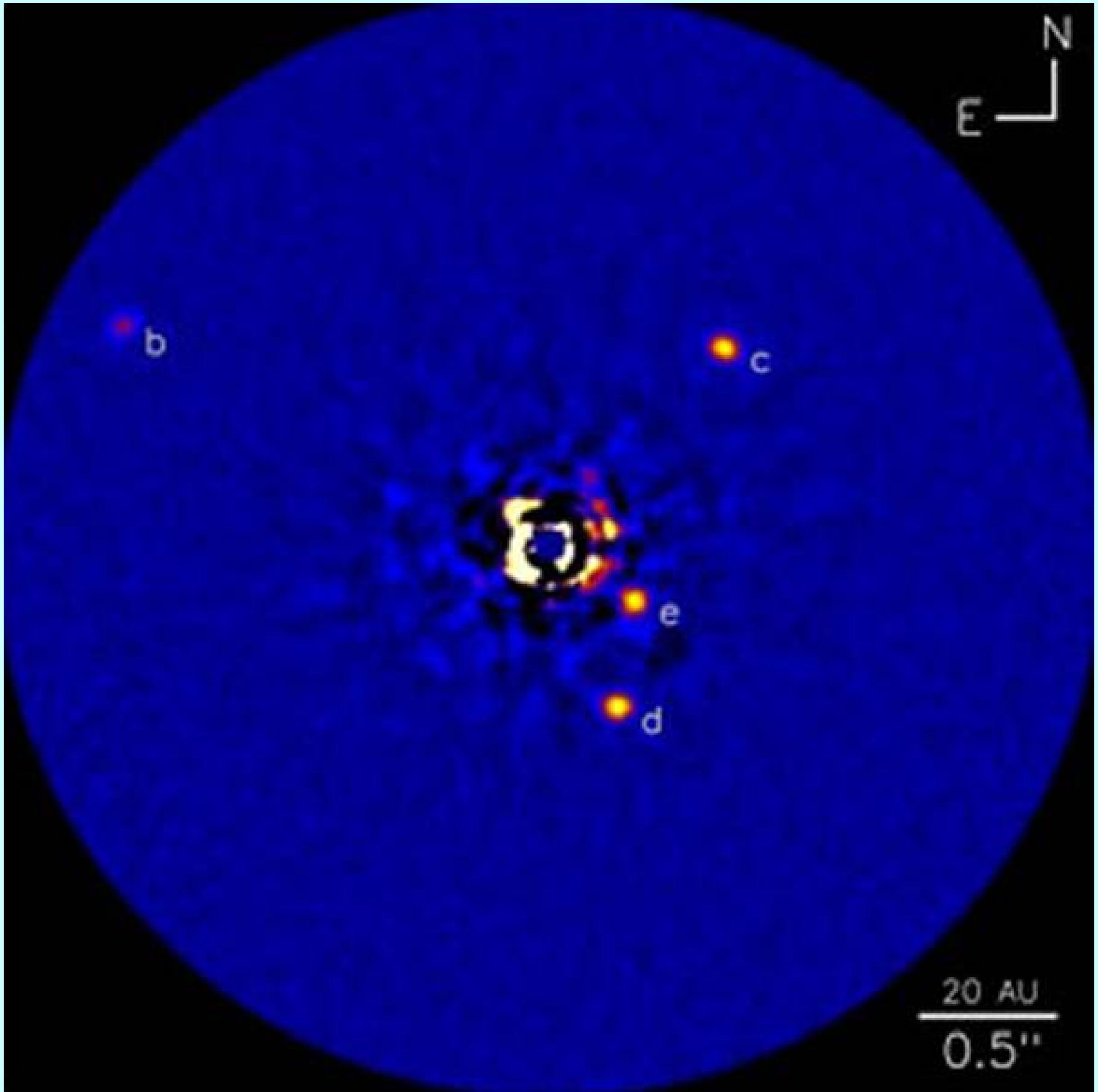
A new frontier: directly imaged planets and brown dwarfs



Brown dwarf basics

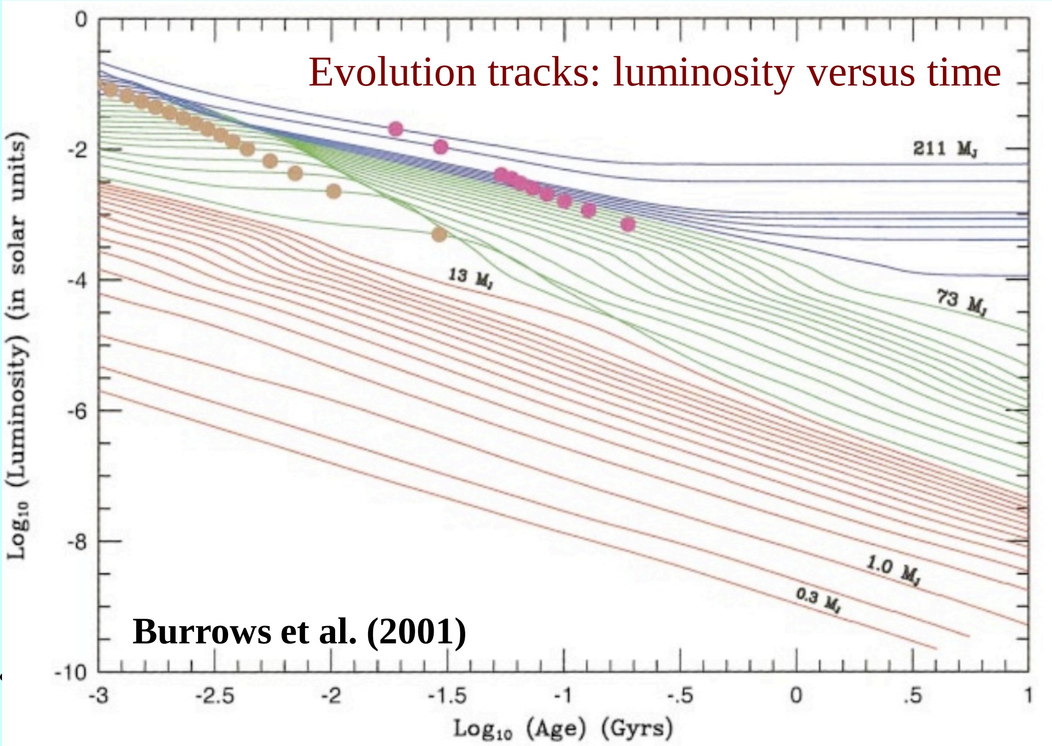
- **Brown dwarfs are fluid hydrogen objects intermediate in mass between giant planets and stars. They are often free floating, though many also orbit stars.**

- **Presumed to form like stars (i.e., directly collapsing from a hydrogen cloud) but have masses too low to fuse hydrogen. Generally defined as objects with masses of 13 to ~80 Jupiter masses.**

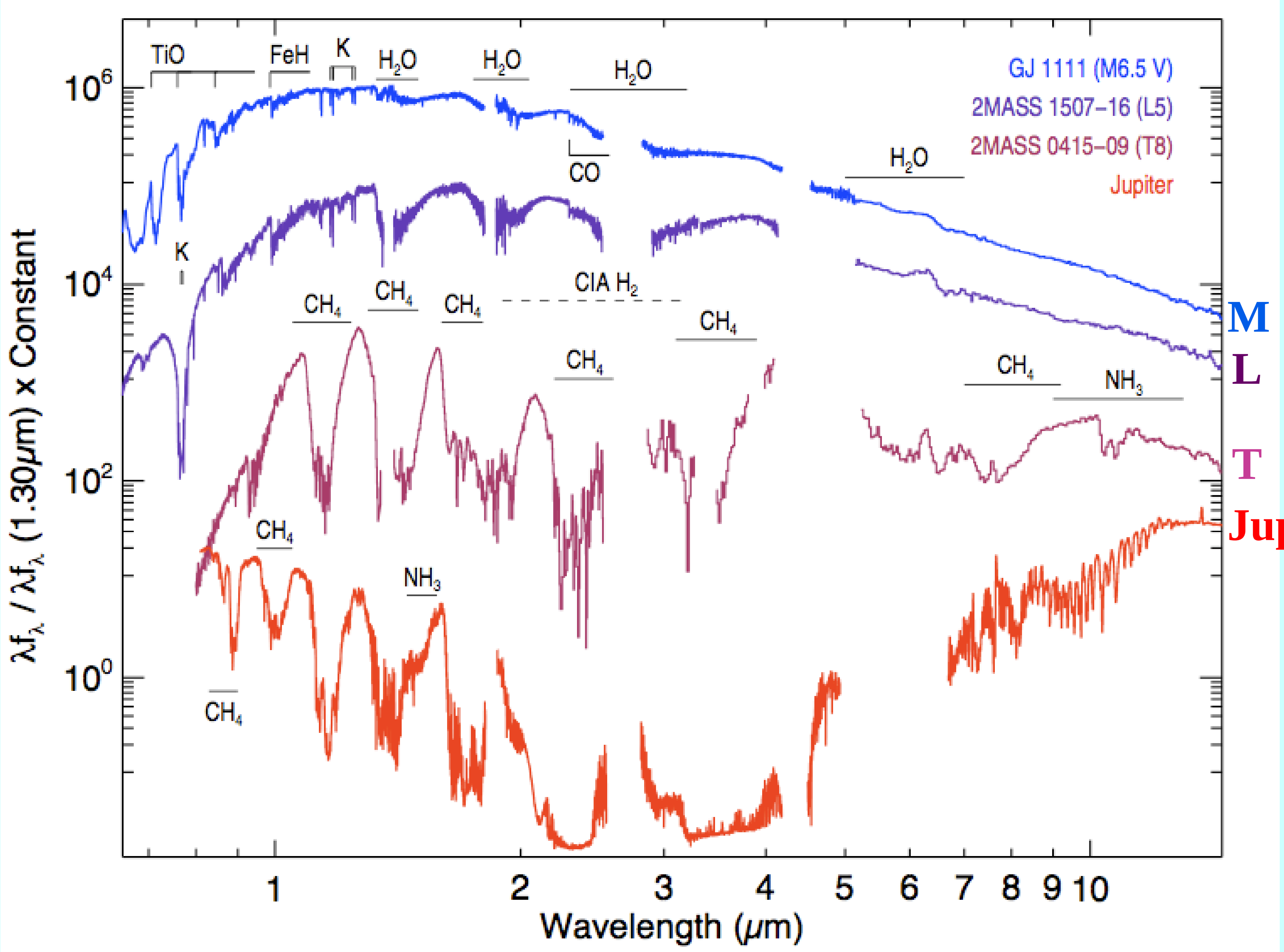
- **Since they cannot fuse hydrogen, they cool off over time (like Jupiter). But massive brown dwarfs cool slowly and can still have surface temperatures >1000 K even after many billions of years**

- **Over a wide mass range (~0.3 to ~80 Jupiter masses), brown dwarfs and giant planets have radii very close to Jupiter's.**

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



Typical brown dwarf infrared spectra

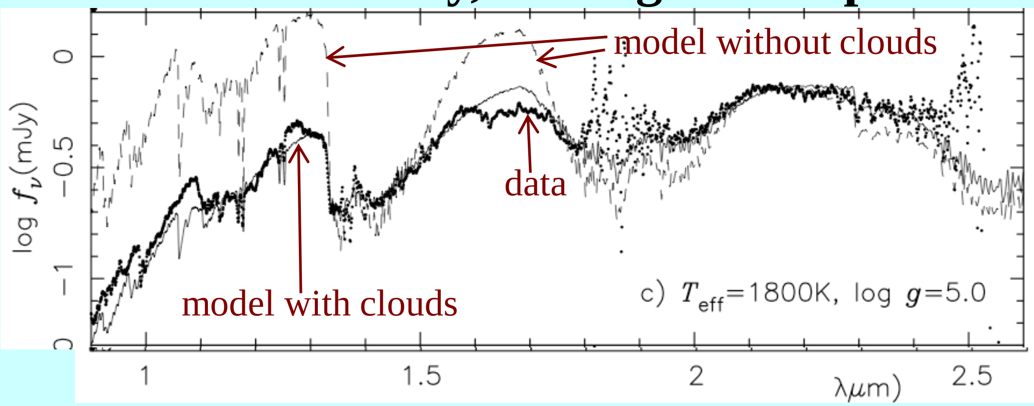


Burgasser (2009, "The brown-dwarf exoplanet connection")

Brown dwarfs are classified according to their IR spectra into M, L, T, and Y (from hot to cold). Unlike most stars, their spectra are dominated by molecular features. Dust (i.e., silicate clouds) affects the spectrum of M and L dwarfs, but not T dwarfs.

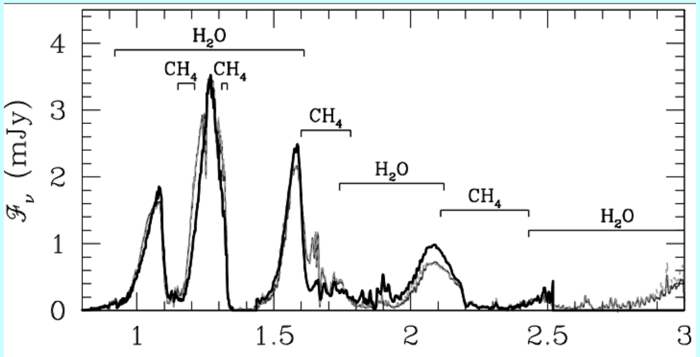
Brown dwarfs show evidence for condensate (dust) clouds

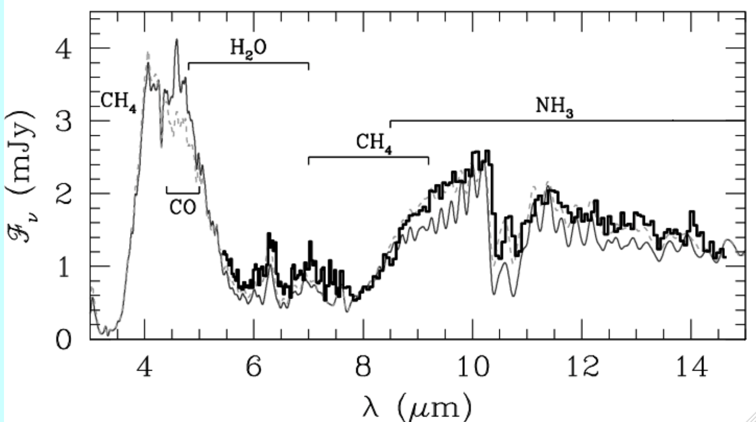
L dwarfs are cloudy, leading to flat spectral features:



Tsuji et al. (2004)

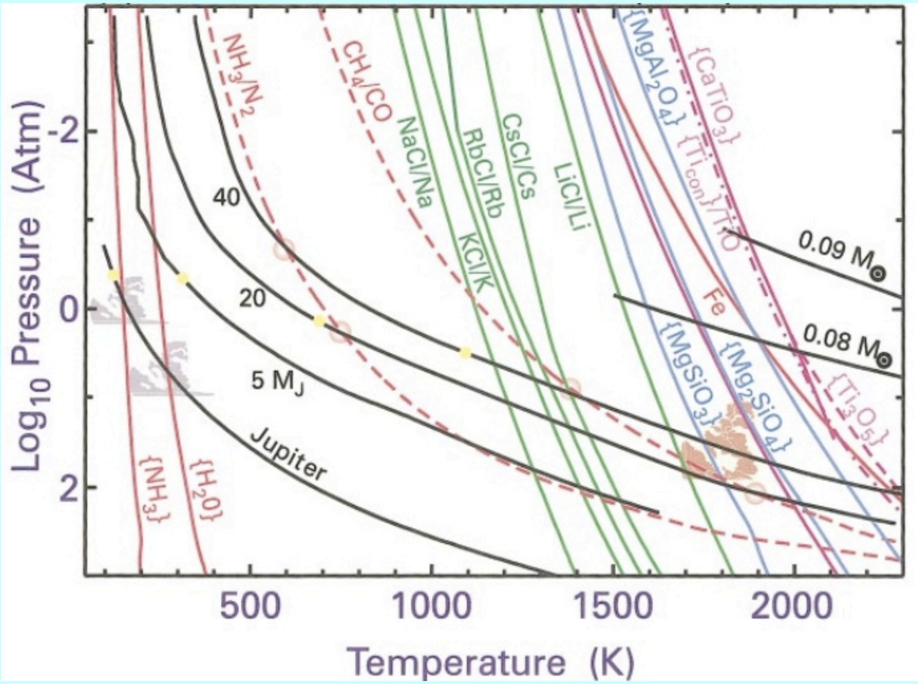
T dwarfs are generally cloud free:





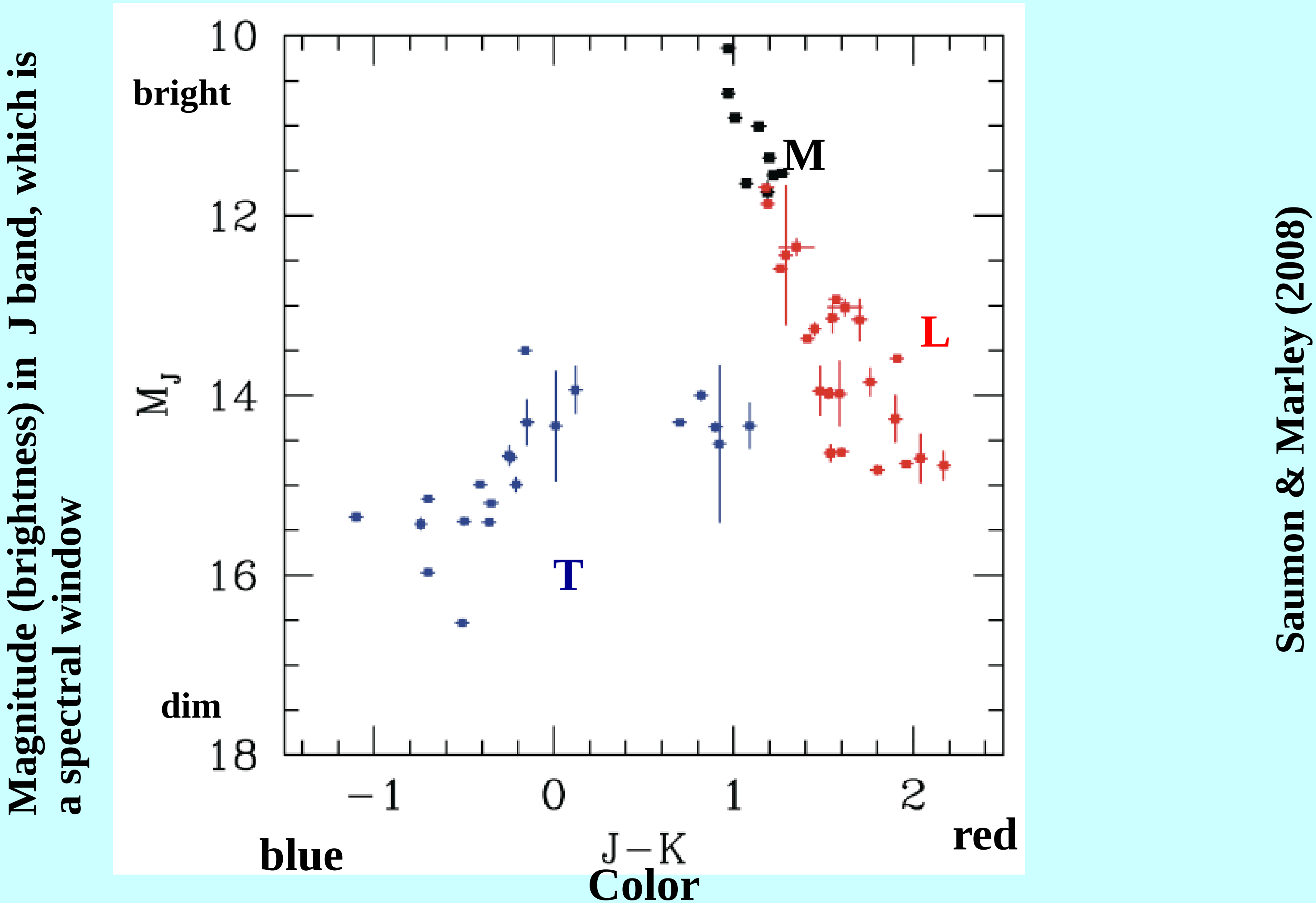
Saumon et al. (2006)

This behavior is explained by the fact that condensate levels lie in the atmosphere for hot objects (M, L dwarfs) but sink into the interior for cool objects (T dwarfs):



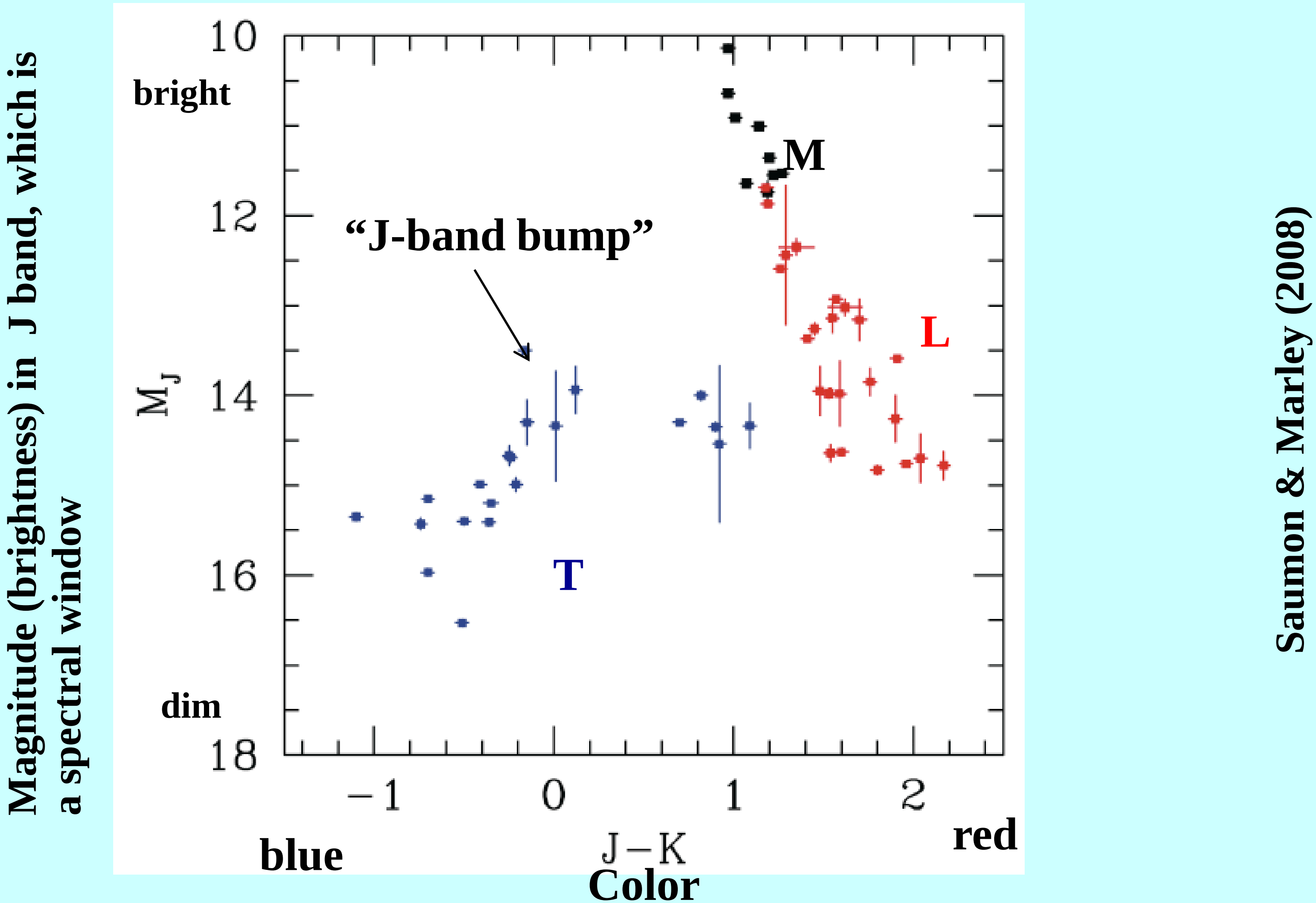
Burrows et al. (2001)

Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs



The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.

Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs



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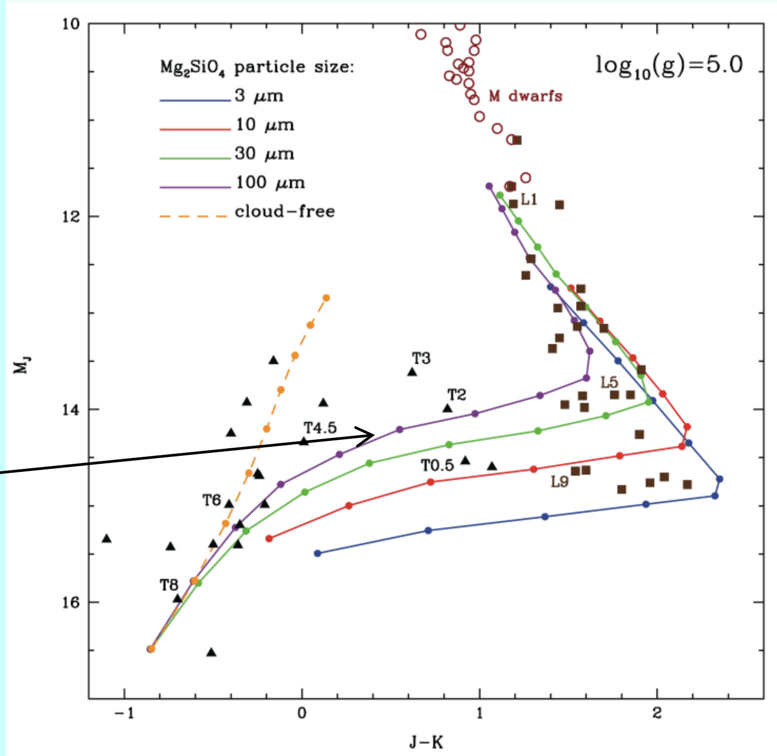
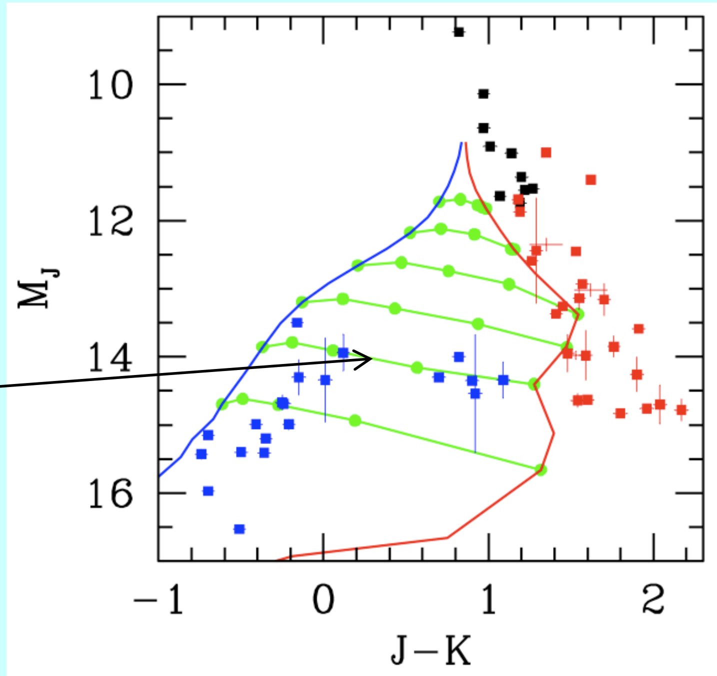
The L/T transition

- **Although the loss of clouds across the L/T transition makes sense, the details are a puzzle: the transition occurs too fast.**
  - **1D models of uniform cloud decks sinking into the interior predict that the J-band flux continually dims across the transition:**
  - **But in reality the J-band flux actually *increases* temporarily across the transition (the "J-band bump"), despite the fact that T dwarfs are cooler than L dwarfs**
  - **This suggests that the cloud decks are not simply disappearing from view, but becoming patchy or getting thin as they do so**
- **1D models that assume the cloud deck gets patchy across the transition do a much better job of reproducing the "J-band bump"**

This suggests a strong role for meteorology in controlling the transition



Burrows et al. (2006)



Marley et al. (2010)

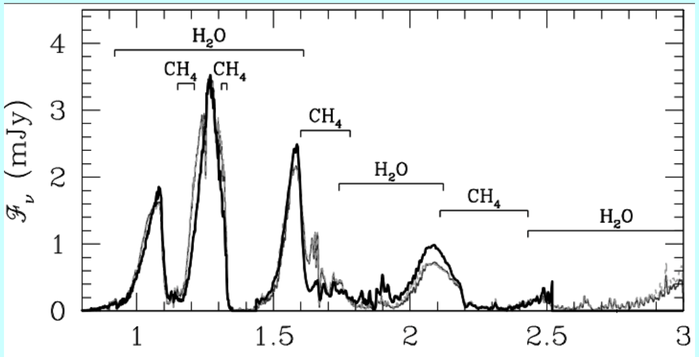
Chemical disequilibrium

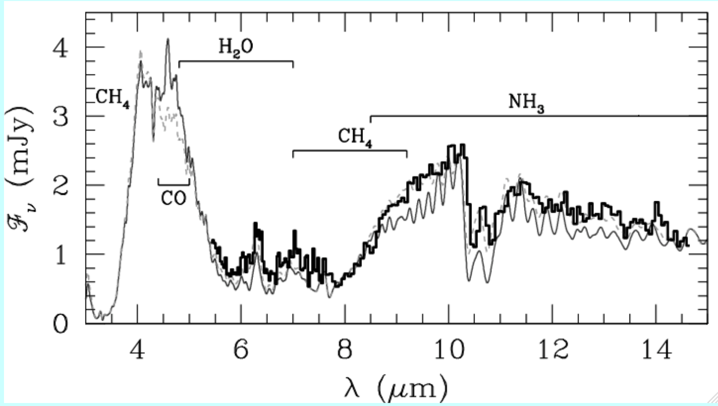
- In cool giant planets and brown dwarfs, the equilibrium form of carbon and nitrogen at the top are CH_4 and NH_3. The equilibrium form at depth are CO and N_2.

- In the absence of dynamics, equilibrium would prevail. But vertical mixing can dredge CO-rich, CH_4-poor, and NH_3-poor air from depth and mix it into the atmosphere.

- This will result in an excess of CO, and a deficit of CH4 and NH3, in the atmosphere

- Just such excesses and deficits are observed, and are interpreted as the result of vertical mixing. The observed abundances can be used to constrain the mixing rates

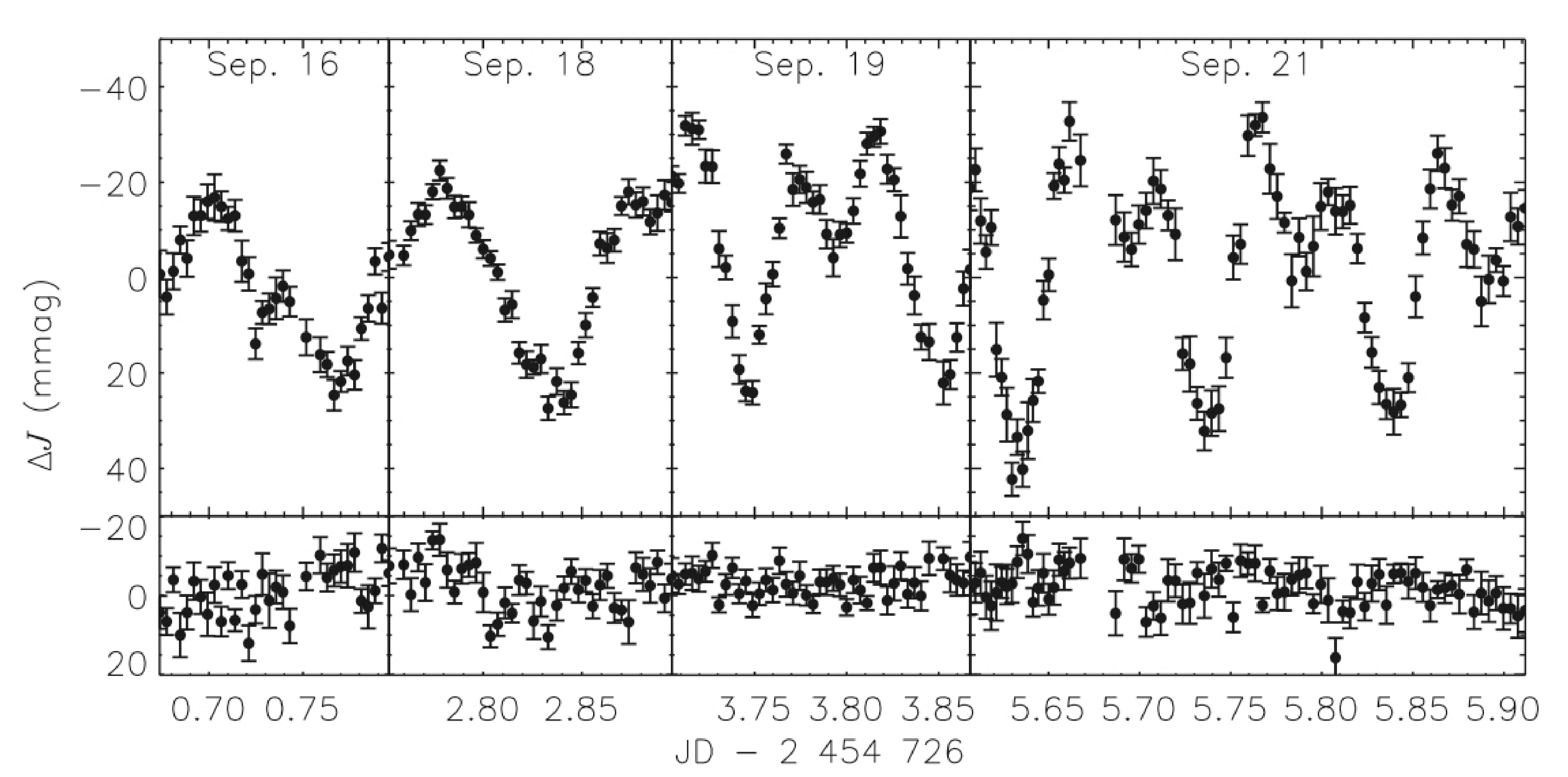




Saumon et al. (2006)

Thus, dynamics is required to explain the chemical disequilibrium

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

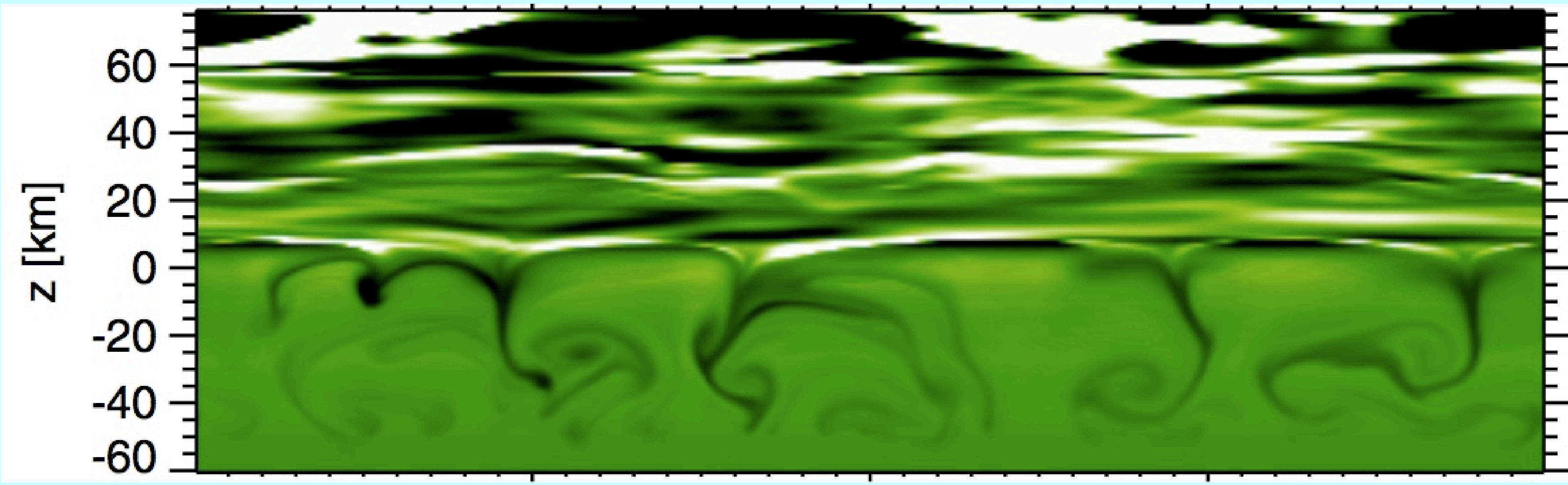
Evidence:

- **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:

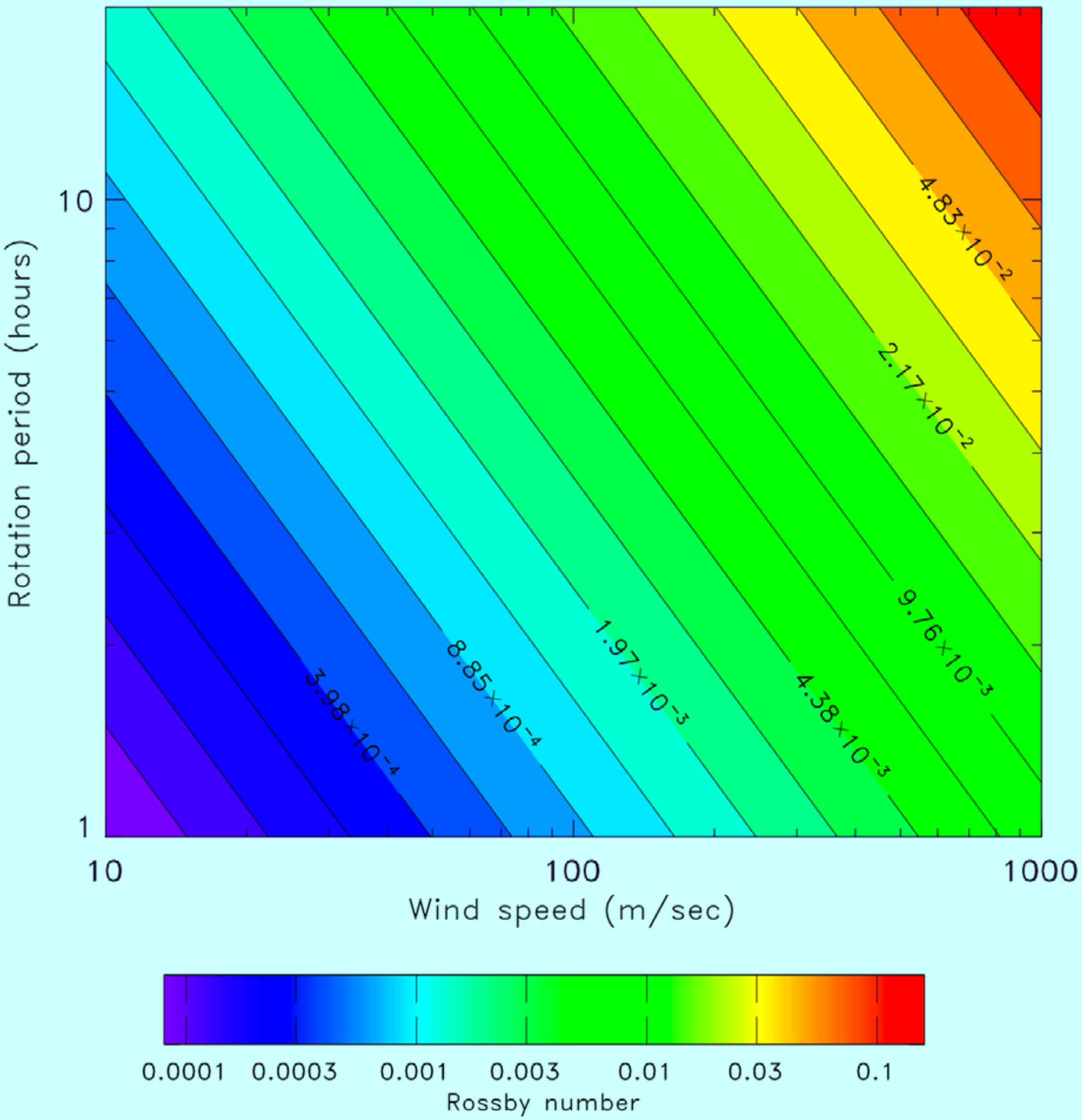
- **Rapid rotation (P ~ 2-12 hours) implies rotational domination**
- **Vigorously convecting interior underlies stably stratified atmosphere**
- **No external irradiation $\Longrightarrow$ no imposed horizontal gradients in heating or temperature (unlike solar system planets or transiting exoplanets)**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

Convection in a brown dwarf drives atmospheric waves



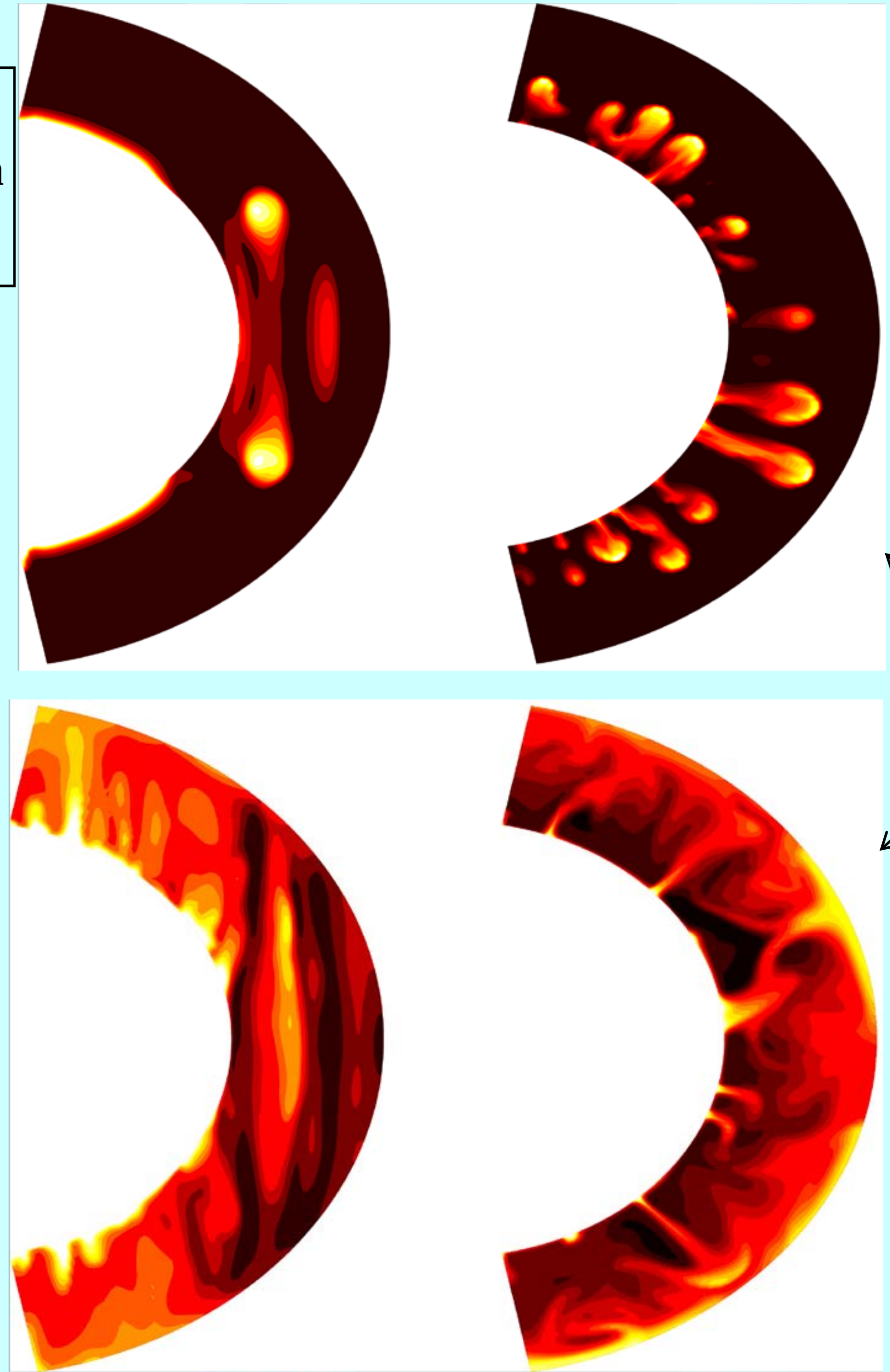
Freytag et al. (2010)

Rossby numbers



Showman & Kaspi (arXiv 1210:7573)

Convection will be dominated by rotation at large scales

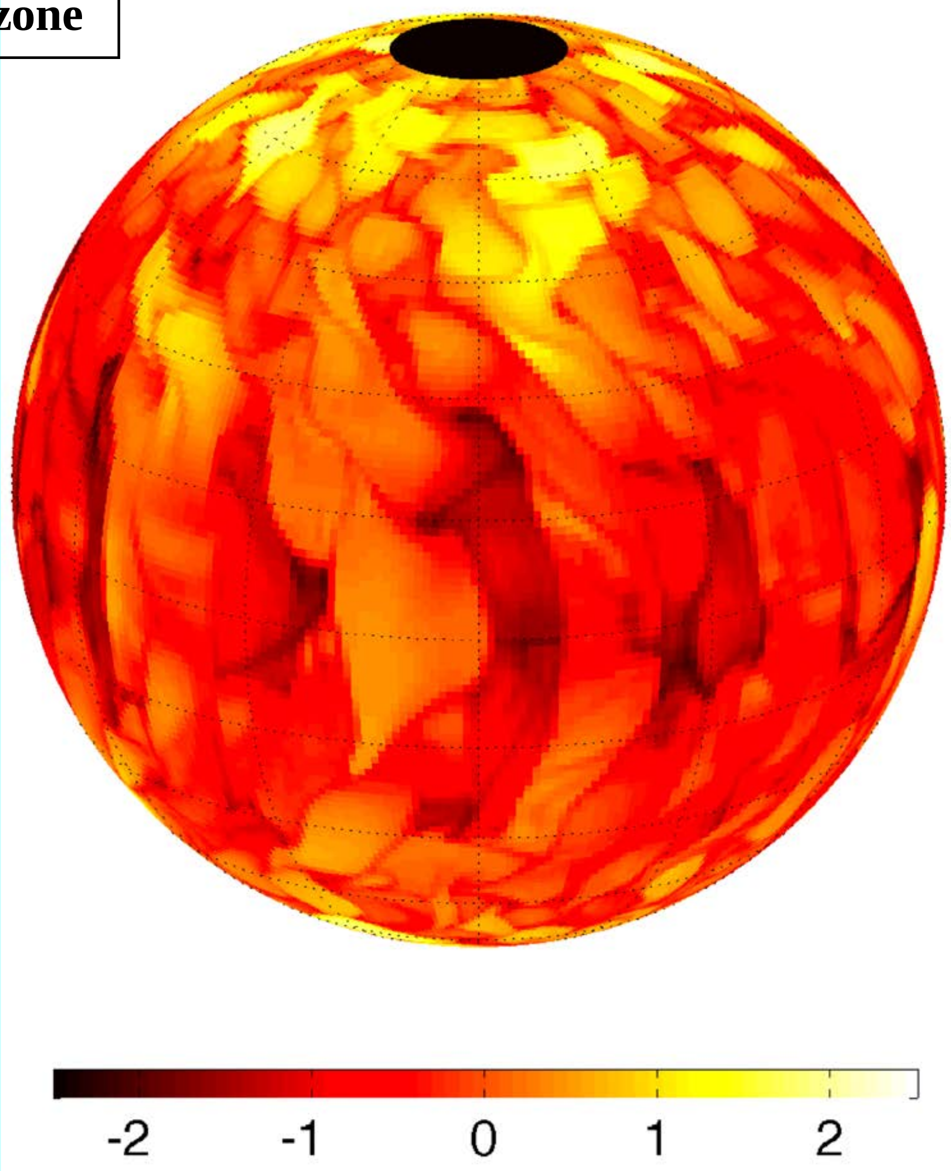


Rapidly rotating model

Slowly rotating model

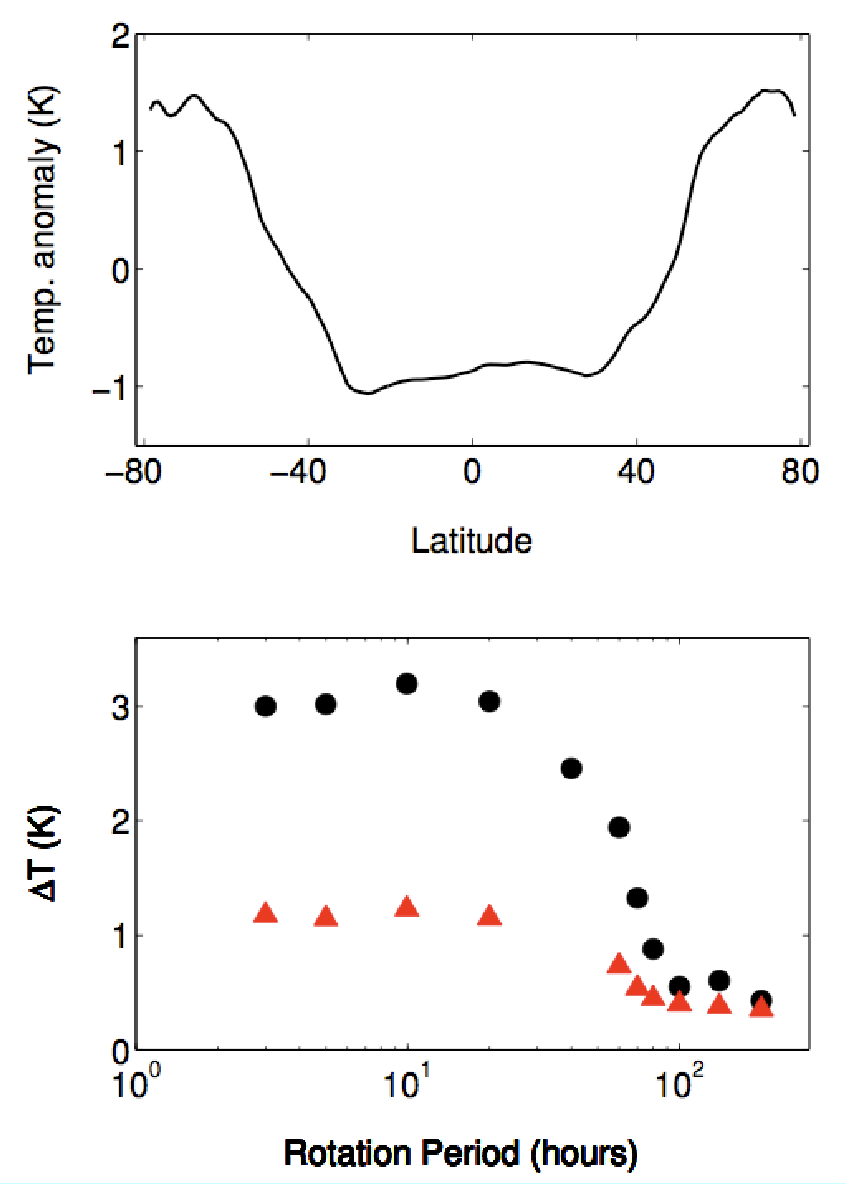
Showman & Kaspi (arXiv 1210:7573)

Temperature perturbations near top of convection zone

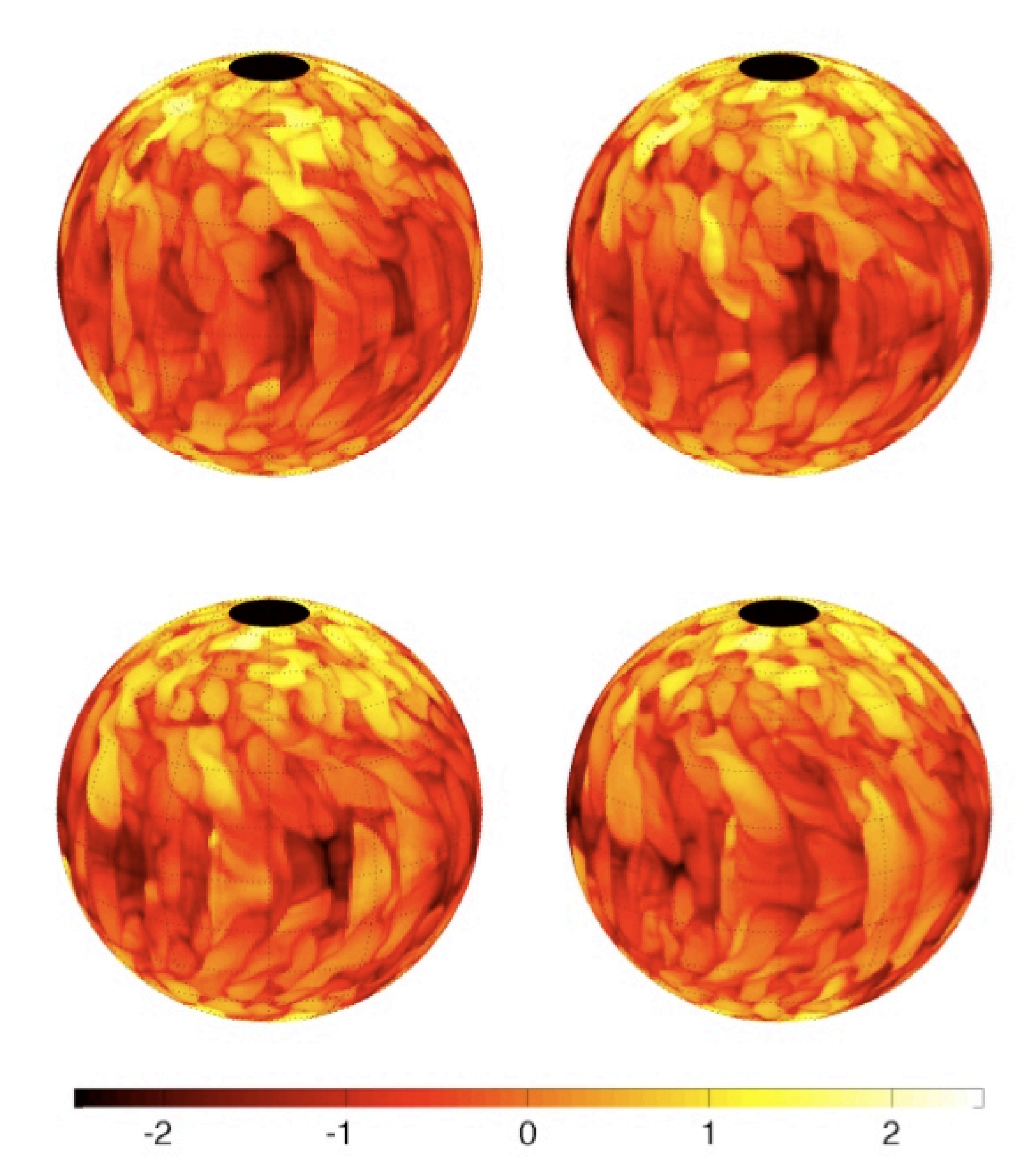


Showman & Kaspi (arXiv 1210:7573)

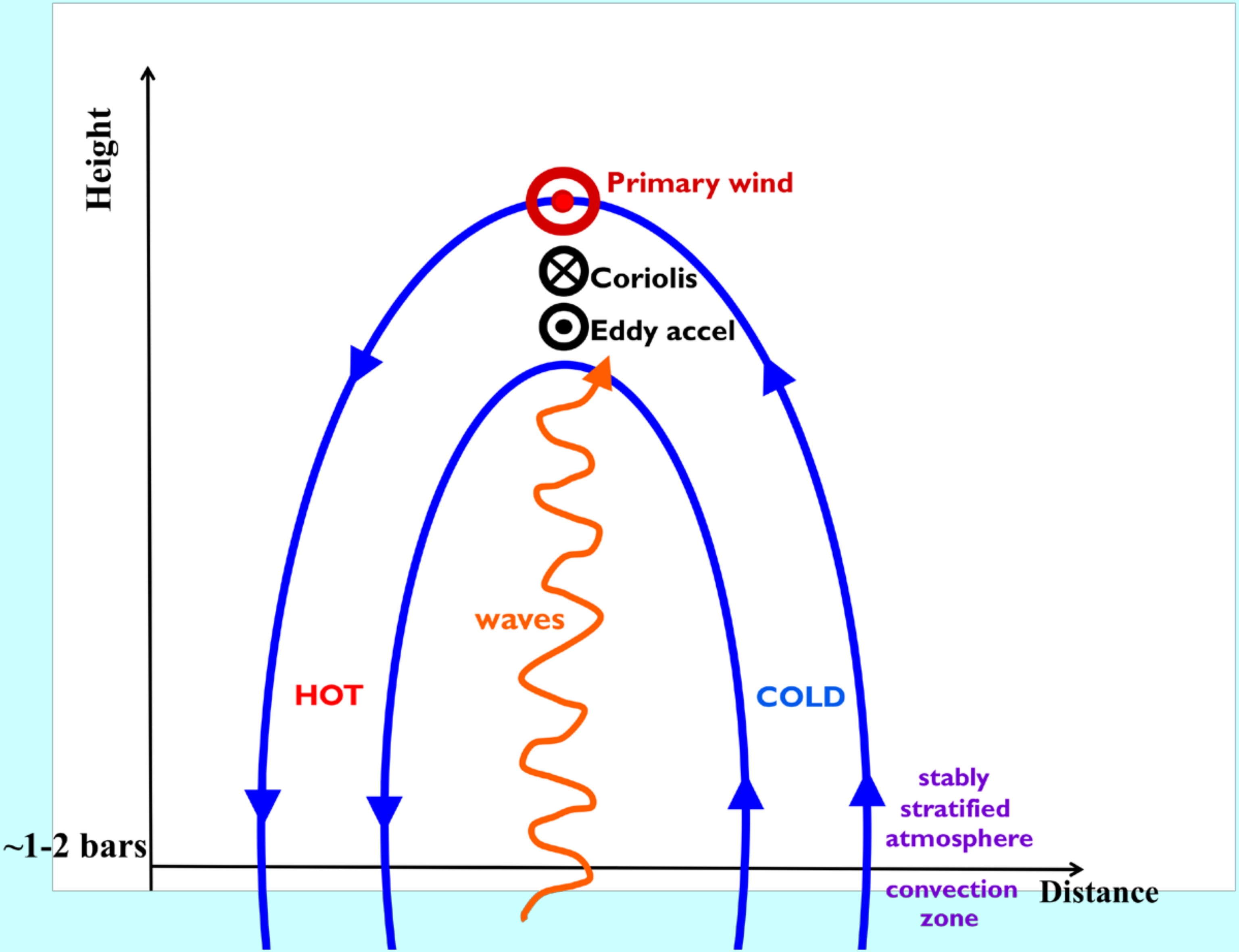
Equator-pole temperature differences at top of convection zone (~1 bar)



Temporal variability



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



Model of wave-driven circulation

- **Assume a given amplitude for the eddy acceleration, *A*, and solve for flow amplitudes using primitive equations in log-pressure coordinates**
- **Zonal momentum balance** $fv \approx A$
- **Continuity** $\frac{\partial v}{\partial y} + e^{z}\left(e^{-z}\varpi\right) = 0$ **which to order-of-magnitude is** $vl \approx \frac{\varpi}{H}$
- **Thermodynamic energy: assume a balance between vertical advection and radiation, parameterized with Newtonian heating/cooling:** $\varpi \frac{H^2 N^2}{R} \approx \frac{\Delta T_{horiz}}{\tau_{rad}}$
- **Meridional momentum balance is thermal wind:** $\Delta U \approx \frac{Rl\Delta T_{horiz} H}{f}$
- **From this set we can derive equations for** $v, \varpi, \Delta T_{horiz}, \Delta U$

$$\Delta T_{horiz} \approx \left(\eta c_p T\right)^{1/2} \frac{NH}{R}$$

$$\Delta U \approx (\eta c_p T)^{1/2} \frac{lH^2 N}{f}$$

$$\varpi \approx \frac{\eta^{1/2} g T^{7/2} \sigma}{c_p^{1/2} p H N} \approx \frac{(\eta c_p T)^{1/2}}{H N \tau_{rad}}$$

where η is a dimensionless efficiency giving fraction of the radiated heat flux that goes into the wave driving

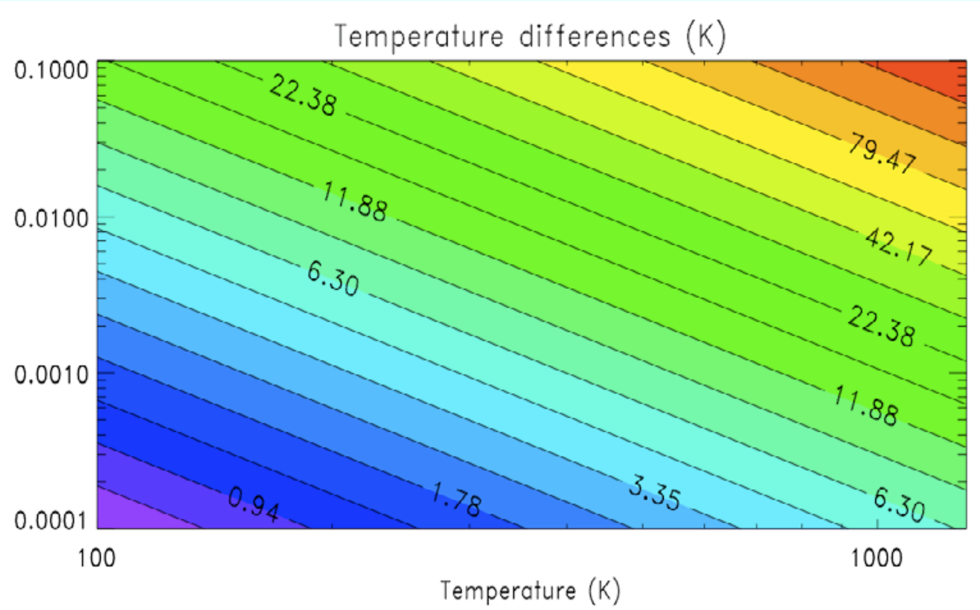
To within factors of order unity,

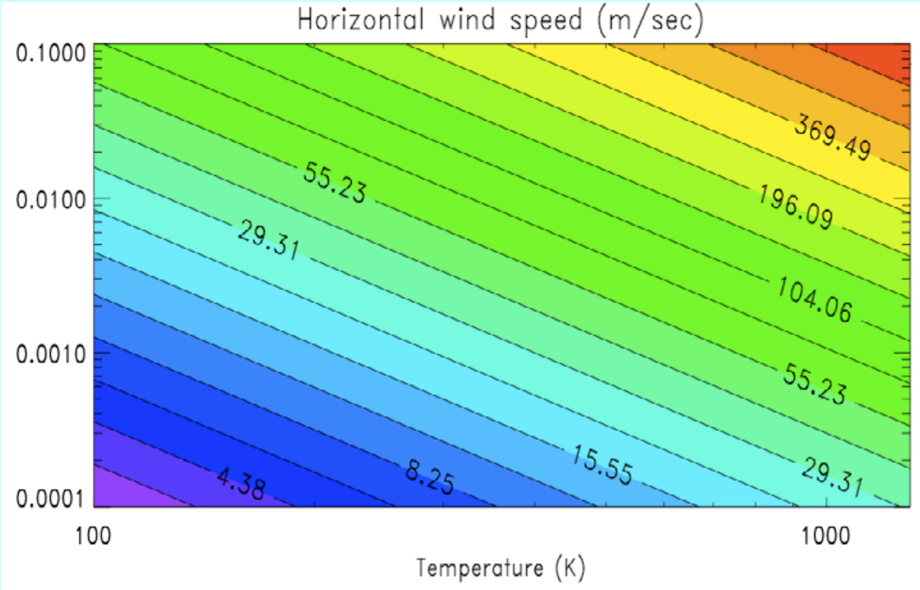
- **$\Delta T_{horiz}/T$ is $\eta^{1/2}$ times the ratio of the gravity wave speed to the sound speed**

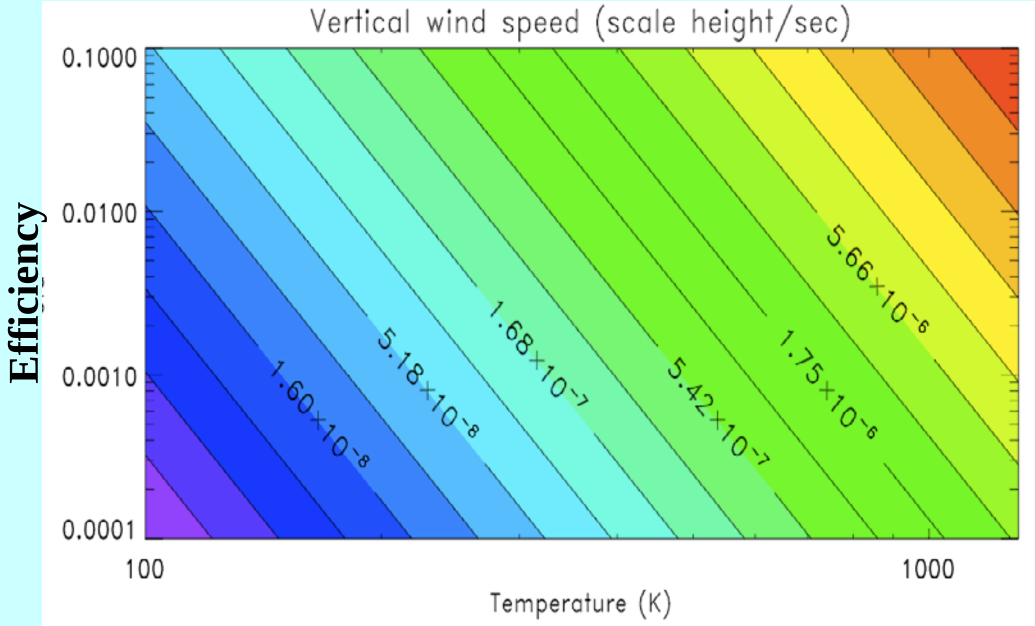
- **ΔU over the sound speed is $\eta^{1/2}$ times the ratio of the Rossby deformation radius to the dominant horizontal length scale of the flow**

- **The time for the flow to advect vertically over a scale height is $\eta^{-1/2}\tau_{rad}$ times the ratio of gravity wave speed to sound speed**

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

- **Extensive evidence now exists for dynamics and weather in shaping observations of brown dwarfs, including the existence of clouds, the properties of the L/T transition, chemical disequilibrium, and temporal variability**

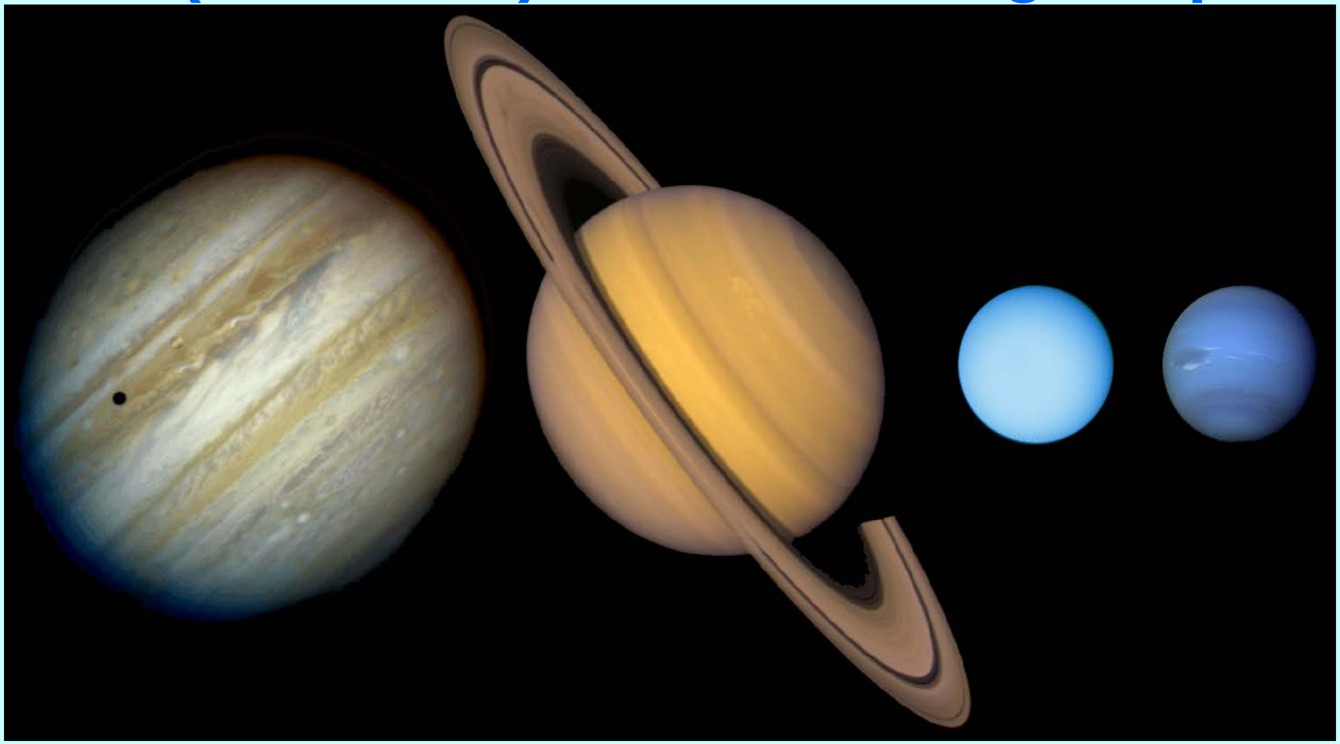
- **We presented the first global models of the atmospheric dynamics on these objects. The dynamics will be rotationally dominated (Ro << 1). At large scales, convection in the interior will align in the direction of the axis of rotation, and the heat flux will be enhanced at the poles relative to the equator.**

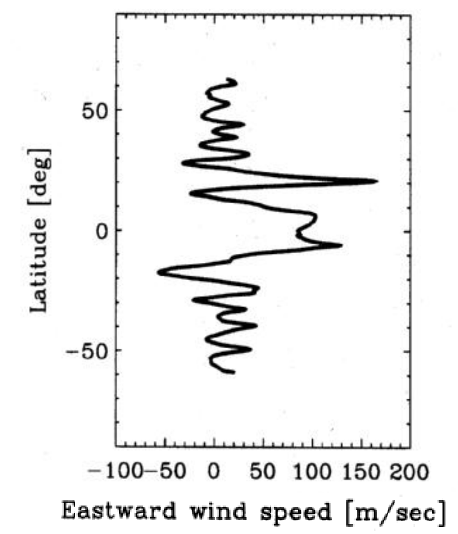
- **The convection will generate a wealth of atmospheric waves. Just as for planets in our solar system, this will drive a large-scale circulation in the stratified atmosphere consisting of geostrophic turbulence possibly organizing into jets and vortices.**

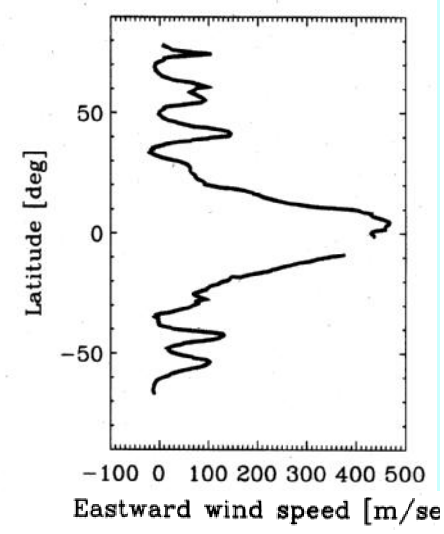
- **We presented a simple analytic theory of this circulation, suggesting the existence of horizontal temperature differences of ~10-100 K, wind speeds of ~10-300 m/sec, and vertical velocities that advect air vertically over a scale height in ~10^5-10^6 sec.**

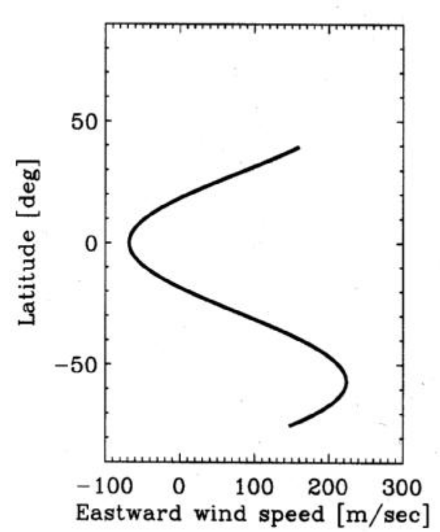
- **This vertical motion can help explain the chemical disequilibrium, and the implied organization of temperature perturbations and winds suggests that patchy clouds can form near the L/T transition, helping to explain observations of variability.**

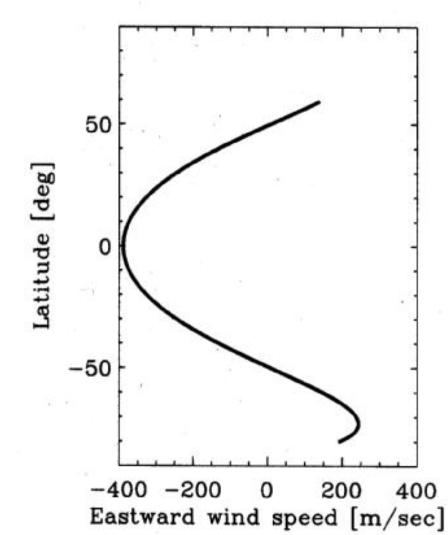
Zonal (east-west) winds on the giant planets









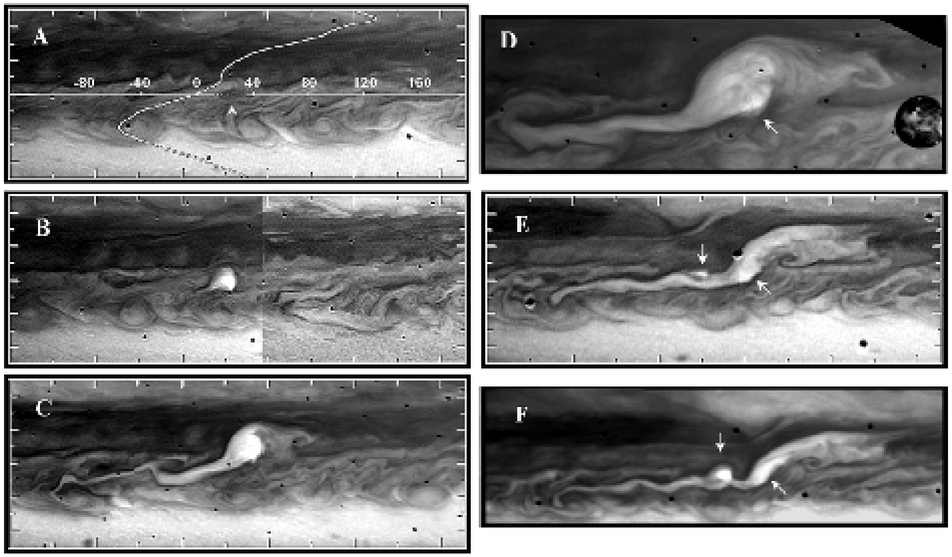


Basic Jet Scenarios

- **Models for jet structure:**
  - **_Shallow_: Jets confined to outermost scale heights below the clouds**
  - **_Deep_: Jets extend through molecular envelope (Taylor-Proudman theorem)**

- **Models for jet pumping:**
  - **_Shallow_: Turbulence at cloud level (thunderstorms or baroclinic instabilities)**
  - **_Deep_: Convective plumes penetrating the molecular envelope**

These issues are among the most important unsolved problems in planetary atmospheres!



Puzzles

- **What causes the banded structure, with ~20 jets on Jupiter and Saturn yet only ~3 on Uranus and Neptune? What is the jet-pumping mechanism?**

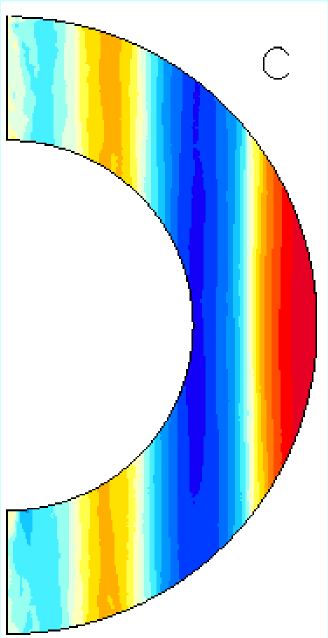
- **How deep do the jets extend?**

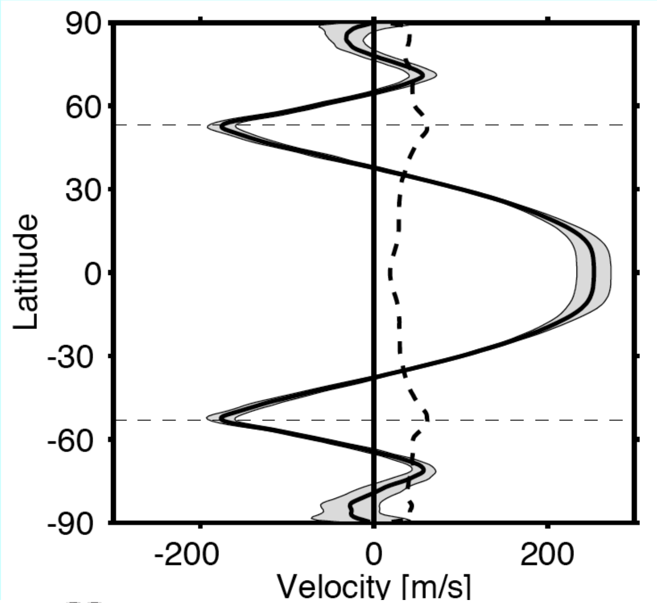
- **Why do Jupiter and Saturn have superrotating equatorial jets whereas Uranus and Neptune do not?**

- **What causes the vortices? What controls their behavior? How do they interact with the jets?**

- **What is the temperature structure and mean circulation of the stratosphere and upper troposphere?**

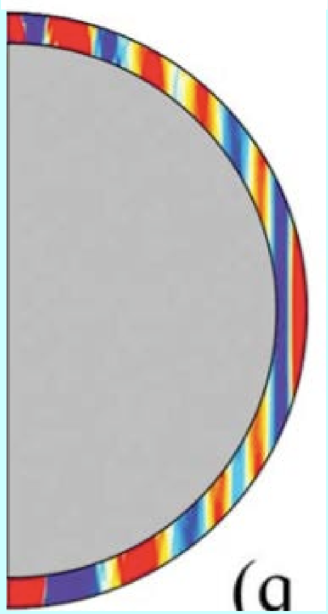
Deep convection models

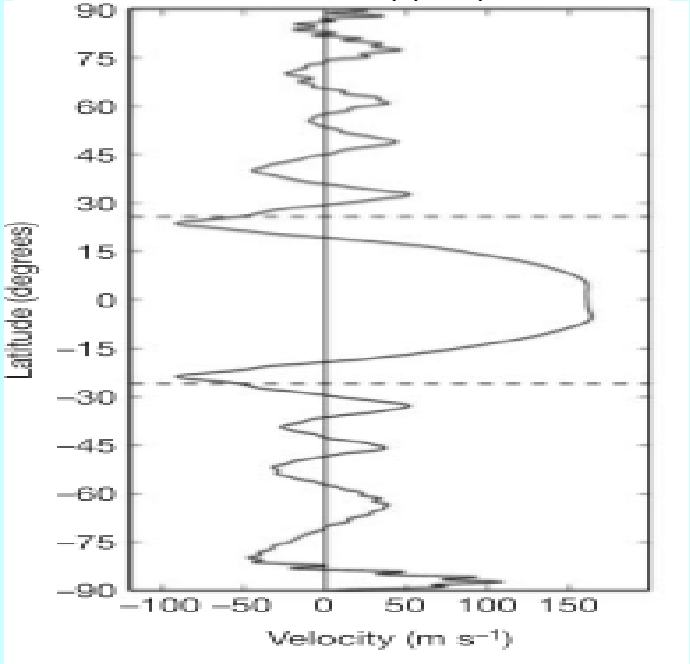




Thick shell

(Christensen 2001, 2002;
Aurnou & Olson 2001;
Kaspi et al. 2009,
Jones & Kuzanyan 2009,
Showman et al. 2011, etc)

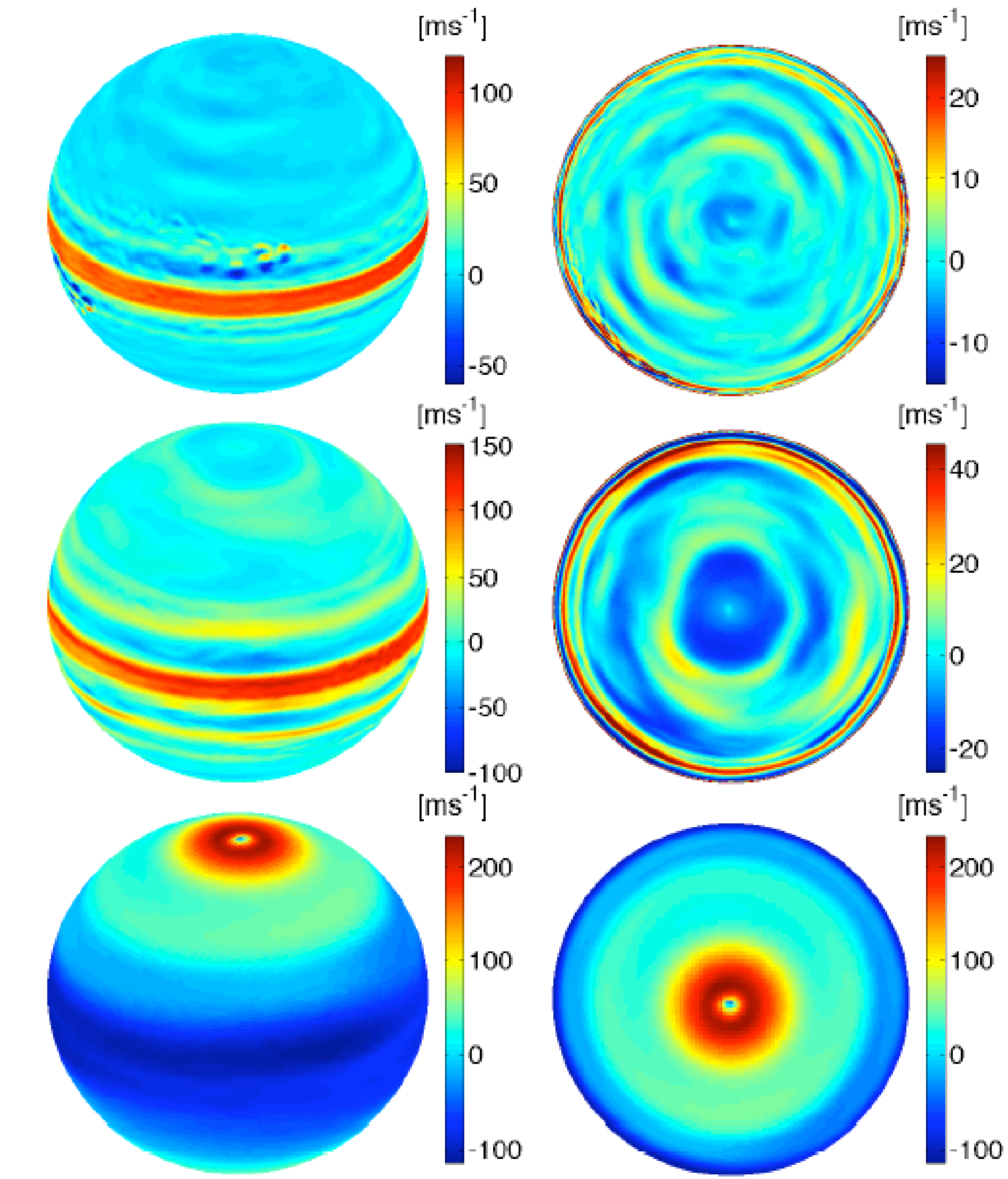




Thin shell

(Heimpel et al. 2005;
Heimpel & Aurnou 2007;
Aurnou et al. 2008)

Lian & Showman (2010)



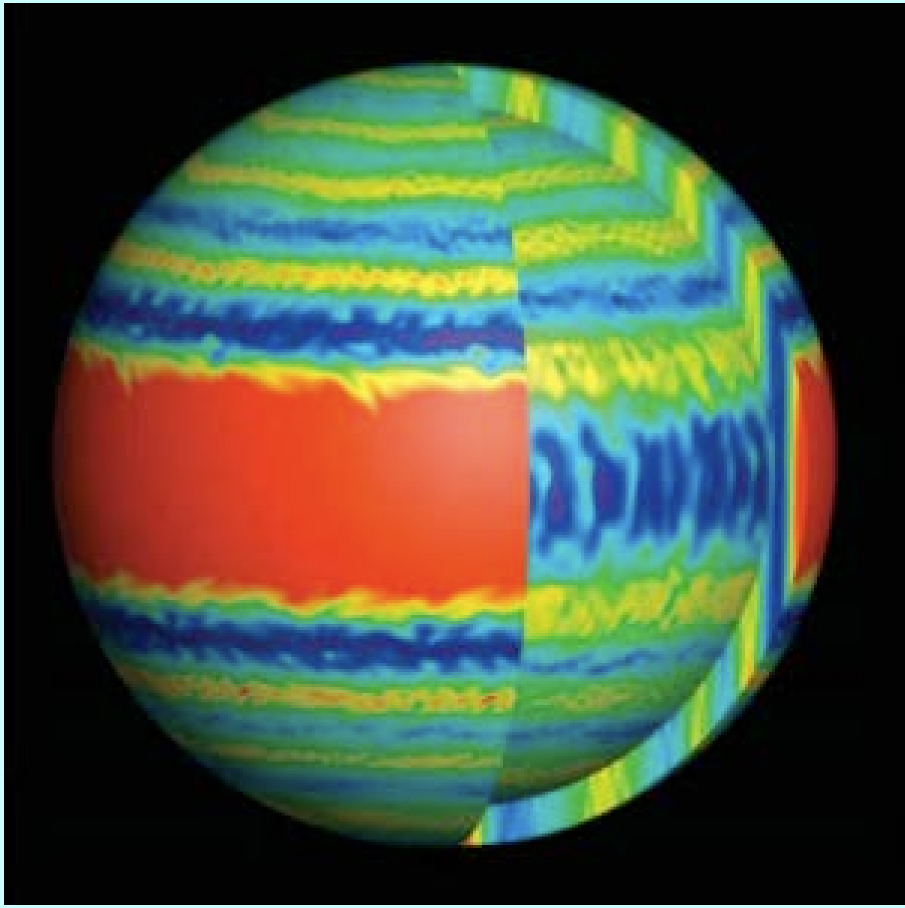
Jupiter

Saturn

Uranus/Neptune

Motivation

- **Convection in interiors of giant planets has been suggested as a mechanism for jet formation (Aurnou and Olson 2001; Christensen 2001, 2002; Heimpel et al. 2005, etc)**
- **But simulations of this process can only be performed at parameter settings far from the Jovian regime.**
- **Are the simulations relevant to the Jupiter? What controls the trends observed in the simulations, and how to extrapolate them to giant planets?**



Heimpel et al. (2005)

Non-Dimensional Parameters

Modified-flux Rayleigh, Ekman, and Prandtl numbers:

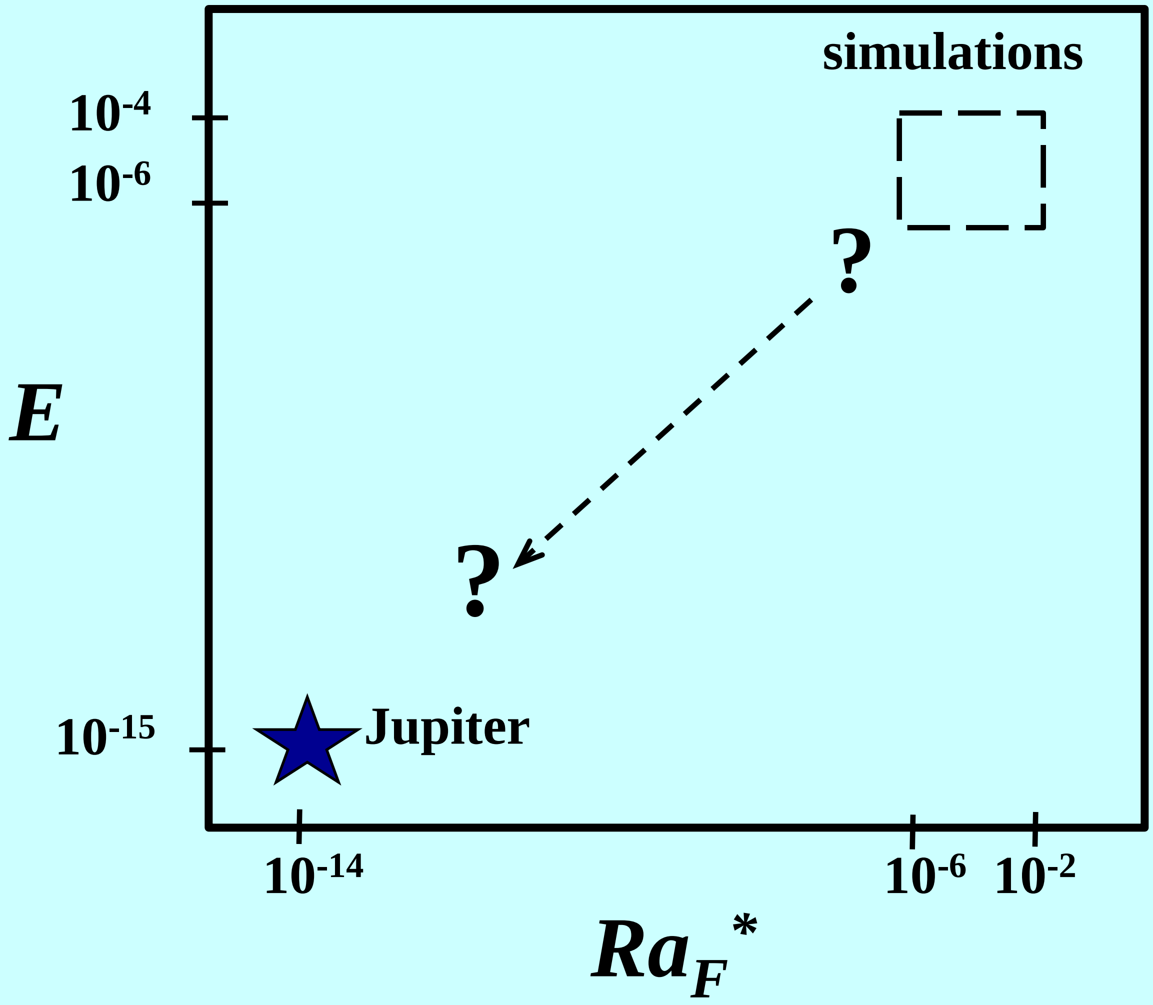
$$Ra_F^{\,*} = \frac{\alpha g F_{\mathrm{tot}}}{\rho c_p \Omega^3 D^2} \qquad E = \frac{\nu}{\Omega D^2} \qquad P = \frac{\nu}{\kappa}$$

On Jupiter, $Ra_F^{\,*} \sim 10^{-14}$, but published simulations generally explore values ~$10^{-6} - 10^{-2}$. This implies that the heat fluxes in the simulations

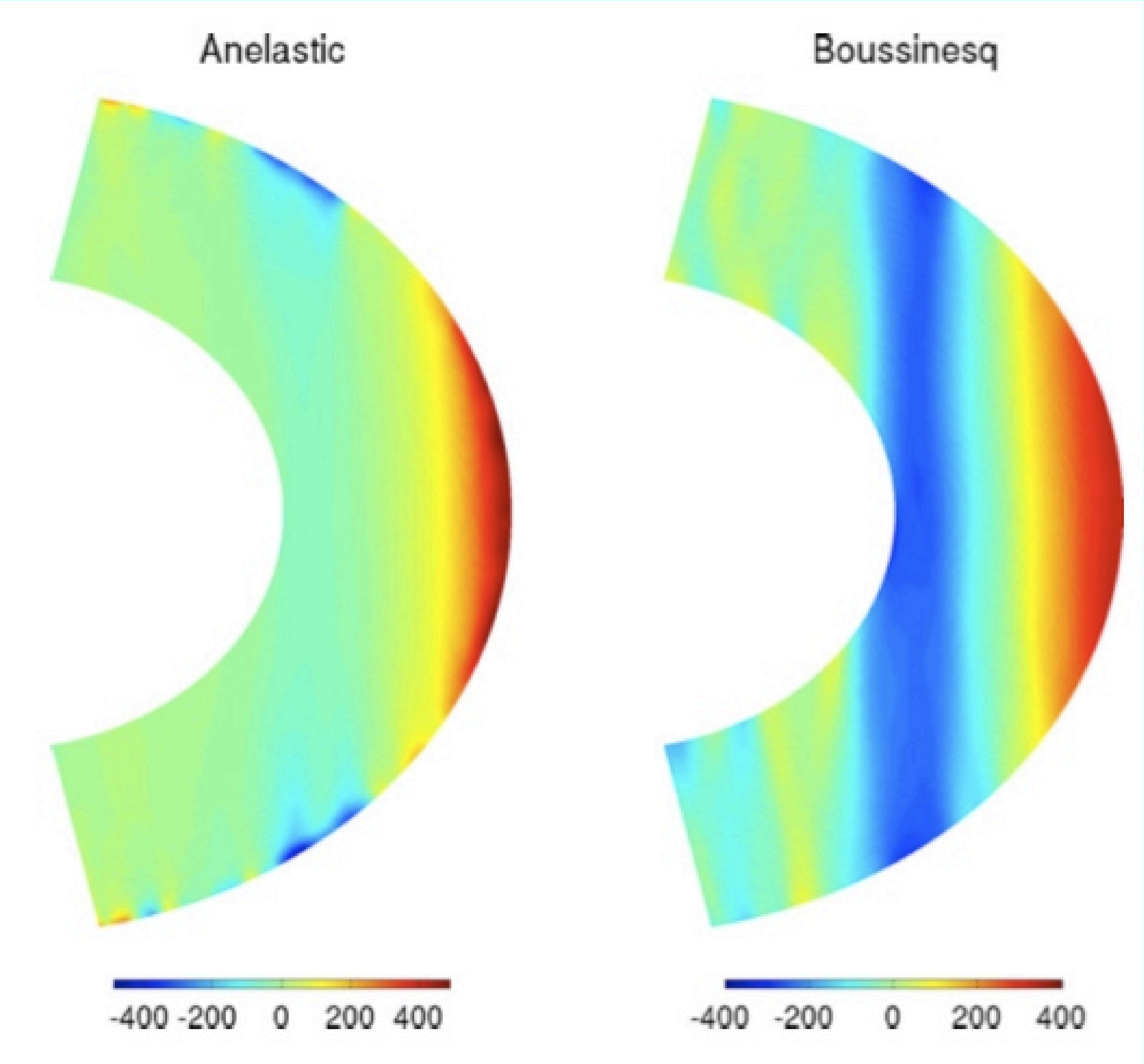
$$F = \frac{\rho c_p \Omega^3 D^2}{\alpha g} Ra_F^{\,*}$$

are too large by a factor of 10^5-10^{10}.

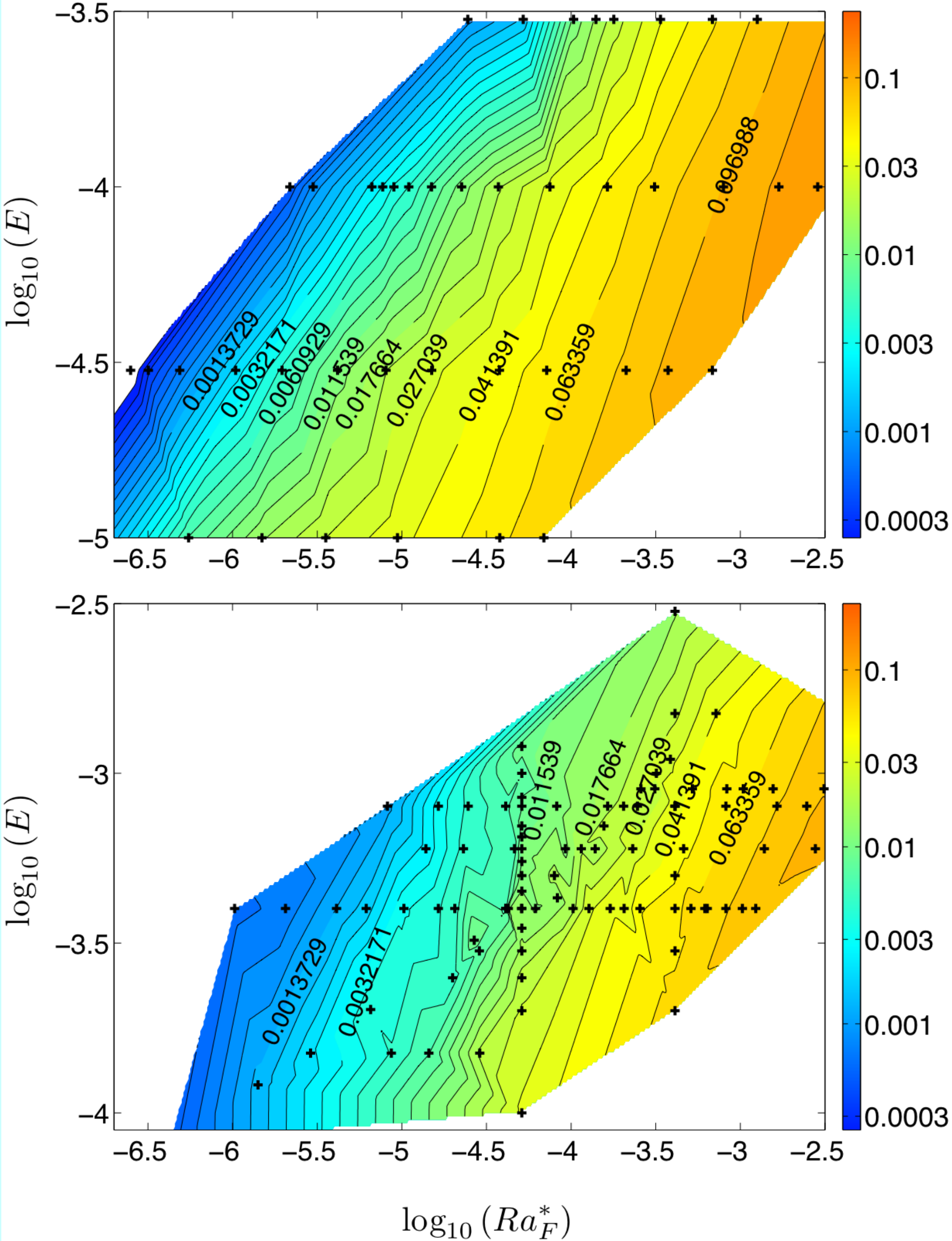
Challenges with deep convection models



Would convection at Jupiter-like Ra_F^* and E produce Jupiter-like wind speeds? How to extrapolate to Jupiter? This is not known!

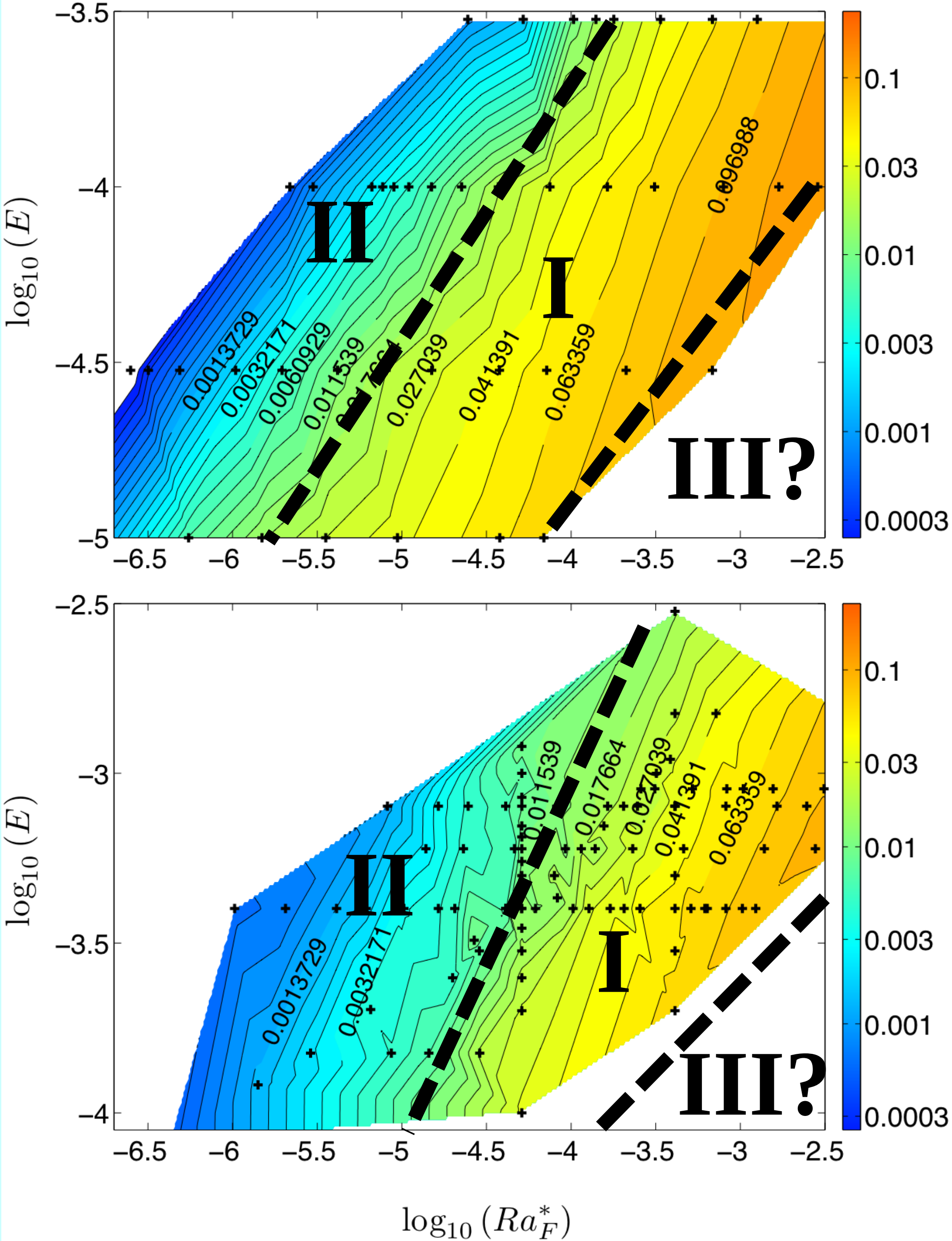


Kaspi, Flierl, Showman (2009)



Simulations from Christensen (2002)

Simulations from Kaspi et al. (2009); Showman et al. (2011)



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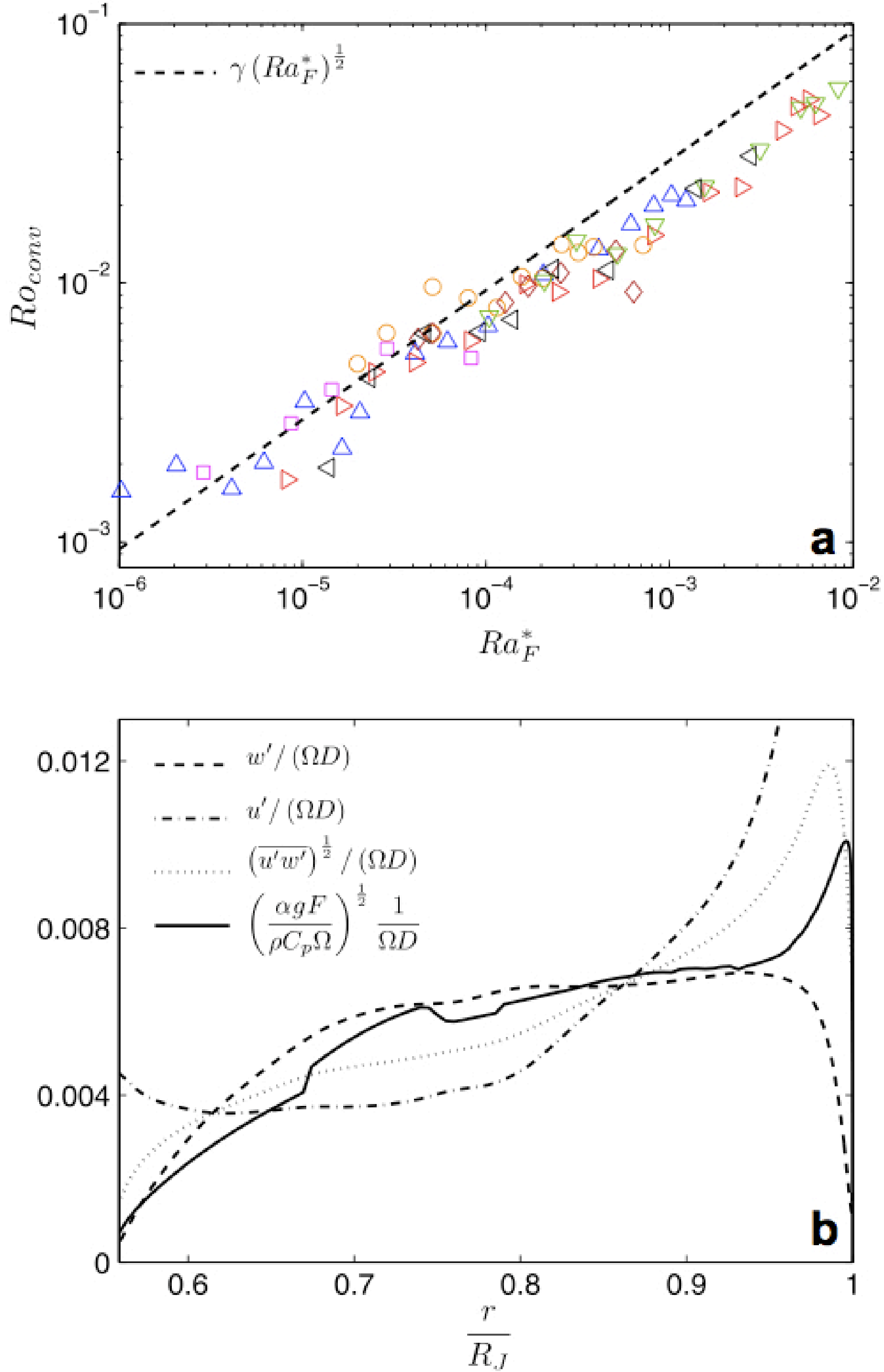


Convective velocities are well explained by the relation

$$w \approx \left(\frac{\alpha g F}{\rho c_p \Omega}\right)^{1/2}$$

which can be nondimensionalized to yield

$$Ro_{conv} \approx \left(Ra_F{}^* - Ra_F{}^{*crit}\right)^{1/2}$$

$$\equiv \left(\Delta Ra_F{}^*\right)^{1/2}$$

Can we understand the dependence of jet speeds on parameters? Consider Regime I.

Convection releases potential energy per mass per unit time

$$\dot{P} \approx \frac{\delta\rho}{\rho} g w \approx \alpha\, \delta T\, g\, w$$

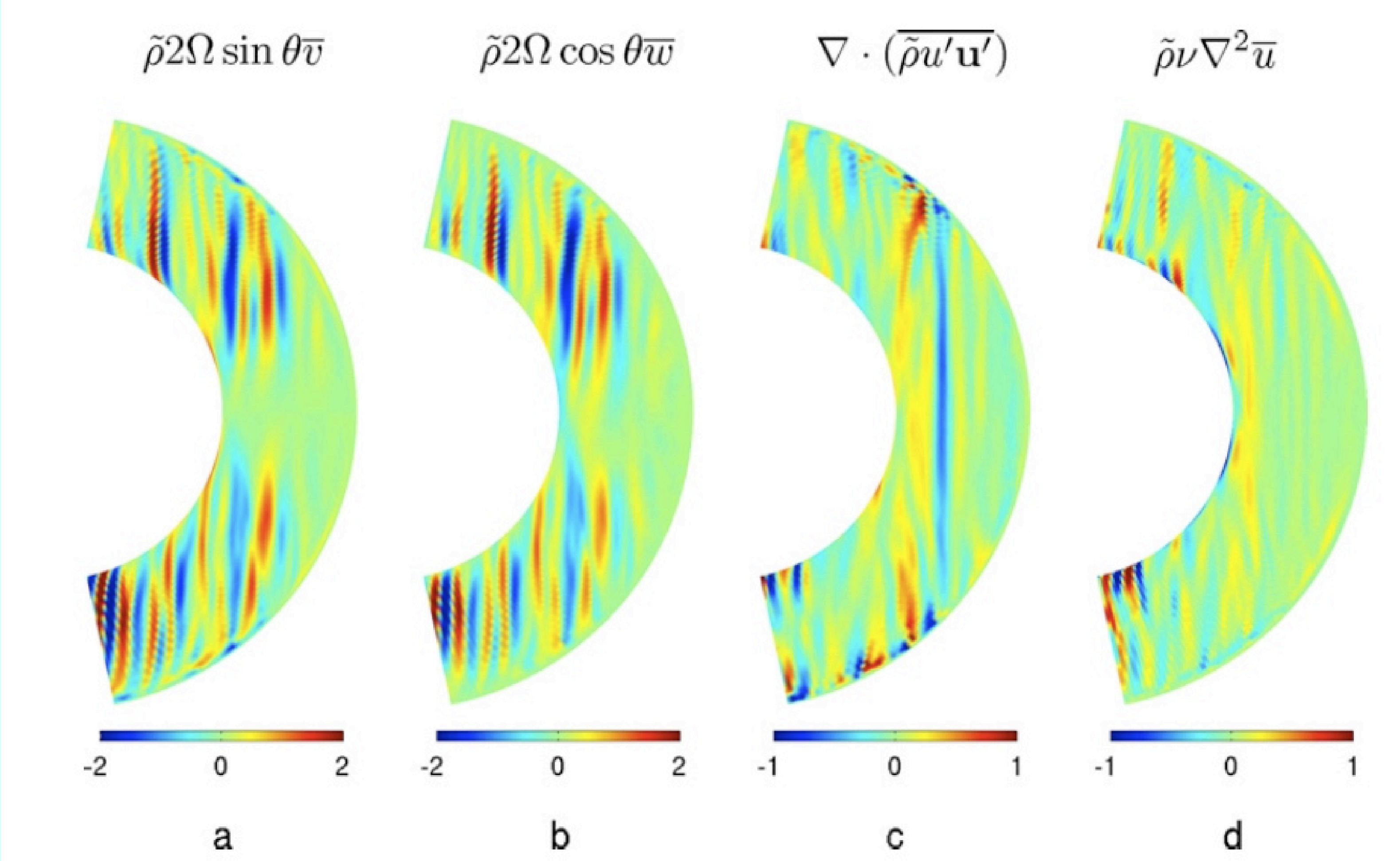
Now $F \approx \rho c_p w \delta T$ **which implies that**

$$\dot{P} \approx \frac{\alpha g F}{\rho c_p}$$

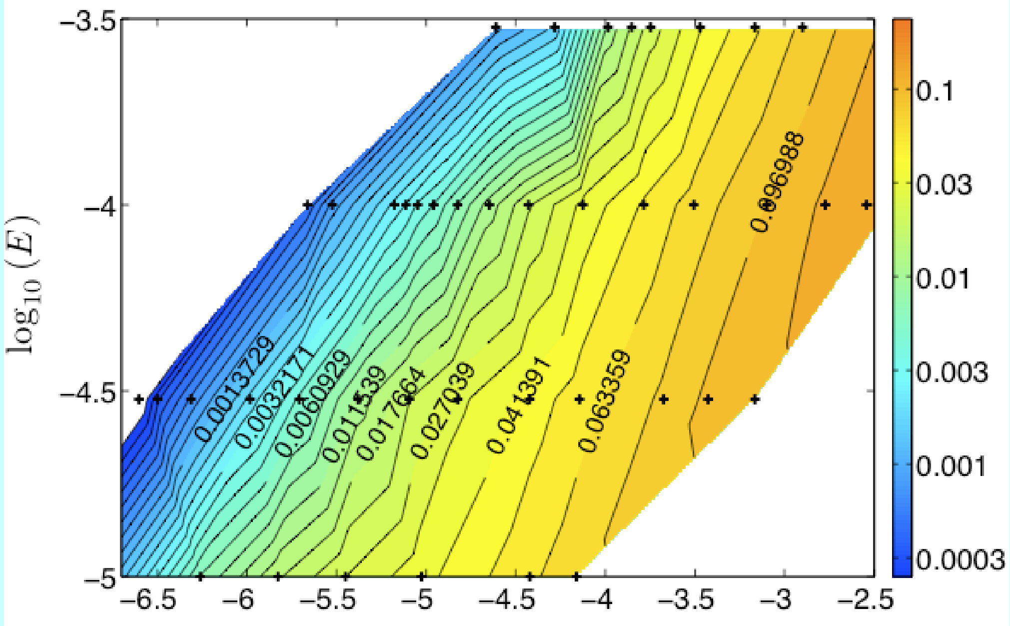
Suppose a fraction ε **of this energy pumps the jets and is resisted by viscous damping with a viscosity** ν**. Then**

$$U \approx k^{-1}\left(\frac{\varepsilon \alpha g F}{\rho c_p \nu}\right)^{1/2} \quad \Rightarrow \quad Ro \approx \frac{\varepsilon^{1/2}}{kD}\left(\frac{Ra_F{}^{*}}{E}\right)^{1/2}$$

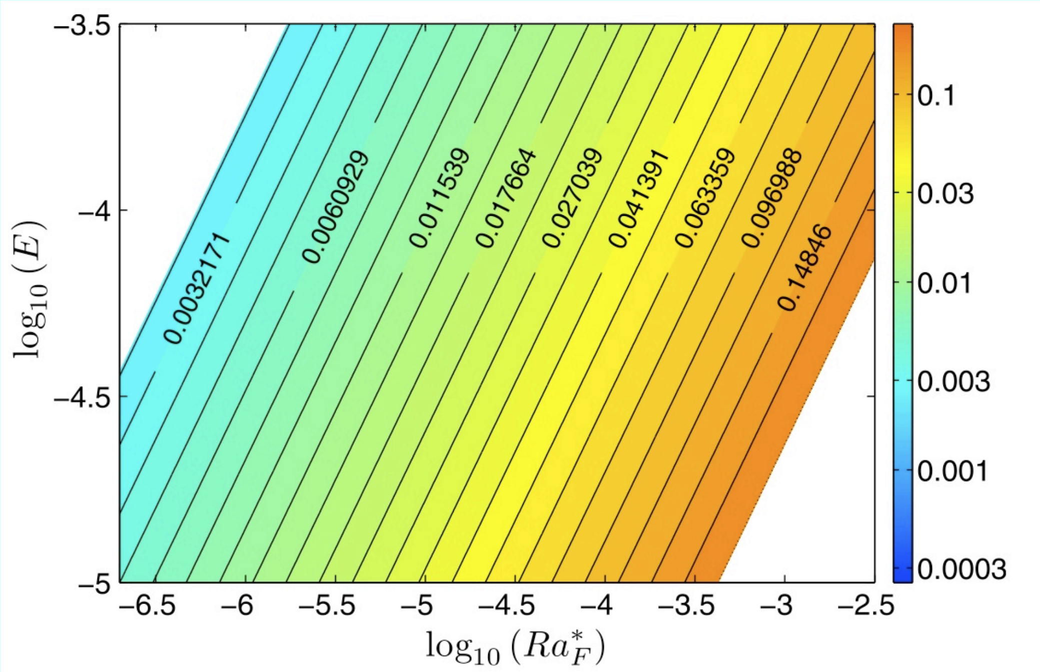
Thus, constant-*Ro* contours should have slopes of one in the $Ra_F{}^{*}$**-*E* plane!**



$\tilde{\rho} 2\Omega \sin\theta \overline{v}$
$\tilde{\rho} 2\Omega \cos\theta \overline{w}$
$\nabla \cdot (\overline{\tilde{\rho} u' \mathbf{u}'})$
$\tilde{\rho} \nu \nabla^2 \overline{u}$
-2 0 2
-2 0 2
-1 0 1
-1 0 1
a
b
c
d



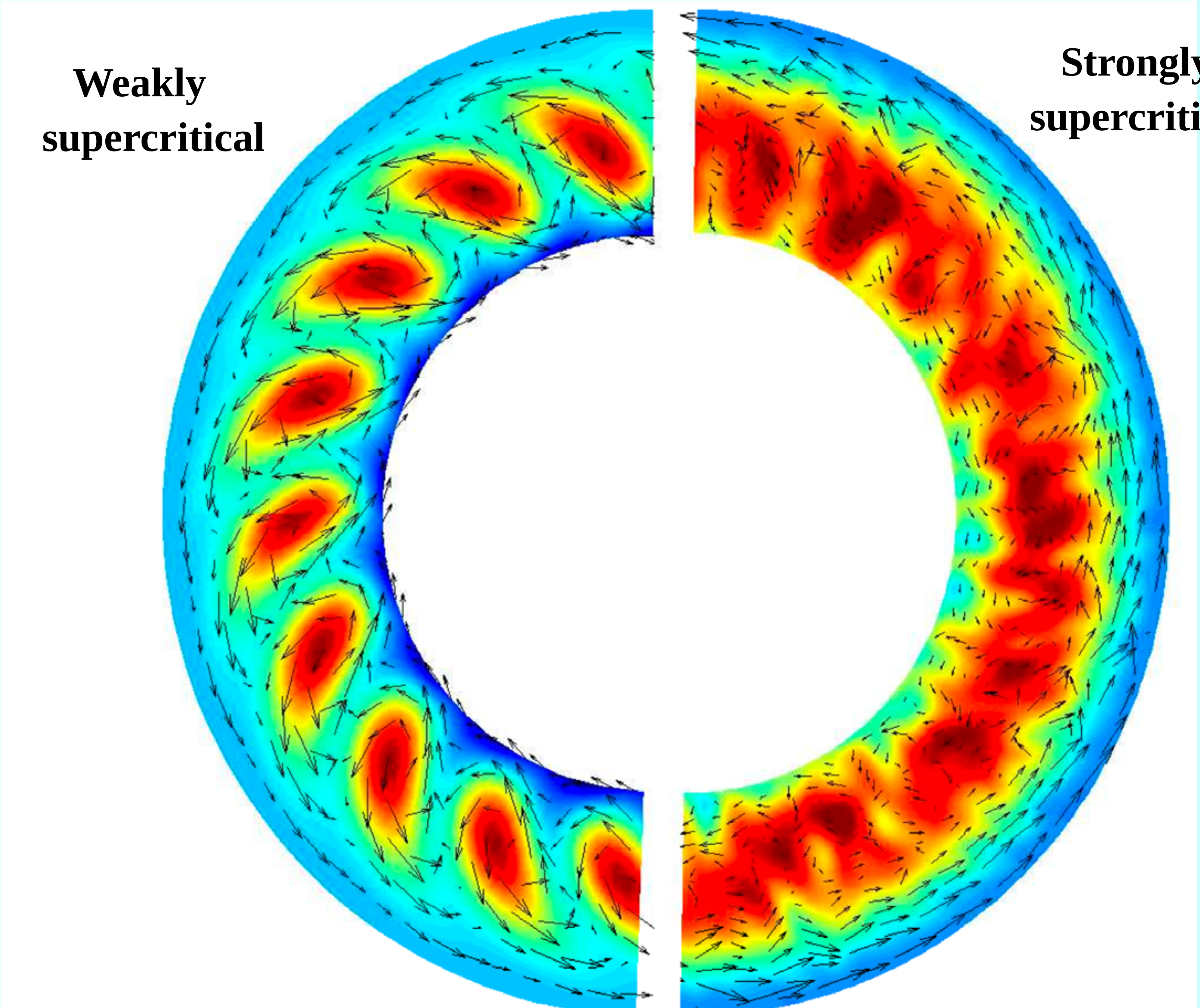
Christensen's (2002) simulations



Analytic scaling for Regime I (constant ε)

Showman et al. (2010)

What about regime II? It exhibits strong zonal/radial velocity correlations



Can we understand the jet speeds in Regime II?

Zonal momentum balance is between jet acceleration and frictional damping:

$$\nabla \cdot (\overline{u'v_s'}) \approx \nu \nabla^2 u$$

which to order of magnitude is $\overline{u'v_s'} \approx \nu k\ u$

If we assume that individual eddy velocities scale with convective velocity, with a correlation coefficient *C*,

$$\overline{u'v_s'} \approx Cw^2$$

Then $u \approx C \dfrac{w^2}{\nu k} \quad \Rightarrow \quad Ro \approx \dfrac{C}{kD} \dfrac{Ro_{conv}^{\ 2}}{E}$

Given our previous expression for the convective velocities, we obtain finally

$$Ro \approx \frac{C}{kD} \frac{\Delta Ra_F^{\ *}}{E}$$

How to combine the two regimes?

The jet-pumping efficiency, ε, is the fraction of convective energy that goes into pumping the jets:

$$\varepsilon = \frac{u\nabla \cdot (\overline{u'v_s'})}{gw\alpha\,\delta T}$$

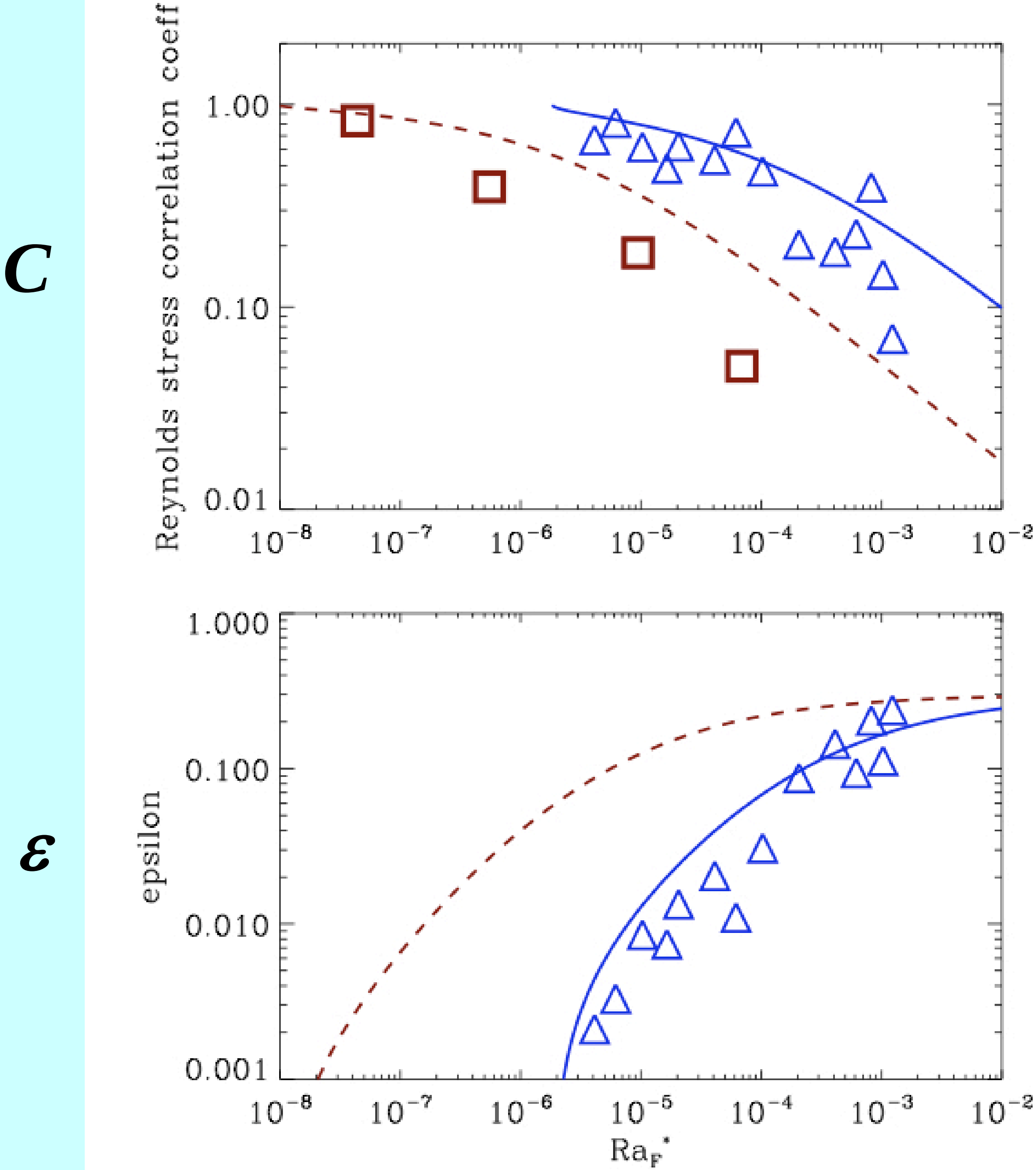
Expressing numerator as $ukCw^2$, the denominator as $g\alpha F/\rho c_p$, and nondimensionalizing leads to

$$\varepsilon \approx \frac{Ro\,kD\,CRo_{conv}^{\;2}}{\Delta Ra_F^{\;*}} \approx C^2 \frac{Ro_{conv}^{\;4}}{E\,\Delta Ra_F^{\;*}}$$

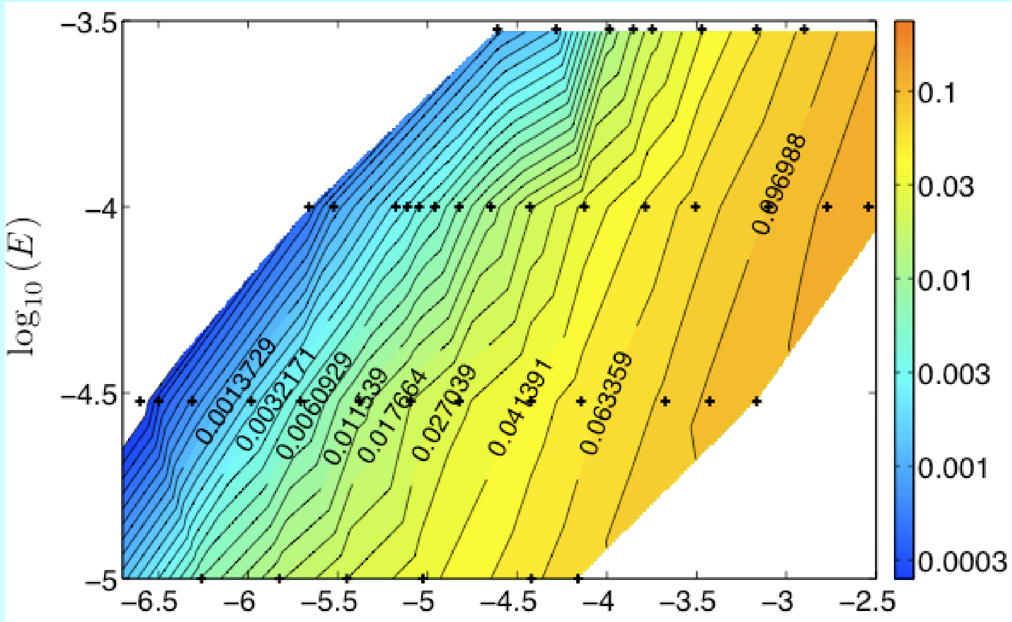
Using our expression for convective velocities, we obtain $\varepsilon \approx C^2 \dfrac{\Delta Ra_F^{\;*}}{E}$

Thus, ε and C cannot simultaneously be constant!

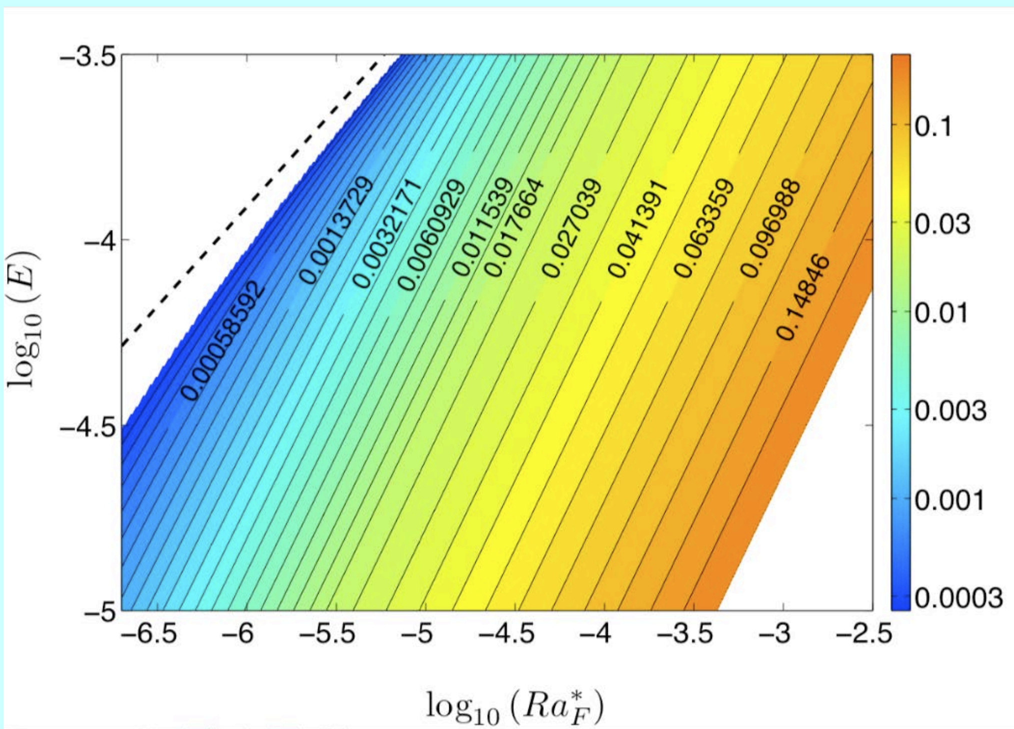
- **If C is constant, then ε must increase with increasing Ra_F^*.**
- **When ε finally plateaus near its maximum value (~1), then C must decrease.**
- **Exactly this behavior is observed in the simulations, and it explains the transition from Regime II to Regime I!**



C
ε
Reynolds stress correlation coeff
1.00
0.10
0.01
epsilon
1.000
0.100
0.010
0.001
10⁻⁸
10⁻⁷
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
Ra_F*



Christensen's (2002) simulations



Analytic scaling that combines Regimes I and II

Showman et al. (2011)

Asymptotic regime?

Christensen (2002) suggested that, at sufficiently small viscosities, the convection approaches an asymptotic regime where the wind speeds (Rossby numbers) become independent of viscosities, empirically following

$$Ro = 0.53\left(Ra_F{}^*\right)^{1/5}$$

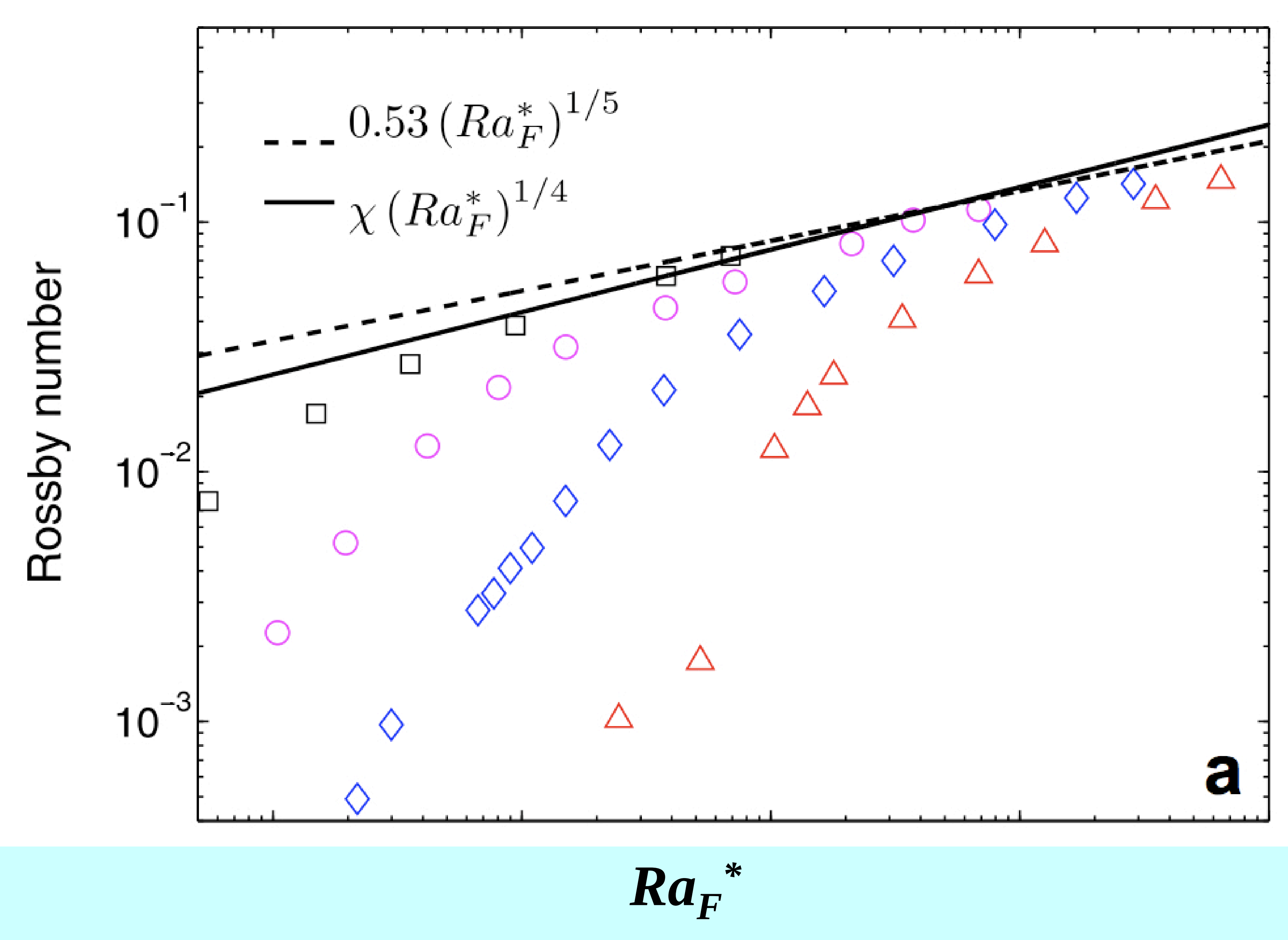
Can we explain this? **Same scaling as before, namely** $U \approx k^{-1}\left(\frac{\varepsilon\alpha g F}{\rho c_p \nu}\right)^{1/2}$

but suppose damping results from an eddy (rather than molecular or numerical) viscosity, given by

$$\nu_{\text{eddy}} \approx wH$$

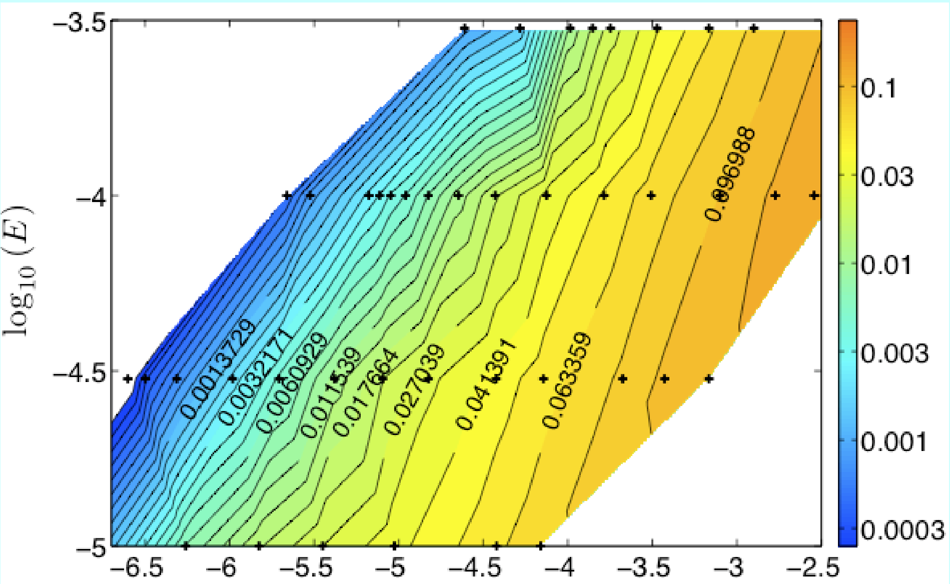
Since $w \propto F^{1/2}$**, we have that** $\nu_{\text{eddy}} \propto F^{1/2}$**, which implies** $U \propto F^{1/4}$

Nondimensionalizing, we obtain $Ro \approx \left(Ra_F{}^*\right)^{1/4}$

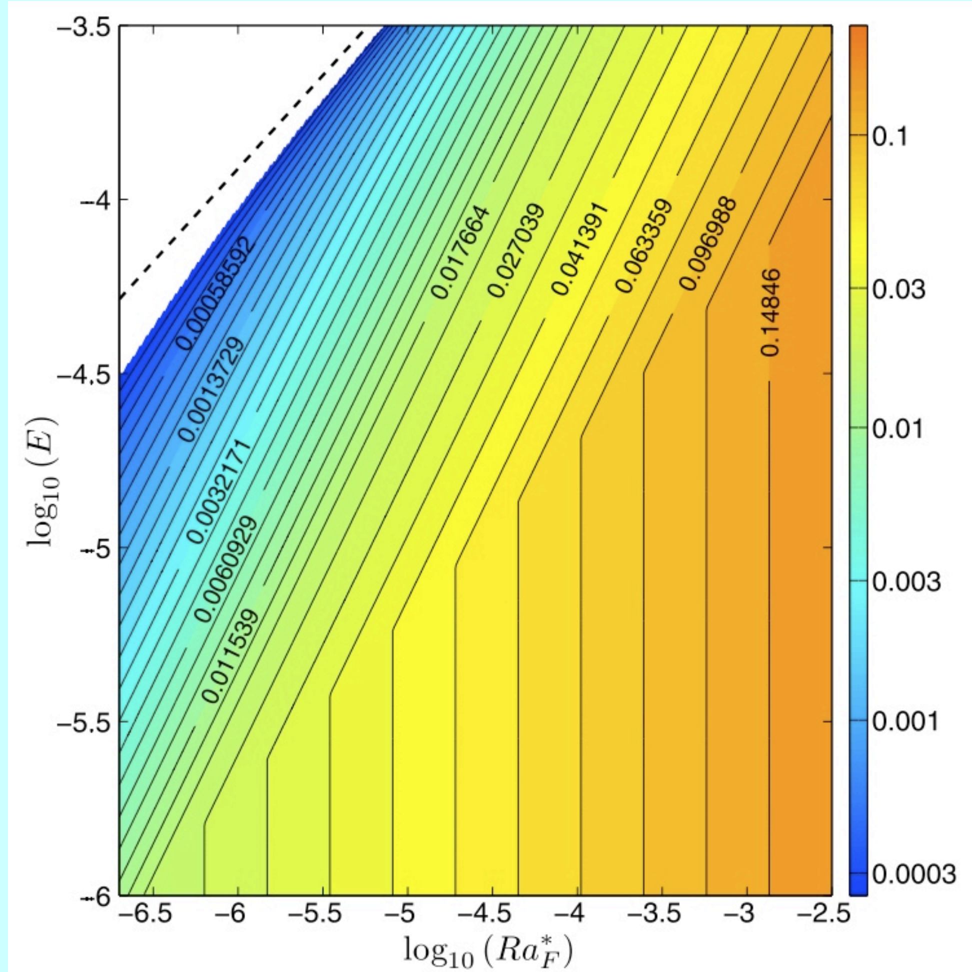


$0.53\,(Ra_F^*)^{1/5}$
$\chi\,(Ra_F^*)^{1/4}$
Rossby number
10^{-1}
10^{-2}
10^{-3}
a
$Ra_F{}^*$

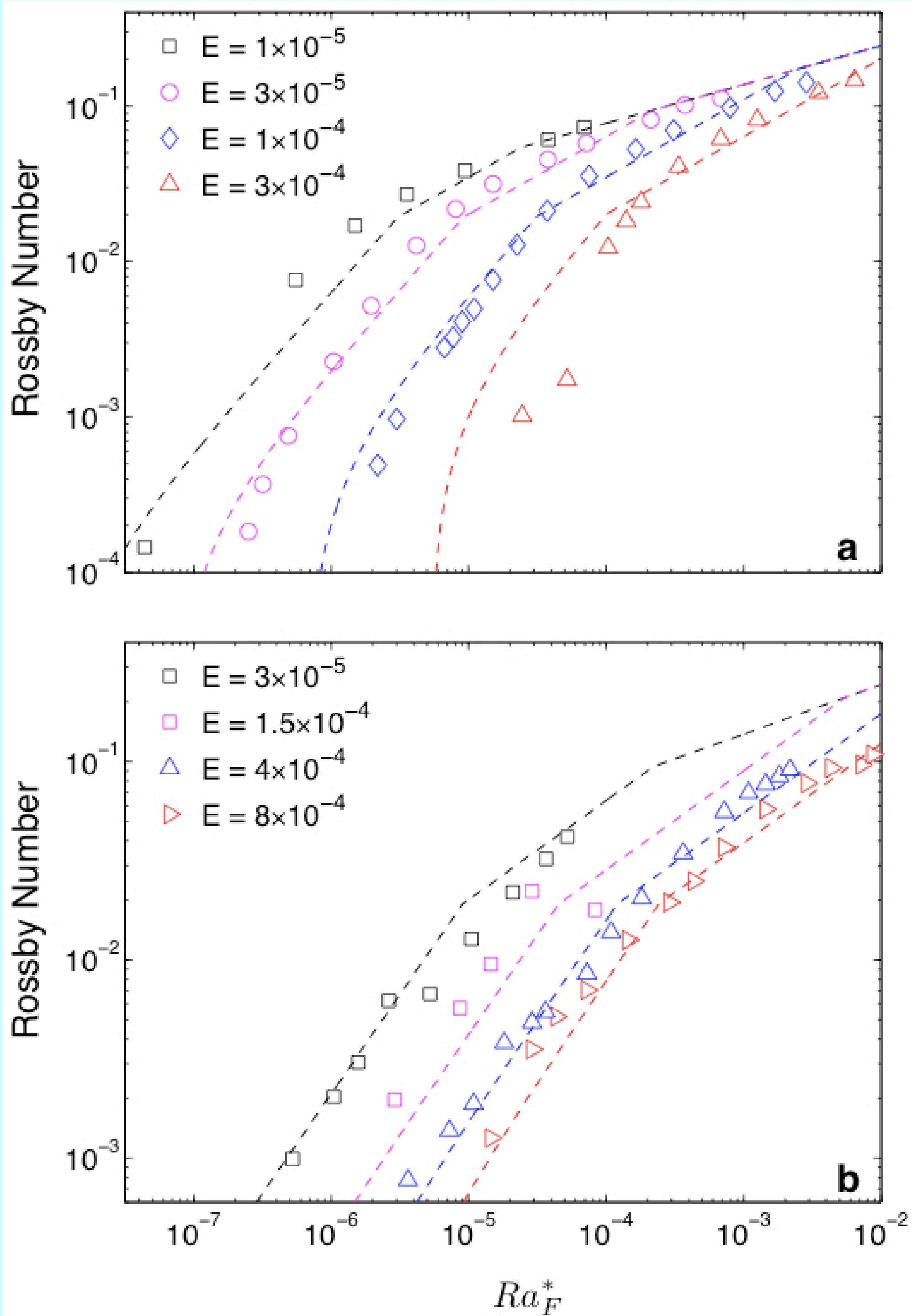
Christensen's (2002) simulations



Analytic scaling combining Regimes I, II, III



Showman et al. (2011)



Showman et al. (2011)

Conclusions

- **Current 3D simulation of convection in giant planet interiors are overforced by factors of 10^5-10^{10}. It has remained unclear how to extrapolate such simulations to the Jovian regime, and even what processes control trends within the simulated regime.**

- **We constructed a simple theory suggesting that, when the viscosity on the jet scale dominates the damping, the mean jet speeds should scale approximately as F/ν at weakly supercritical Rayleigh numbers and $(F/\nu)^{1/2}$ at strongly supercritical Rayleigh numbers, where F is heat flux and ν is the numerical viscosity. This explains the mean jet speeds found by Christensen (2002) and Kaspi et al. (2009) to within a factor of ~2 over a wide range of parameters.**

- **The relationship between the correlation coefficient C and the jet-pumping efficiency ε naturally explains how the transition between these regimes occurs.**

- **If at low viscosity the mean jet speeds become independent of viscosity (as suggested by Christensen), our simple theory predicts that mean jet speeds should scale as $F^{1/4}$. This compares favorably with an empirical fit to simulation results by Christensen, which suggested an $F^{1/5}$ dependence.**

- **When extrapolated to Jupiter's heat flux, both asymptotic scalings suggest that wind speeds in Jupiter's molecular envelope are weak. Juno will help test this prediction.**