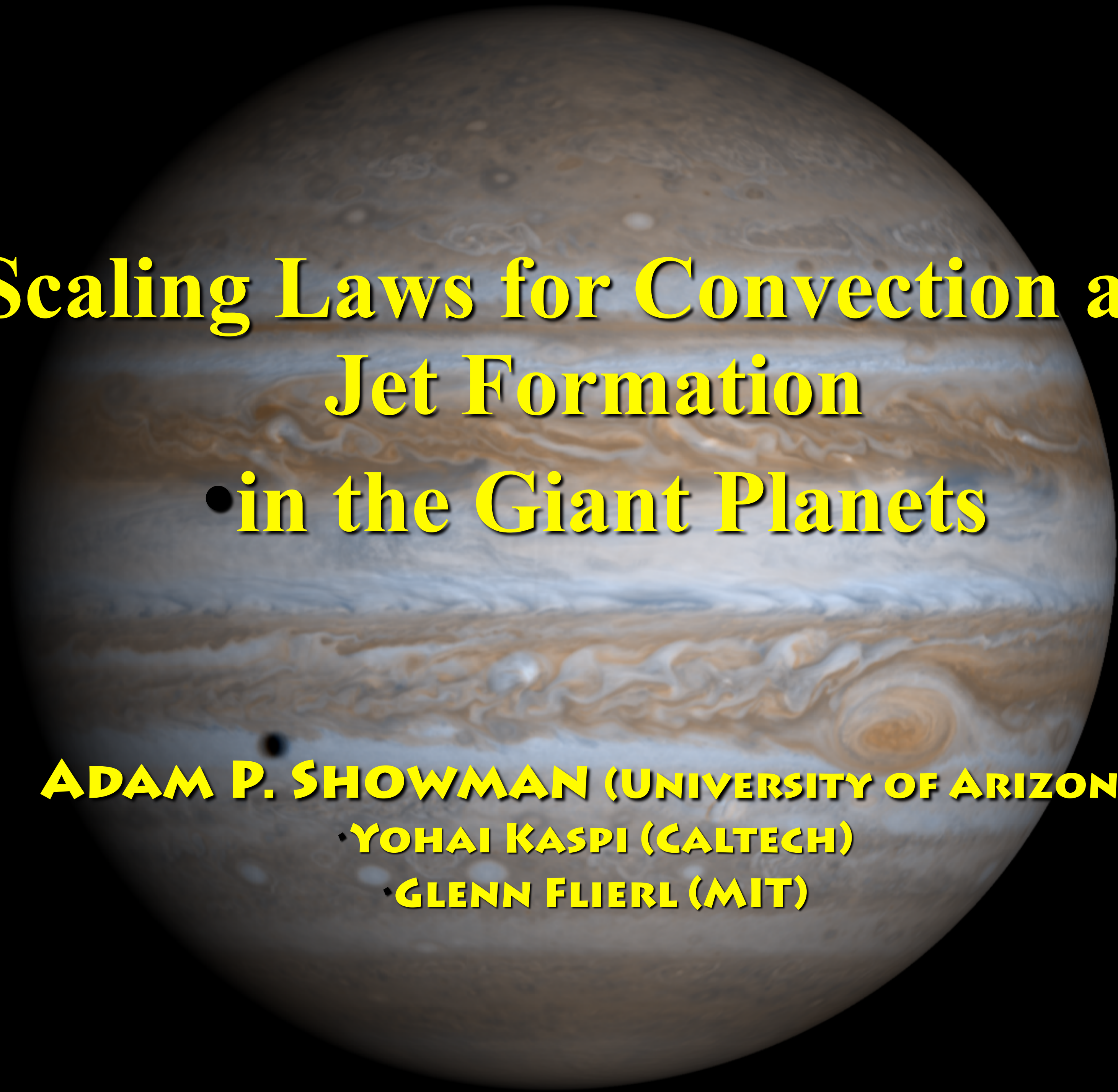
Scaling Laws for Convection and Jet Formation in the Giant Planets

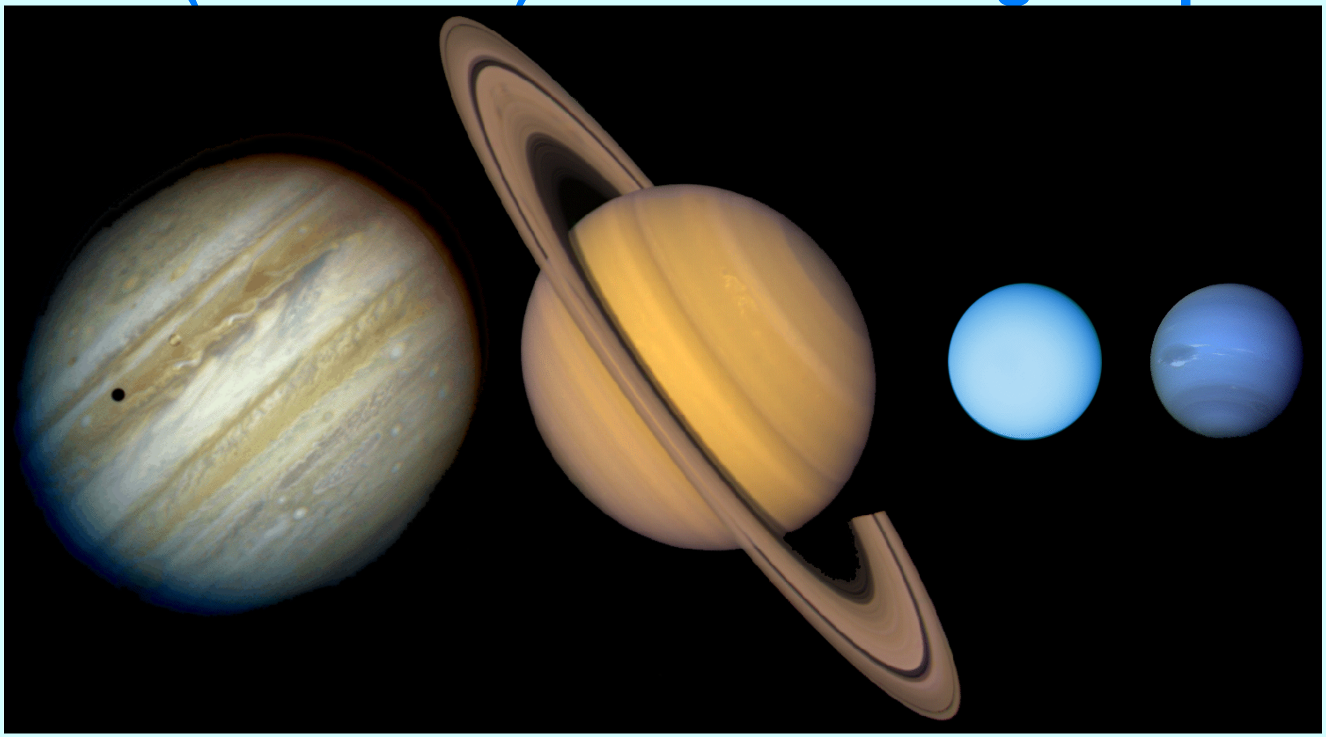


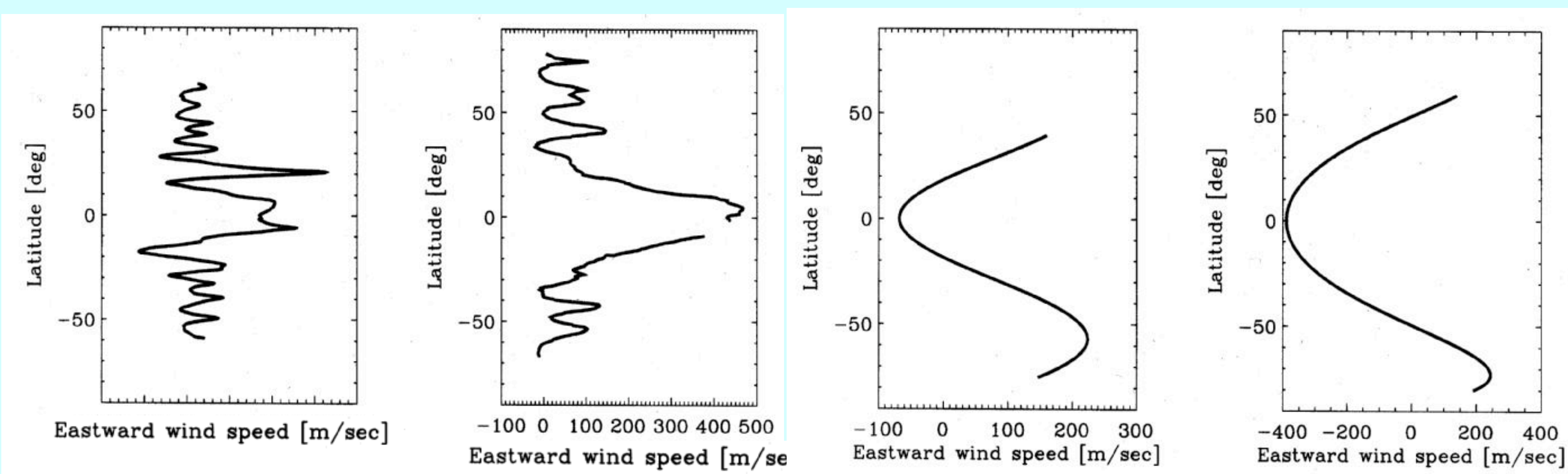
Adam P. Showman (University of Arizona)

Yohai Kaspi (Caltech)

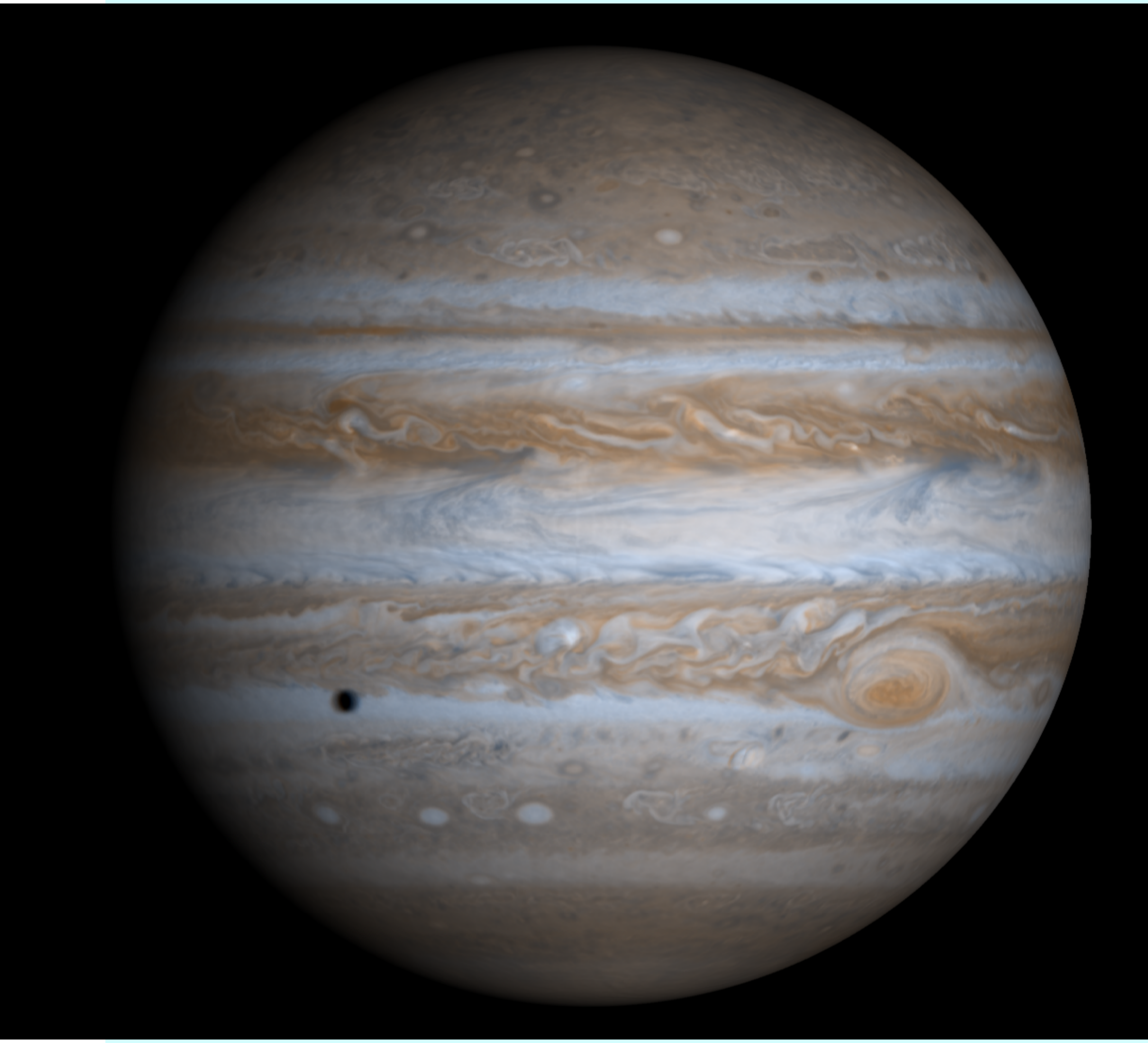
Glenn Flierl (MIT)

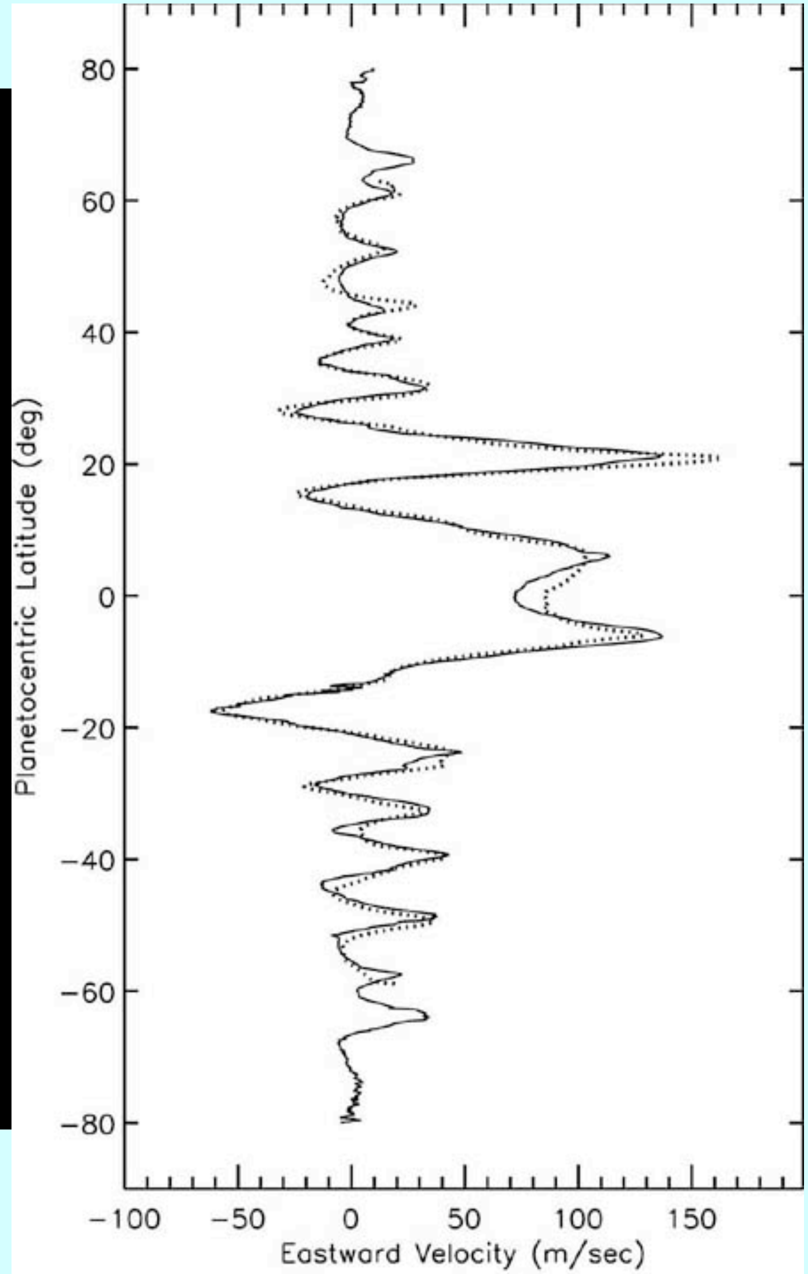
Zonal (east-west) winds on the giant planets





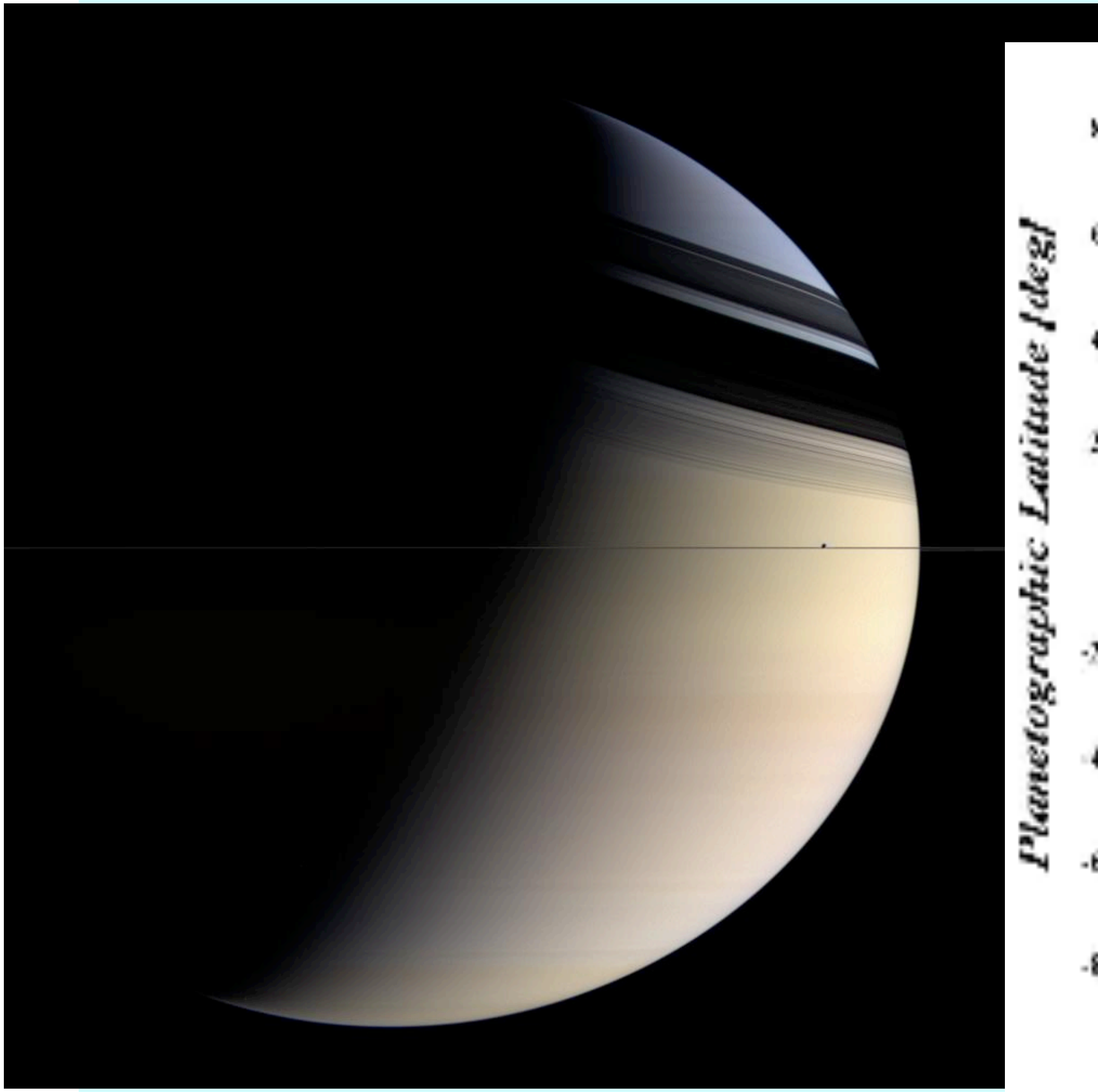
Jupiter's Zonal Winds

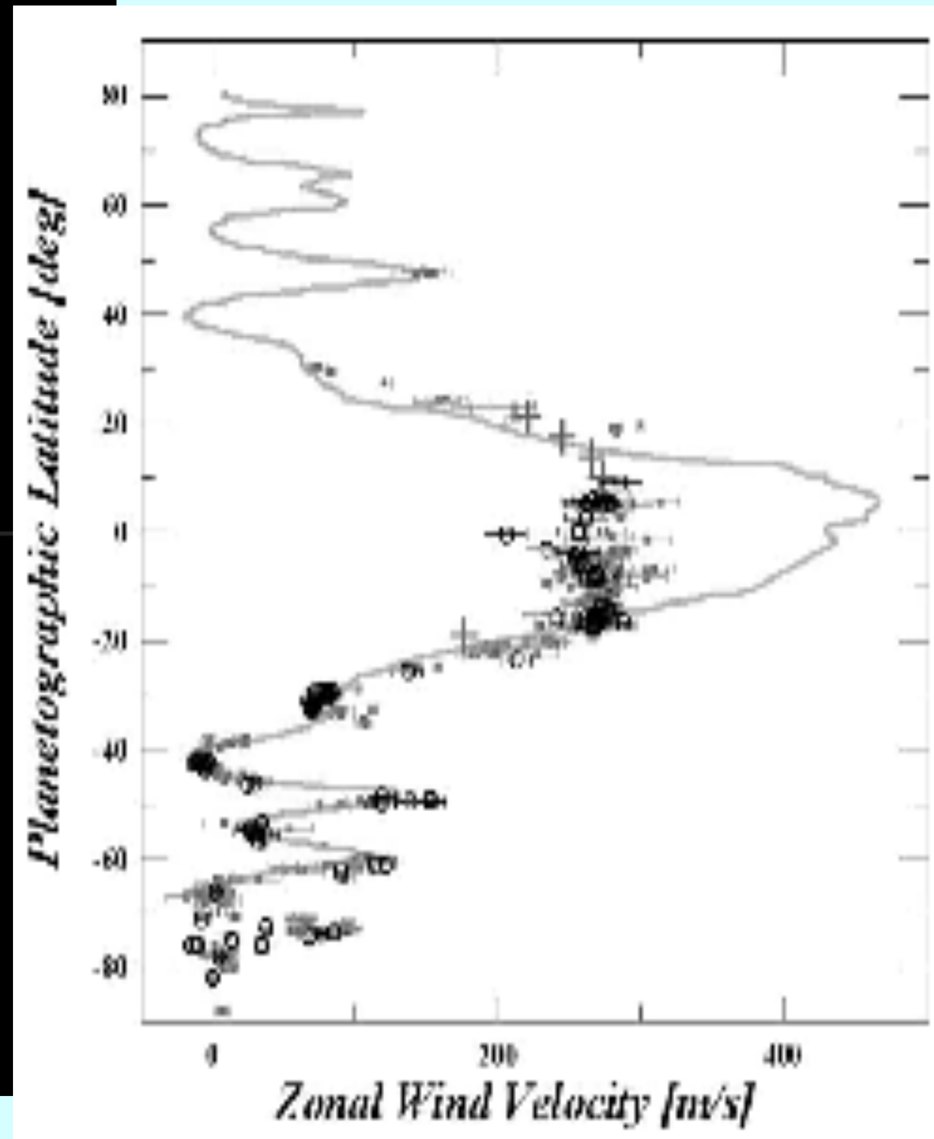




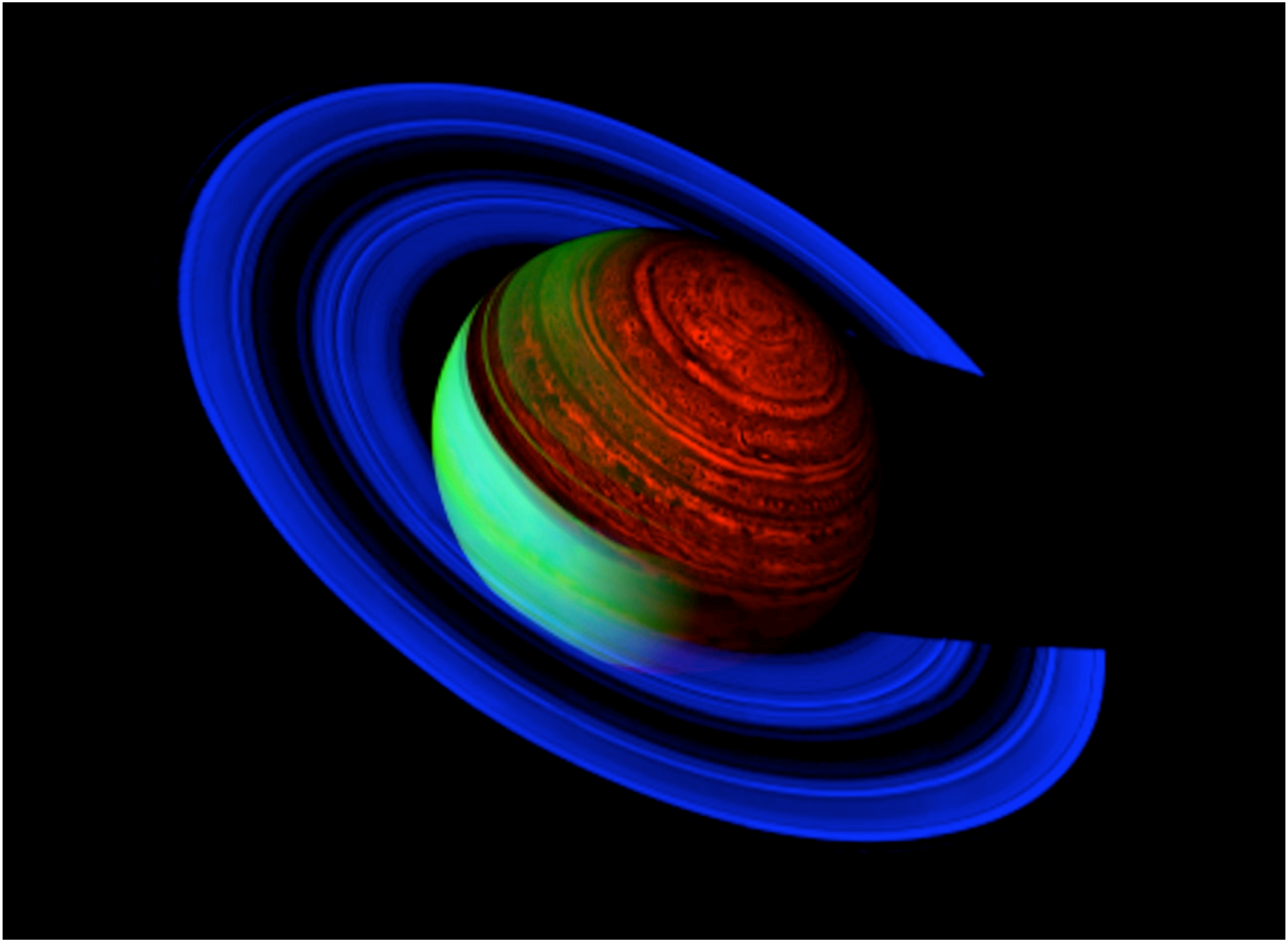
Limaye (1986), Porco et al. (2003)

Saturn’s zonal winds

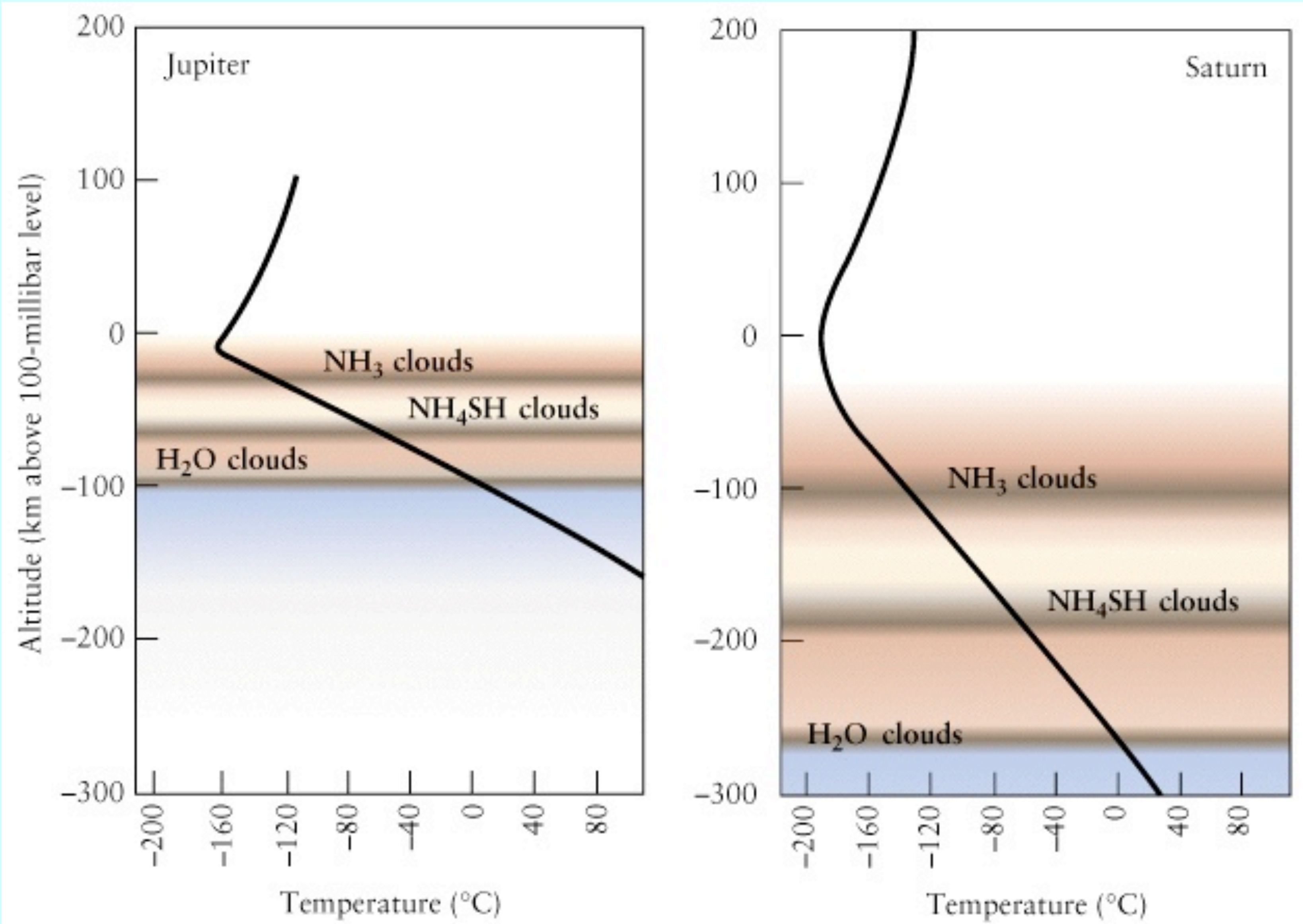




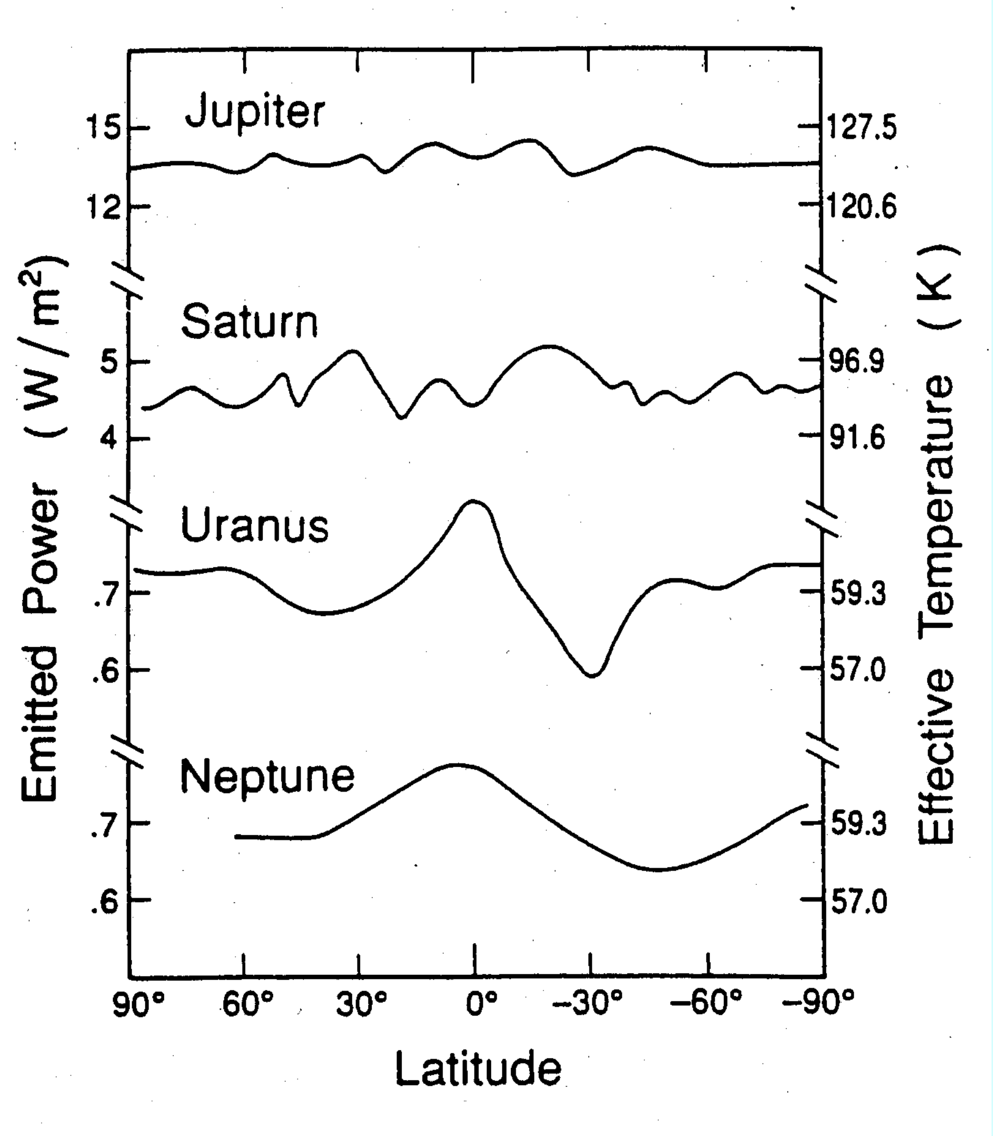
Sanchez-Lavega et al. (2004, 2007); Porco et al. (2005)



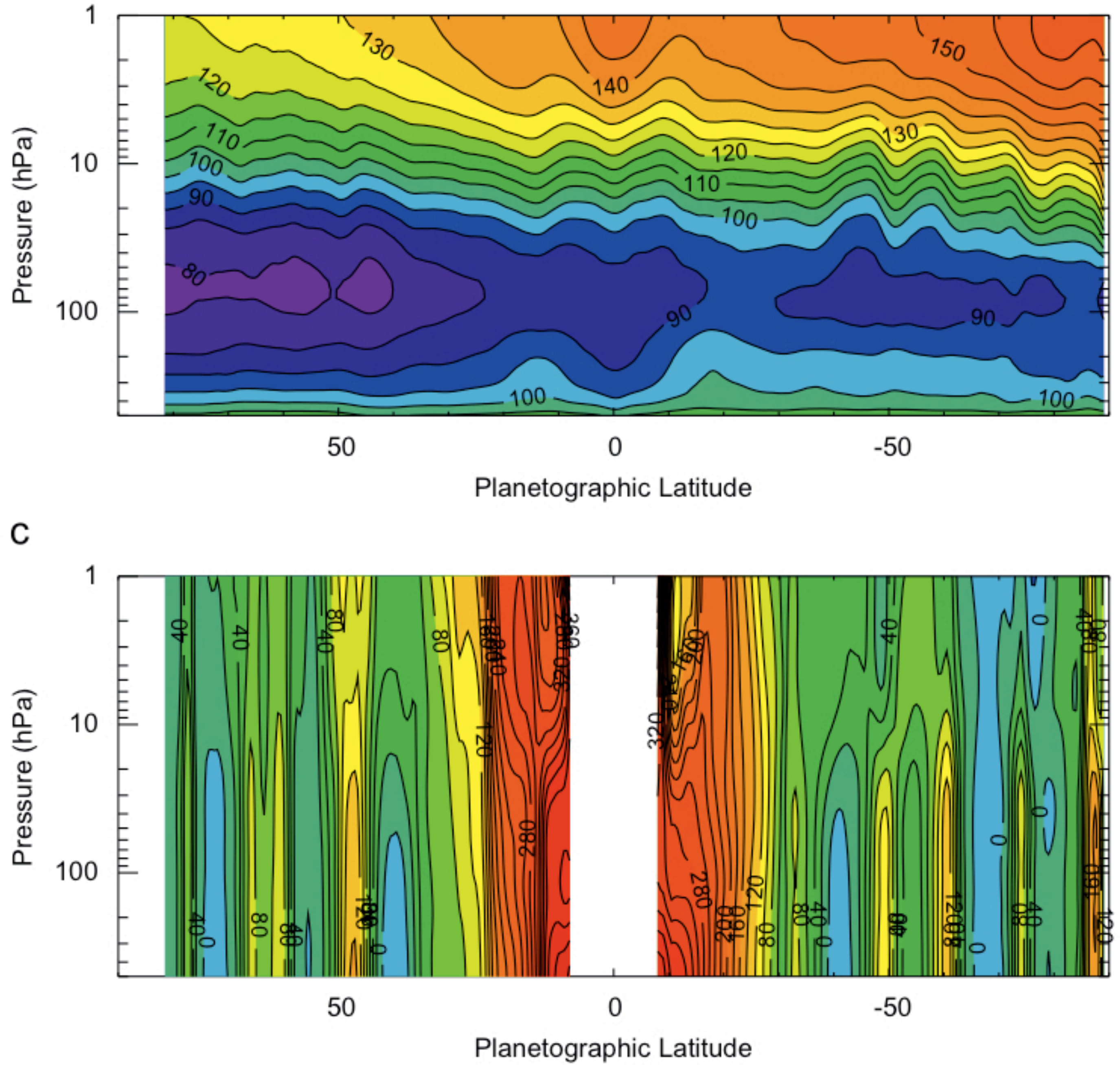
Jupiter and Saturn's temperatures and clouds



Temperatures are relatively homogeneous:



Ingersoll (1990)

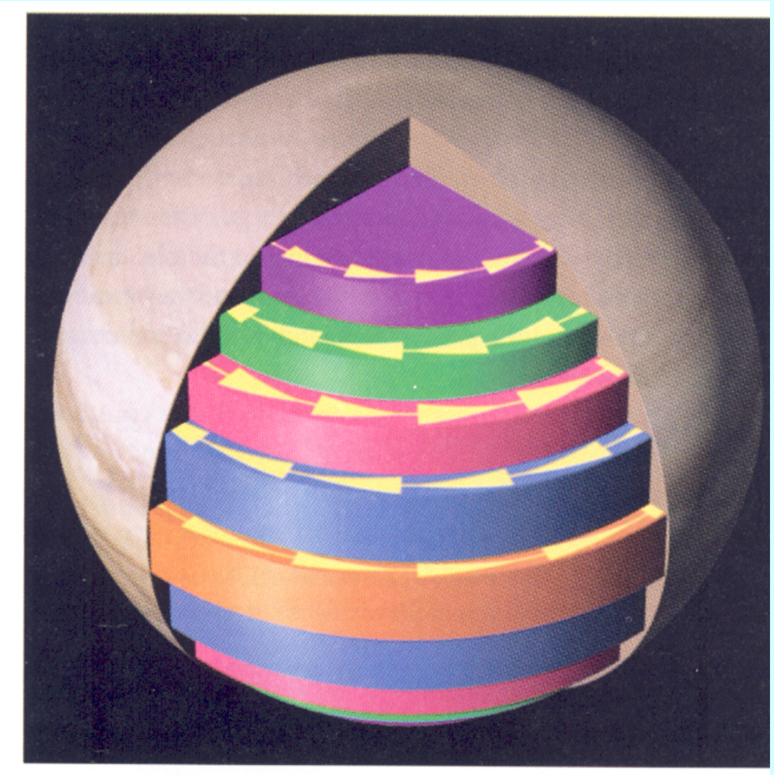


Read et al. (2009)

Puzzles

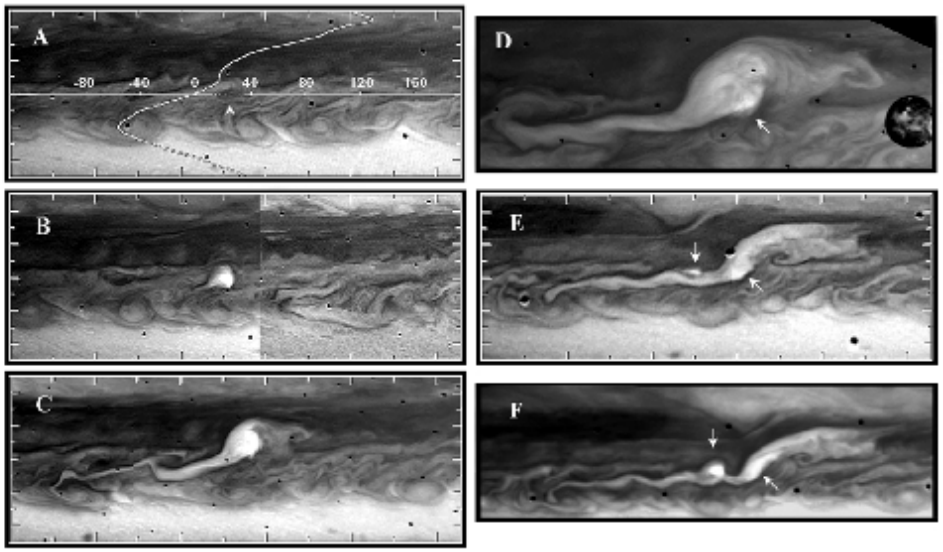
- **What causes the banded structure, with ~20 jets on Jupiter and Saturn yet only ~3 on Uranus and Neptune? What is the jet-pumping mechanism? How deep do the jets extend?**
- **Why do Jupiter and Saturn have superrotating equatorial jets whereas Uranus and Neptune do not?**
- **What causes the vortices? 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?**

Basic Jet Scenarios



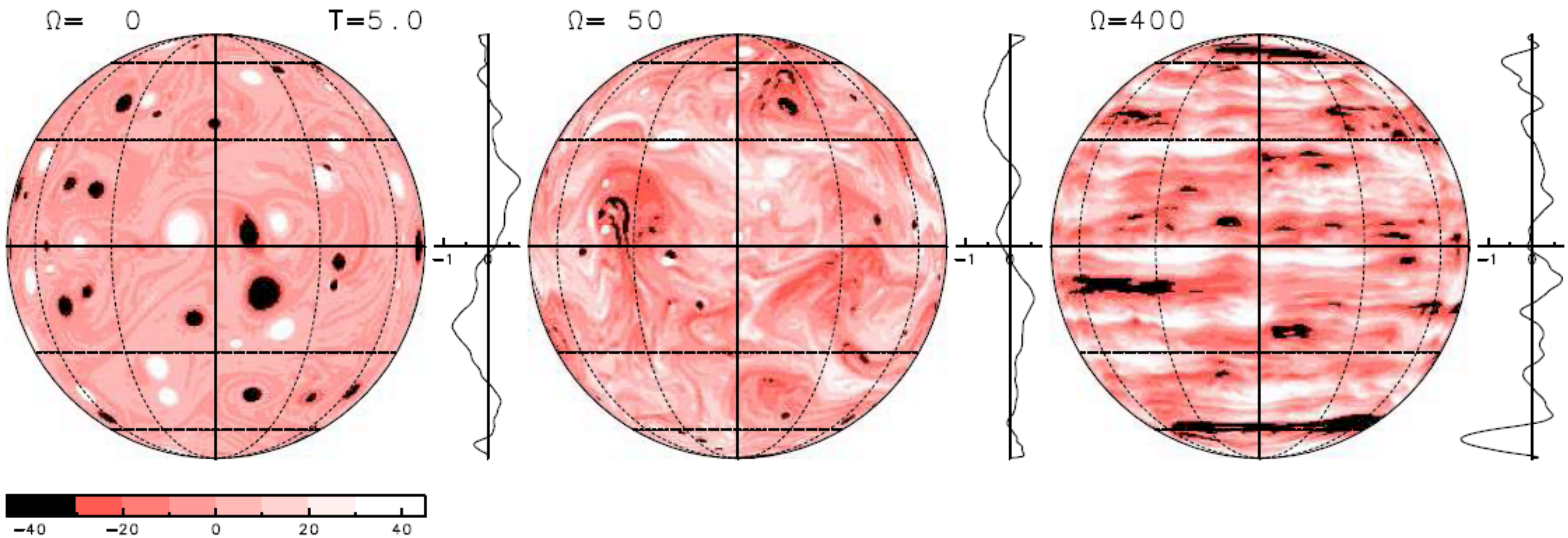
- **Models for jet structure:**
  - ***<u>Shallow:</u>*** **Jets confined to outermost scale heights below the clouds**
  - ***<u>Deep:</u>*** **Jets extend through molecular envelope (Taylor-Proudman theorem)**

- **Models for jet pumping:**
  - ***<u>Shallow:</u>*** **Turbulence at cloud level (thunderstorms or baroclinic instabilities)**
  - ***<u>Deep:</u>*** **Convective plumes penetrating the molecular envelope**



One must distinguish jet *structure* and *forcing* – they are distinct issues!

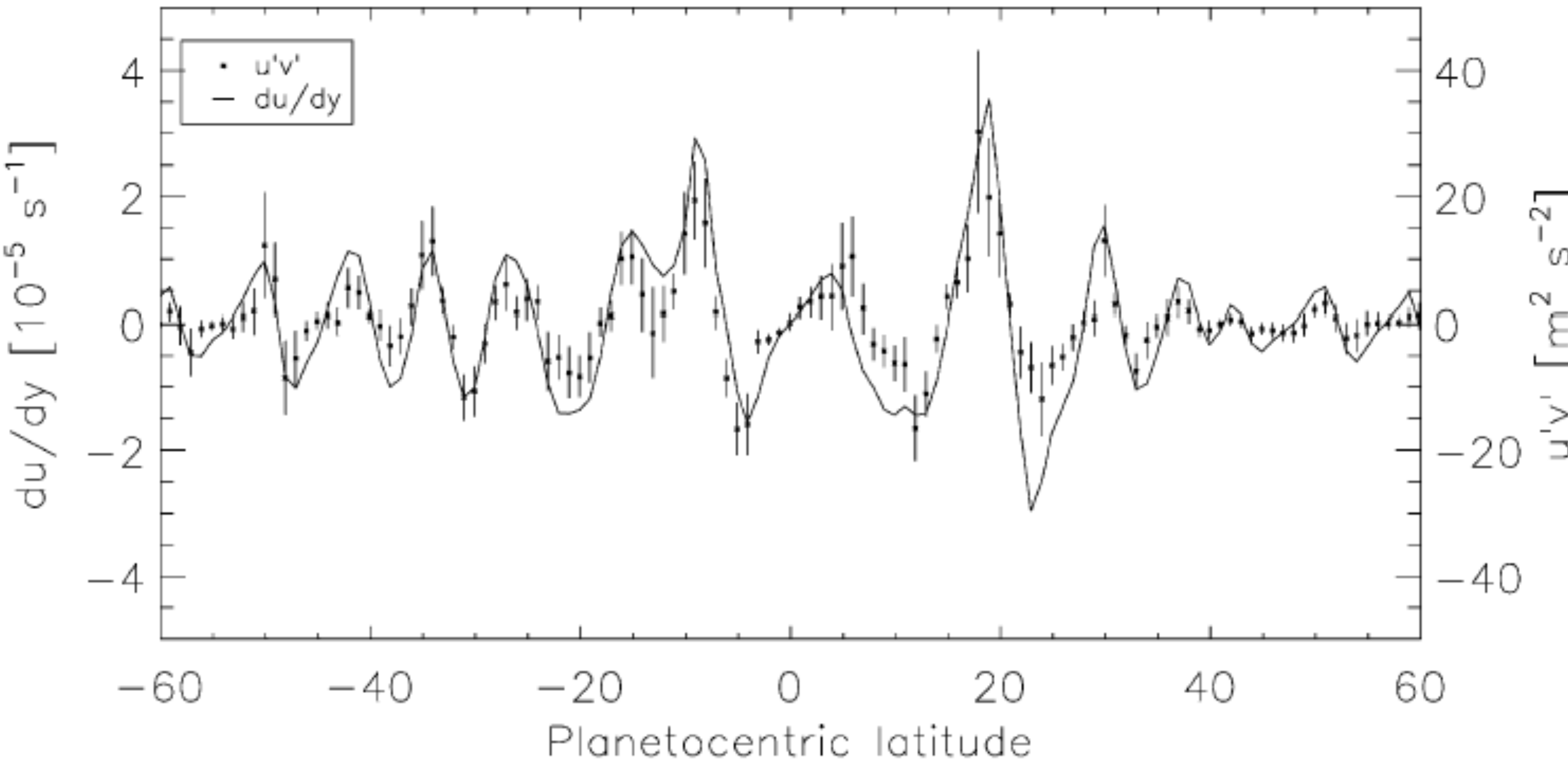
Banded structure results from modification of turbulent interactions by the β effect



Hayashi et al. (2000)

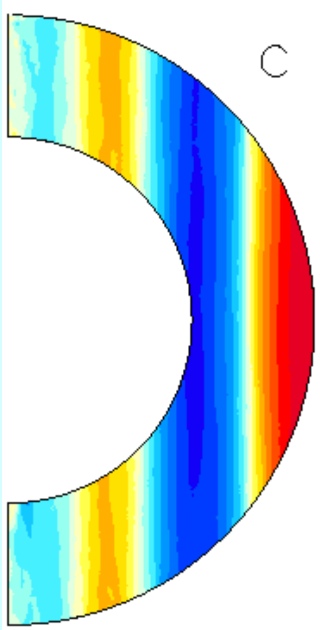
Evidence for jet pumping at the cloud level

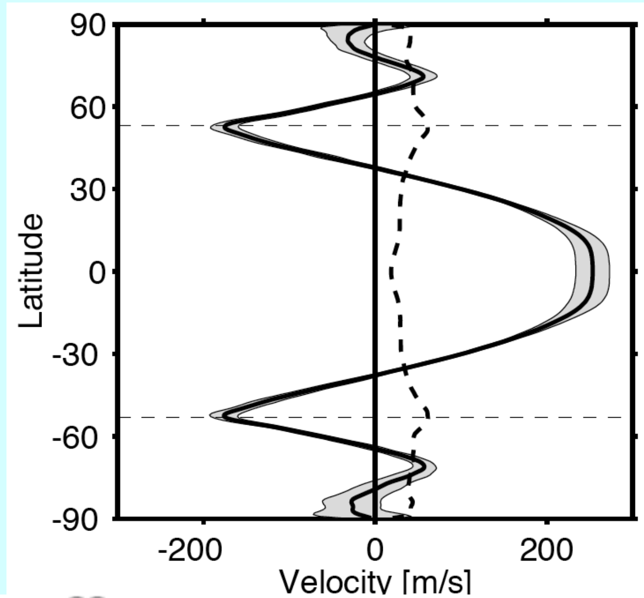
Small eddies transport momentum upgradient into the jets, thereby accelerating them. This transfers energy directly from the small eddies to the large jets:



Salyk et al. (2006); Del Genio et al. (2007)

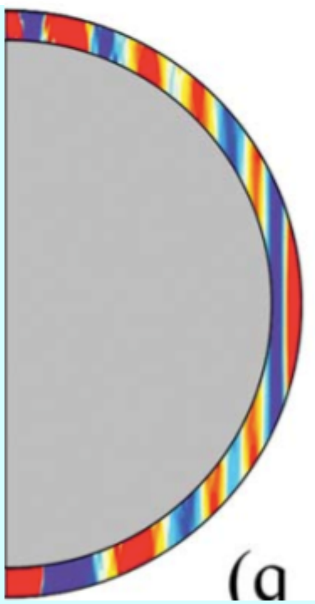
Deep convection models

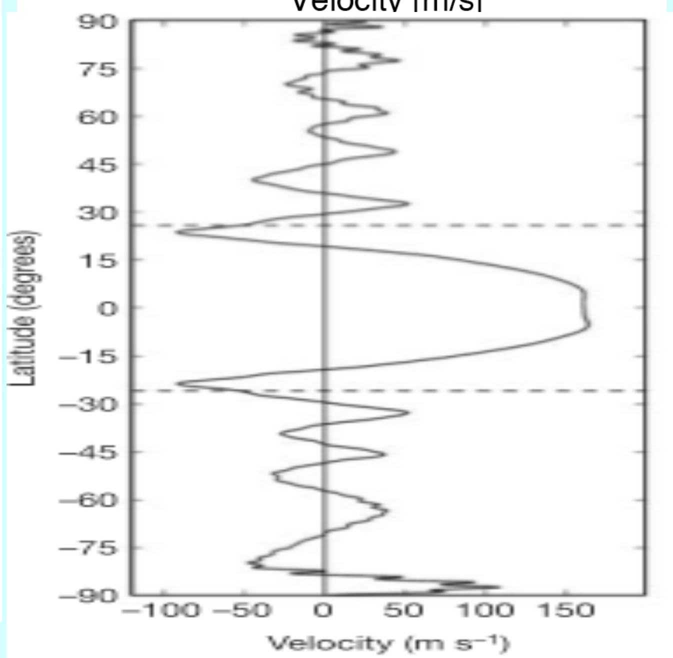




Thick shell

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





Thin shell

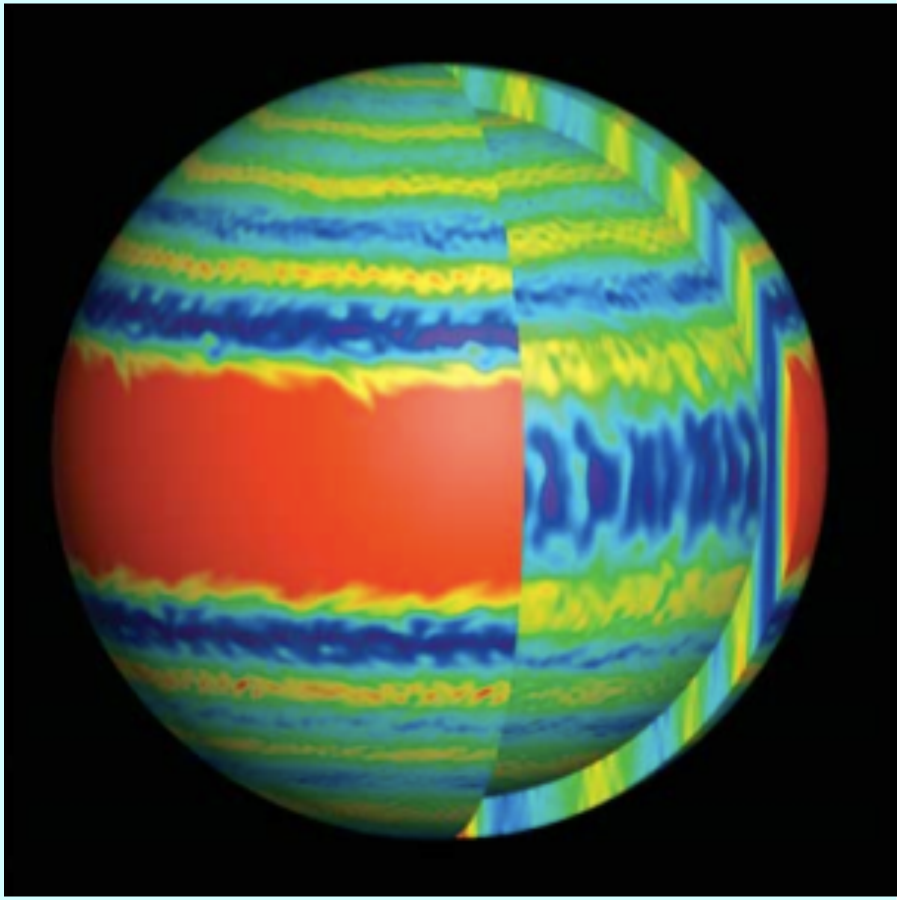
(Heimpel et al. 2005; Heimpel & Aurnou 2007; Aurnou et al. 2008)

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:

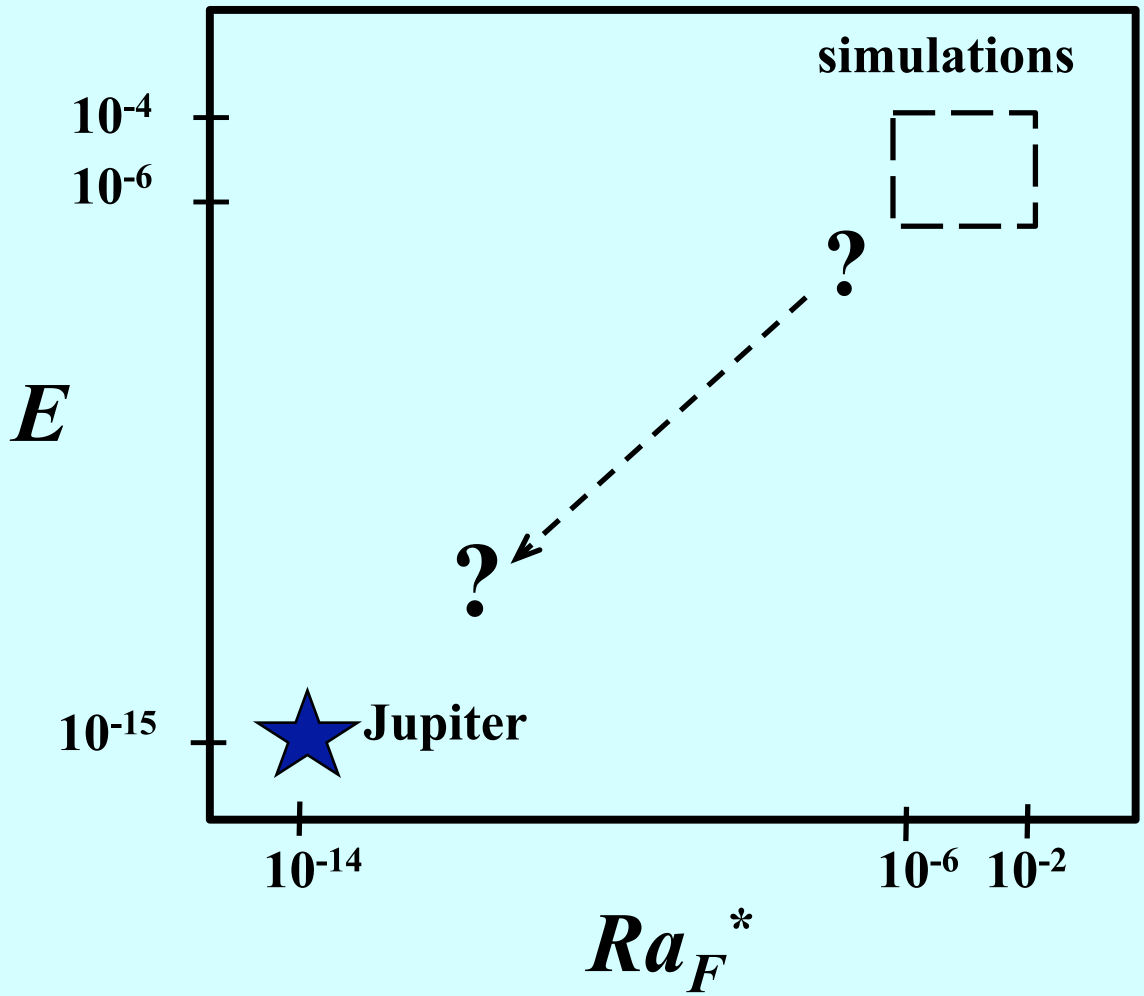
$$Ra_F^{\ *} = \frac{\alpha g F_{\mathrm{tot}}}{\rho c_p \Omega^3 D^2} \qquad E = \frac{\nu}{\Omega D^2} \qquad P = \frac{\nu}{\kappa}$$

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

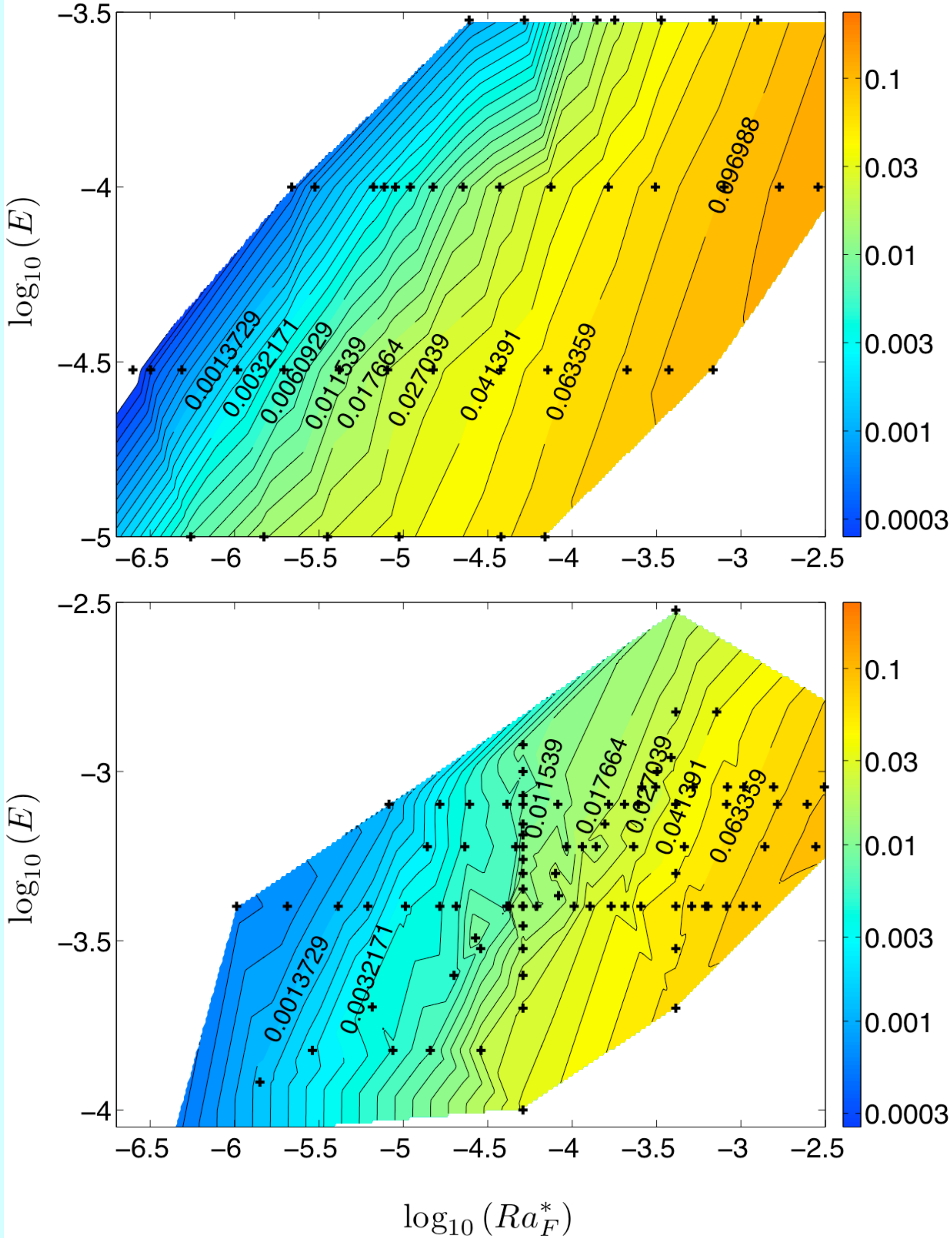
$$F = \frac{\rho c_p \Omega^3 D^2}{\alpha g} Ra_F^{\ *}$$

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

Challenges with deep convection models

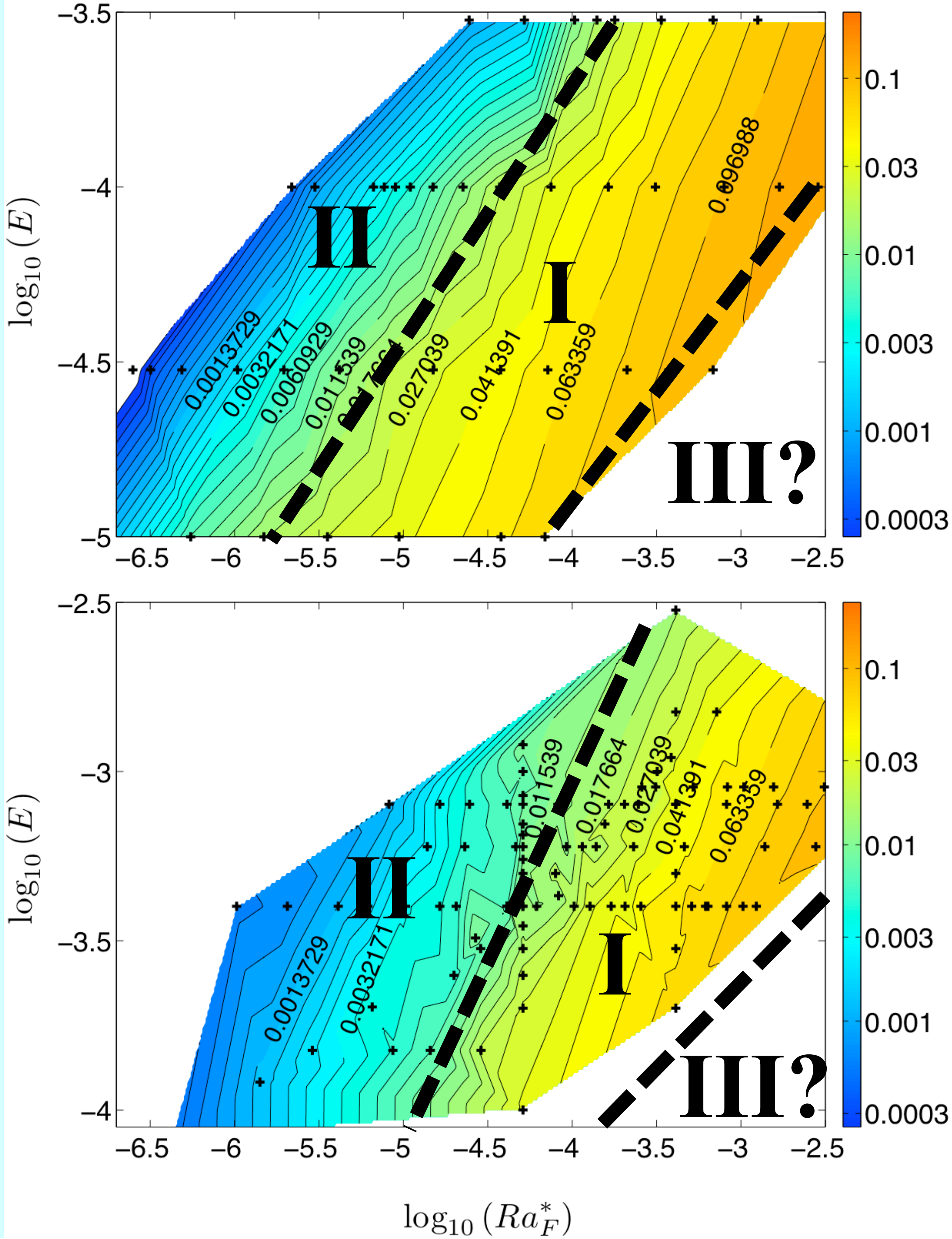


Would convection at Jupiter-like Ra_F^* and E produce Jupiter-like wind speeds? How to extrapolate to Jupiter? This is not known!



Simulations from Christensen (2002)

Simulations from Kaspi et al. (2009); Showman et al. (2010)



Simulations from Christensen (2002)

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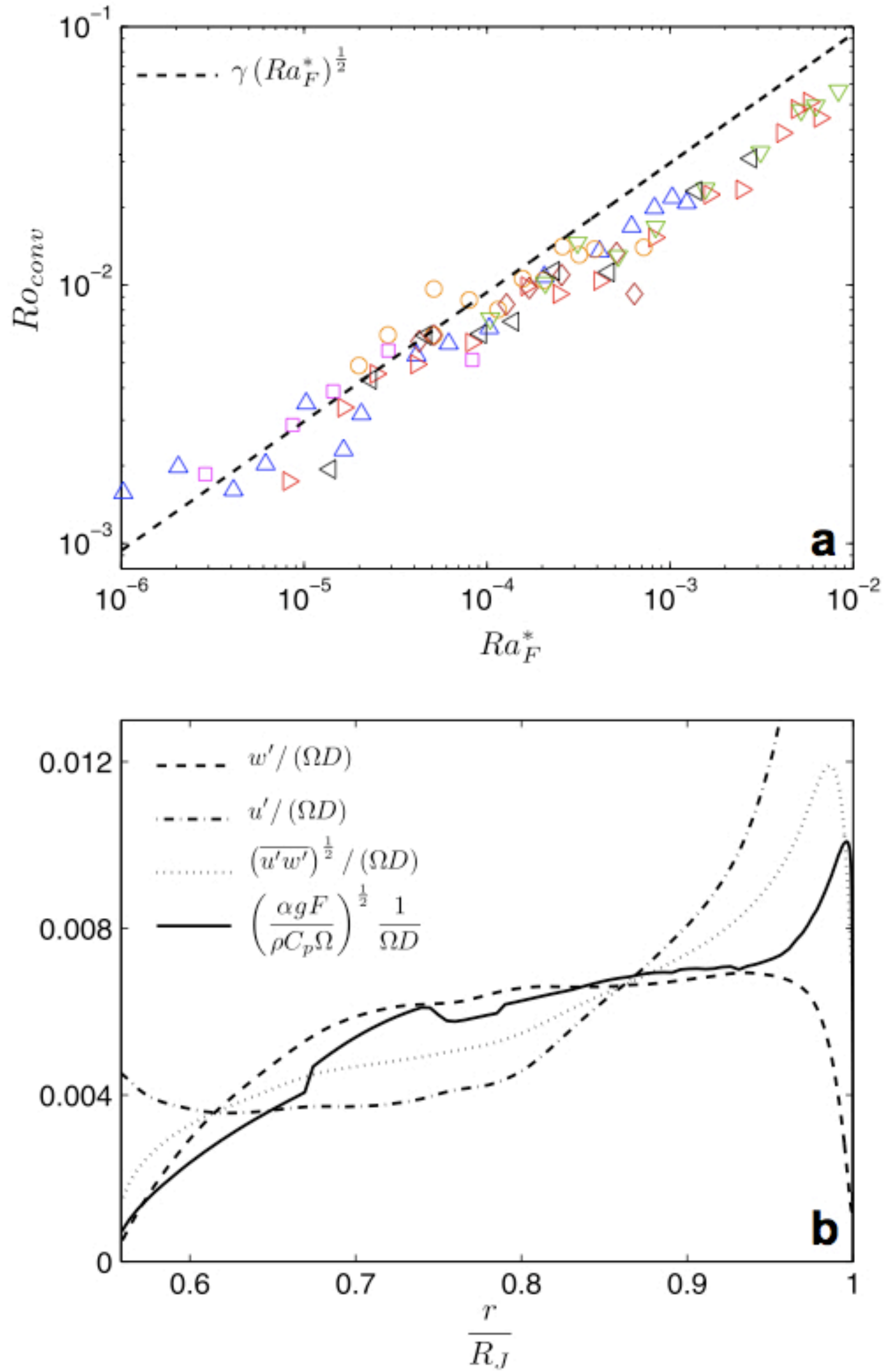


Convective velocities are well explained by the relation

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

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

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

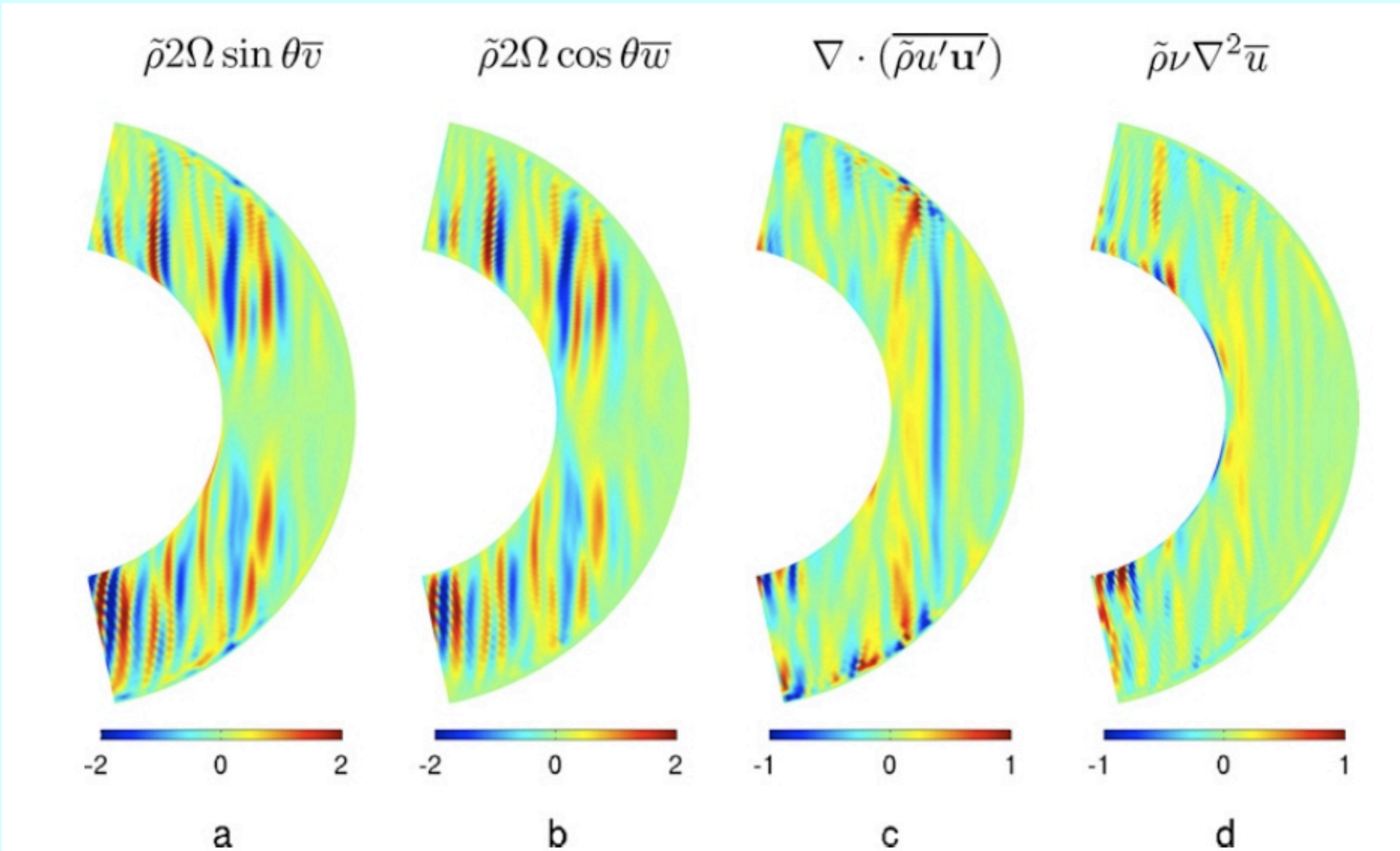
Now $F \approx \rho c_p w \delta T$ **which implies that**

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

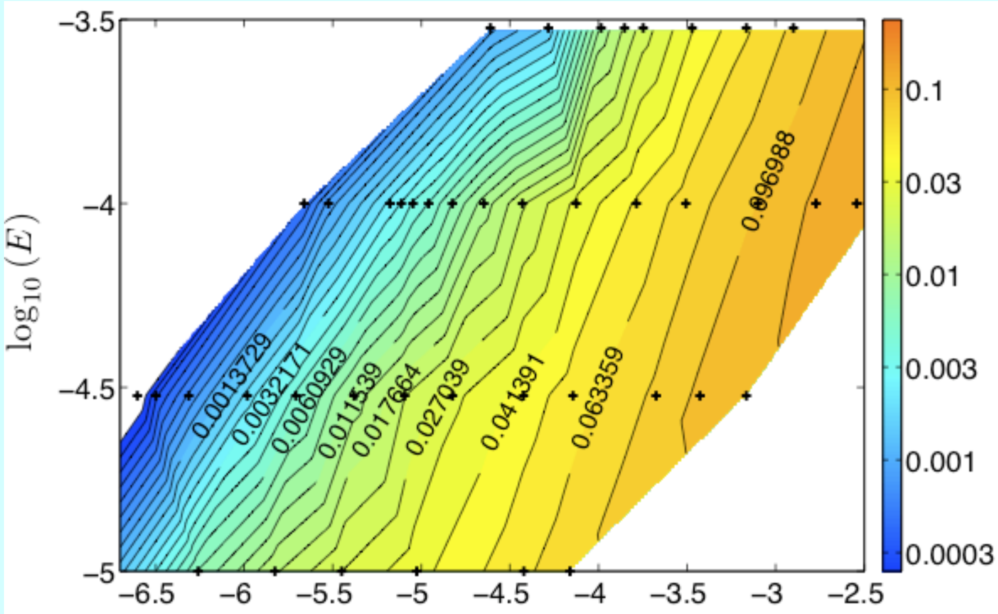
Suppose a fraction ε of this energy pumps the jets and is resisted by viscous damping with a viscosity ν. Then

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

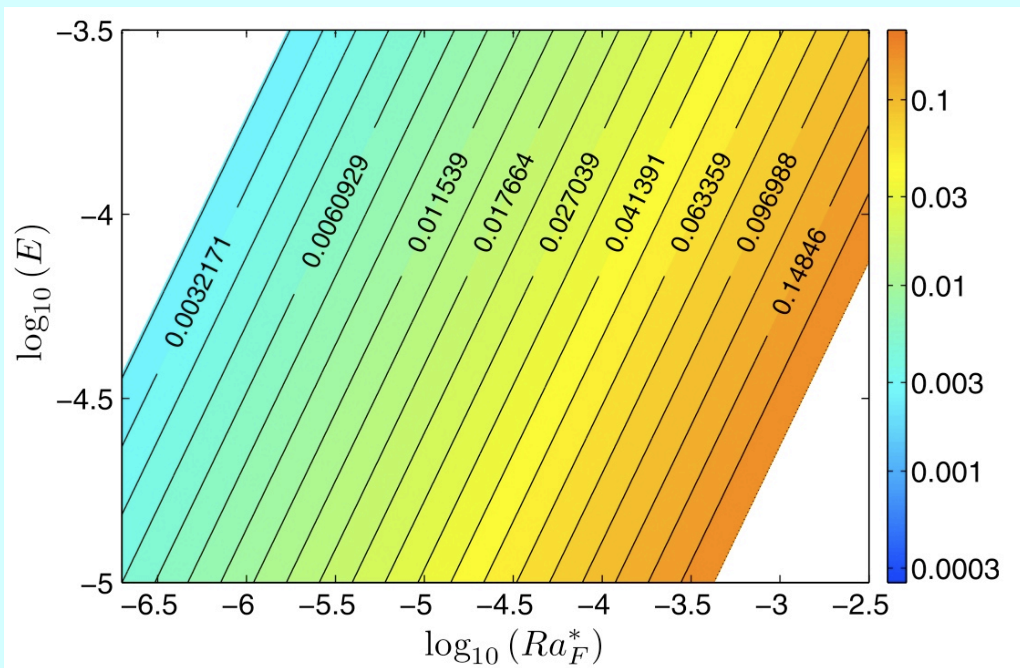
Thus, constant-*Ro* contours should have slopes of one in the $Ra_F{}^{*}$-E plane!



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



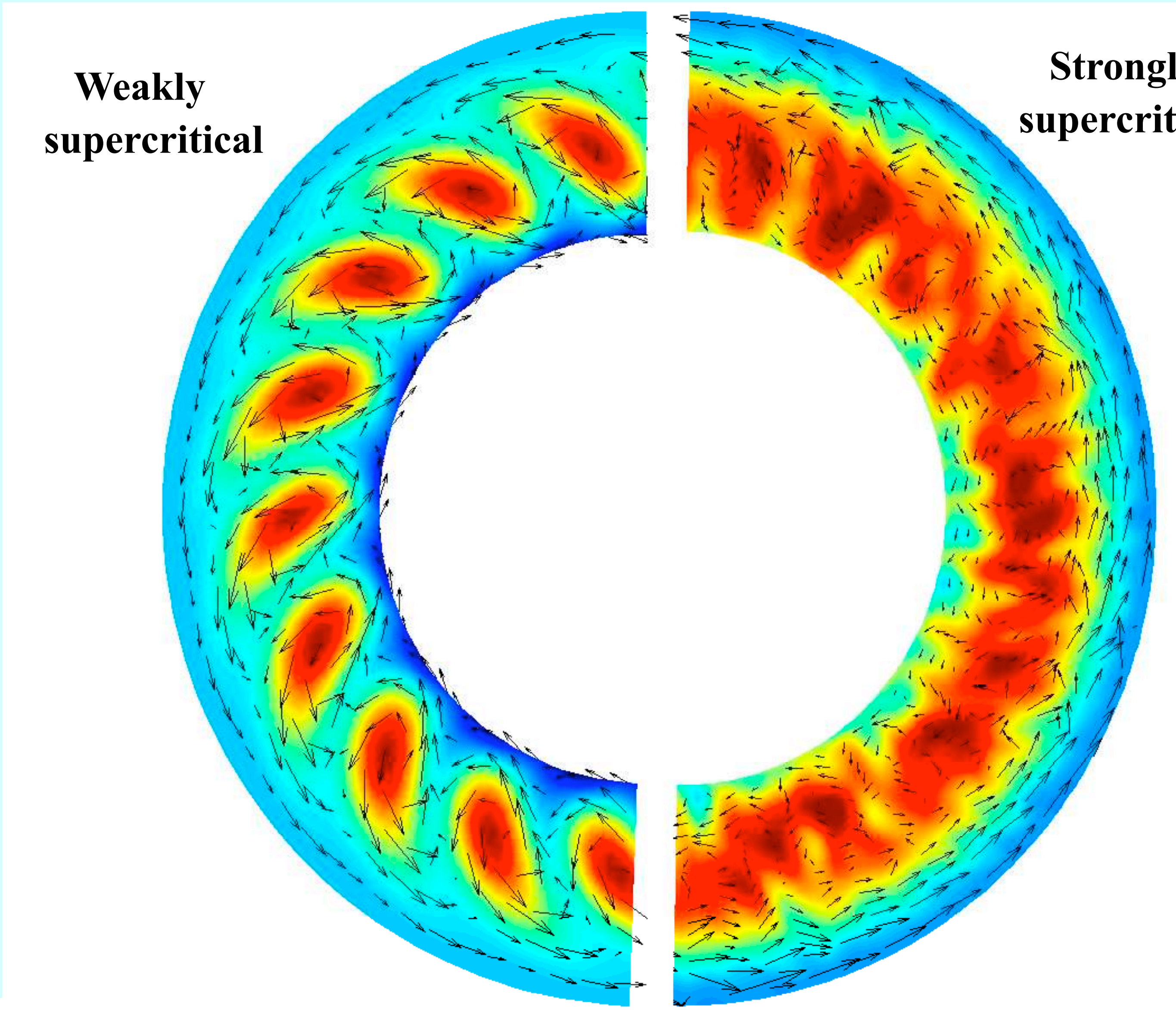
Christensen's (2002) simulations



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*****,**

$$\overline{u' v_s'} \approx C w^2$$

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

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

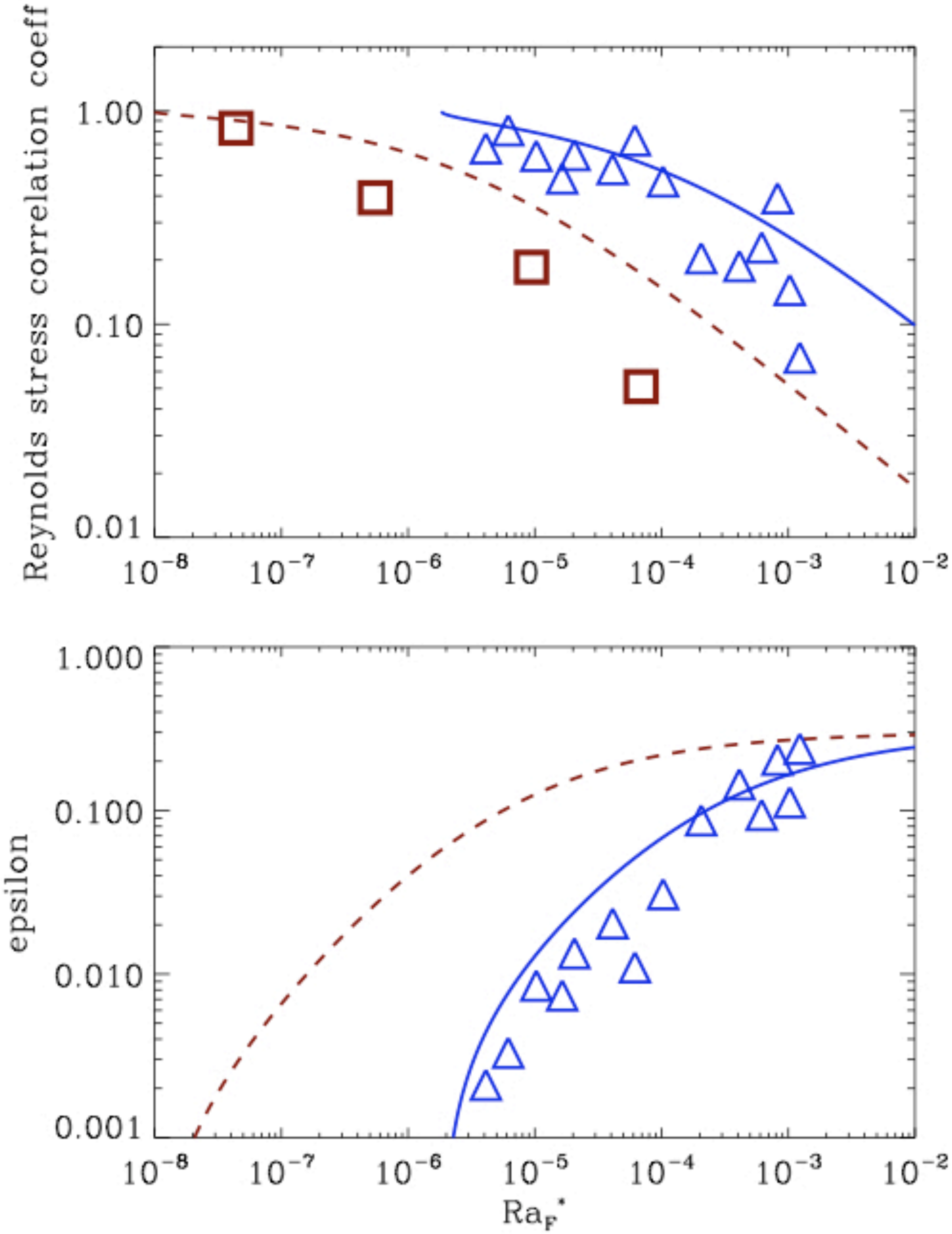
Using our expression for convective velocities, we obtain $\varepsilon \approx C^2 \dfrac{\Delta Ra_F^{\;*}}{E}$

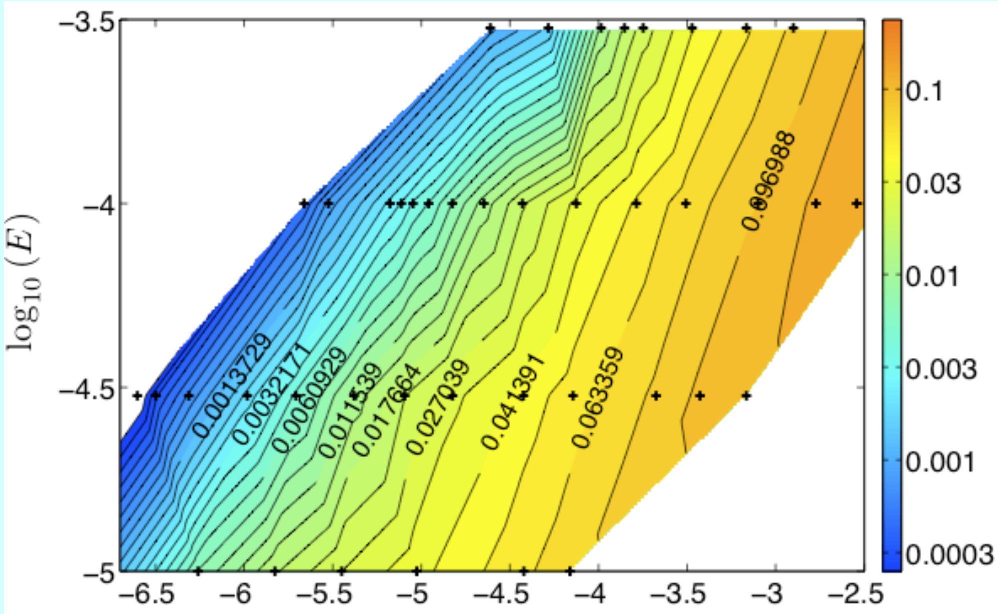
Thus, ε and C cannot simultaneously be constant!

- **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!**

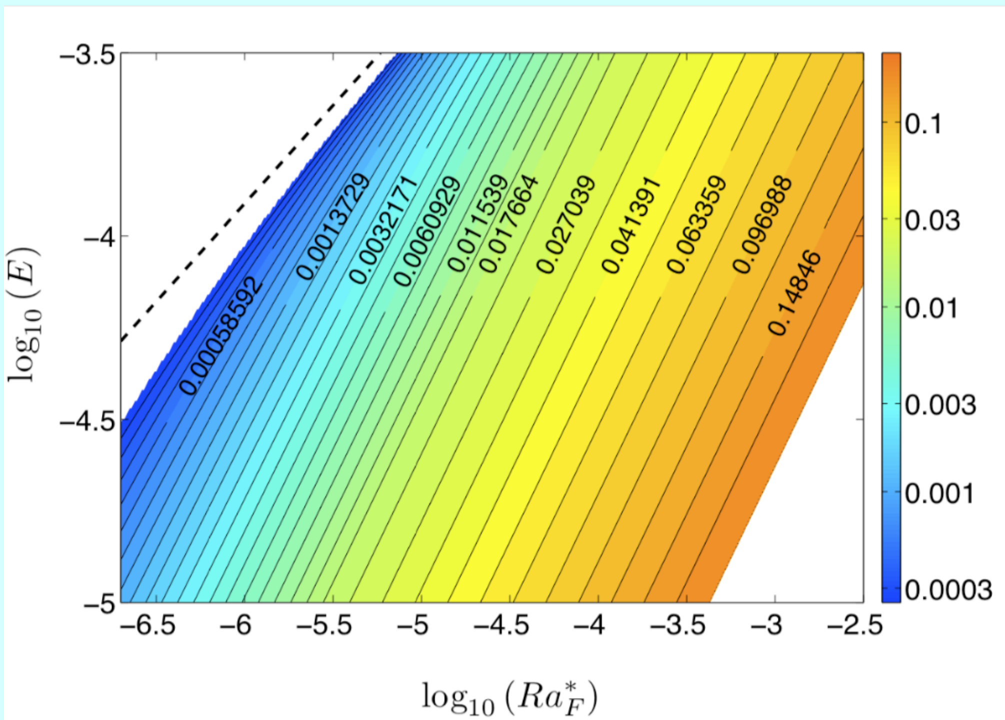
C

ε





Christensen's (2002) simulations



Analytic scaling that combines Regimes I and II

Showman et al. (2010)

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

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

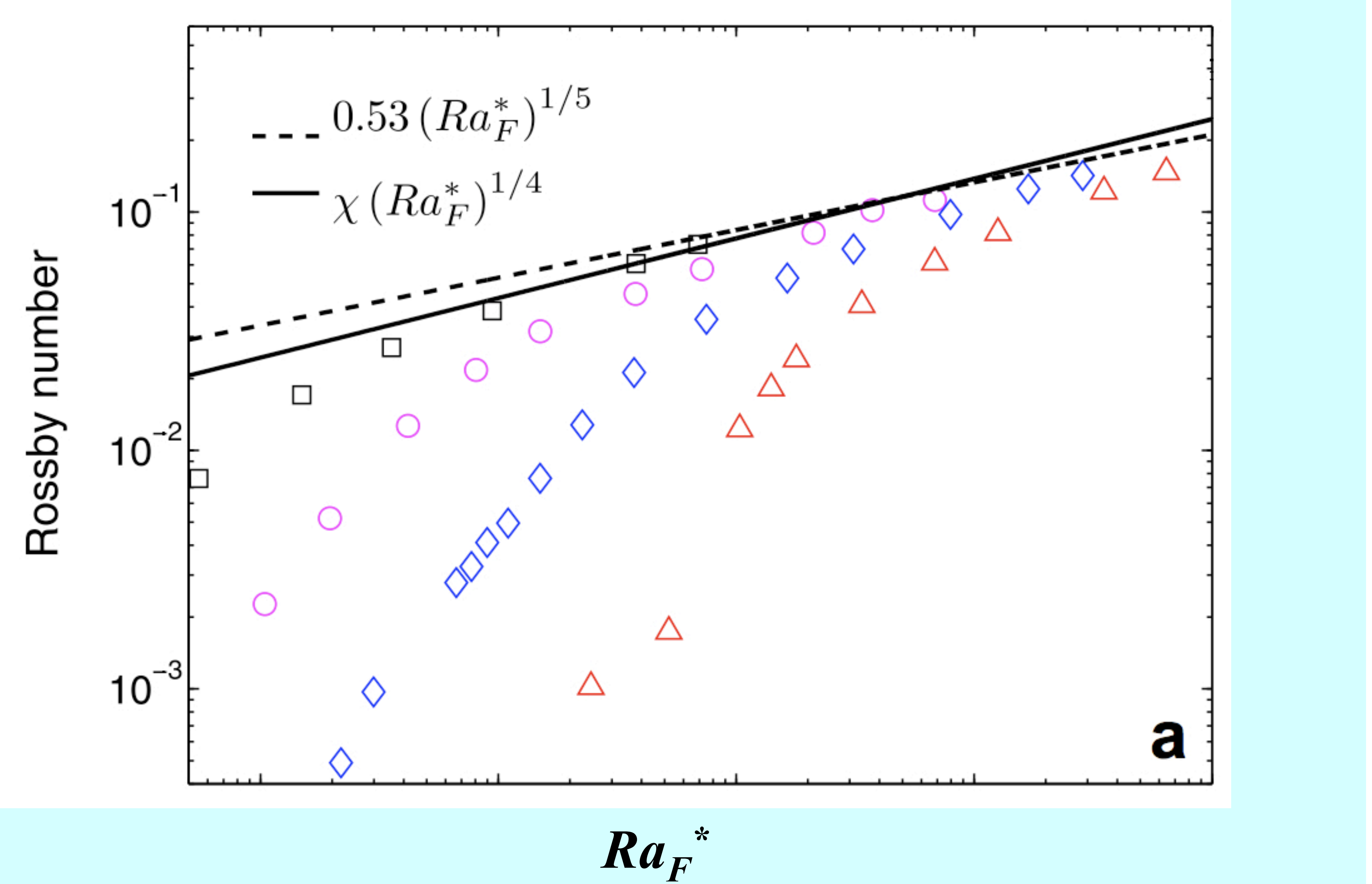
Can we explain this? **Same scaling as before, namely** $U \approx k^{-1}\left(\dfrac{\varepsilon\alpha g F}{\rho c_p \nu}\right)^{1/2}$

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

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

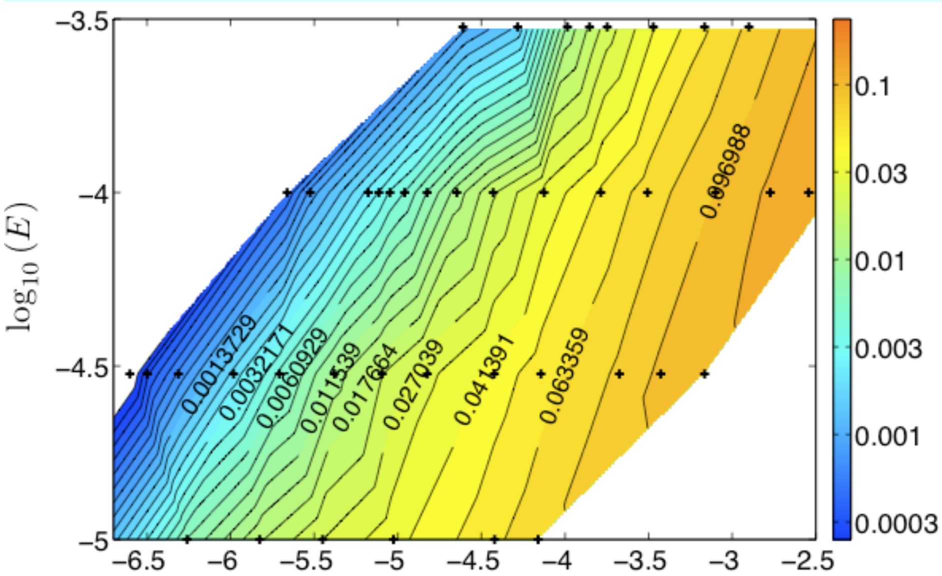
Since $w \propto F^{1/2}$**, we have that** $\nu_{\text{eddy}} \propto F^{1/2}$**, which implies** $U \propto F^{1/4}$

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

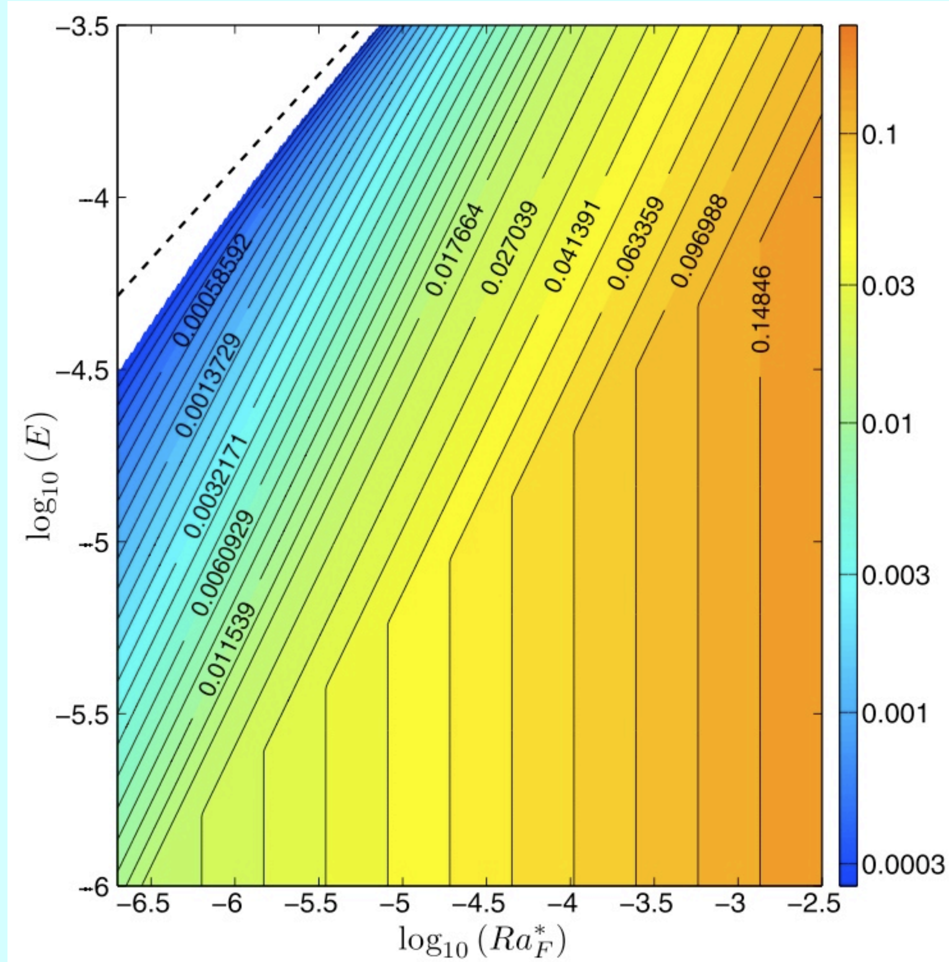


$0.53\,(Ra_F^*)^{1/5}$
$\chi\,(Ra_F^*)^{1/4}$
Rossby number
10^{-1}
10^{-2}
10^{-3}
a
$Ra_F{}^*$

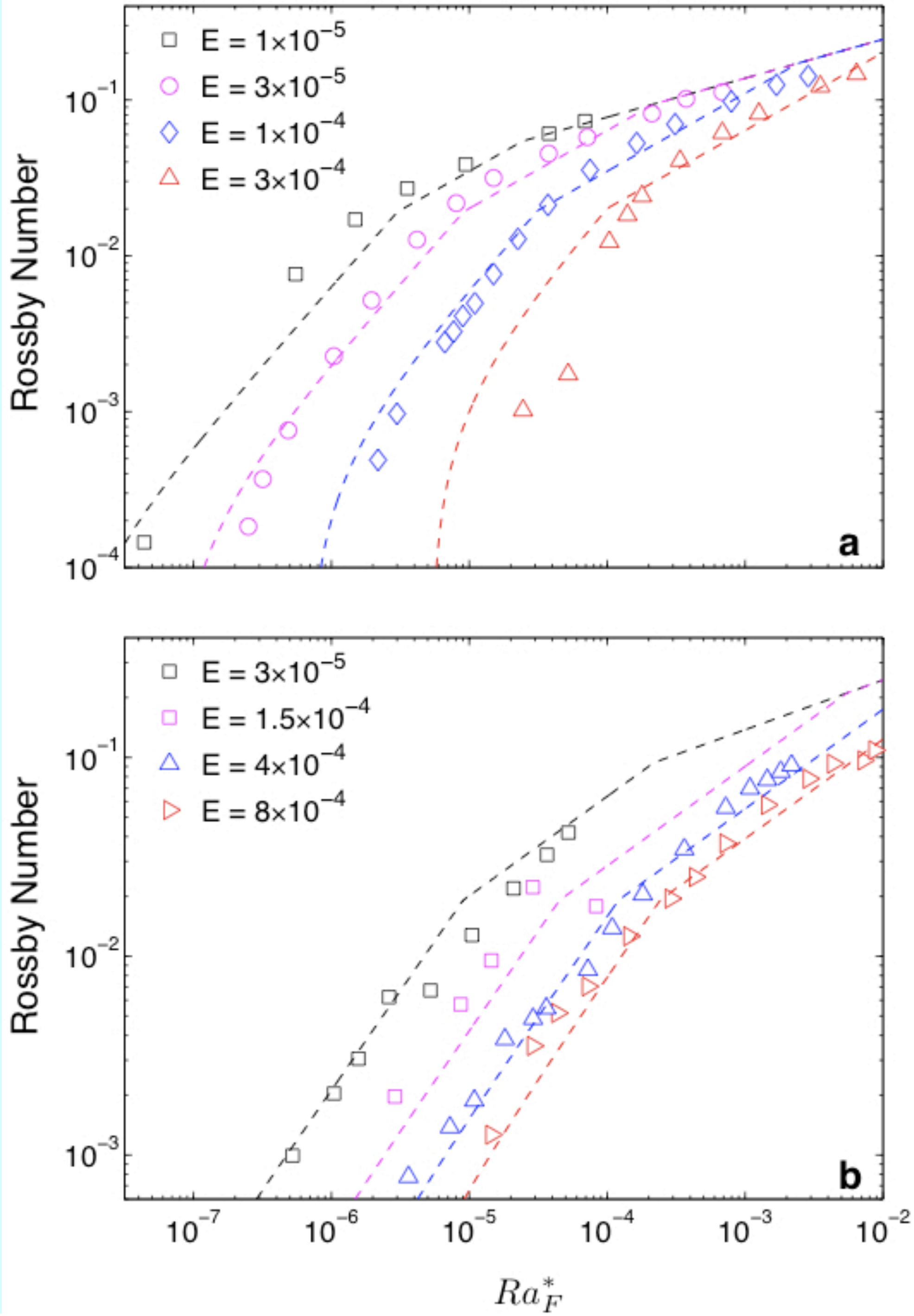
Christensen's (2002) simulations



Analytic scaling combining Regimes I, II, III



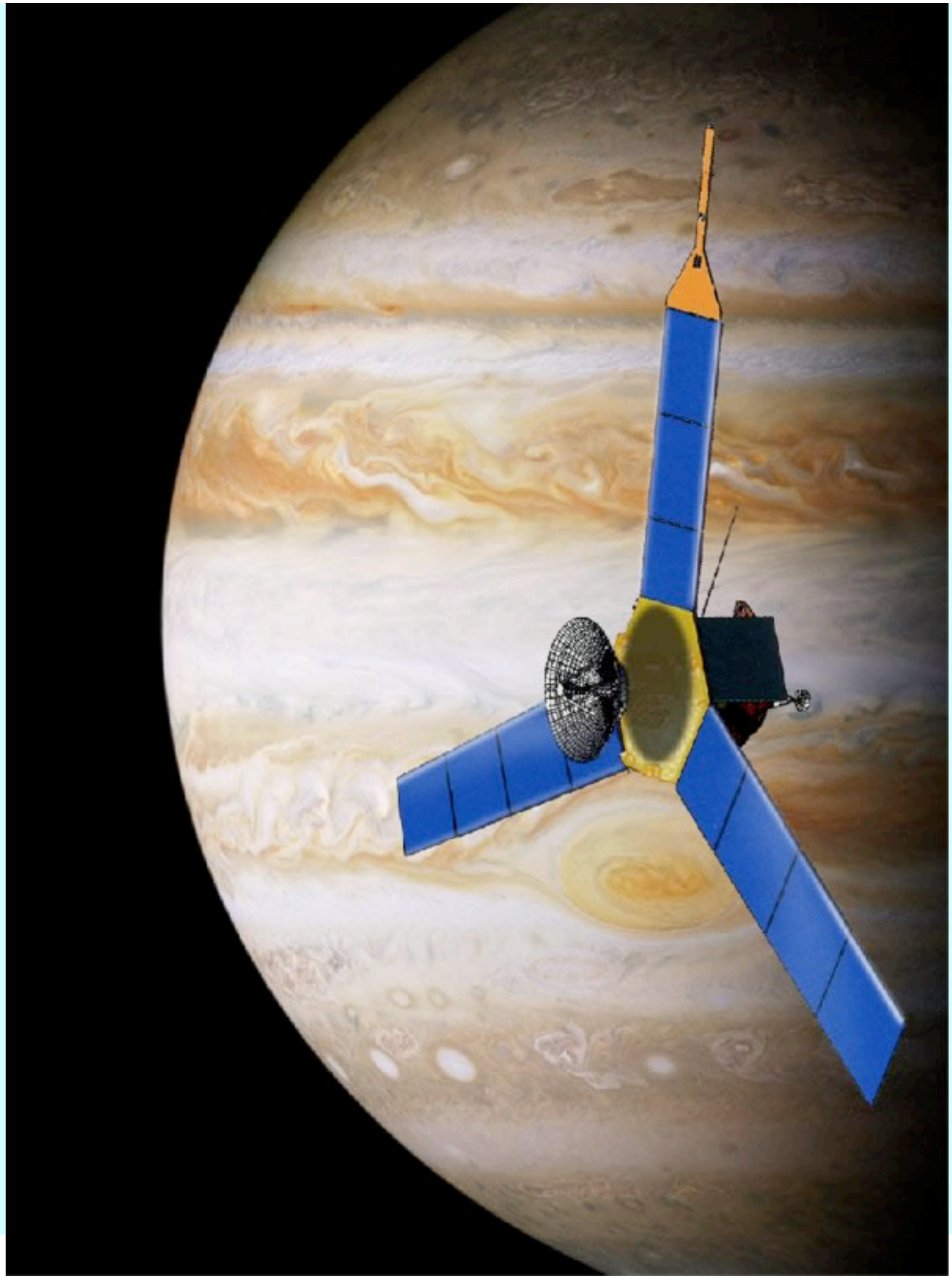
Showman et al. (2010)



Showman et al. (2010)

NASA Juno Mission

- Launch August 2010
- Arrival 2016
- Dedicated Jupiter mission

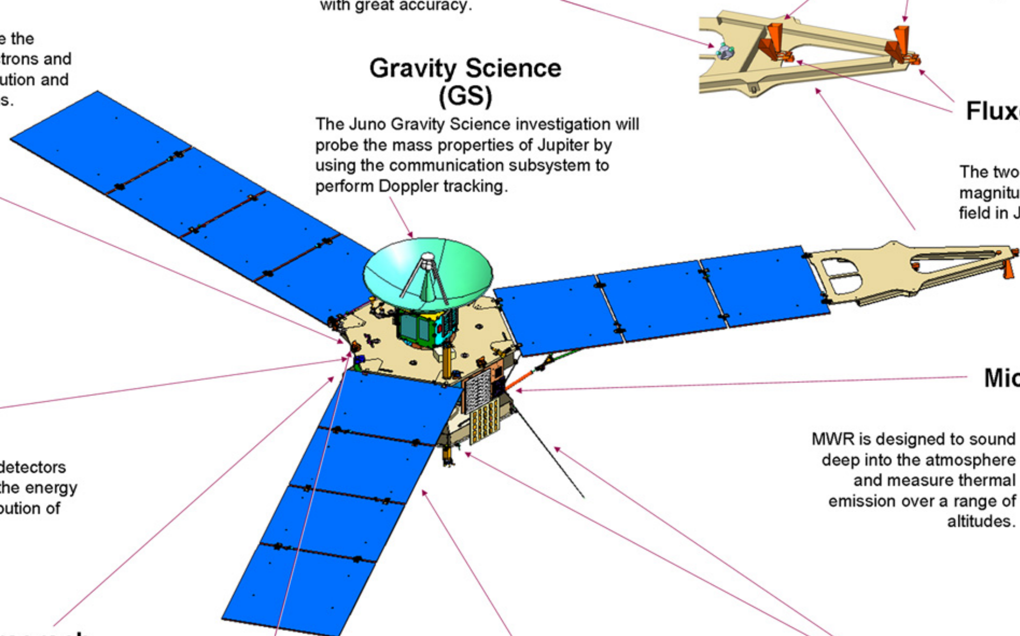


National Aeronautics and Space Administration

Juno Payload System Overview

Phillip Morton, Payload System Manager **Mark Boyles, Deputy Payload System Manager** **Randy Dodge, Payload System Engineer**

Jet Propulsion Laboratory, California Institute of Technology



Scalar Helium Magnetometer (SHM)

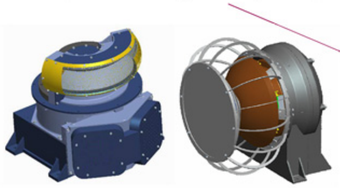
SHM will measure the magnitude of the magnetic field in Jupiter's environment with great accuracy.

Advanced Stellar Compass (ASC)

ASC accurately measures the orientation of the magnetometers.

Jovian Auroral Distributions Experiment (JADE)

JADE will measure the distribution of electrons and the velocity distribution and composition of ions.



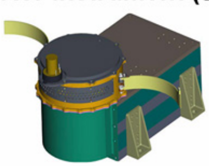
Gravity Science (GS)

The Juno Gravity Science investigation will probe the mass properties of Jupiter by using the communication subsystem to perform Doppler tracking.

Fluxgate Magnetometer (FGM)

The two FGM sensors will measure the magnitude and direction of the magnetic field in Jupiter's environment.

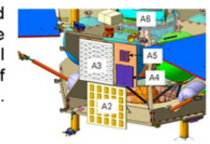
Jupiter Energetic-particle Detector Instrument (JEDI)



JEDI is a suite of detectors that will measure the energy and angular distribution of charged particles.

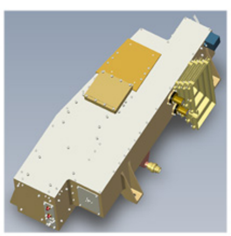
Microwave Radiometer (MWR)

MWR is designed to sound deep into the atmosphere and measure thermal emission over a range of altitudes.

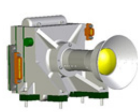


Ultraviolet Spectrograph (UVS)

UVS is an imaging spectrograph that is sensitive to ultraviolet emissions.



JunoCam



JunoCam will provide visible-color images of the Jovian cloud tops.

Jovian Infrared Auroral Mapper (JIRAM)

JIRAM will acquire infrared images and spectra of Jupiter. JIRAM is located on the bottom deck.

Plasma Waves Instrument (Waves)

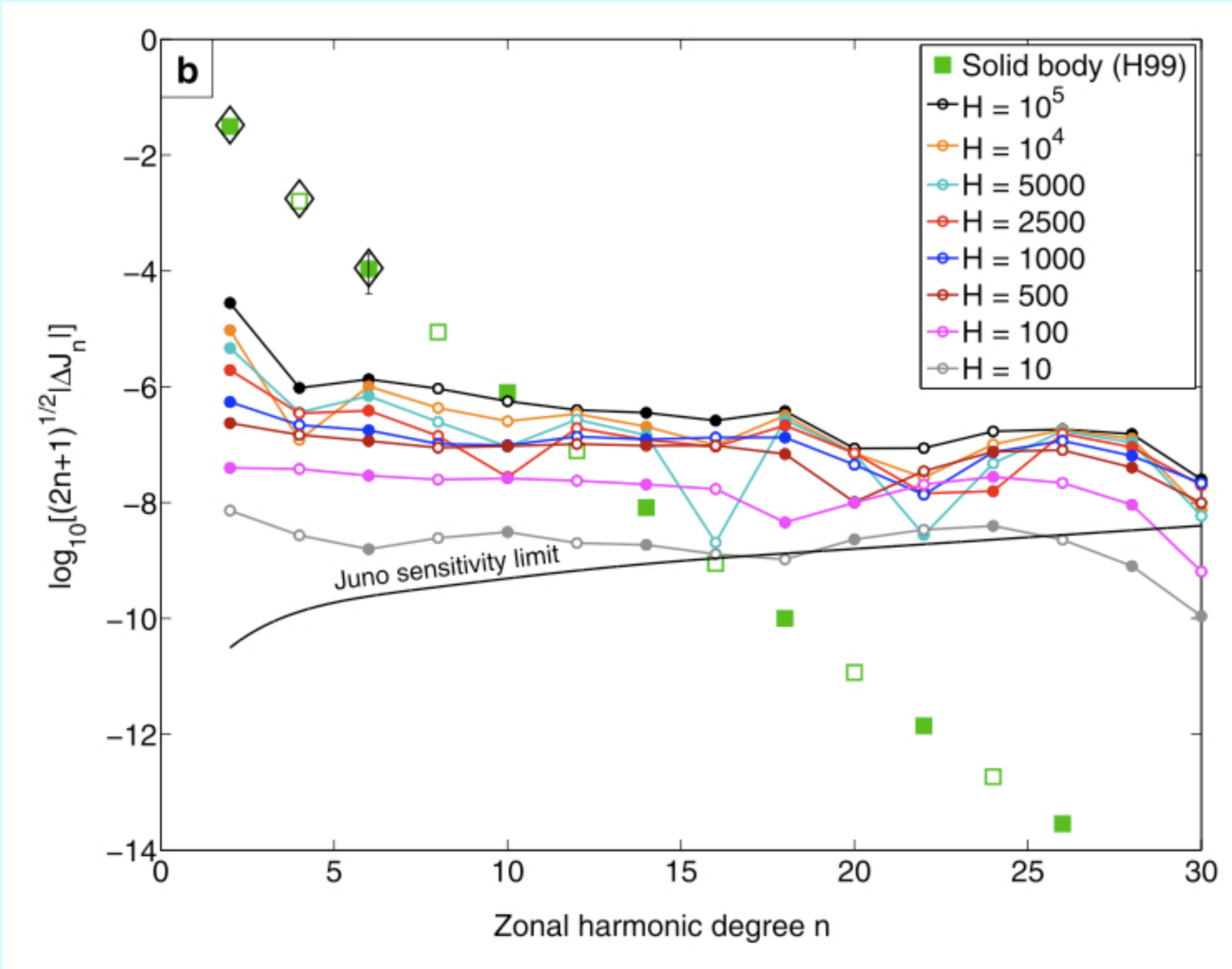
Waves will measure plasma waves and radio waves in Jupiter's magnetosphere.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Juno on July 18, 2011

July 25, 2011: Juno getting ready for delivery

Juno will characterize depth of Jupiter's jets



Kaspi, Hubbard, Showman, & Flierl (2010, GRL)

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.**