

A misty, overcast landscape with snow-covered trees and a distant town. The scene is captured from an elevated position, looking down into a valley. The foreground is dominated by bare, snow-laden branches of trees. In the middle ground, a dense forest of evergreen trees is visible, some with snow on their branches. In the background, a small town or village is nestled in the valley, with several buildings and a church spire visible. The sky is a uniform, greyish-blue, suggesting a heavy overcast or fog. The overall atmosphere is quiet and somewhat somber.

# Magnetic Drag in Hot Jupiter Atmospheres and Observable Consequences

Emily Rauscher  
Sagan Fellow  
University of Arizona

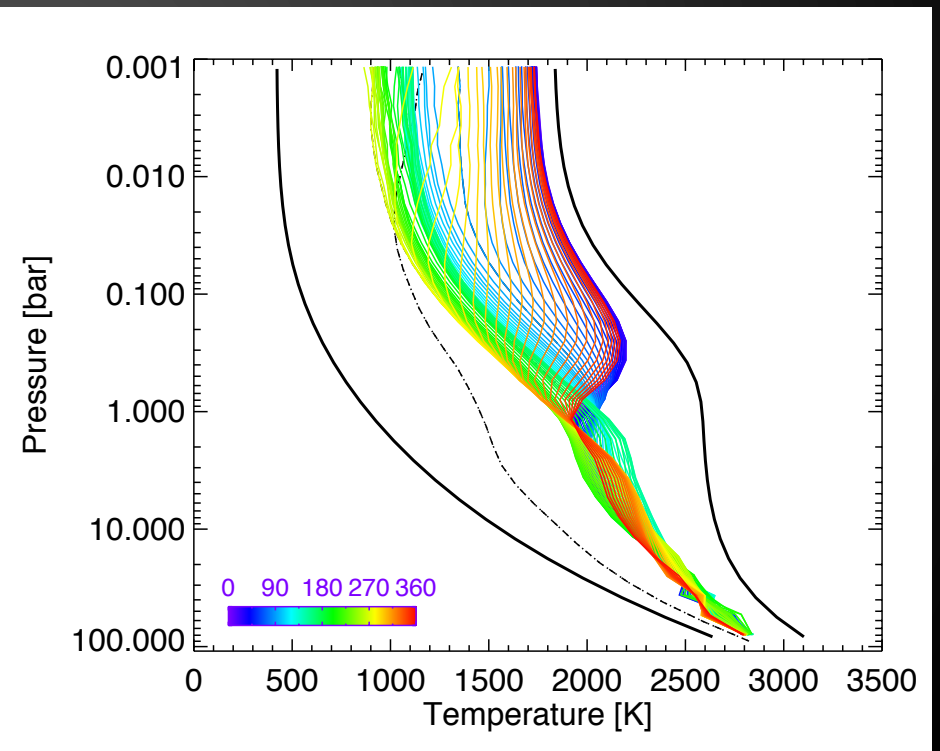
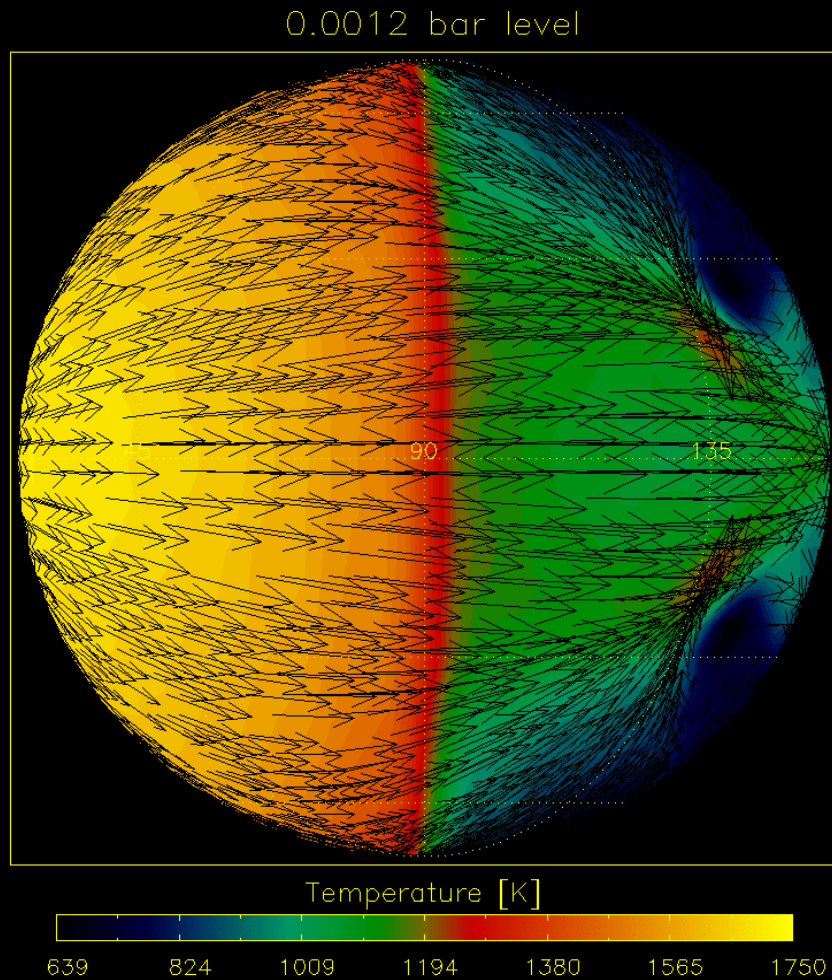
# Atmospheric structure

*Upper atmosphere:*

day = hot night = cold

*Lower atmosphere:*

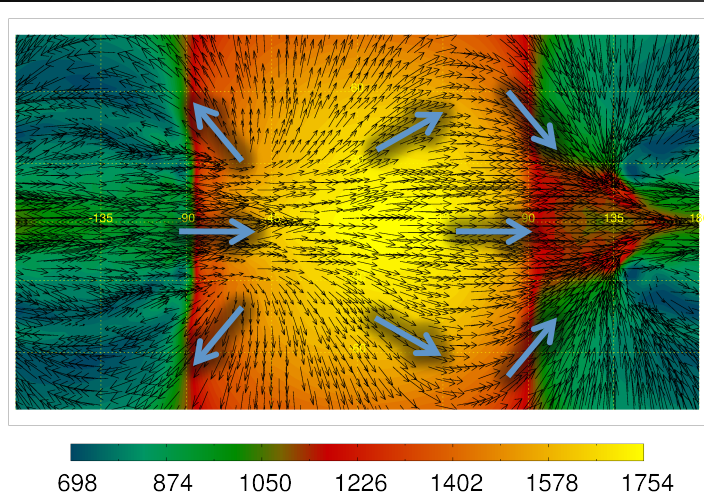
equator = hot poles = cold



Rauscher & Menou (2011)

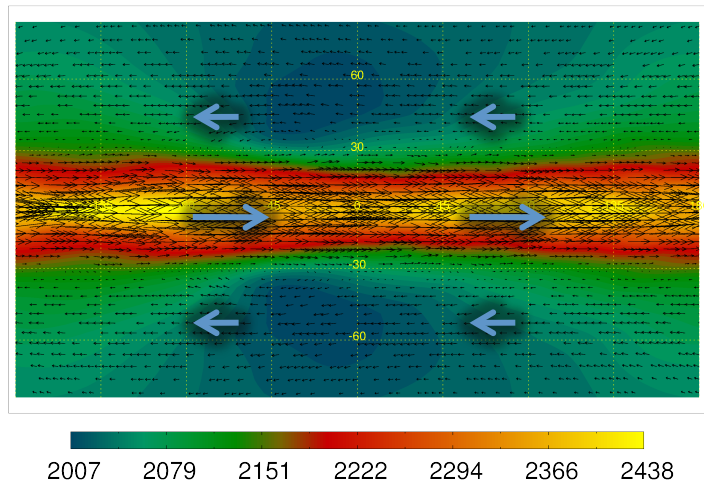
# Thermal ionization + winds

Temperature [K]



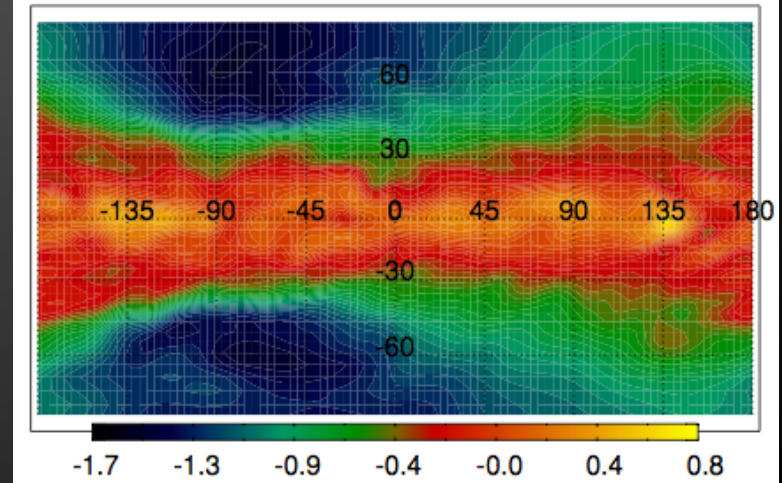
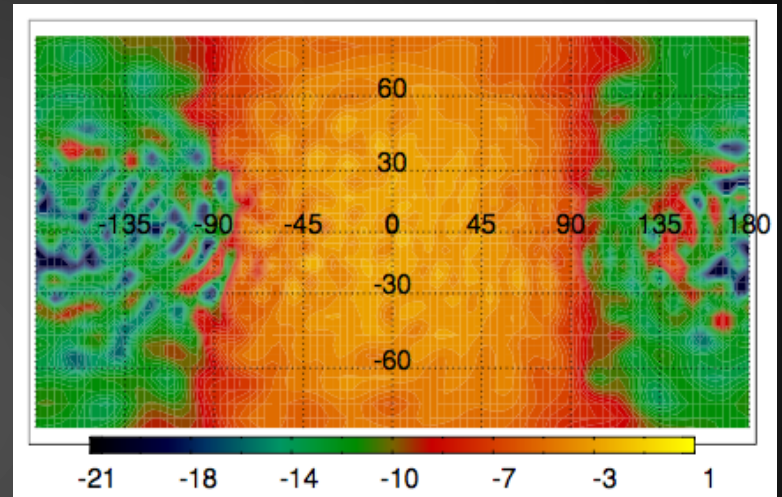
1 mbar

$$V \approx c_s$$



10 bar

$\log_{10}$ (magnetic Reynolds number)



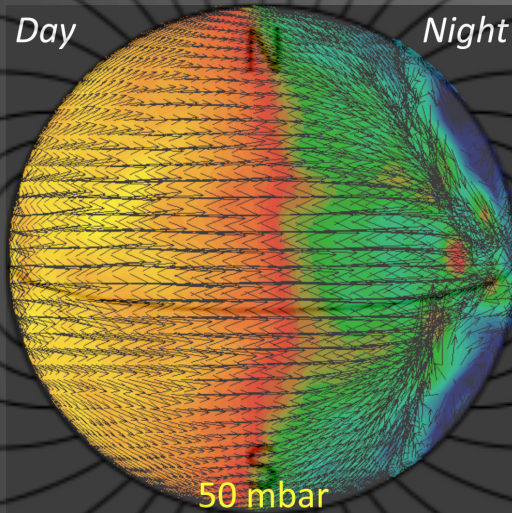
Perna, Menou, & Rauscher (2010a)

# Magnetic Drag

The latitudinal component of the induced current, which depends on  $v$ ,  $B$ , and the local resistivity:

$$j_{\theta}(r, \theta, \phi) = -\frac{c \sin \theta}{4\pi r \eta(r, \theta, \phi)} \int_r^R dr' r'^2 \left( \frac{\partial \Omega}{\partial r'} B_r + \frac{1}{r'} \frac{\partial \Omega}{\partial \theta} B_{\theta} \right)$$

where  $\Omega = v_{\phi} r^{-1} \sin^{-1} \theta$  in spherical coordinates  $(r, \theta, \phi)$ .



The momentum equation for the (mostly neutral) flow now includes an ion drag term:

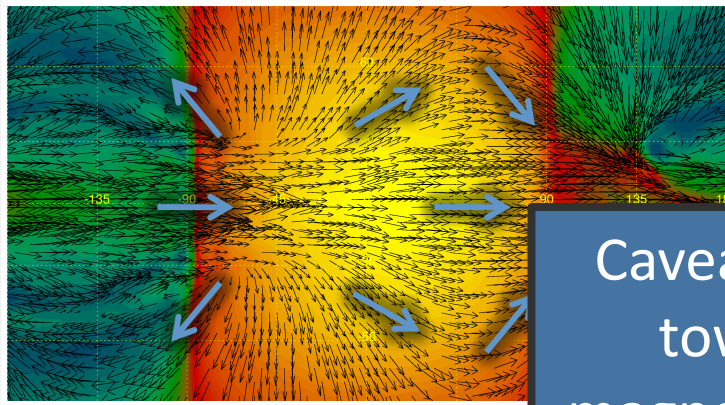
$$\rho \frac{d\mathbf{v}}{dt} \propto \frac{1}{c} \mathbf{j} \times \mathbf{B}$$

from which we can calculate a drag timescale:

$$\tau_{\text{drag}} \sim \frac{\rho |v_{\phi}| c}{|\mathbf{j}_{\theta} \times \mathbf{B}|}$$

# Complex drag structure

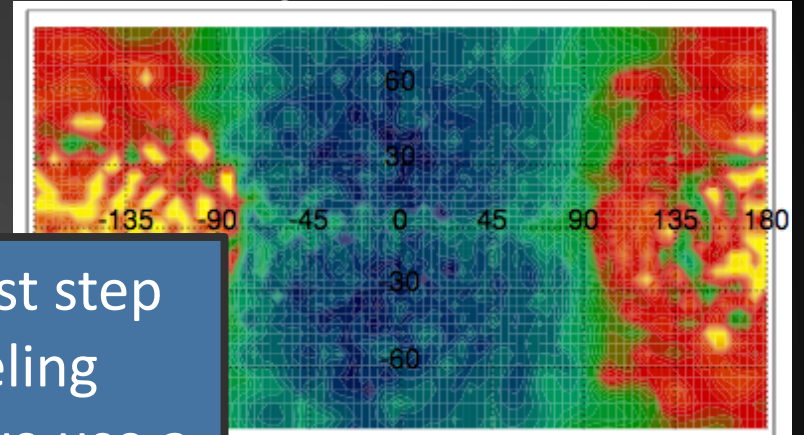
Temperature [K]



698 874 1050 1226 1402

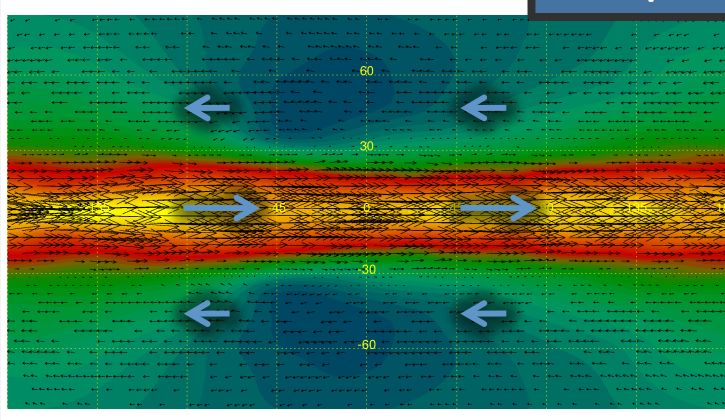
1 mbar

$\text{Log}_{10}(\tau_{\text{drag}})$ : blue = strong drag



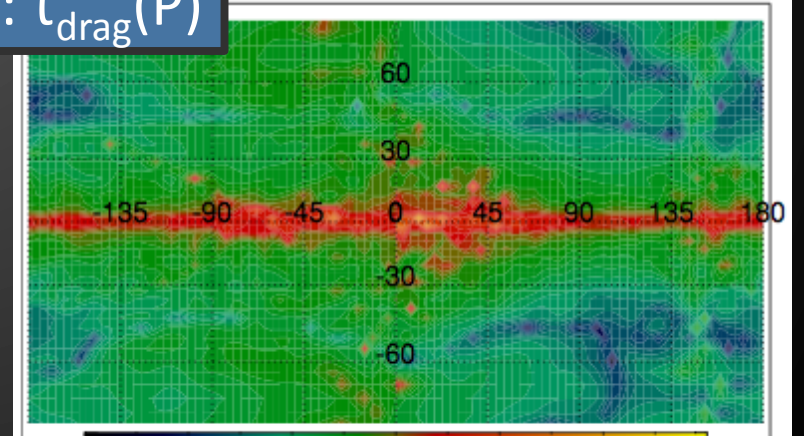
12 16 21 25 30

Caveat! As a first step toward modeling magnetic drag, we use a simple treatment:  $\tau_{\text{drag}}(P)$



2007 2079 2151 2222 2294 2366 2438

10 bar

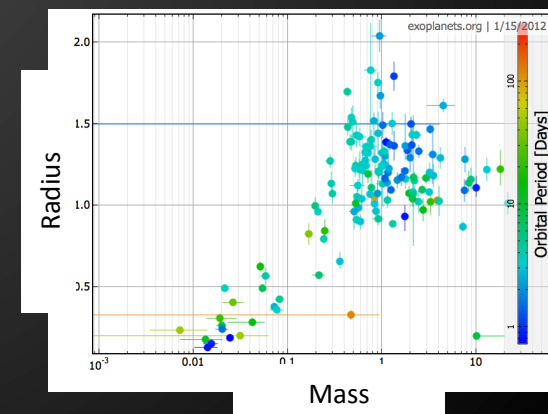
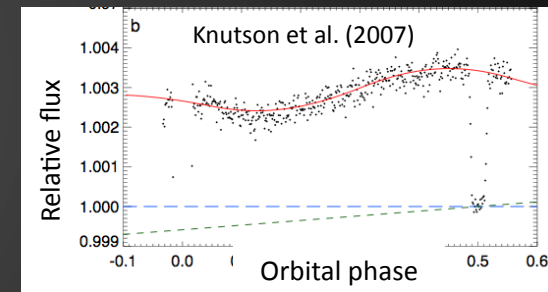
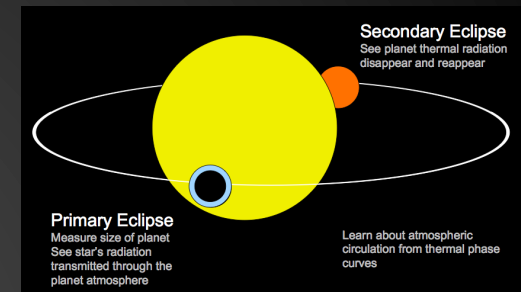


5 6 8 10 11 13 14

Perna, Menou, & Rauscher (2010a)

# Observable Consequences

- Slower winds
  - direct measurement of wind speeds?
- Altered temperature structure
  - phase offset of flux maximum
- Ohmic dissipation and extra heating
  - amount of radius inflation



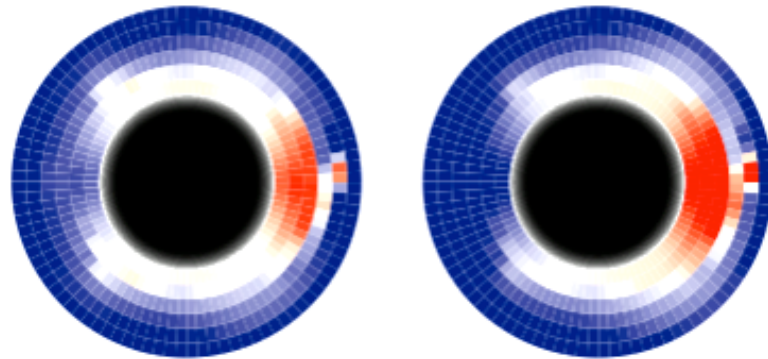
# Wind speeds

1 bar to 10  $\mu$ bar

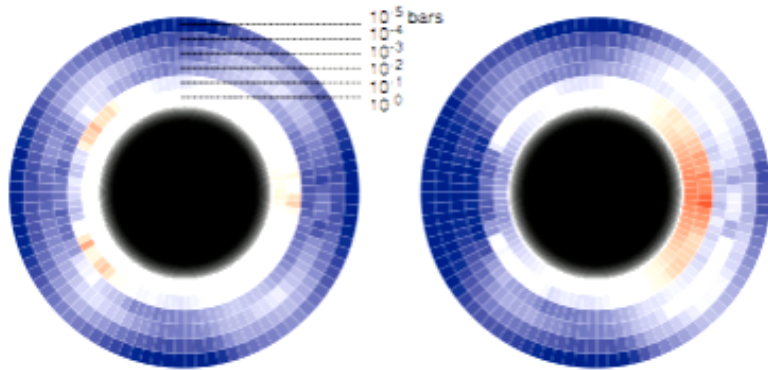
$\leq -5$  km/s

$\geq 5$  km/s

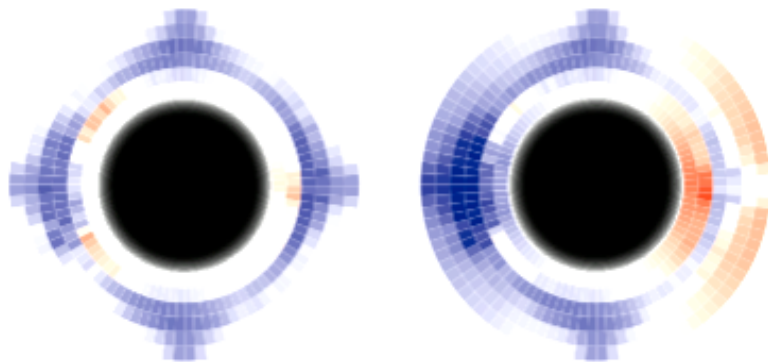
drag-free



with magnetic drag, version 1

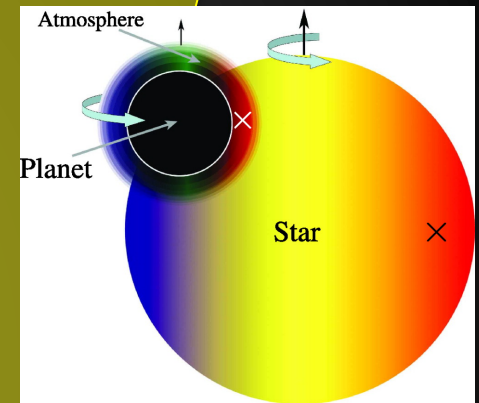


with magnetic drag, version 2



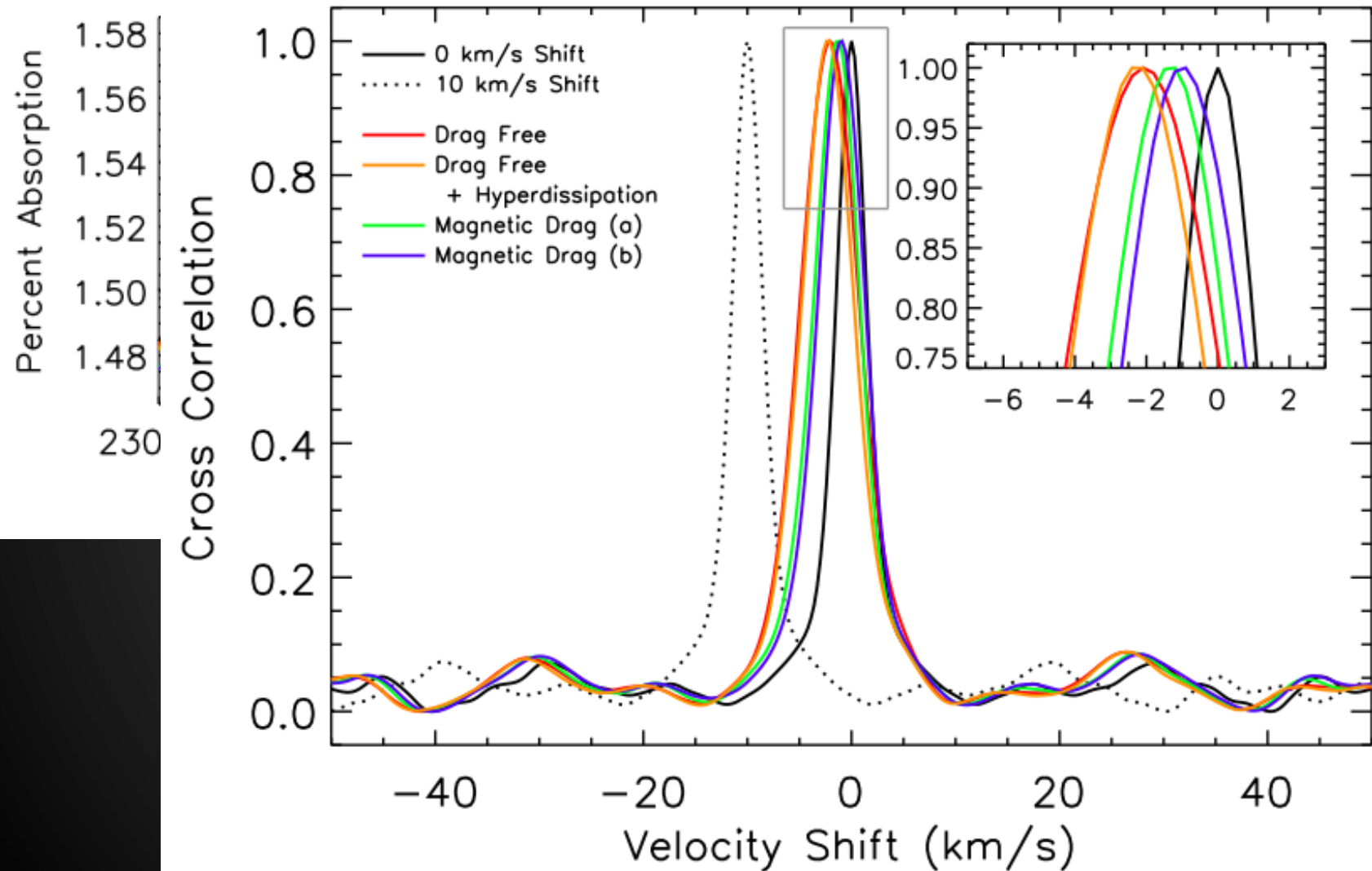
Kempton &  
Rauscher (2011)

Spiegel et al. (2007)



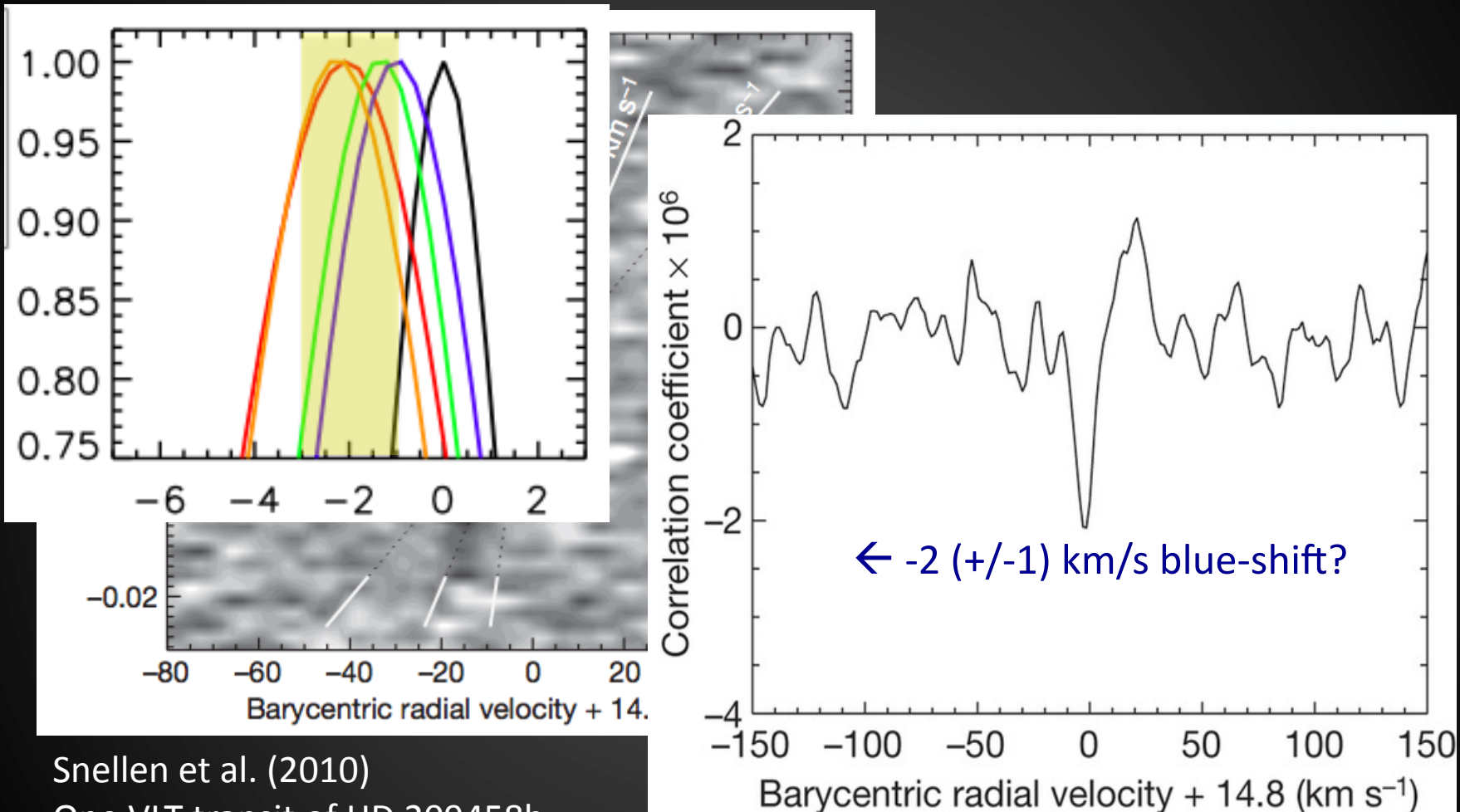
including rotation

# Transmission spectra





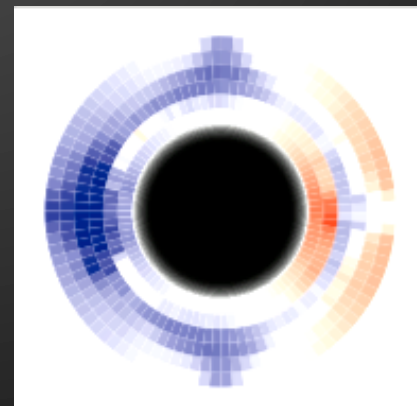
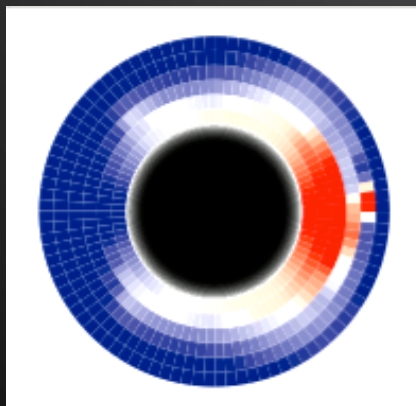
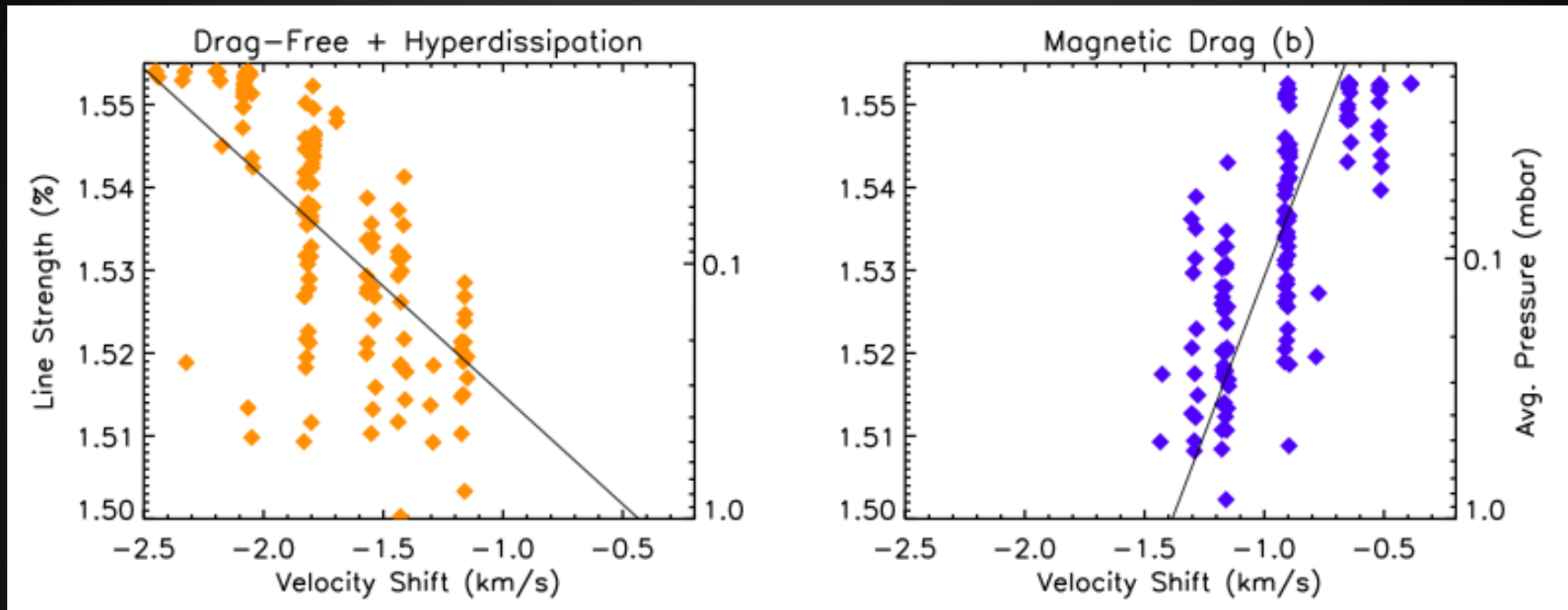
# Direct measurement of wind speed (?)



Snellen et al. (2010)  
One VLT transit of HD 209458b,  
from 2291 to 2349 nm, with  $R = 10^5$ .

(see also Redfield et al. 2008, Jensen et al. 2011)

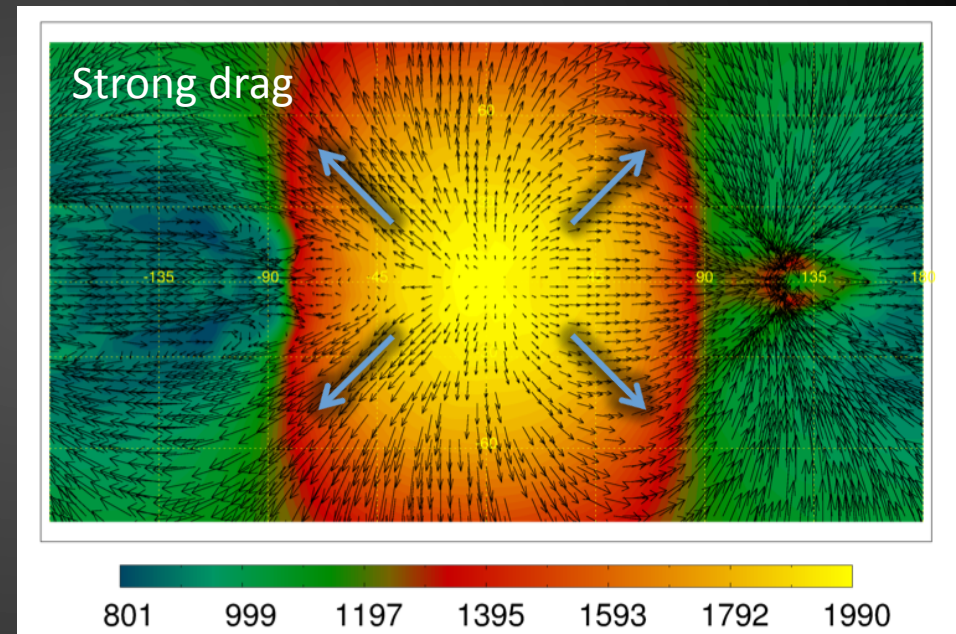
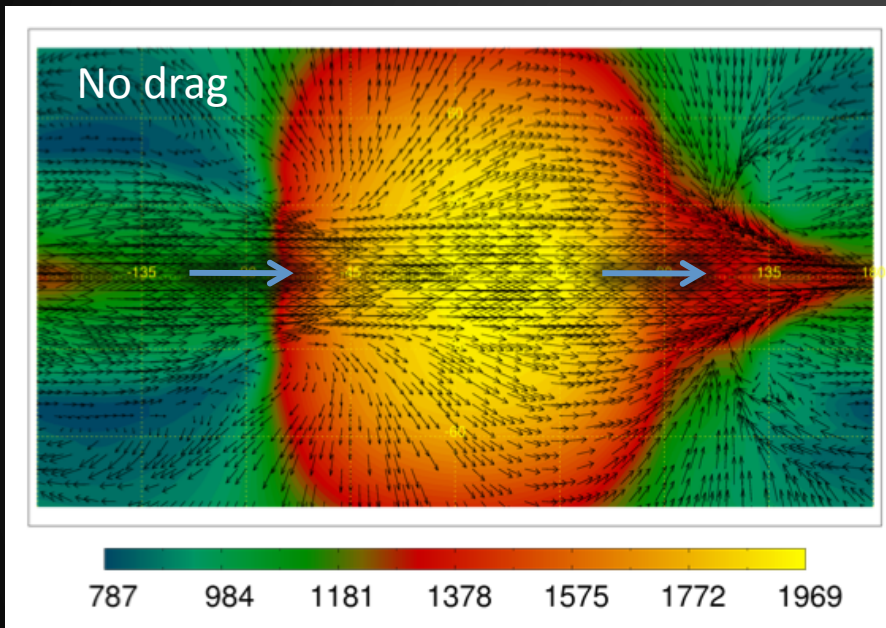
# In the more distant future ... vertical wind shear



# Magnetic drag $\rightarrow$ less efficient advection

Maximum wind speed: 8 km/s

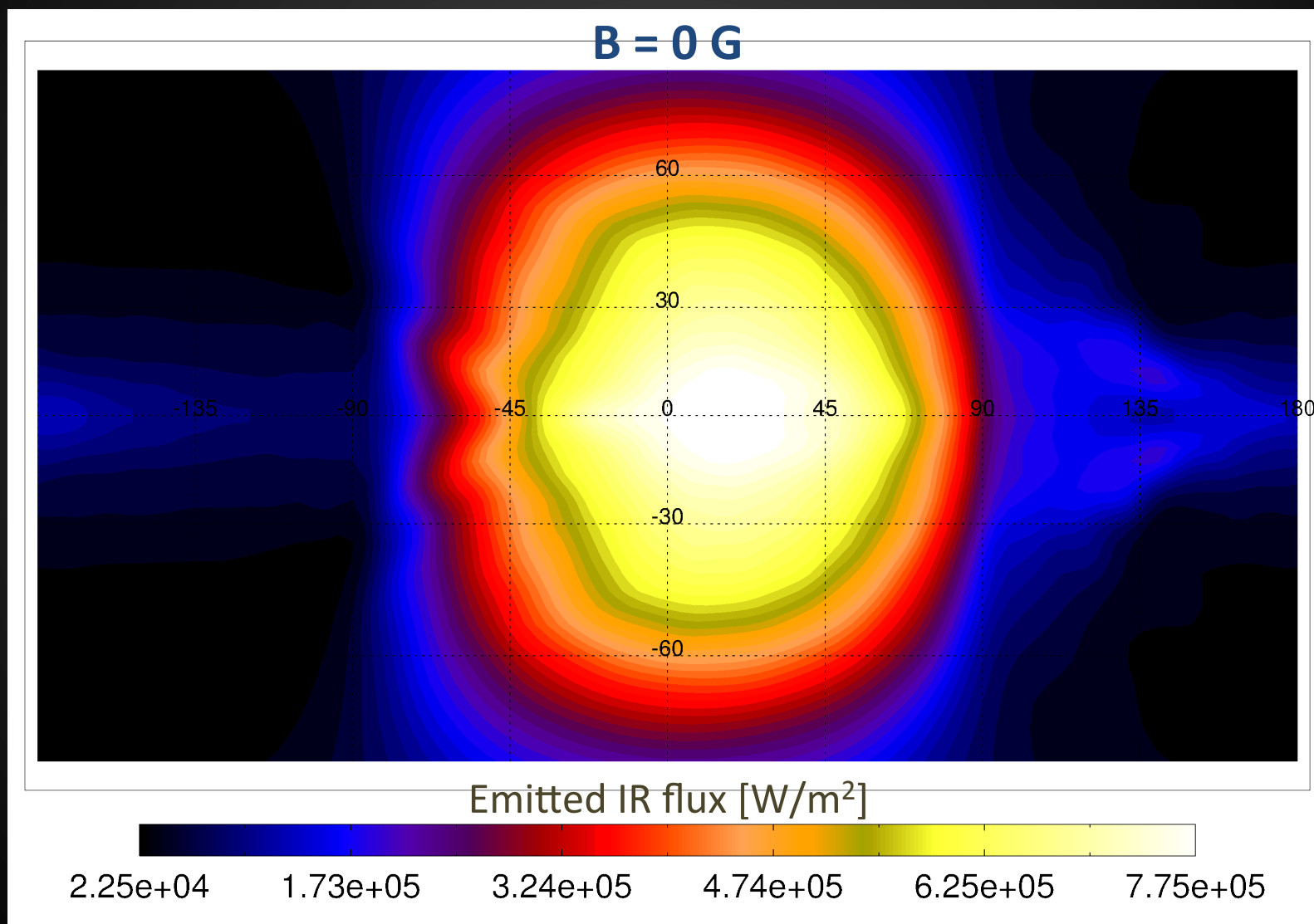
Maximum wind speed: 6 km/s



Temperature [in K]  
at photosphere,  $P = 50$  mbar

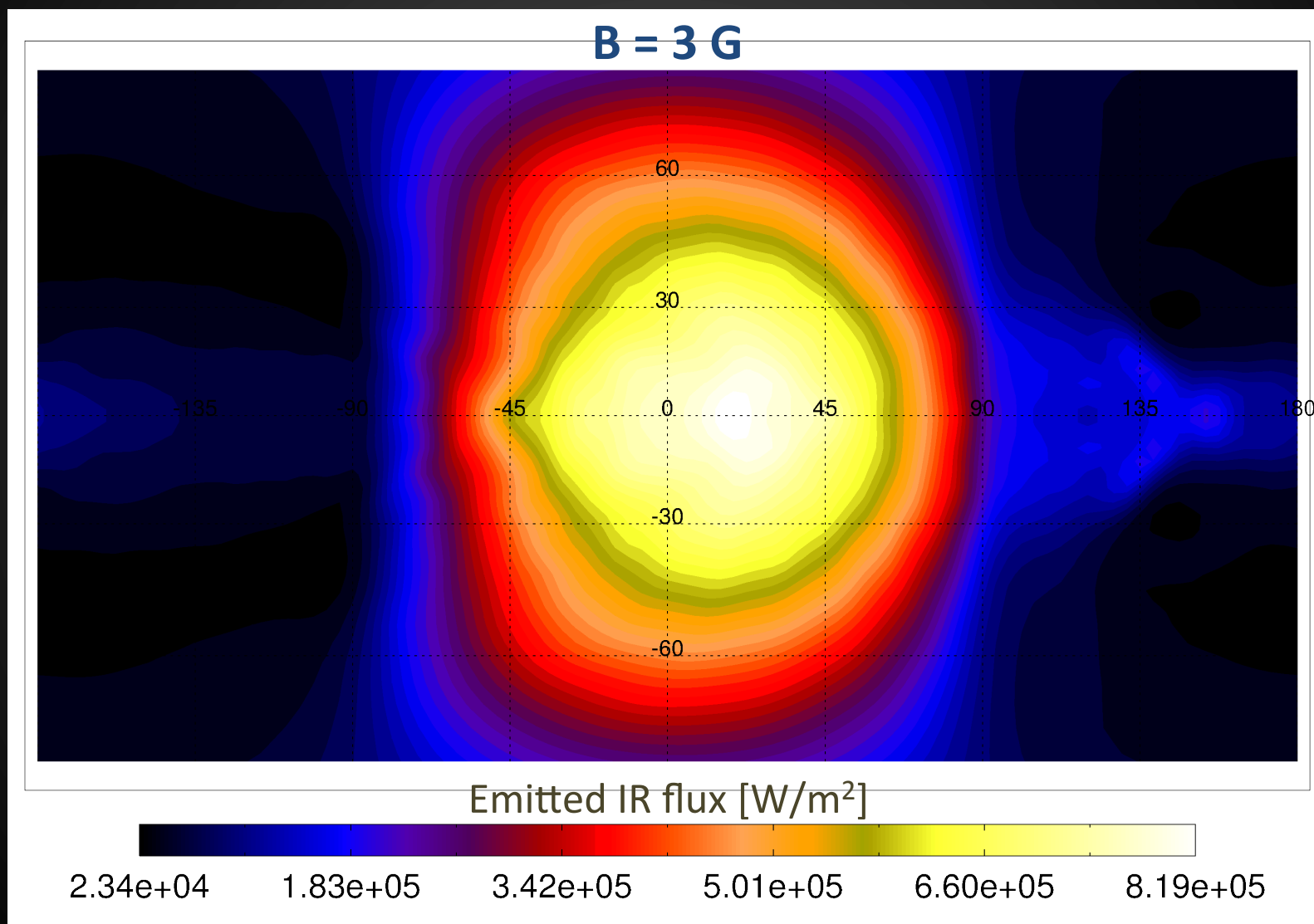
Rauscher & Menou (2011)

# Changes in longitude of hotspot



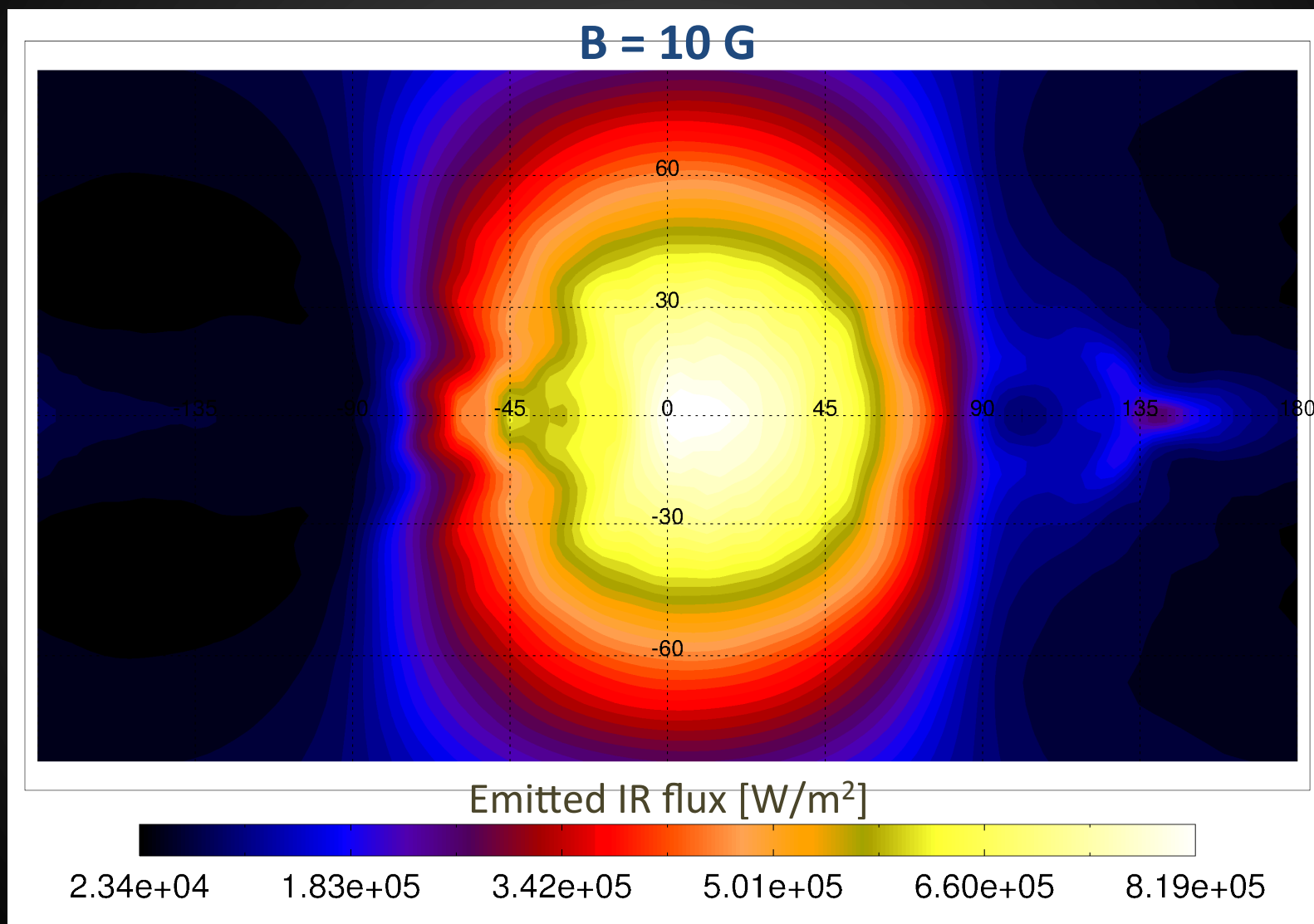
Rauscher & Menou (2011)

# Changes in longitude of hotspot

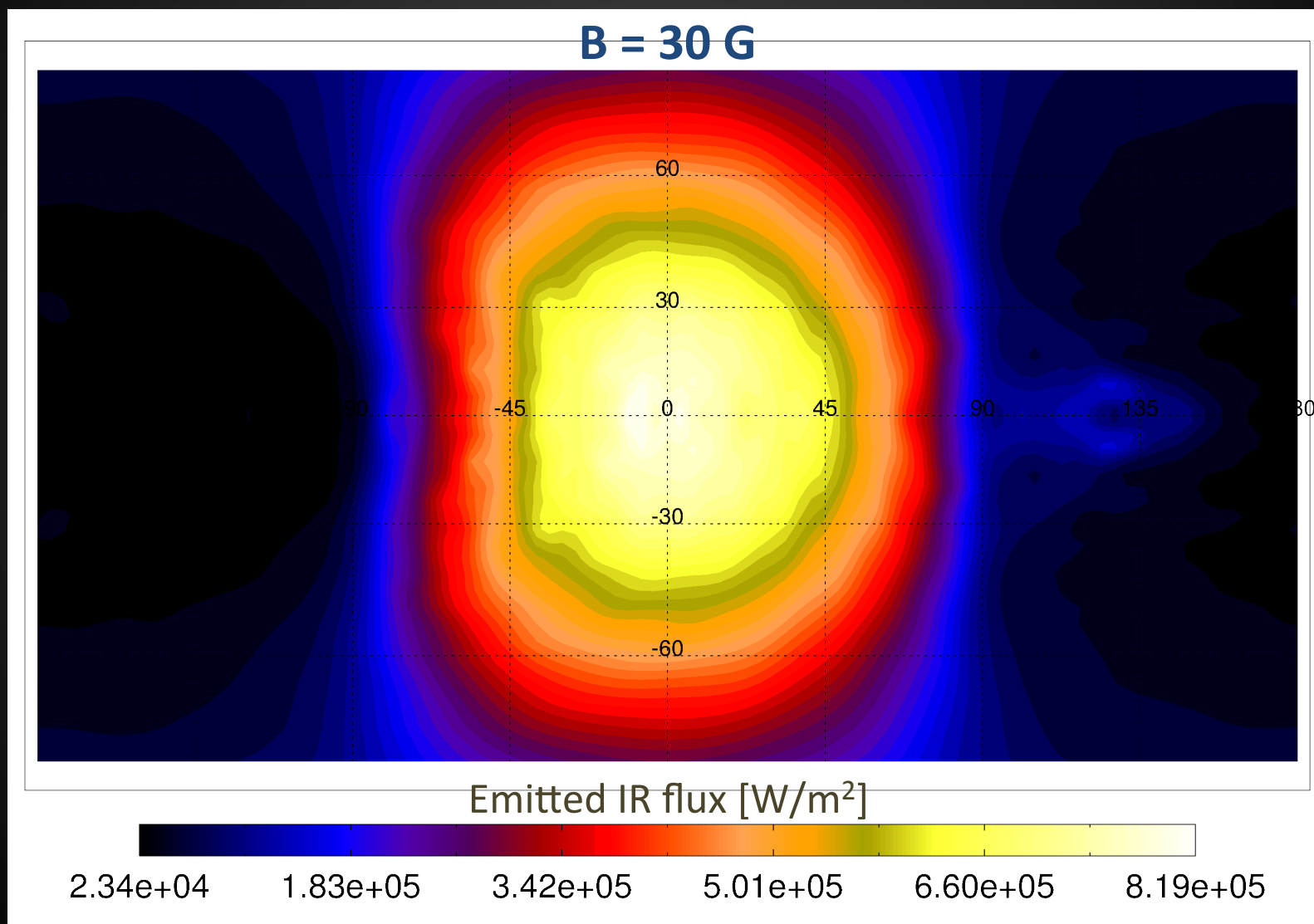


Rauscher & Menou (2011)

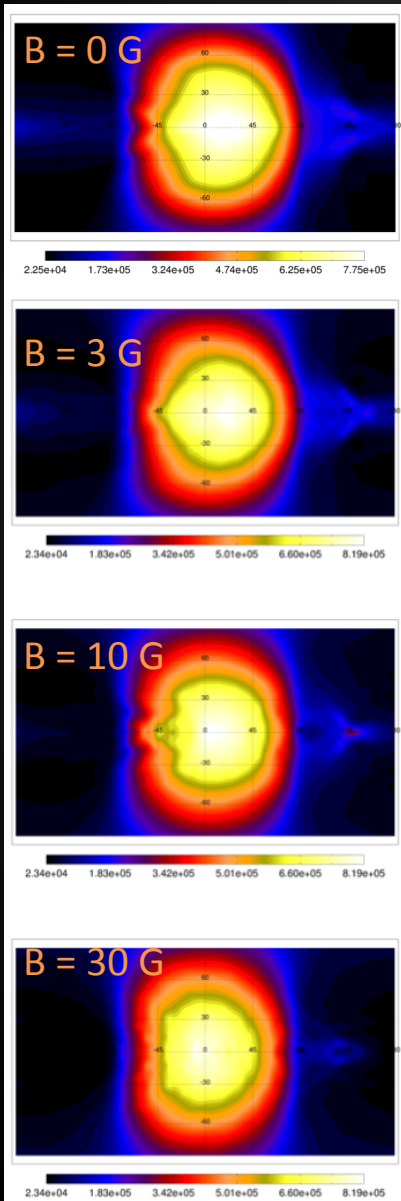
# Changes in longitude of hotspot



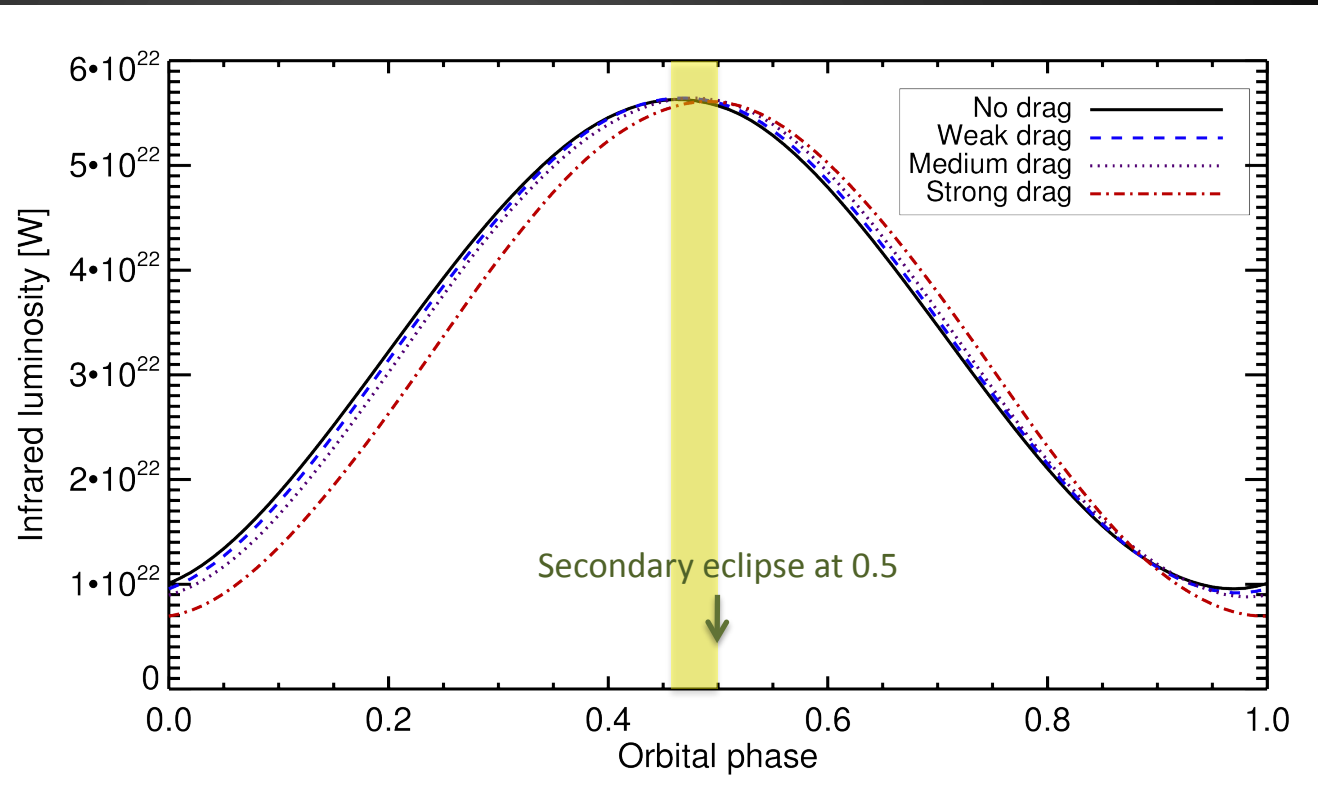
# Changes in longitude of hotspot



# Changes in phase offset of max flux



	$B = 0\text{ G}$	$B = 3\text{ G}$	$B = 10\text{ G}$	$B = 30\text{ G}$
Phase of max flux	0.467	0.469	0.481	0.494



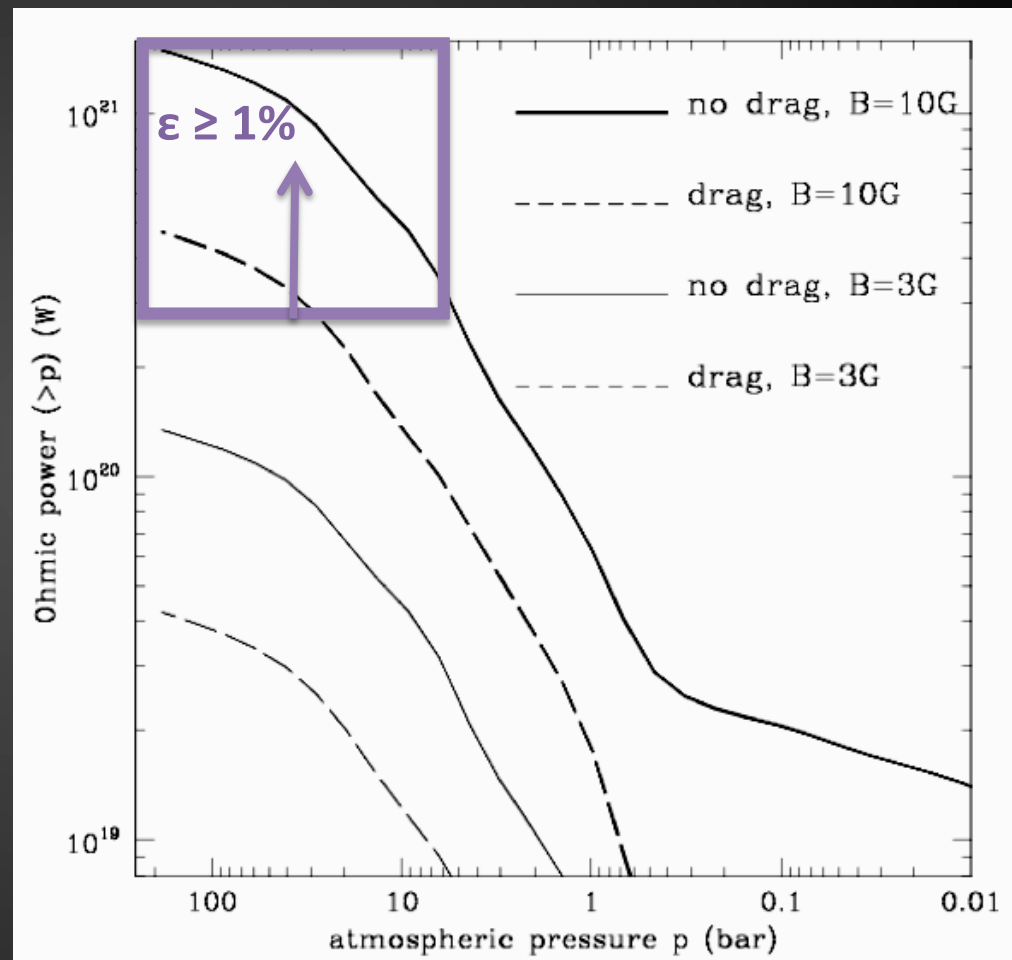


# Ohmic dissipation and heating

$$Q_J(r, \theta, \phi) = \frac{[j_\theta(r, \theta, \phi)]^2}{\sigma_e(r, \theta, \phi)}$$

Efficiency:  $\epsilon = \frac{\text{ohmic heating}}{\text{stellar heating}}$

$$\epsilon = \frac{\text{KE lost through drag}}{\text{stellar heating}}$$



Perna, Menou, & Rauscher (2010b)

see also Batygin & Stevenson (2010), Batygin et al. (2011), Laughlin et al. (2011), Menou (2011)

# Summary: set of related observables

	B = 0 G	B = 3 G	B = 10 G	B = 30 G
Ohmic heating efficiency, $\epsilon$	0%	0.6%	3%	60%
Longitude of hotspot	12°	11°	7°	2°
Blueshift of transmission lines	2 km/s			1 km/s

caveat: these numbers will change for more complex (complete) models

As the strength of the magnetic field  $\uparrow$ :

$\uparrow$  the amount of **ohmic heating** and **radius inflation**

$\downarrow$  the **longitude of the hotspot** and **offset in the phase curve**

$\downarrow$  the **wind speeds** (constrained by **transmission spectra**?)

... but not without limit.