Hot Jupiters: astrophysical laboratories for extreme weather

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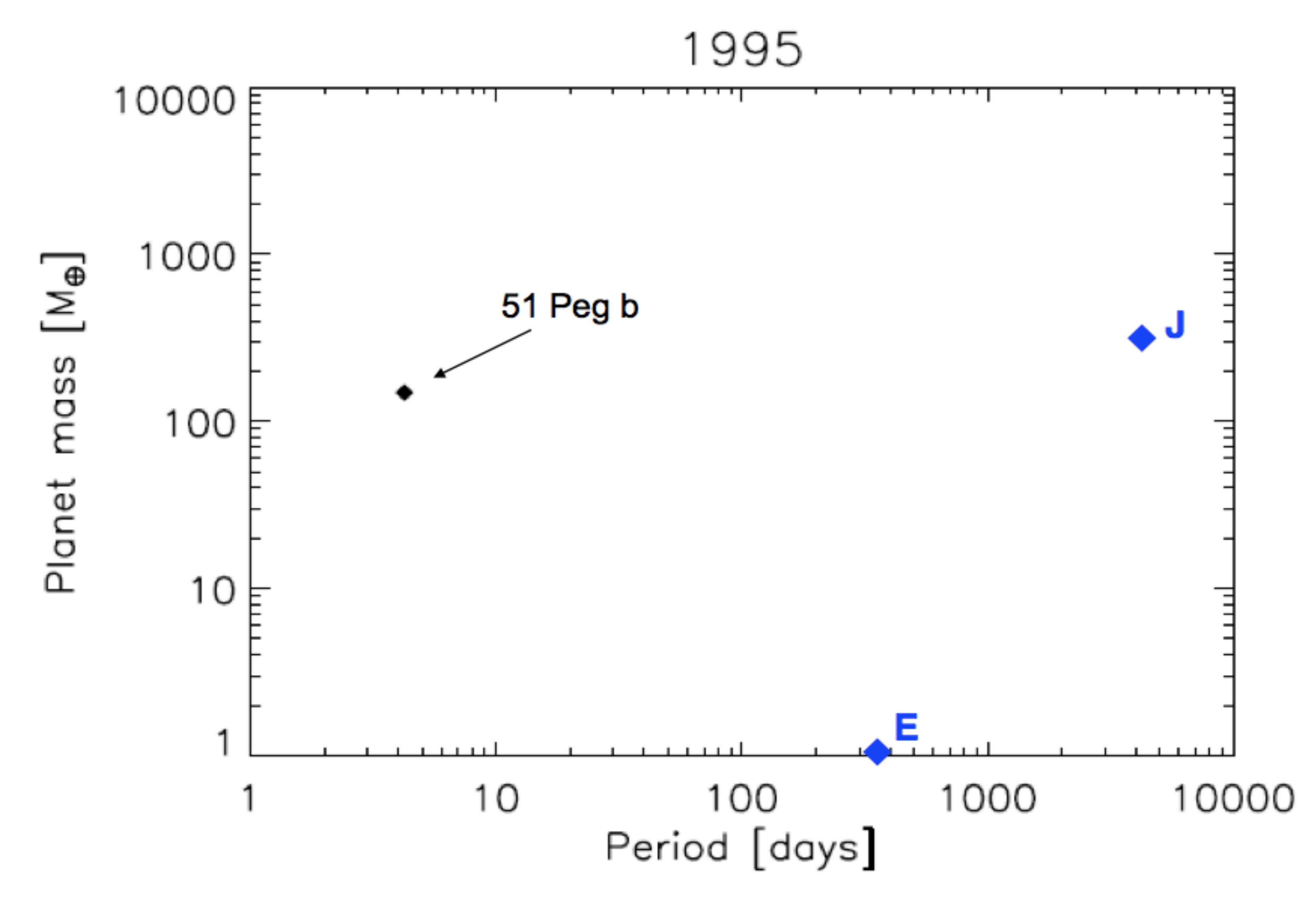
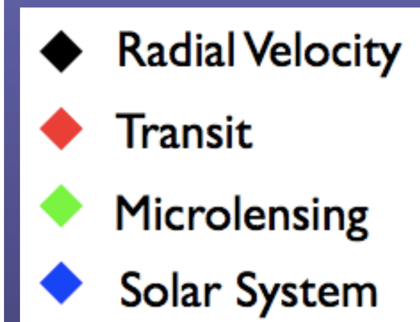
Planet detections: year 1995



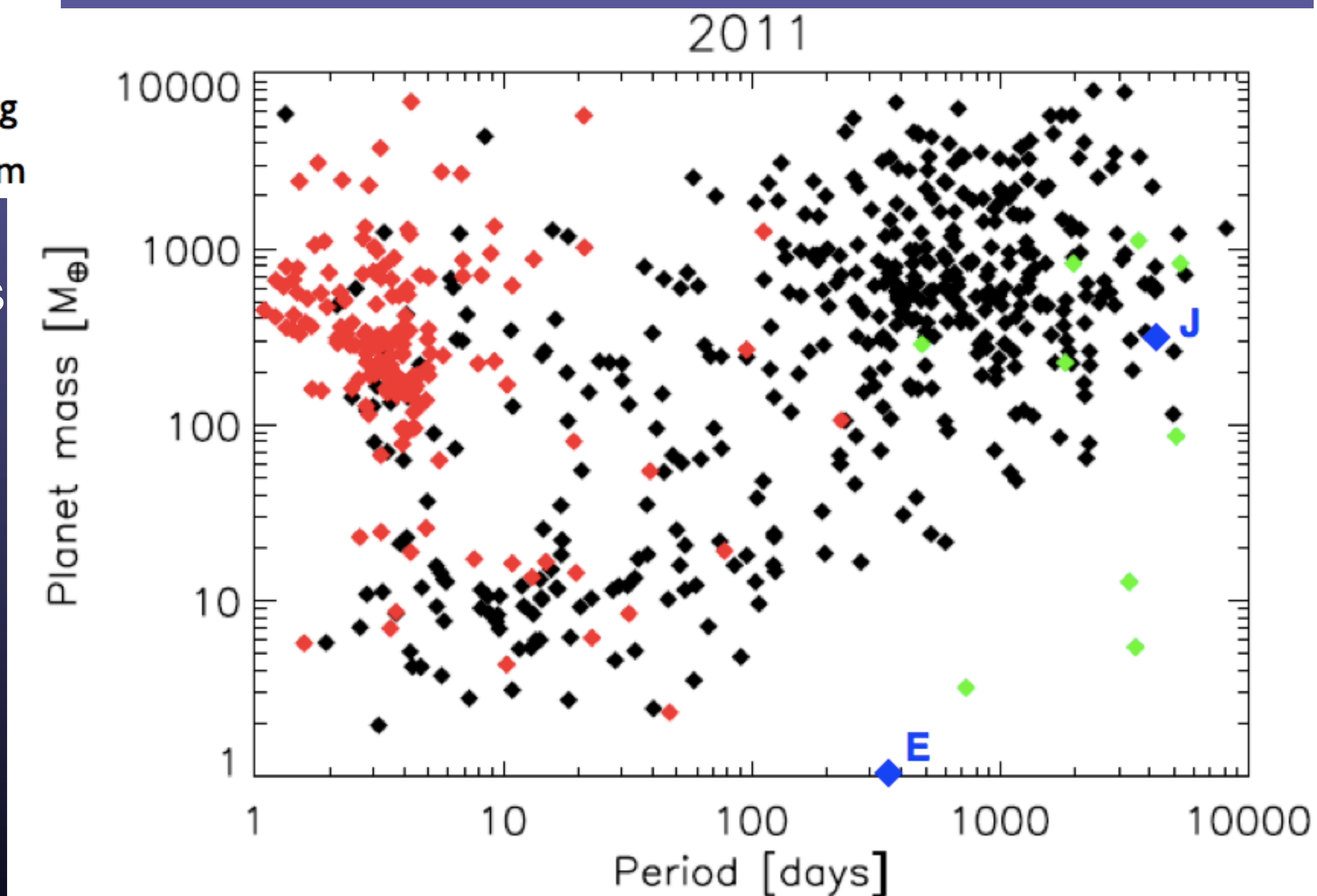
[Image credit: E. Kempton]

Planet detections: year 2015

About 1900 planets discovered!

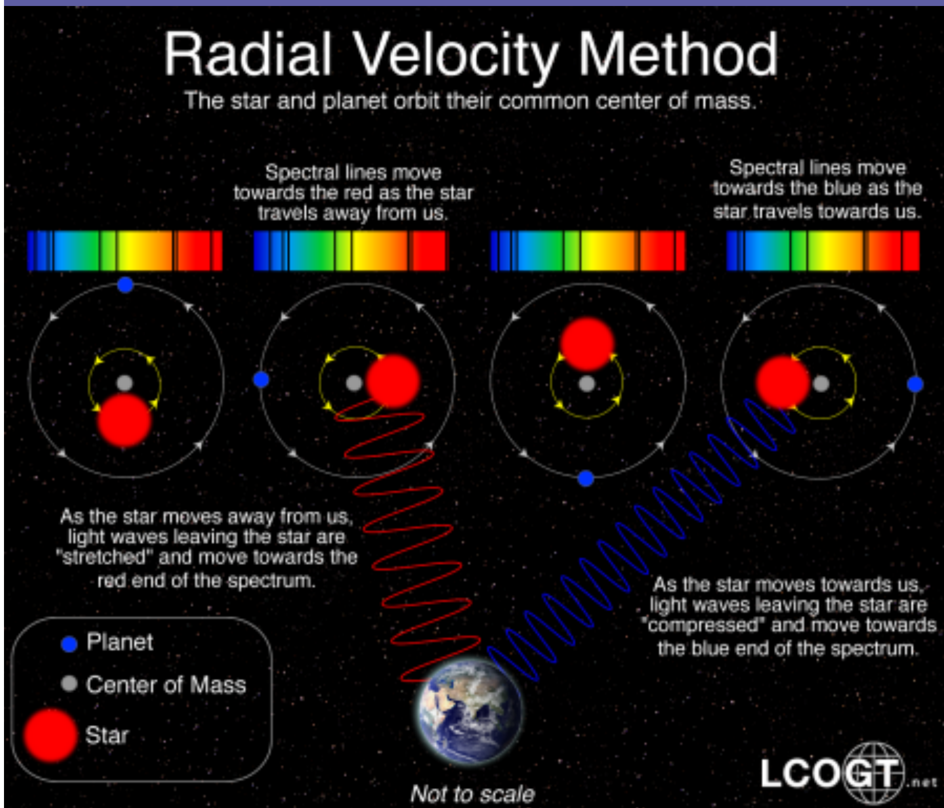


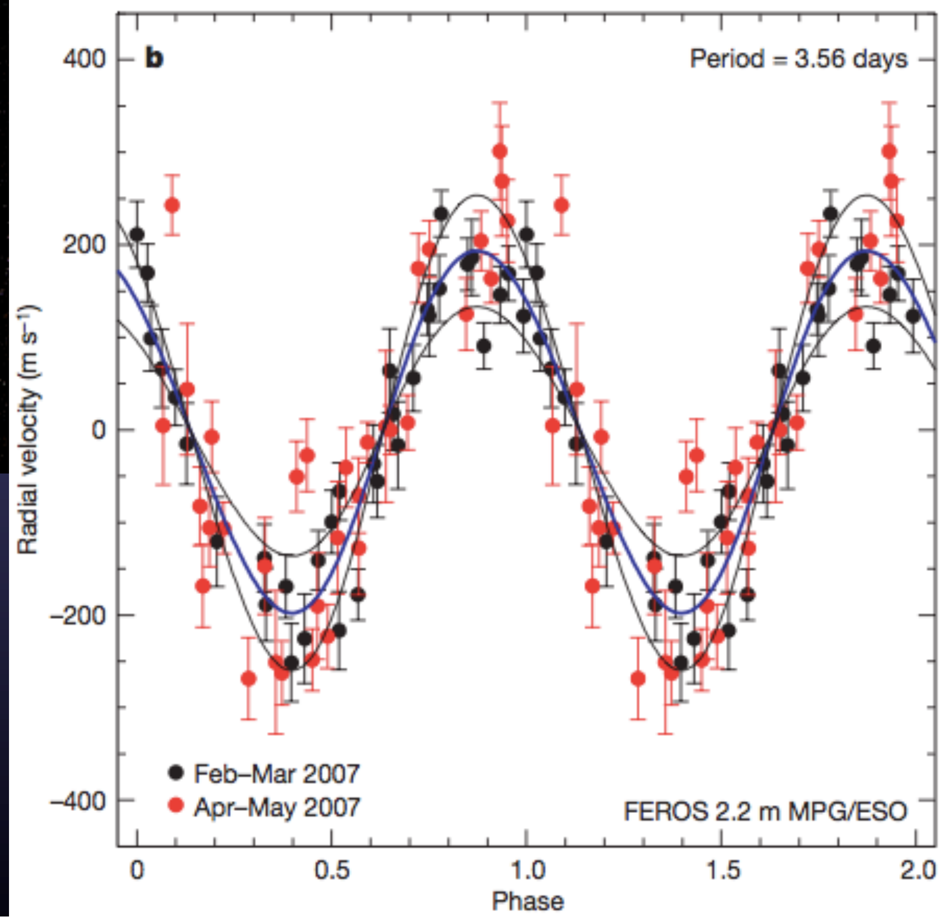
Discoveries also by Direct Imaging



[Image credit: E. Kempton]

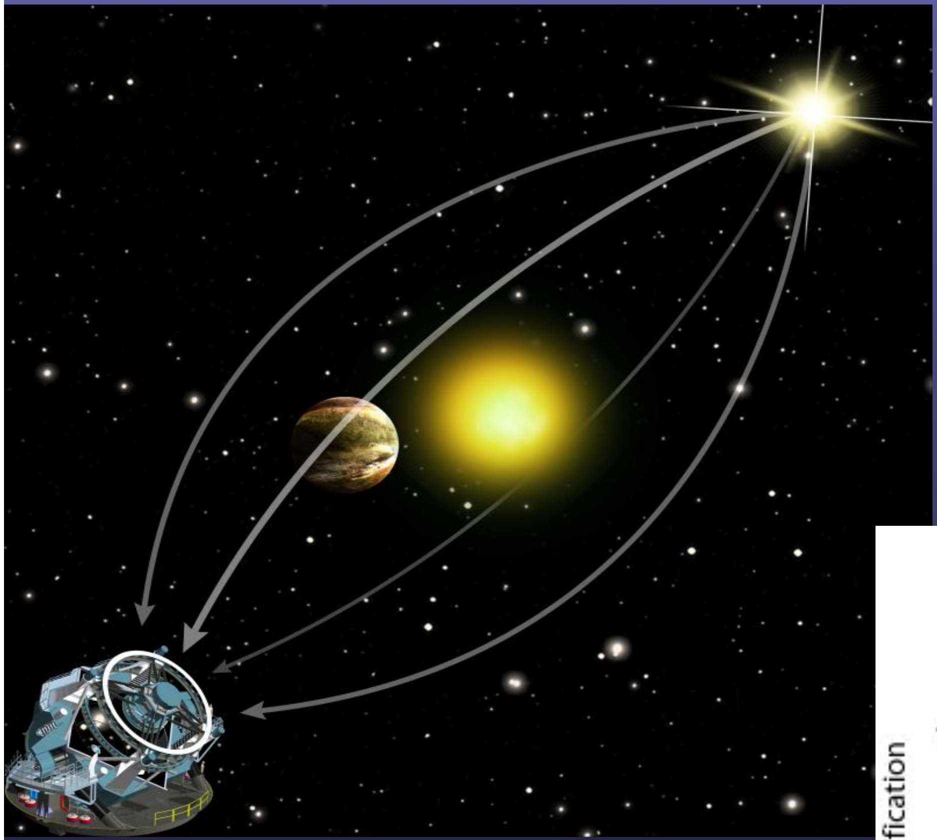
Various Detection techniques: *Radial Velocity*





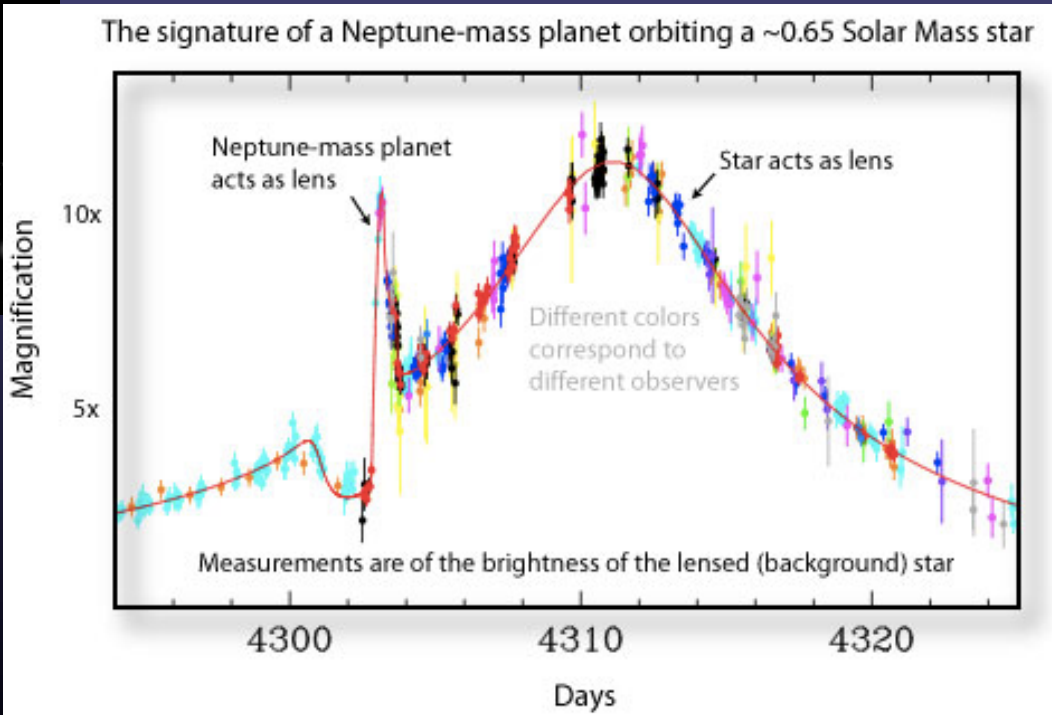
[Setiawan et al. 2008]

Various Detection techniques: *Microlensing*

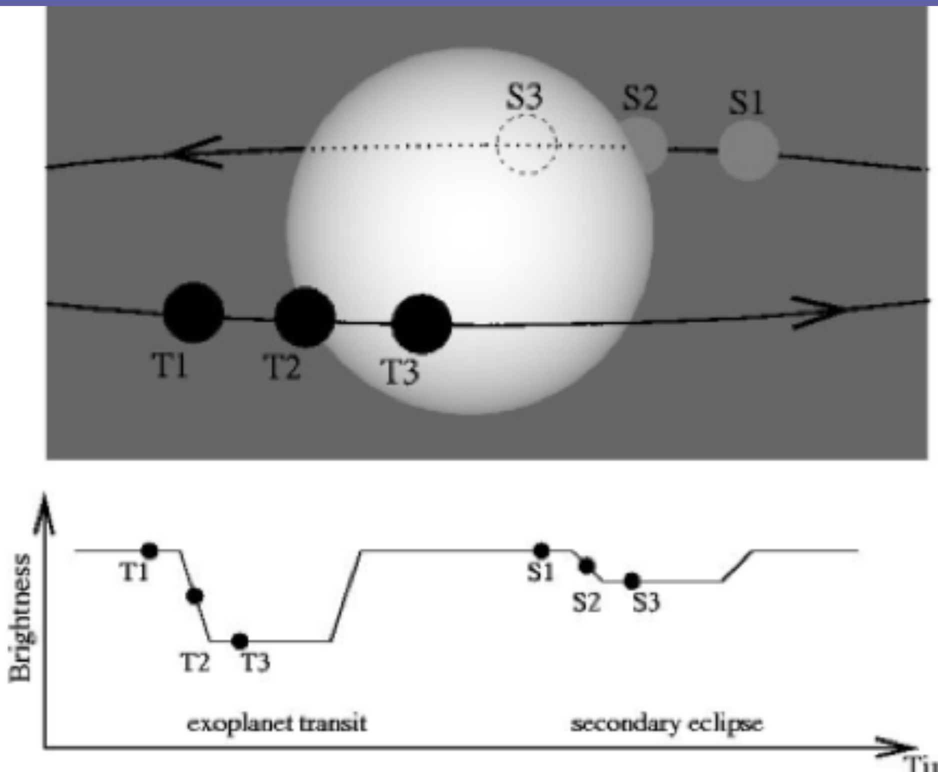


[Image credit: LSST corp.]

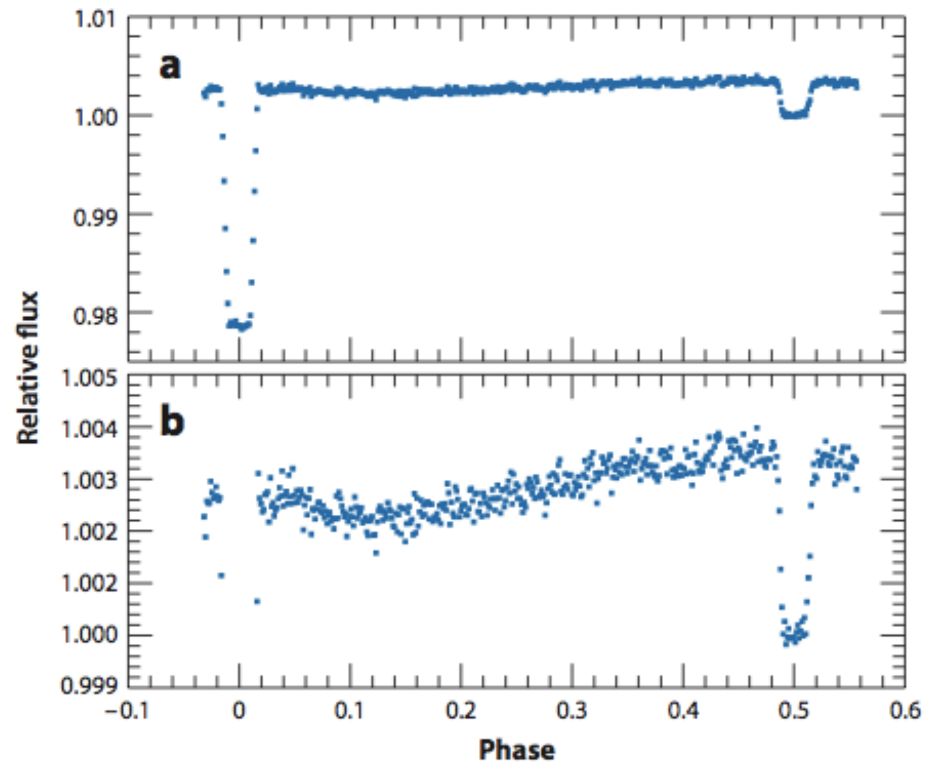
[Sumi et al. 2010]



Various Detection techniques: *Transit*

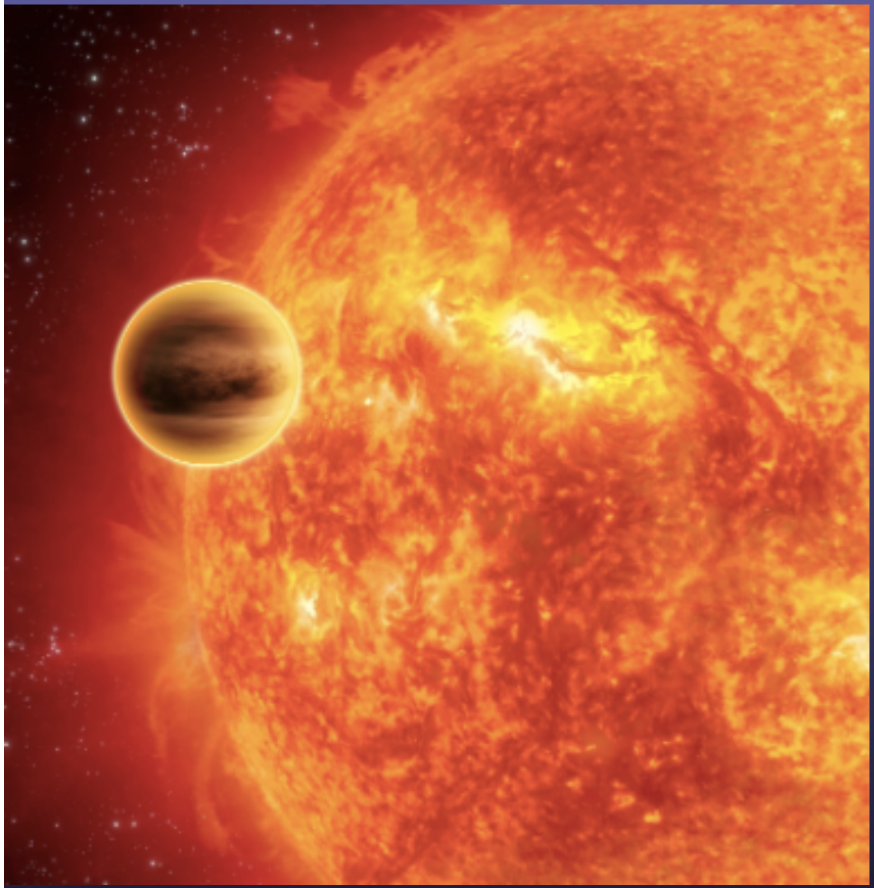


[Image credit: E. Kempton]

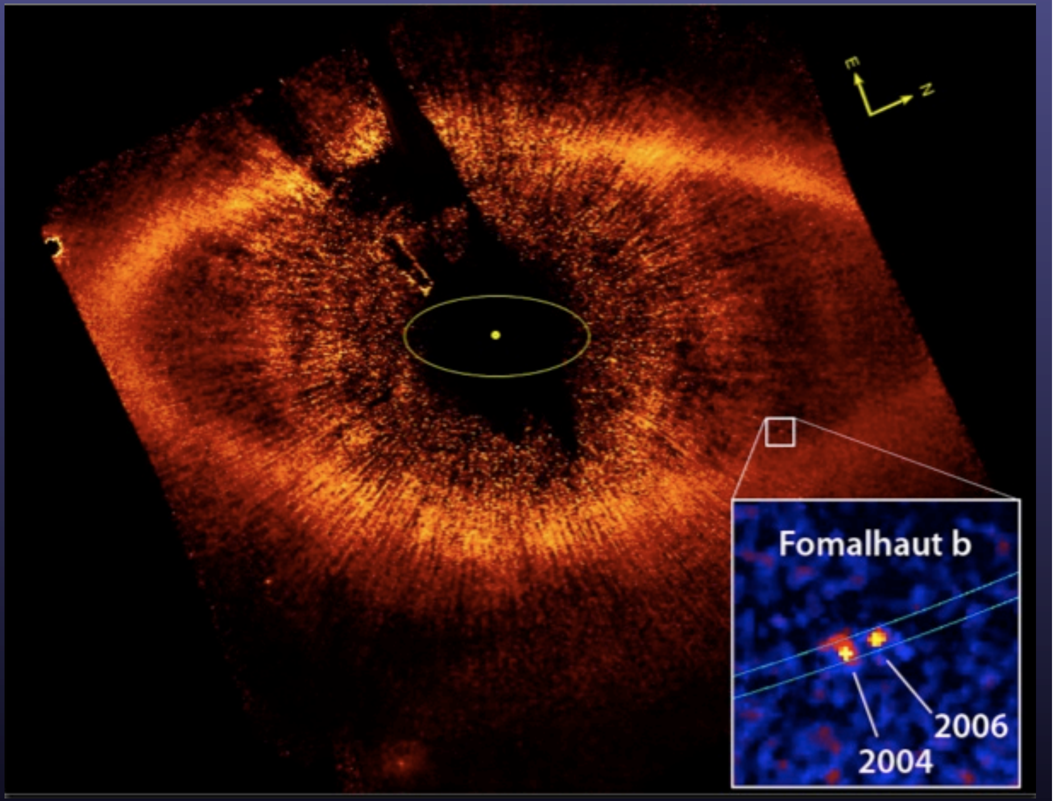


[Knutson et al. 2007]

Various Detection techniques: *Direct Imaging*

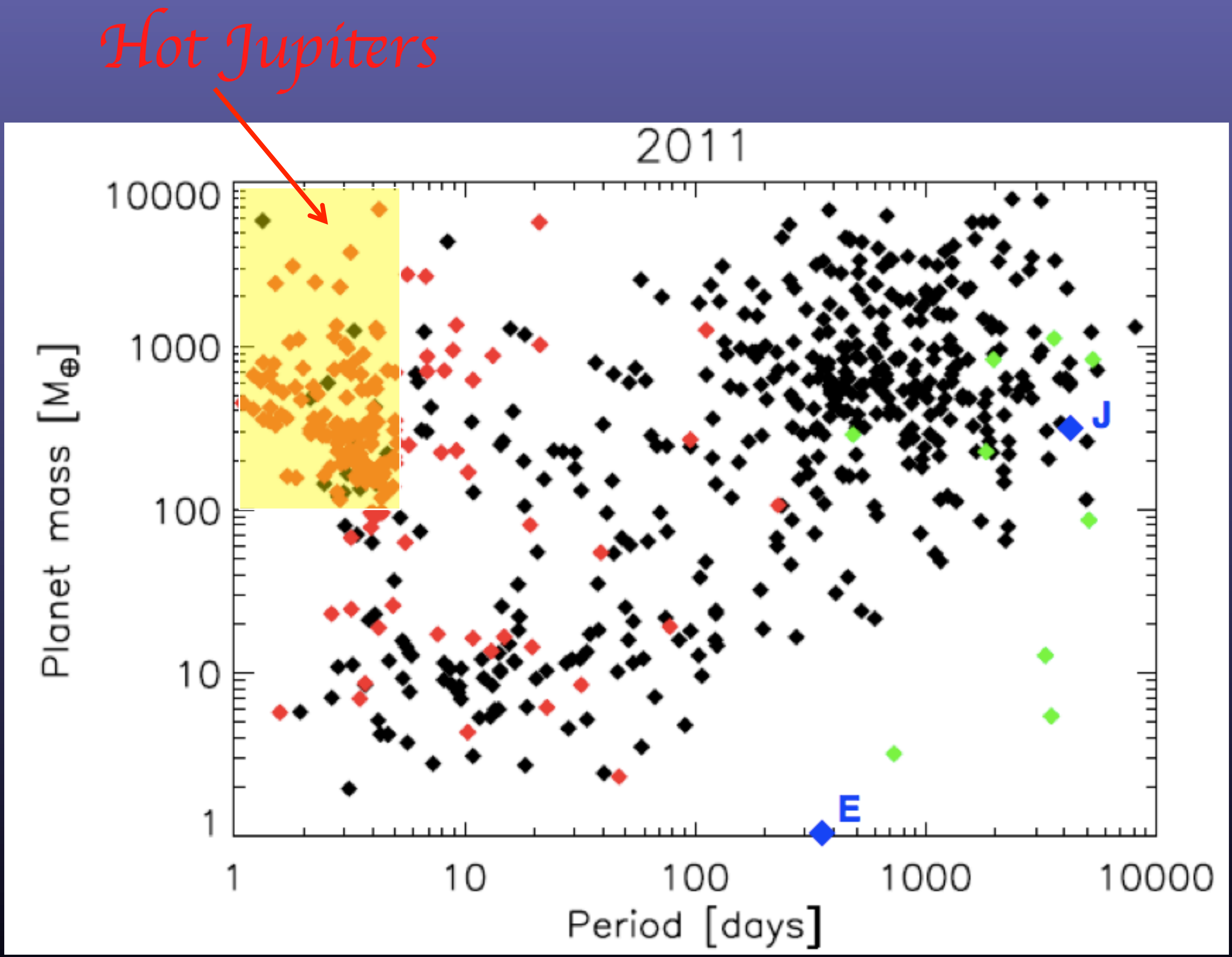


[Image credit: NASA]



[Kalas et al 2008]

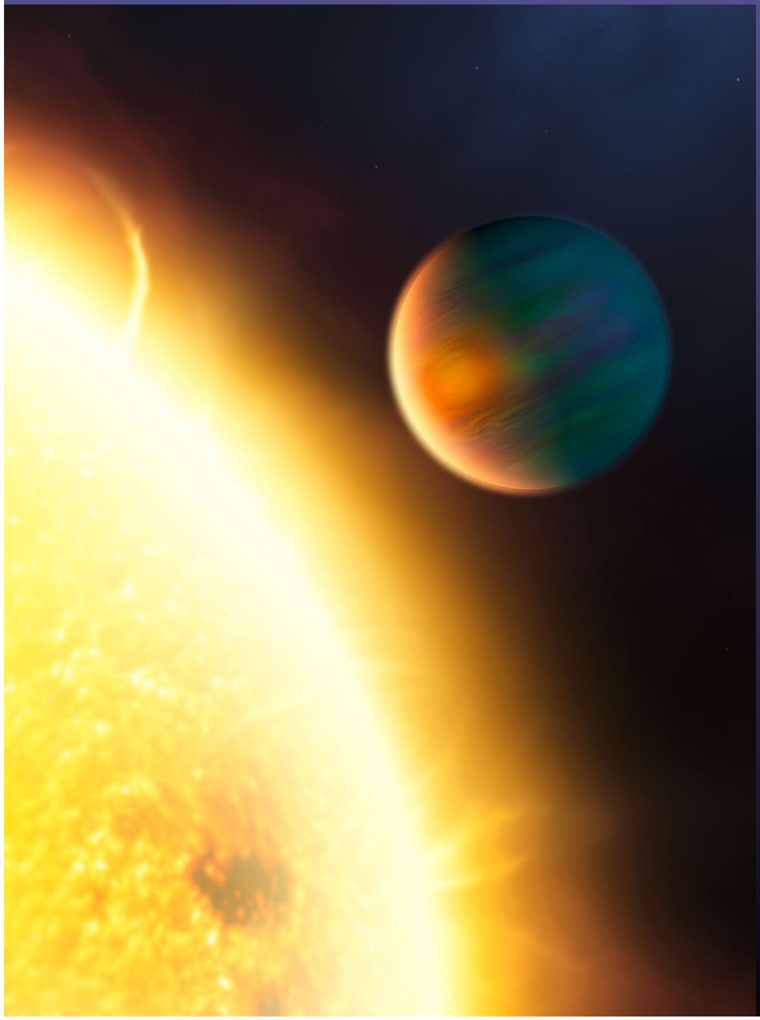
A special class of Exoplanets…



Hot Jupiter Atmospheres

HOT Jupiters: similar to Jupiter but closer to star

- recent discovery of several of them

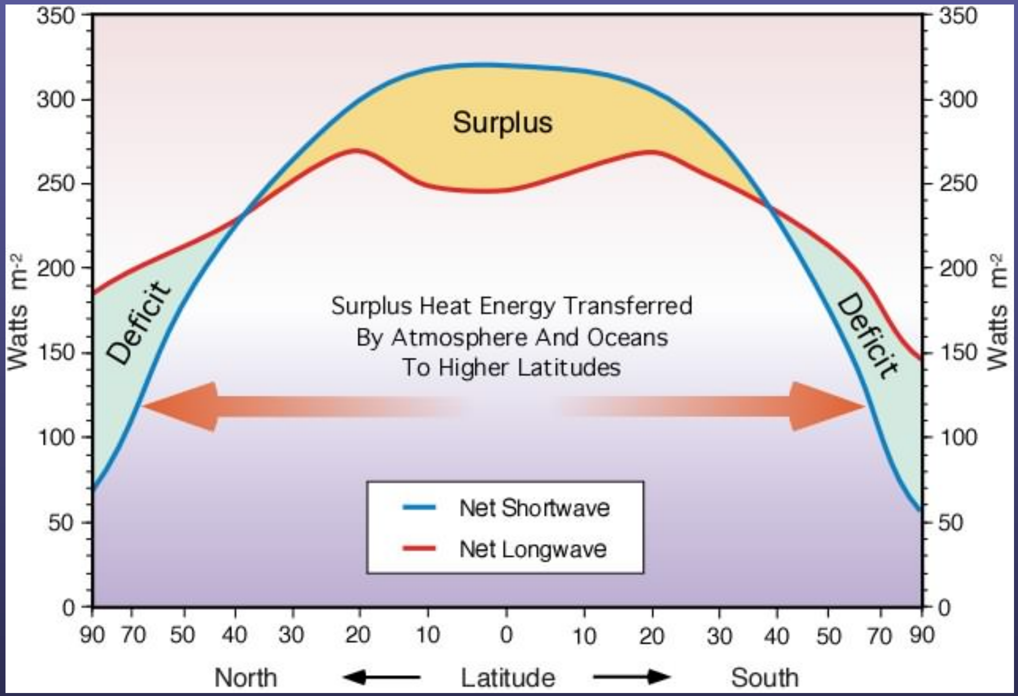


New regimes:

- Tidal Locking
- Asymmetric day/night radiative forcing
- High day-side temperatures
- Day/night temperature gradient

[Image credit: ESA- NASA]

Theoretical interpretation of the data requires modeling the circulation pattern

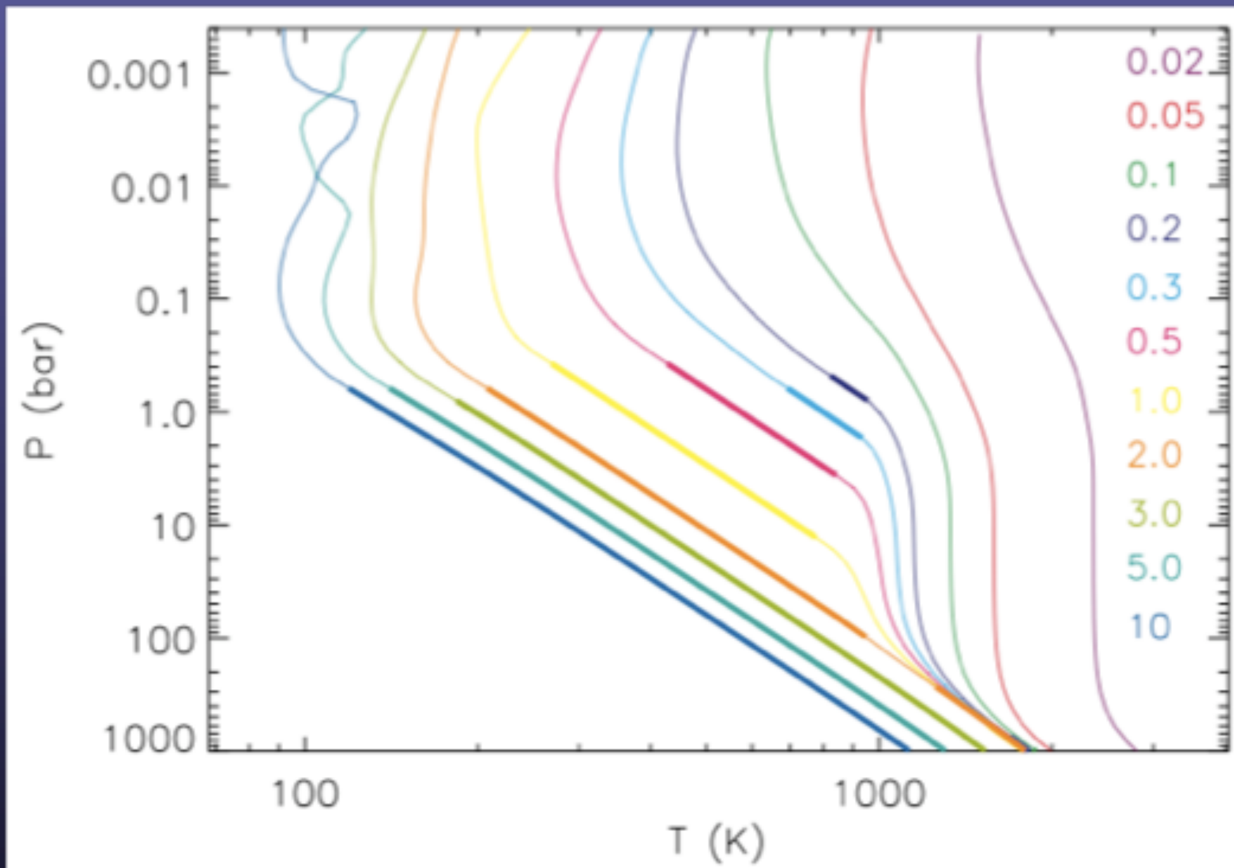


[Showman, Cho & Menou 2010]

- Emergent properties result from combined radiation and advection ("radiation-hydrodynamics")

Modeling Hot Jupiters (1D)

Jupiter Hot Jupiters



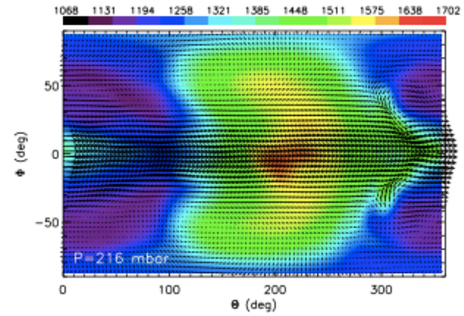
Fortney & Nettelmann (2010)
(1D averaged radiative equilibrium models)

<u>Deep Atmosphere:</u>

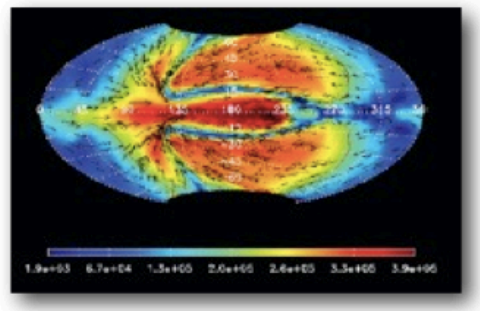
Radiative region
'weather layers'

Convective region
'inert layers'

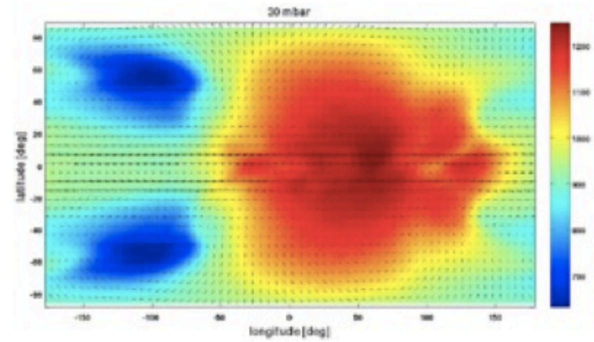
Modeling Hot Jupiters (2D and 3D)

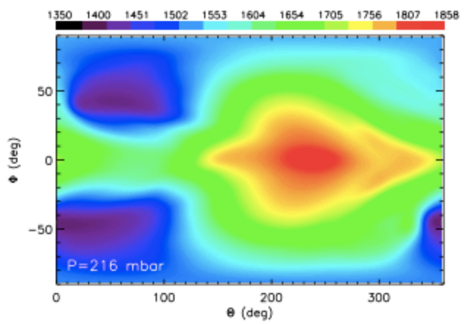


Heng, Menou & Phillipps (2011)

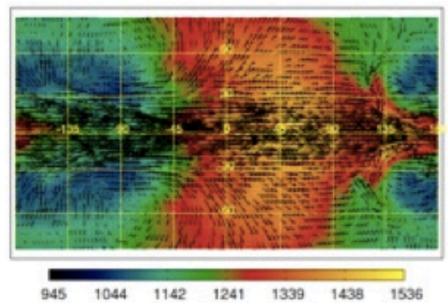


Dobbs-Dixon & Lin (2008),
Dobbs-Dixon, Cumming & Lin (2010)

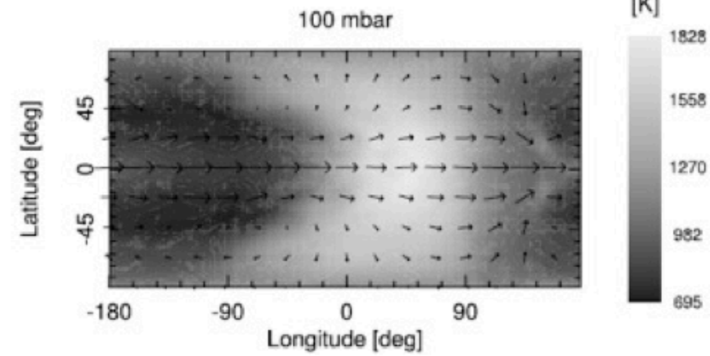

Showman et al. (2009)



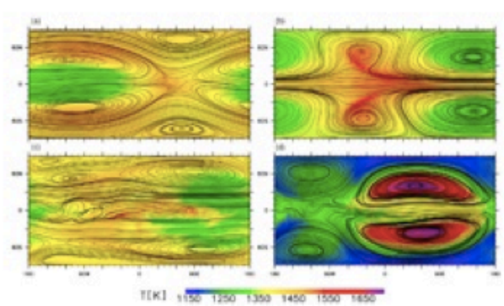
Heng, Frierson & Phillipps (2011)

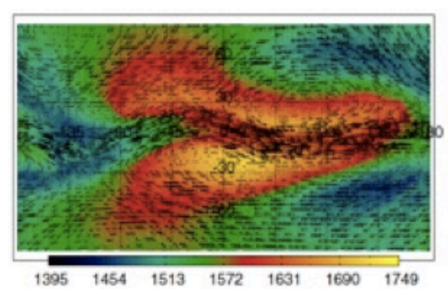


Rauscher & Menou (2010)

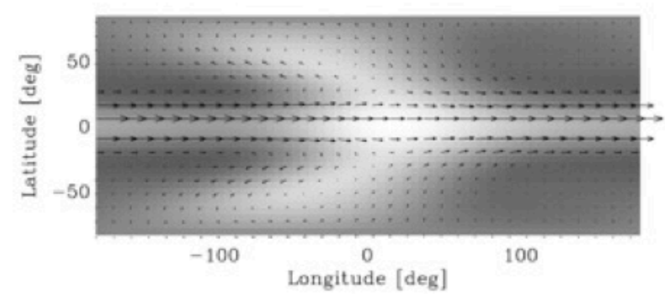


Showman et al. (2008),
Cooper & Showman (2005, 2006)


Thrastarson & Cho (2010, 2011)

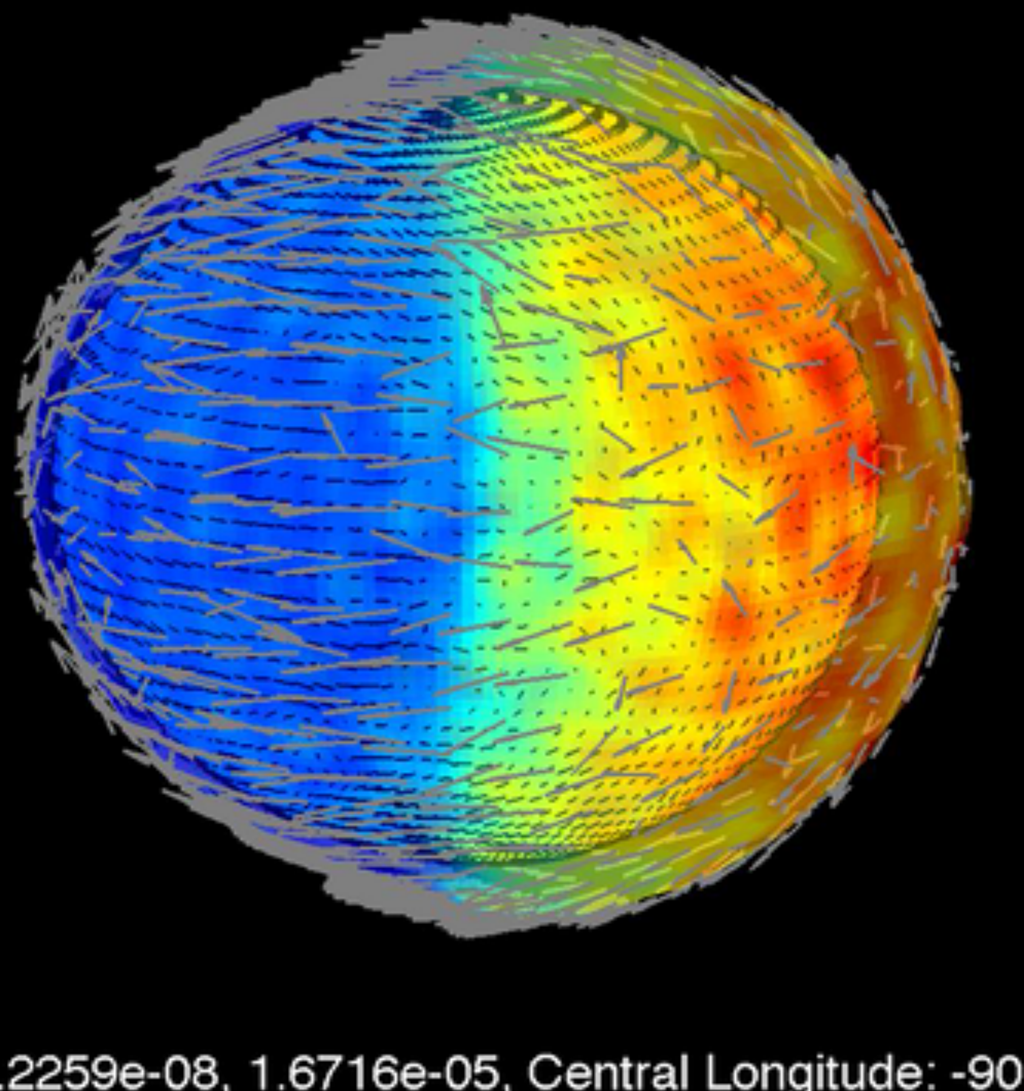


Menou & Rauscher (2009)



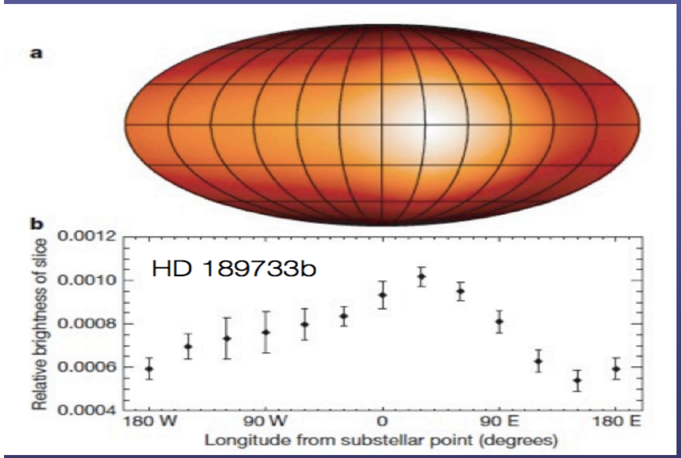
Showman & Guillot (2002)

[Burrows et al. 2010;
courtesy of D. Spiegel]



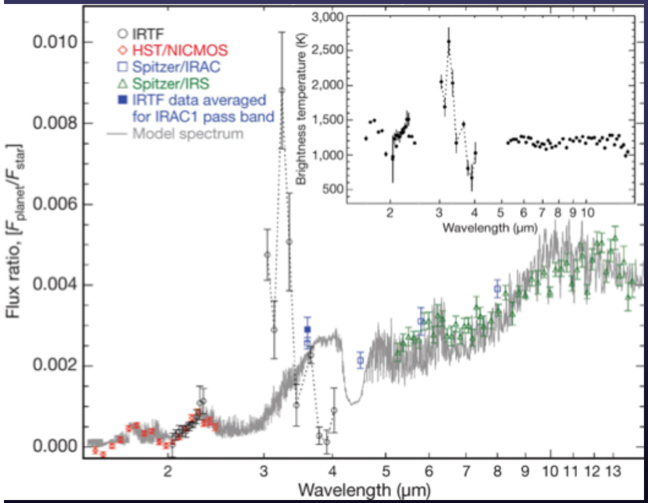
Connecting theory to observations

Observables / Inferences



[Knutson et al. 2007]

Phase curves ⟷ Atmospheric Dynamics

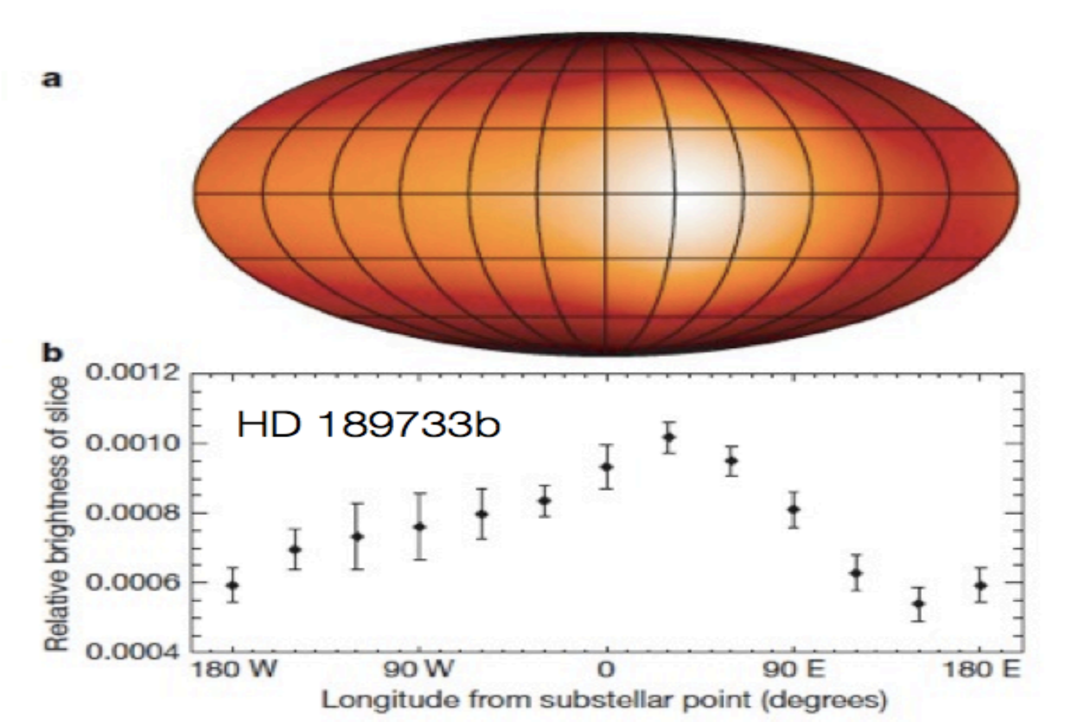


[Swain et al. 2010]

Spectra ⟷ Atmospheric Chemistry

Connecting theory to observations

Phase Curves

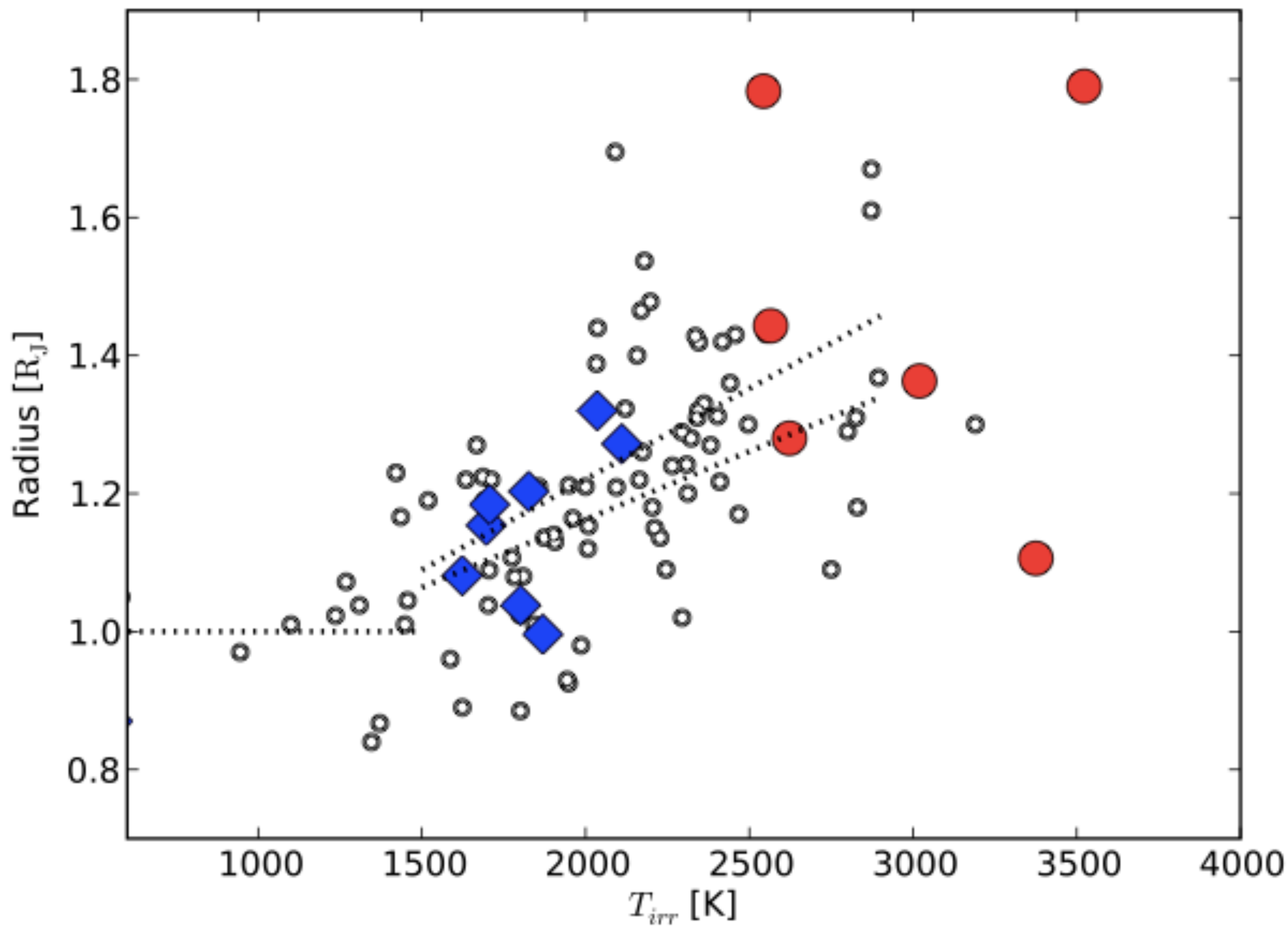


[Knutson et al. 2007]

Measure:

- F_{DAY}/F_{NIGHT}
- Hot Spot Location

Observations show…..

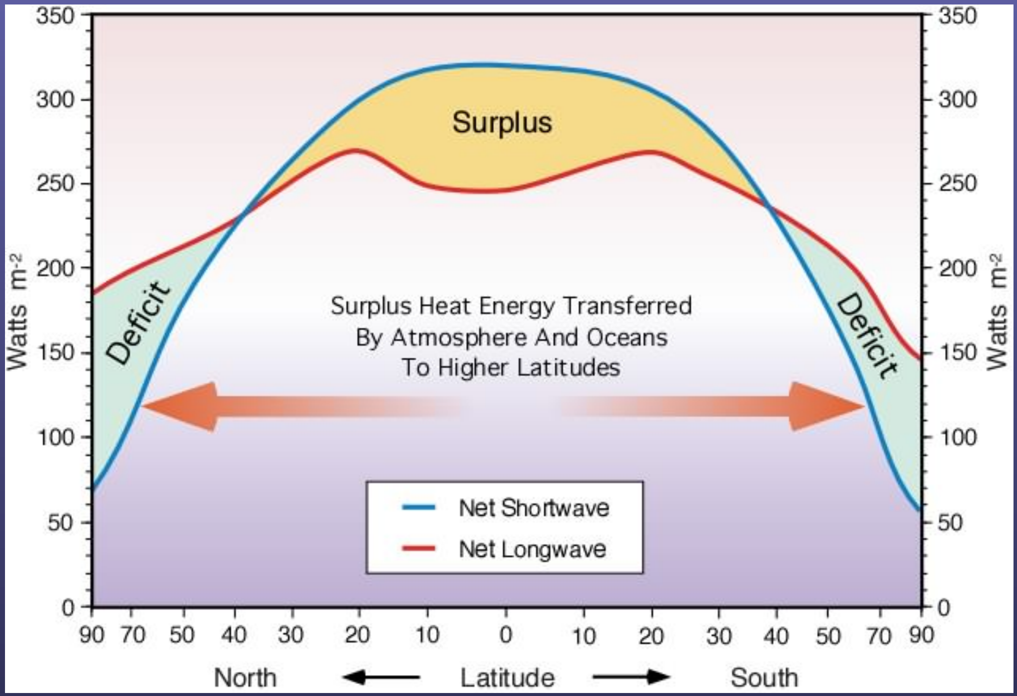


Strong Day/Night contrast

Efficient redistribution

[figure from Perna, Heng & Pont 2012]

What regulates this behavior?

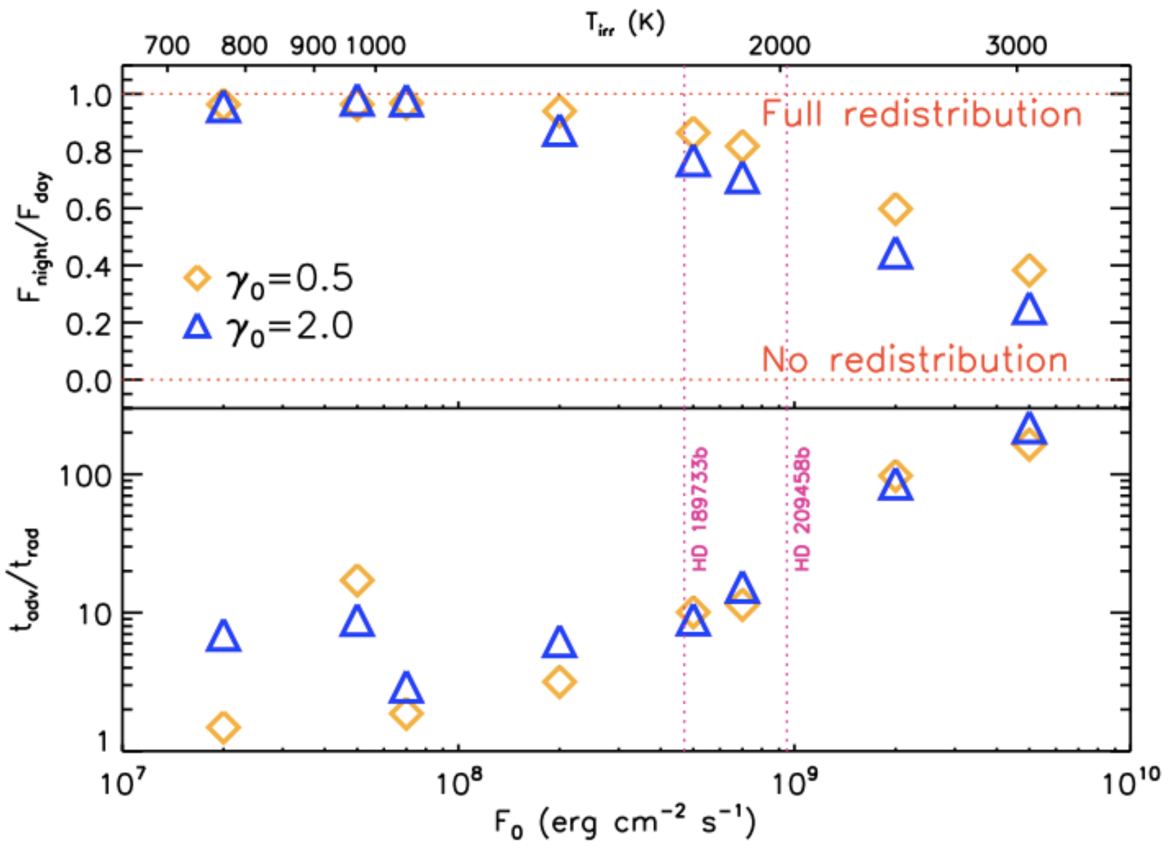


[Showman, Cho & Menou 2010]

Two counteracting effects:

- Irradiation from the star heats one surface but not the other, hence inducing temperature gradients
- Temperature gradients induce circulation which tends to redistribute heat

Results from numerical investigation

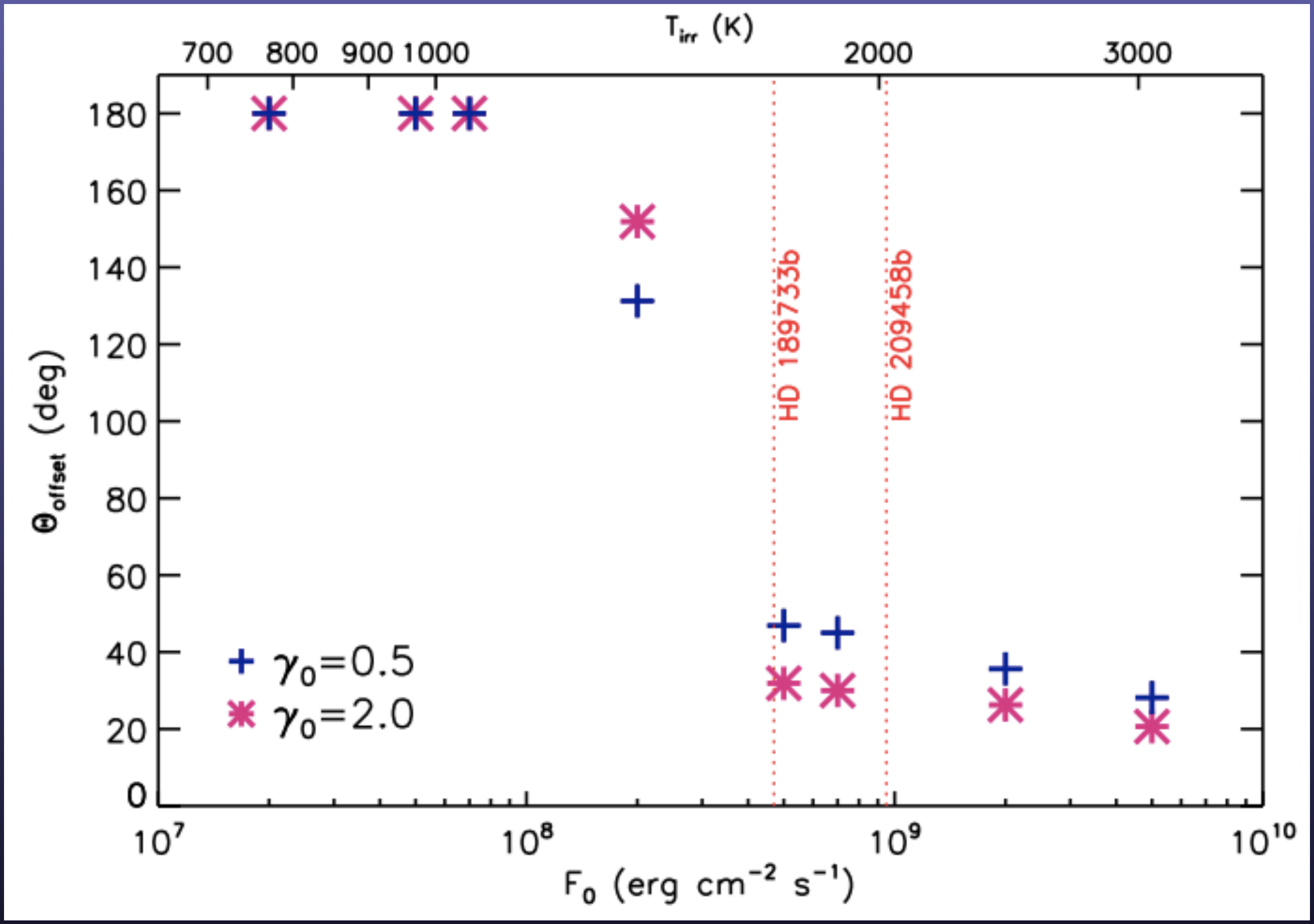


For $T_{irr} \gtrsim$ 2000 K, redistribution breaks down

Physical behavior determined by interplay between advective and radiative timescales

[Perna, Heng & Pont 2012]

Predictions for hot spot location



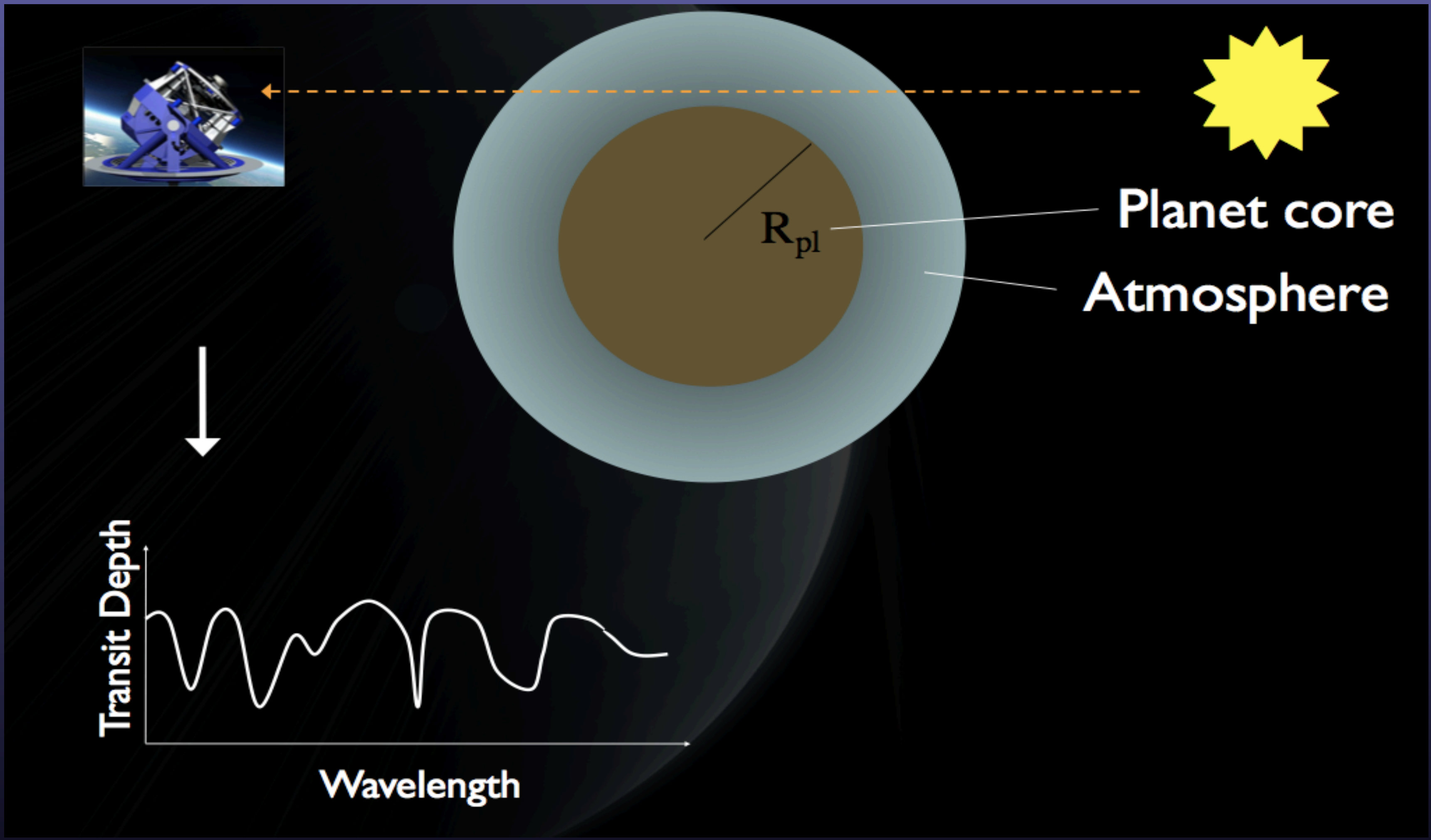
HD 189733b:

Measured offset between 16-34 deg (Knutson et al. 2007, 2009), in agreement with our results

[Perna, Heng & Pont 2012]

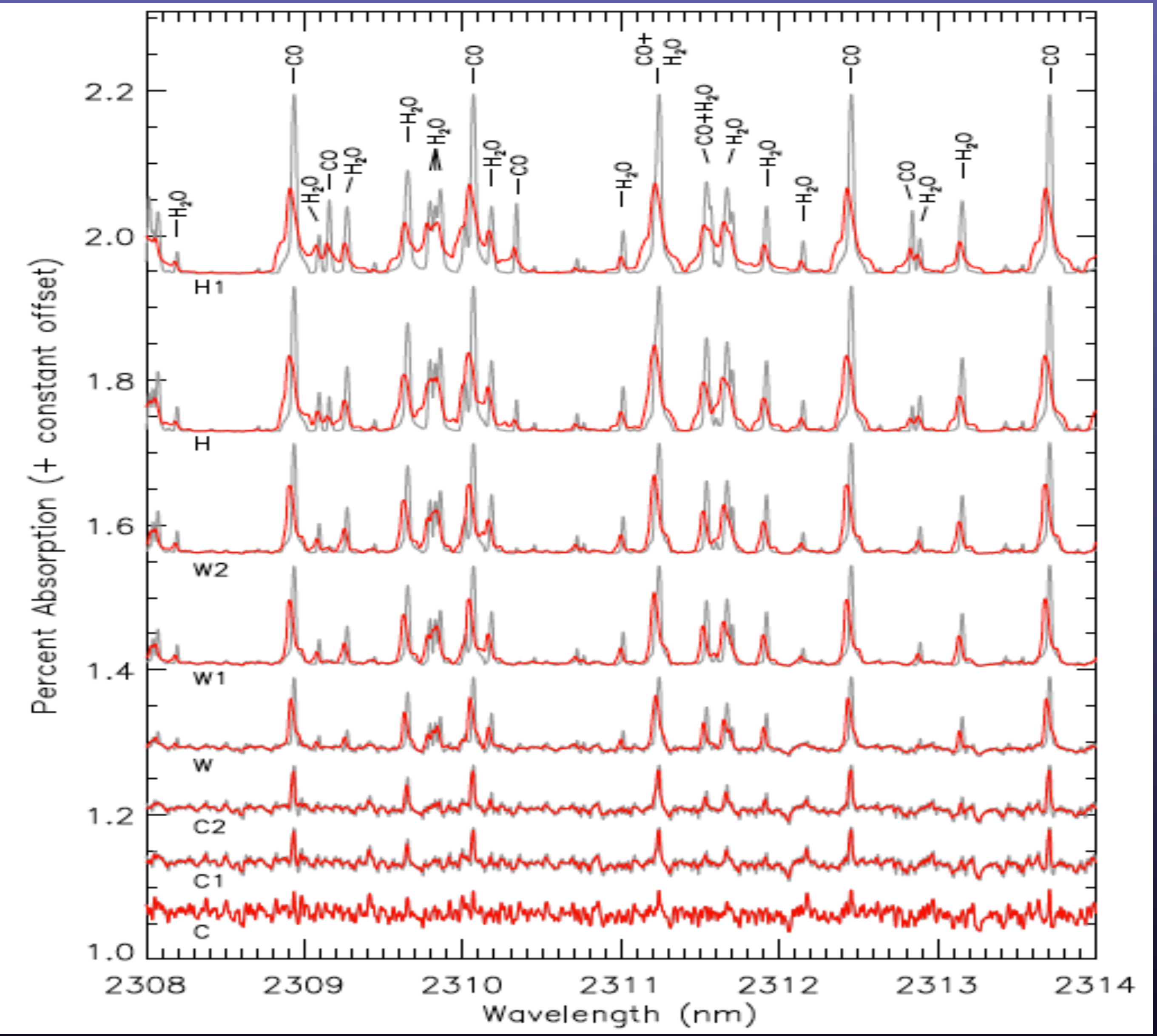
Connecting theory to observations

Transmission Spectra



[Figure credit: E. Kempton]

We can learn about atmosphere chemistry



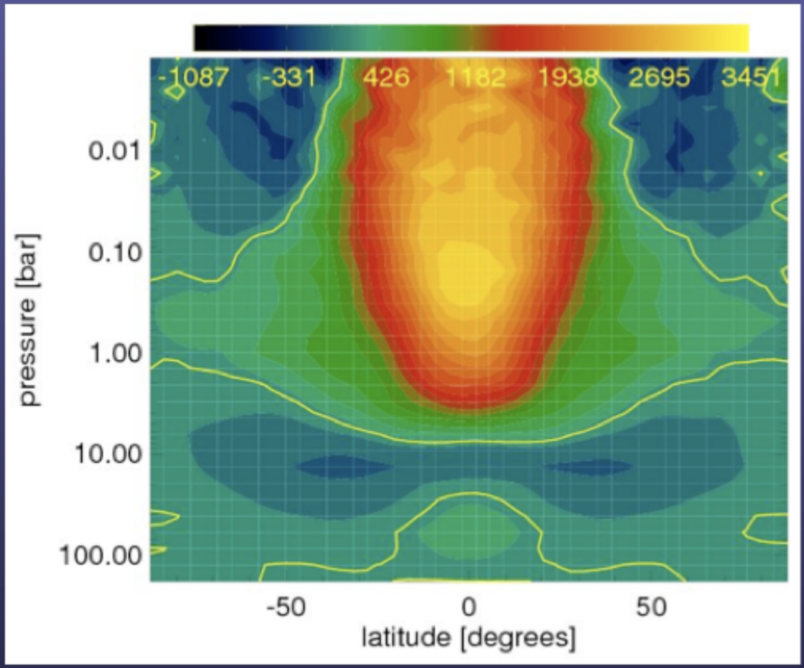
Theoretical spectra from planets with various degree of irradiation strength.

Information on *wind speeds* and on *atmospheric composition*

[Kempton, Perna & Heng, 2014]

Several open questions…

Zonal average of zonal (east-west) wind (m/s)



Weather layer
(heated)

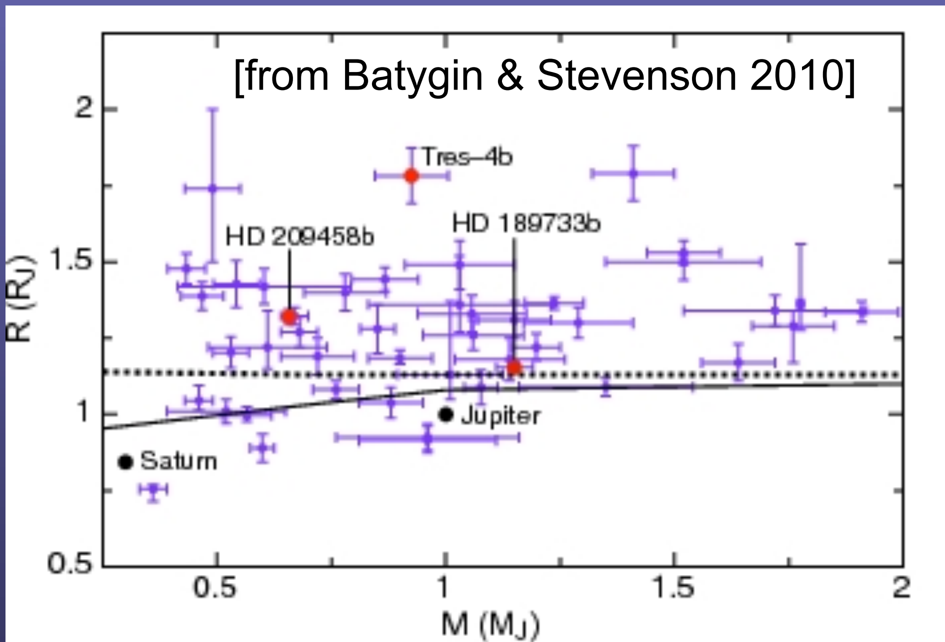
Inert layers
(large depository
of angular momentum)

- Are they really inert?

- What are the factors limiting the wind speeds?

- ‘Other’ sources of heating besides direct irradiation?

An outstanding puzzle: the *'Inflated radii'* of hot Jupiters



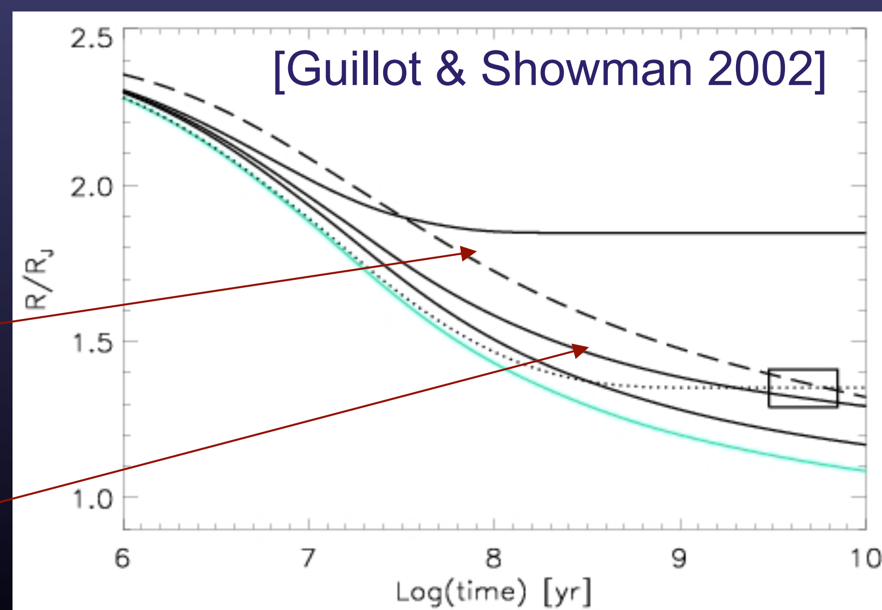
Well known problem: evolutionary models predict planet radii smaller than what is observed.

→ *Extra source of heat needed*

Evolutionary models with extra heating source

Evolution with extra 2.4×10^{28} erg at 11 bar

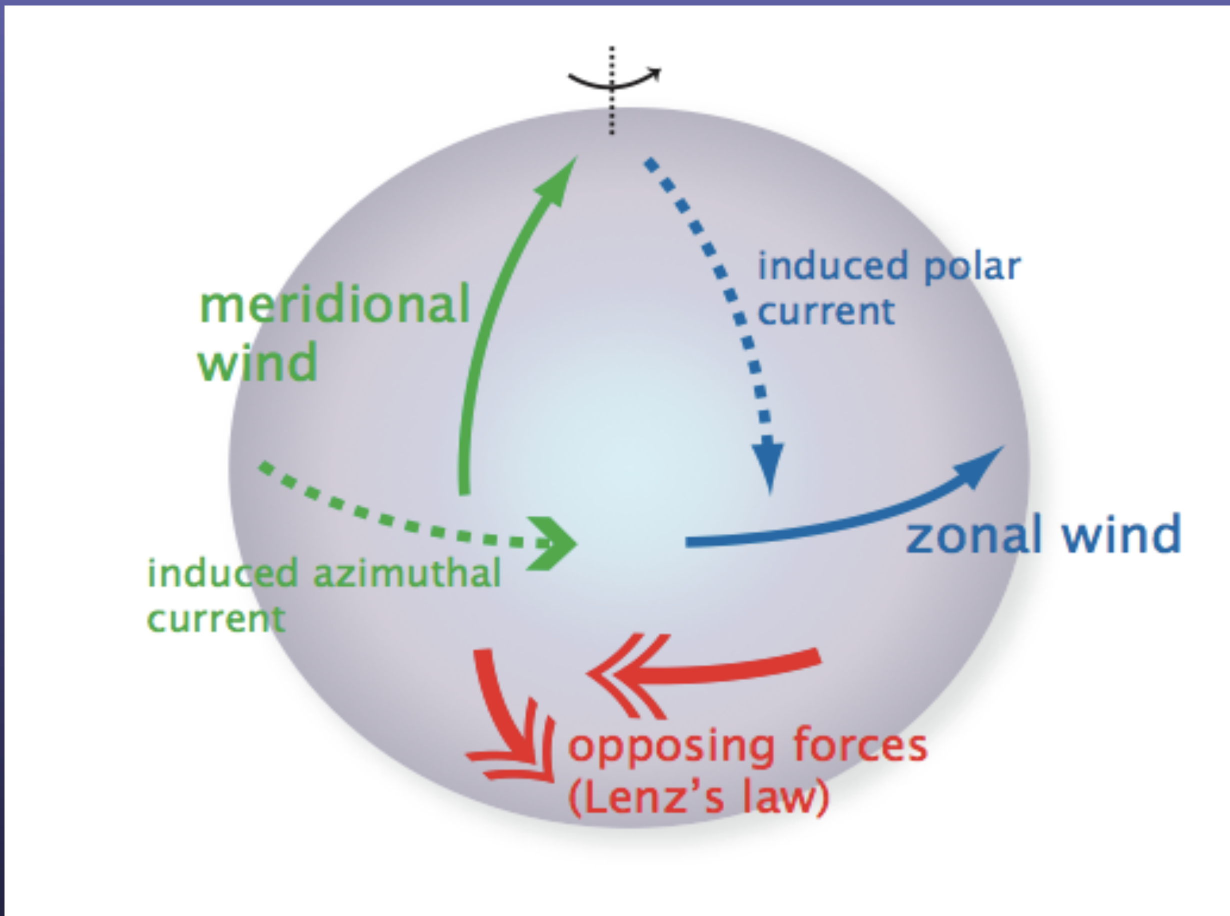
Evolution with extra 2.4×10^{27} erg at 21 bar



Various Explanations…

- Enhanced opacity or atmosphere stratification (Burrows et al 2007; Baraffe et al. 2010)
- Tidal dissipation of orbital eccentricity (e.g. Bodenheimer et al 2001; Liu et al. 2008; Spiegel & Burrows 2012)
- Dissipation of thermal tides (Arras & Socrates 2009; 2010)
- Dissipation of gravity waves (Guillot & Showman 2002)
- Forced turbulent mixing in radiative layer (Youdin & Mitchell 2010)
- *Magnetic effects* (Batygin & Stevenson 2010; Perna , Menou & Rauscher 2010)
  - Provide extra heat (Ohmic dissipation)
  - Limit wind speed (magnetic drag)
  - Depend on F_{irr}

MAGNETIC DRAG



[Figure credit: K. Heng]

- Irradiation frees e^- from metals N_a, K
- Partially ionized atmosphere advects B field lines, inducing currents
- Lorentz force causes drag on charged particles, which are coupled to neutrals

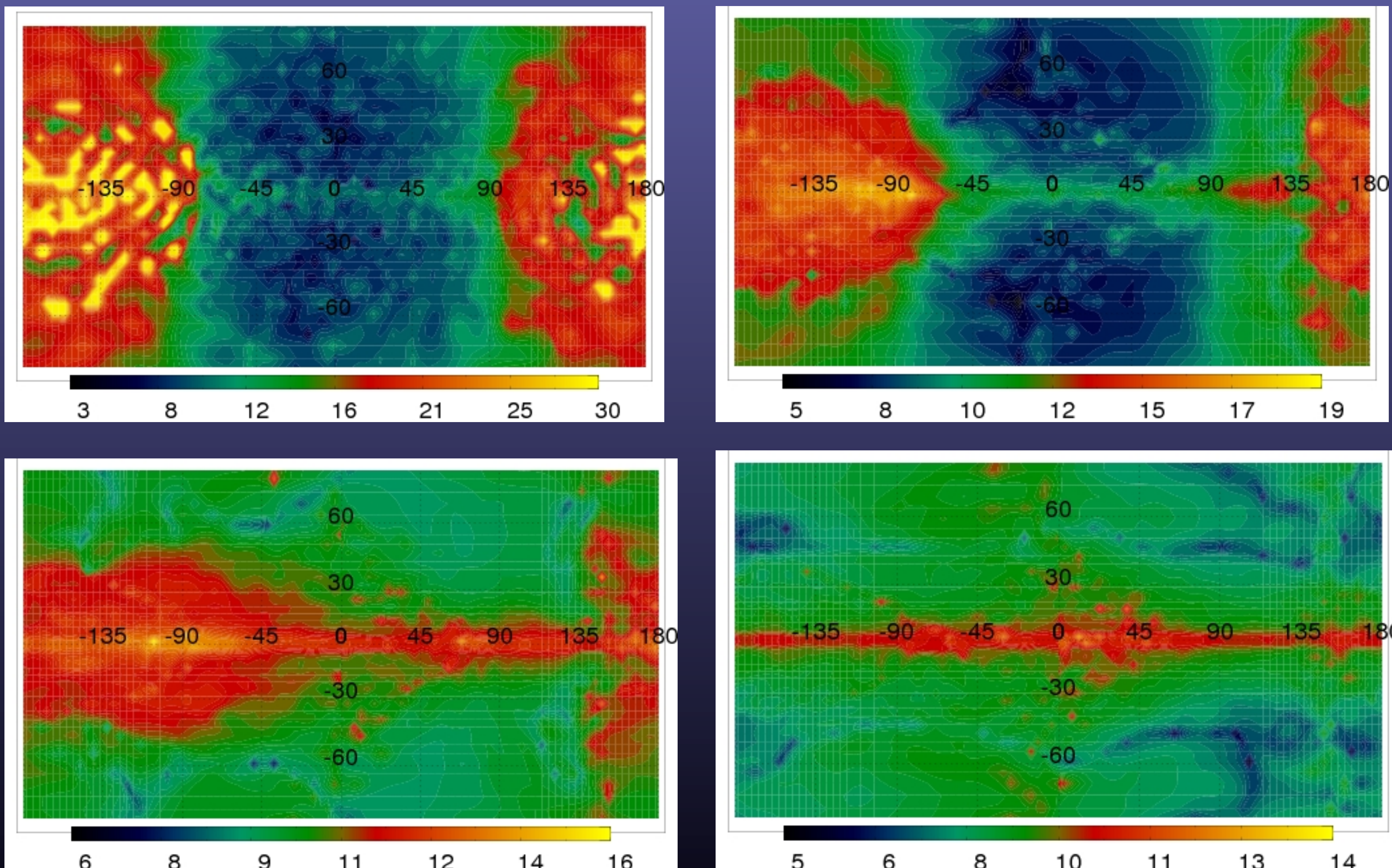
→ *Flow speeds are reduced*

$$\tau_{drag} \sim \frac{\rho v c}{|\vec{j} x \vec{B}|}$$

Drag Time

Typical timescale to slow down the flow by magnetic drag

[Perna, Menou & Rauscher 2010a]

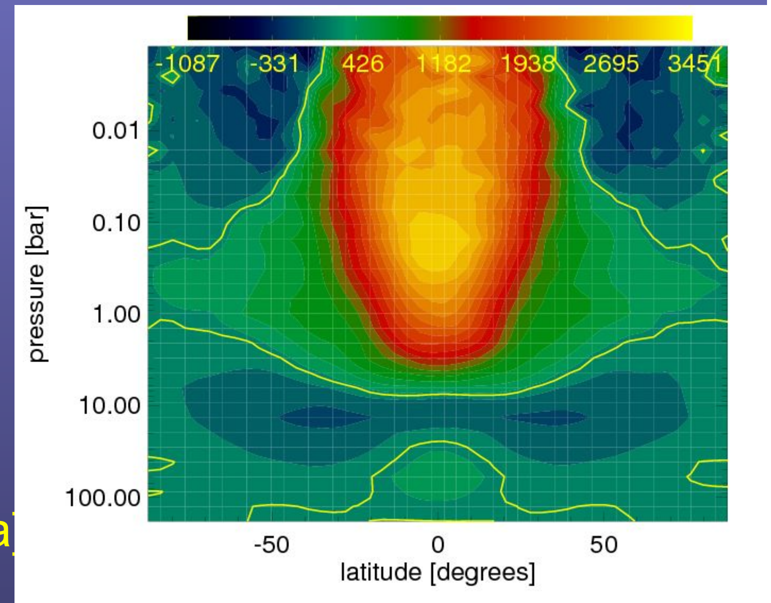


Log [t_{drag}(s)]

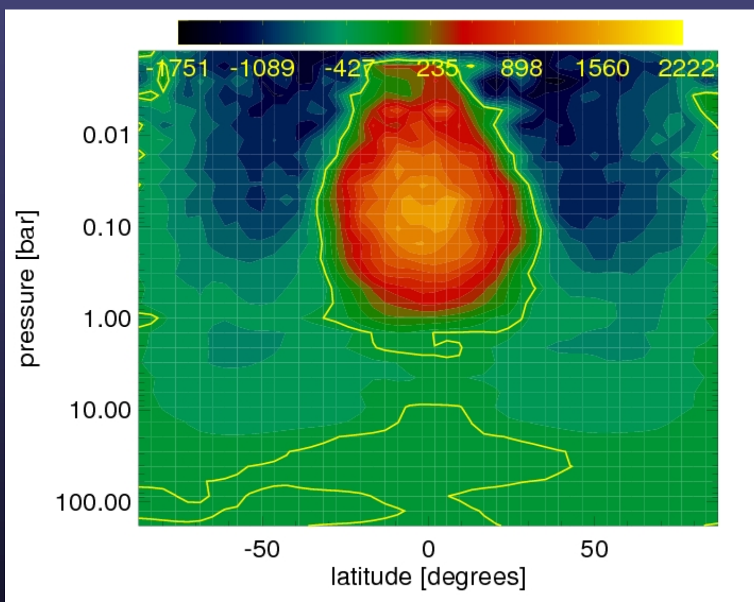
Log [t_{drag}(s)]

Drag time comparable to
wind acceleration time in some regions
→ magnetic drag may play an
important role in limiting wind speeds

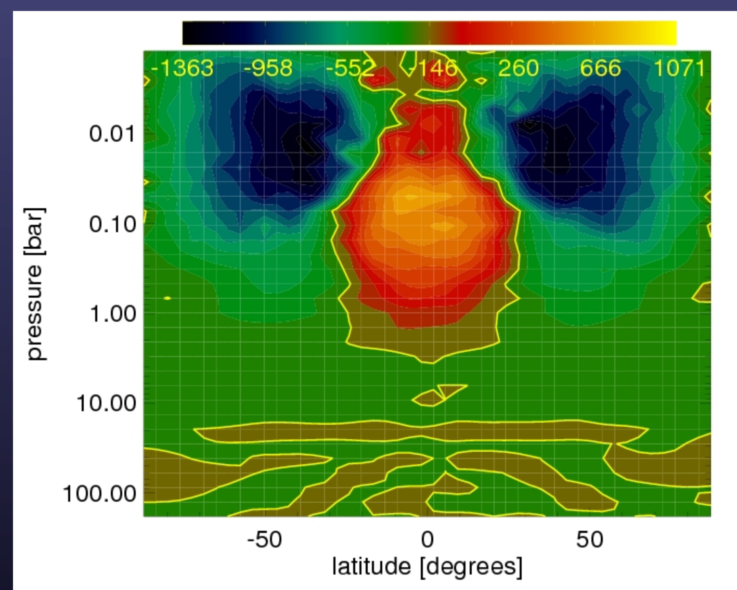
First results from simple
implementation [Perna, Menou, Rauscher 2010a]



[from Rausher & Menou 2010 - NO DRAG]



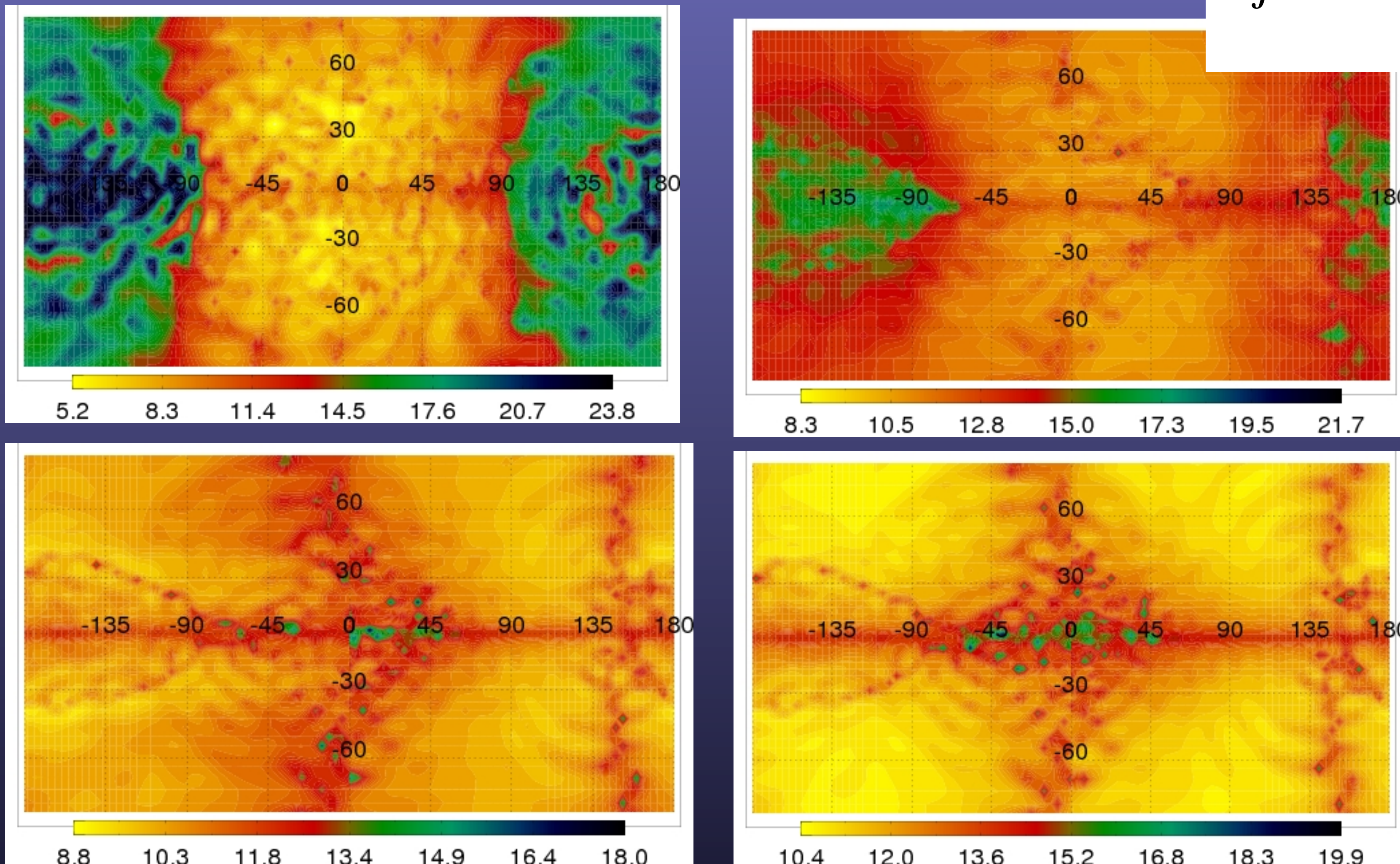
$$6x10^{5}s \leq \tau_{drag} \leq 8x10^{7}s$$



$$6x10^{4}s \leq \tau_{drag} \leq 8x10^{6}s$$

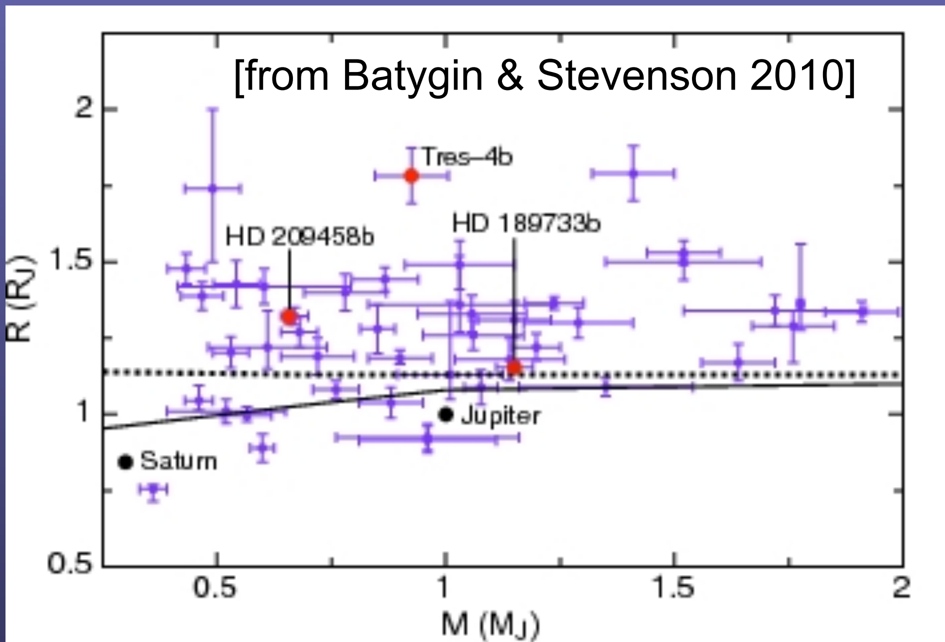
Ohmic Heating: Joule Time

$$\tau_J \sim \frac{\rho C_p T}{Q_J}$$



- Joule time <~ Irradiation time for p>~ a few bars
- Non-uniformity of Joule heating can lead to Joule-driven circulation in the inert layers. [Perna, Menou & Rauscher 2010b]

Ohmic Dissipation and the Radius Problem

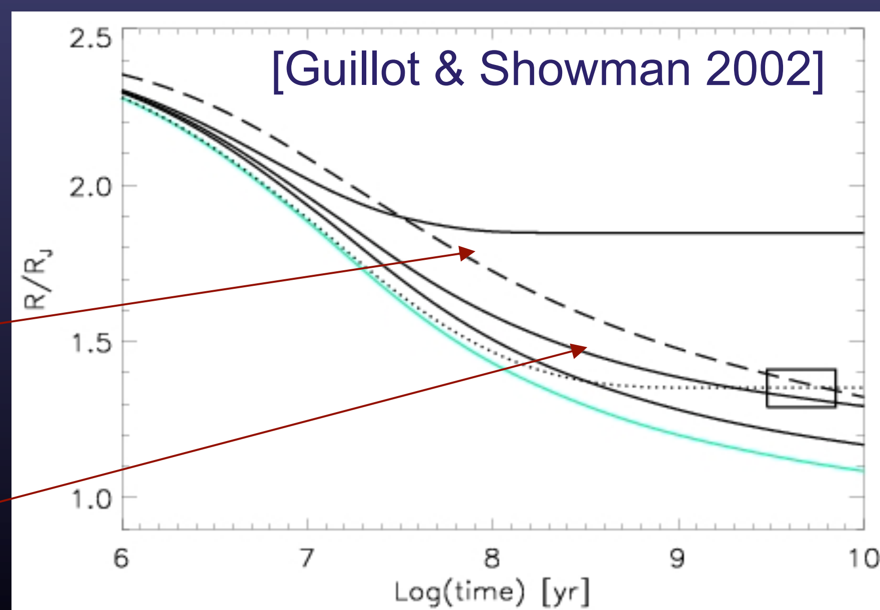


Can Ohmic dissipation account for the needed ‘extra’ source of heating?

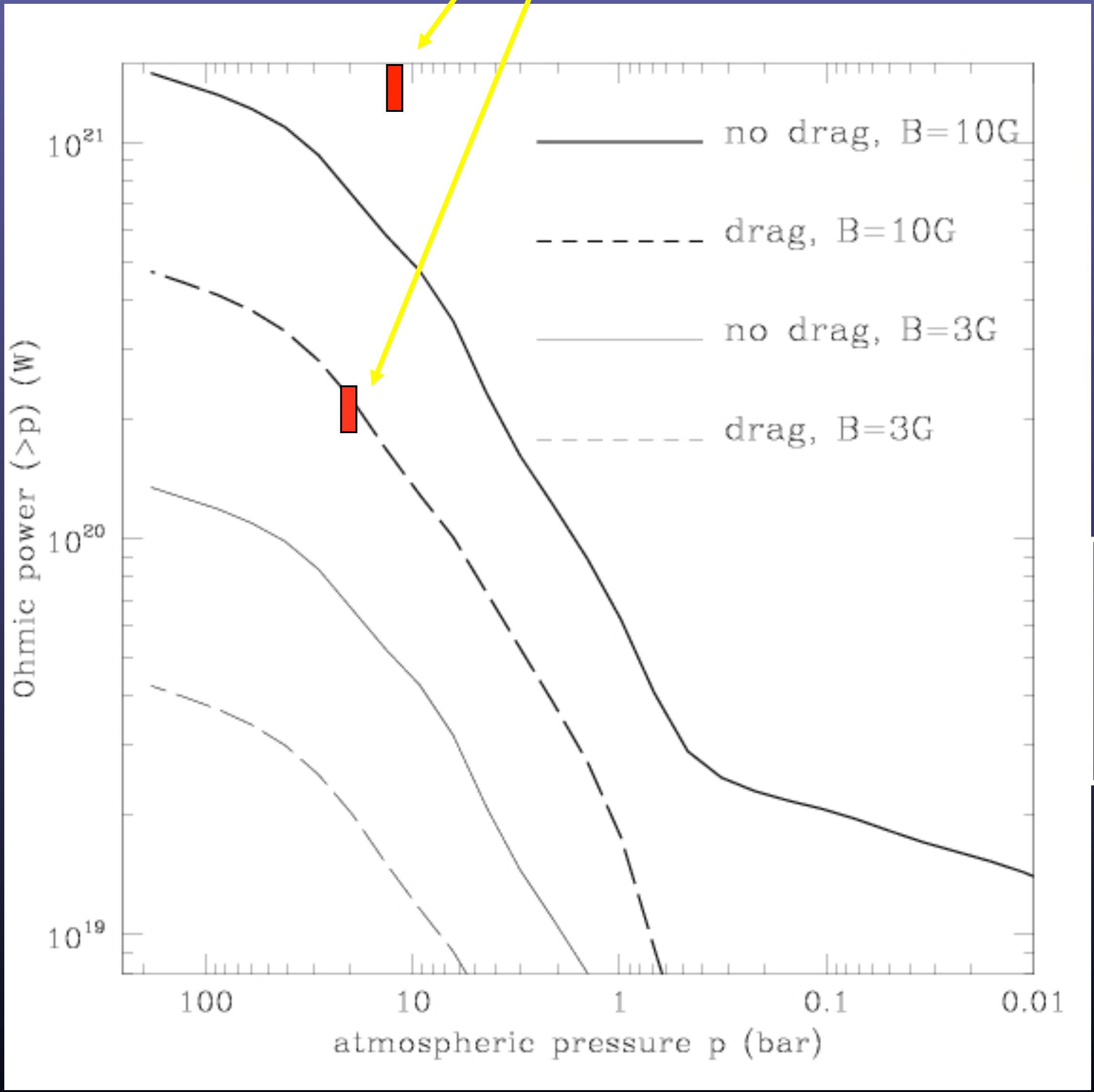
Evolutionary models with extra heating source

Evolution with extra 2.4×10^{28} erg at 11 bar

Evolution with extra 2.4×10^{27} erg at 21 bar



Extra heating amounts required to explain the radius of HD 209458b
[Guillot & Showman 2002]

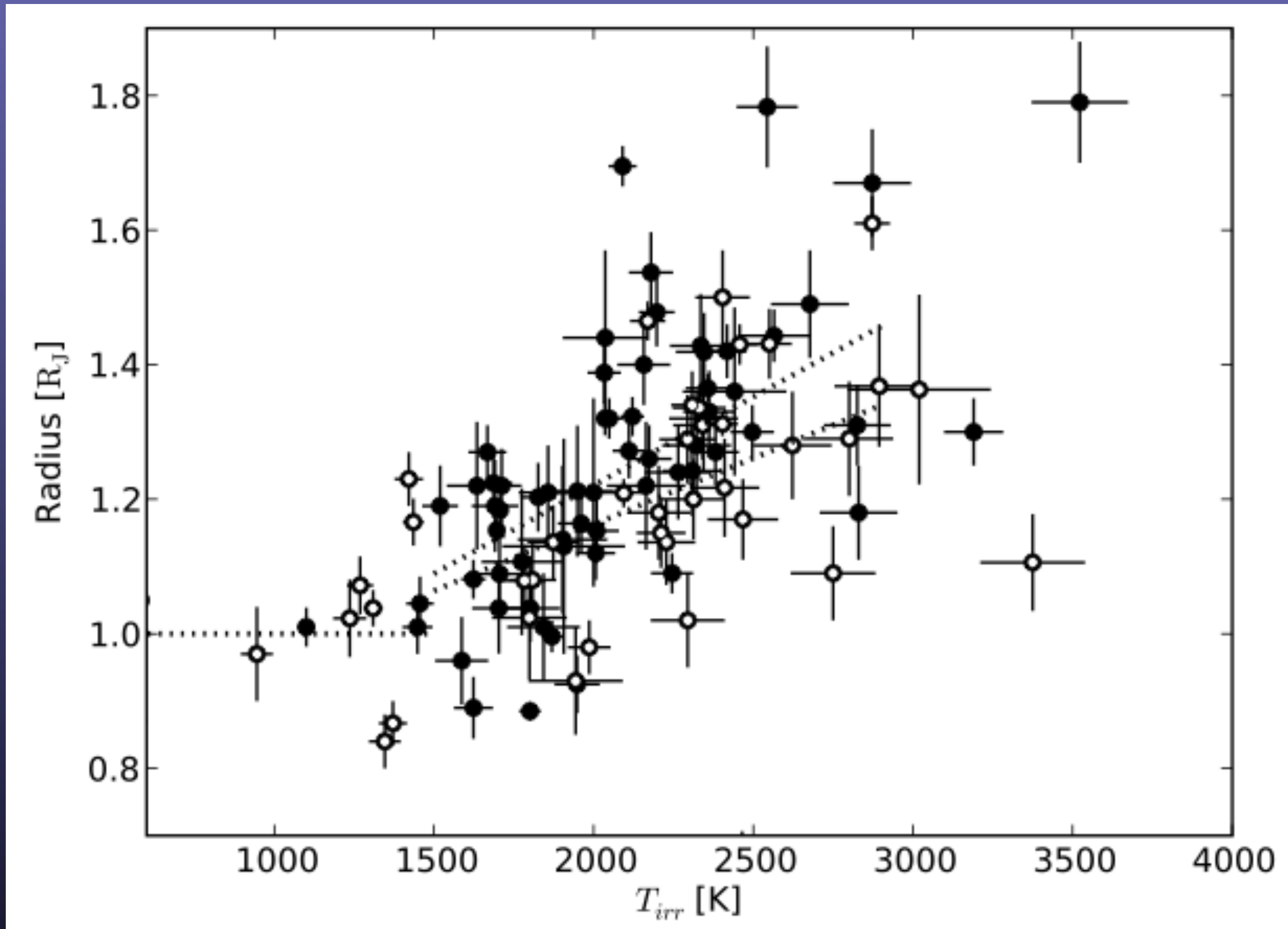


OHMIC DISSIPATION naturally provides an extra source of heat for magnetic fields B>~ 10 G.

Ohmic dissipation may provide the solution to the radius problem

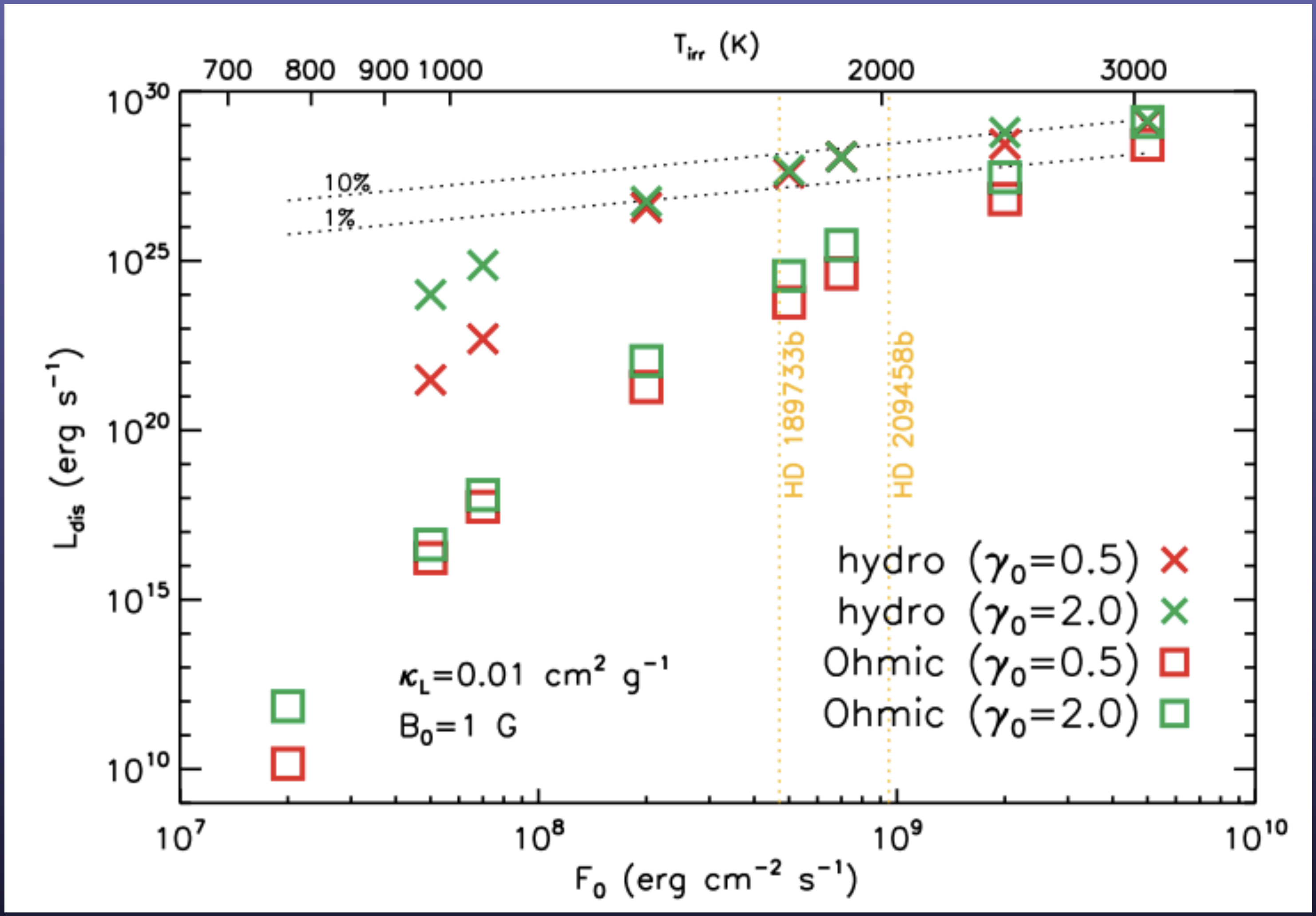
[Perna, Menou & Rauscher 2010b; Batygin & Stevenson 2010, but see Rogers & Showman 2014]

How common is the radius problem?



Observations show a clear dependence on the strength of the irradiating flux

Ohmic dissipation as a function of irradiation flux



[Perna, Heng & Pont 2012]

Ohmic dissipation very strong function of irradiation strenght !

SUMMARY

- 20 years ago: we did not even know whether planets existed beyond our solar system

- Today: we are able to detect planets with a variety of techniques and characterize their atmospheric dynamics and chemistry

- Next 20 years: what will they bring us?