The Effects of Irradiation on Hot Jovian Atmospheres

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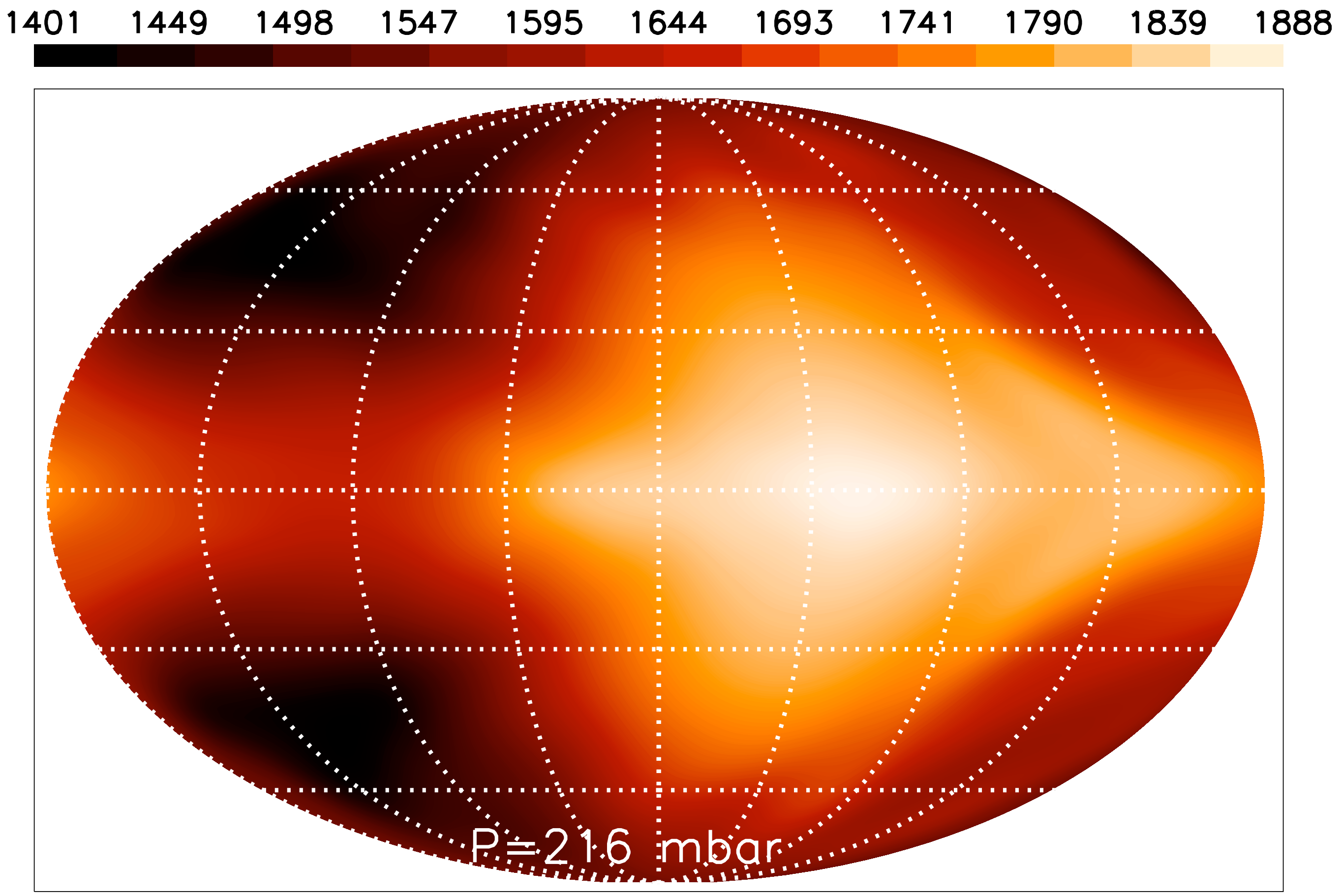


Mollweide projection of temperature map near IR photosphere of a hot Jupiter

The puzzle of inflated hot Jupiters: an effect driven by stellar irradiation

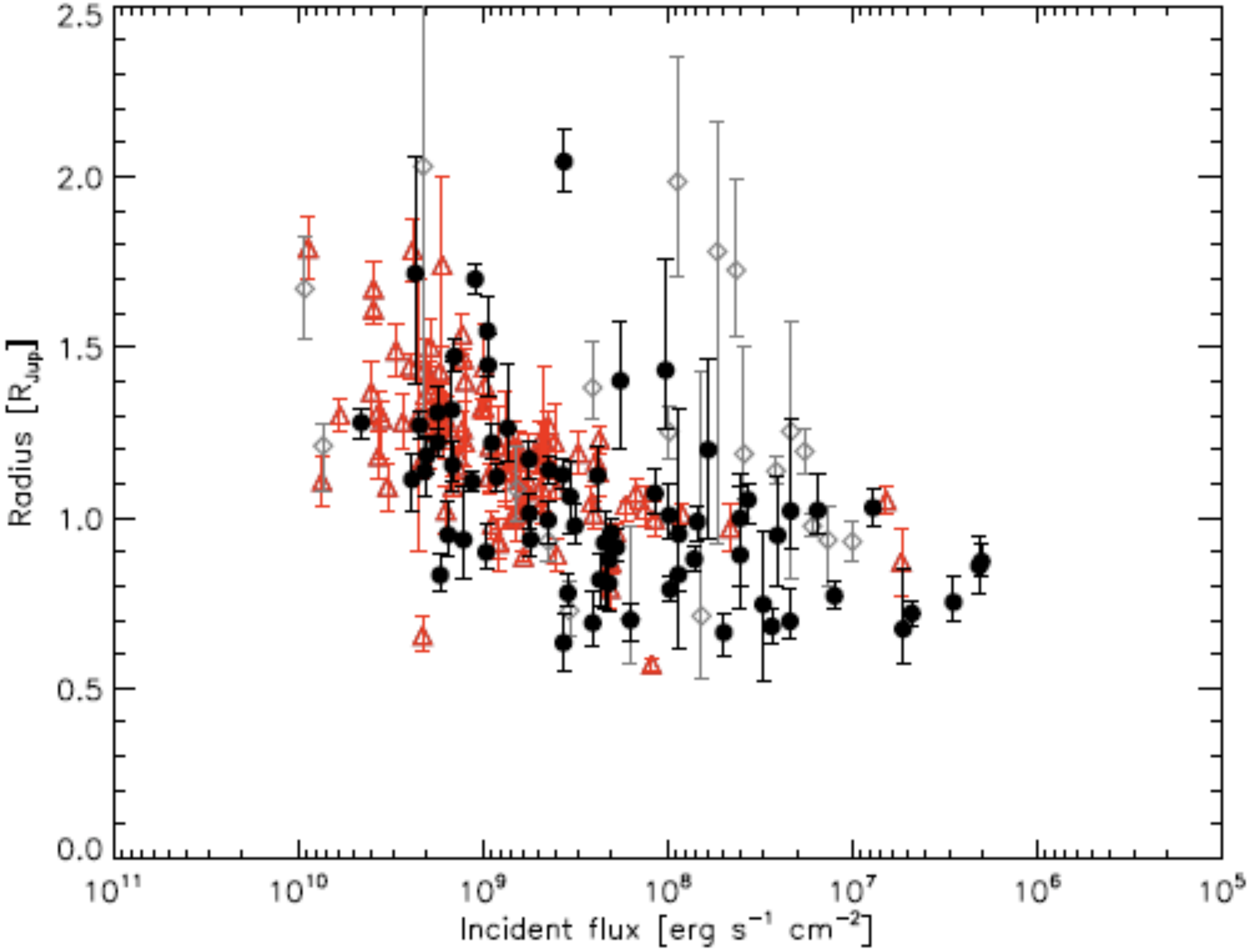


FIG. 1.— Planetary radii as a function of incident flux. Black filled circles are KOI ranked as planetary candidates in the frame of this work while gray diamonds represent KOI whose origin is ambiguous (see Sect. 3). Transiting giant planets previously published, and mostly from ground-based surveys, are shown as red triangles. The relevant parameters R_p, R_s, T_{eff} and a have been drawn from http://www.inscience.ch/transits on August 29, 2011.

The observations tell us that the mechanism is related to or driven by the intensity of starlight, but they do not tell us *what* the mechanism is.

Black points: Kepler candidates
Red points: others

Demory & Seager (2011)

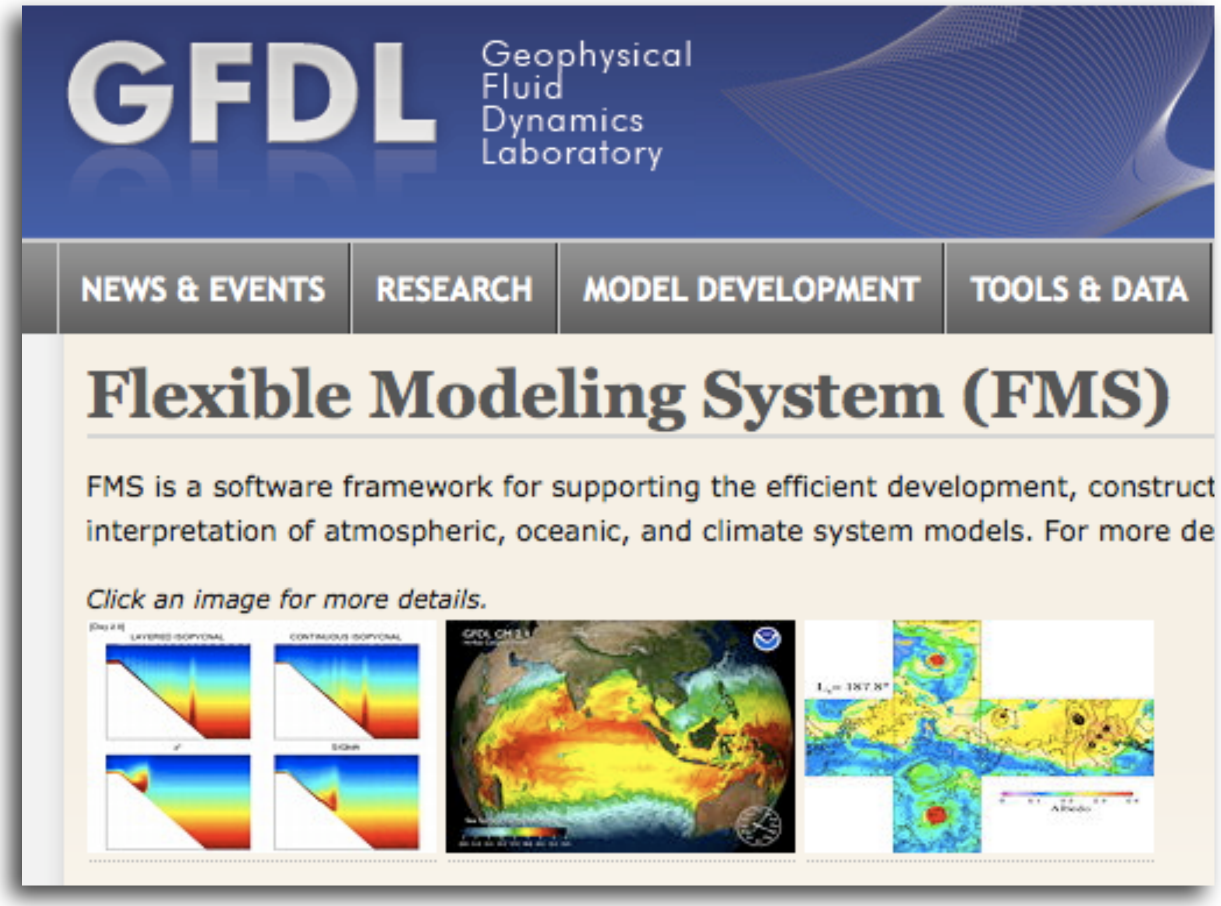
See also: Miller & Fortney (2011)

Key Questions:

How does dissipation and heat redistribution in hot Jupiters depend upon stellar irradiation?

Are the simulated trends broadly consistent with observations?

The GCM we use: the Flexible Modeling System (FMS)



Flexible Modeling System (FMS)

FMS is a software framework for supporting the efficient development, construct interpretation of atmospheric, oceanic, and climate system models. For more de

Click an image for more details.

Screen shot of FMS web page

- Simulation platform developed at the Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton.
- Robustly tested, parallel codes.
- Three dynamical core options:
  1. Spectral
  2. Finite difference
  3. Finite volume ("cubed sphere")
- Multitude of modules for different physics.

Gordon & Stern (1982); Anderson et al. (2004); Frierson, Held & Zurita-Gotor (2006, 2007).
Exoplanet applications: Heng, Menou & Phillipps (2011); Heng, Frierson & Phillipps (2011);
Pierrehumbert (2011); Heng & Vogt (2011).

The dual-band approximation

(also called "double-grey")

Stellar irradiation and thermal emission (from hot Jupiters) occur at distinct wavelengths: ***shortwave*** *versus* ***longwave***

$$\kappa_{\rm S} \equiv \frac{\int_{\rm S} \kappa_\nu J_\nu \, d\nu}{\int_{\rm S} J_\nu \, d\nu},$$

Shortwave opacity: absorption mean

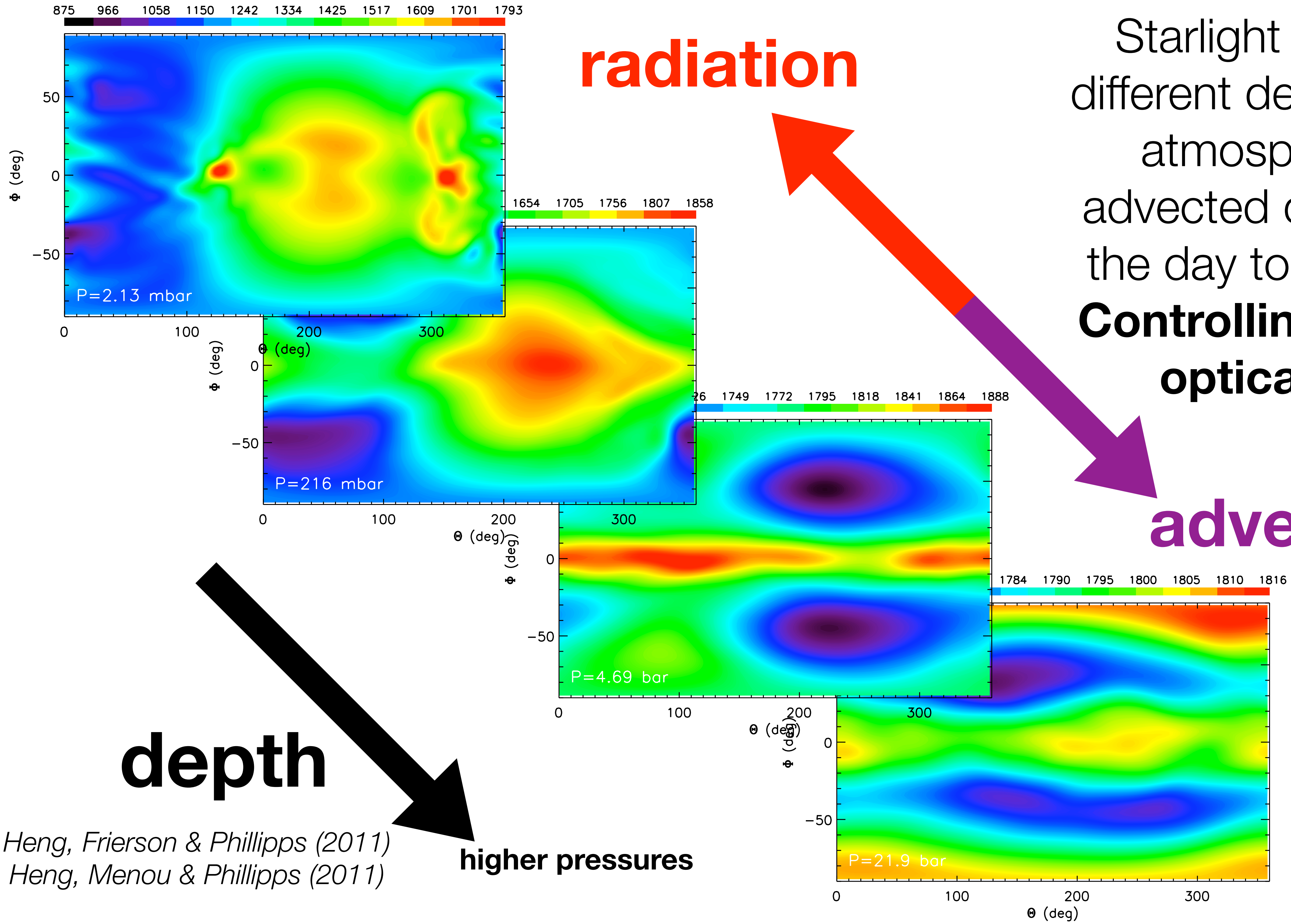
$$\kappa_{\rm L} \equiv \frac{\int_{\rm L} \kappa_\nu J_\nu \, d\nu}{\int_{\rm L} J_\nu \, d\nu} \approx \frac{\int_{\rm L} \kappa_\nu B_\nu \, d\nu}{\int_{\rm L} B_\nu \, d\nu},$$

Longwave opacity: Planck mean

Mihalas (1978); Hubeny, Burrows & Sudarsky (2003); Hansen (2008); Guillot (2010); Heng, Hayek, Pont & Sing (2012)

GCMs: Frierson, Held & Zurita-Gotor (2006); Heng, Frierson & Phillipps (2011); Rauscher & Menou (2012b)

Hot Jupiters are 3D beasts



radiation

Starlight deposited at different depths within the atmosphere will be advected differently from the day to the night side
Controlling parameter: optical opacity!

advection

depth

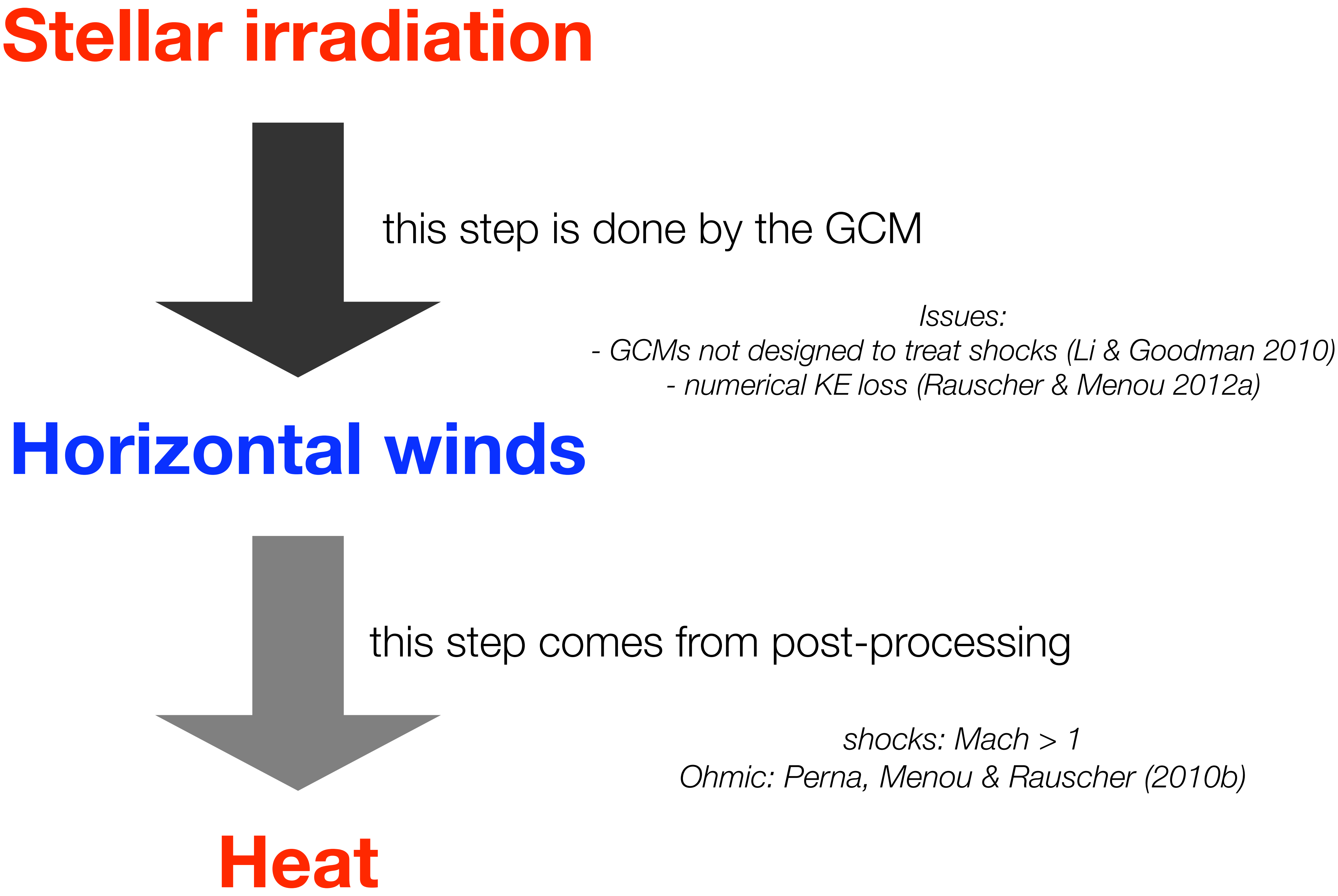
higher pressures

Simulated temperature maps

Heng, Frierson & Phillipps (2011)
Heng, Menou & Phillipps (2011)

See also work by Dobbs-Dixon et al., Rauscher & Menou, Showman et al., Thrastarson & Cho.

Hot Jupiters as heat engines



Stellar irradiation

this step is done by the GCM

Issues:
- GCMs not designed to treat shocks (Li & Goodman 2010)
- numerical KE loss (Rauscher & Menou 2012a)

Horizontal winds

this step comes from post-processing

shocks: Mach > 1
Ohmic: Perna, Menou & Rauscher (2010b)

Heat

See also: Goodman (2009)

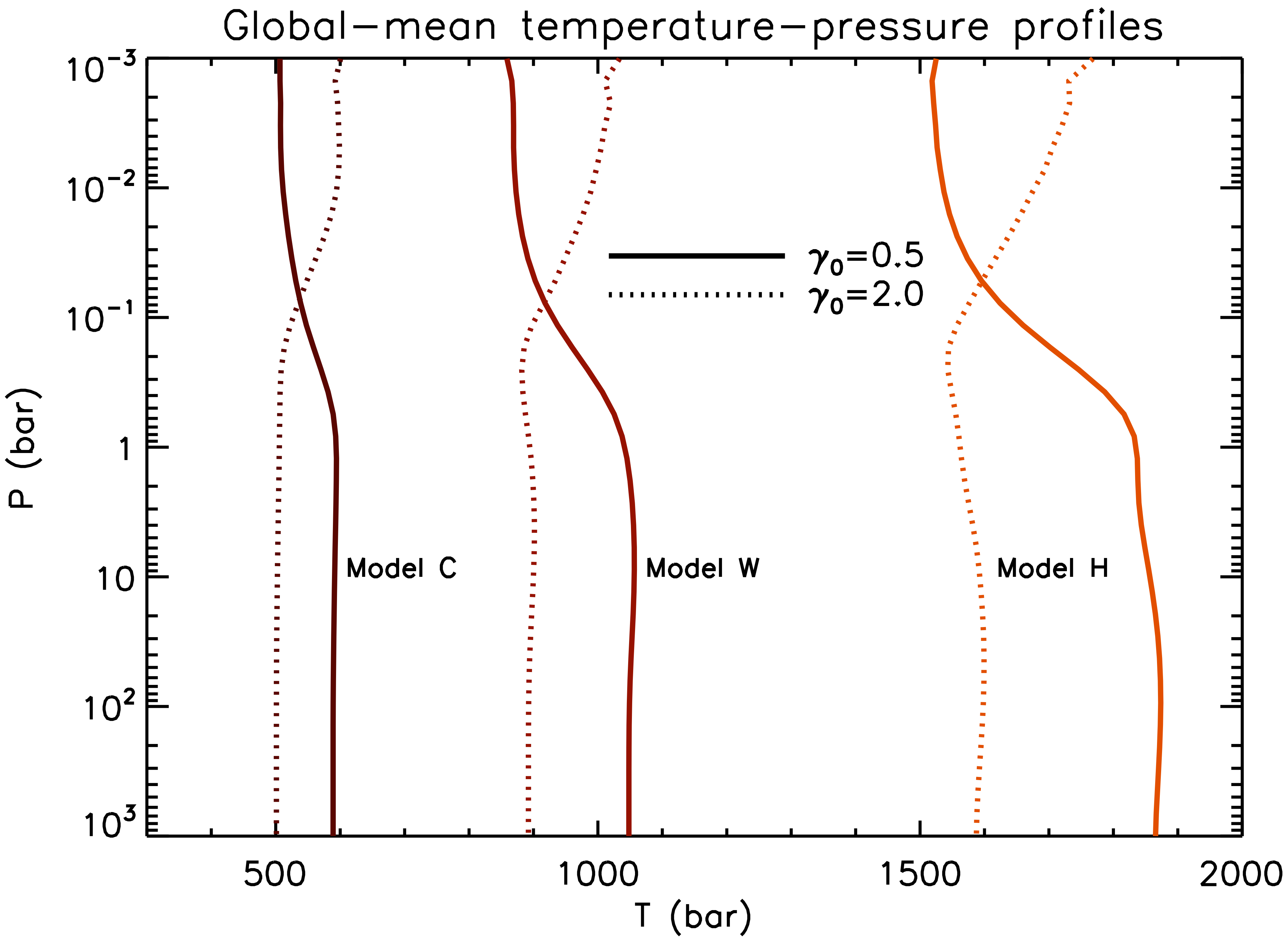
Three baseline models

Cold: irradiation is 0.1 times threshold value

Warm: irradiation is threshold value suggested by Demory & Seager (2011)

Hot: irradiation is 10 times threshold value

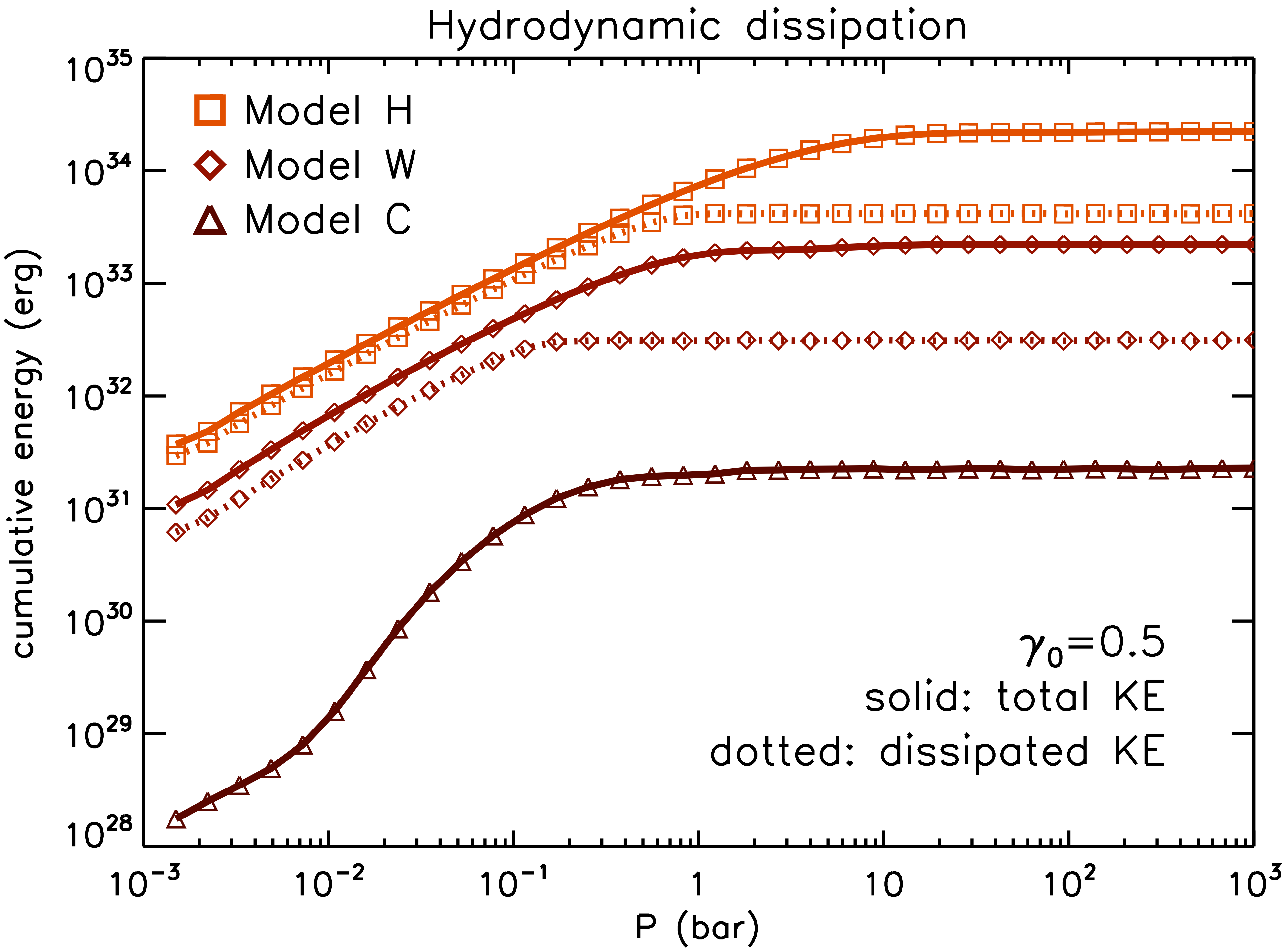
Three baseline models: temperature-pressure profiles



Analytical models: Guillot (2010); Heng, Hayek, Pont & Sing (2012)

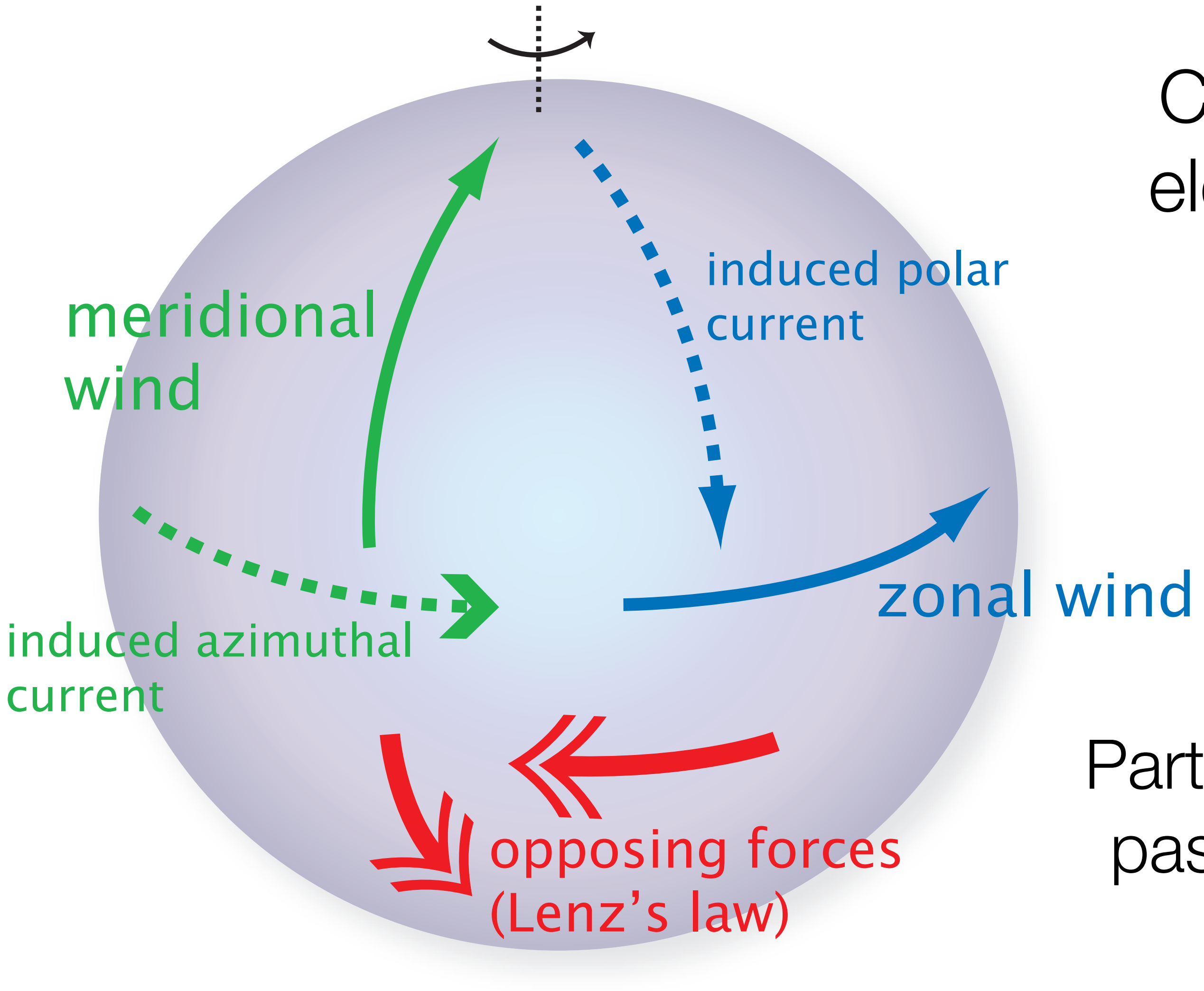
Perna, Heng & Pont (2012, to be submitted)

Dissipation of energy via shocks



Perna, Heng & Pont (2012, to be submitted)

Magnetic drag and Ohmic dissipation



Collisional ionization liberates electrons from Group I metals (Na, K)

Partially ionized atmosphere advected past magnetic field induces currents and opposing forces

cf. E. Rauscher's talk

A global, exoplanetary-scale manifestation of Lenz's law

Perna, Menou & Rauscher (2010a,b); Batygin & Stevenson (2010); Batygin, Stevenson & Bodenheimer (2011)

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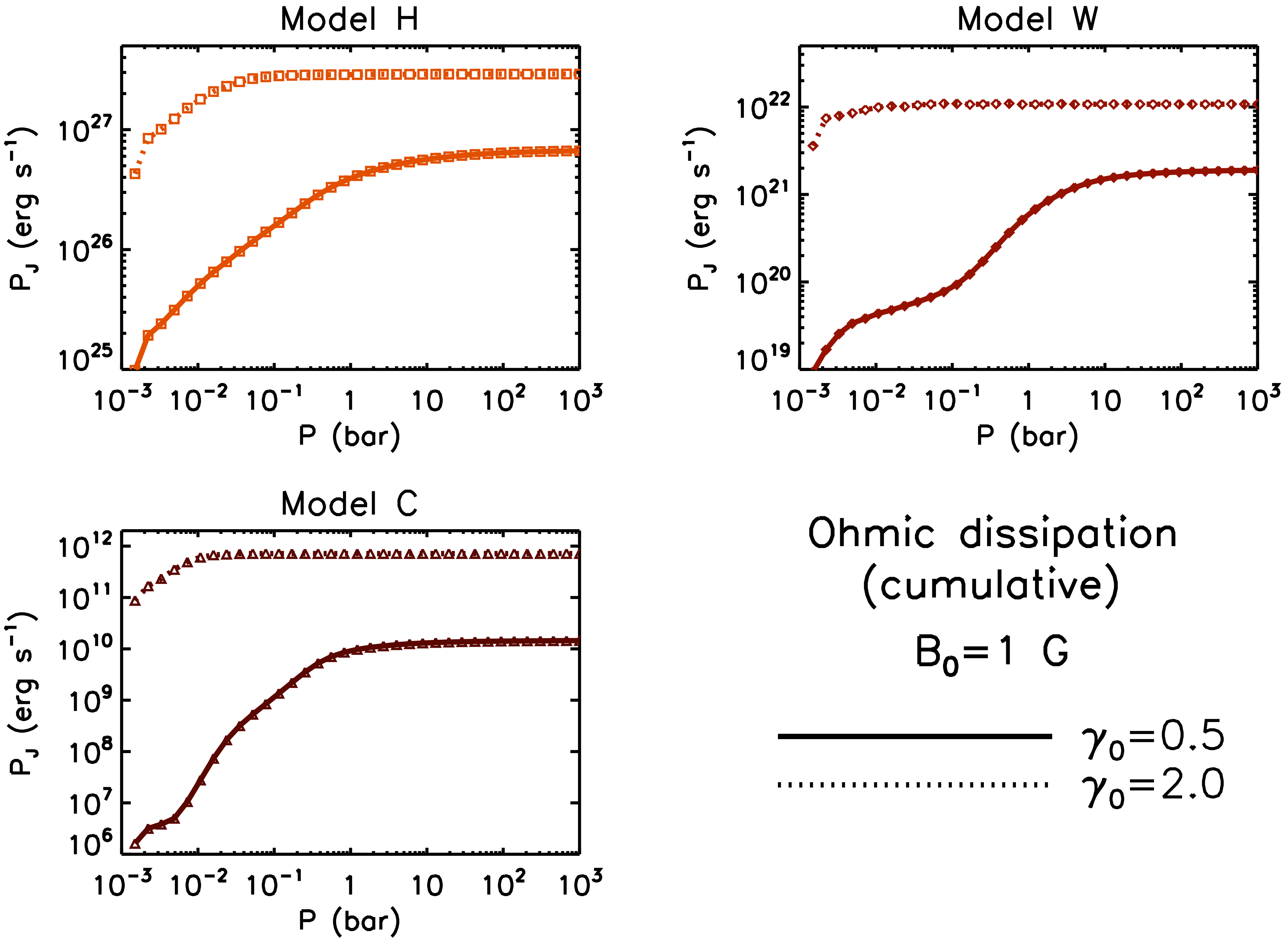
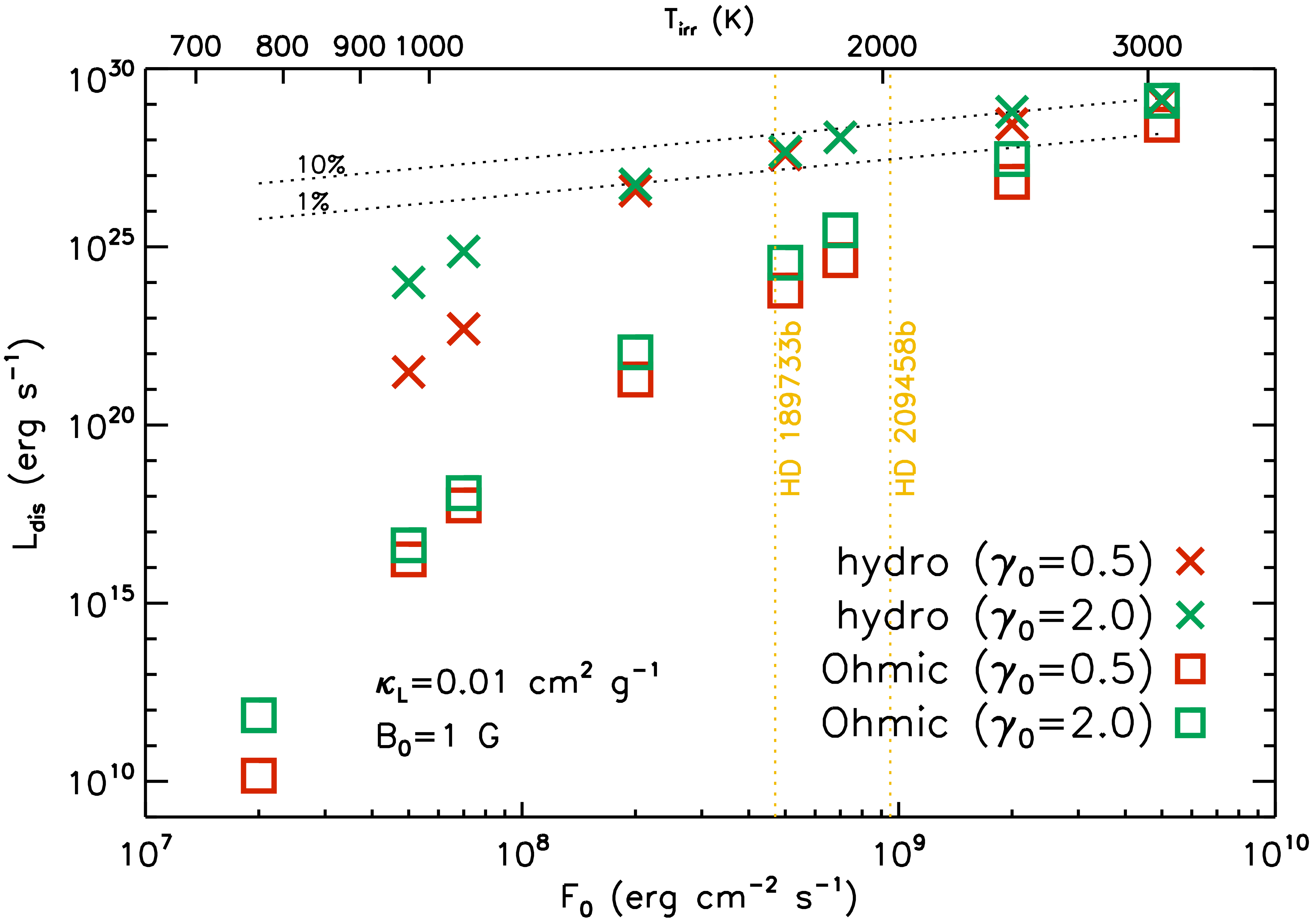
Ohmic dissipation: dependence of penetration depth on opacity



Perna, Heng & Pont (2012, to be submitted)

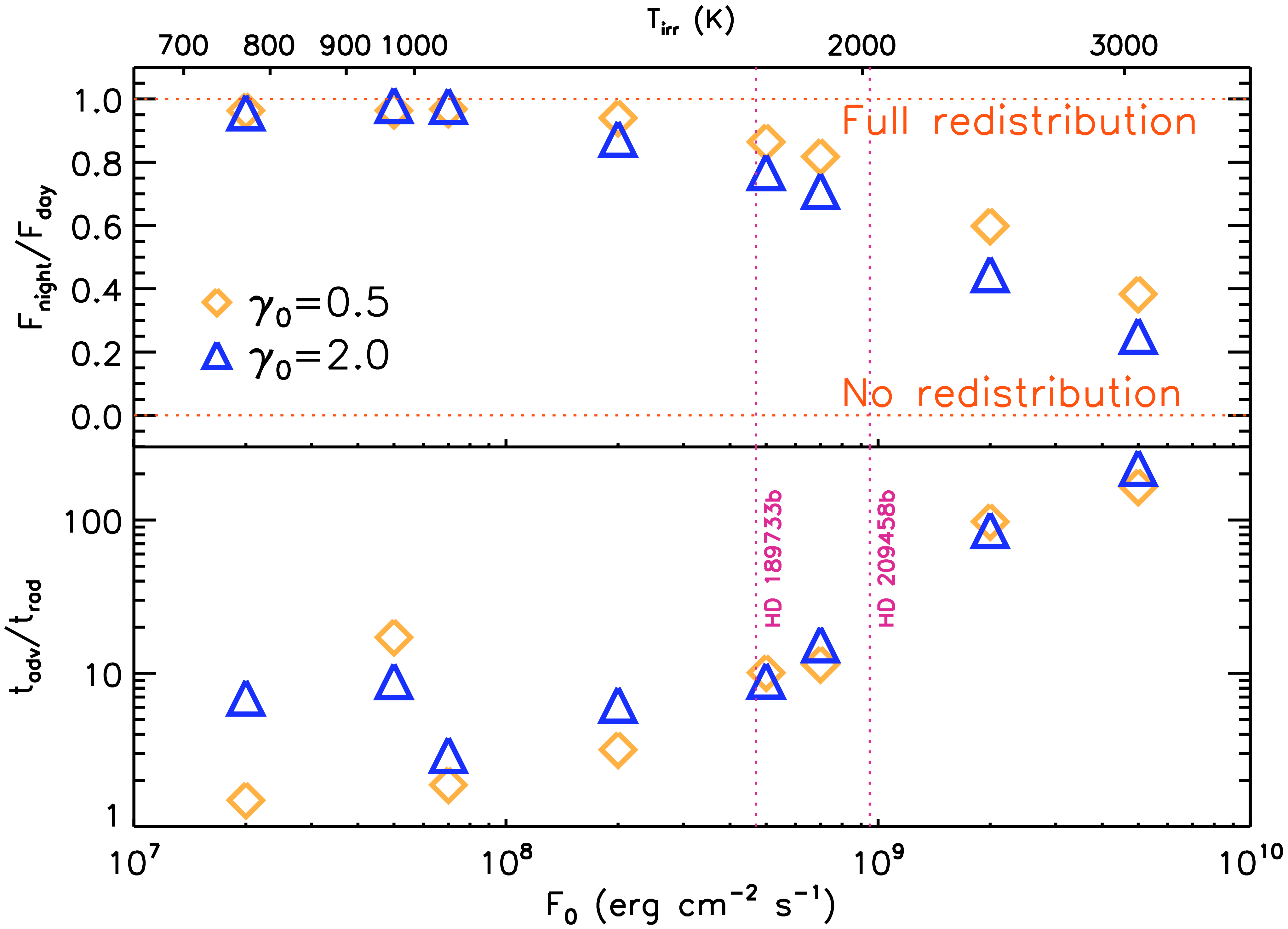
Dissipation as a function of stellar irradiation



See also: Menou (2012b)

Perna, Heng & Pont (2012, to be submitted)

Heat redistribution: a competition between radiative cooling and advection



See also: Showman & Guillot (2002), Cowan & Agol (2011)

Perna, Heng & Pont (2012, to be submitted)

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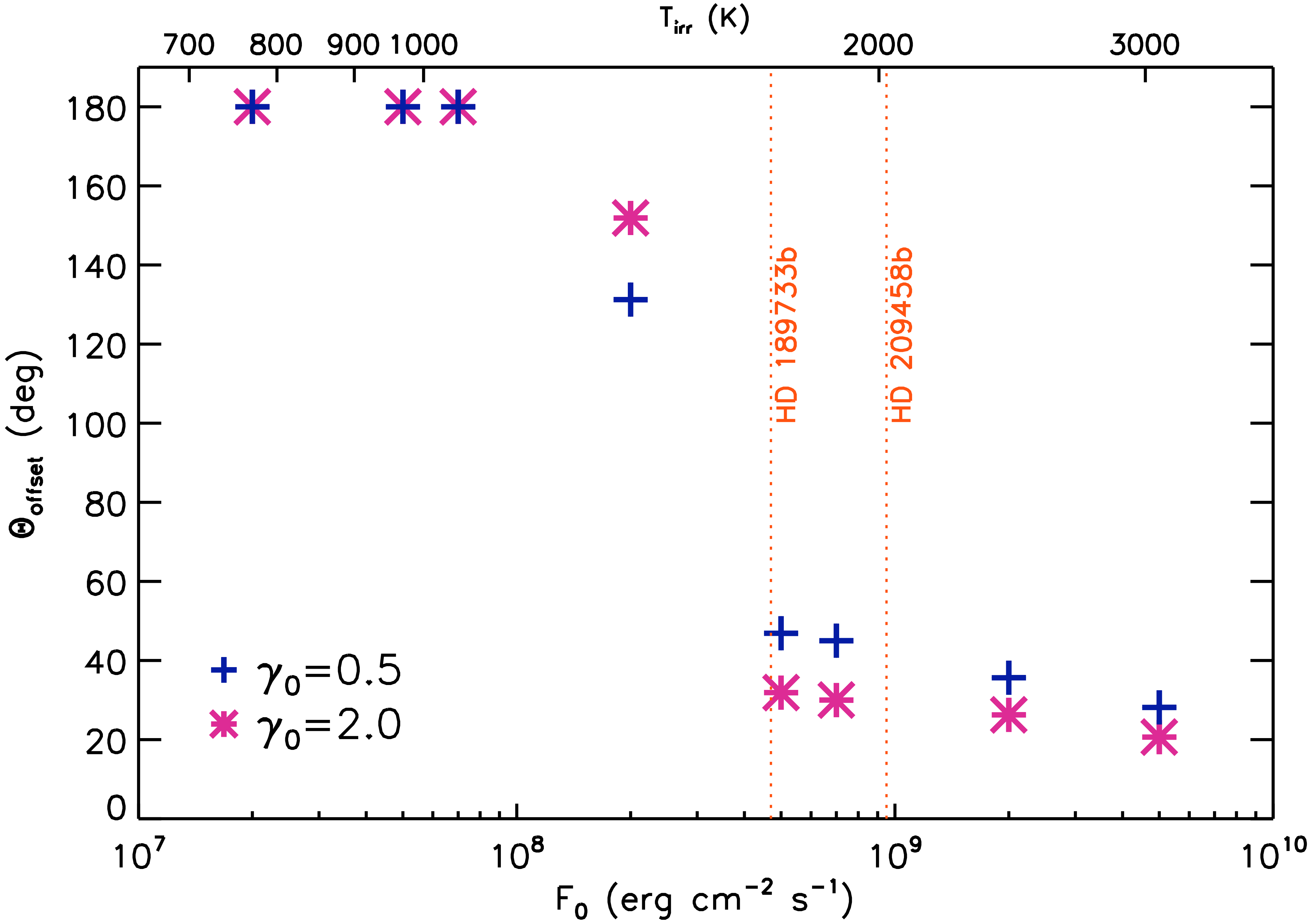
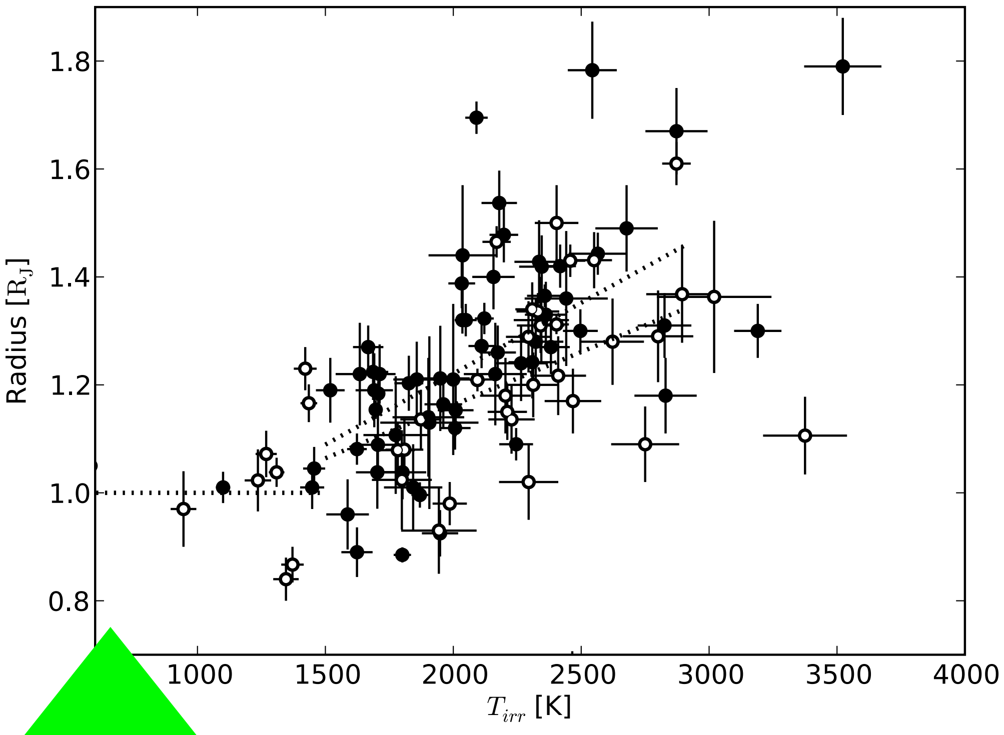
The hotspot offset is an indication of the efficiency of heat redistribution



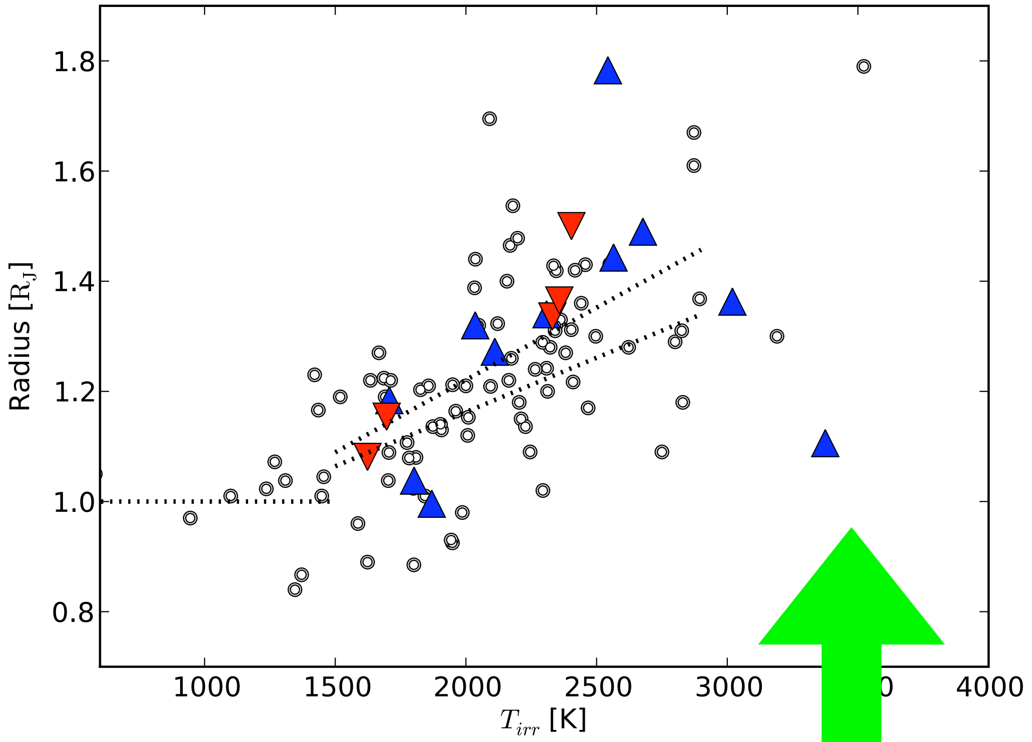
See also: Showman & Guillot (2002), Cowan & Agol (2011)

Perna, Heng & Pont (2012, to be submitted)

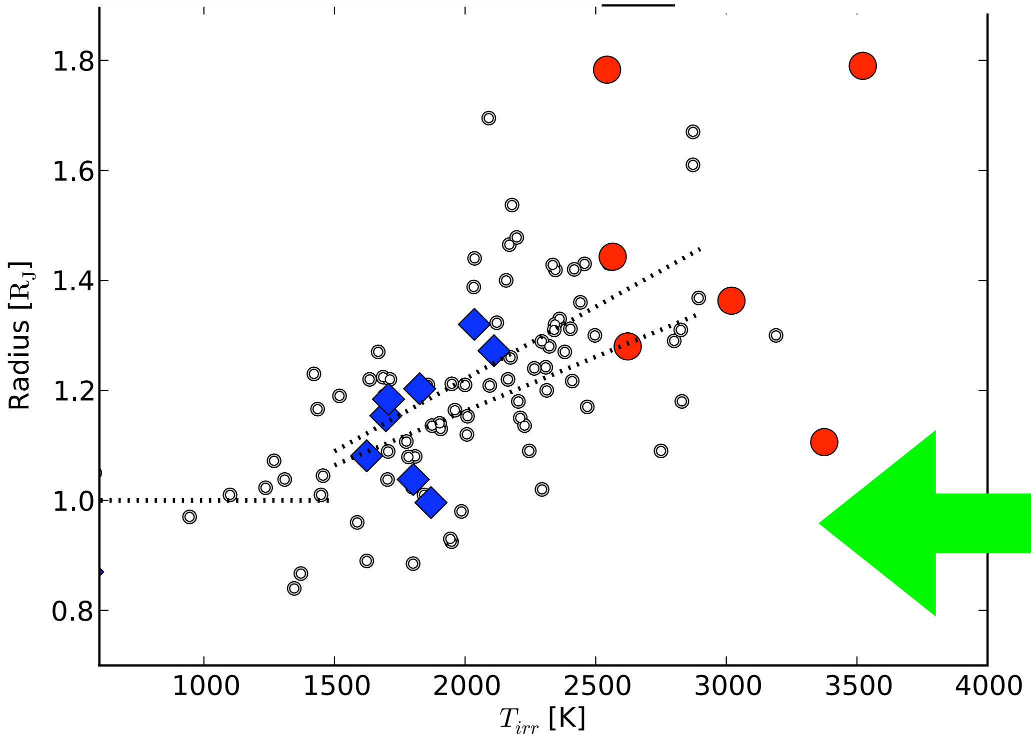
What do the observations tell us?



Massive vs. less massive



inverted vs. non-inverted



Efficient vs. poor redistribution

See also: Harrington (2011, DPS) and Exoclimes II talk by J. Harrington

Perna, Heng & Pont (2012, to be submitted)

Summary

Our simulations suggest that irradiation is the main driver of varying dissipation and heat redistribution, with opacity variations introducing a scatter.

Our results are broadly consistent with the existing observational trends.

1D models of temperature-pressure profiles **with scattering**

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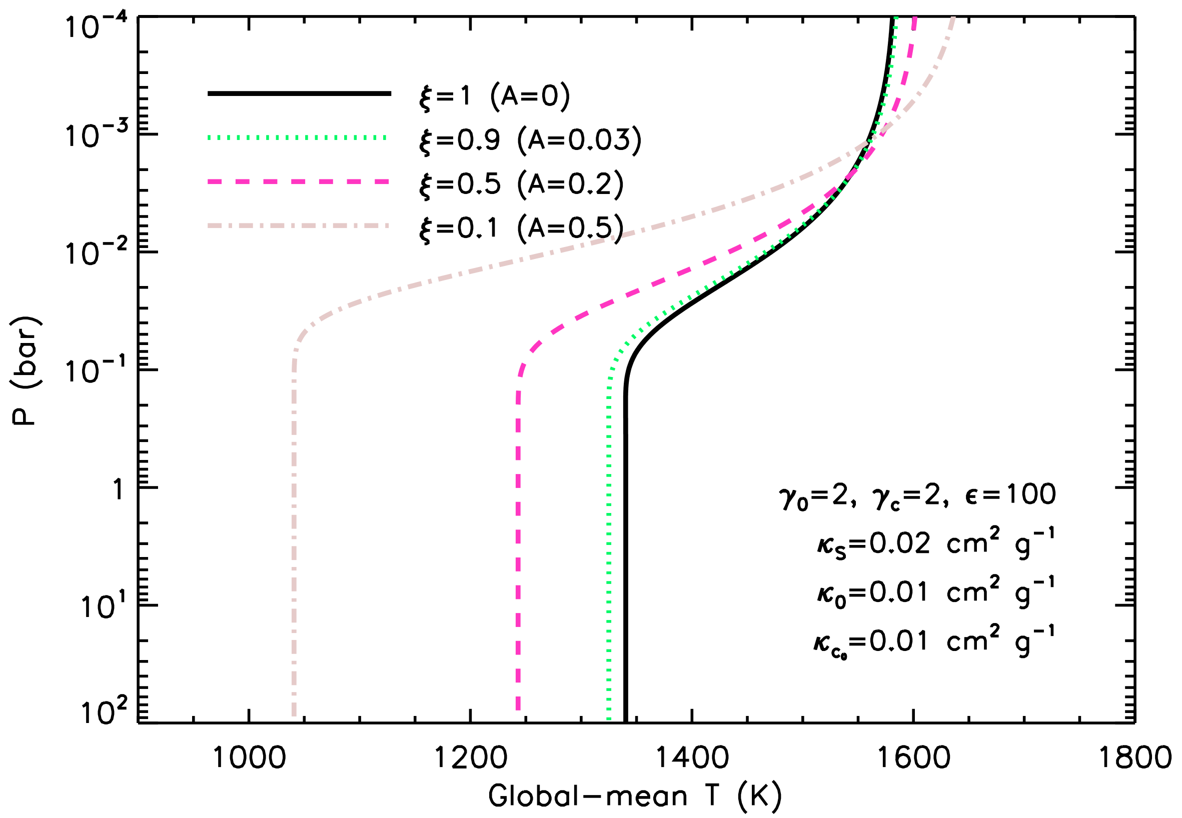
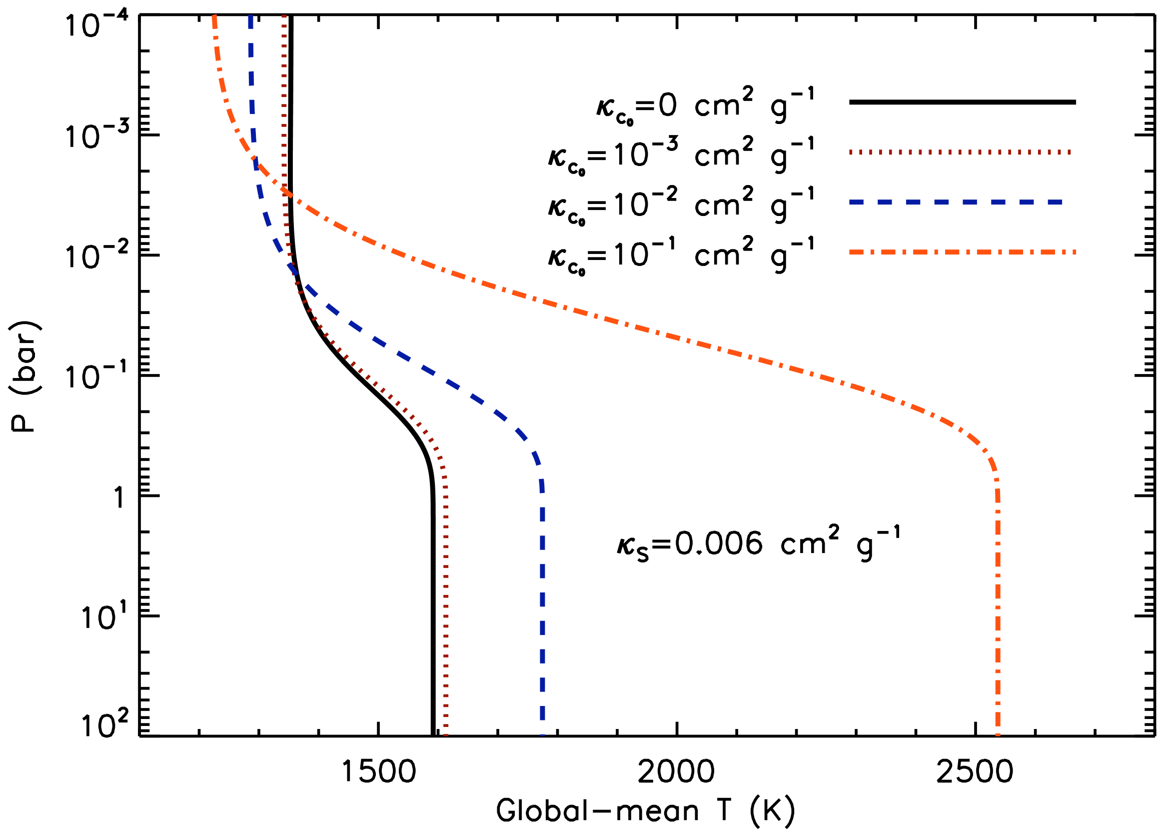
Clouds/hazes introduce competing effects to the T-P profile of a hot Jupiter





Scattering in the optical cools/heats the lower/upper atmosphere

Absorption in the infrared heats/cools the lower/upper atmosphere

Also mimics collision-induced absorption via linear term

See also: Mihalas (1978); Hubeny et al. (2003); Hansen (2008); Guillot (2010)

See also work+talks by Benneke, Fortney, Helling, Marley, Morley, Parmentier.

Heng, Hayek, Pont & Sing (2012)