Inflating Hot Jupiters:
Ohmic Dissipation and the Mechanical Greenhouse

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Acknowledgements:

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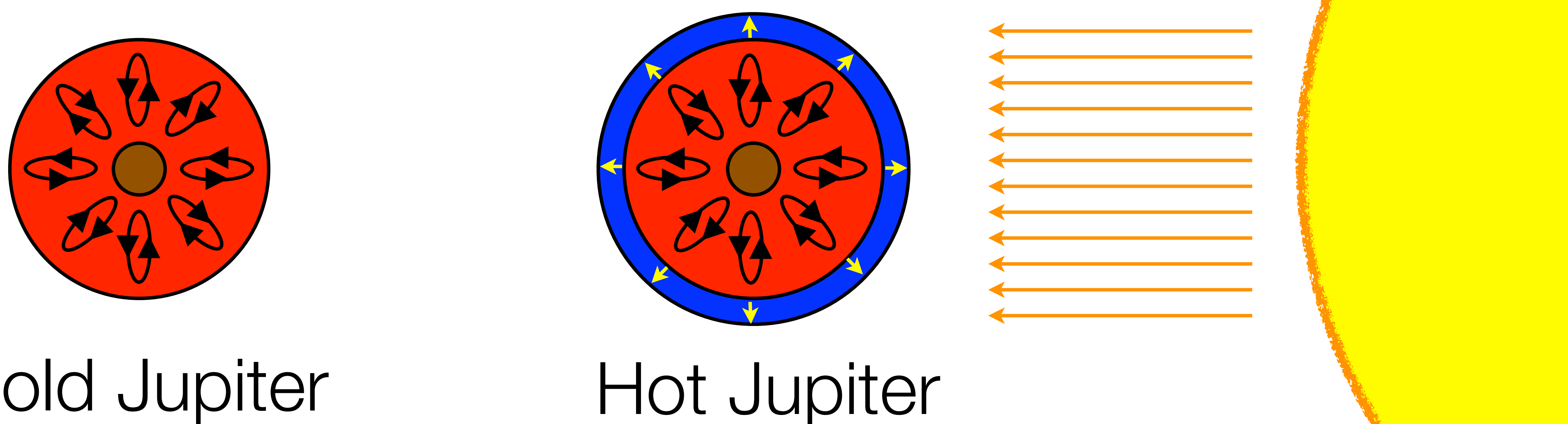
Thanks to: Nick, Frederic & ACP

DAVID BOWIE AS NIKOLA TESLA

Cold vs. Hot Jupiters

Radiative
Convective



Size (mostly) determined by entropy (adiabat) of convective interior.

Radiative layer mediates cooling & contraction

Recipes to Inflate Hot Jupiters
(b/c irradiation not enough)

- Ideas:
  - Add Heat
  - Slow Cooling

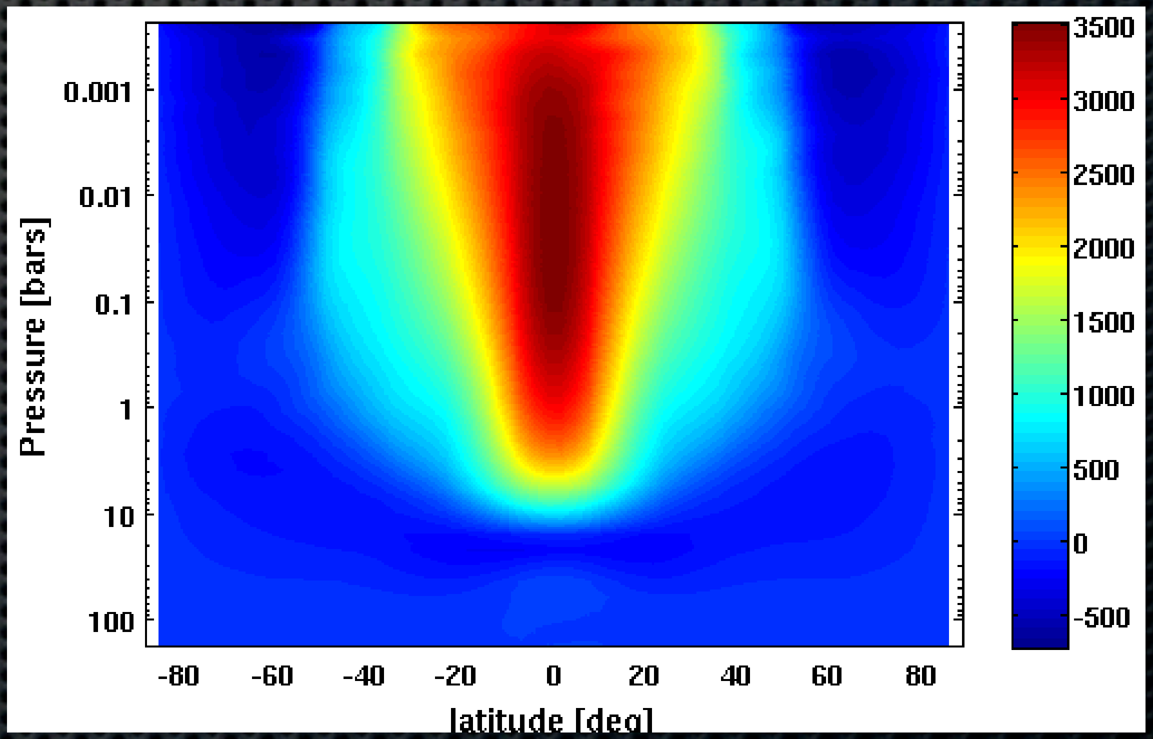
- Mechanisms:
  - Tides
  - Winds
    - Hydrodynamic Dissipation
    - Ohmic Dissipation
    - Mechanical Greenhouse
  - Opacity effects

Energetics of Hot Jupiter Inflation

$$\epsilon = \frac{dE/dt}{L_{\rm irr}} = \frac{d(E/A)/dt}{F_{\rm irr}}$$

- Matters where & efficiency
- 0.1% in convective interior
  (Bodenheimer et al. 2001)
- 1% near "surface"
  - between 1- 40 bars
    (Guillot & Showman 2002)
- At convective boundary:

$$\epsilon \sim \frac{F_{\rm core}}{F_{\rm irr}} \sim \left(\frac{150\ {\rm K}}{1500\ {\rm K}}\right)^4 \sim 10^{-4}$$

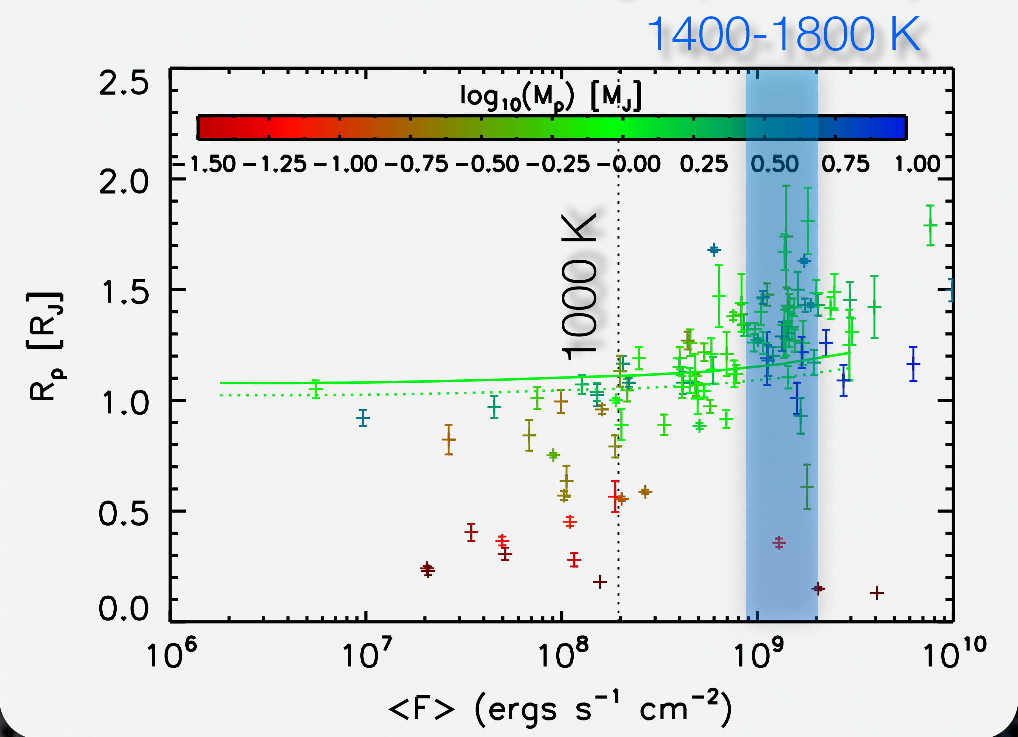


Zonal Winds:
Not quite deep enough(?)
(Showman et al. 2009)

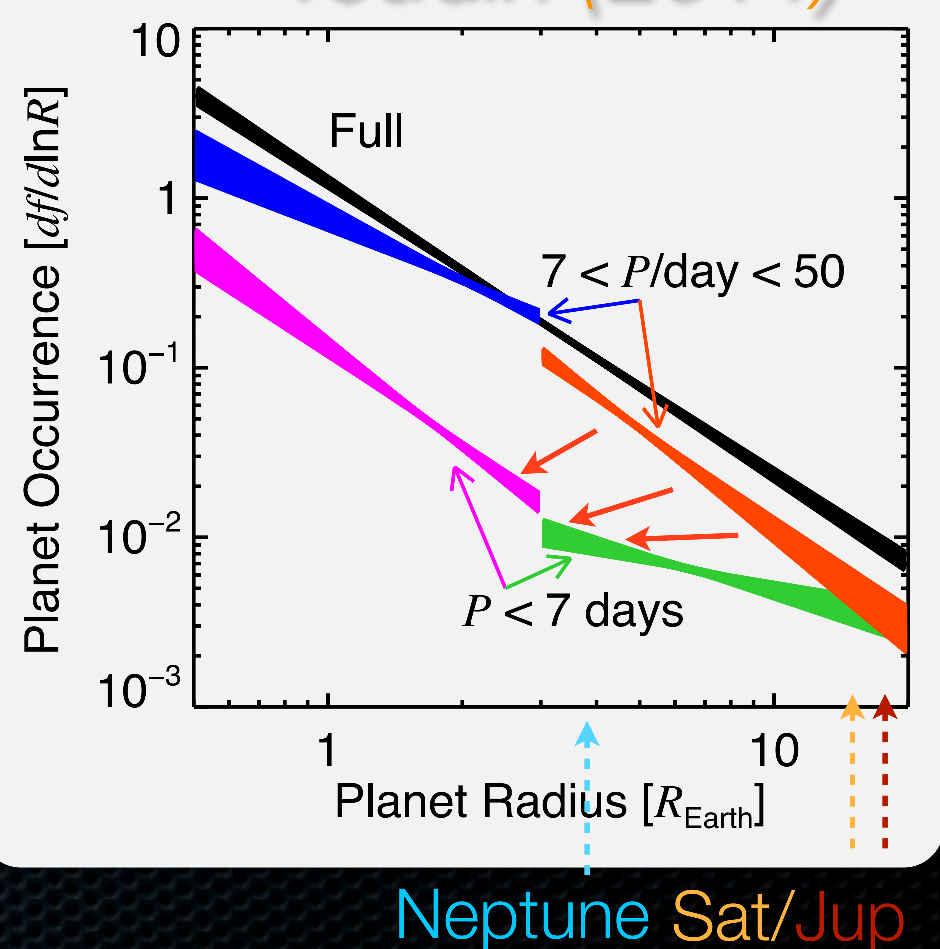
Observational Clues / Tests

- Only HOT Jupiters are inflated
  - above T_{irr} = 1000 K
  - *also Demory & Seager (2011)*
- Easier to inflate (and evaporate?) lower mass planets *(Bodenheimer et al. 2001)*
  - Evidence of period dependence of *Kepler* size distributions *(Youdin 2011)*

Miller & Fortney (2011)

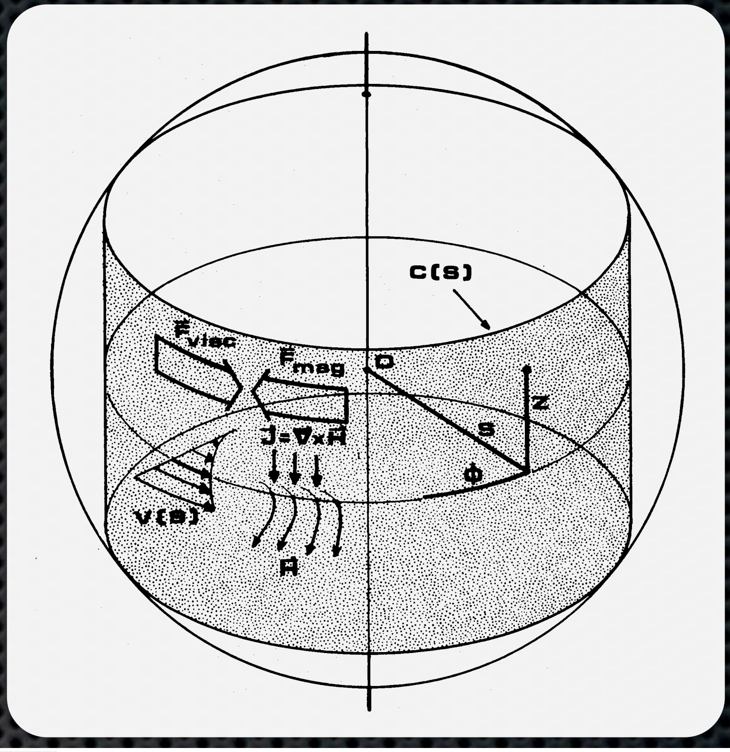


Youdin (2011)

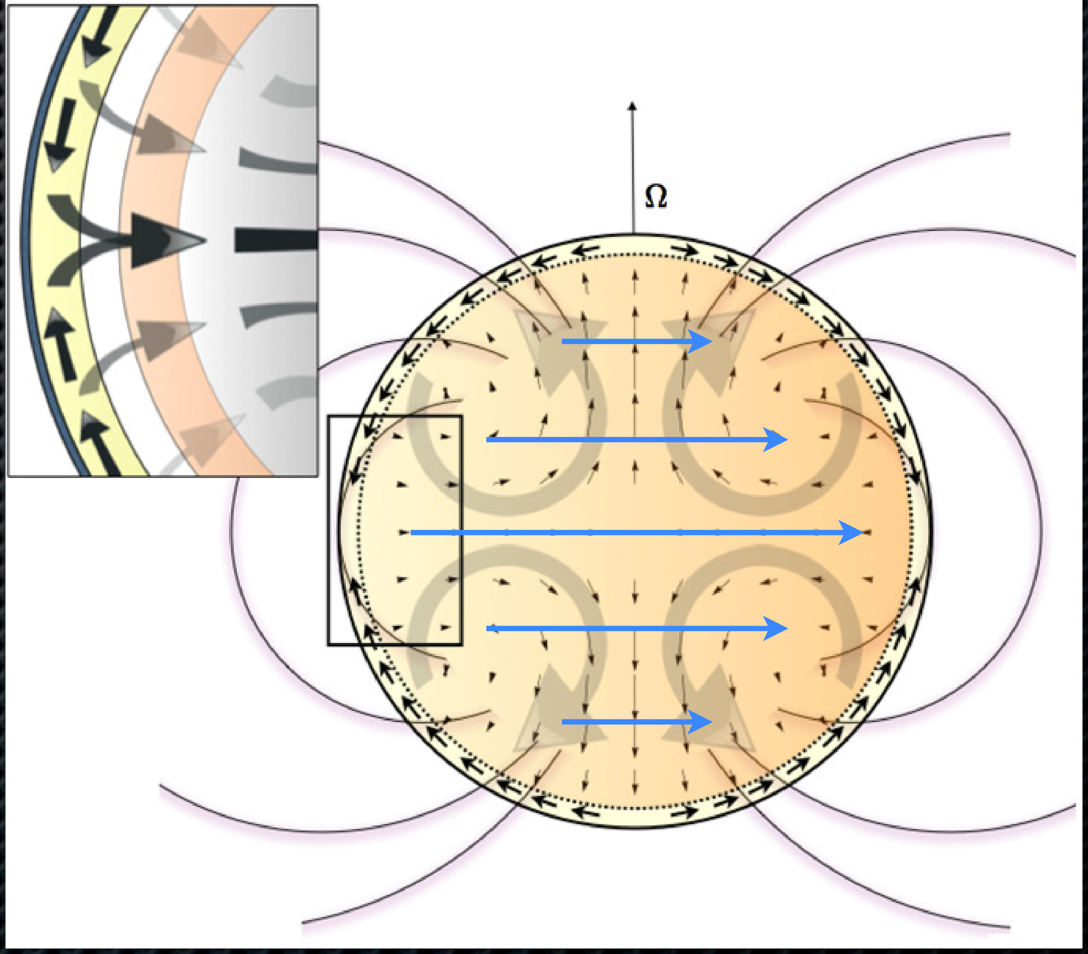


Ohmic Dissipation

Kirk & Stevenson (1987)



- Surface winds induce currents which dissipate (at depth?)
  - $\boldsymbol{J} = \sigma\,(\boldsymbol{v} \times \boldsymbol{B} + \boldsymbol{E})$
- Applied to SS *(Liu et al. 2008)* and to Hot Jupiters
  - Upper atmosphere crucial for wind driving/damping *(Perna, Menou, Rauscher 2010, etc.)*
  - Global models study inflation

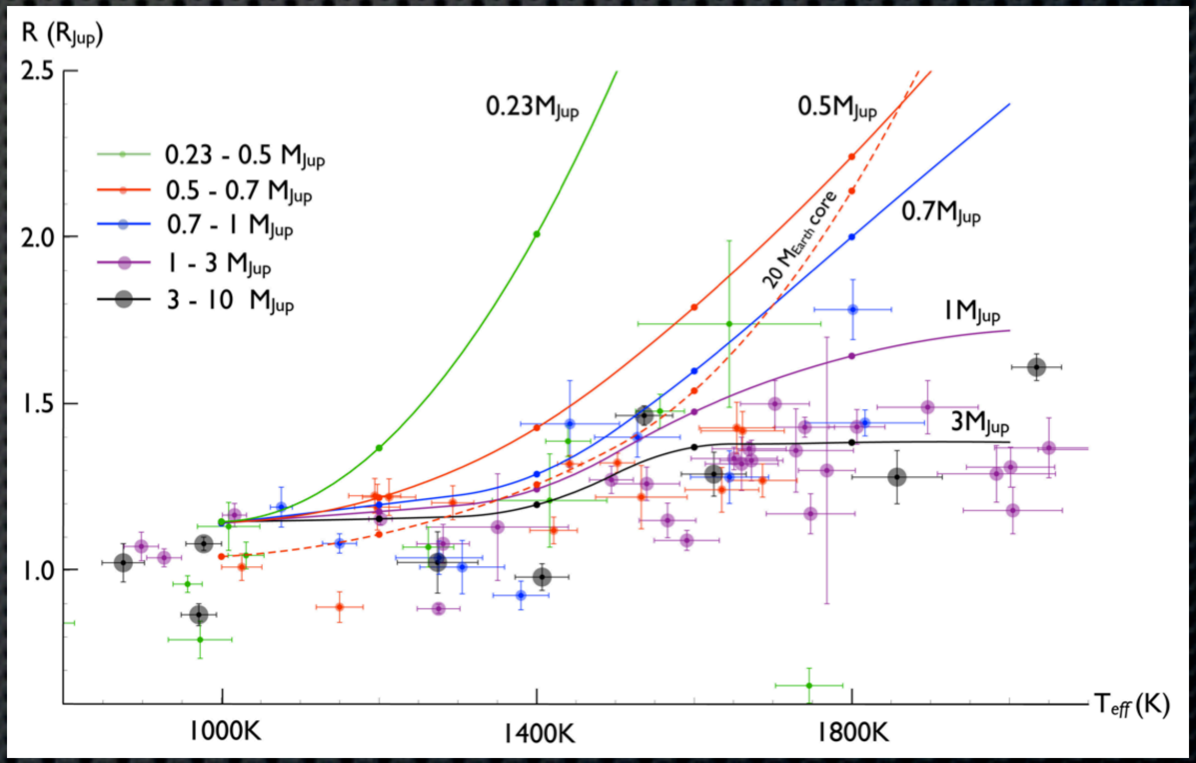


Batygin & Stevenson (2010)

Inflating Hot Jupiters with Ohmic Dissipation

- Fixed wind profile (to 10 bars)
- Hot Jupiters bloated for fixed dissipative efficiency ≥ 1%
  - Consistent with Guillot & Showman (2002)
- Fixed efficiency and calculated conductivity means...
  - $v_{\rm wind} \times B$ adjusts to what is required

$\varepsilon = 1\%$

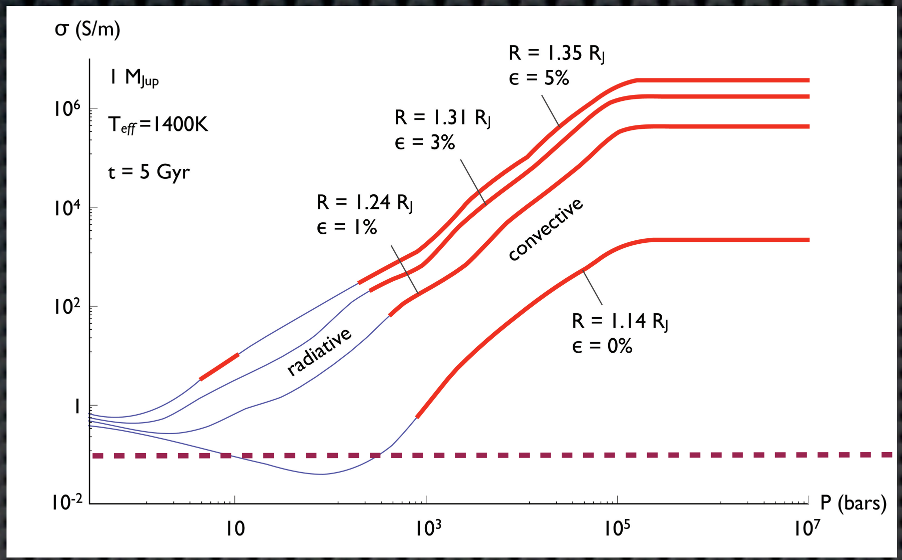


Batygin, Stevenson & Bodenheimer (2011)

Large B-fields Required

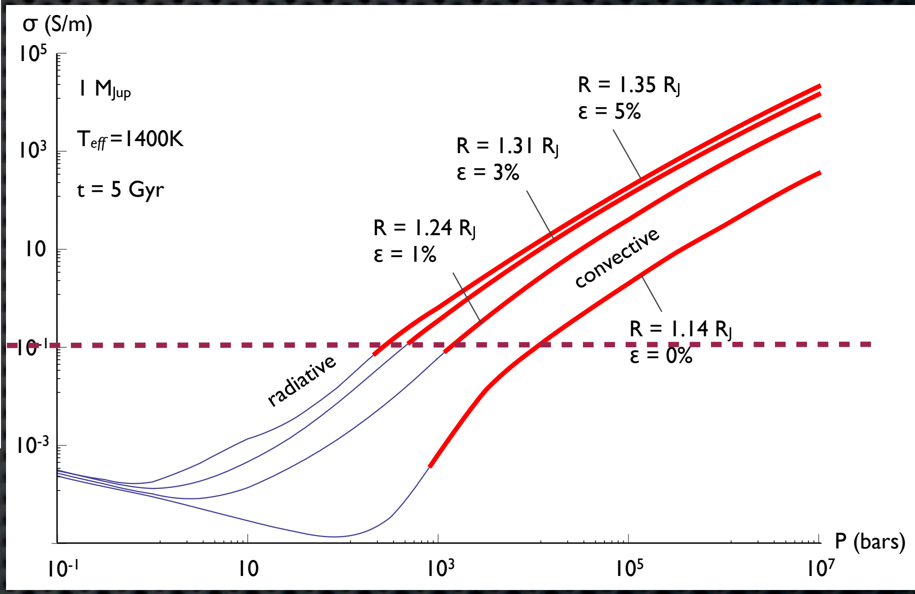
Conductivities revised downward by 10^3 :

0.1 S/m → 10^{-4} S/m



Batygin et al. (2011, ApJ)

corrected (v3, arXiv)



BSB11 scalings...

$$\tau_L = \rho/\sigma B^2 \sim 10^6 \left(\frac{\rho}{0.1\mathrm{kg/m^3}}\right)\left(\frac{0.1\mathrm{S/m}}{\sigma}\right)\left(\underbrace{\frac{10^{-3}\mathrm{T}}{B}}_{10\ \mathrm{G}}\right)^2 \mathrm{sec.} \quad (8)$$

$$\epsilon \sim \rho v_\phi^2 H/(\tau_L \sigma_{SB} T_{eff}^4)$$

$$\sim 0.01\left(\frac{\rho}{0.1\mathrm{kg/m^3}}\right)\left(\frac{v_\phi}{1\mathrm{km/s}}\right)^2\left(\frac{H}{1000\mathrm{km}}\right)\left(\frac{1500\mathrm{K}}{T_{eff}}\right)^4 \quad (17)$$

... then imply

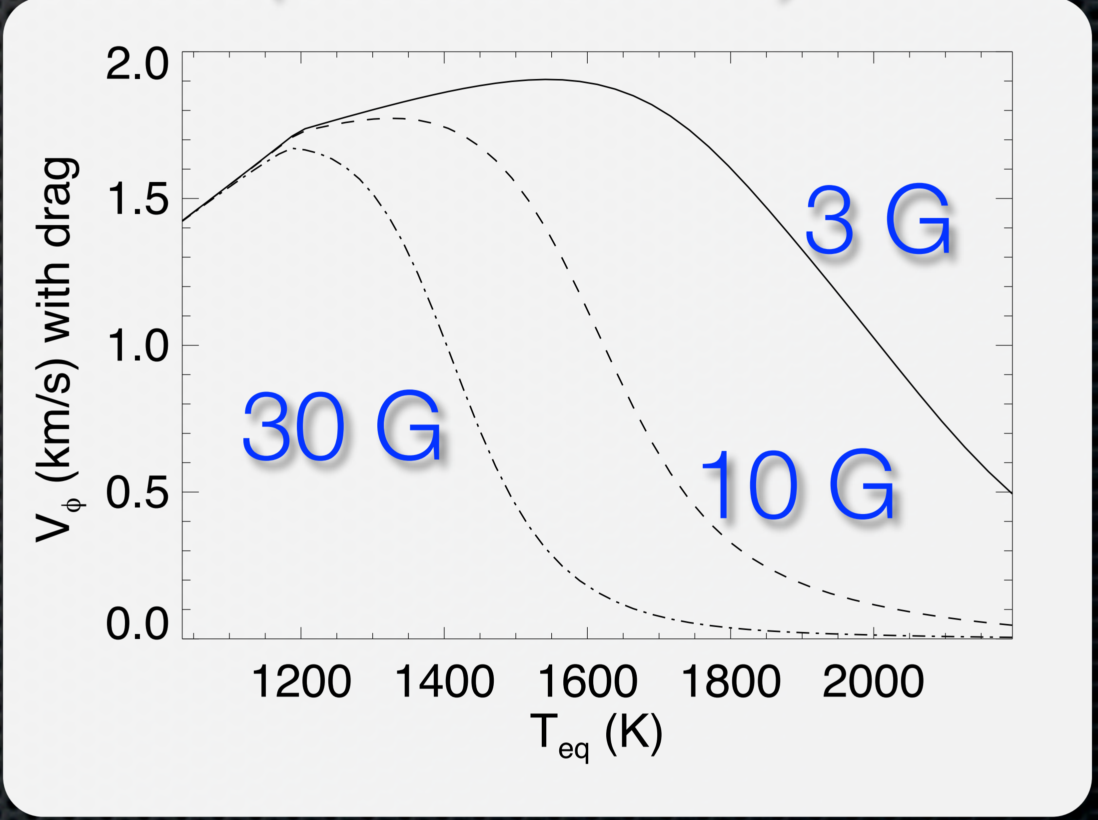
$$B \sim \frac{1}{v_\phi}\sqrt{\frac{\epsilon}{\sigma_e}\frac{F_{\rm irr}}{H}}$$

$$\sim 300 \left(\frac{\mathrm{km/s}}{v_\phi}\right)\sqrt{\frac{\epsilon}{0.01}\frac{10^{-4}\ \mathrm{S/m}}{\sigma_e}}\ \mathrm{G}$$

Constraint on Ohmic Inflation

- Ohmic dissipation (up high) limits wind speeds
  - For strong B-fields &
  - High temp. (ionization)
- Need all three for inflation
  - More study needed to determine severity of constraint

Photospheric Wind Speeds *(Menou 2011)*



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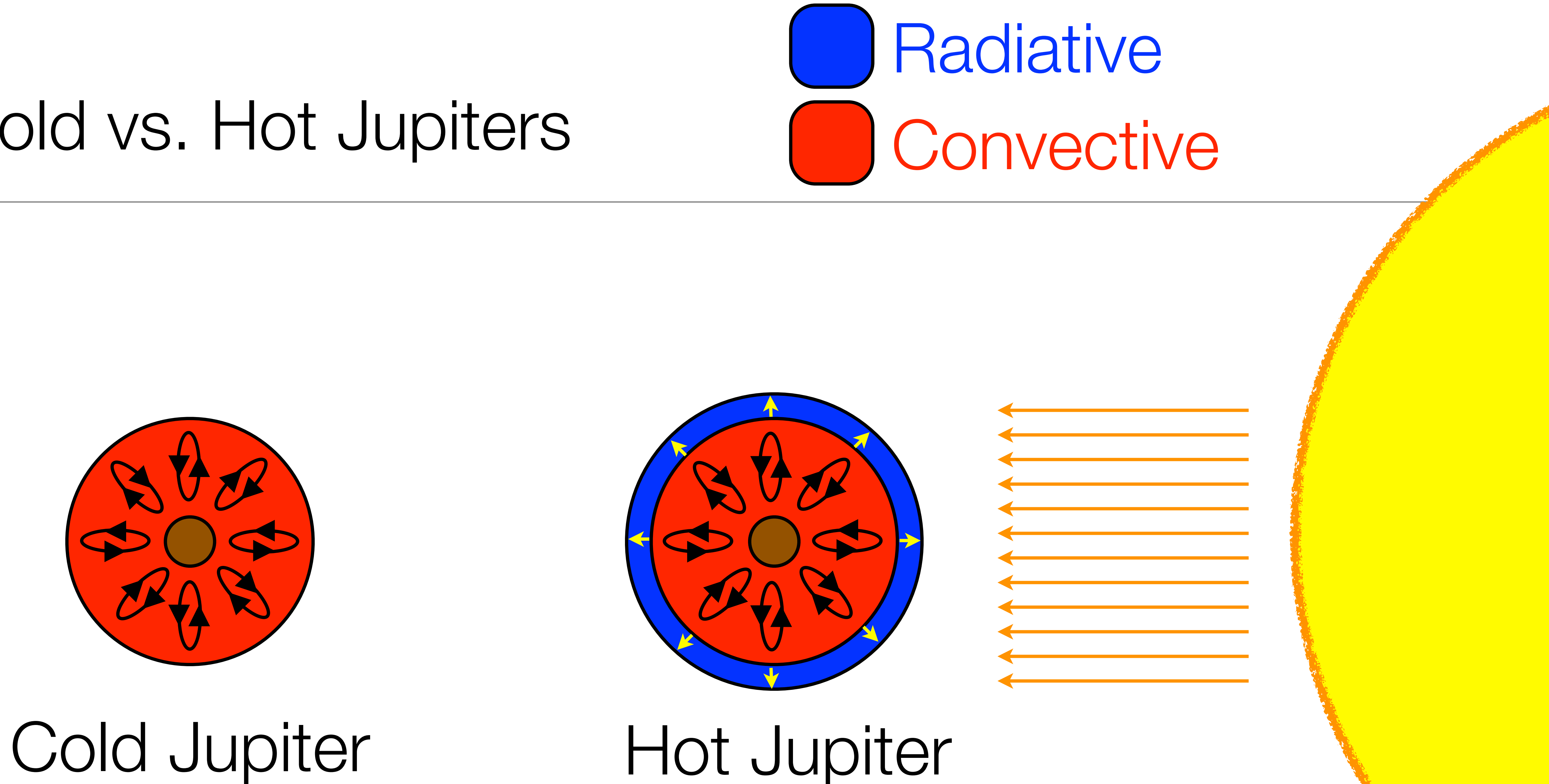
Cold vs. Hot Jupiters



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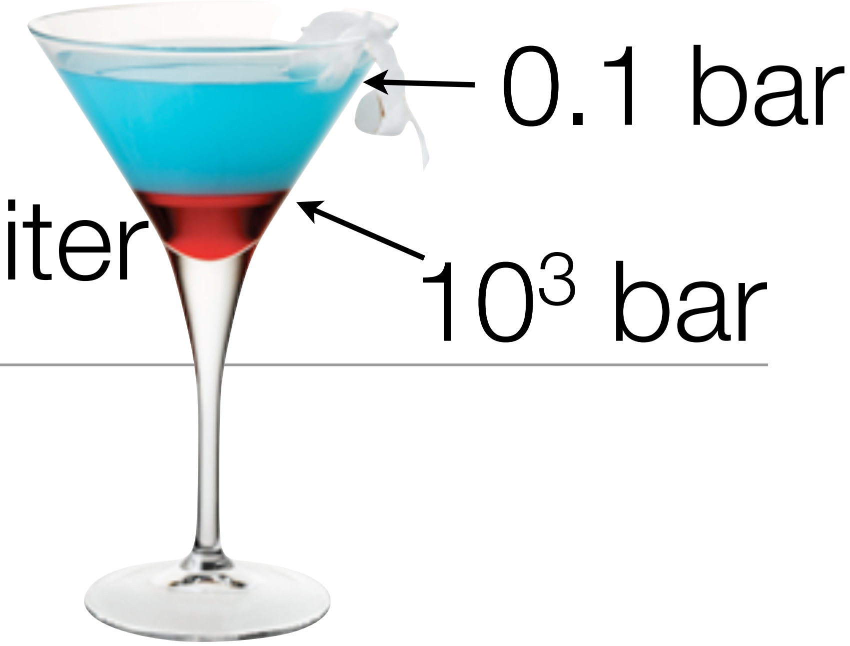
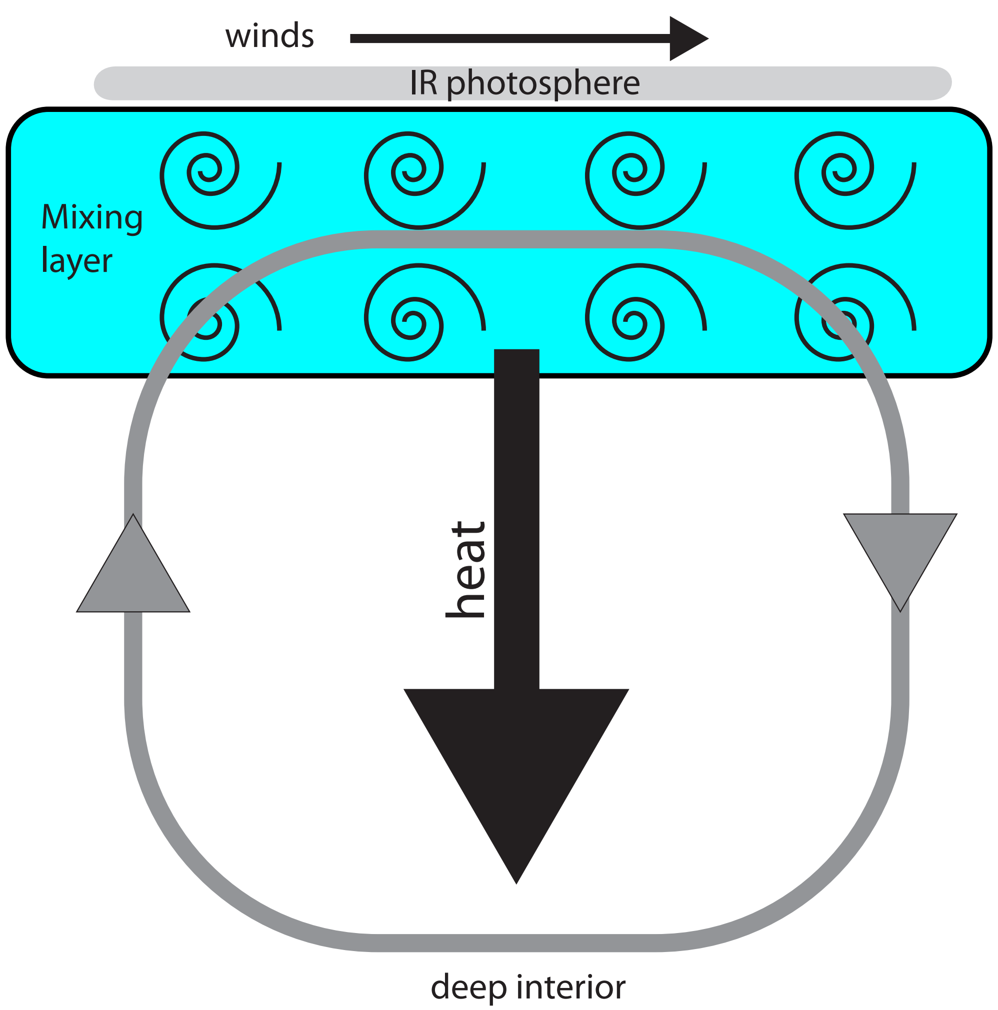
Radiative layer mediates cooling & contraction

The Mechanical Greenhouse: Consequences of Mixing a Hot Jupiter



- Radiative zones of Hot Jupiters likely turbulent, with diffusion coefficient K_{zz}
    - Delivers dust & disequilibrium molecules to the photosphere
    - Driven by winds and/or ohmic heating
- Buries heat, inflates planet
    - convection in reverse!

$$\boxed{F_{\text{eddy}}} = -K_{zz}\rho T\frac{dS}{dz}$$
$$= -K_{zz}\rho g\left(1 - \frac{\nabla}{\nabla_{\text{ad}}}\right)$$



Youdin & Mitchell (2010)

Energy Transport Basics: Radiation vs. Convection

- Simple analogy for planetary (or stellar) atmosphere
- Radiation transports modest heat fluxes, F_{rad}
- Too much heat triggers convection
  - Can drive large heat flux, F_{eddy}

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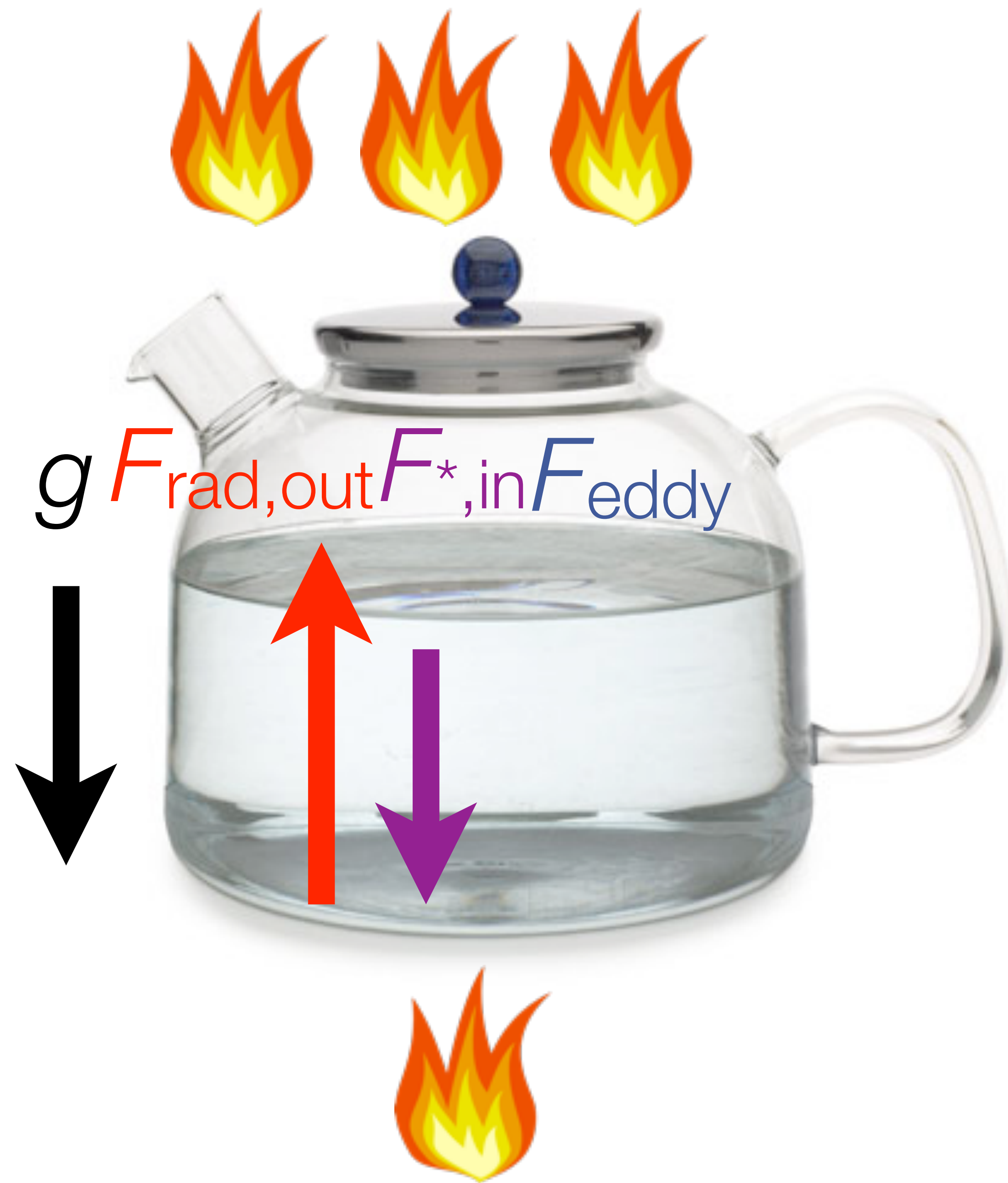
A Hot Jupiter Analogue with Mechanical Mixing

- Flux from star, $F_{*,in}$ >> cooling flux
    - suppresses convection (hot over cold) in outer layers
- Forced turbulence drives "anti-convective" flux, the "Mechanical Greenhouse
    - replaces cooling flux & heats interior
- Dissipation adds more heat, further aids inflation



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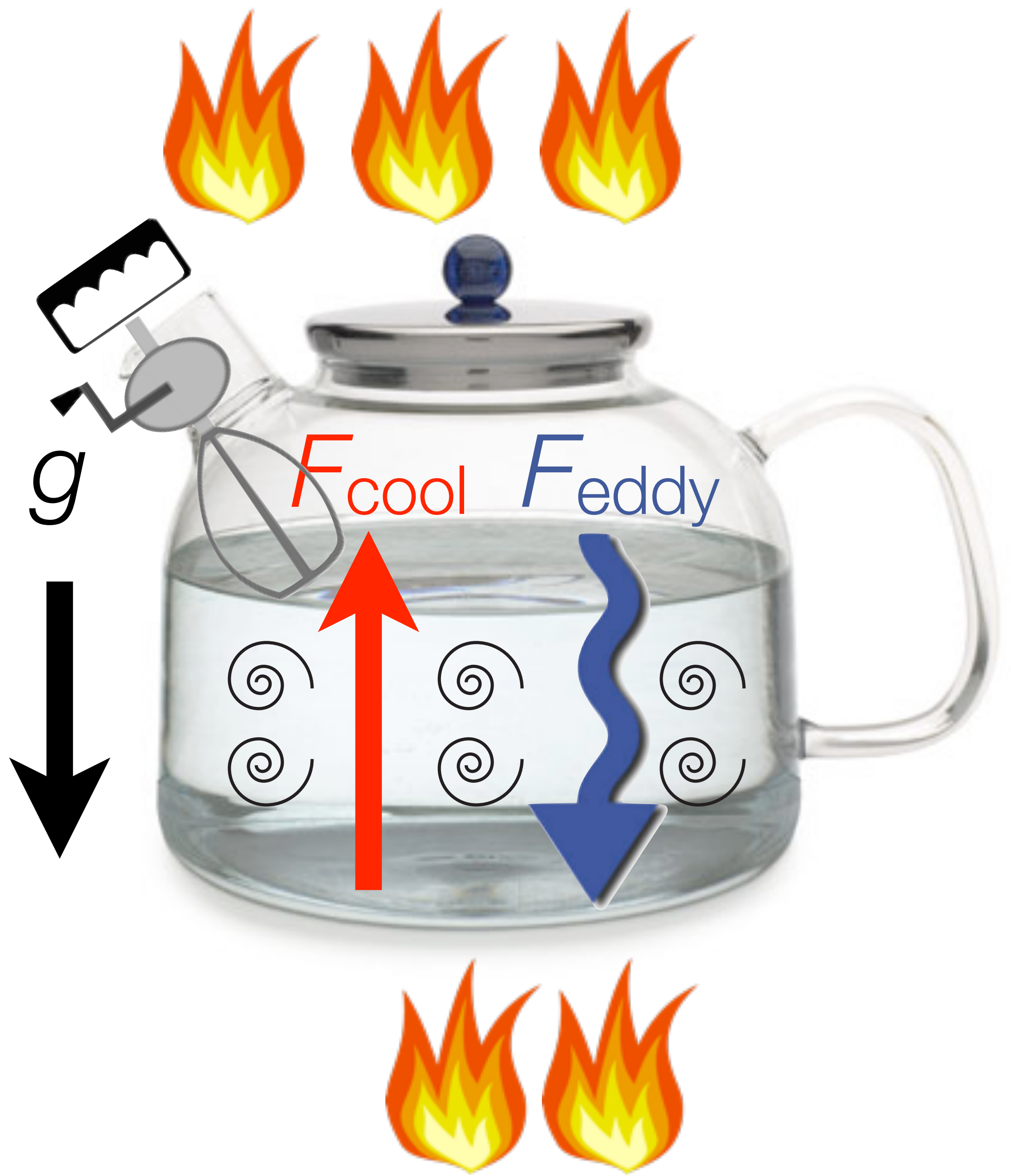

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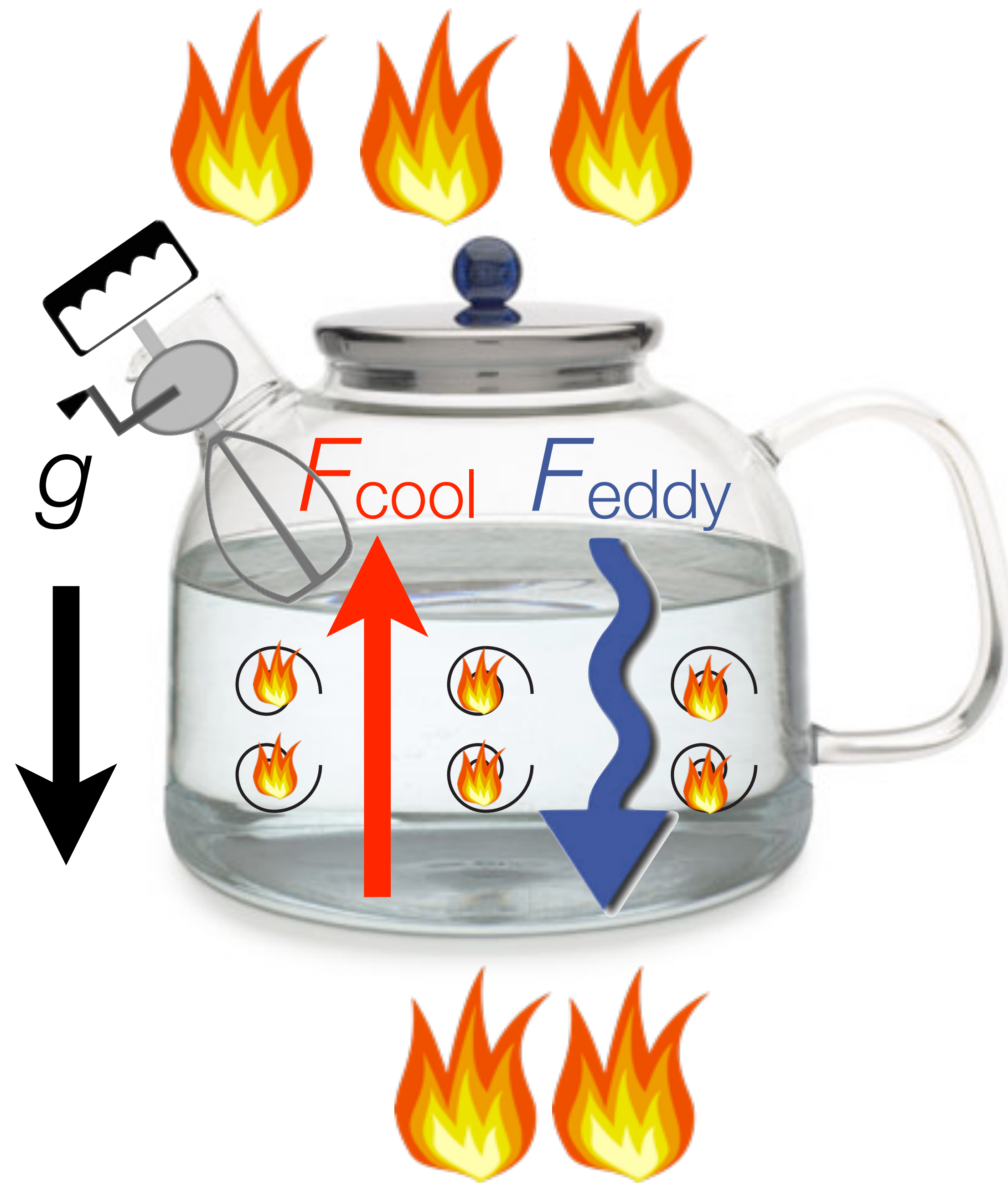


(Youdin & Mitchell 2010)

Energy Balance: Radiation + Turbulence

Youdin & Mitchell (2010)

- Radiative flux in diffusion approximation
- Turbulence:
  - Heat burial via eddy flux
  - Dissipates (ϵ)
- Compute Temperature profile
  - Solution for location of radiative-convective boundary ⇒ cooling rate

Net Flux

$$F = F_{\rm rad} + F_{\rm eddy}\,.$$

$$F_{\rm eddy} = -K_{zz}\rho T \frac{dS}{dz} = -K_{zz}\rho g \left(1 - \frac{\nabla}{\nabla_{\rm ad}}\right)$$

$$\frac{dF}{dP} = -\frac{\epsilon}{g}\,.$$

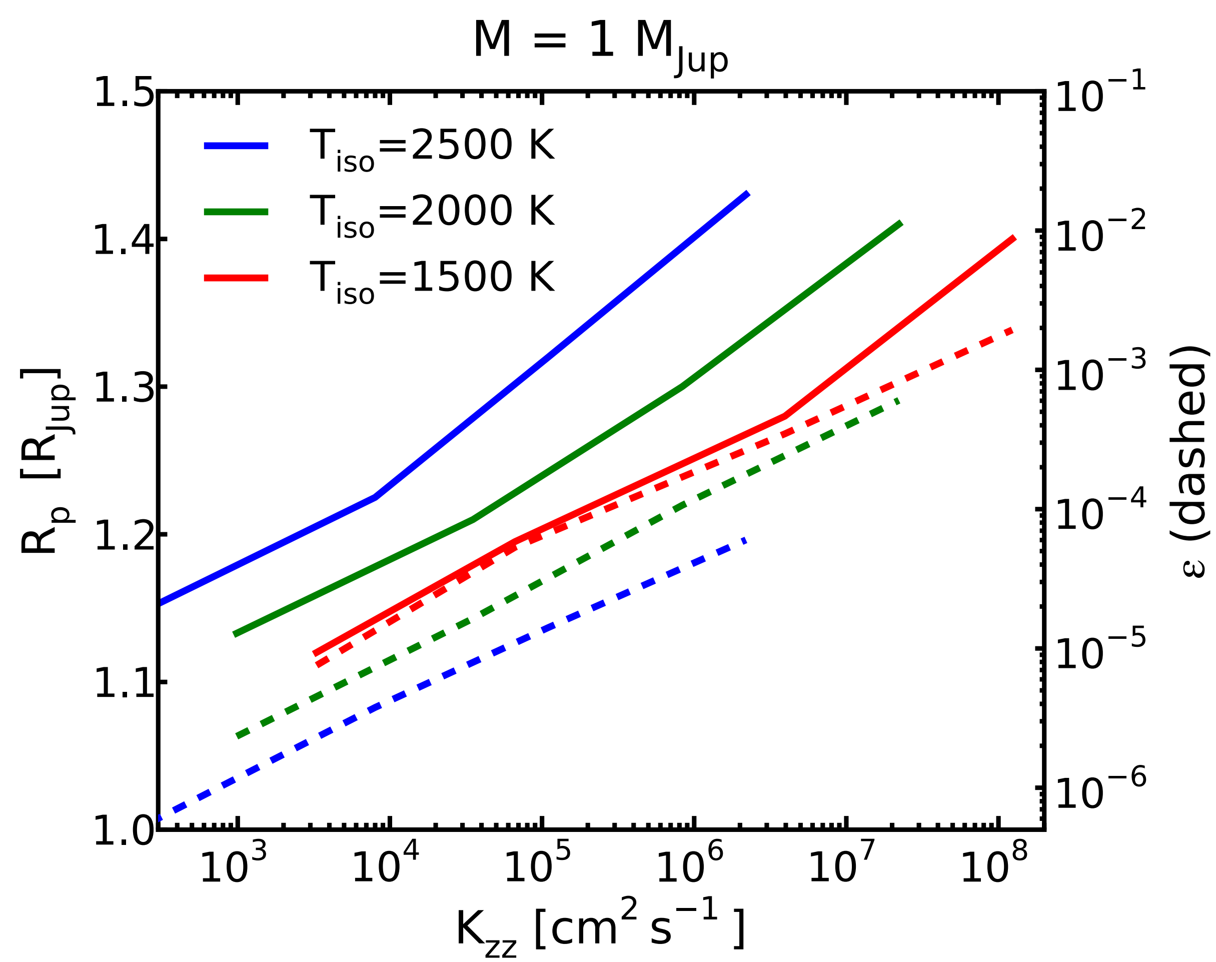
$$\frac{dT}{dP} = \frac{F + F_{\rm iso}}{k_{\rm rad} + F_{\rm iso} P/(\nabla_{\rm ad} T)}$$

$$F_{\rm iso} \equiv K_{zz}\rho g$$

Inflation by the Mechanical Greenhouse Effect

(Youdin et al., in prep/preliminary)

- Preferentially inflates hotter planets
    - Also lower mass giants (not shown)
- Efficient way to inflate a hot Jupiter
    - Simply replaces core flux
- Constraints: delivery of condensates to photosphere (TiO, dusty hazes)
    - See poster by *Nawal Husnoo et al.*
    - K_{zz} relevant for photochemical models



Solutions match mechanical greenhouse flux to structure models of Arras & Bildsten (2006)

Conclusions

- Hot Jupiters are inflated ... or never shrank
  - Need a mechanism to enhance effects of irradiation
- Ohmic Dissipation hypothesis: self-consistency not yet demonstrated
  - Strong B-fields damp strong winds in hot atmosphere ... all required
- Mechanical Greenhouse: turbulent mixing efficiently replaces cooling flux
  - Source of deep, weak turbulence unspecified (meridional, MHD)
  - Observational connections to condensate/photochemical mixing models