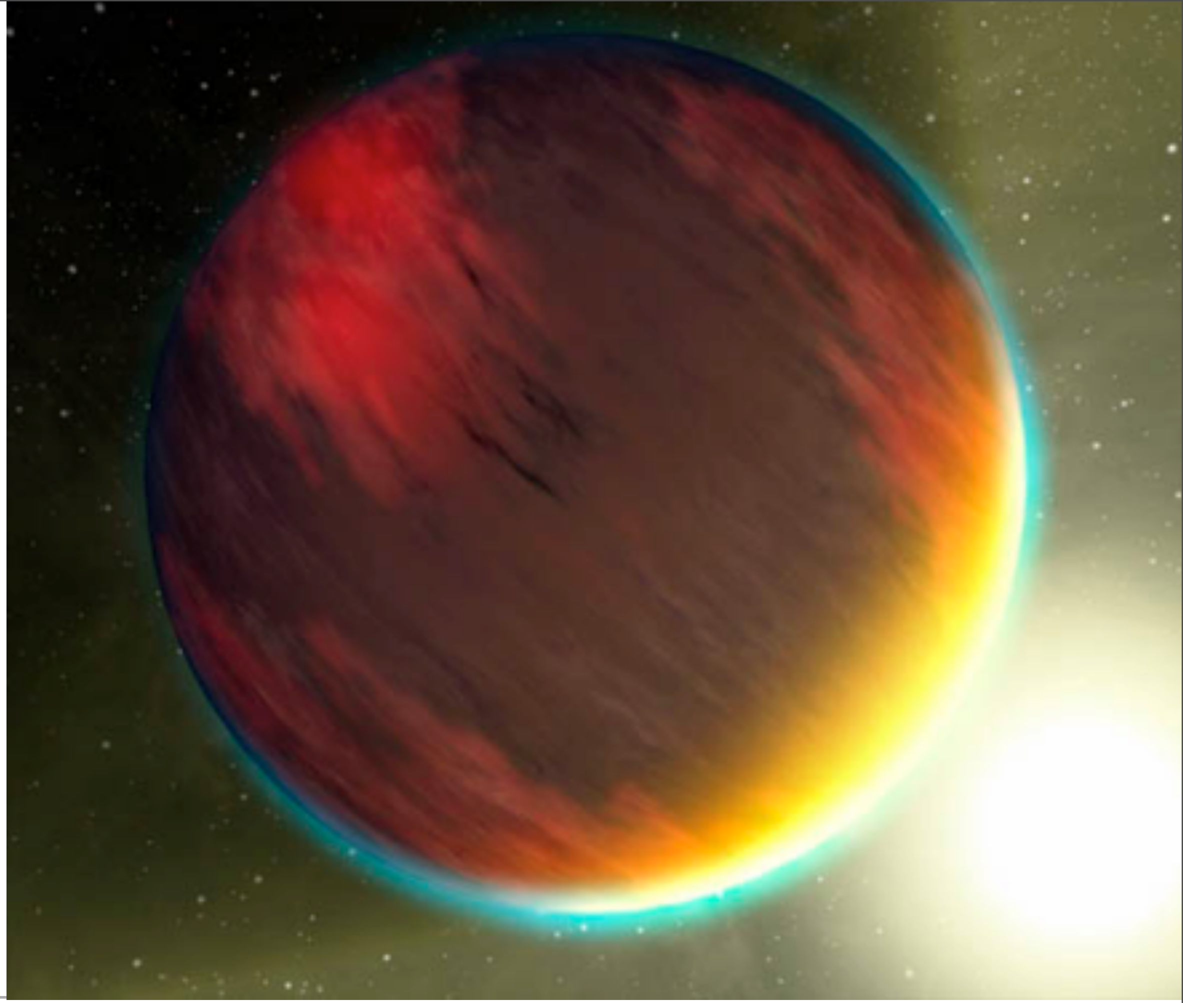
# The Mechanical Greenhouse: Turbulent Heat Burial in Hot Jupiter Atmospheres

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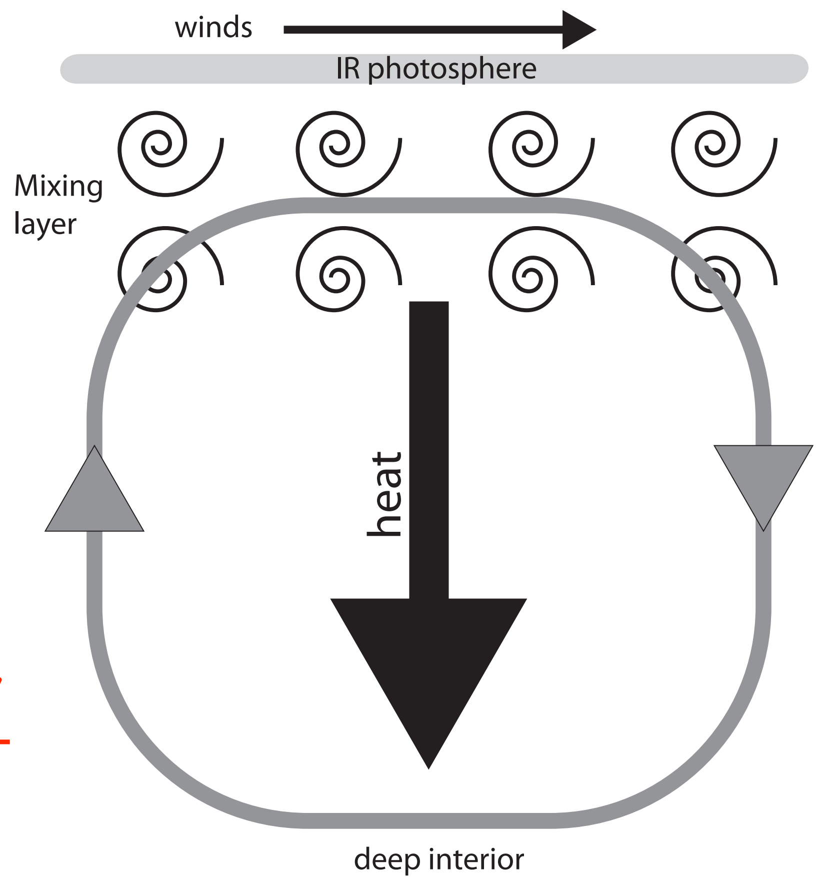



http://www.cita.utoronto.ca/~youd/Papers/MechanicalGreenhouse.pdf

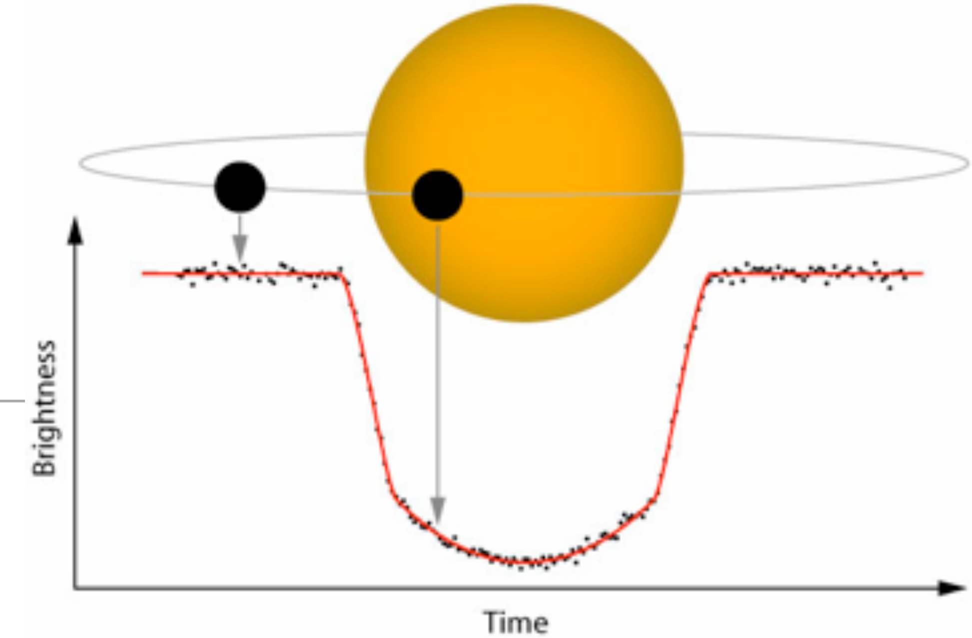
# Outline

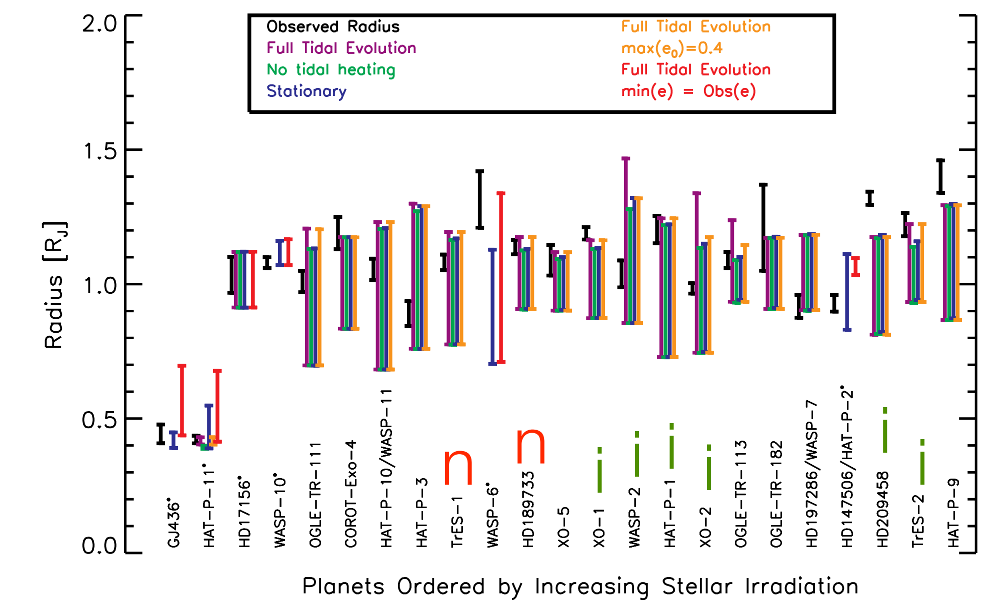
- Motivation: (Some) hot Jupiters are inflated and have thermally inverted stratospheres
- Technique: Steady-state energy balance irradiated, plane parallel atmosphere
    - Consider: Effect of turbulence in stratified (vs. convective) layers
- Findings:
    - Turbulence drives downward heat flux, can inflate planets
    - TiO hypothesis for thermal inversions in doubt, would over-inflate planets

# Inflated Hot Jupiters

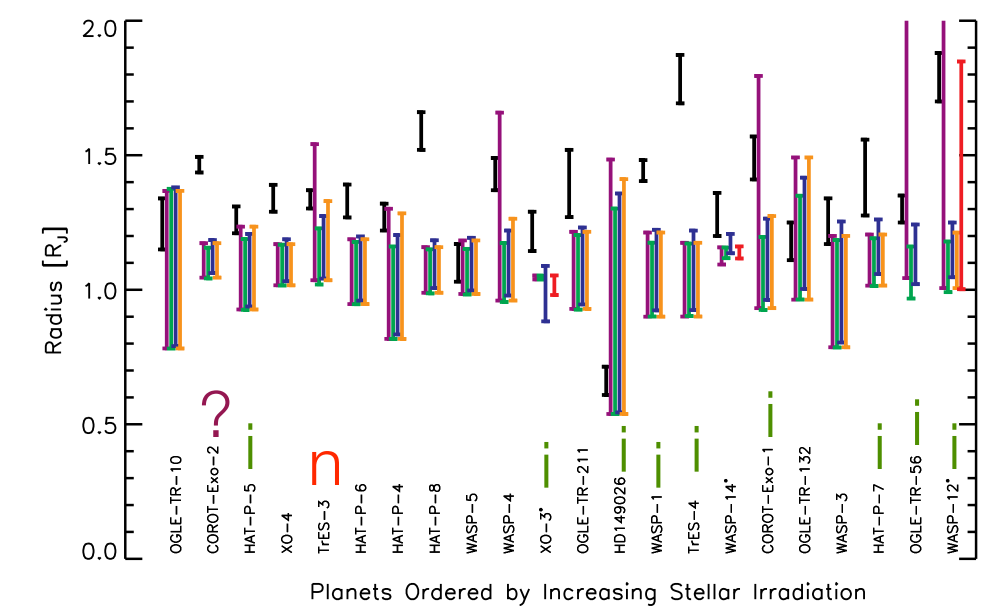
- Larger transit radii than standard models, even with no core & including irradiation

- Possible solutions
  - Slow cooling by thermal blanketing
    - High opacity *(Burrows et al. 2007)*, dissipation of atmospheric winds *(Guillot & Showman 2002)*
  - Add heat to interior, dissipation at depth
    - Tidal *(Bodenheimer et al. 2001)*, magnetic *(Batygin & Stevenson 2010)*




(a)

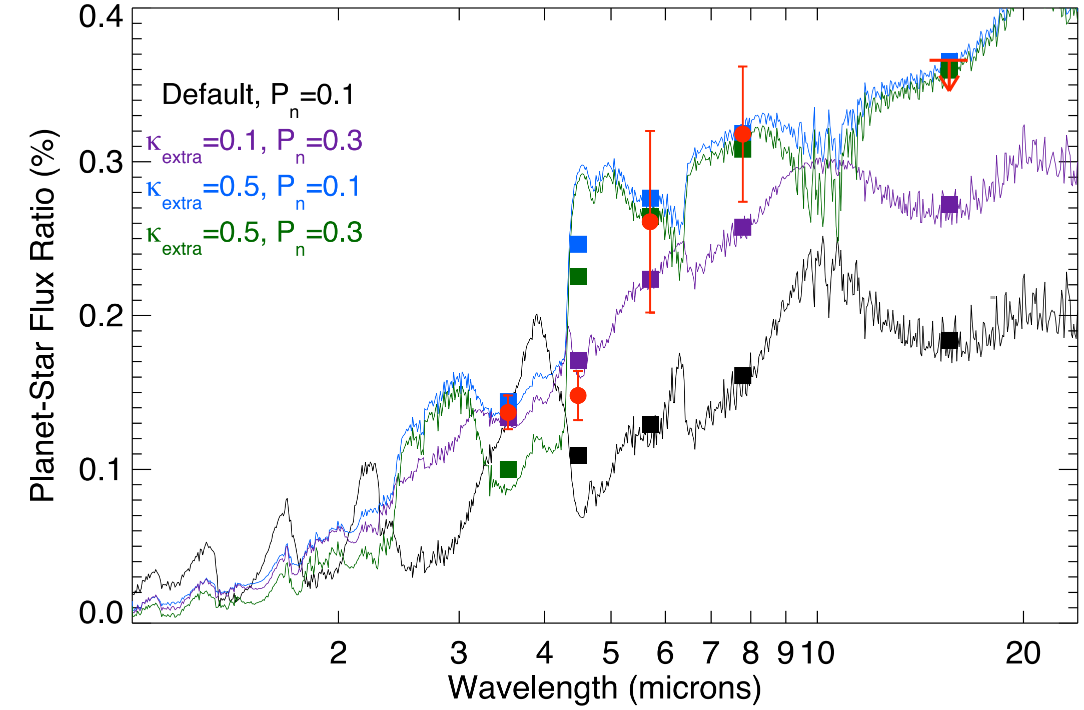


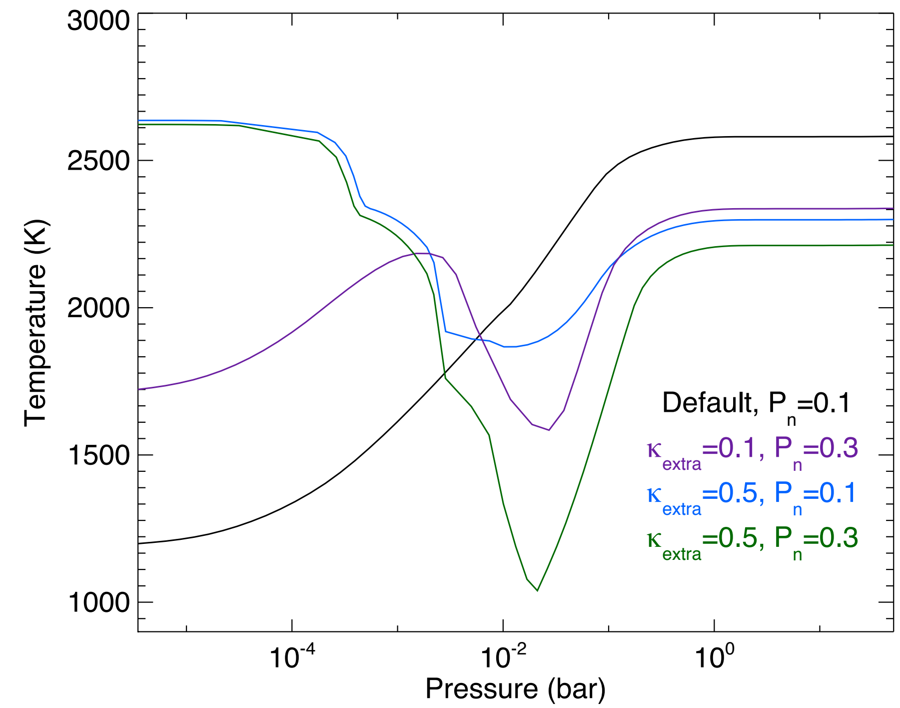

*Miller et al. (2009)*

# Thermal Inversions

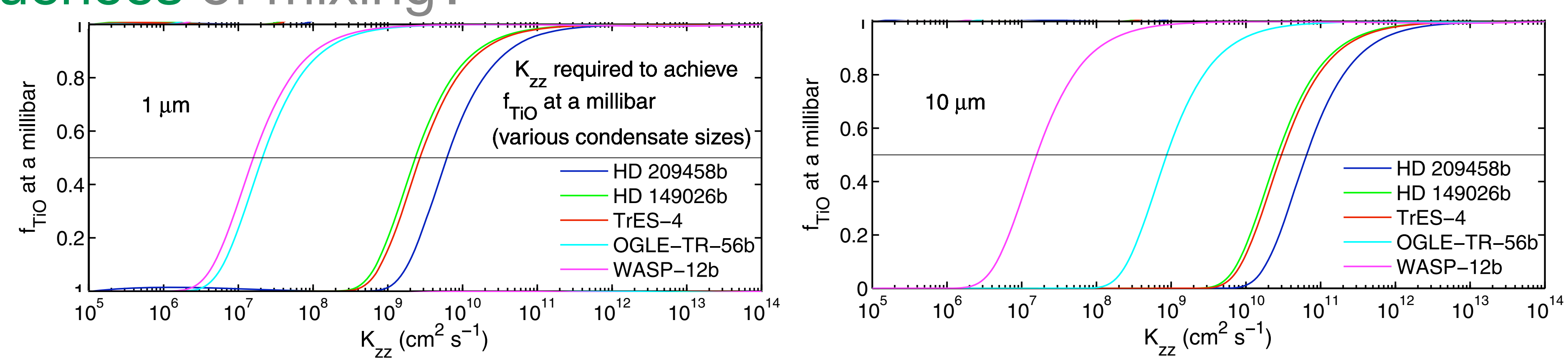
- Transit spectra suggest hot stratospheres
  - Optical absorbers in upper atmosphere: TiO *(Hubeny et al. 2003)*, Sulfur *(Zahnle et al. 2009)*
- Eddy diffusion needed to overcome settling, including rainout from cold traps
  - $K_{zz} \sim 10^7$—$10^{10}$ cm$^2$/s to loft TiO
  - Energetic consequences of mixing?

*Knutson et al. (2009)*



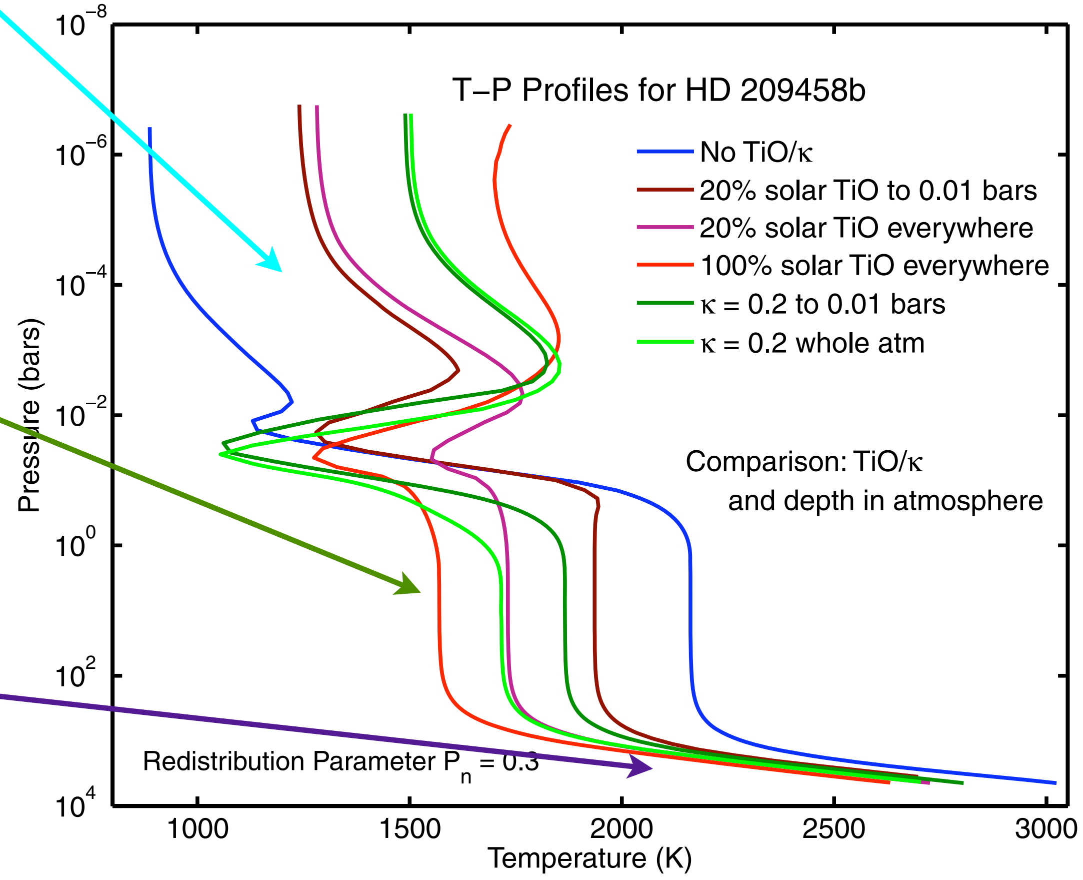

*Spiegel et al. (2009)*



# Basic Structure of Hot Jupiters

- Optically thin regions ($P$ <~ $10^{-3}$ bar)
  - Complex radiative transfer & dynamics
- Deep Isotherm ($P$ <~ $10^{3}$ bar)
  - $F_{irr} >> F_{int}$
- Adiabat of Convective Interior
  - Determines radius
- Radiative Convective Boundary (RCB): Where Cooling Rate Determined

*Spiegel et al. (2009)*

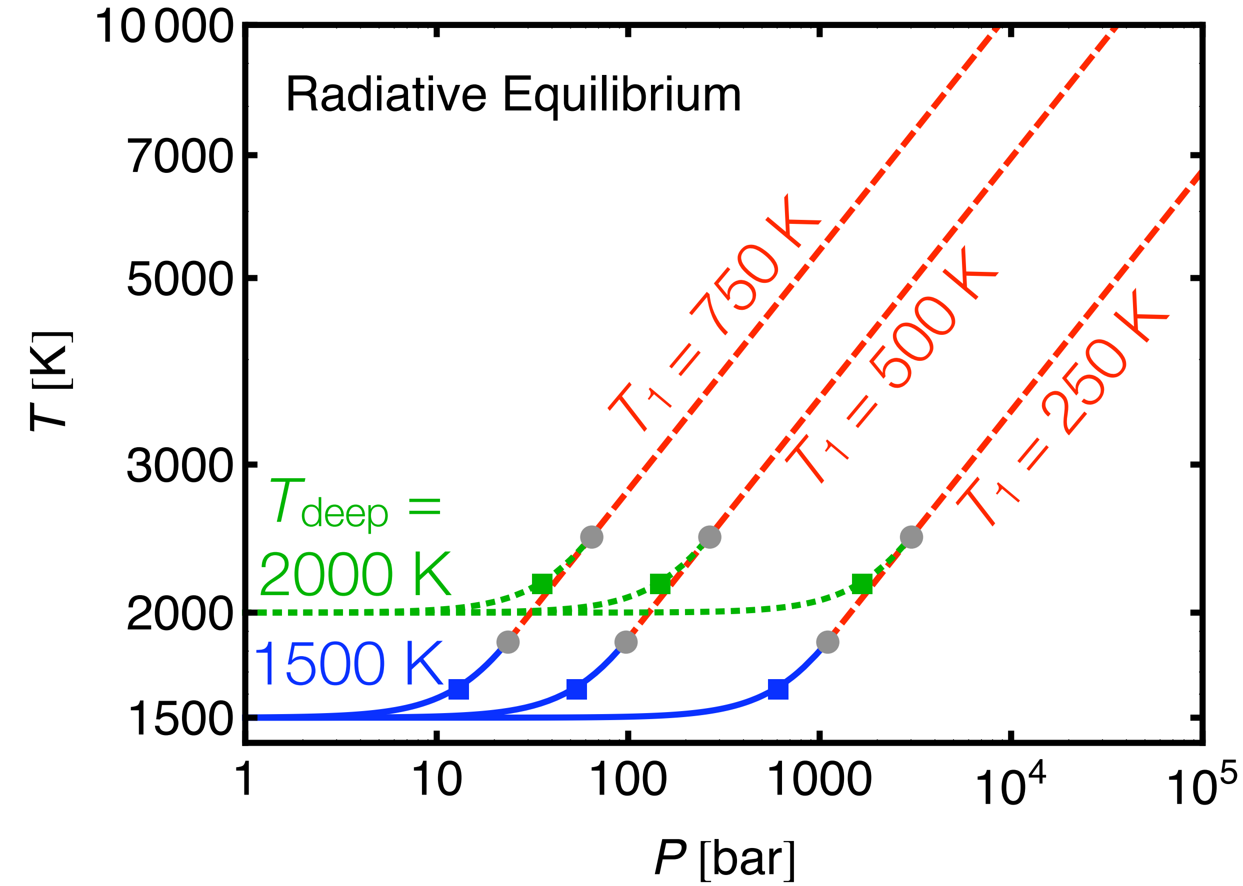


$$\frac{dT}{dP} = \frac{F_{\rm rad}}{k_{\rm rad}} \qquad k_{\rm rad} = \frac{16\sigma T^3 g}{3\kappa},$$

$$\kappa = \kappa_1 P^\alpha T^\beta$$

# Radiative Equilibrium Solutions

- In radiative zones, typically assume
  - All flux by radiation
  - Flux is constant: no dissipation
- Simplified, optically thick solutions
  - Fix $T_{\rm deep}$ at top of radiative region
  - Radiative diffusion w/ grey powerlaw opacity
- Match onto internal adiabat ($T_1$ label)




Cooling flux depends on irradiation & internal entropy

$$F_{\rm c} = k_F \frac{g}{\kappa_1}\left(\frac{T_1}{T_{\rm deep}^{1-\nabla_{\rm ad}/\nabla_\infty}}\right)^{(1+\alpha)/\nabla_{\rm ad}} \propto \frac{T_1^7}{T_{\rm deep}^3}.$$

# (Forced) Turbulence in Radiative Zones

Myth: Dissipation must occur in convective interior to explain inflated radii

- Motivated by inversions and atmospheric (day-night) circulation
- Breaks Rad. Eq. because turbulence:
  - Dissipates ($\epsilon$)⇔ flux not constant
  - Buries heat ⇔ mechanical flux
- How does this affect energy balance in hot Jupiters? Steady state model:

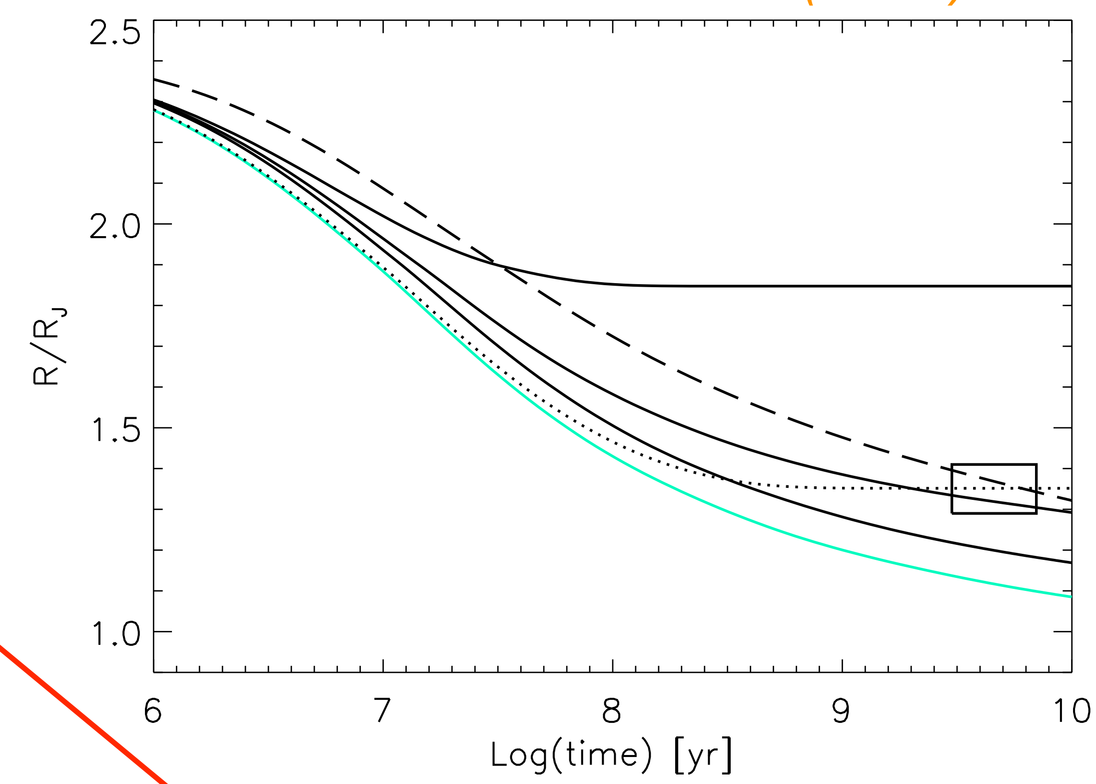
$$\frac{dT}{dP} = \frac{F + F_{\rm iso}}{k_{\rm rad} + F_{\rm iso}P/(\nabla_{\rm ad}T)}$$

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

Eddy Diffusion

$K_{zz} \sim w \cdot \ell$

Guillot & Showman (2002)




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

Net Flux

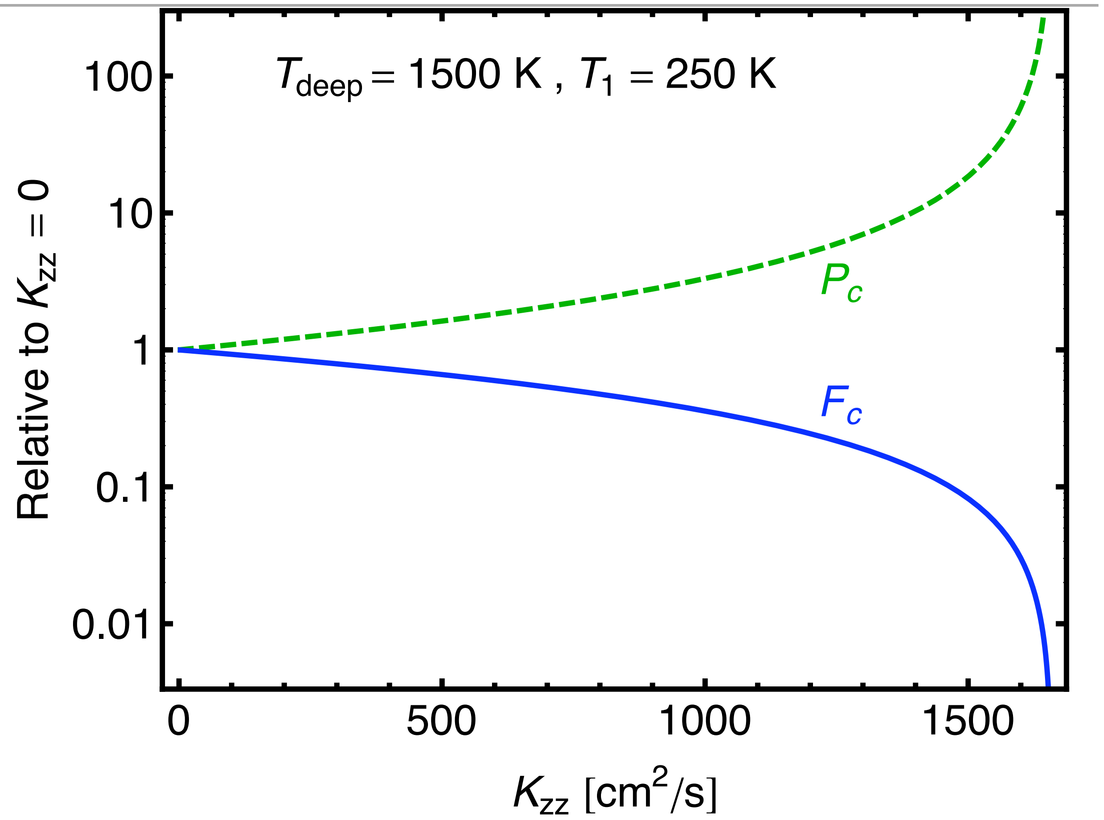
$$F = F_{\rm rad} + F_{\rm eddy}.$$

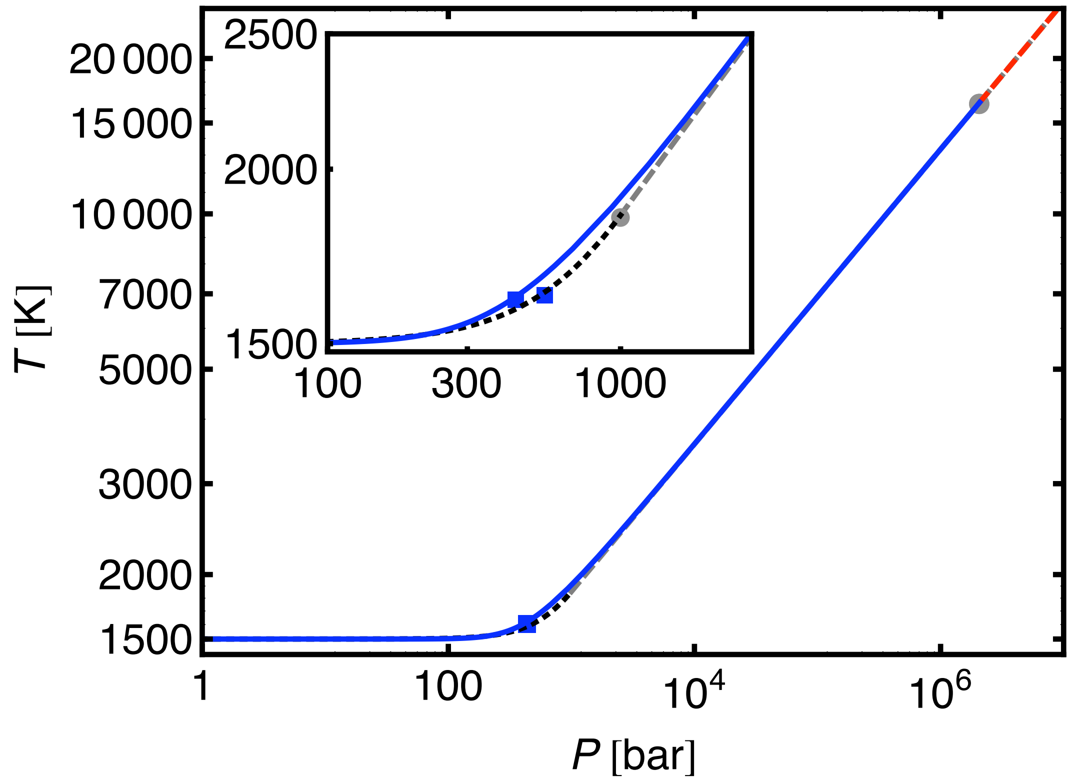
$$F_{\rm eddy} = -K_{zz}\rho T\frac{dS}{dz}$$

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

# Effect of Eddy Heat Flux (Ignoring Dissipation)

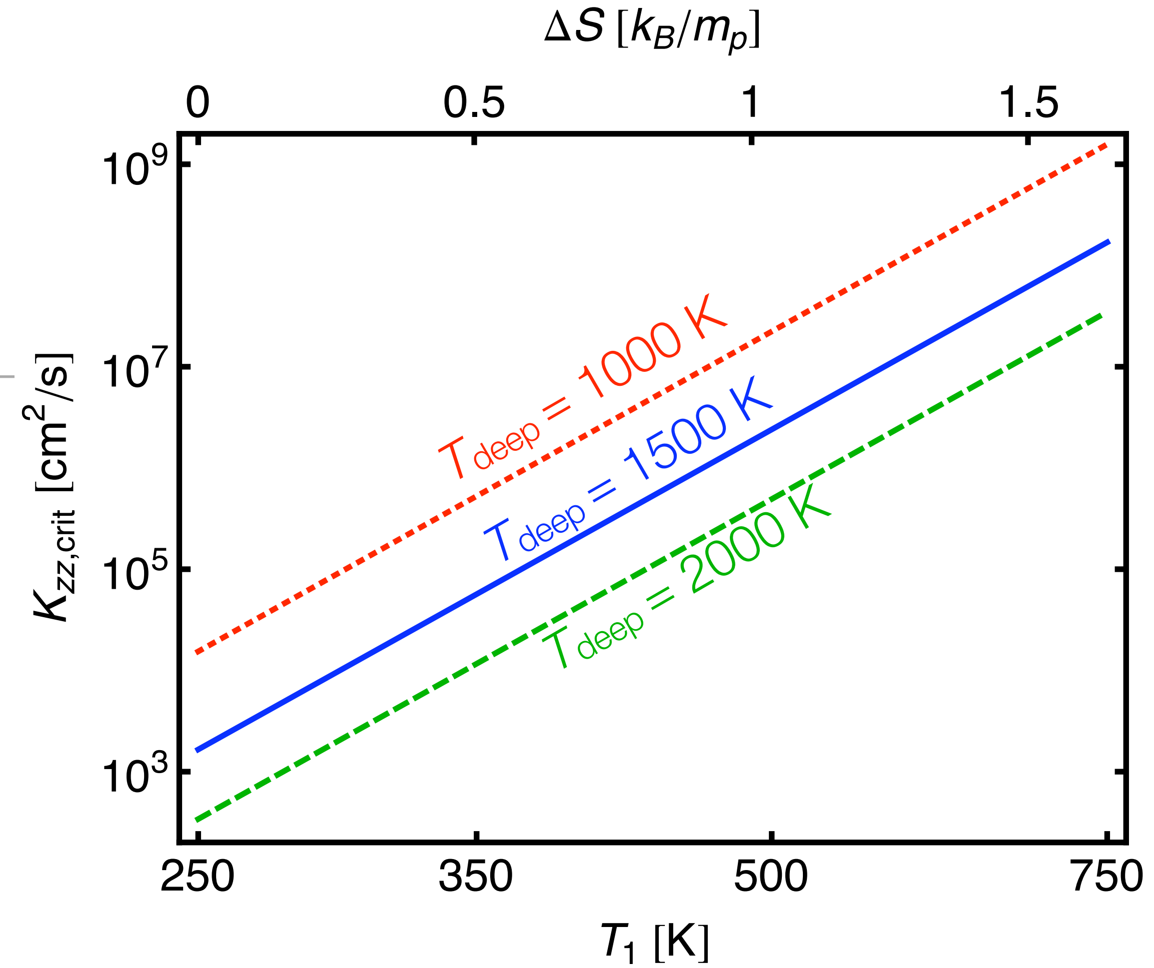
- Increasing Eddy Diffusion drives RCB (radiative convective boundary) deeper
  - Reduces cooling flux
  - Effect on T-P profile is modest
- Critical eddy diffusion, $K_{zz,crit}$
  - Eddy flux exceeds cooling rate associated with entropy
  - $K_{zz} > K_{zz,crit} \Rightarrow$ heat interior

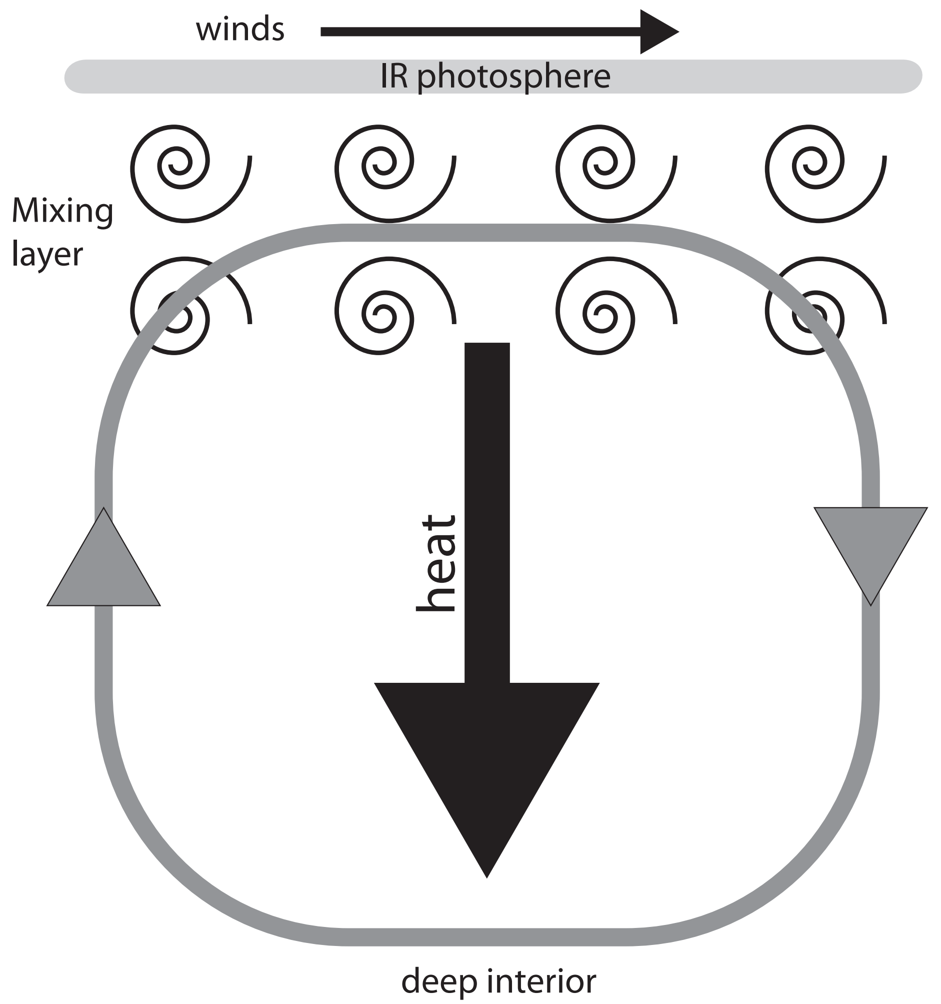


# Inflation

- Self-regulation: if $K_{zz} > K_{zz,crit}$
    - entropy & $K_{zz,crit}$ increase
      $\Rightarrow$ $K_{zz} = K_{zz,crit}$
    - Balance eddy & radiative fluxes, i.e. heat burial & cooling
- Inversions lower $T_{deep}$
    - $K_{zz,crit}$ rises, limiting inflation
    - No simple relation between inversions & inflation



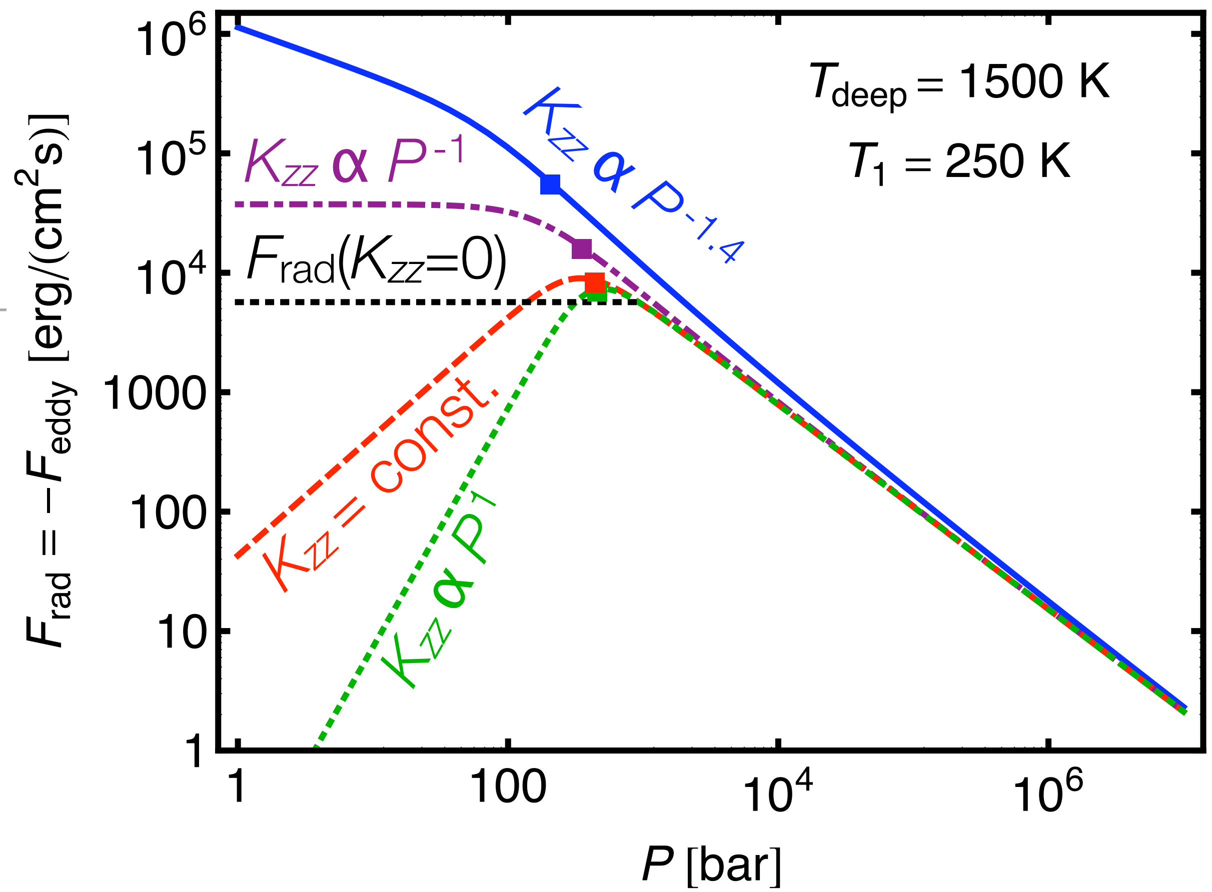
# Complexity

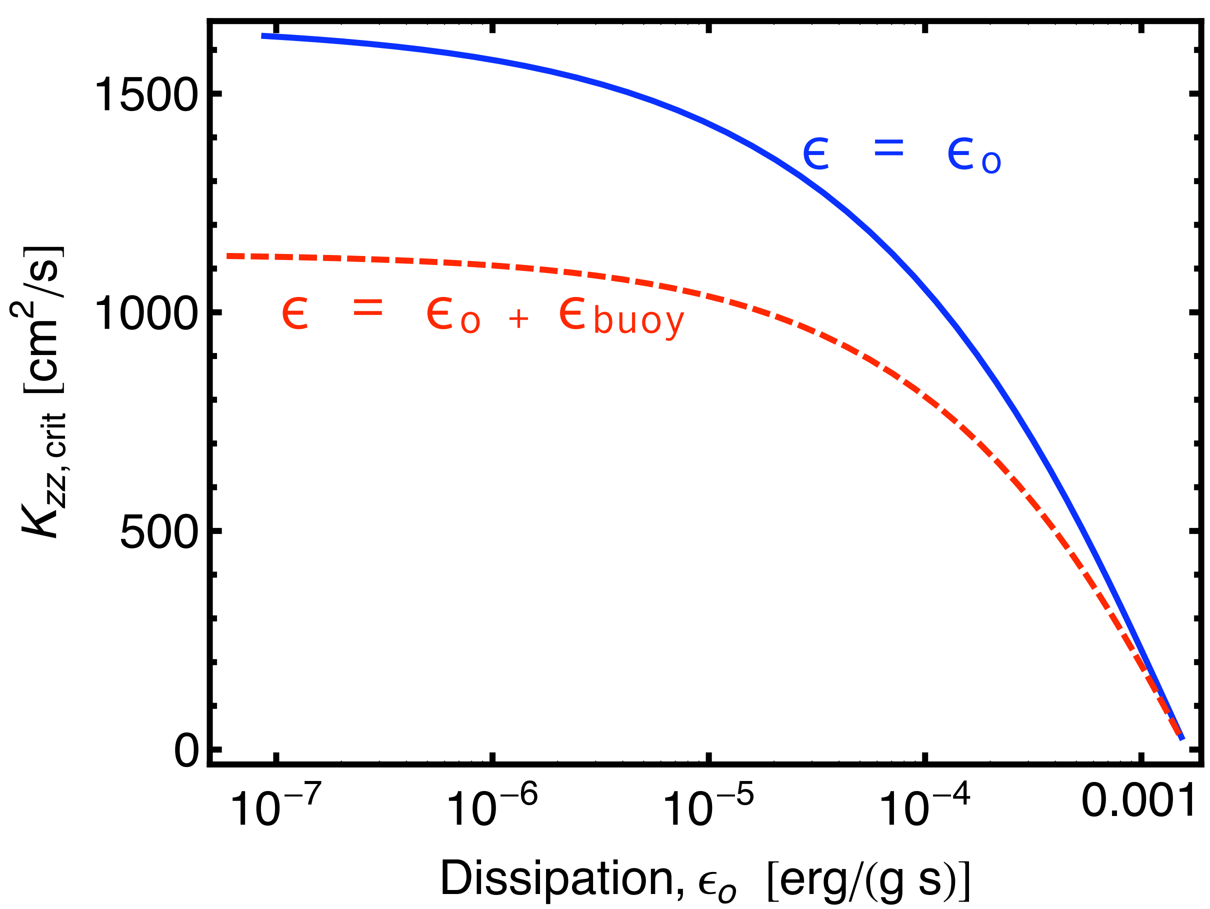
- Letting diffusion vary with height
  - $K_{zz,crit}$ applies near RCB
  - Carnot efficiency constrains mixing at top, i.e. photosphere

$$K_{zz,\mathrm{top}} < \frac{f_* F_*}{\rho_{\mathrm{top}} g}$$

$$\approx 10^9 \; \frac{\mathrm{cm}^2}{\mathrm{s}} \left(\frac{P_{\mathrm{top}}}{0.1\ \mathrm{bar}}\right)^{-1} \left(\frac{T_{\mathrm{deep}}}{1500\ \mathrm{K}}\right)^5 \frac{f_*}{1\%}$$

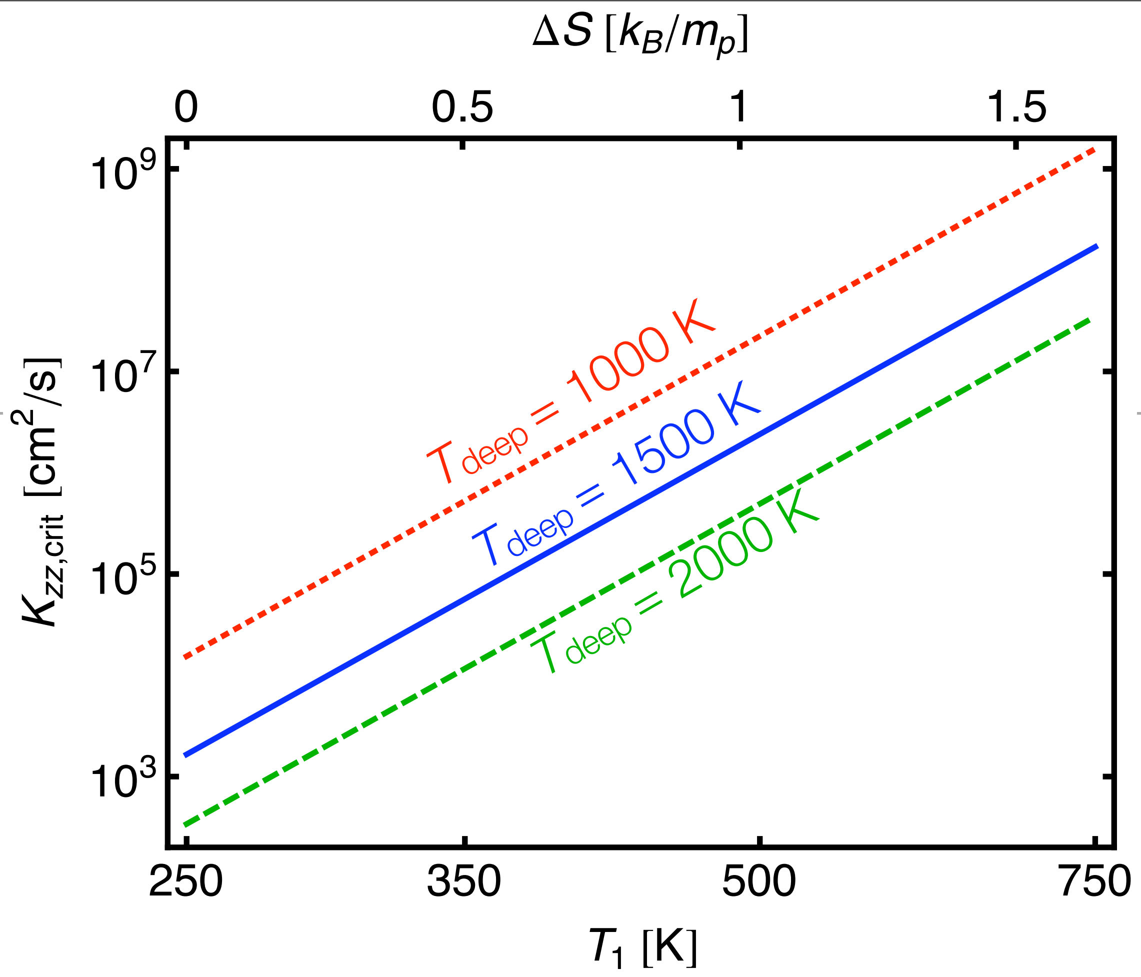
- Adding dissipation
  - Lowers $K_{zz,crit}$
  - Easier for turbulent flux to inflate

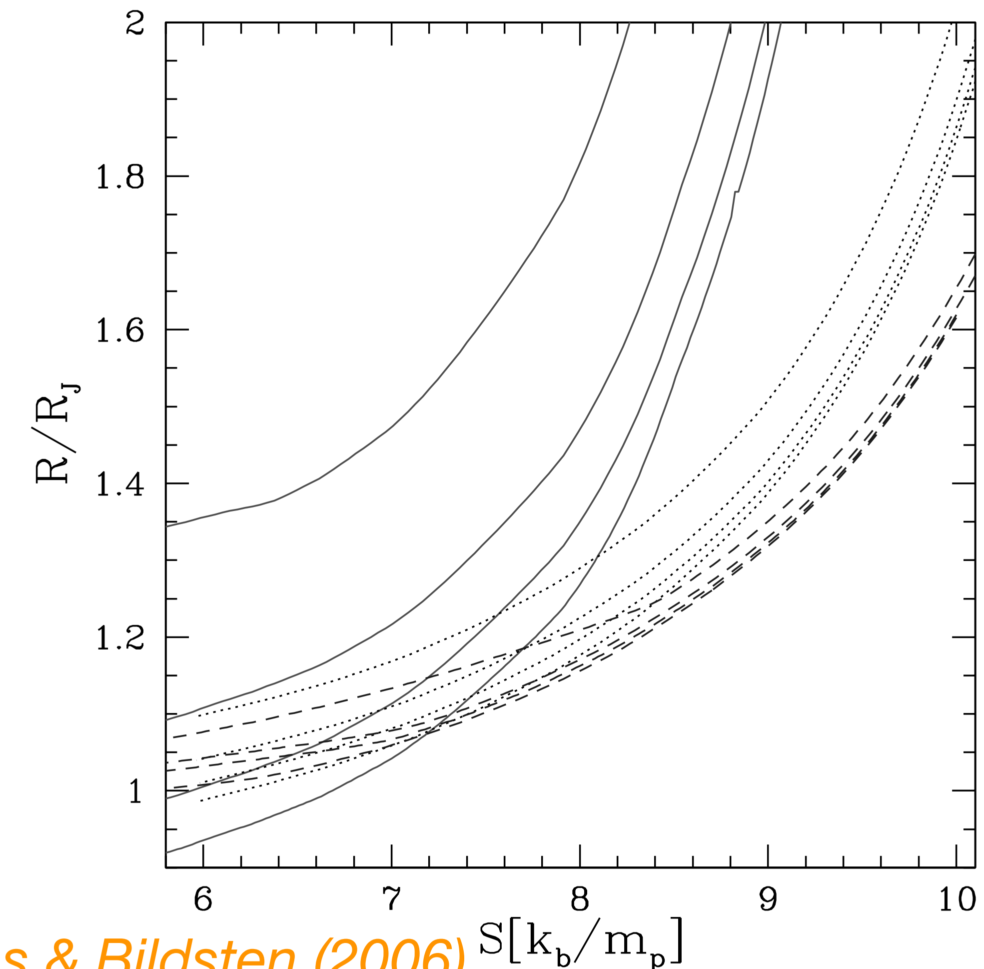


# Implications

- Turbulent diffusion needed for TiO hypothesis appears excessive
    - Would over-inflate planets, close to nail in coffin
- Smaller turbulent fluxes can inflate hot Jupiters
    - Compliments dissipation
    - Inefficient for cold Jupiters, requires a deep stratified layer



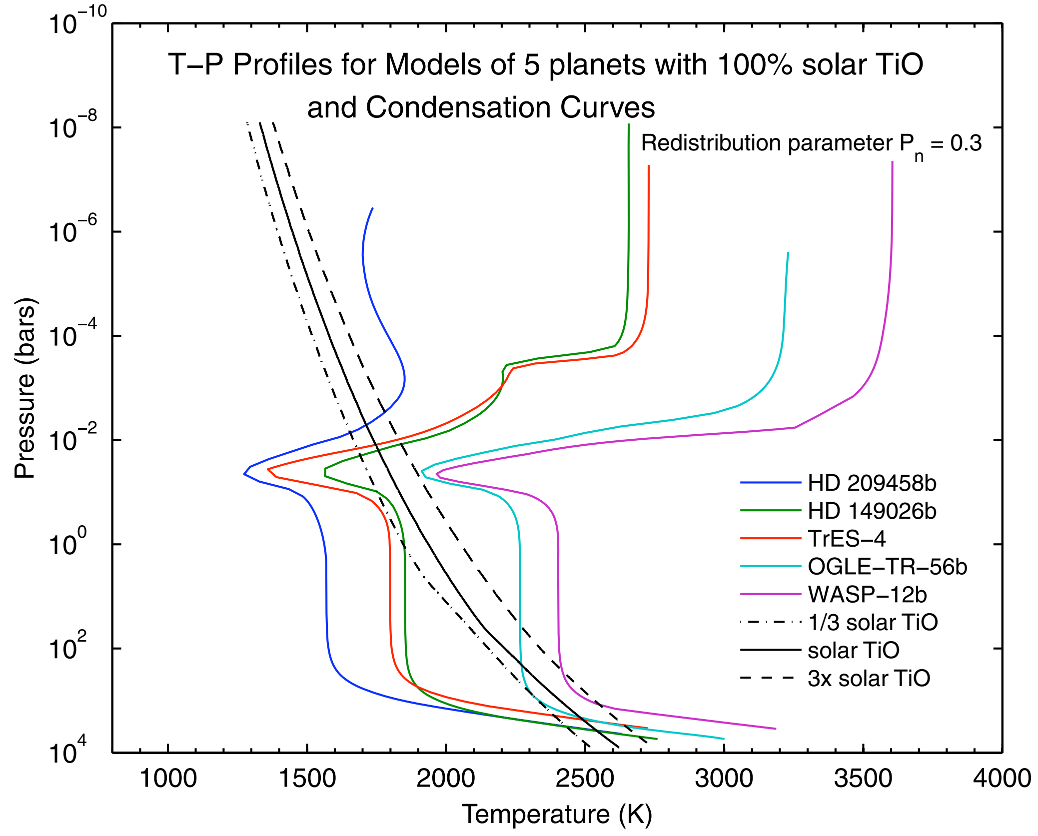




Arras & Bildsten (2006)

# Future Work

- Add realistic physics
  - 1st step: Compute turbulent fluxes for existing T-P profiles w/ detailed EOS & opacity *(courtesy Dave Speigel)*
  - Self-consistent solution: Include eddy flux in radiative-convective model
- Generalize analysis to optically thin regions: How fragile is inversion itself to mixing?
- Be useful: Develop sub-grid prescriptions for GCMs (global circulation models)

*Spiegel et al. (2009)*




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

# Summary

- Hot Jupiters have deep surface radiative layers which regulate the evolution of planetary radius
- Turbulence in radiative layers bury heat and affects the emergent spectrum
  - Helps explain inflated transit radii
  - Mixing needed for TiO to cause thermal inversions appears excessive
  - Actual profile of turbulent (and other) mixing in radiative layers? Subject to dynamical constraints *(this morning's lectures)*