Magnetic Turbulence in Inner Radii of Protoplanetary Disks

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August 6, 2014
Non-ideal MHD, Stability, and Dissipation in Protoplanetary Disks
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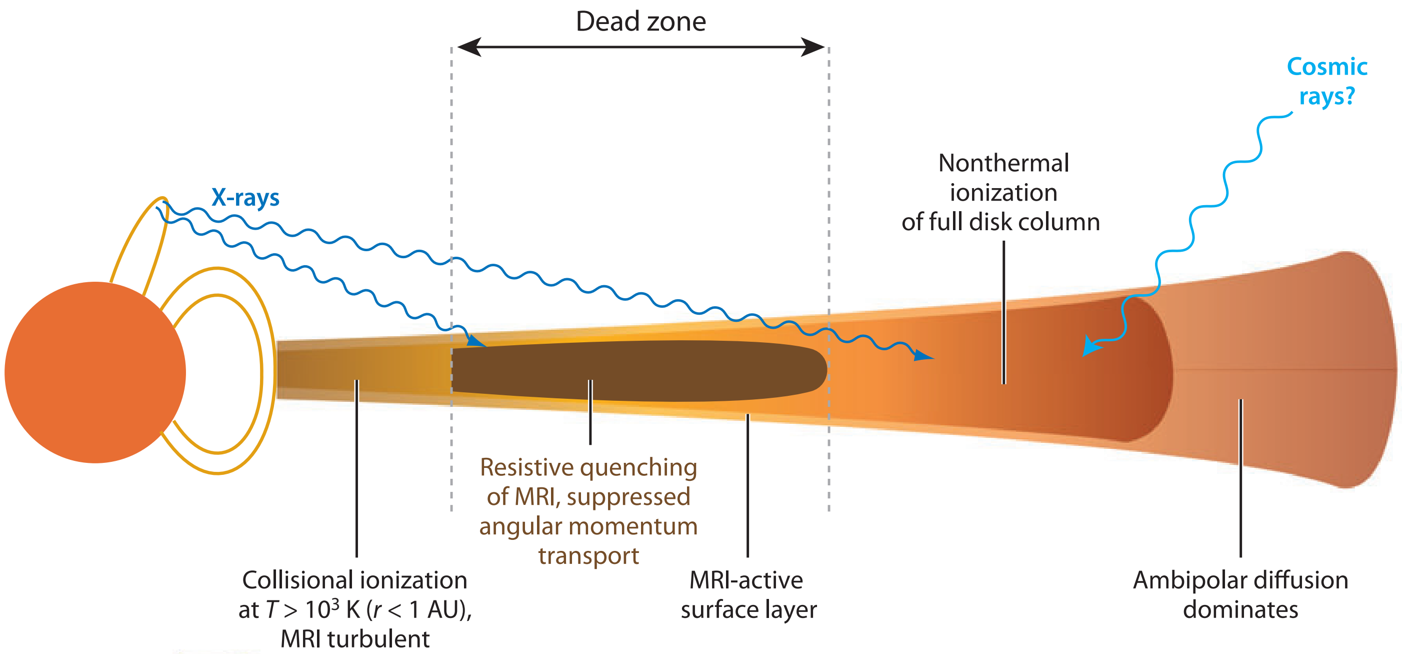
Ideal MHD Expected in Inner Radii of Protoplanetary Disks

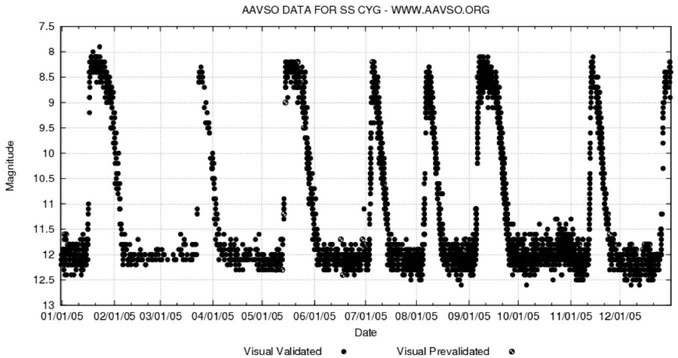
- Thermal ionization can revive ideal MHD in inner radii.
- What is the MRI turbulence with ionization transitions there?



from Armitage 2011

Outbursts in Accretion Disks

- ☐ Episodical outbursts (sudden increase in $\dot{M}$) are observed in some systems.



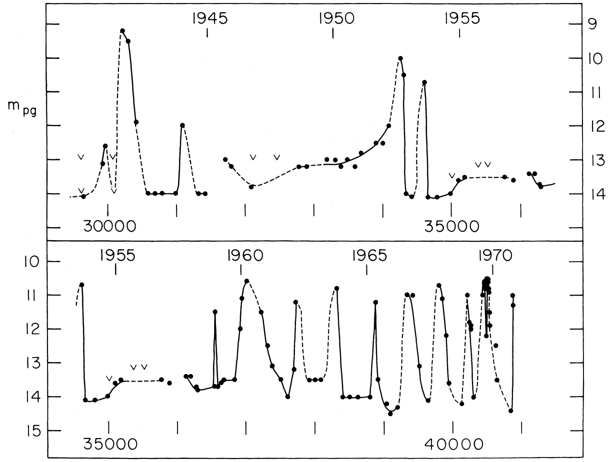
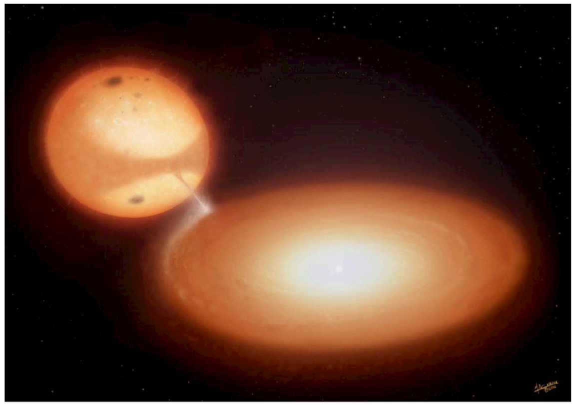
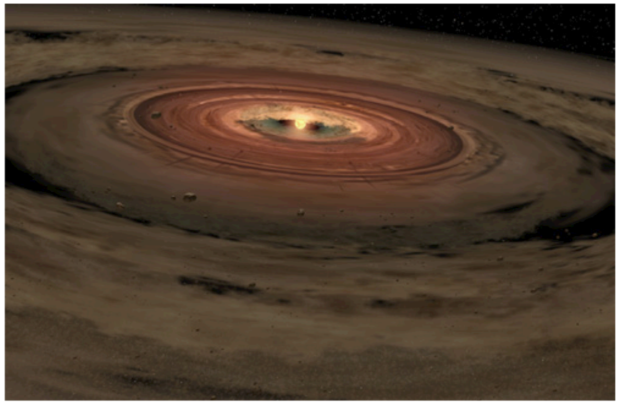


FIG. 15.—The photographic light curve of VY Tau, from Meinunger (1969, 1971)



accretion disk + white dwarf
(Dwarf nova)

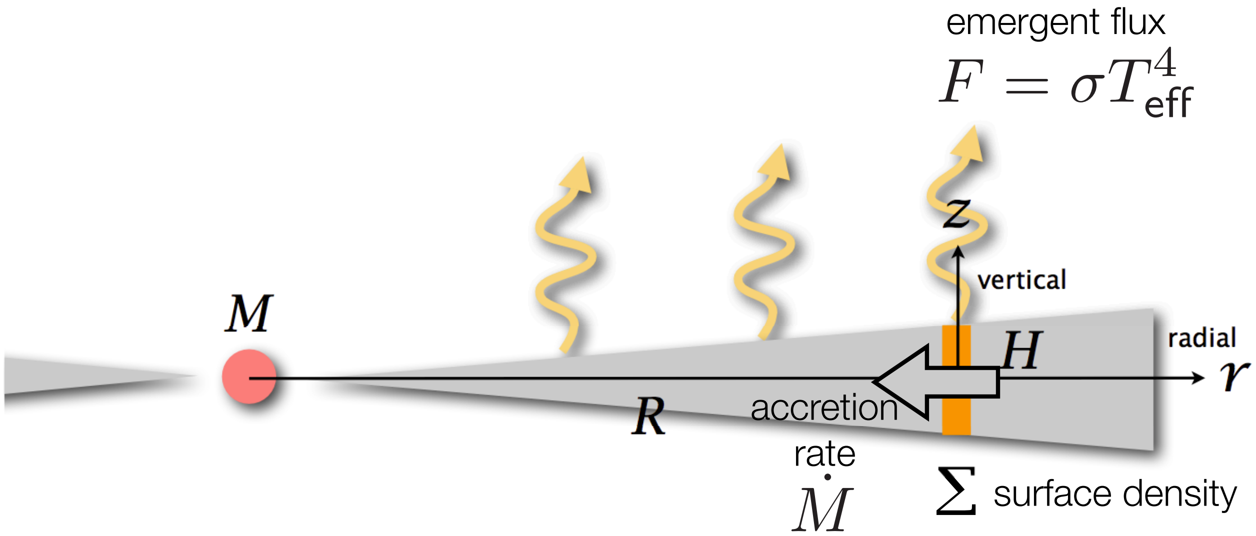


protoplanetary disk
(FU Ori outbursts)

Thermal Equilibrium Curve

- Thermal balance in a vertical column (angular velocity Ω):

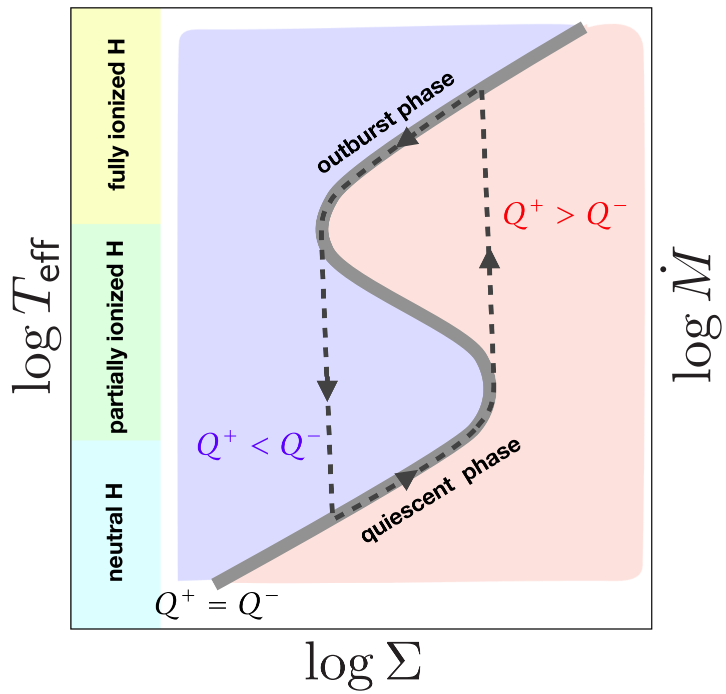
$$\underbrace{2\sigma_{\rm B}T_{\rm eff}^4}_{\text{cooling}} = \underbrace{\frac{3}{4\pi}\dot{M}\Omega^2}_{\text{heating}} = \frac{3}{2}\Omega\int w_{r\phi}dz = \underbrace{\frac{3}{2}\Omega\alpha\int pdz}_{\alpha\text{ prescription}} \sim \alpha T_{\rm mid}\Sigma.$$



- $T_{\rm eff} = T_{\rm eff}(\Sigma)$ or $\dot{M} = \dot{M}(\Sigma)$: $\dot{M}$ or $T_{\rm eff}$ is uniquely determined by Σ (thermal equilibrium curve).
- This is a non-trivial relation due to $T_{\rm mid} = T_{\rm mid}(T_{\rm eff})$, which is determined by thermodynamics in the vertical column.

Disk Instability Model (DIM) of Outbursts

- "S-shaped" thermal equilibrium curve is associated with hydrogen ionization transition around $T = 10^4$K (Hoshi 79).



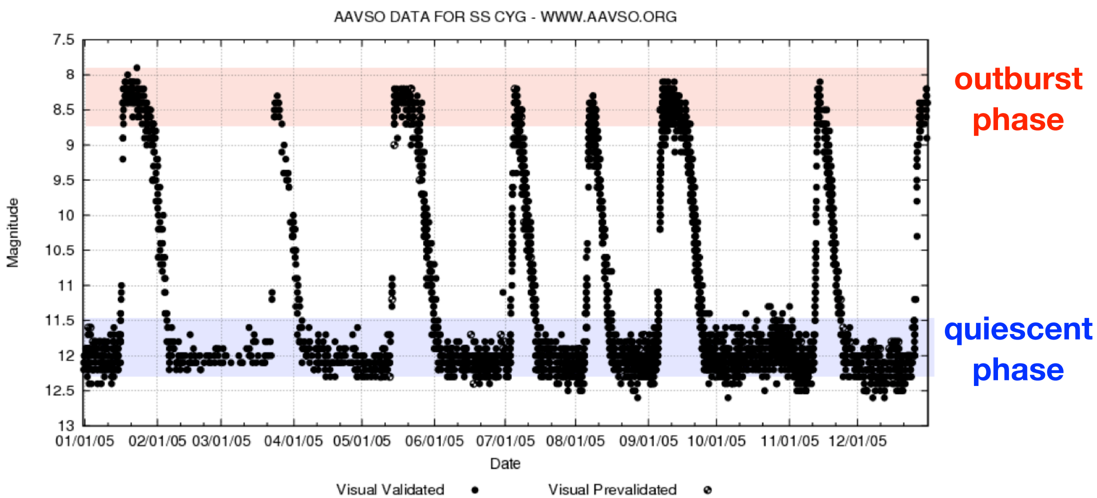
- Episodical outbursts is well modeled as a limit-cycle on an "S-shaped" thermal equilibrium curve (e.g. Mineshige & Osaki 83).
- Outburst phase corresponds to a hot and fully-ionized gas state while quiescent phase corresponds to a cool and neutral gas state.

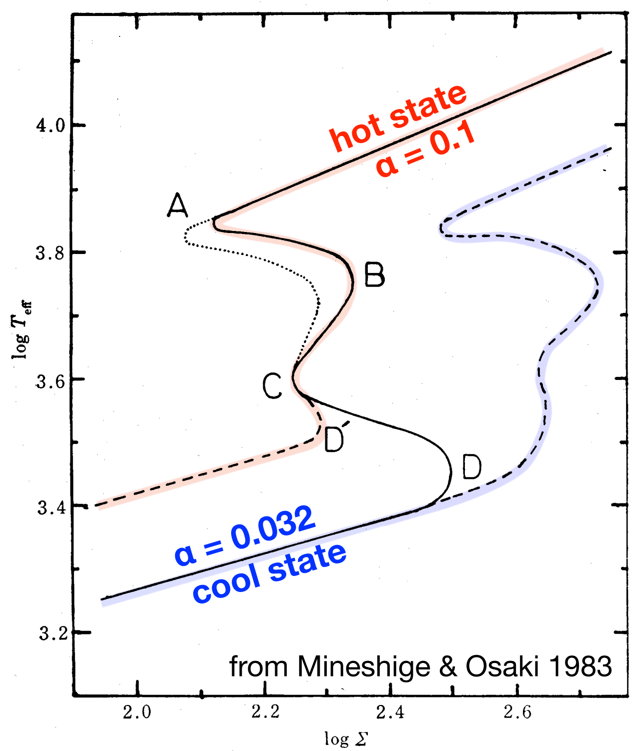
Observational Constraint on Saturation Level of Turbulence

- The most reliable estimate on "alpha" in acccretion disks is obtained from the decay time of the outbursts (e.g. Smak 99):

$$\alpha_{\mathrm{hot}} = 0.1 \sim 0.3$$

- The value in quiescent phases is estimated as $\alpha_{\mathrm{cool}} \sim 0.01$ from comparison of duration times.





Saturation Level of MRI Turbulence

- Ideal MHD simulations without net vertical fields show a universal value of α:

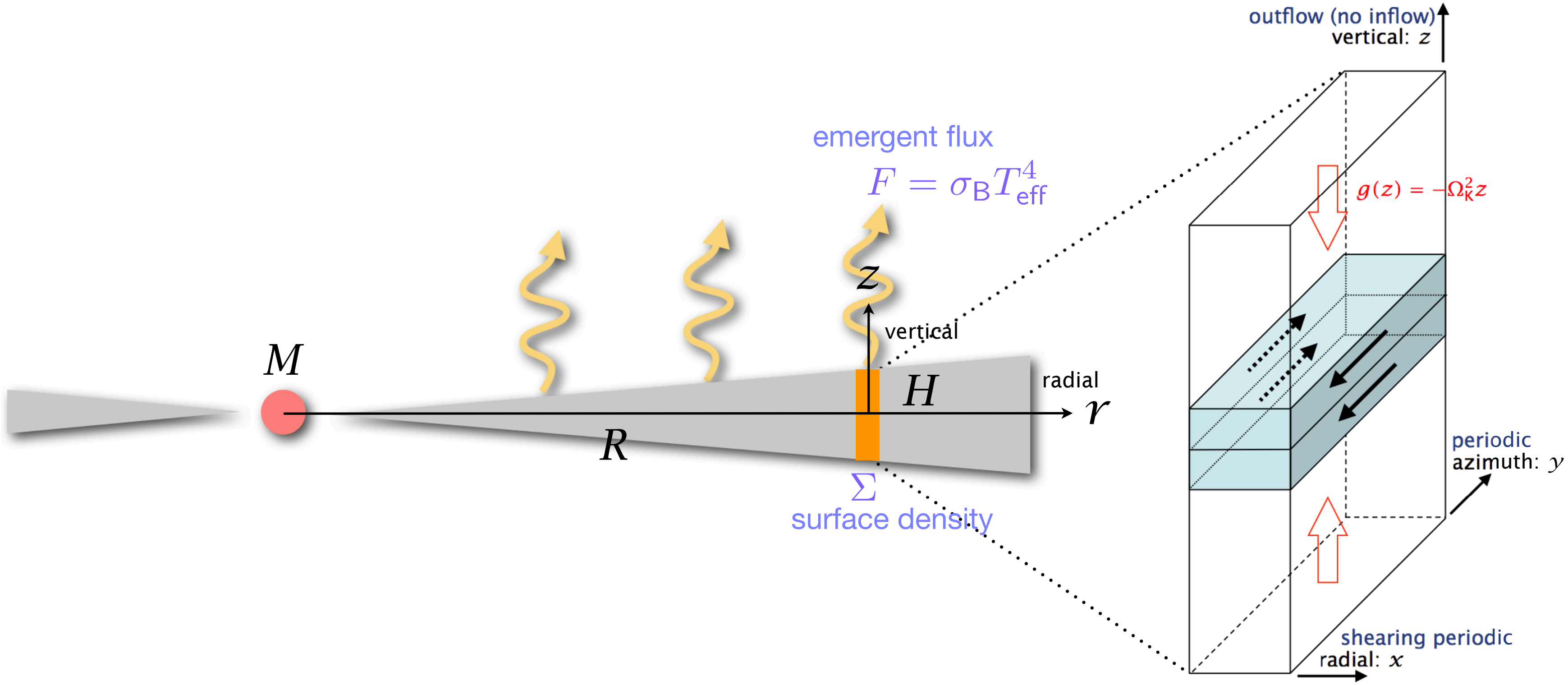
  $$\alpha_{\text{MRI}} = 0.01 \sim 0.02$$

- Non-negligible discrepancy between alpha in the hot ionized state (α_{hot}) and alpha in MRI turbulence assuming ideal MHD (α_{MRI}) (King+ 07).
- Where the discrepancy comes from? Cannot MRI explain the turbulence in fully-ionized accretion disks?

- CAVEAT: MRI turbulent stress depends on net vertical flux: $\propto B_z^2$ (e.g. Suzuki+ 11)
- CAVEAT: Isothermal process is usually assumed in the MRI simulations.

In This Work

- Magnetic turbulence in accretion disks with ionization transitions is studied by 3D radiation MHD simulations using realistic opacities and EOS.
- Stratified shearing box is employed with angular velocity $\Omega =$
  - 6.4×10^{-3}s^{-1}: dwarf nova case $M_* = 0.6 M_\odot$, $r = 14 R_*$ (Hirose+ 14)
  - 2.5×10^{-5}s^{-1}: protoplanetary disk case $M_* = M_\odot$, $r = 0.05$AU
- To map out a thermal equilibrium $\dot{M} = \dot{M}(\Sigma)$ (or $T_{\rm eff} = T_{\rm eff}(\Sigma)$), we repeat a simulation to measure $\dot{M}$ (and α) for a given Σ.



Basic Equations

- ideal MHD + radiative transfer with FLD approximation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = -\nabla p + \frac{1}{4\pi}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \frac{\kappa^{\mathsf{R}} \rho}{c} \boldsymbol{F}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e \boldsymbol{v}) = -(\nabla \cdot \boldsymbol{v}) p - (4\pi B - cE)\kappa^{\mathsf{P}} \rho$$

$$\frac{\partial E}{\partial t} + \nabla \cdot (E \boldsymbol{v}) = -\nabla \boldsymbol{v} : \mathsf{P} + (4\pi B - cE)\kappa^{\mathsf{P}} \rho - \nabla \cdot \boldsymbol{F}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) = 0$$

$$\boldsymbol{F} = -\frac{c \lambda_{\mathsf{limiter}}}{\kappa^{\mathsf{R}} \rho} \nabla E$$ FLD approximation

- pre-computed EOS and opacities

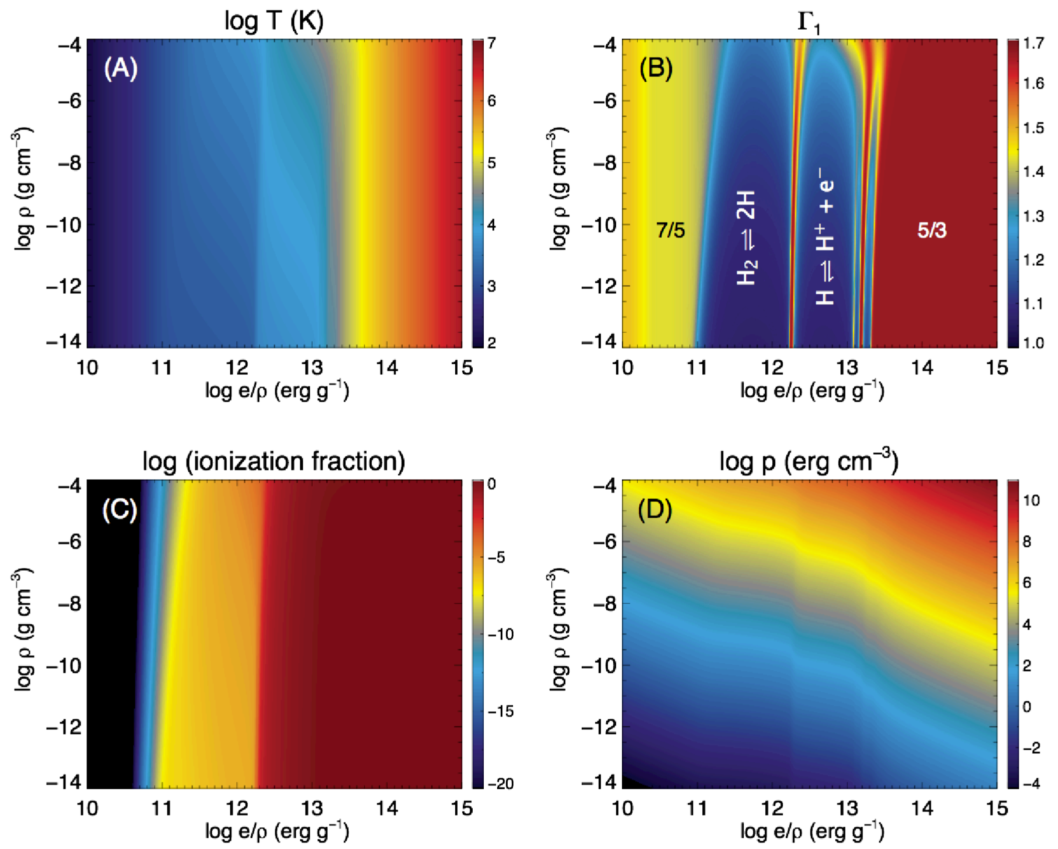
$p = p(\rho, e/\rho), \quad T = T(\rho, e/\rho)$ non-ideal EOS

$\kappa^{\mathsf{R}} = \kappa^{\mathsf{R}}(\rho, T)$ Rosseland-mean opacity

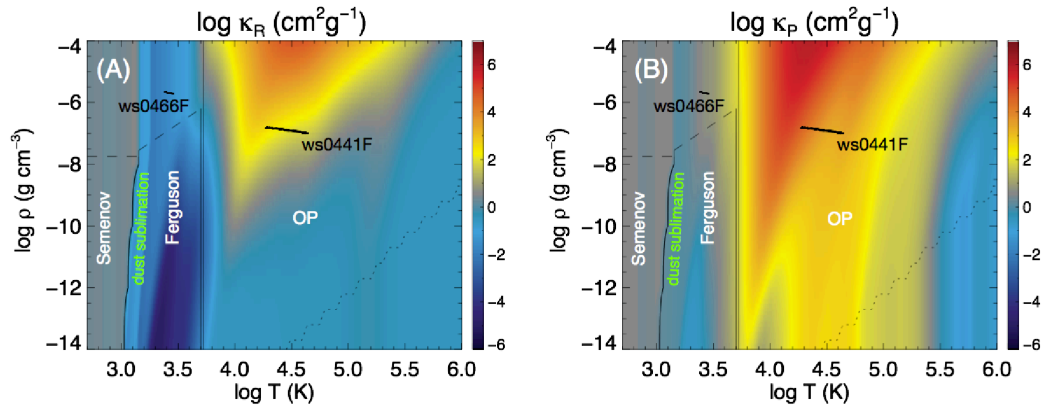
$\kappa^{\mathsf{P}} = \kappa^{\mathsf{P}}(\rho, T)$ Planck-mean opacity

Pre-computed EOS and Opacities

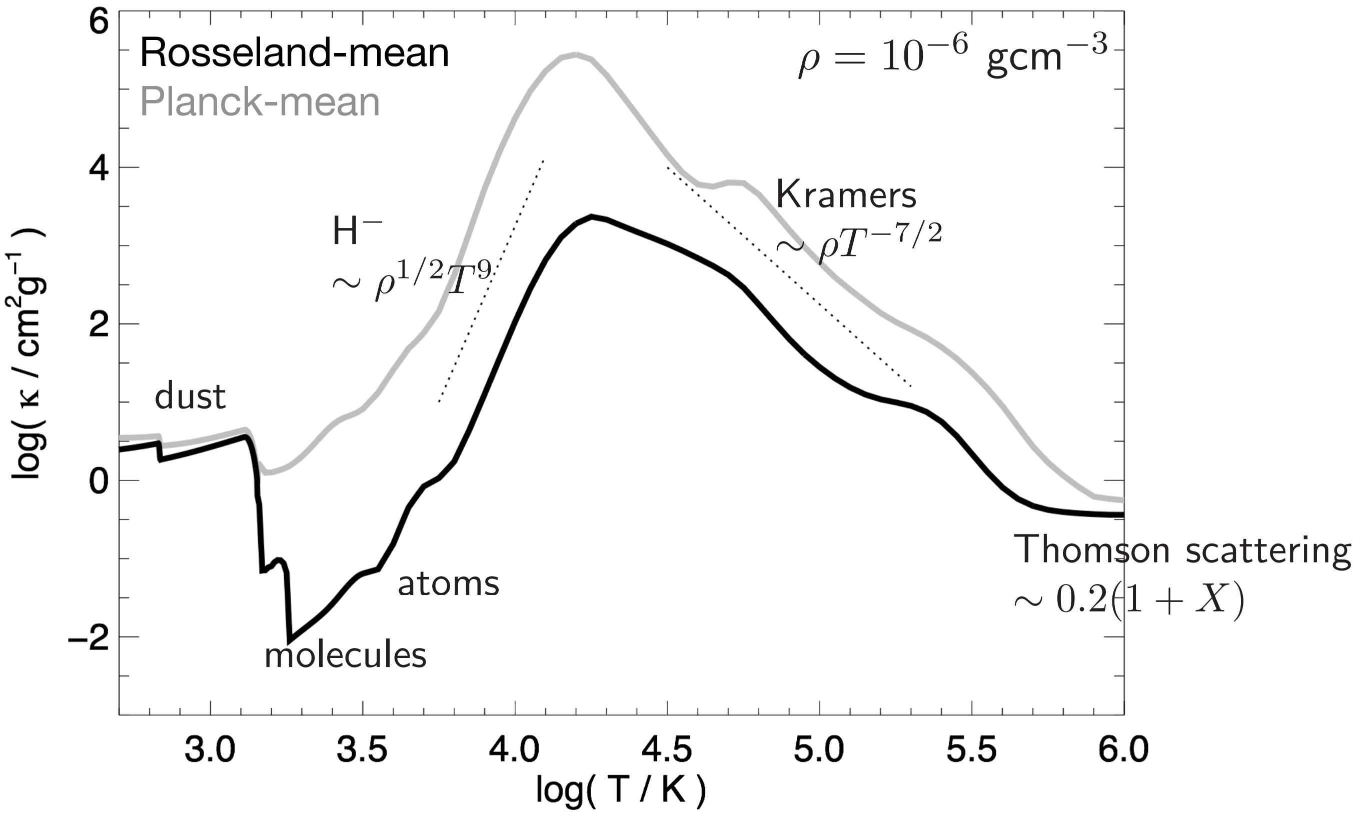
- EOS
  - Solar abundance
  - chemical equilibrium



- Mean opacities
  - Semenov+ 03
  - Ferguson+ 05
  - Opacity Project



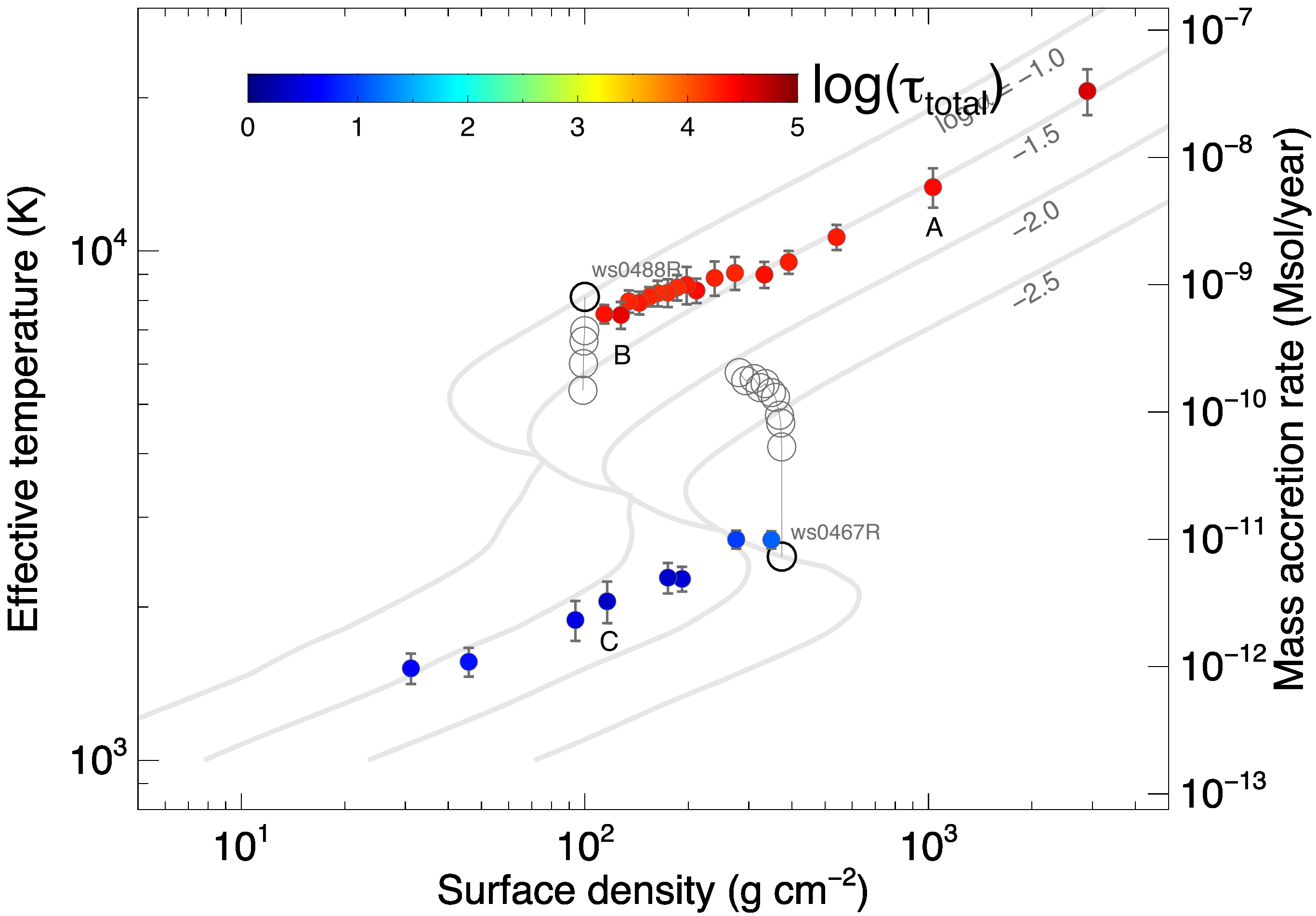
Temperature Dependence of Opacities



Opacities peak around $T = 10^4$K.

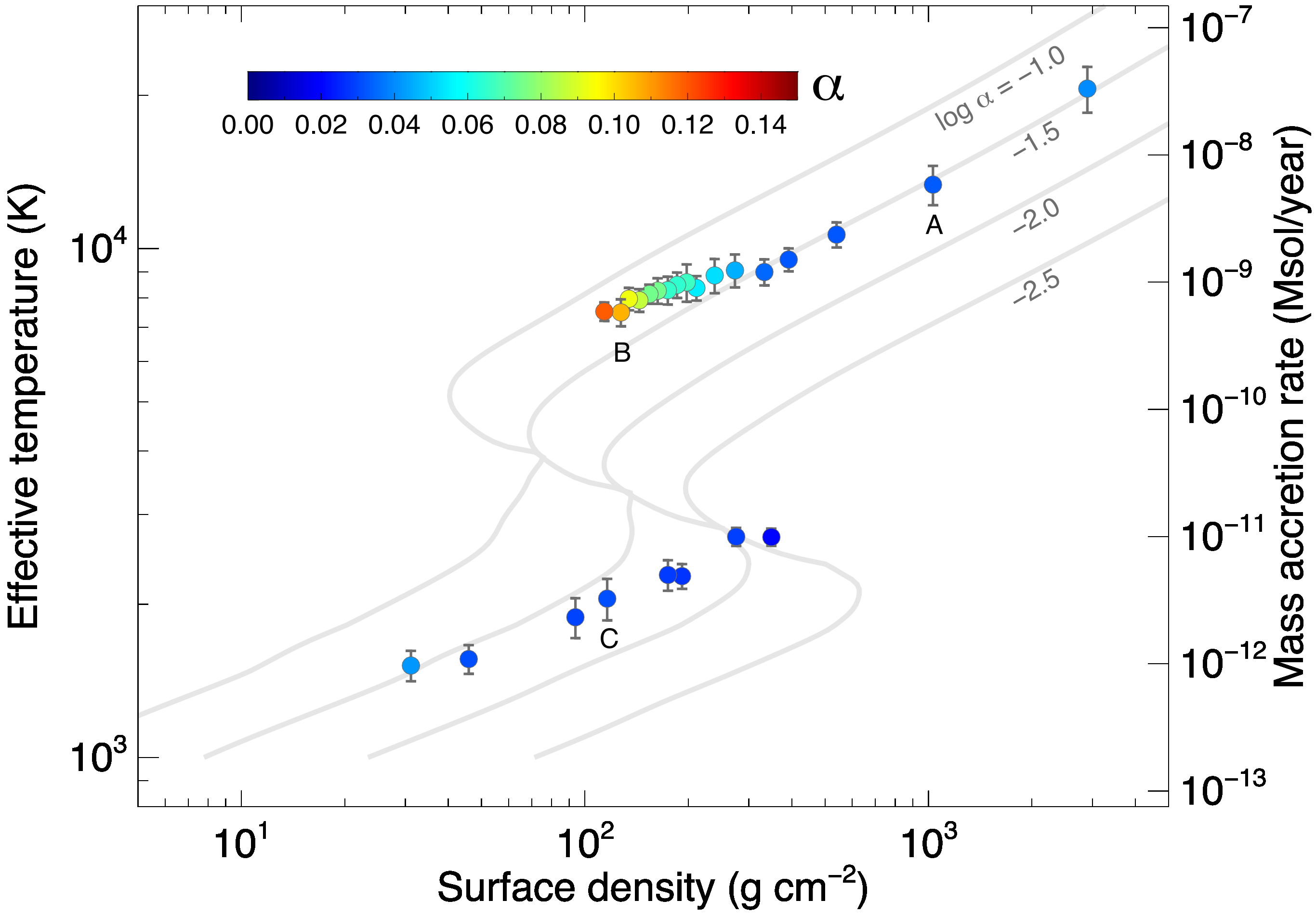
Thermal Equilibrium Curve

- Two solution branches are obtained:
  - upper hot branch with large optical thickness ($\tau_{\text{tot}} > 10^4$)
  - lower cool branch with small optical thickness ($\tau_{\text{tot}} < 10$)
- System shows bistability ($\Sigma_{\text{min}} = 100$ and $\Sigma_{\text{max}} = 350$ g cm^{-2}).
- (Anticlockwise) limit cycle is indicated.



Saturation Level of Turbulence (alpha = stress / pressure)

- Most solutions show typical values of MRI turbulence (~ 0.03).
- Solutions near the low–Σ end of the upper branch show larger values (up to ~ 0.12).



Vertical Profiles of Heat Fluxes

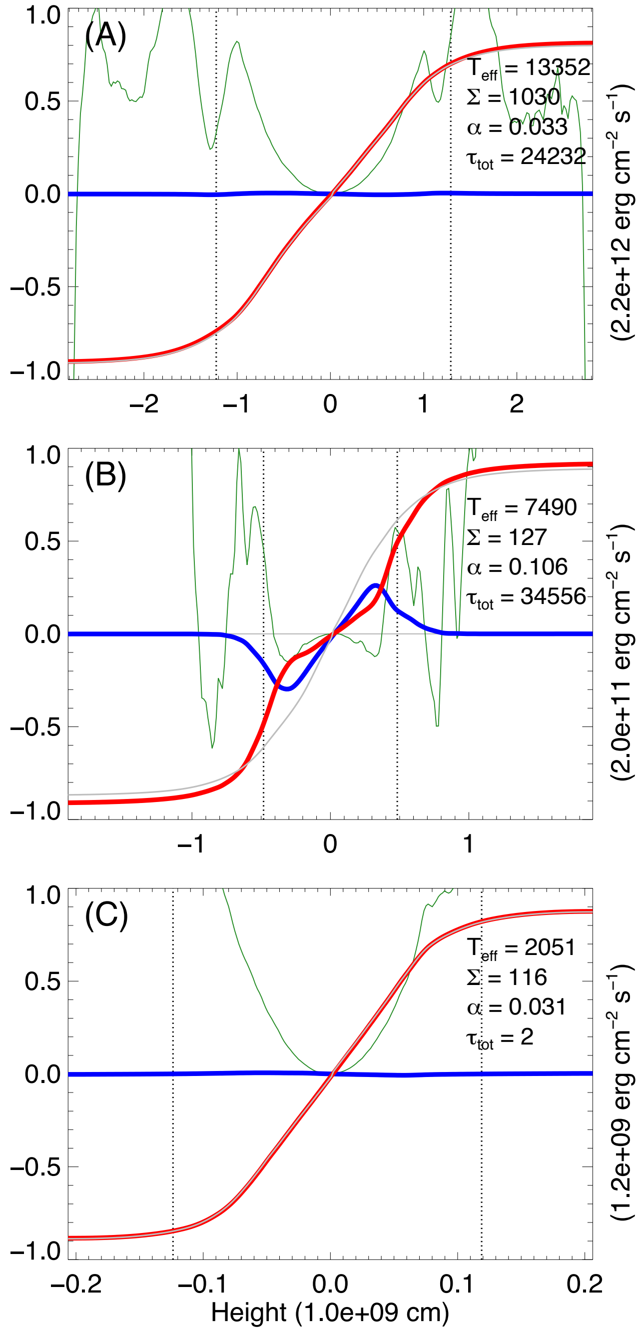
- Radiation and advection account for heat transport:

$$\bar{F}^{-}_{\mathrm{rad}}(z) \equiv [\langle F_z \rangle] \quad \text{radiation}$$

$$\bar{F}^{-}_{\mathrm{adv}}(z) \equiv [\langle (e+E) v_z \rangle] \quad \text{advection}$$

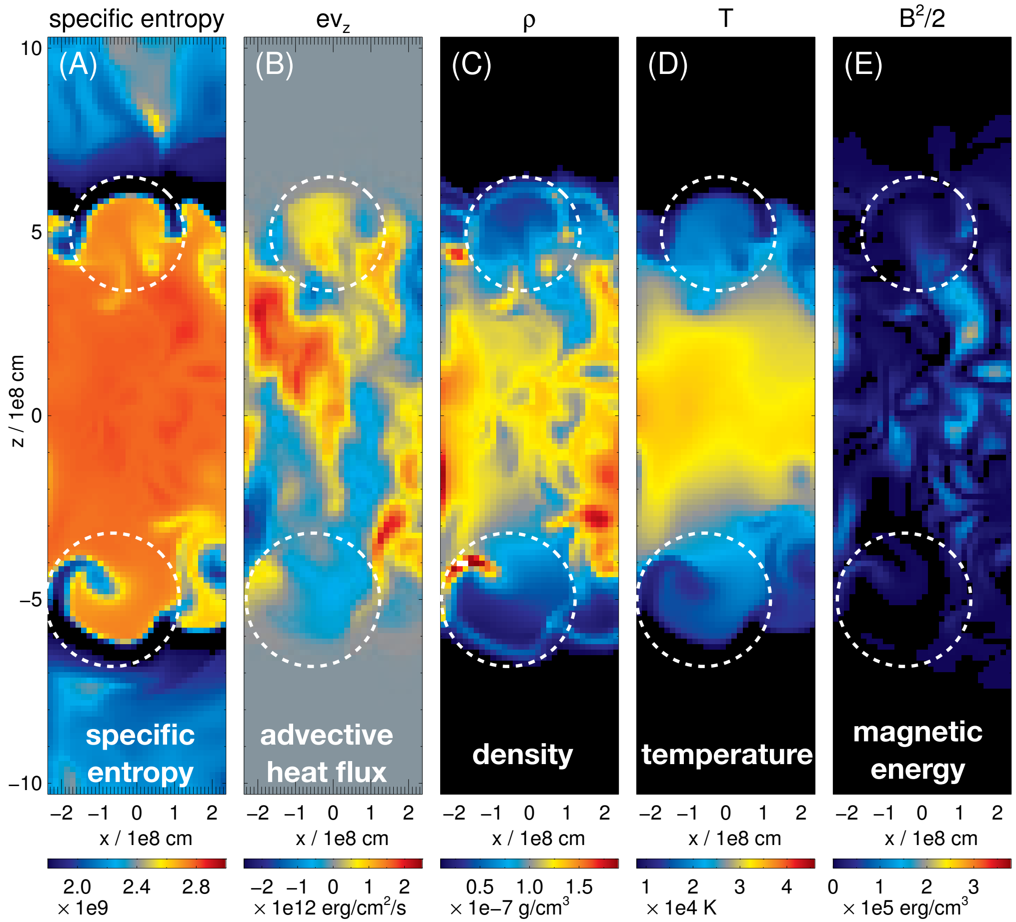
- Radiation carries heat when α is a typical value of MRI turbulence (solutions (A) and (C)).
- Advective cooling dominates near the midplane when α is large (solution (B)).
- Advective cooling is confirmed to be associated with thermal convection due to large opacities around $T = 10^4$K.

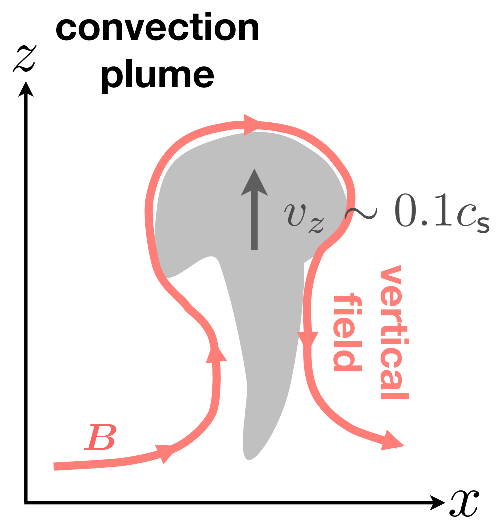
$$\frac{N^2}{\Omega^2} \equiv \frac{1}{[\langle \Gamma_1 \rangle]} \frac{d \ln [\langle p \rangle]}{d \ln z} - \frac{d \ln [\langle \rho \rangle]}{d \ln z}$$



Why α is enhanced by convection?

- Convective plumes create coherent vertical fields that seed axisymmetric MRI, which enhances turbulent stress and dissipation.
- Convection enhances cooling, which suppresses pressure increase due to the increased dissipation.

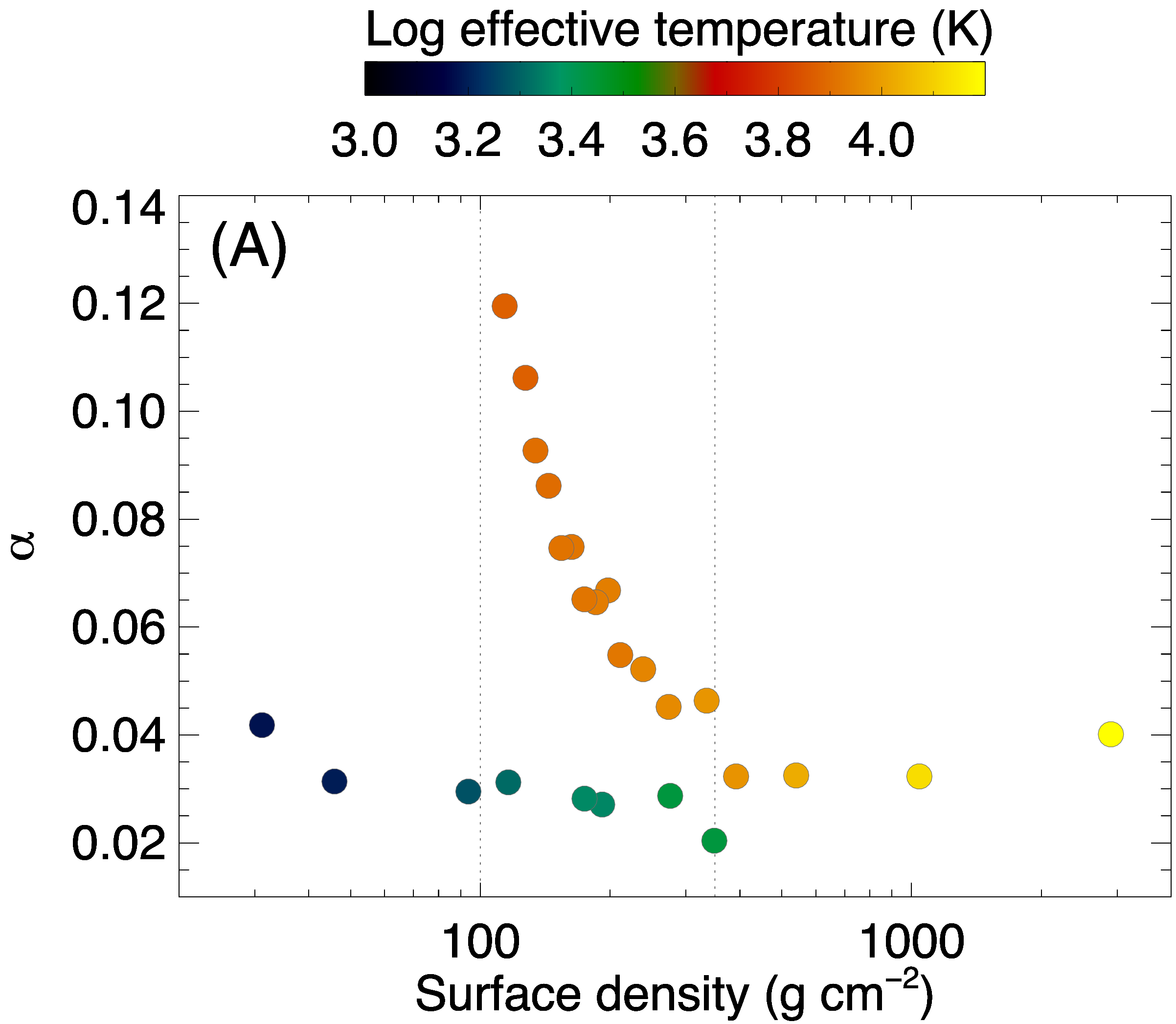




$$\alpha \equiv \frac{\text{turbulent stress}}{\text{pressure}}$$

Convection Causes Enhanced Magnetic Turbulence

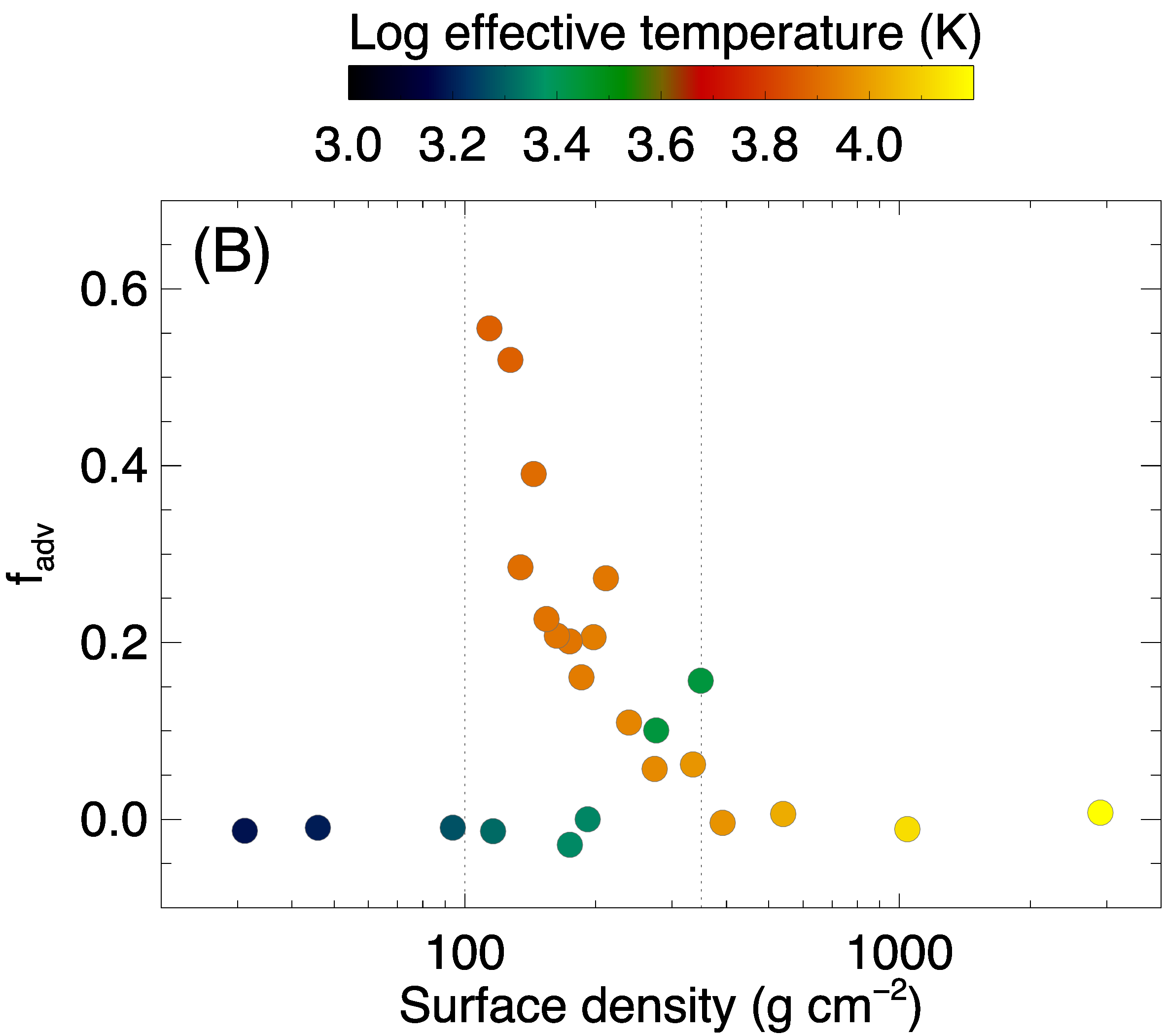
- The α value increases near the low Σ end of the upper branch.



Convection Causes Enhanced Magnetic Turbulence

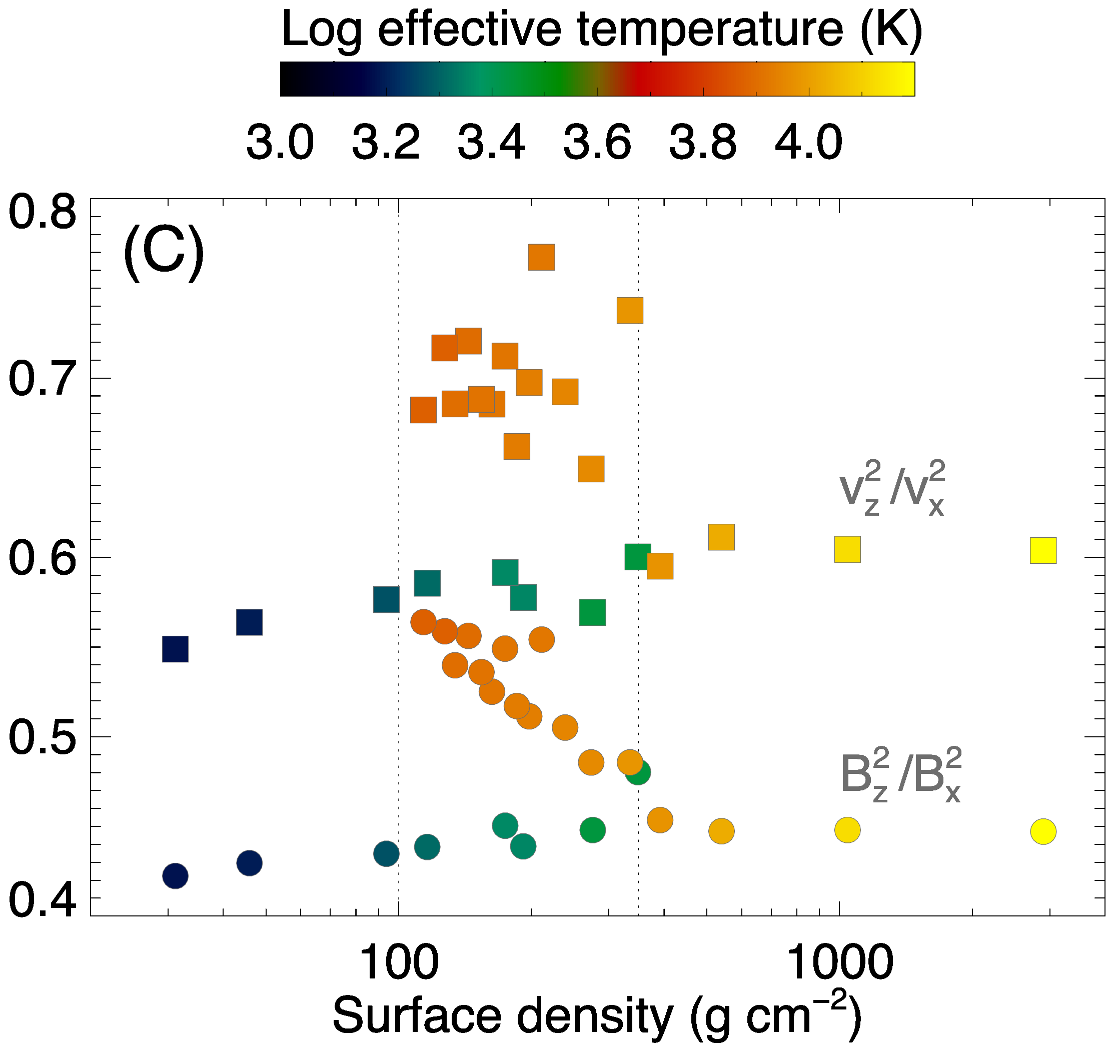
- The α value has a good correlation with f_{adv}.

$$\bar{f}_{\text{adv}} \equiv \frac{\int \left[\langle (e+E)\, v_z \rangle\right] \mathrm{sgn}(z) \left[\langle p_{\text{thermal}} \rangle\right] dz}{\int \left[\langle (e+E)\, v_z \rangle + \langle F_z \rangle\right] \mathrm{sgn}(z) \left[\langle p_{\text{thermal}} \rangle\right] dz}$$



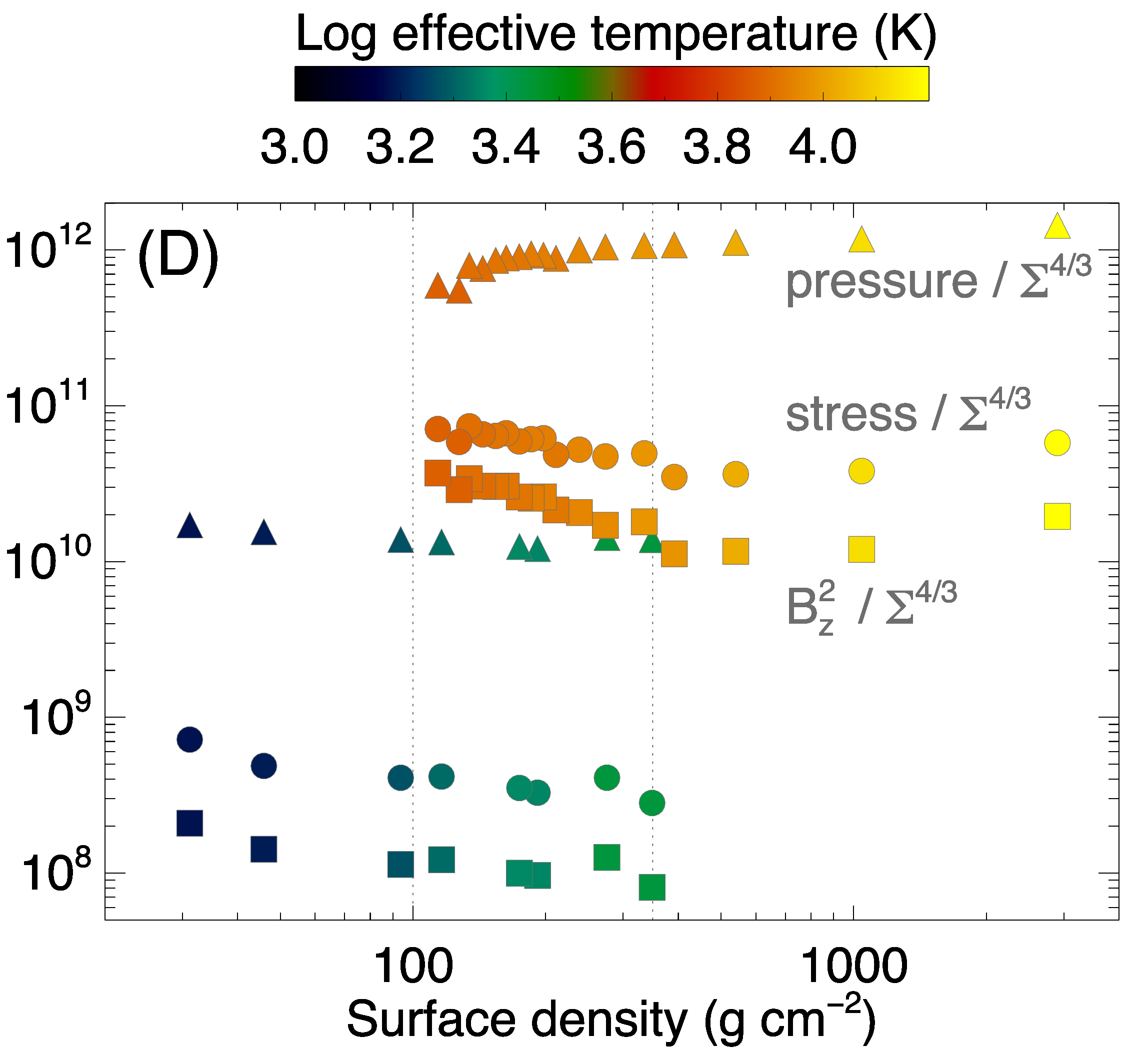
Convection Causes Enhanced Magnetic Turbulence

- $\langle V_z^2 \rangle$ and $\langle B_z^2 \rangle$ are strengthened when f_{adv} is large.



Convection Causes Enhanced Magnetic Turbulence

- Stress increases as $\langle B_z^2 \rangle$ does while pressure does not, hence $\alpha =$ stress / pressure increases.

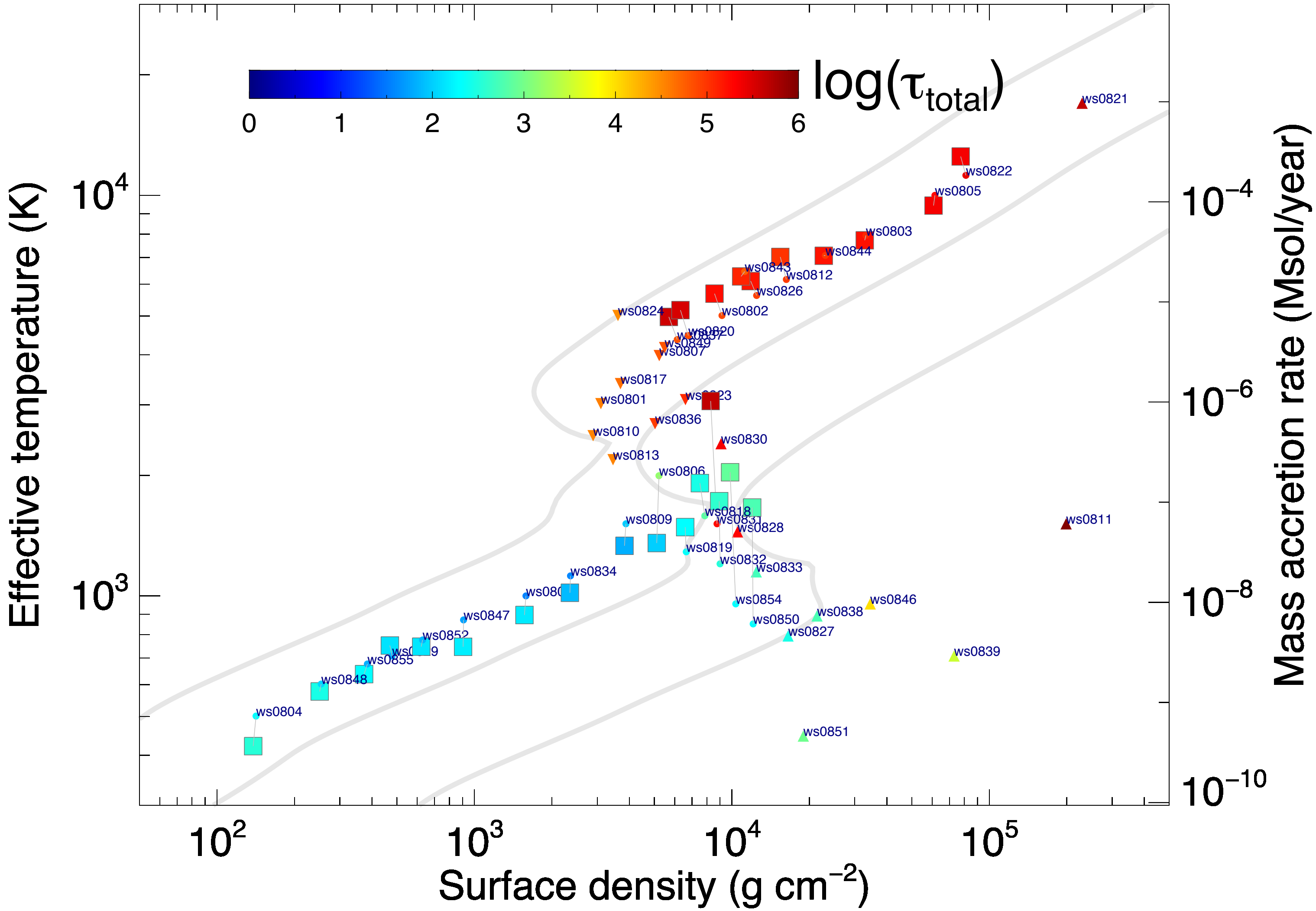


Summary 1

- Thermal equilibrium states in accretion disks with ionisation transitions are determined by 3D radiation MHD simulations using realistic opacities and EOS.
- Thermal equilibrium curve $\dot{M} = \dot{M}(\Sigma)$ that is consistent with DIM was obtained.
  - two stable solution branches
    - upper hot branch with large optical thickness ($> 10^4$)
    - lower cool branch with small optical thickness (< 10)
  - anti-clockwise limit cycle in the Σ–$\dot{M}$ plane
- α is significantly enhanced near the low-Σ end of the hot branch.
  - Strong convection necessarily occurs due to large opacities around the hydrogen ionization temperature $T \sim 10^4$K.
    - Convection creates vertical fields feeding axisymmetirc MRI to strengthen turbulent stress.
    - Pressure increase is suppressed by cooling enhanced by convection.
  - Large α in the outbursts can be naturally explained by MRI turbulence enhanced by thermal convection.

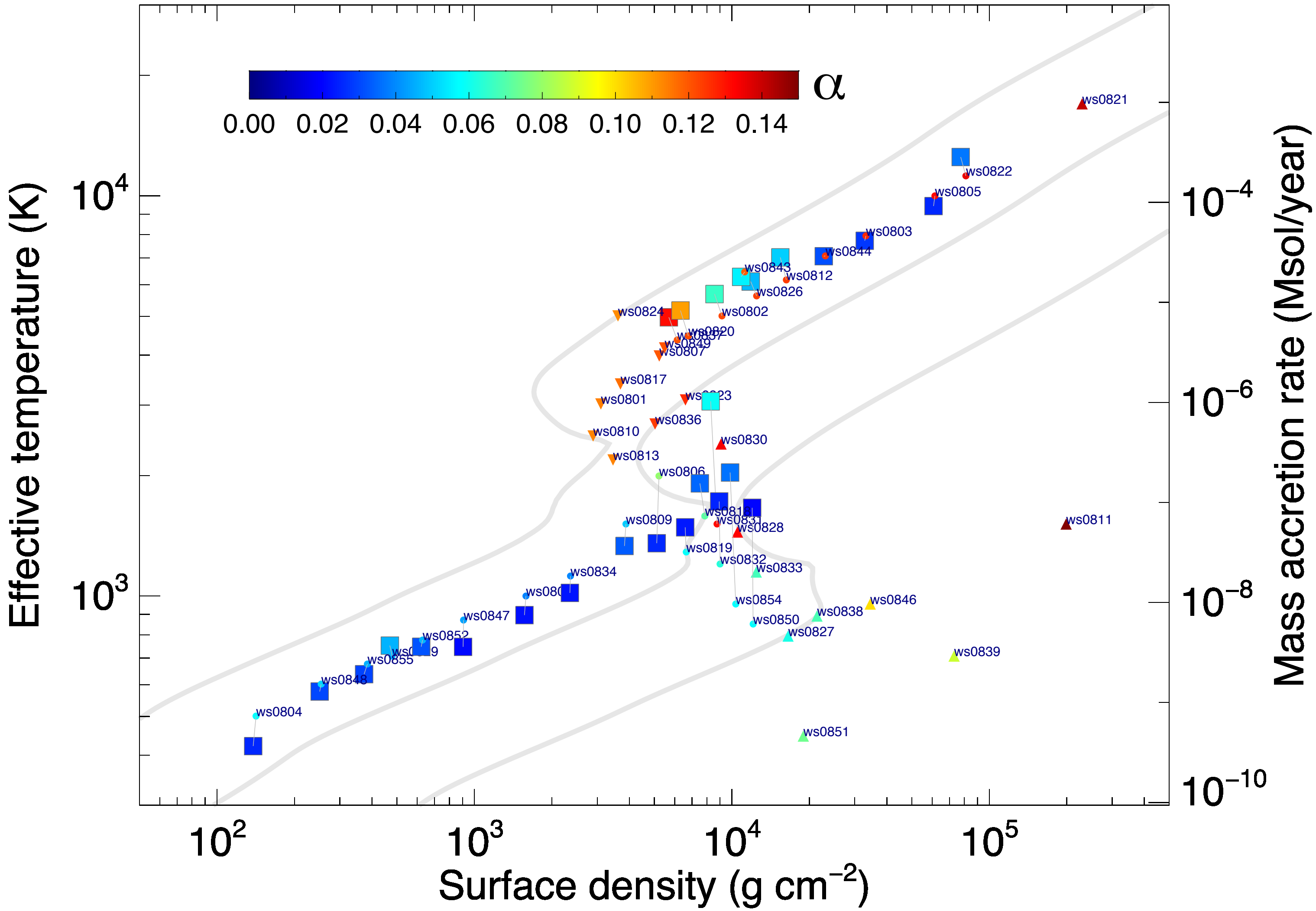
S-curve at 0.05 AU in a Protoplanetary Disk

- Hot, optically thick branch and cool, optically thin branch
- Smaller $\Sigma_{max}/\Sigma_{min}$



S-curve at 0.05 AU in a Protoplanetary Disk

- α enhanced at the low-Σ end of the upper branch (> 0.1)
- $\alpha \sim 0.03$ for others



Summary 2

- Two stable branches with smaller $\Sigma_{\text{max}}/\Sigma_{\text{min}}$
- $\alpha_{\text{hot}} \sim 0.1$ (enhanced by convection) and $\alpha_{\text{cool}} \sim 0.03$
  - $\alpha_{\text{hot}} \sim 10^{-3}$ and $\alpha_{\text{cool}} \sim 10^{-4}$ are required to explain light curves of FU Ori outbursts ($\tau_{\text{high}} \sim 10^2$yr and $\tau_{\text{FU}} \sim 10^3$yr).

TABLE 2

RESULTS OF OUTBURST MODELS

α_c	α_h	$\dot{M}_{\text{in}}$ ($10^{-6}\ M_\odot\ \text{yr}^{-1}$)	τ_{rise} (yr)	τ_{high} (yr)	τ_{FU} (yr)	$\dot{M}_{\text{FU}}$ ($10^{-6}\ M_\odot\ \text{yr}^{-1}$)	L_{bol}[a] ($L_\odot$)	T_{eff}[b] (K)
10^{-4}	10^{-3}	1	25	85	780	10	14	5600
	...	3	50	140	900	30	35	6800
		5	60	170	1050	40	60	7300
		10	80	250	1150	50	85	8000
10^{-4}	3×10^{-4}	3	90	270	700	7	11	5000
10^{-3}	10^{-2}	3	6	12	160	40	65	8500

[a] The bolometric luminosity given is the peak during outburst and includes radiation from only one surface of the disk.

[b] Temperature is the maximum value during outburst.

from Bell & Lin 94

- Another mechanisms (non-ideal MHD effects and gravitational instability) are proposed to reproduce outburst cycles (e.g. Armitage+ 01, Zhu+ 09).
- Need to include the stellar irradiation, non-thermal ionization, and B_z