Gravito-turbulence in Irradiated Protoplanetary Disks

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Confronting MHD Theories of Accretion Disks with Observations
KITP

Outline

1. Gravitational instability (GI) in accretion disks

2. Shearing box simulations of GI at 50 AU in irradiated protoplanetary disks
   (SH and Shi, in review)

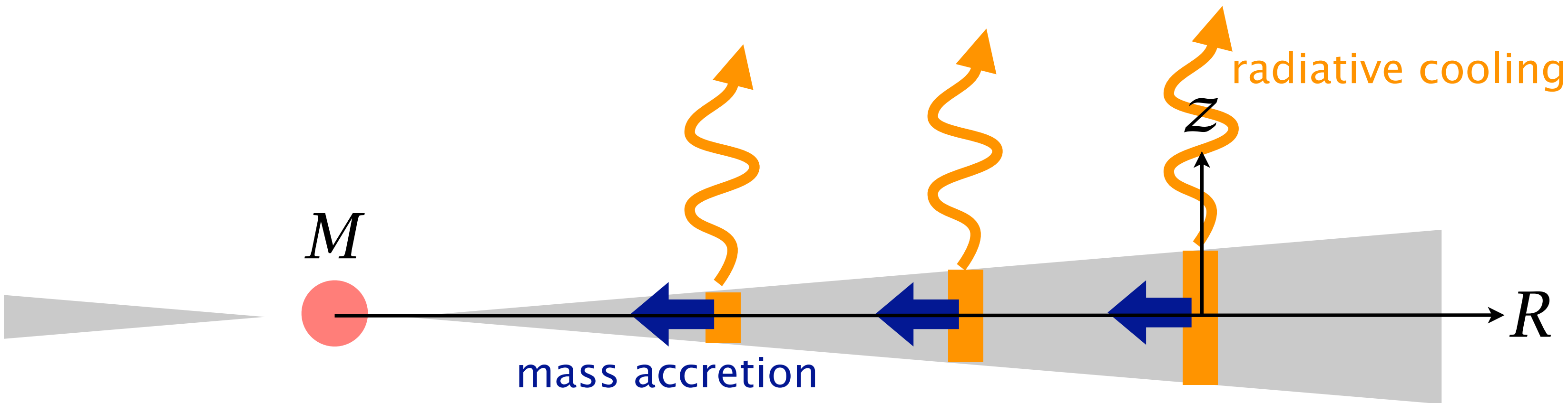
3. Radial dependence of GI in irradiated protoplanetary disks
   (SH and Shi, in preparation)

Angular momentum transport in accretion disks

- The evolution equation of surface density $\Sigma(r,t)$ is written as

$$\frac{\partial \Sigma}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{2}{r\Omega}\frac{\partial}{\partial r}\left(r^2 W_{r\phi}\right)\right) = 0$$

- If shear stress is locally determined as $W_{r\phi}(\Sigma; r)$, the evolution equation can be solved as a diffusion equation.



Origin of shear stress in accretion disks

$$W_{r\phi} = \int \langle -B_r B_\phi \rangle \, dz + \int \langle \rho v_r \delta v_\phi \rangle \, dz + \int \left\langle \frac{g_r g_\phi}{4\pi G} \right\rangle dz$$

Maxwell stress

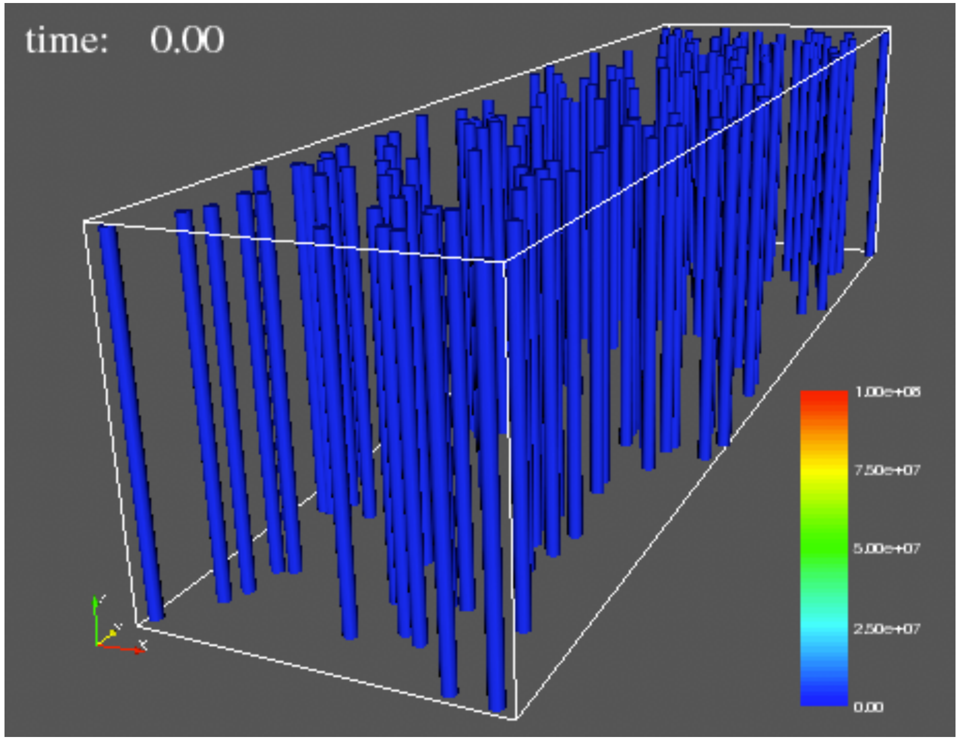
magneto-rotational instability (MRI)
dΩ / dr < 0

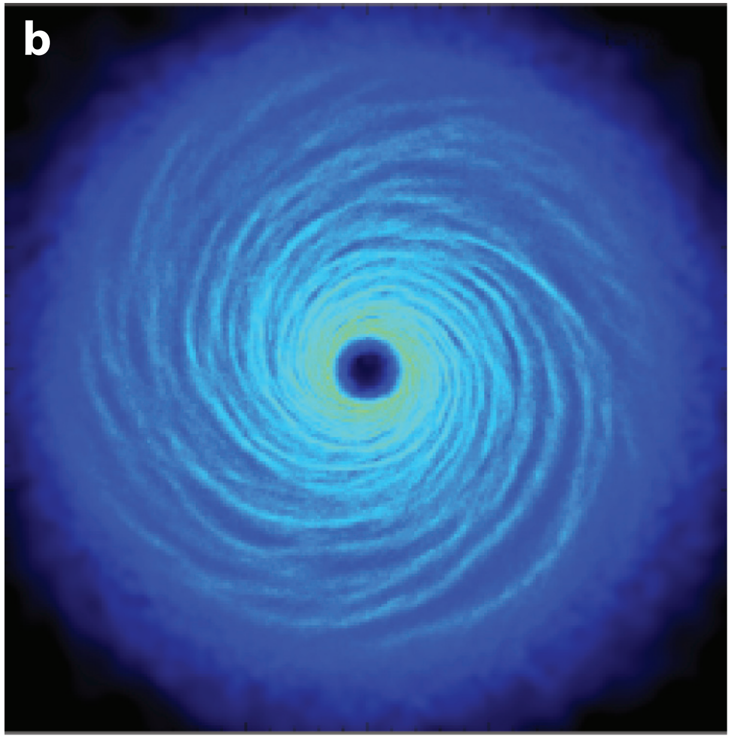
Reynolds stress

vertical shear instability, …

gravitational stress

gravitational instability (GI)
Q < 1





Kratter and Lodato (2016)

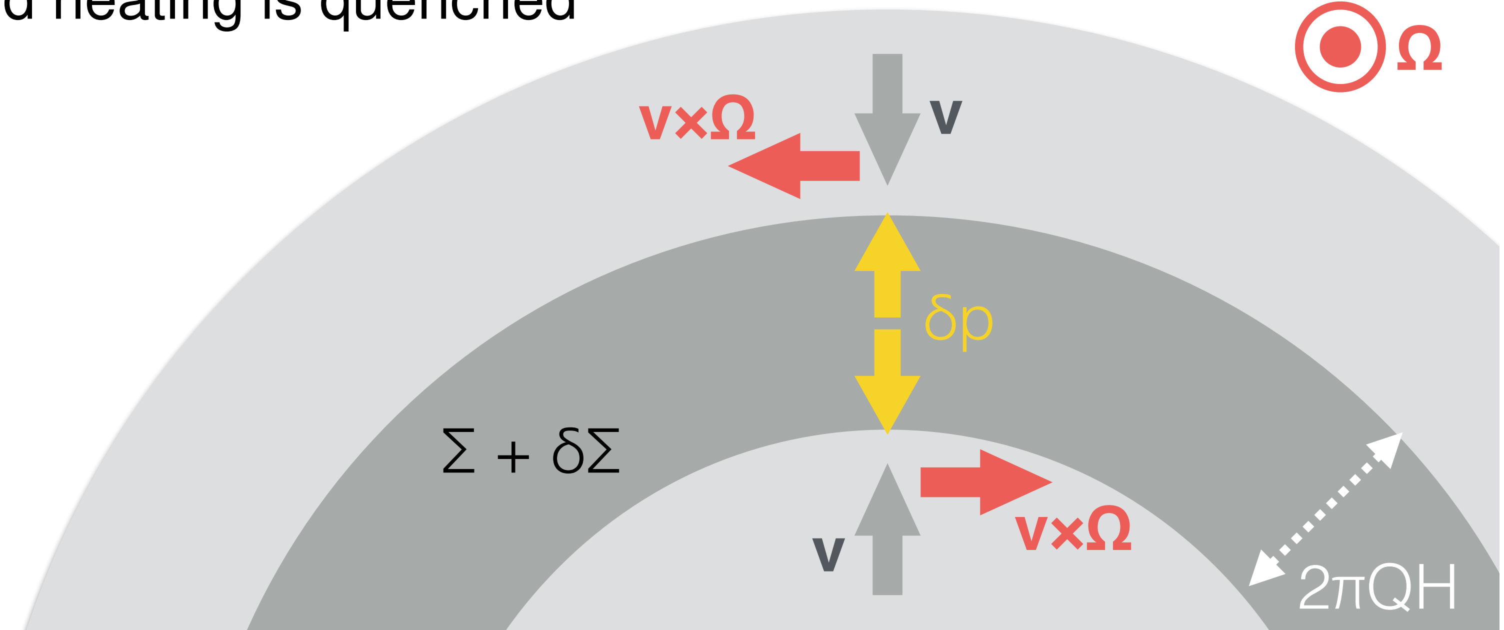
Gravitational instability in accretion disks

- Instability condition for the axisymmetric mode in infinitesimally thin disks (Toomre 1964)

$$Q \equiv \frac{c_s \Omega}{\pi G \Sigma} < 1$$

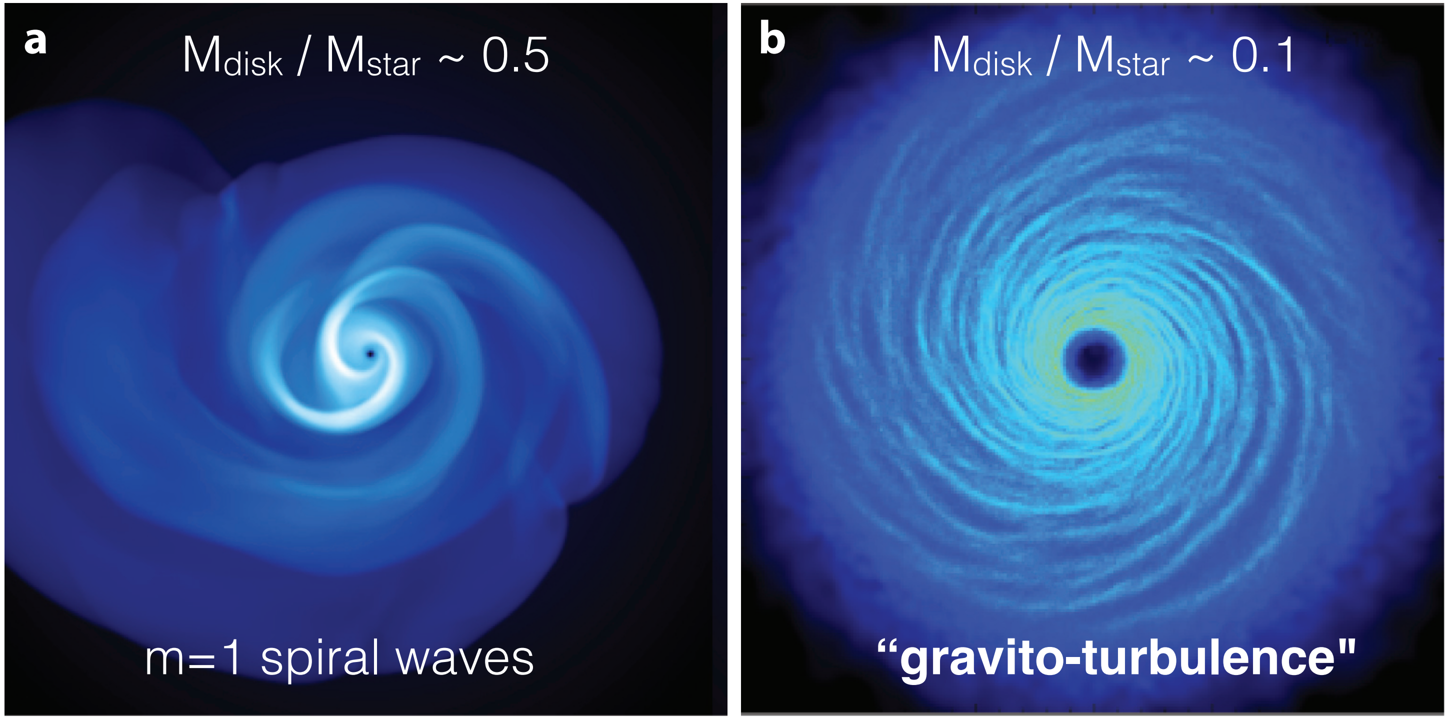
- Q tends to be self-regulated to ~ 1 (Paczynski 1978)

  1. $Q < 1$: GI and heating sets in
  2. T increases if heating overcomes cooling
  3. $Q > 1$: GI and heating is quenched
  4. T decreases
  5. $\rightarrow 1$



Angular mom. transport by GI depends on M_{disk} / M_{star}

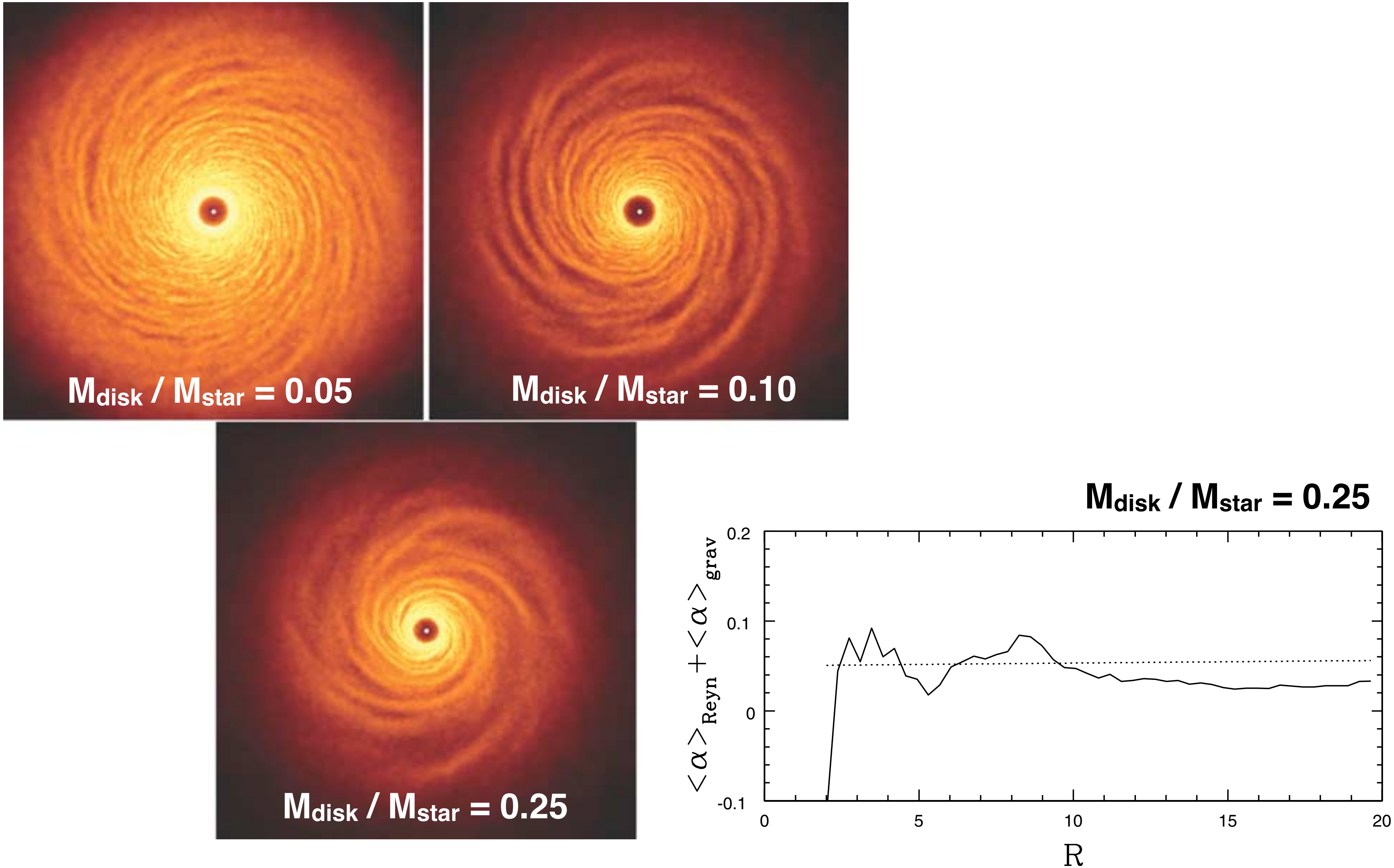
Kratter and Lodato (2016)



M_{disk} / M_{star}	large	**small**
angular mom. transport	non-local	**local**

Locality of angular momentum transport

- Transport is local when $M_{\text{disk}}/M_{\text{star}} \leq 0.25$ (Lodato & Rice 2005)



Lodato and Rice (2005)

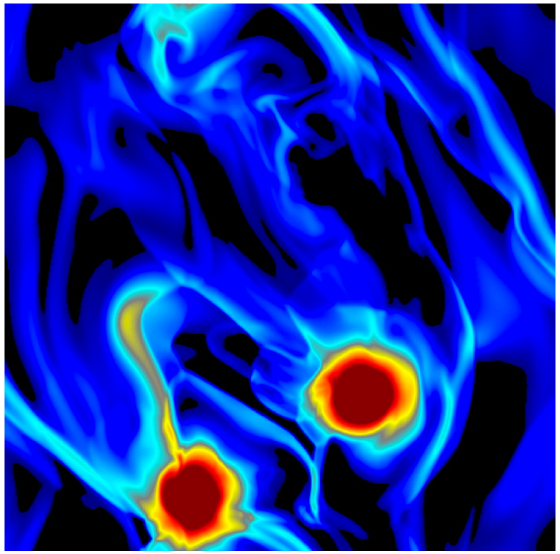
Gravito-turbulence vs. fragmentation

- Using a simple cooling function with β being constant cooling time

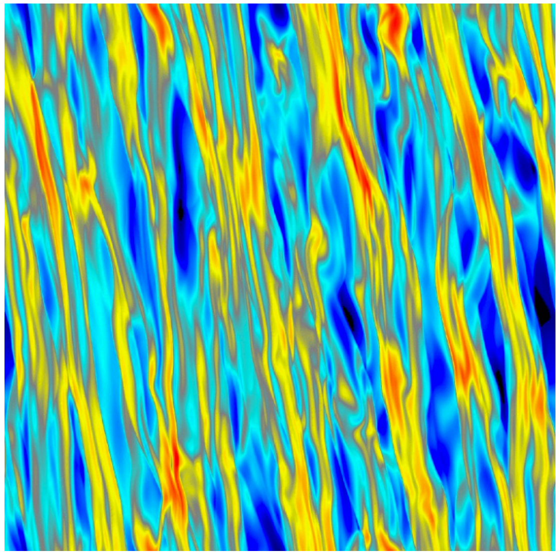
$$\frac{\partial e}{\partial t} = -\frac{e}{\beta \Omega^{-1}},$$

Gammie (2001) found for 2D (razor thin) disks of $\gamma = 2$

$$\begin{cases} \beta > 3 & \text{gravito-turbulence with } Q \sim 1 \\ \beta < 3 & \text{fragmentation.} \end{cases}$$



β = 2
(strong cooling)



β = 10
(weak cooling)

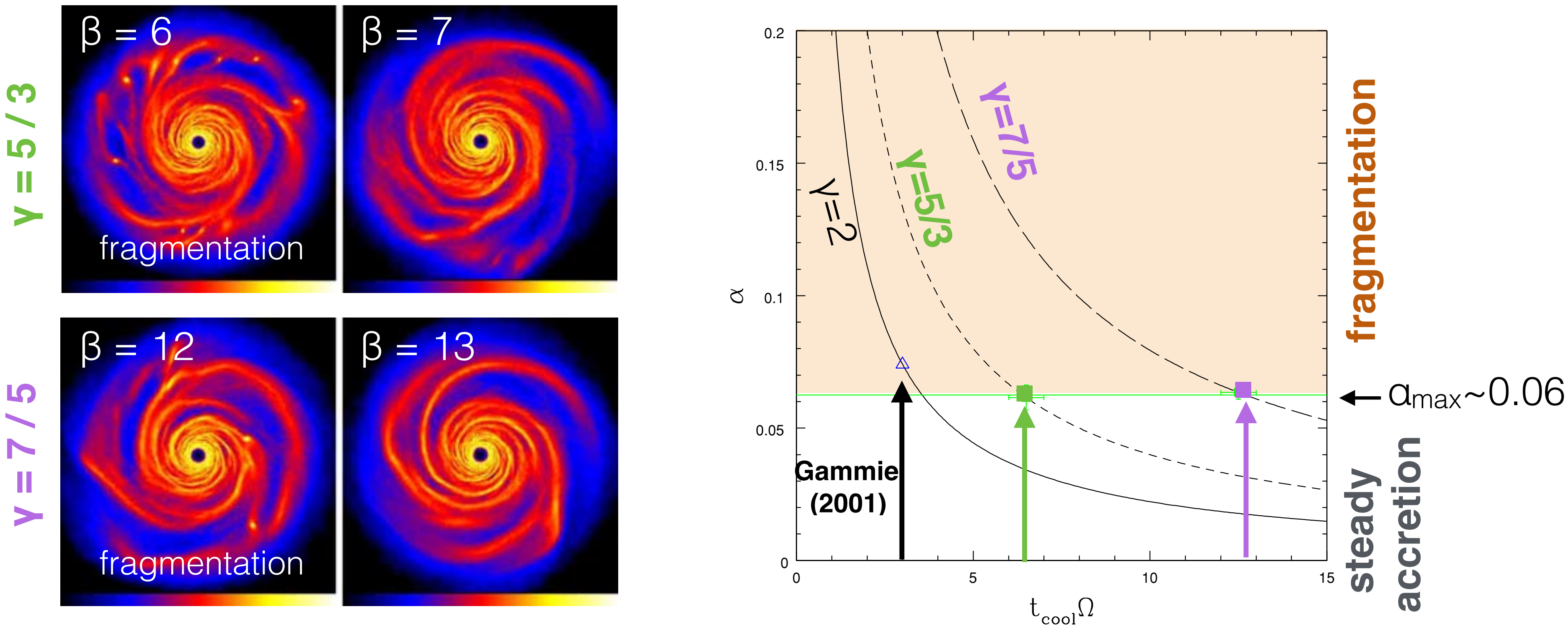
Gammie (2001)

Fragmentation criterion in terms of α

- In thermal equilibrium where the β cooling equals the α dissipation,

$$\alpha = \frac{4}{9}\frac{1}{\gamma(\gamma-1)\beta}$$

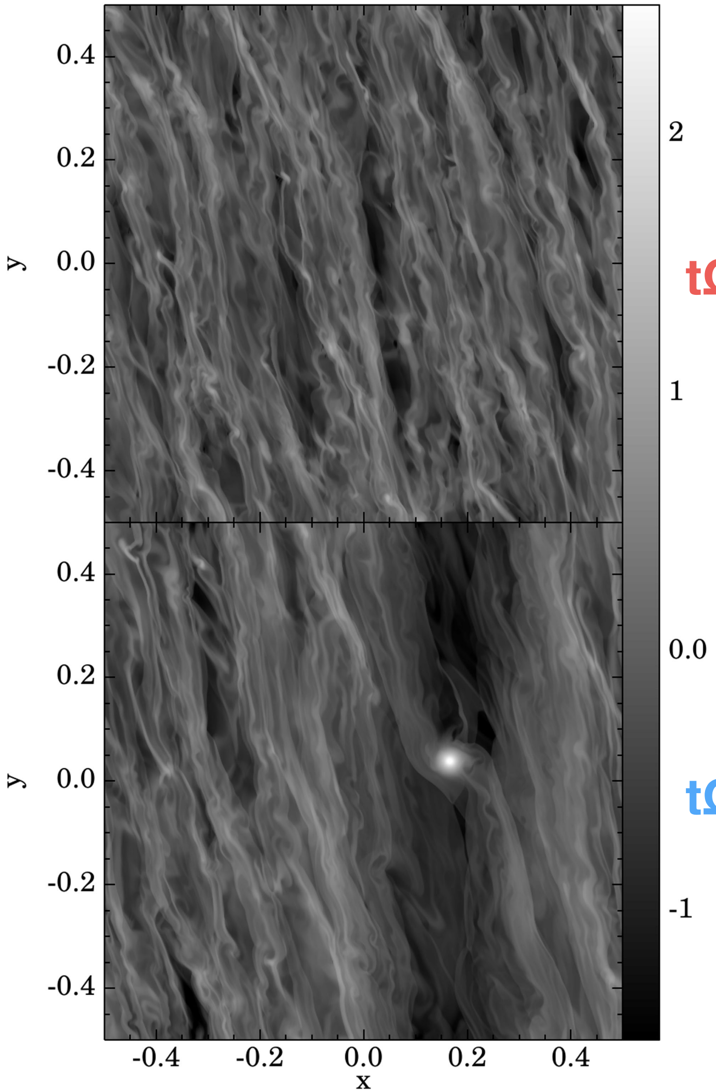
- Gravito-turbulence of $\alpha > \alpha_{\mathrm{max}} \sim 0.06$ cannot be sustained (Rice, Lodato & Armitage 2005).



Rice, Lodato and Armitage (2005)

No solid fragmentation criterion?

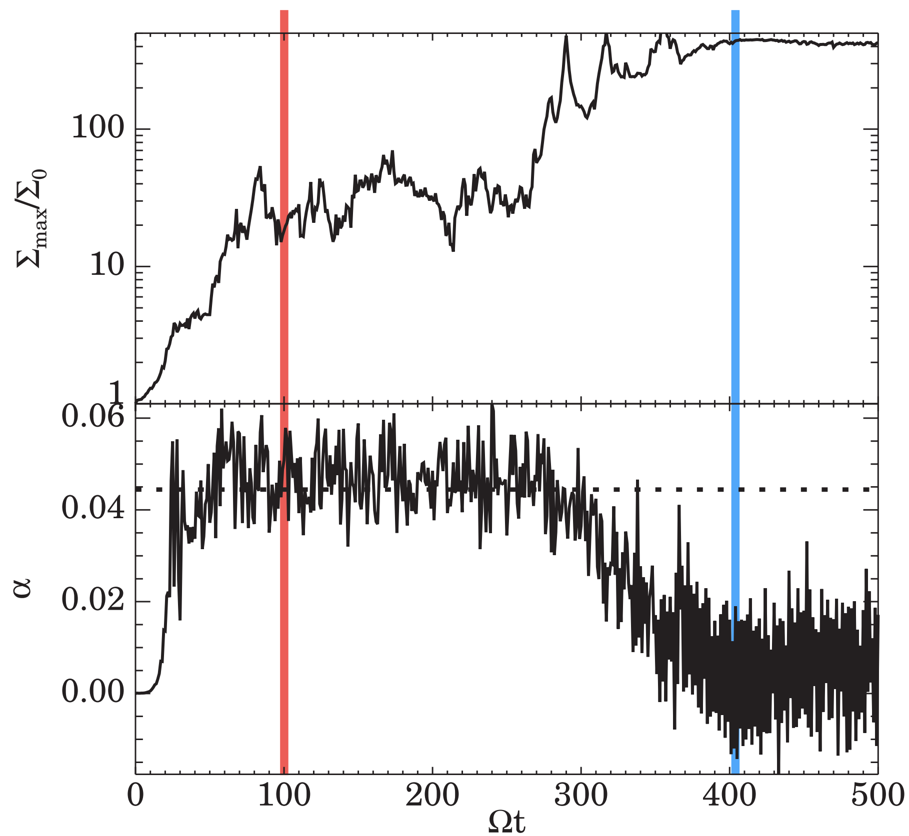
- Fragmentation is stochastic since shock heating is very localized.
- Fragmentation becomes increasingly rare for larger β.



tΩ = 100

tΩ = 400

β = 5



Paardekooper (2012)

Key parameters in GI in accretion disks

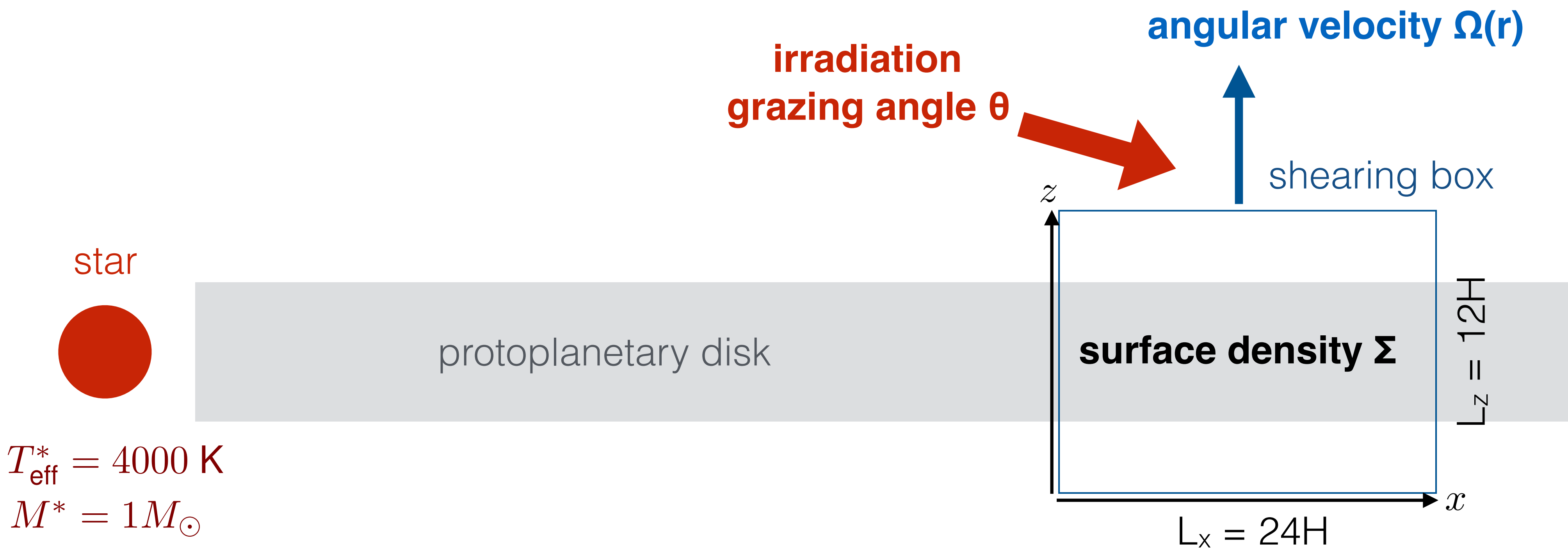
- Toomre parameter $Q \equiv \dfrac{c_\mathrm{s}\Omega}{\pi G \Sigma}$
  - self-regulated to $Q \sim 1$
- disk-star mass ratio $M_\mathrm{disk}/M_\mathrm{star}$ and angular momentum transport
  - local for small $M_\mathrm{disk}/M_\mathrm{star}$ and global for large $M_\mathrm{disk}/M_\mathrm{star}$
- cooling time $\beta \equiv t_\mathrm{cool}\Omega$
  - fragmentation criterion: $\beta_\mathrm{min} = 3$ for $\gamma = 2$ ($\alpha_\mathrm{max} = 0.06$)
  - no solid criterion due to stochastic fragmentation?

Our approach to GI in accretion disks

- Toomre parameter $Q \equiv \frac{c_\mathrm{s}\Omega}{\pi G \Sigma}$
  - self-regulated to $Q \sim 1$
- disk-star mass ratio $M_\mathrm{disk}/M_\mathrm{star}$ and angular momentum transport
  - local for small $M_\mathrm{disk}/M_\mathrm{star}$ $\rightarrow$ shearing box simulations
- ~~cooling time $\beta \equiv t_\mathrm{cool}\Omega$~~ $\rightarrow$ realistic thermodynamics with irradiation
  - fragmentation criterion: $\beta_\mathrm{min} = 3$ for $\gamma = 2$ ($\alpha_\mathrm{max} = 0.06$)
  - no solid criterion due to stochastic fragmentation?
- 3D — vertical stratification

Purpose of this study and simulation setup

- to explore nonlinear outcome of GI in irradiated protoplaneatary disks
  - nature of gravito-turbulence
  - fragmentation criterion
- using 3D stratified shearing box simulations
  - realistic thermodynamics (opacities and equation of state)
  - irradiation



Basic equations

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

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \boldsymbol{v}) = -\nabla p - \rho \nabla \Phi + \frac{\kappa_{\mathsf{R}} \rho}{c} \boldsymbol{F},$$ momentum eq.

$$\frac{\partial e}{\partial t} + \nabla \cdot (e \boldsymbol{v}) = -(\nabla \cdot \boldsymbol{v}) p - (4\pi B(T) - cE)\, \kappa_{\mathsf{P}} \rho,$$ gas energy eq.

$$\frac{\partial E}{\partial t} + \nabla \cdot (E \boldsymbol{v}) = -\nabla \boldsymbol{v} : \mathsf{P} + (4\pi B(T) - cE)\, \kappa_{\mathsf{P}} \rho - \nabla \cdot \boldsymbol{F},$$ rad. energy eq.

solved time-implicitly

$$\boldsymbol{F} = -\frac{c\lambda}{\kappa_{\mathsf{R}} \rho} \nabla E,$$ FLD approx.

$$\nabla^2 \Phi = 4\pi G \rho.$$ Poisson eq.

Fiducial run

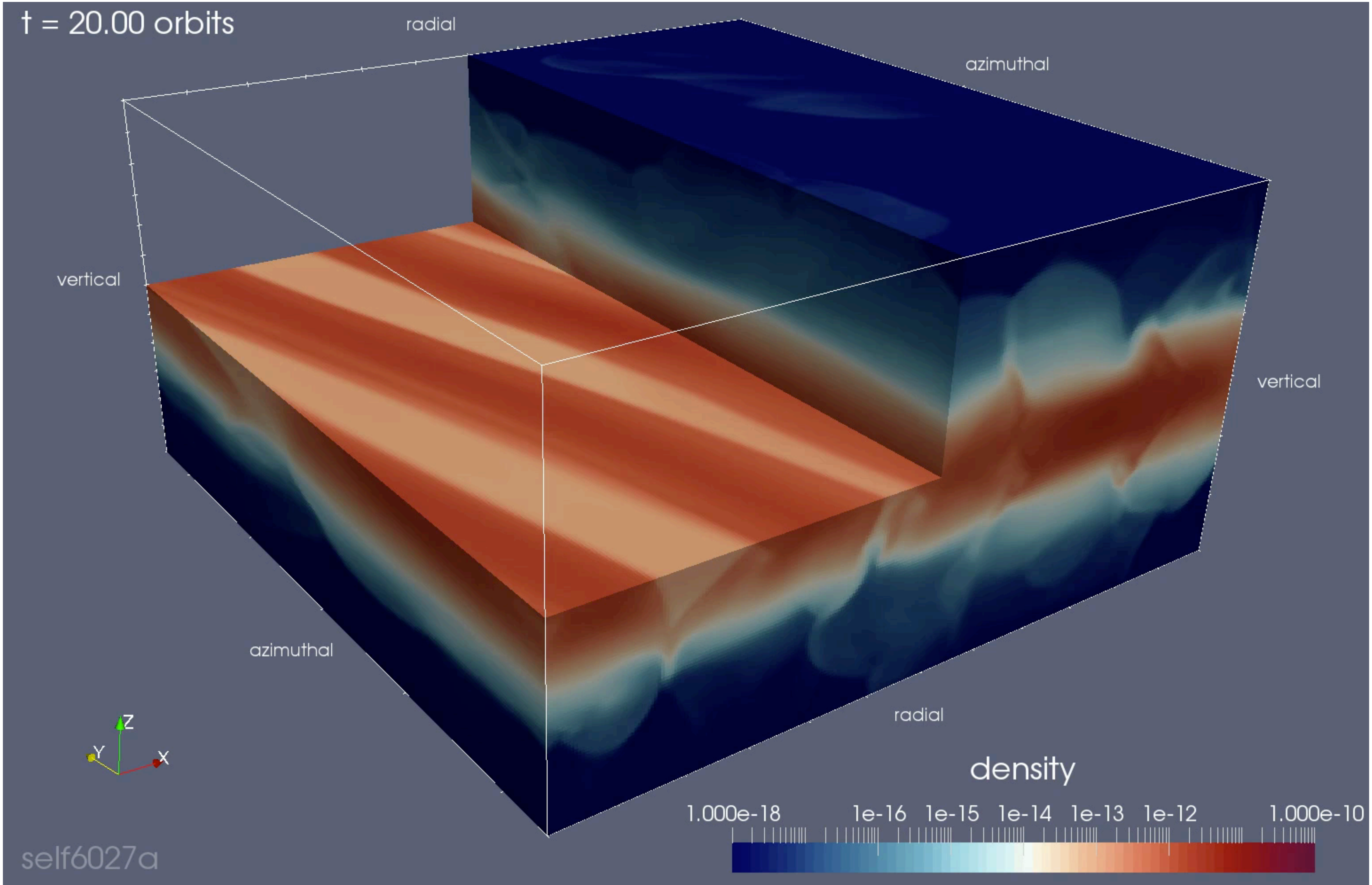
$\theta = 0.02$

$r = 50AU$

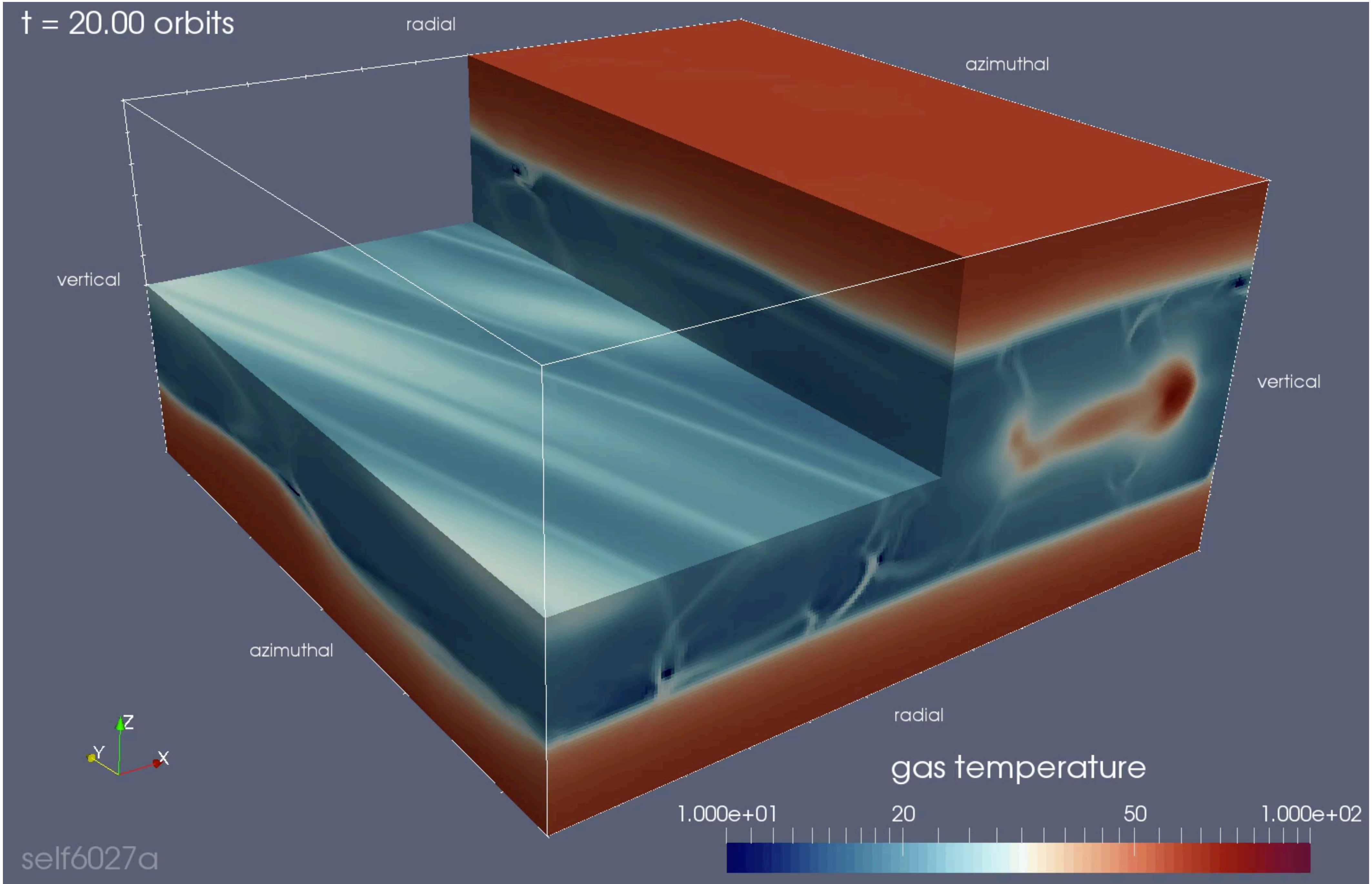
$\Sigma = 100\ gcm^{-3}$

$(M_{disk} / M_{star} \sim 0.09)$

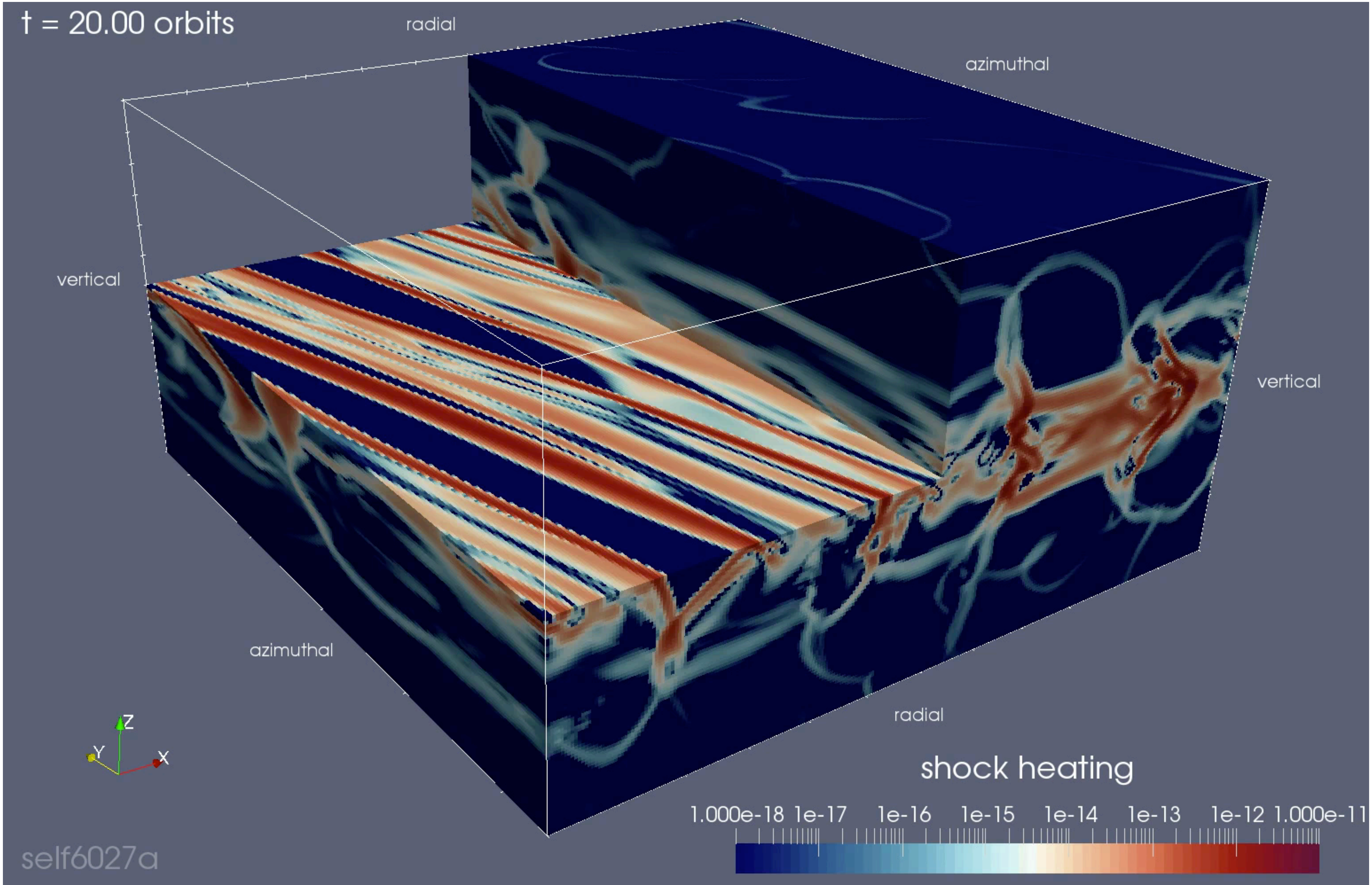
Gravito-turbulence



Gravito-turbulence

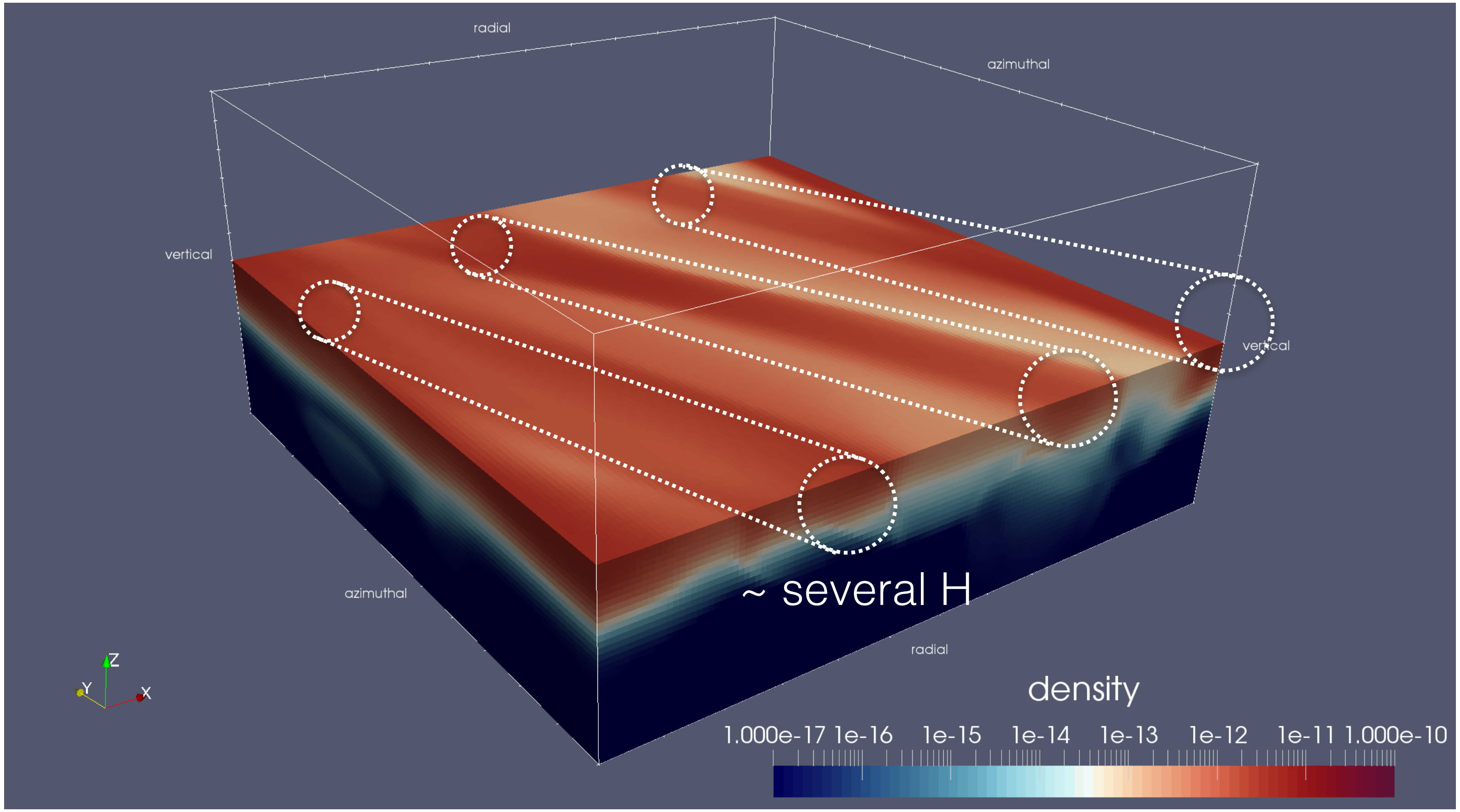


Gravito-turbulence

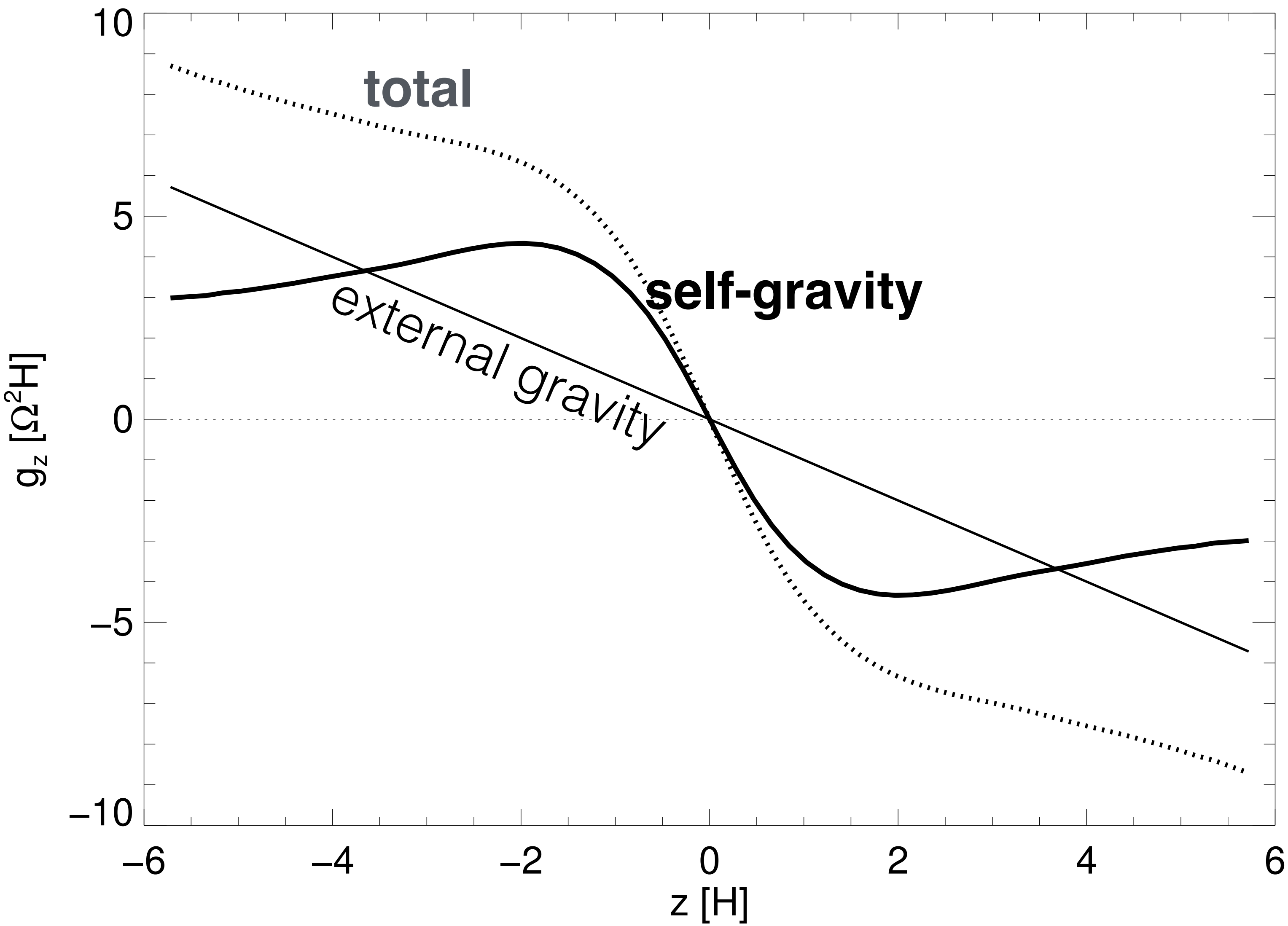


Gravito-turbulence is not usual “turbulence”

- There is no apparent turbulent cascade with energy dissipation occuring on the smallest scales.
- GI repeatedly excites density waves, which dissipate through shock waves and compressional heating.

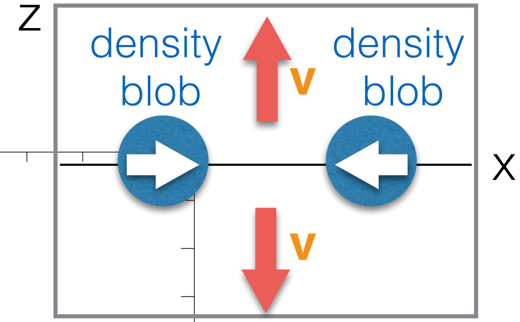


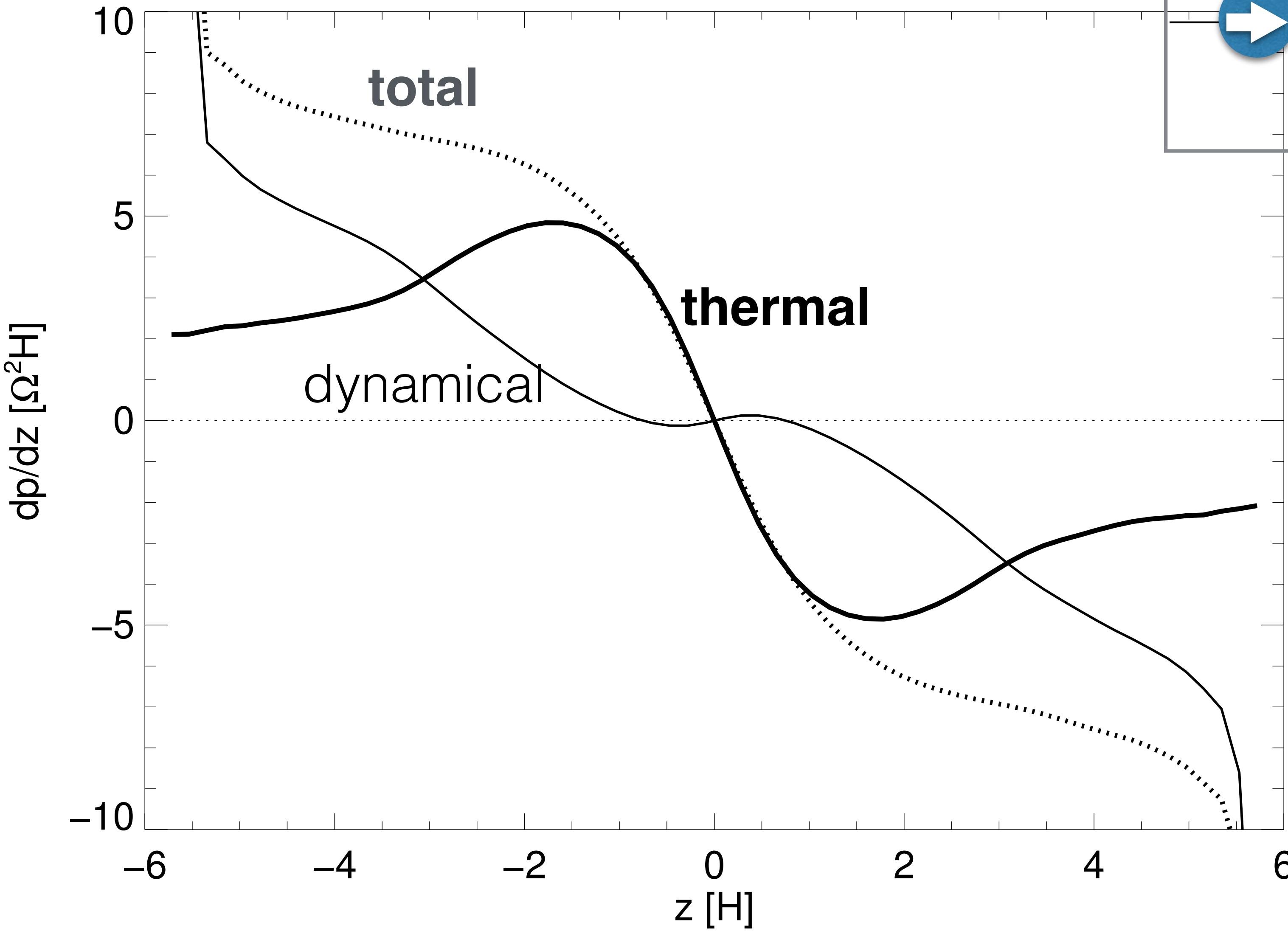
Hydrostatic balance (gravitational accelerations)



self6000: 20 – 100

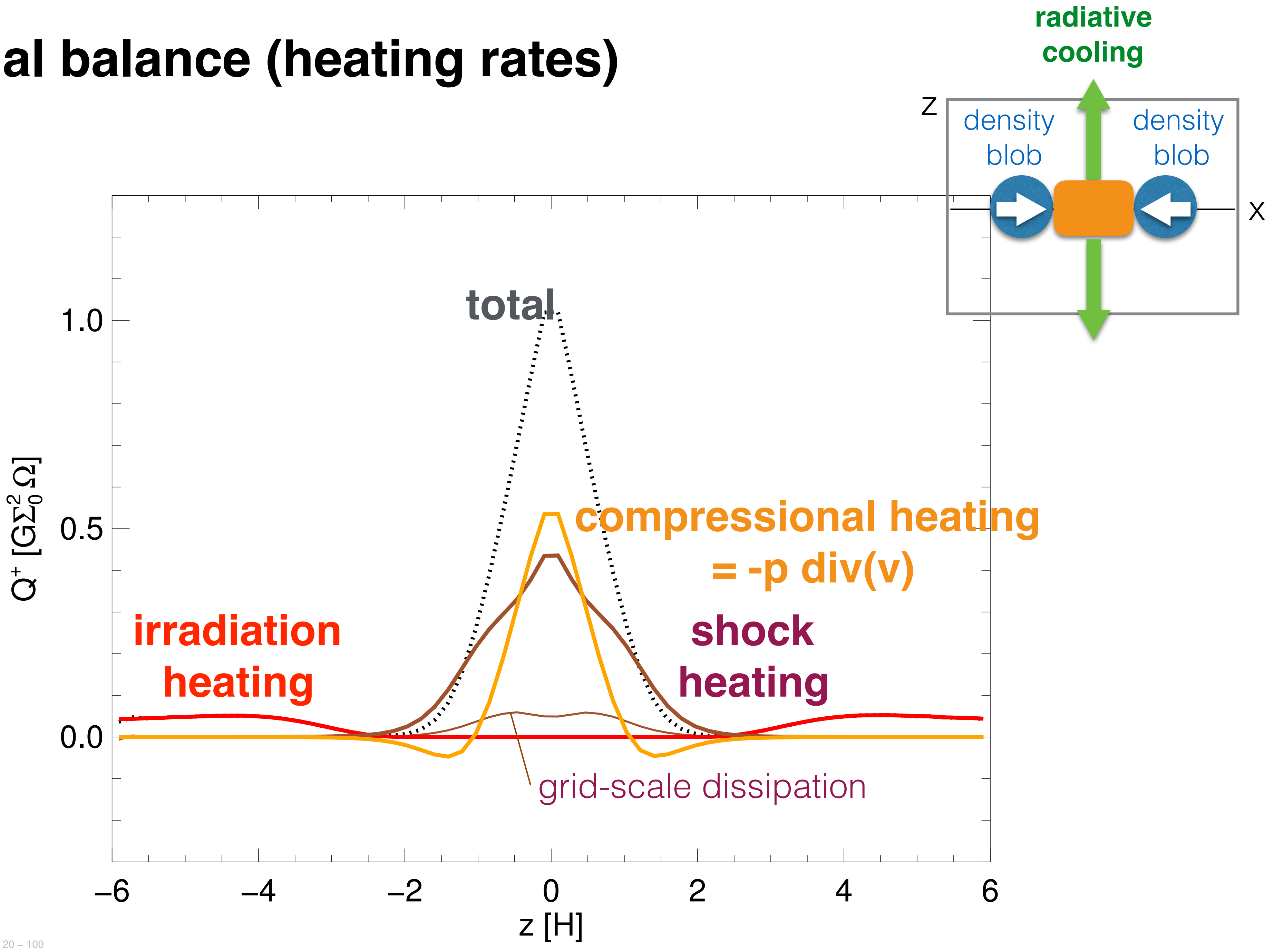
Hydrostatic balance (pressure gradients)



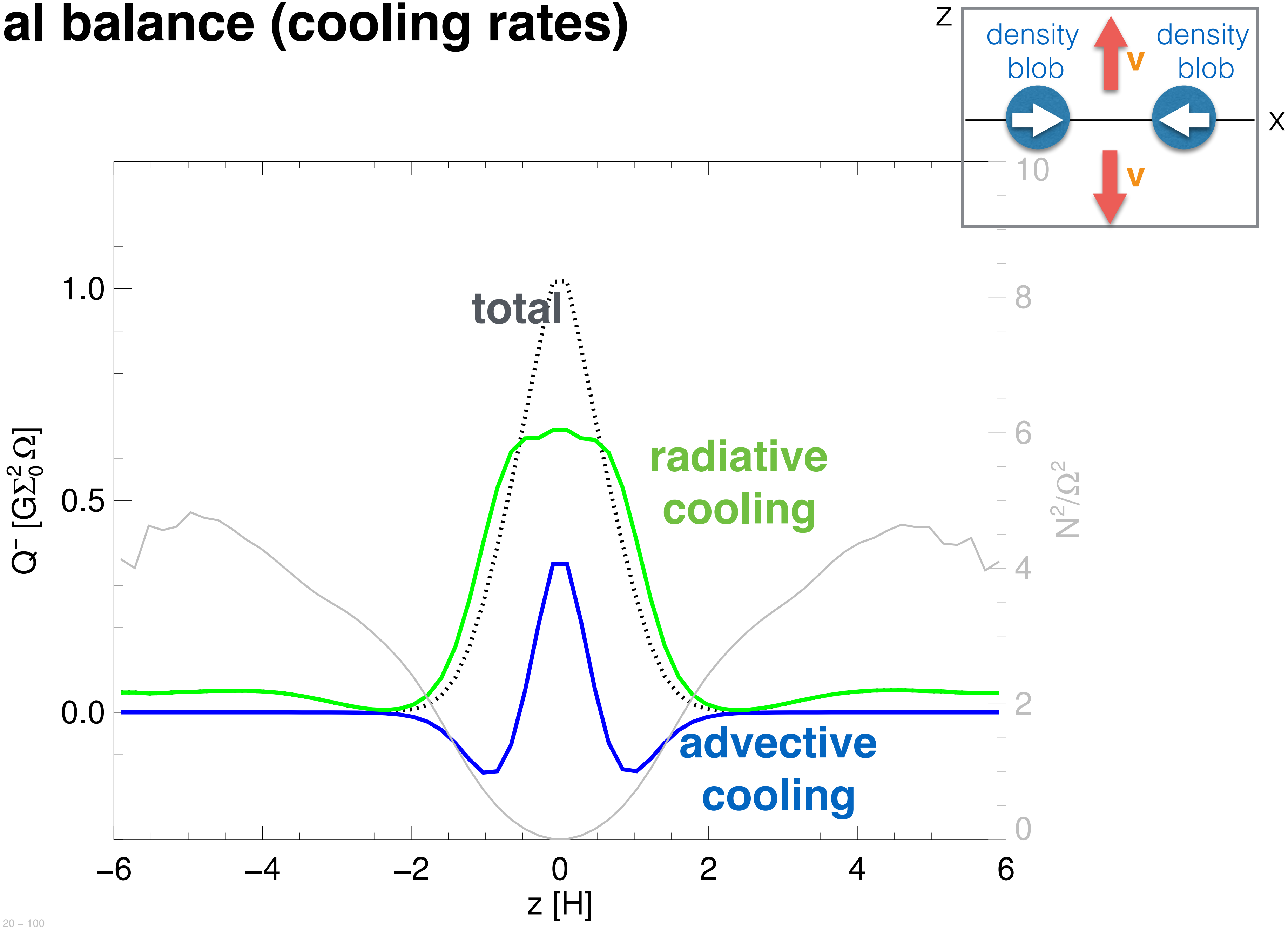


self6000: 20 – 100

Thermal balance (heating rates)



Thermal balance (cooling rates)



self6000: 20 – 100

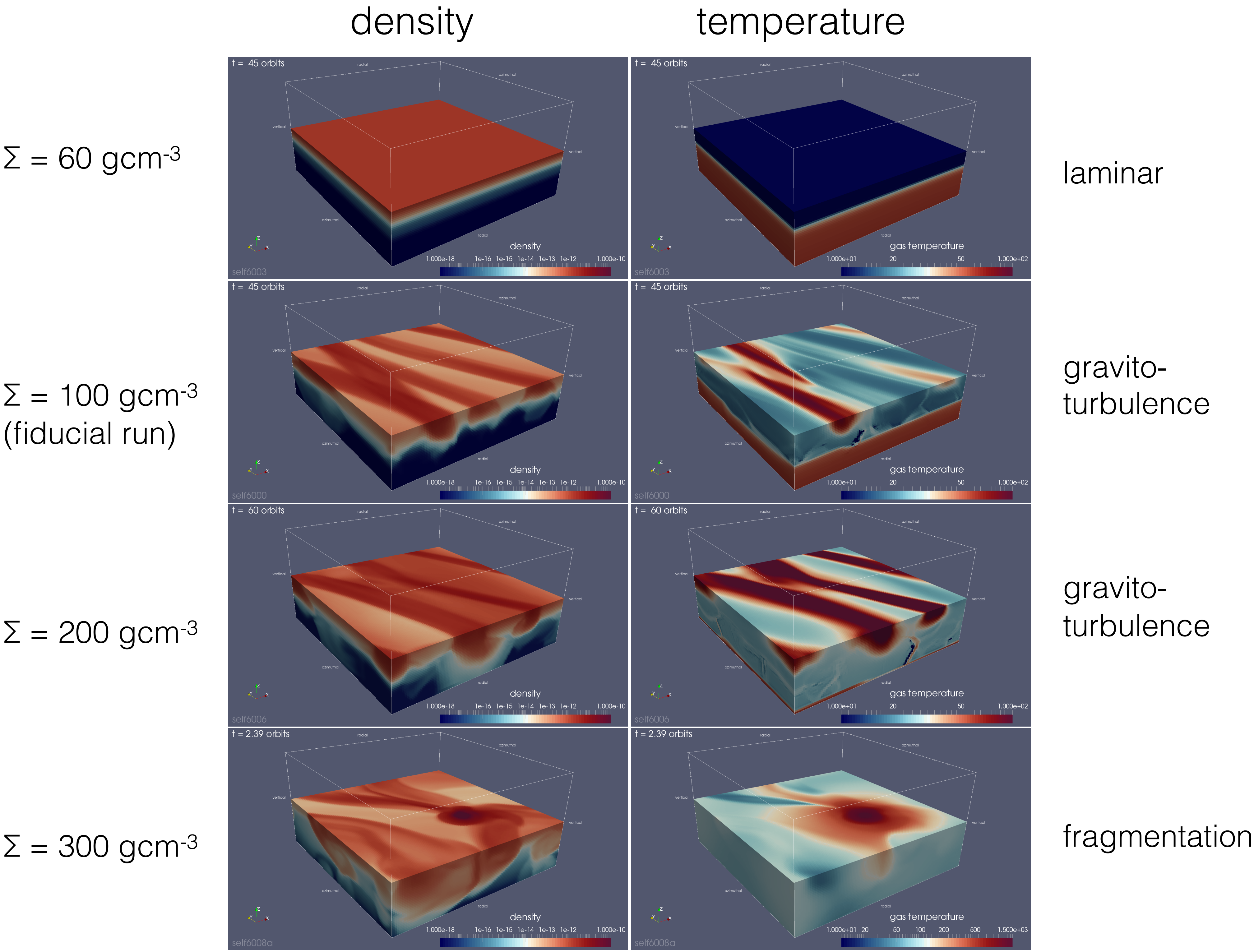
Dependence on surface density Σ

$\theta = 0.02$

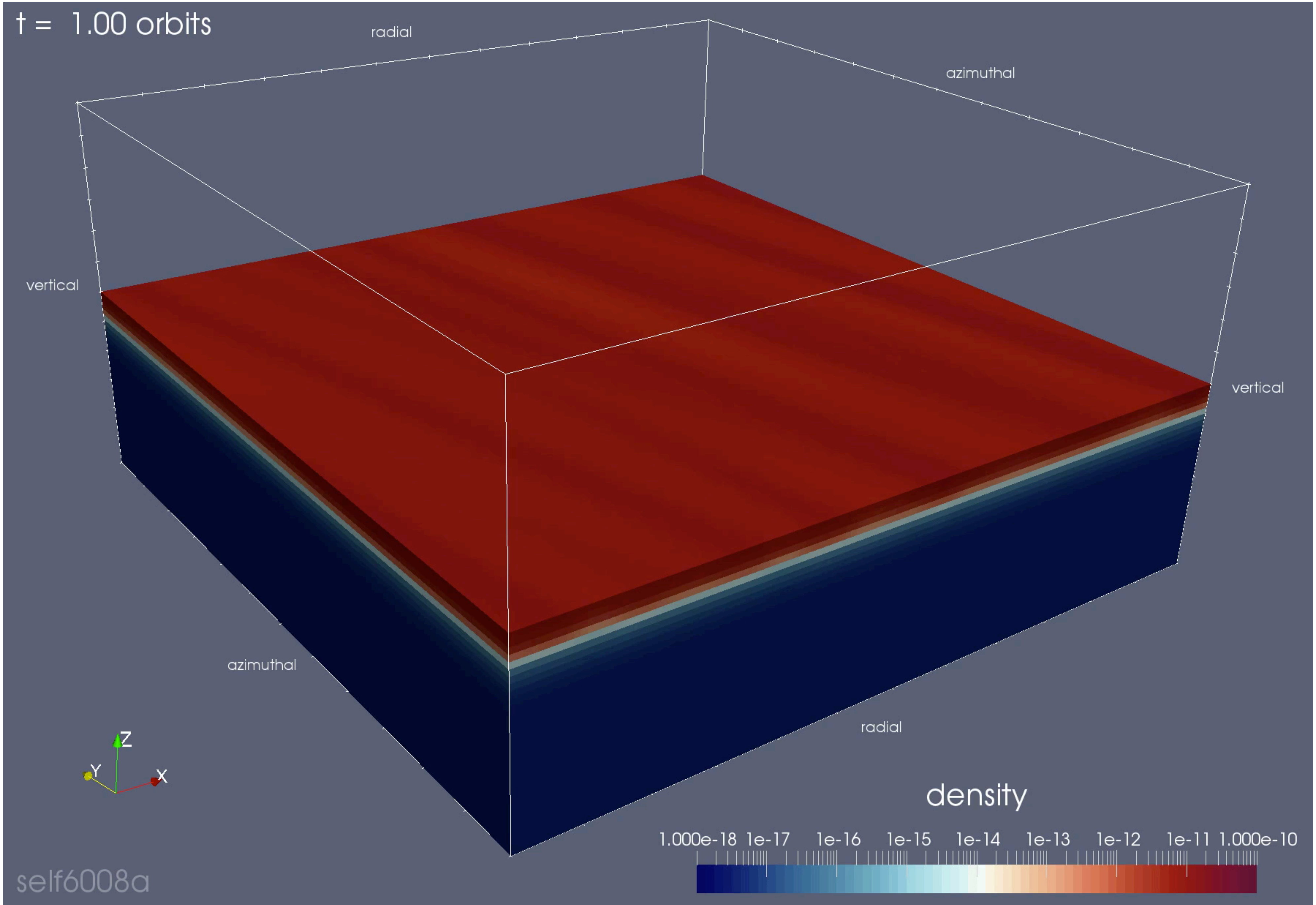
$r = 50AU$

$30 < \Sigma < 300\ gcm^{-2}$

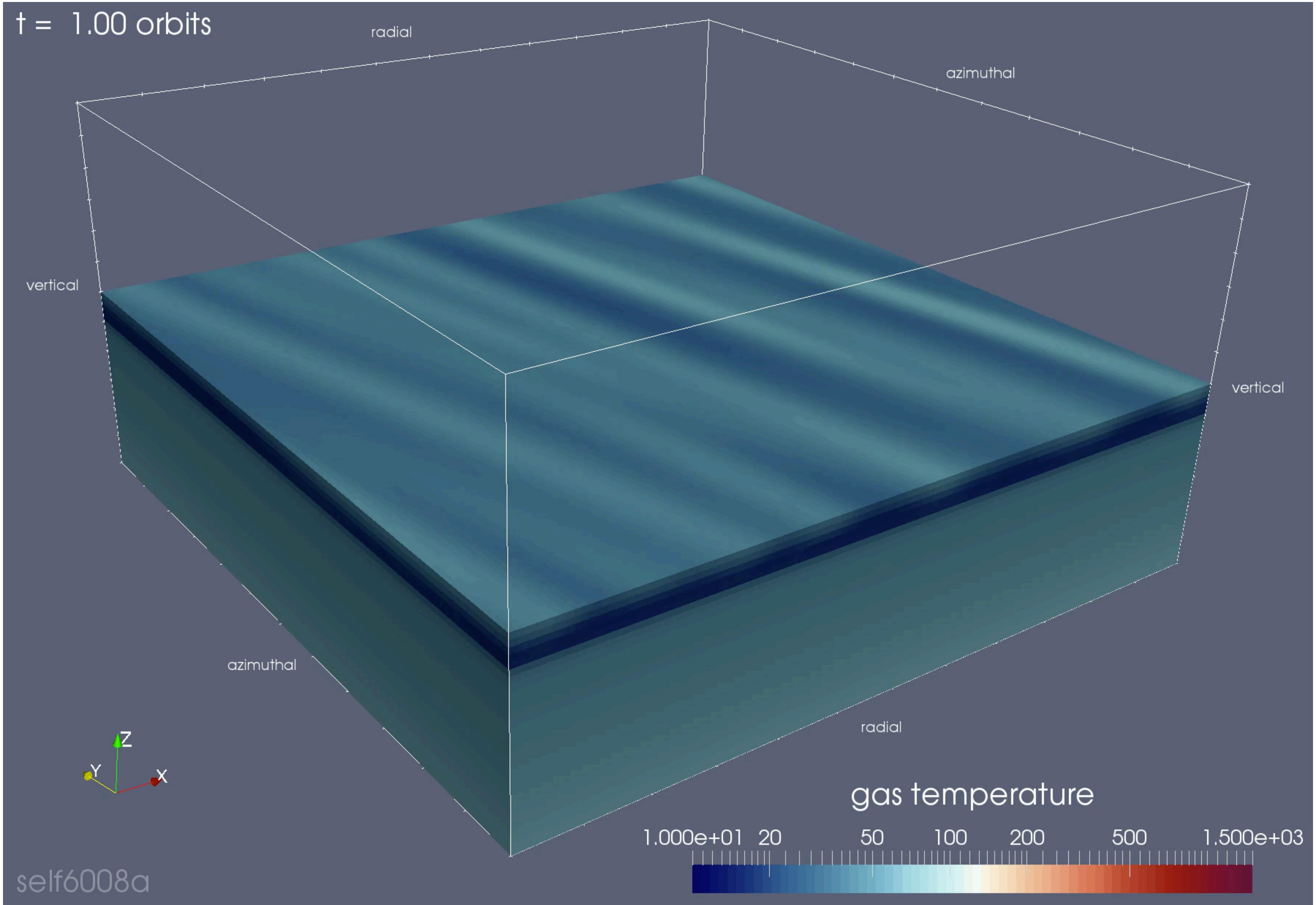
$(0.03 < M_{disk} / M_{star} < 0.26)$


density
temperature
Σ = 60 gcm-3
laminar
Σ = 100 gcm-3
(fiducial run)
gravito-
turbulence
Σ = 200 gcm-3
gravito-
turbulence
Σ = 300 gcm-3
fragmentation
t = 45 orbits
t = 60 orbits
t = 2.39 orbits
density
gas temperature
self6003
self6000
self6006
self6008a

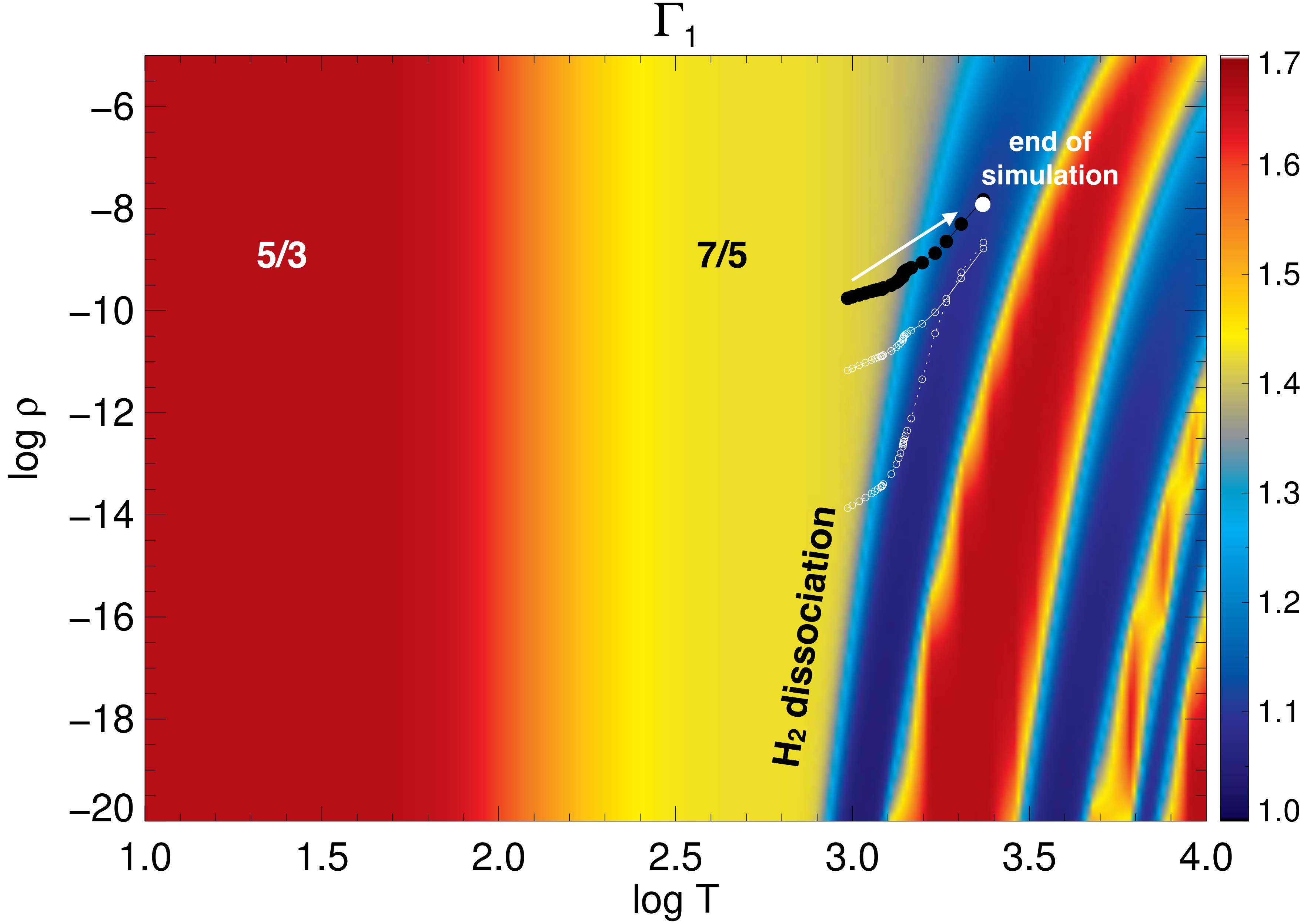
Fragmentation run (Σ = 300 gcm^{-3})



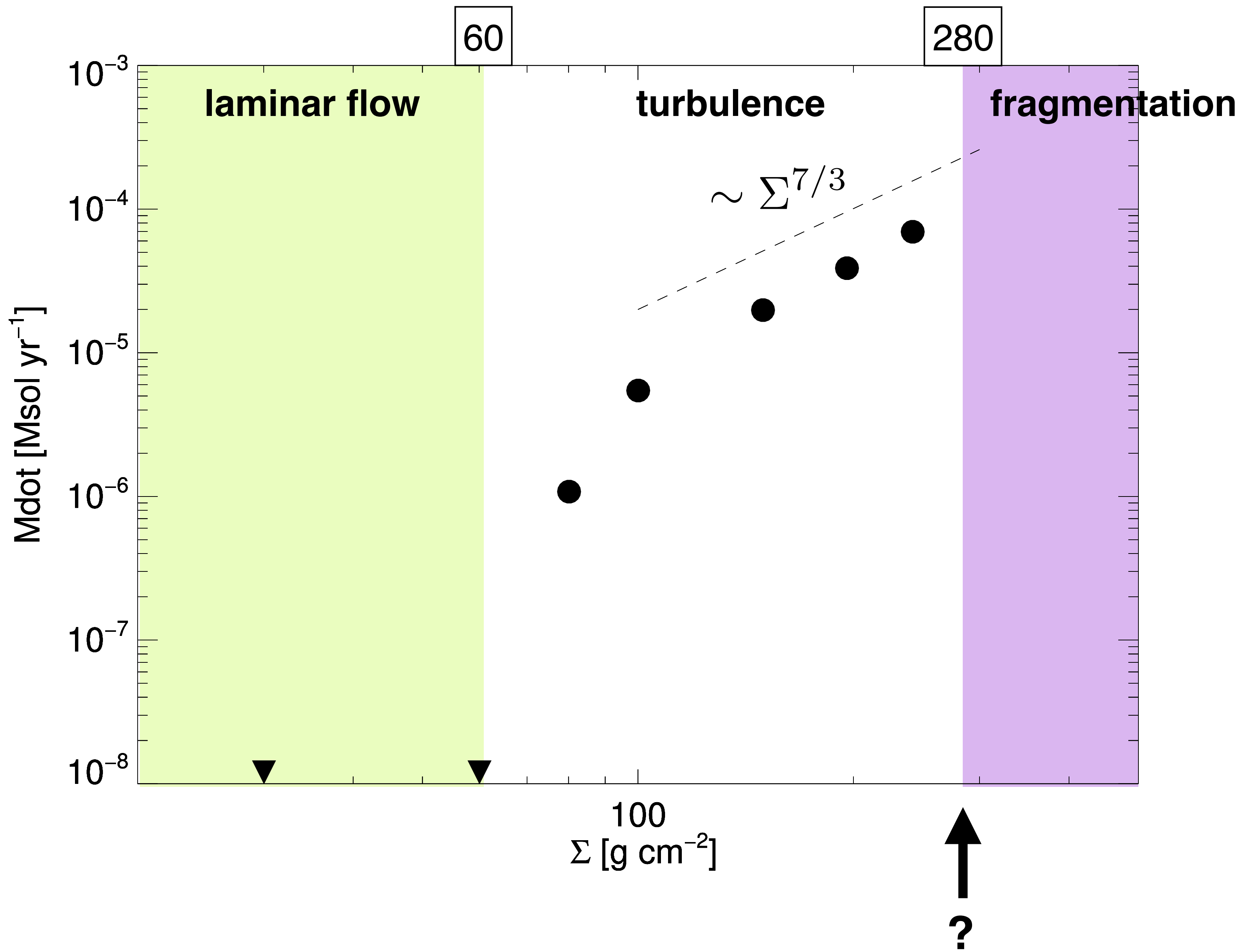
Fragmentation run (Σ = 300 gcm^{-3})



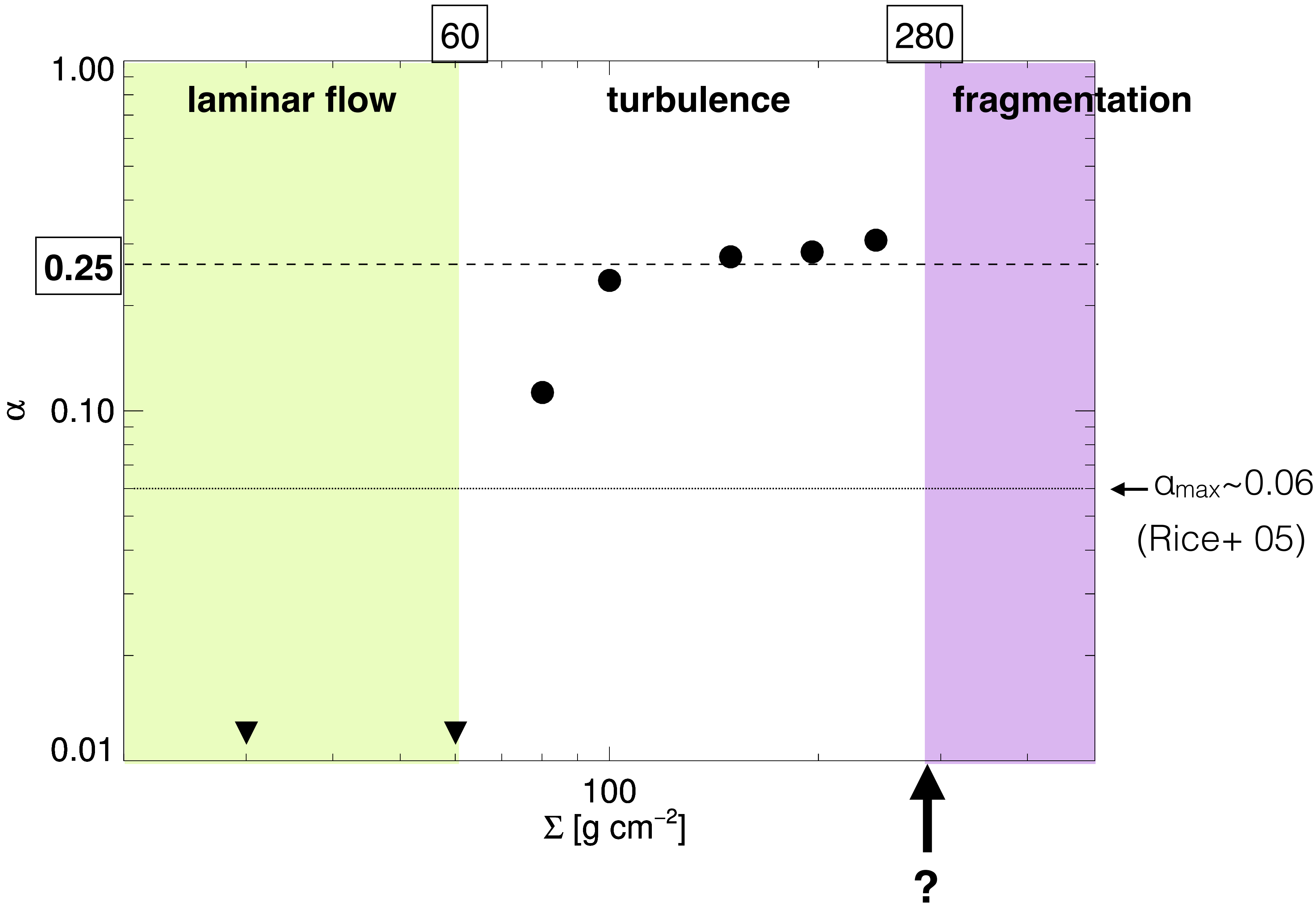
“First core collapse”



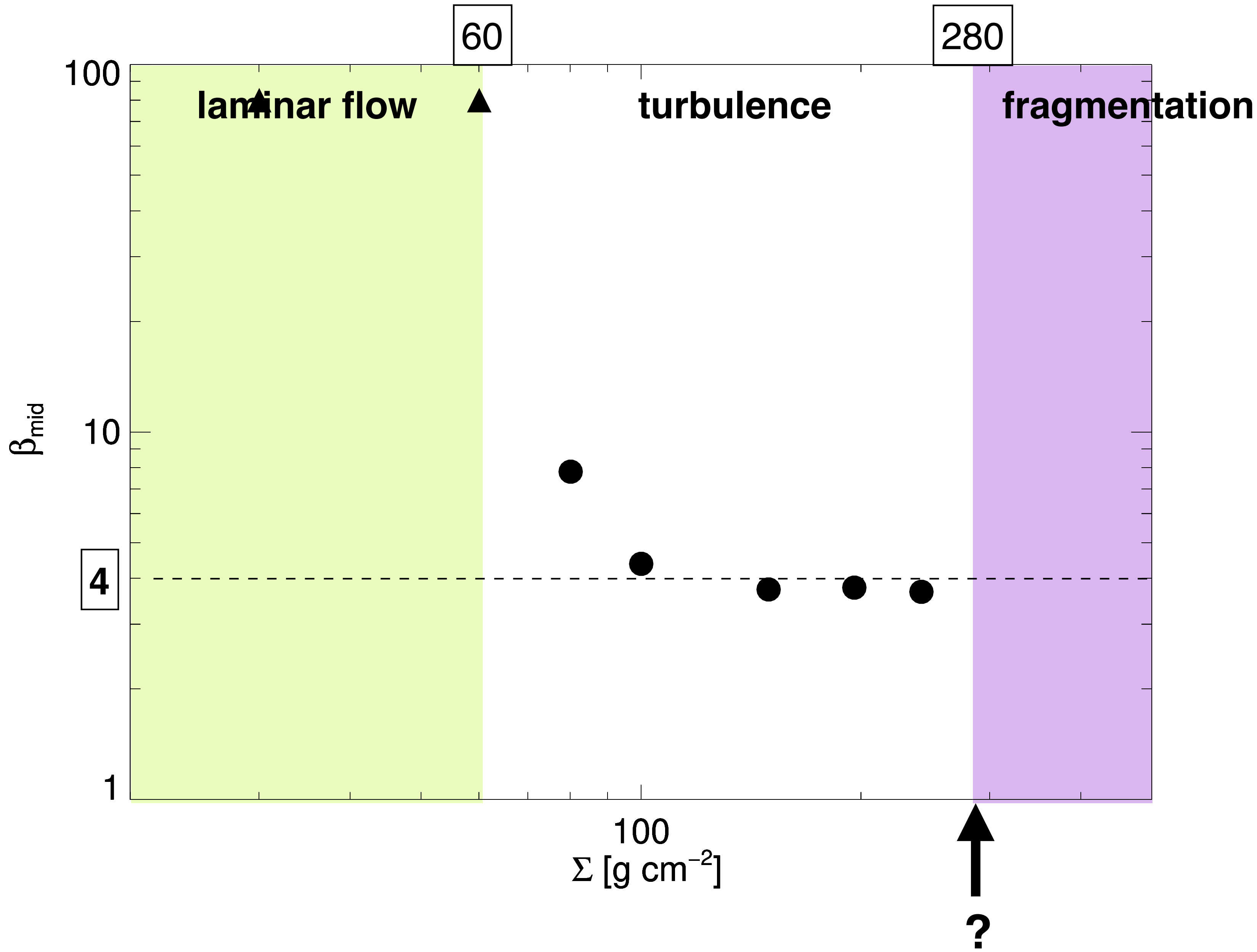
Mass accretion rate as a function of Σ



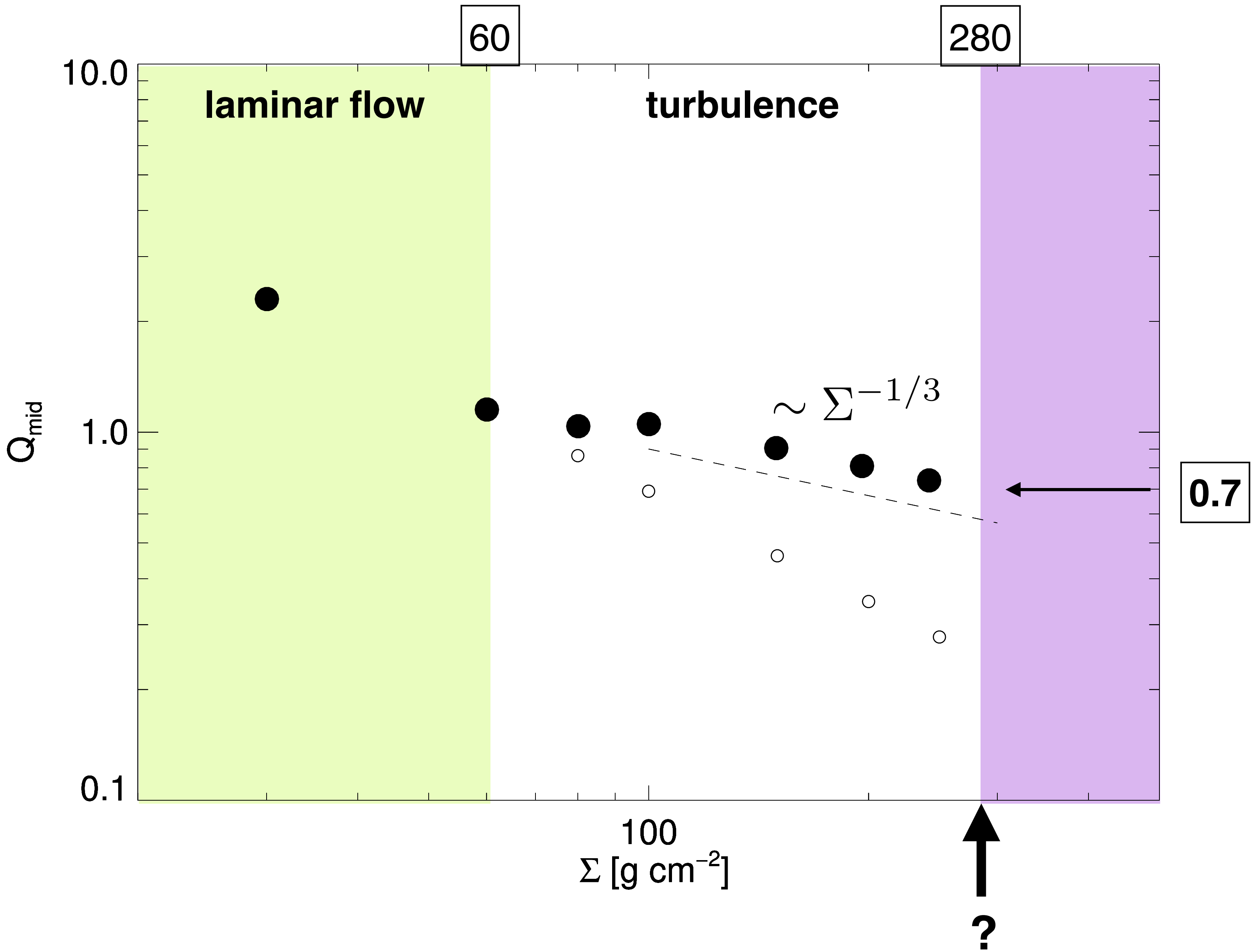
alpha as a function of Σ



Cooling time β as a function of Σ



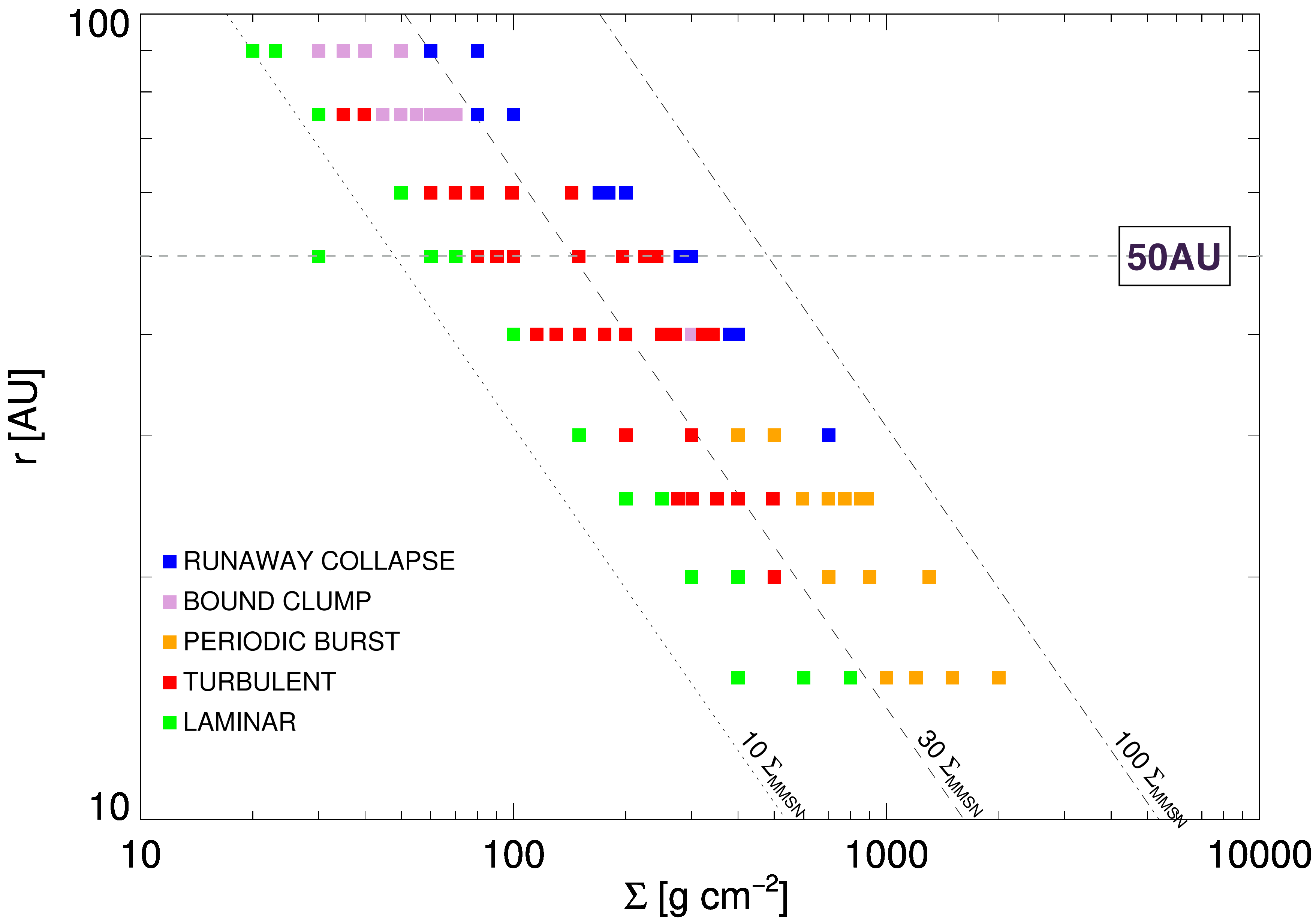
Toomre Q as a function of Σ



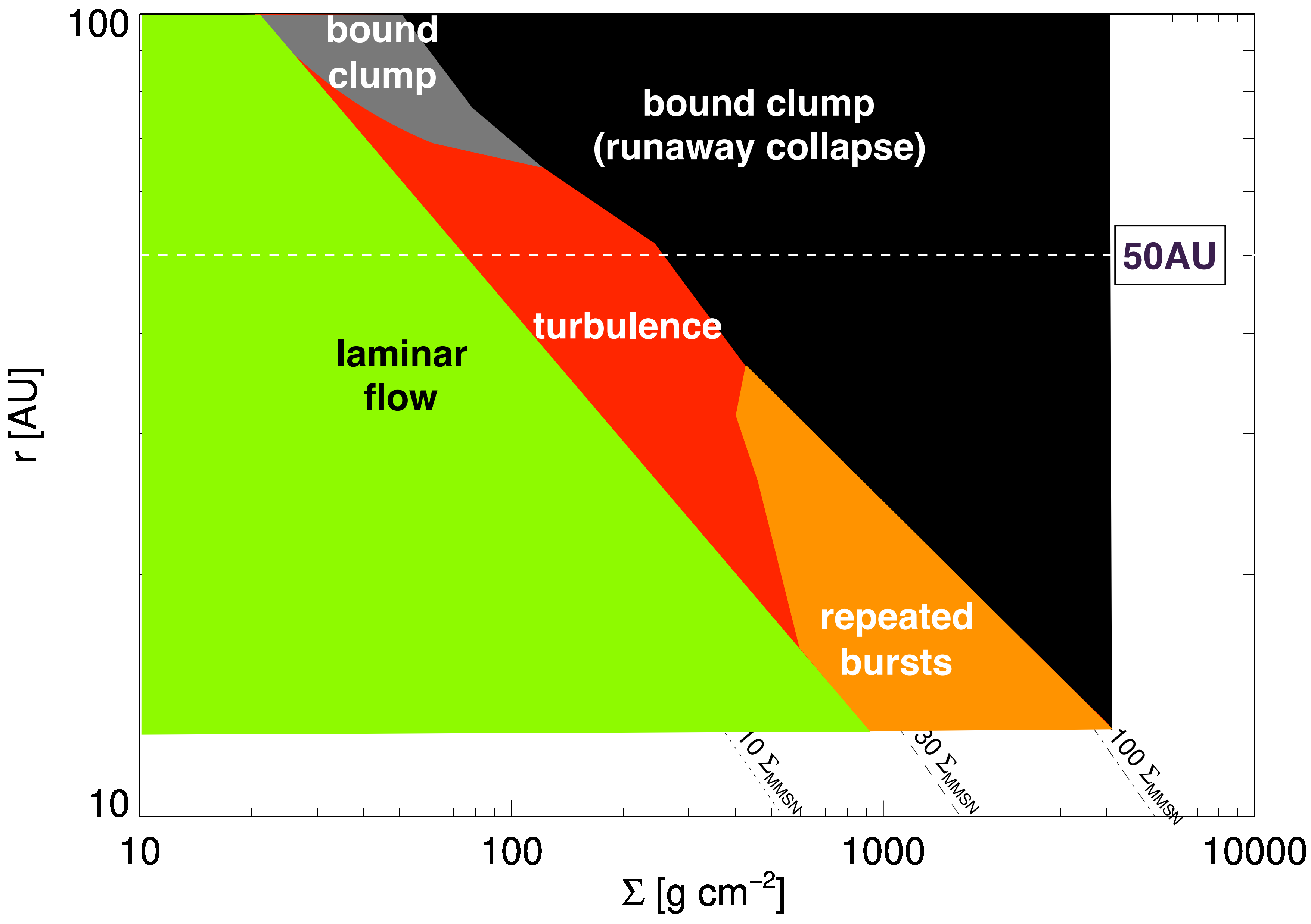
Dependence on radius r and surface density Σ

$\theta = 0.02$

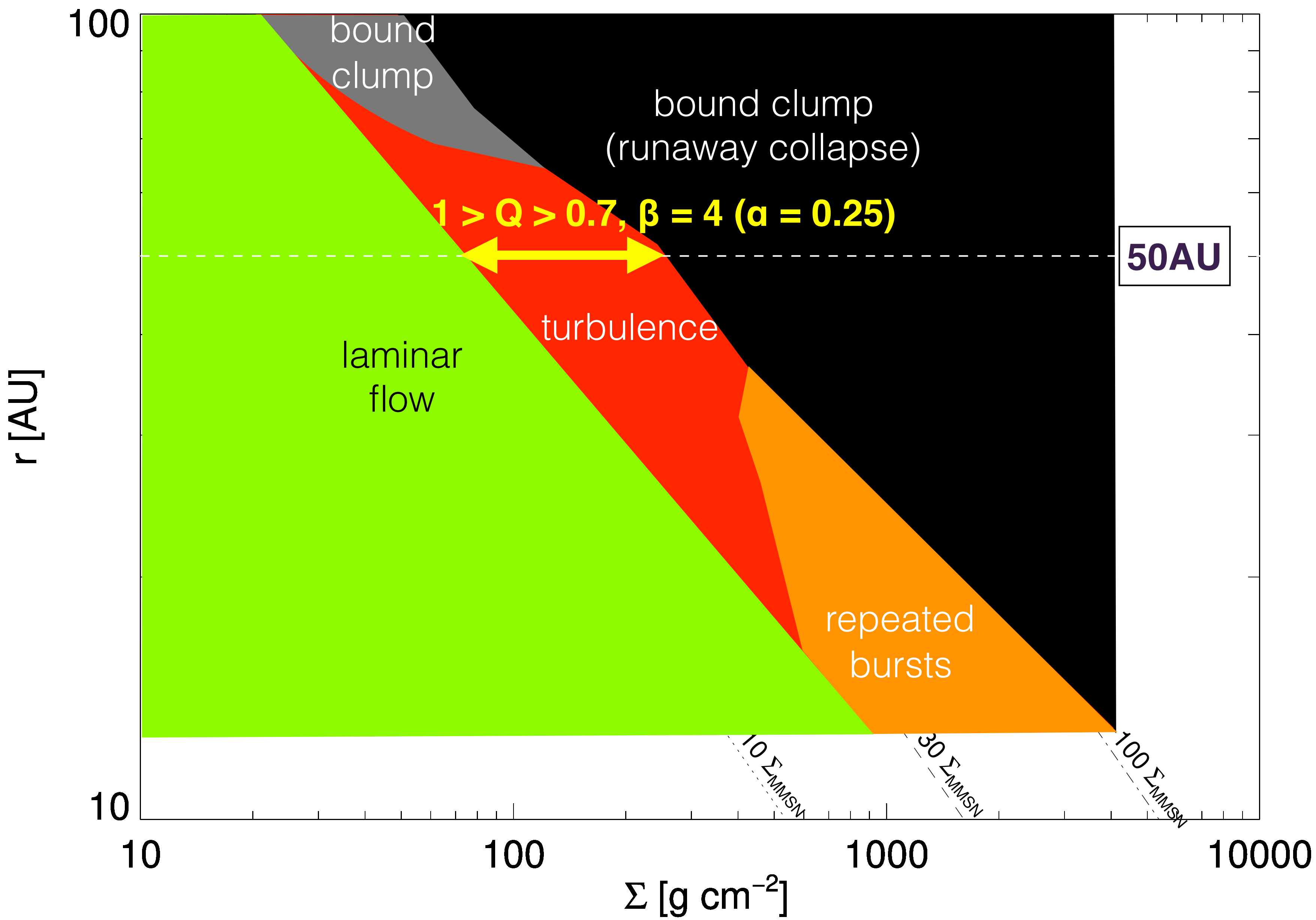
Nonlinear outcome of GI in protoplanetary disks



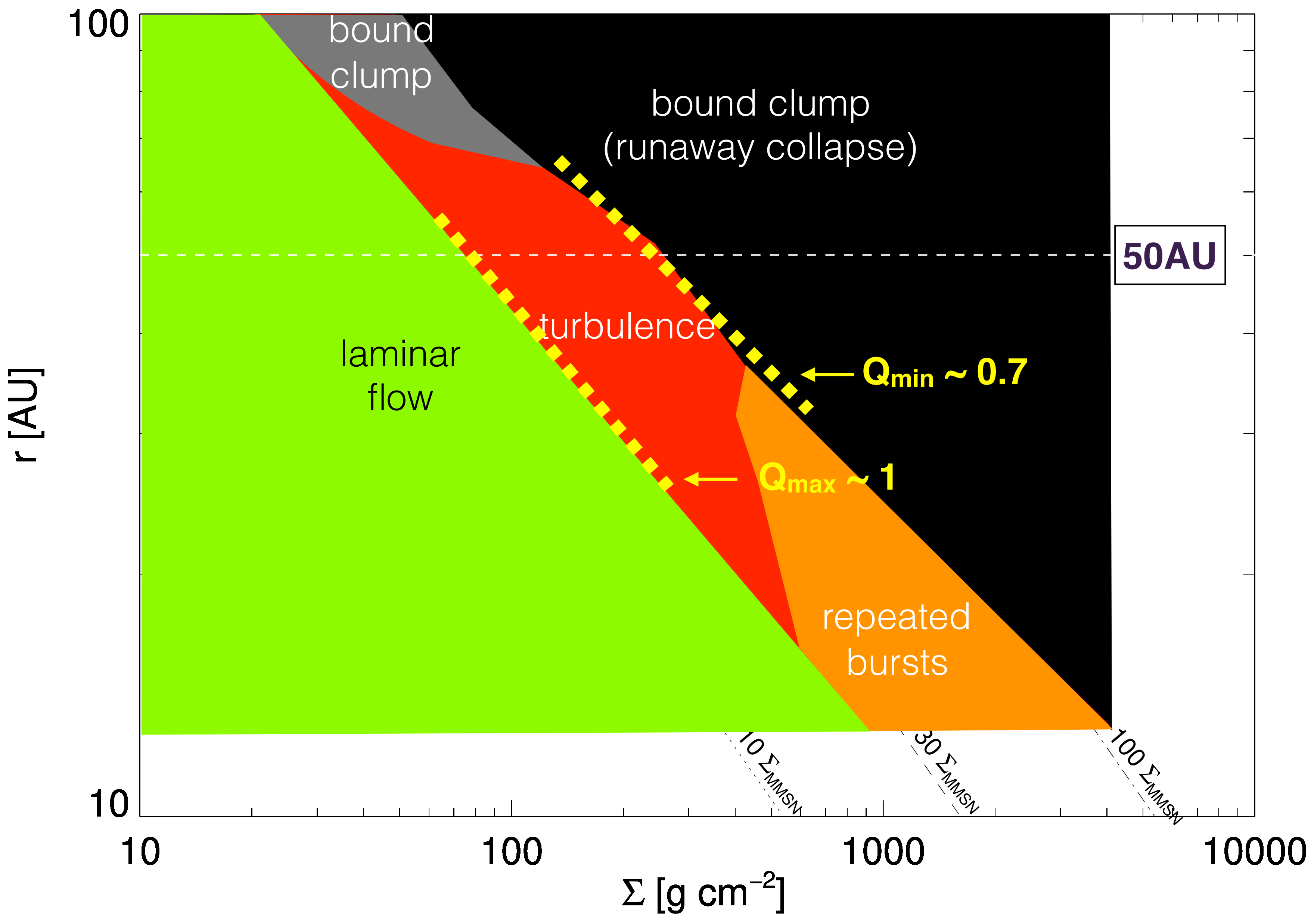
Phase diagram of nonlinear outcome of GI



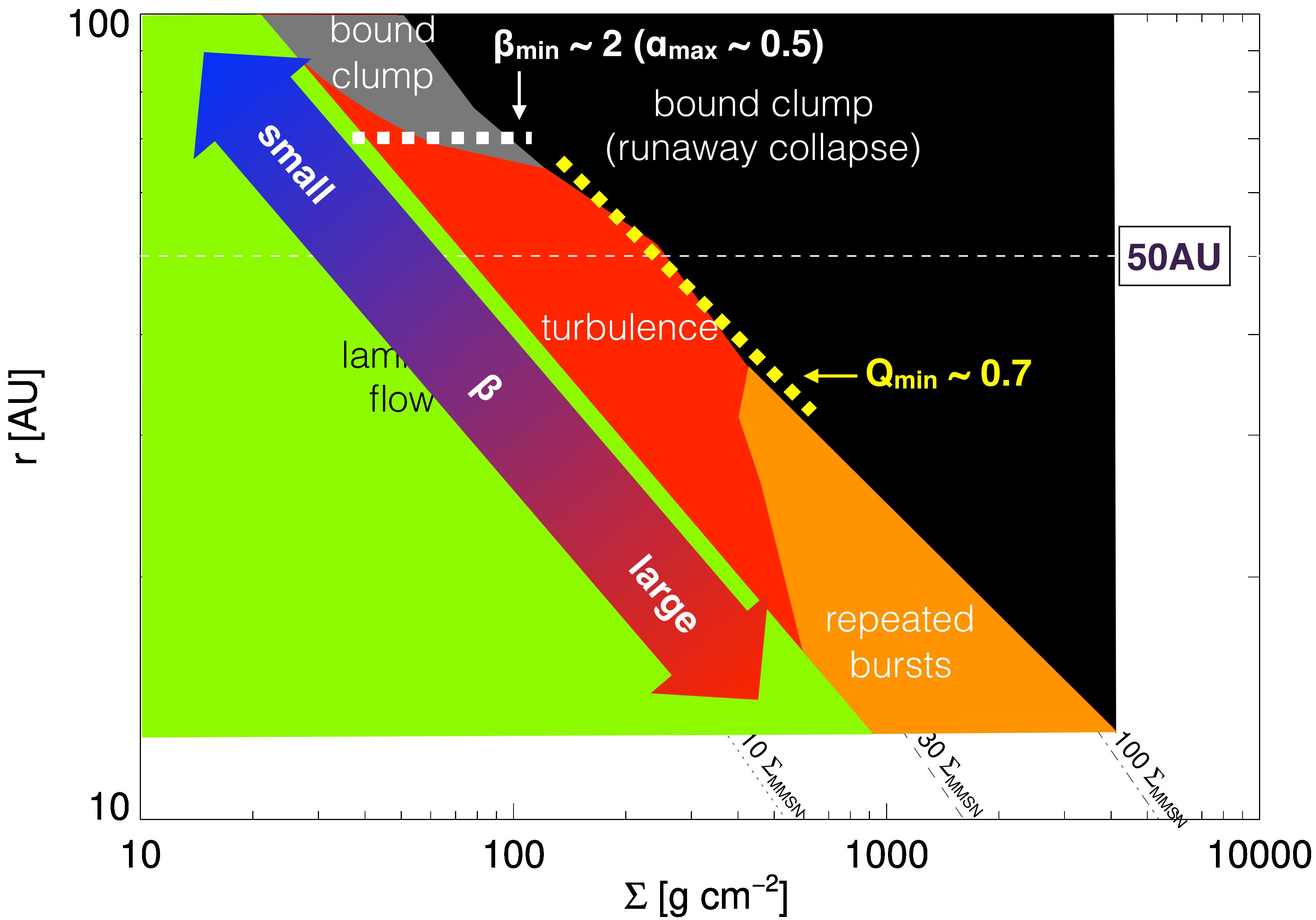
Gravito-turbulence is sustained when 1 > Q > 0.7



Fragmentation criterion on Q



Another fragmentation criterion on β (or α)



Summary

1. We investigated the nonlinear outcome of GI in irradiated protoplanetary disks using radiation hydrodynamics simulations.

2. At a fixed radius of 50AU, gravito-turbulence is sustained for a range of Σ corresponding to $0.7 \leq Q \leq 1$, where β tends to be constant.

3. In gravito-turbulence, density waves excited by GI dissipate through both shock waves and compressional heating.

4. Vertically diverging flows generated by collision of the density waves contribute to both hydrostatic and thermal balances.

5. From parameter survey on both r and Σ, fragmentation seems to occur when either $Q \leq 0.7$ or $\beta \leq 2$ is satisfied.