First Radiation Magnetohydrodynamic Global Simulations Of Protoplanetary Disks

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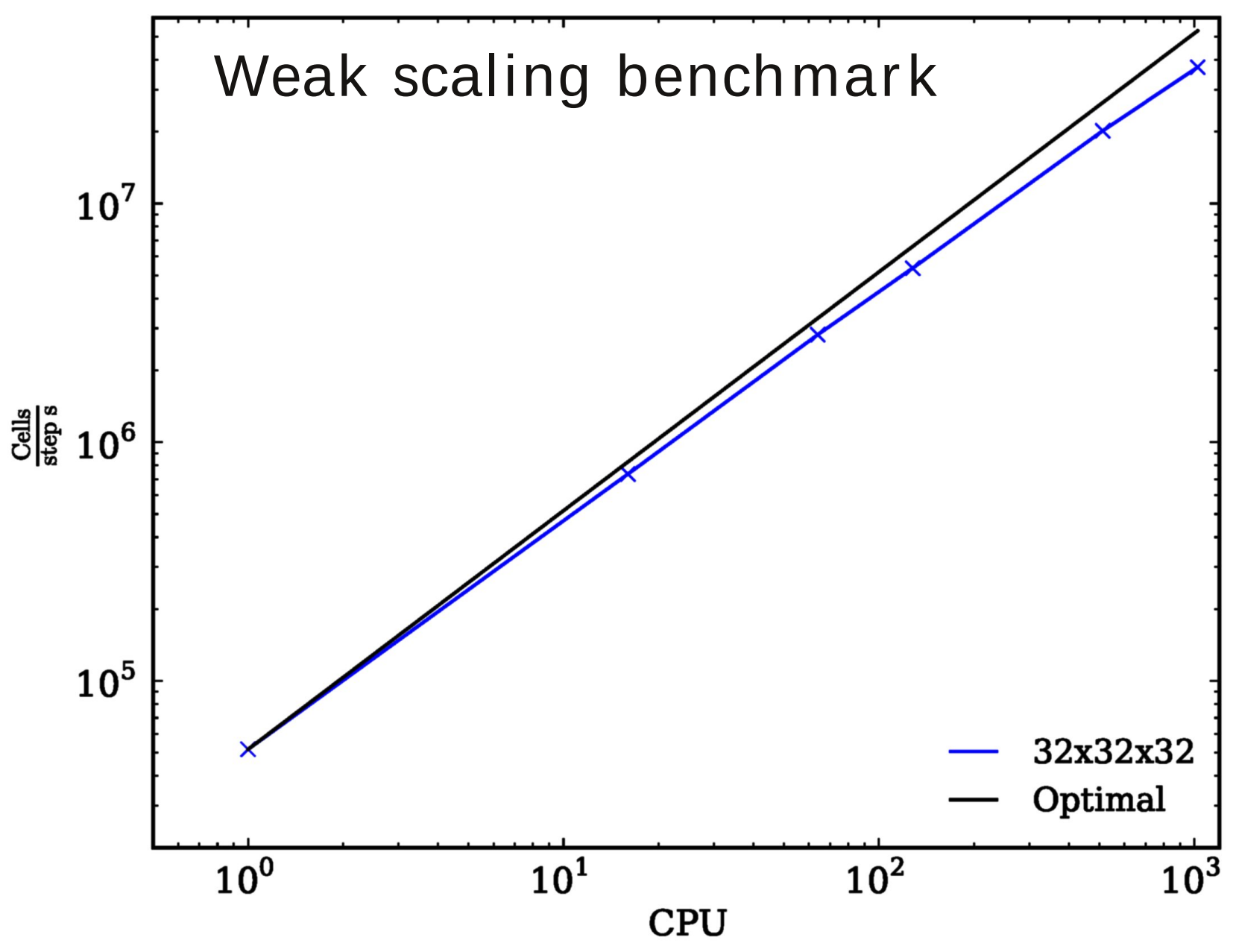
Method

We developed a radiative transfer method based on the flux-limited diffusion approach (Commerçon et al. 2011) including frequency dependent irradiation (Kuiper et al. 2010), using dust opacities by Draine & Lee (1984).



Our radiation module is implemented in the PLUTO code. The FLD module is three times faster than the MHD module even for a mostly optical thin disk setup. We reach a weak scaling of 70% up to 1024 cores.

Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \tilde{v}) = 0, \tag{1}$$

$$\frac{\partial \rho \tilde{v}}{\partial t} + \nabla \cdot \left[\rho \tilde{v}\tilde{v}^T - \tilde{B}\tilde{B}^T\right] + \nabla P_t = -\rho \nabla \Phi, \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[(E + P_t)\tilde{v} - (\tilde{v} \cdot \tilde{B})\tilde{B}\right] = -\rho \tilde{v} \cdot \nabla \Phi, \tag{3}$$

$$\frac{\partial B}{\partial t} + \nabla \times (\tilde{v} \times \tilde{B}) = 0, \tag{4}$$

$$\partial_t \rho \epsilon = -\kappa_P(T)\rho c(a_R T^4 - E_R) - \nabla \cdot F_*, \tag{5}$$

$$\partial_t E_R - \nabla \frac{c\lambda}{\kappa_R(T)\rho} \nabla E_R = +\kappa_P(T)\rho c(a_R T^4 - E_R), \tag{6}$$

Disk setup

The disk model follows the system AS 209 in the star-forming region Ophiuchus (Andrews et al. 2009). We start from radiative hydrostatic initial conditions. Fig. 1 shows the initial temperature profile. We start with a pure toroidal magnetic field which triggers the Magneto-Rotational Instability (MRI).

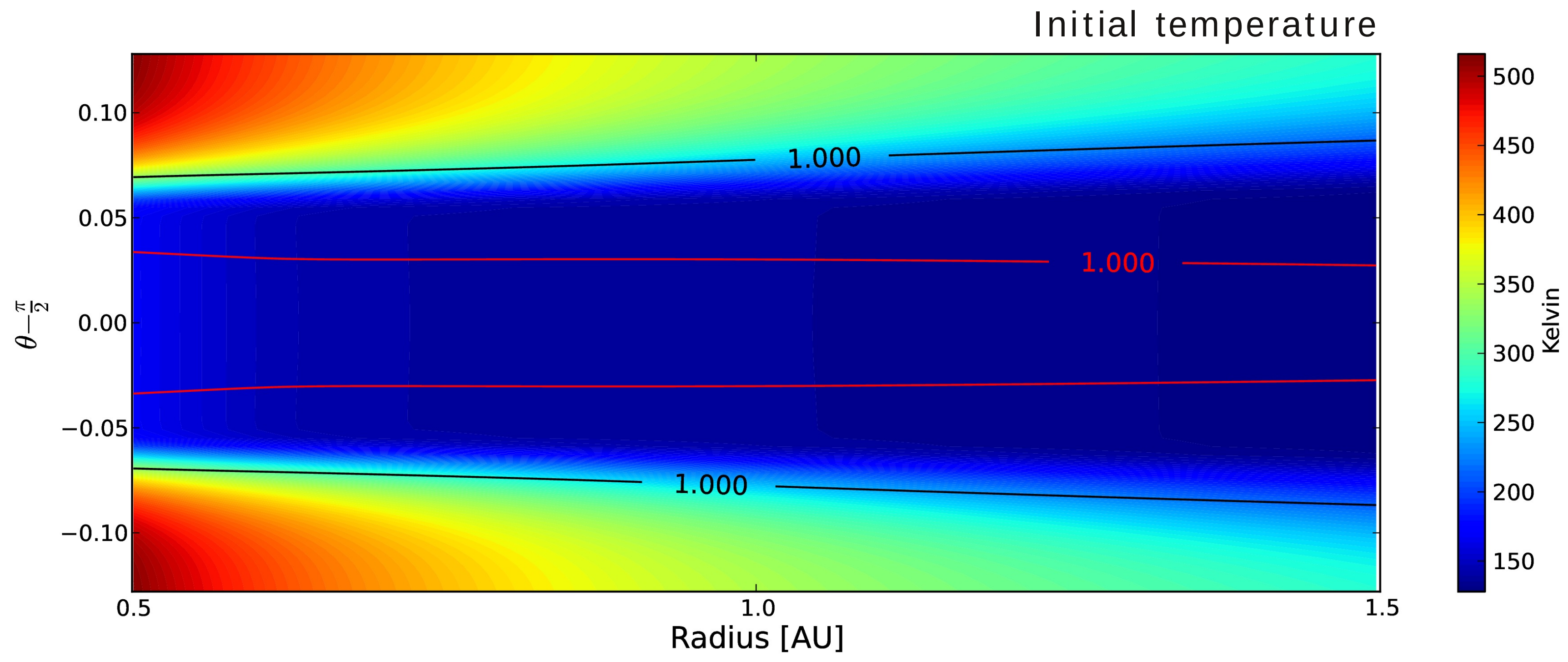


Fig. 1: Radial integrated τ=1 line for the irradiation (black solid line).
Vertical integrated τ=1 line for the thermal emission (red solid line).

Domain and resolution

(Radius: 0.5-1.5) (θ: ± 0.13) (ϕ: $\pi/3$)
$512 \times 128 \times 512$

Stellar and disk parameter

$$T_* = 4250\mathrm{K}$$

$$M_* = 0.9 M_{sun}$$

$$R_* = 2.3 R_{sun}$$

$$\Sigma^*_{dust} = 0.017 \mathrm{gcm}^{-2} \left(\frac{r}{1\mathrm{AU}}\right)^{-0.9}$$

$$\Sigma_{gas} = 1700 \mathrm{gcm}^{-2} \left(\frac{r}{1\mathrm{AU}}\right)^{-0.9}$$

$$\beta = \frac{2P}{B_\phi^2} = 40$$

*We specify only the amount of small sized dust $< 1\mu m$ due to the dust opacity.

Results

We successfully performed the first global 3D radiative MHD stratified disk simulation of a protoplanetary disk.

Fig. 3

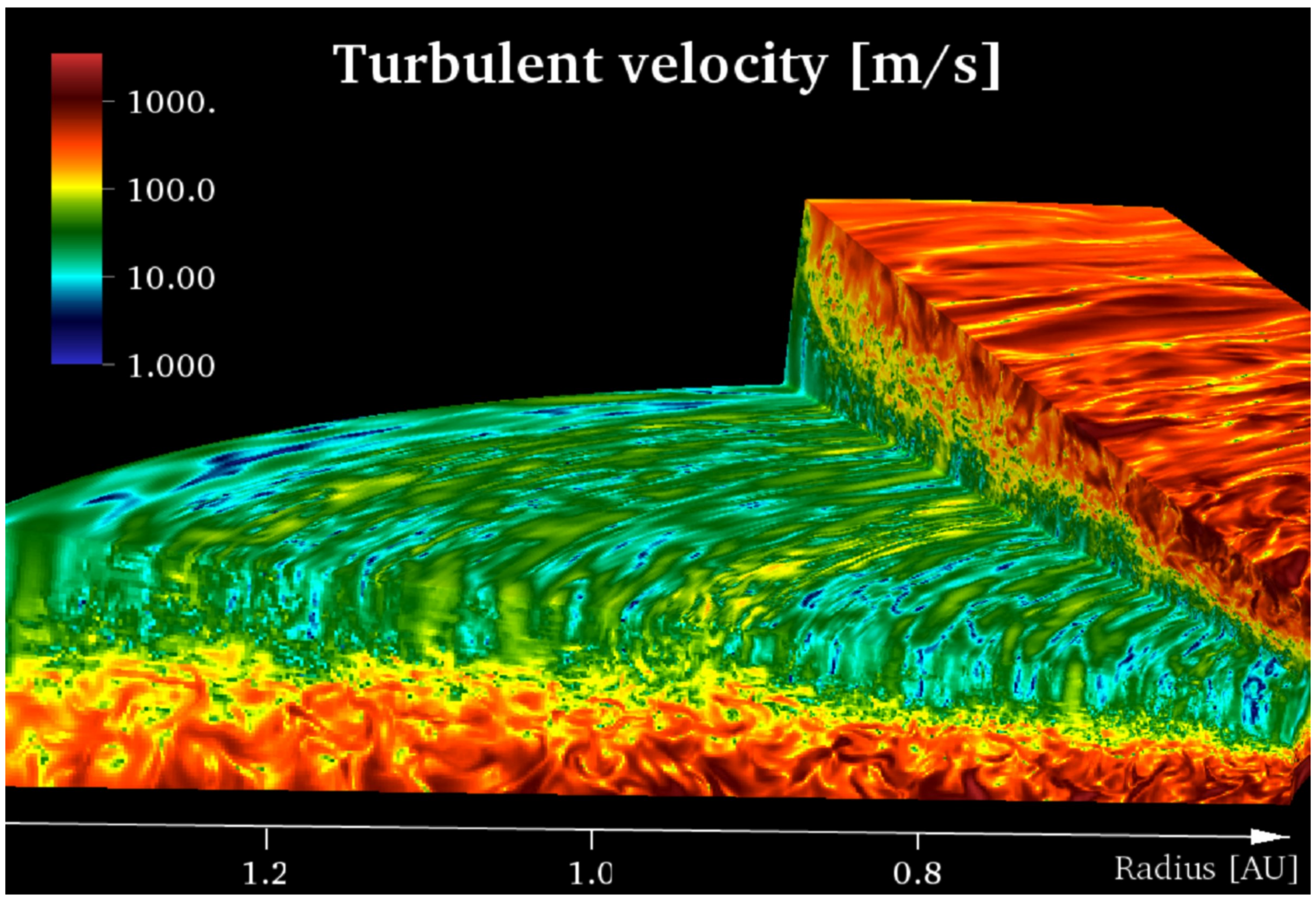
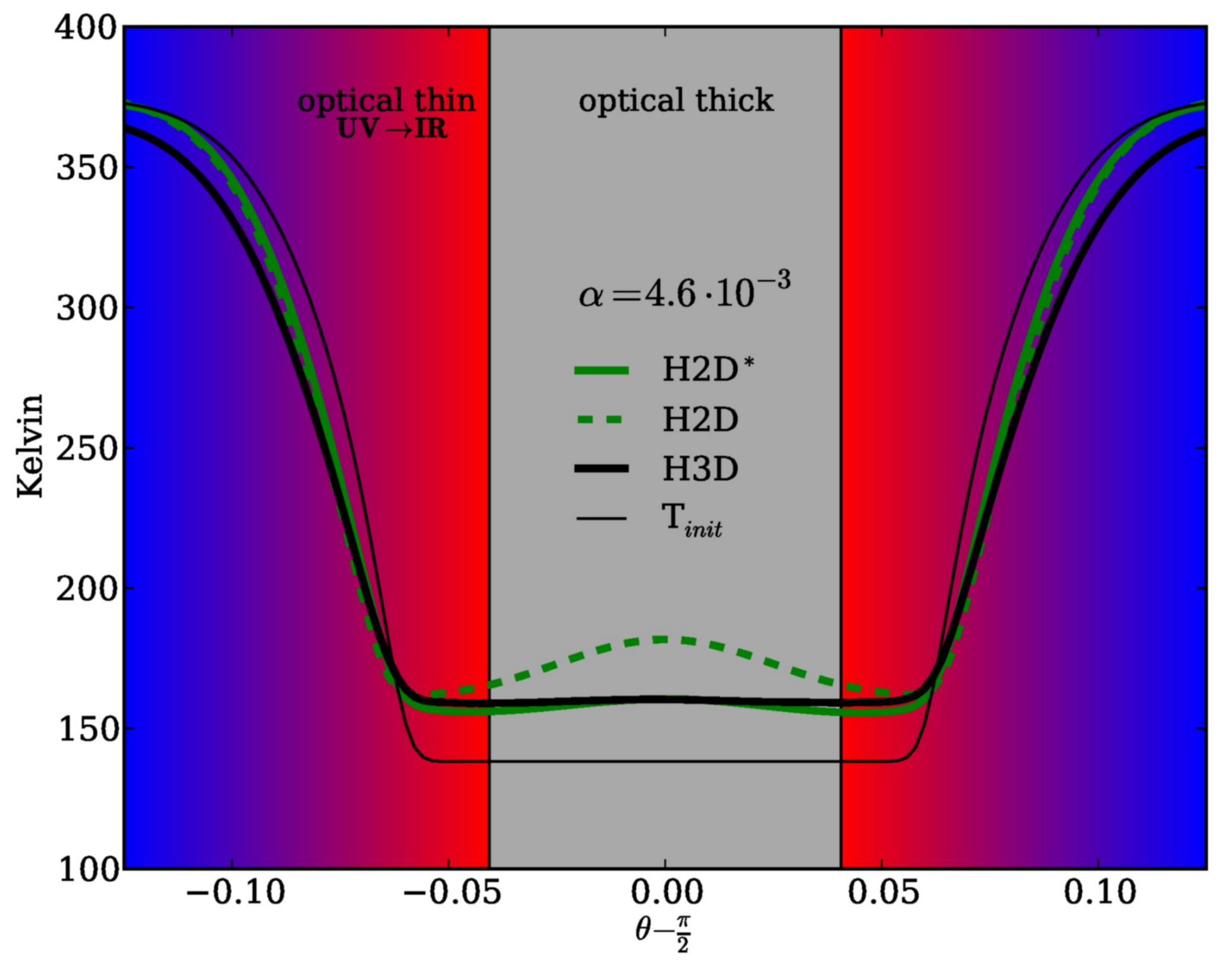
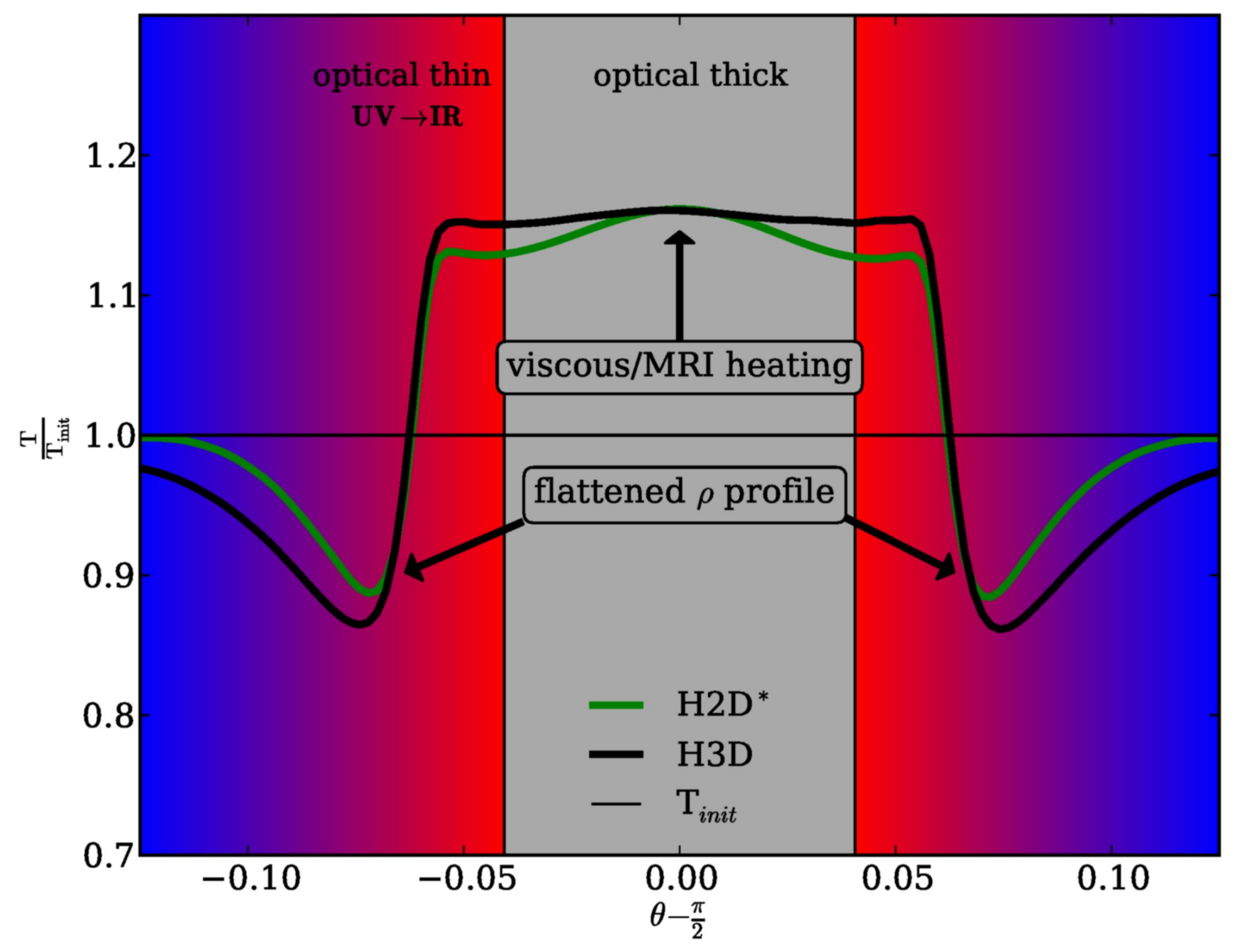


Fig. 2

Vertical temperature profile of the 3D radiative MHD run (black line) and the viscous radiative HD runs (green lines) at 1 AU.
Model H2D uses a constant alpha.
Model H2D* uses α ~ 1/ρ



Relative temperature profile compared to the initial passive disk.



The vertical temperature profile shows no temperature peak at the midplane as it is the case in classical viscous disk models. A roughly flat vertical temperature profile establishes at the midplane region shielded from external irradiation. We reproduce the midplane temperature of the full 3D RMHD run using 2D viscous disk simulations with a constant dynamical viscosity of **ν ~ αρ** ~ constant (Fig. 2).
The turbulent velocity of the gas is around 10 to 100m/s at the midplane and up to 1000 m/s in upper heights of the disk (Fig. 3).

References:
Andrews, S. M., Wilner, D. J., Hughes, A. M., Qi, C., & Dullemond, C. P. 2009, ApJ, 700, 1502
Commerçon, B., Teyssier, R., Audit, E., Hennebelle, P., & Chabrier, G. 2011, A&A, 529, A35
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