Modeling protoplanetary disks with adaptive mesh refinement techniques

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Abstract

So far, most numerical approaches in planet formation or accretion disks make use of Lagrangian-based smoothed-particle hydrodynamics (SPH) techniques or grid-based 2D axisymmetric simulations. Here, we present a new setup to model **gravitational instabilities in 3D** with the **adaptive mesh refinement** (AMR) **hydrodynamics** code Enzo. We explore the potential impact of AMR techniques to model the **first stages of giant planet formation** via gravitational instabilities (GI), in particular the fragmentation and clumping due to large-scale instabilities using different numerical setups. As our reference model we consider the temporal evolution of a compact ($r = 10$ AU) and massive ($M_{\text{disk}} \approx 0.05 M_\odot$) protoplanetary disk around a central object of subsolar mass ($M_\star = 0.646 M_\odot$), which was suggested to form through common-envelope events by Schleicher & Dreizler (2014).

Adopting a simple thermodynamical profile corresponding to a marginally stable disk, we show that **fragmentation and clumping** can be observed in the disk structure. In the numerical model, **clumps are formed by GI** but eventually vanish due to tidal disruptions. The latter reflects the absence of radiative feedback from the central star, which may stabilize the clumps on larger scales. Our simulations illustrate the **capabilities of AMR-based modeling techniques for planet formation simulations**. We expect that the inclusion of additional physics like radiative feedback and the formation of sink particles will provide a detailed framework to study the formation of planets via gravitational instabilities.

Initial density structure

We set the column density structure of the disk according to a **Mestel power-law profile** (Mestel, 1963)

$$\Sigma(r) = \Sigma_0 \frac{r_{\text{out}}}{r}, \tag{1}$$

with the outer radius $r_{\text{out}} = 10\,\text{AU}$. The column density is normalized to

$$\Sigma_0 = \frac{1}{2\pi} \frac{M_{\text{disk}}}{r_{\text{out}}^2}, \tag{2}$$

with the disk mass $M_{\text{disk}} = 0.05\,M_\odot$, consistent with the **fiducal system NN Serpentis** (Schleicher & Dreizler, 2014). With hydrostatic balance in the vertical direction, the initial density structure (see Figure 1) is given as

$$\rho(r,z) = \frac{\Sigma(r)}{H(r)\sqrt{2\pi}} \exp\left(-\frac{z^2}{2H(r)^2}\right), \tag{3}$$

with the scale height $H(r) \approx 0.62 H_\star = 0.62 c_s/\Omega$ (Lodato, 2008).

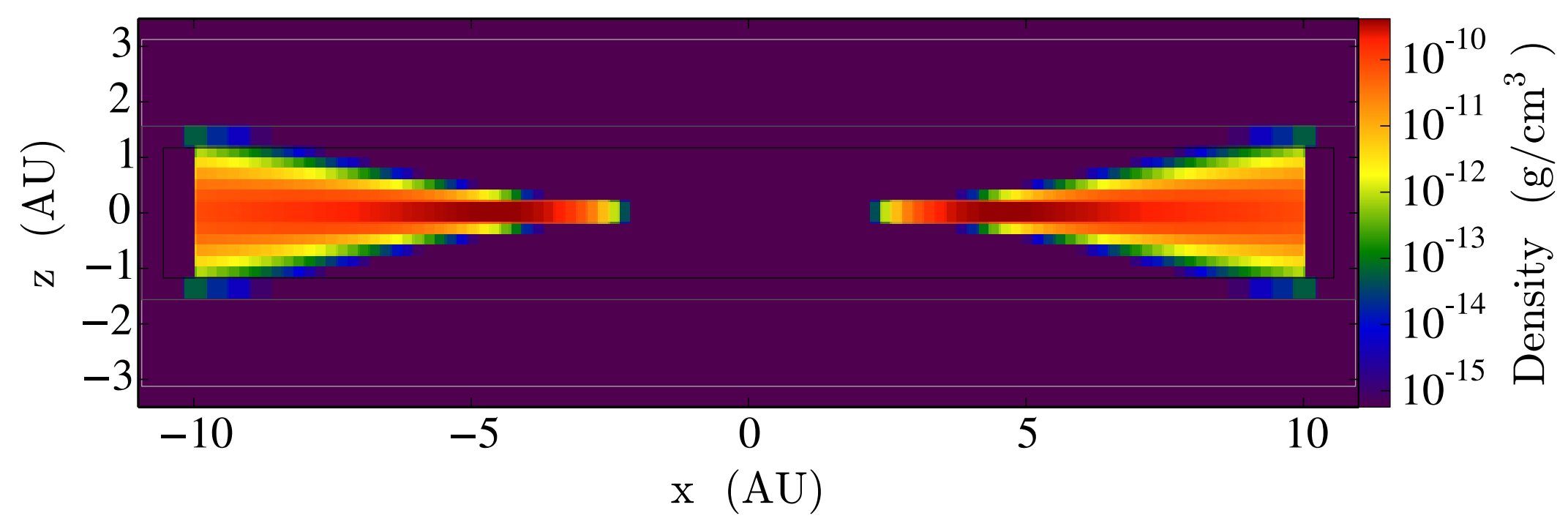

Fig. 1: Slice through the initial density structure of the disk in an edge-on view.

Built-in dynamics

The gravitational influence of both the central object with $M_\star = 0.646\,M_\odot$ and the disk material induce

$$v^2(r) = \frac{GM_\star}{r} + 2\pi G \Sigma r. \tag{4}$$

The disk's global dynamics are characterized by the **Toomre parameter** (Toomre, 1964)

$$Q = \frac{c_s \kappa}{\pi G \Sigma} \approx \frac{c_s \Omega}{\pi G \Sigma}, \tag{5}$$

which is fixed to marginal stability ($Q = 1$) or instability ($Q = 0.9$). From this we infer the temperature profile via the **Newton-Laplace equation** to be

$$T(r) = \frac{c_s^2 \mu m_p}{\gamma k_B}. \tag{6}$$

The ratio of specific heats γ is varied in the simulations to account for **different equations of state**. The gas is composed of neutral diatomic hydrogen (H_2), i.e., $\mu = 2.0$.

The gravitational potential in the simulations is modeled by an **external gravity field**, composed of the gravity of the **central object and the disk's self-gravity**.

Vertical structure

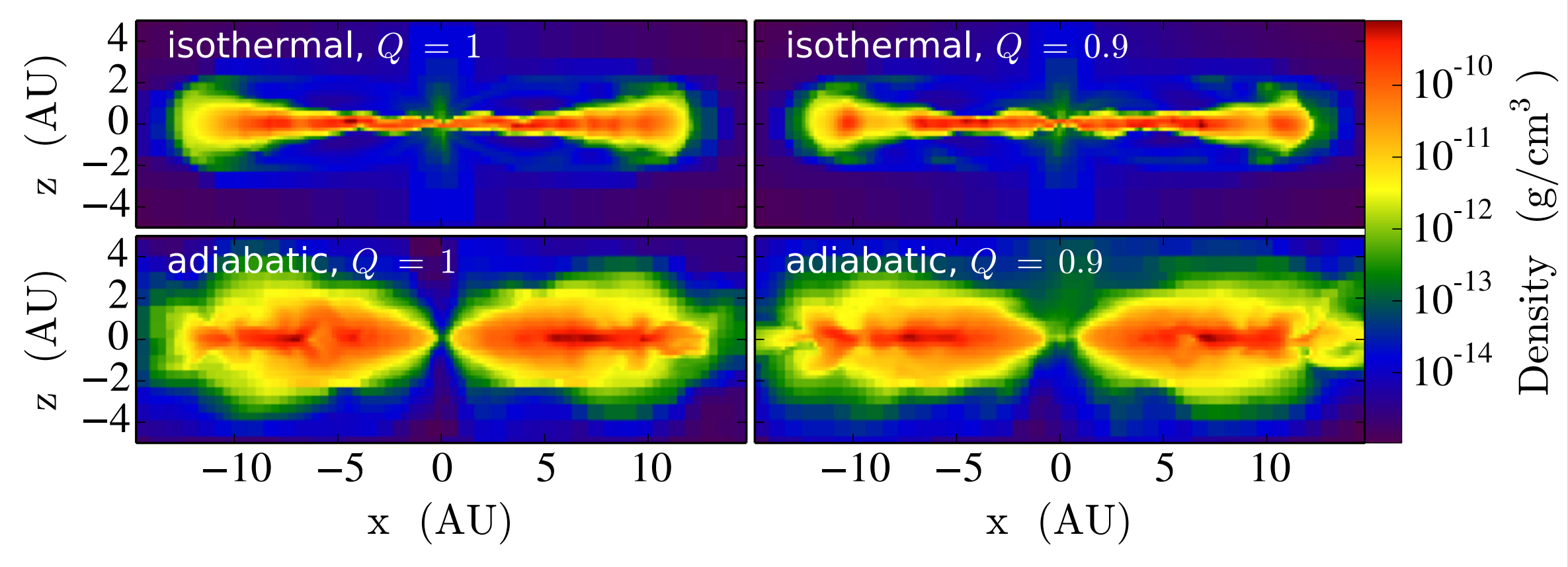

Fig. 2: Comparison of the vertical temperature structure for $t = 80$ yr for all runs.

Disk evolution

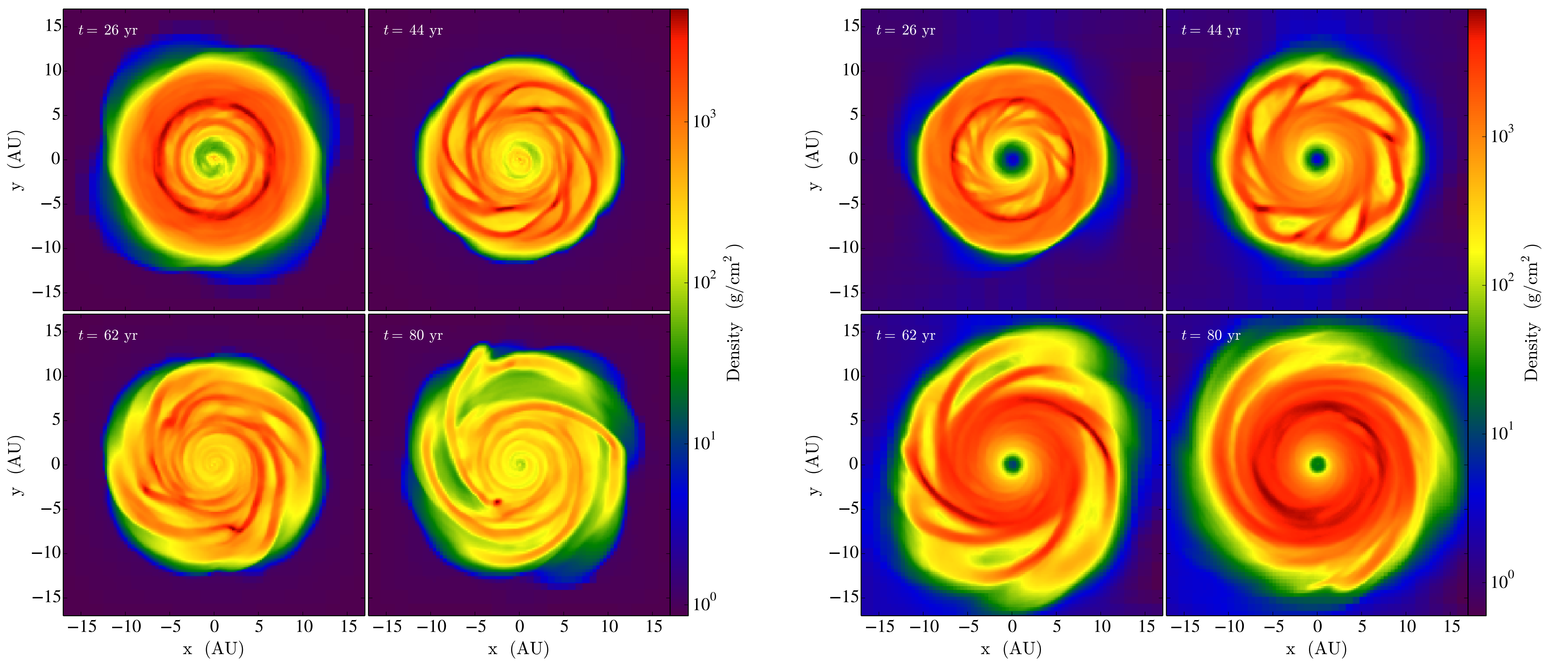

Fig. 3: Evolution of the column density for an isothermal disk (left, $\gamma = 1$) and an adiabatic disk (right, $\gamma = \frac{5}{3}$). Both disks inherit an initial marginally unstable configuration ($Q = 0.9$) and thus show fragmentation and clumping during their evolution.

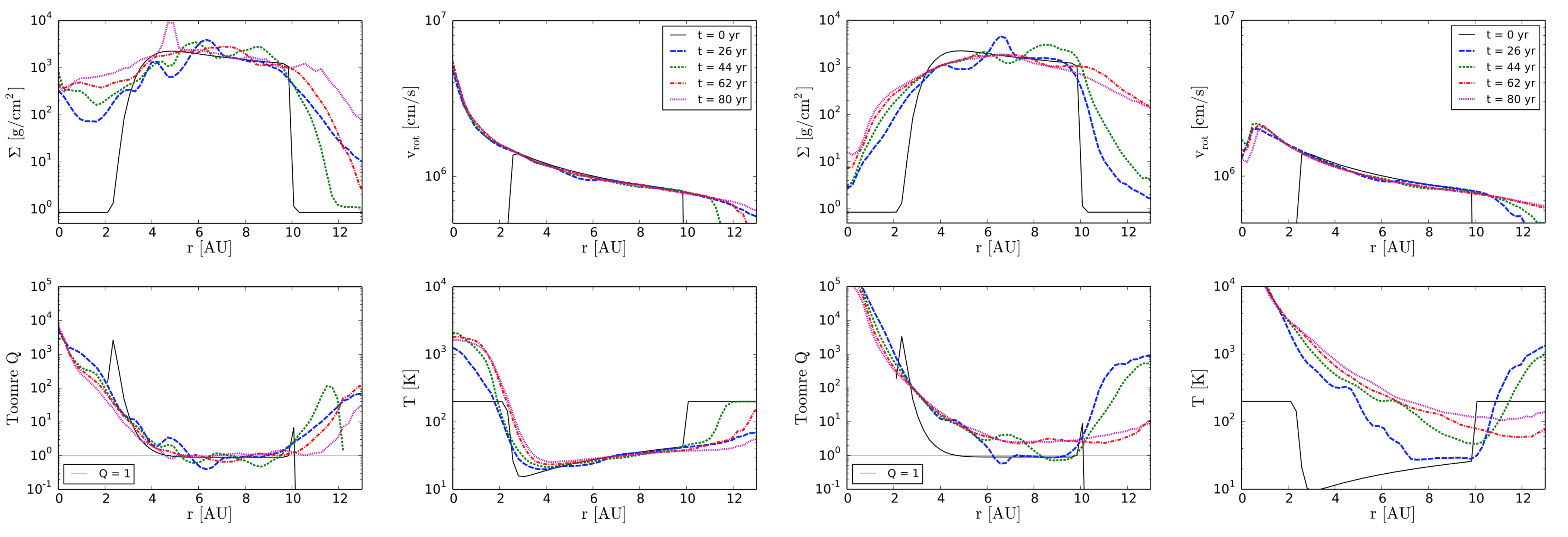

Fig. 4: Radial profiles of the temporal evolution of column density, rotational velocity, temperature and Toomre Q for the above isothermal and adiabatic simulation runs.

Conclusions & outlook

We have presented here **some of the very first AMR simulations** exploring the GI in self-gravitating compact disks. We expect that this technique can provide additional insight into the **formation of massive self-gravitating clumps** in future simulations, which is highly complementary to the existing numerical approaches. This technique **can be combined with additional physics modules** like the chemistry package KROME (Grassi et al., 2014), radiation transport techniques (Wise & Abel, 2011) and a sink particle algorithm (Latif et al., 2013) for an improved modeling of the formation of planets.

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