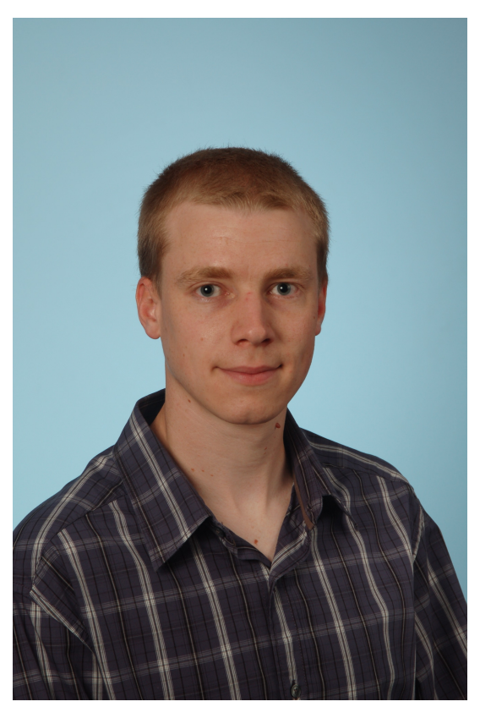
Magnetically driven outflows during massive star formation



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Abstract

We present 3-D MHD collapse simulations of magnetized, rotating prestellar cores. We examine the influence of the magnetic field strength and the rotational energy on the formation of outflows and the stability of protostellar disks. We find a strong dependency of the outflow morphology on the magnetic field strength. Furthermore, for strong magnetic fields the accretion rates depend only weakly on the initial rotational energies.

Introduction

We performed several collapse simulations of rotating prestellar cores using the hydrodynamic code FLASH2.5. The cloud cores contain a mass of **100 M$_\odot$** and are threaded by a magnetic field, which is aligned with the rotation axis. Initially, the core rotates with a **constant angular frequency** and has a density profile **$\rho(r) \sim r^{-1.5}$**. For the heating and cooling processes we use a parametrised cooling function [1]. In the initial setup the **strength of the magnetic field** and the **amount of rotational energy** are varied to study their influence on the outflow formation and the stability properties of the disk. In order to follow the evolution of the outflow over a longer period of time we introduce sink particles above a certain density threshold [2].

The starting points of the simulations are chosen to lay around the line where the magnetic and rotational energy are equal. The initial values of the magnetic and rotational energy (normalized to the gravitational energy) for the different runs are shown in Fig. 1.

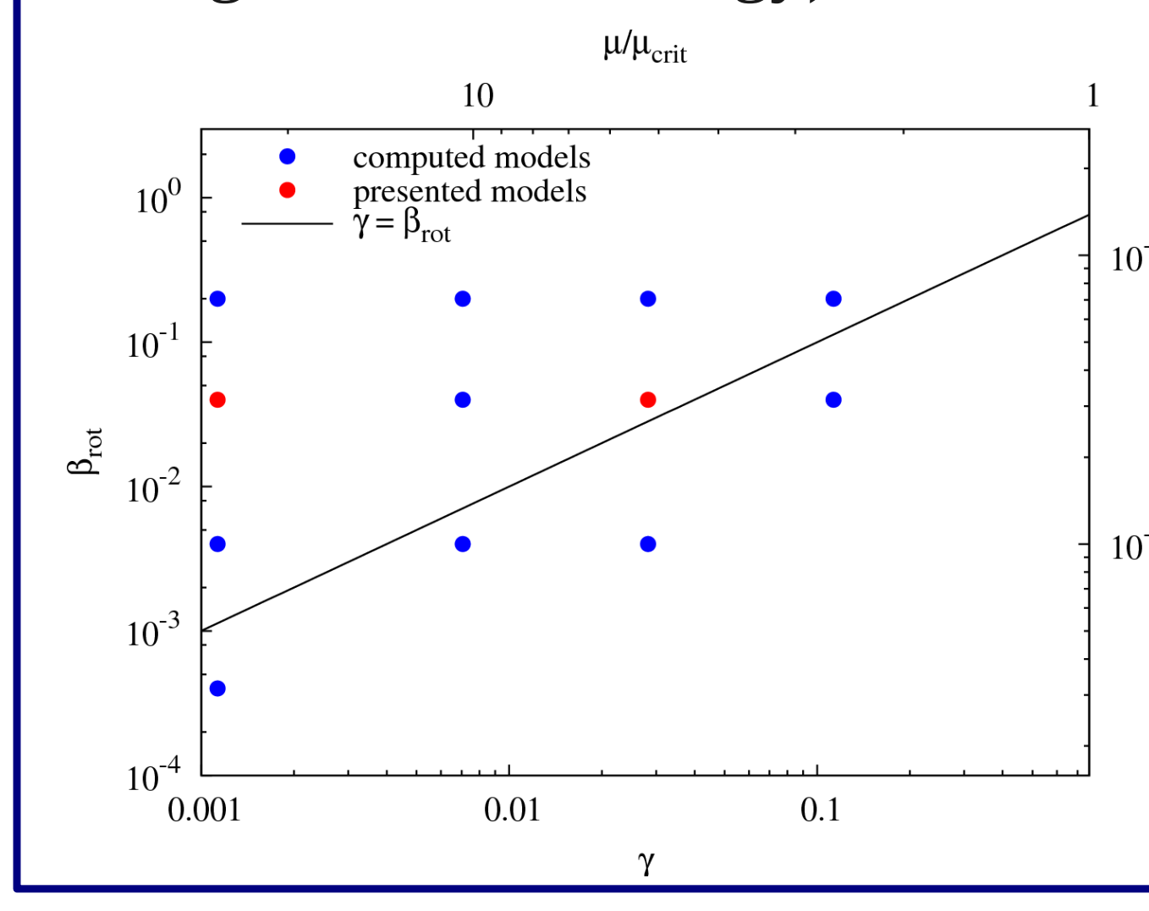

Fig. 1: Initial values of the magnetic (γ) and rotational energy (β_{rot}) normalized to the gravitational energy for the different simulations performed. Also shown are the corresponding μ, which is the mass-to-flux ratio normalized to the critical mass-to-flux ratio, and the angular frequency ω. The models presented here are marked red.

Disk properties

In the following we show results for the runs with a constant β_{rot} = 0.04 but different mass-to-flux ratios of μ = 26 and 5.2.

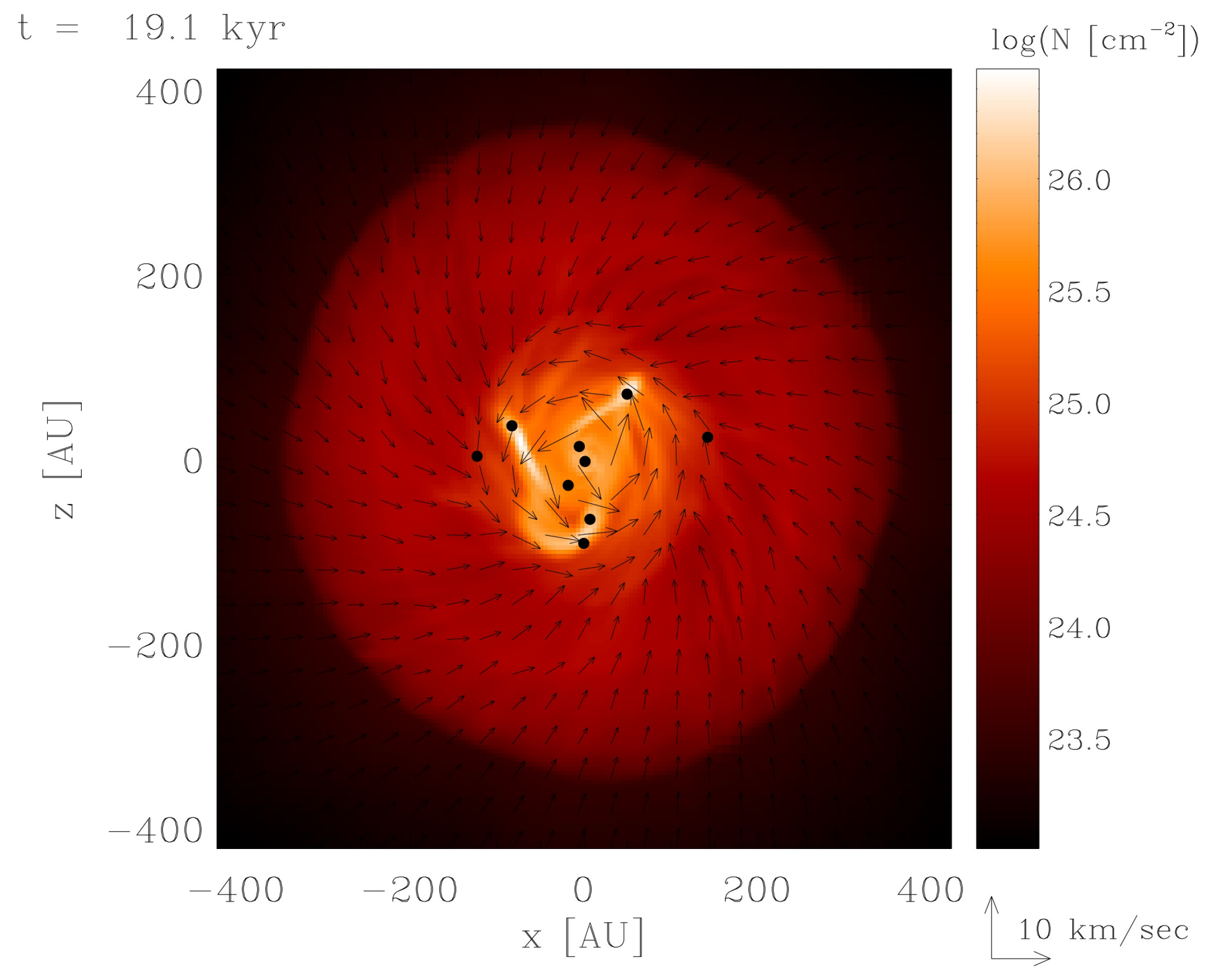

Fig. 2: Density slice through the midplane for the run with β_{rot} = 0.04 and μ = 26. A rotationally supported disk structure develops, which starts to fragment in its subsequent evolution. Black dots show the positions of the individual sink particles. Despite the strong fragmentation, the disk remains still well defined in this late stage.

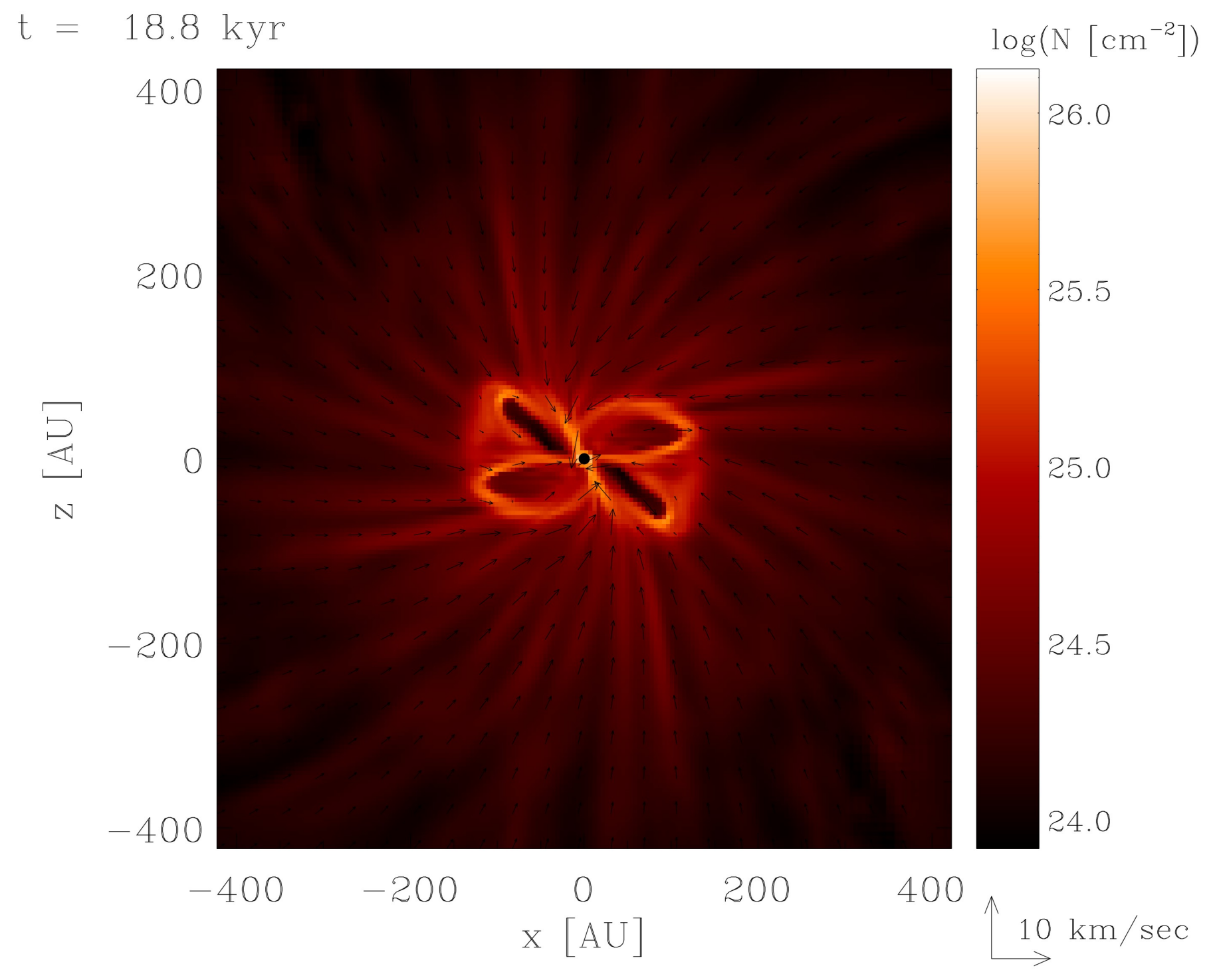

Fig. 3: In the case of a strong magnetic field (μ = 5.2), magnetic braking is very efficient in transporting angular momentum outwards, which prevents a disk from forming. The overall structure differs significantly from the μ = 26 case.

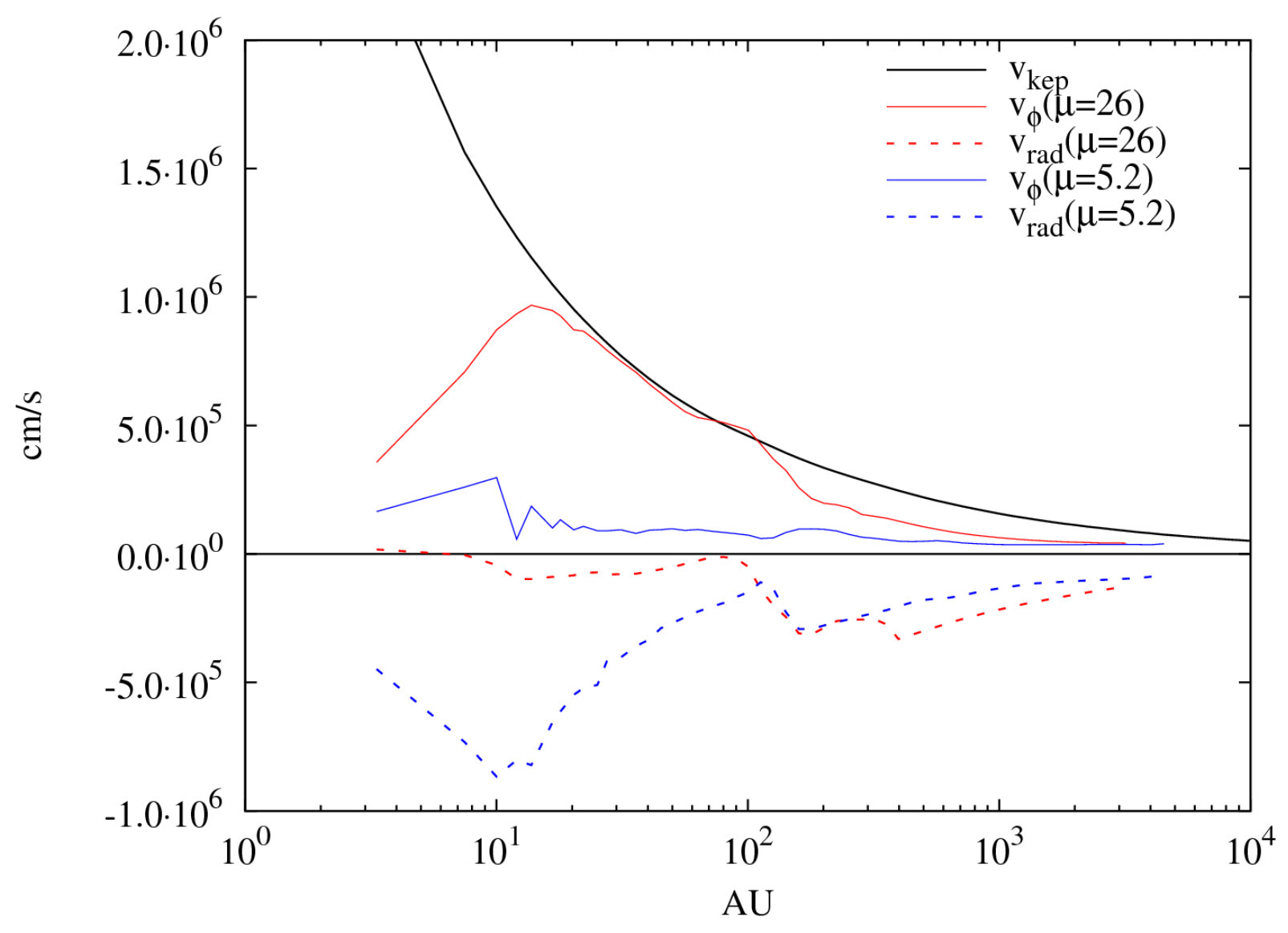

Fig. 4: Keplerian (black), rotation (solid) and radial velocity (dashed) for the same runs as in Fig. 2 and 3. In the weak field case (red) the rotation velocity is close to the Keplerian velocity and a well defined disk has been formed. As can be seen, several centrifugal barriers occur, where the radial velocity drops to zero or even reverts. For a strong magnetic field (blue) magnetic braking gets efficient and the rotation velocity is significantly below the Keplerian velocity and also smaller than the radial velocity.

Outflow formation

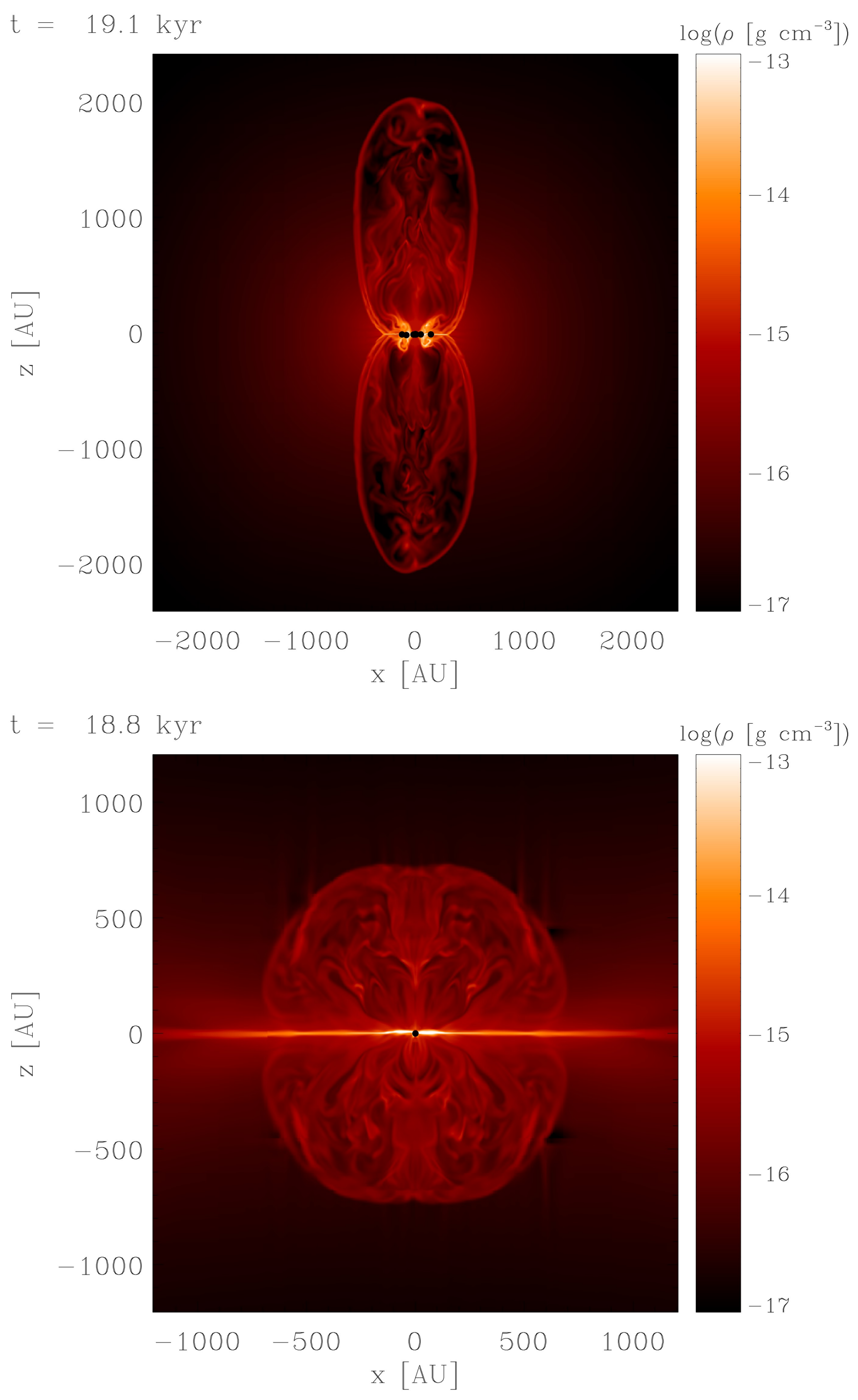

Fig. 5: Density slice along the rotation axis for same runs as in Fig. 2 and 3. There occur large morphological differences in the shape of the outflows. In the weak field case (μ = 26, upper panel) a well collimated outflow develops, while for μ = 5.2 (bottom panel) a sphere-like bubble emerges. We consider both outflows to be magnetic towers [3], which are driven by the magnetic pressure of the toroidal B-field. Both outflows exhibit small-scale substructures generated by hydrodynamical instabilities. Interestingly, for the weak magnetic field the outflow is still expanding further although the disk has already fragmented heavily (see Fig. 2). An interesting observation in the strongly magnetized run is that the outflow bubble grows with roughly the same speed in the horizontal and vertical direction. Also shown are the projected positions of the sink particles (black dots). We note that the upper panel has twice the spatial size as the bottom panel.

Accretion properties

Of special interest is also the influence of the initial setup on the accretion rates. In Fig. 6 we show the dependency of the accretion rates on the initial β_{rot} for some of the simulations performed.

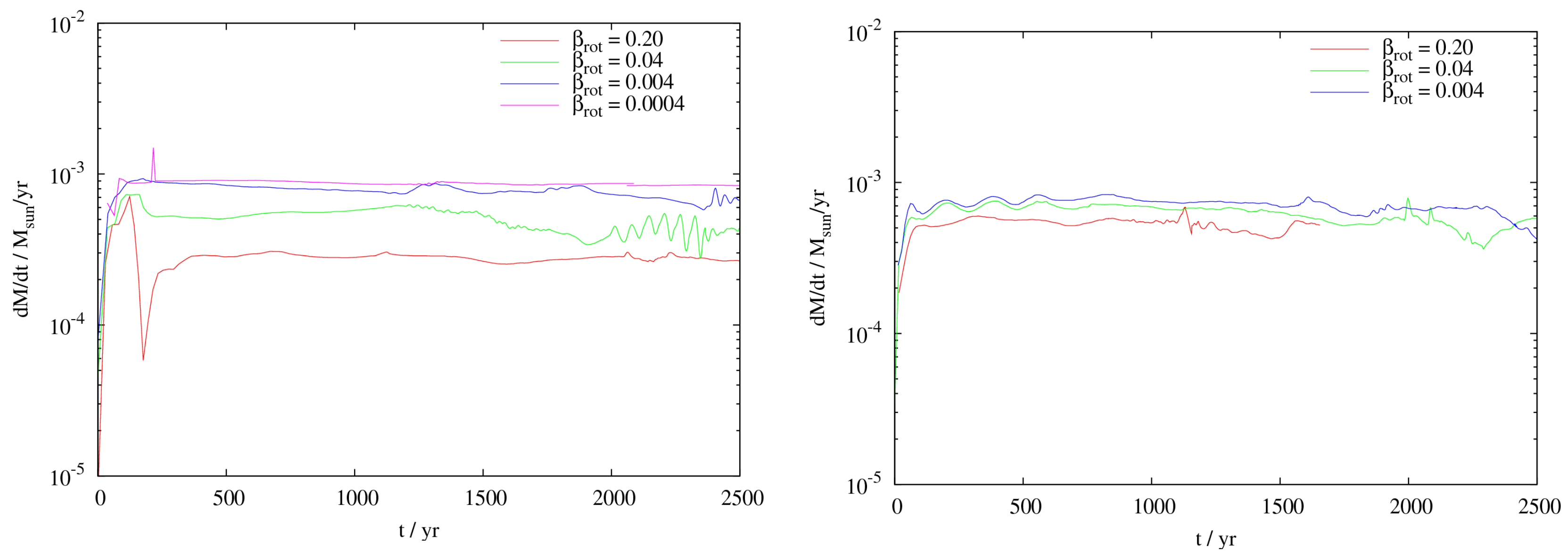

Fig. 6: Accretion rates for simulations with different rotational energies and μ = 26 (left) and μ = 5.2 (right). As expected, for both sets of simulations the accretion rates decrease with increasing rotational energy. One can observe that for stronger magnetic fields (right panel) the differences in the accretion rates are smaller than for weak magnetic fields. This is due to the magnetic braking effect, which – for strong fields – reduces the angular momentum to roughly the same level independent of the initial rotational energy content.

Comparing accretion rates for different field strengths but equal rotational energies reveals no clear trend. This is due to the ambiguous effect of magnetic fields. On the one hand, magnetic fields can increase the accretion rate by removing angular momentum via the magnetic braking mechanism. On the other hand, magnetic pressure and tension counteract the gravitational force and therefore lead to smaller accretion rates. Which of these both effects influences the dynamics stronger, depends strongly on the strength of the magnetic field and the amount of angular momentum.

From Fig. 6 one can see that the accretion rates reach values up to several 10^{-4} M$_\odot$/yr. Such high accretion rates lead to protostellar masses of a few M$_\odot$ within several thousand years. So far, the most massive protostars in this simulations have masses of up to 3.5 M$_\odot$.

Conclusions

Outflow evolution and fragmentation properties of disks in high mass star forming regions depend strongly on the initial state of the prestellar core. In all simulations performed so far, outflows, driven by magnetic pressure, develop though shape and growth rates differ significantly. Stronger magnetic fields also seem to suppress the formation of protostellar disks by removing angular momentum. Interestingly, the accretion rates for different setups only vary by a factor of a few though trends depending on the initial conditions are observable. For further studies it is planned to include an improved cooling function as well as initial turbulent motion which are observed frequently in massive prestellar cores.

[1] Banerjee R., Pudritz, R., Anderson, D.W. 2006, MNRAS, 3737, 1091
[2] Federrath, C., Banerjee, R., Clark, C., Klessen, R.S. 2010, ApJ, 713, 269
[3] Lynden-Bell, D. 2003, MNRAS, 341, 1360