The early era
How do protostellar discs form?

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Introduction

Discs are key element in star and planet formation: protostars probably grow by accreting material from protostellar accretion discs, which at later stage are the natural progenitors of planets. The formation of discs is a challenging theoretical question, and the conditions for their presence remain unclear.
Magnetic fields certainly play an important role, and they can efficiently transport angular momentum away from the central regions of the collapsing core, thereby preventing the early formation of massive discs. This occurs even for relatively low magnetic field intensities [3, 4, 5], at a level largely in accordance with the observational measurement of core magnetizations [6, 7]. However, most of previous simulations were yet performed in a particular configuration, where the magnetic field and the rotation axis are initially aligned and without turbulence.
We therefore perform three-dimensional, adaptive mesh, numerical simulations of magnetically supercritical collapsing dense cores in both non-turbulent and turbulent environment, using the magneto-hydrodynamic code Ramses [8, 9].

Initial conditions: the ingredients

The key ingredients to form stars and discs are:

1. a density profile [11, 10]: $\rho = \dfrac{\rho_0}{1+(r/r_0)^2}$;
2. a magnetic field [6, 7]:

$$\mu = \frac{M/\Phi}{(M/\Phi)_{\text{crit}}}, \quad \text{with} \left(\frac{M}{\Phi}\right)_{\text{crit}} \sim \frac{1}{3\pi}\left(\frac{5}{G}\right)^{1/2}$$

(M is the mass of the core, Φ the magnetic flux threatening it);

3. a bit of rotation [12]: $\beta = E_{\text{rot}}/E_{\text{grav}} \sim 0.03$;
4. some turbulence (preferably transonic [13]): Mach number $\mathcal{M}$ between 0 and 1.9.

Focus on $\mu = 5$ (intermediate magnetization)

Angular momentum transport

- the momentum conservation is given by:

$$\partial_t \rho \mathbf{v} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v} - \mathbf{B} \otimes \mathbf{B}/4\pi) + \nabla P = 0,$$

- from its azimuthal component in cylindrical frame, one gets:

$$\partial_t(\rho r v_\phi) + \nabla \cdot \left[\rho r v_\phi \mathbf{v} + r\left(P + \frac{B^2}{8\pi} - \frac{g^2}{8\pi G}\right)\mathbf{e}_\phi + \frac{r g_\phi \mathbf{g}}{4\pi G} - \frac{r B_\phi \mathbf{B}}{4\pi}\right] = 0$$

It gives the angular momentum evolution with respect to:

- **dynamical torque**: $\rho r v_\phi \mathbf{v}$ $\Rightarrow$ bipolar outflows, accretion
- **magnetic torque**: $r B_\phi \mathbf{B}/4\pi$ $\Rightarrow$ magnetic braking
- **gravitational torque**: $r g_\phi \mathbf{g}/4\pi G$ $\Rightarrow$ gravitational waves

Orientation matters [1]

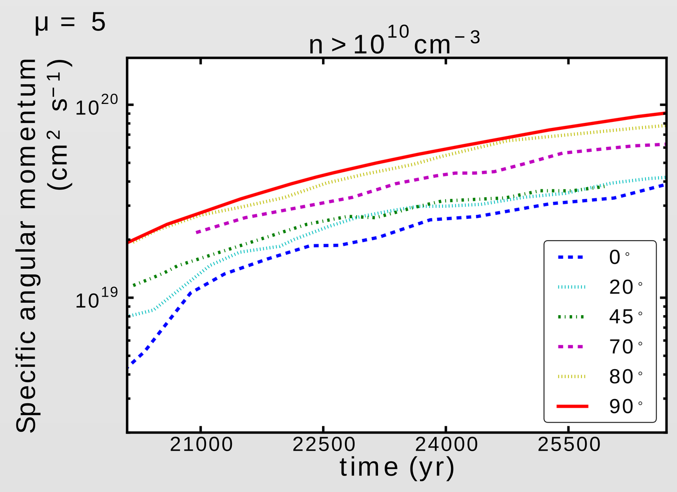
We realize a set of simulations with an initial mass of 1 $M_\odot$ and an angle α between the rotation axis and the magnetic field varying from 0 to 90°.

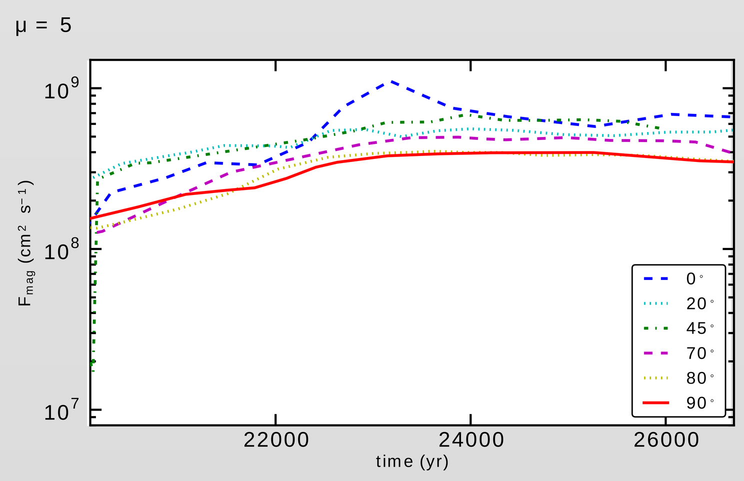
- it affects the transport of angular momentum: specific angular momentum increases with α;
- indeed, transport processes are less efficient when α increases

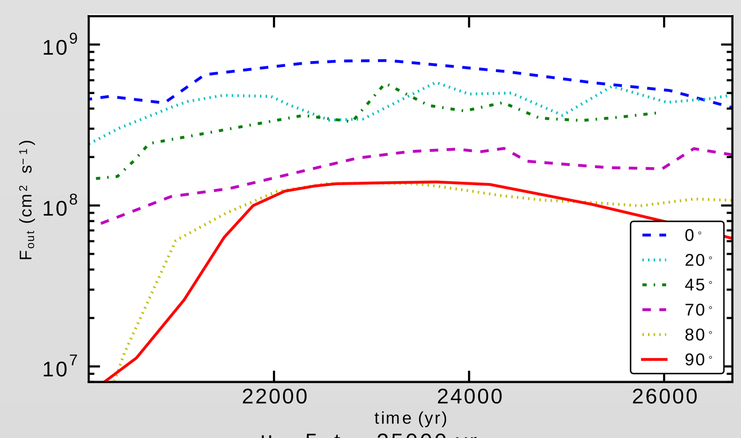
Magnetic and dynamic torques are given by:

$$F_{\text{mag}} = \left|\int_S r\frac{B_\phi}{4\pi}\mathbf{B}\cdot d\mathbf{S}\right| \text{ and}$$

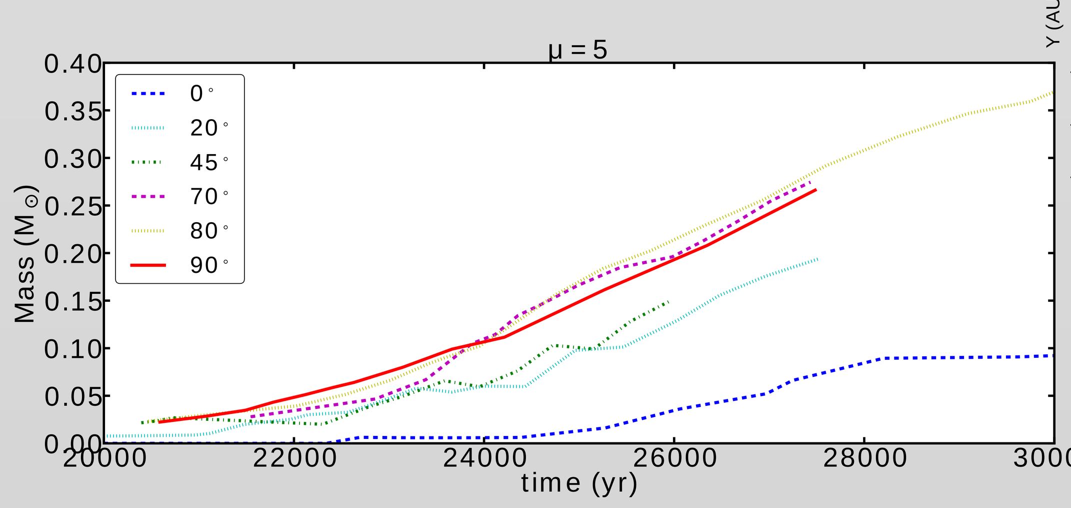
$$F_{\text{out}} = \left|\int_S \rho r v_\phi \mathbf{v}\cdot d\mathbf{S}\right|, \ \mathbf{v}\cdot d\mathbf{S} > 0$$

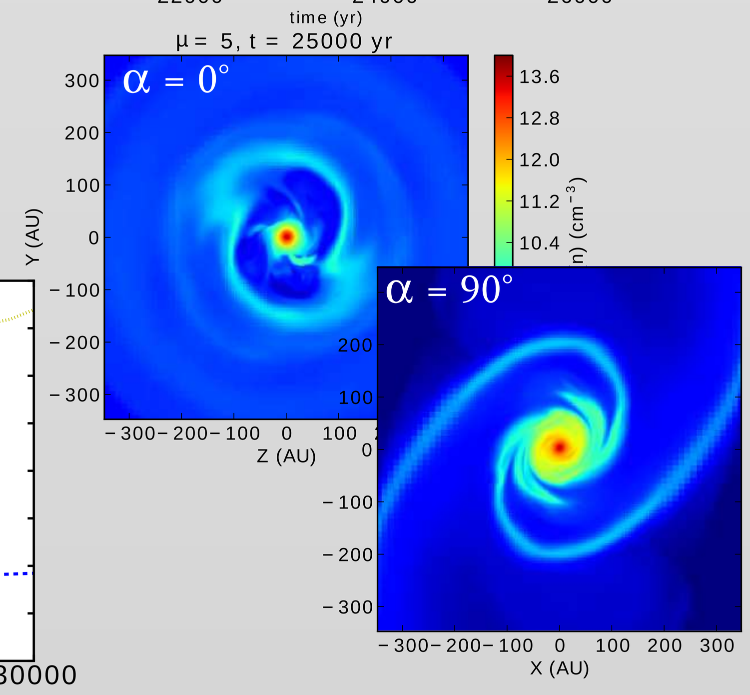






- **more massive discs can form**





The role of turbulence [2]

The initial mass of the core is 5 $M_\odot$; more massive clouds are expected to be more turbulent [14].

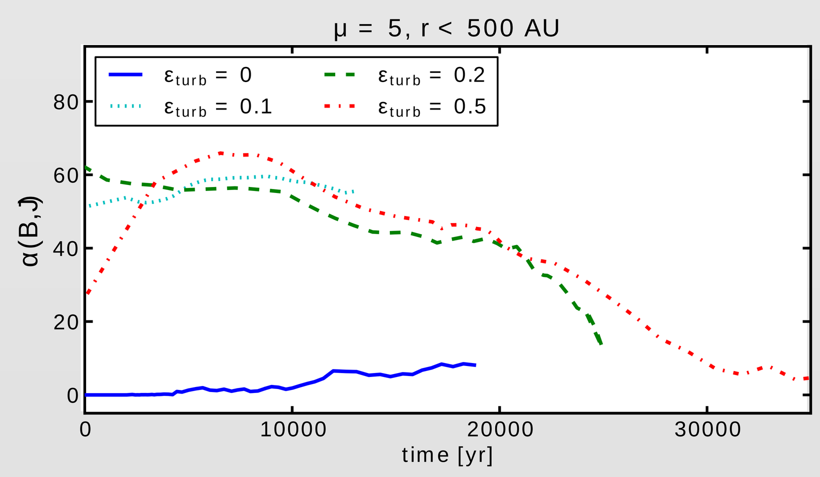
Note that ϵ_{turb} = 0, 0.1, 0.2 and 0.5 stand for Mach number $\mathcal{M}$ = 0, 0.85, 1.2 and 1.9.

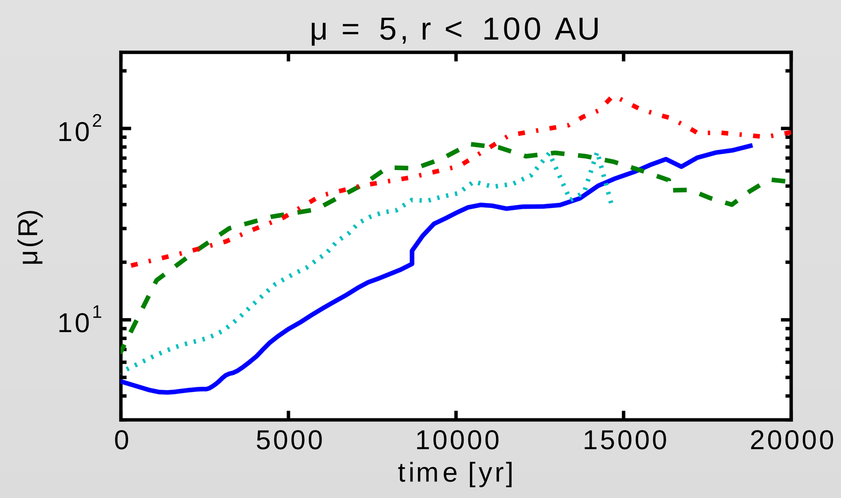
Two effects can be seen:

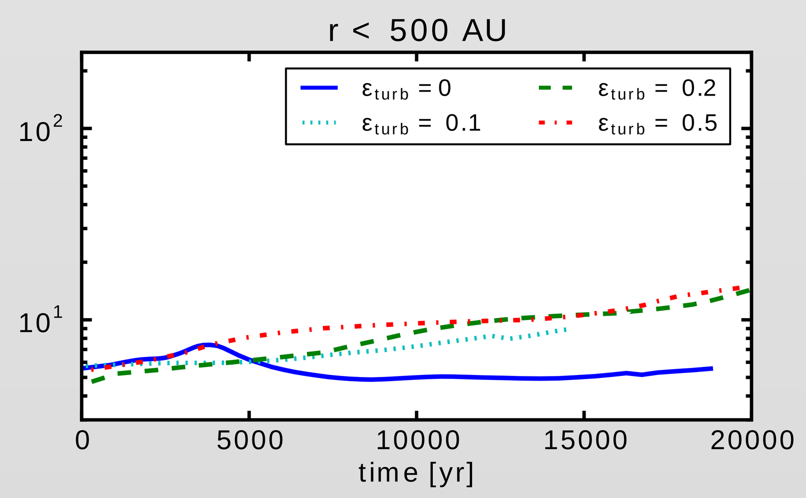
- turbulence tilts the rotation axis;
- turbulence diffuses out efficiently the magnetic flux

it can be estimated with:

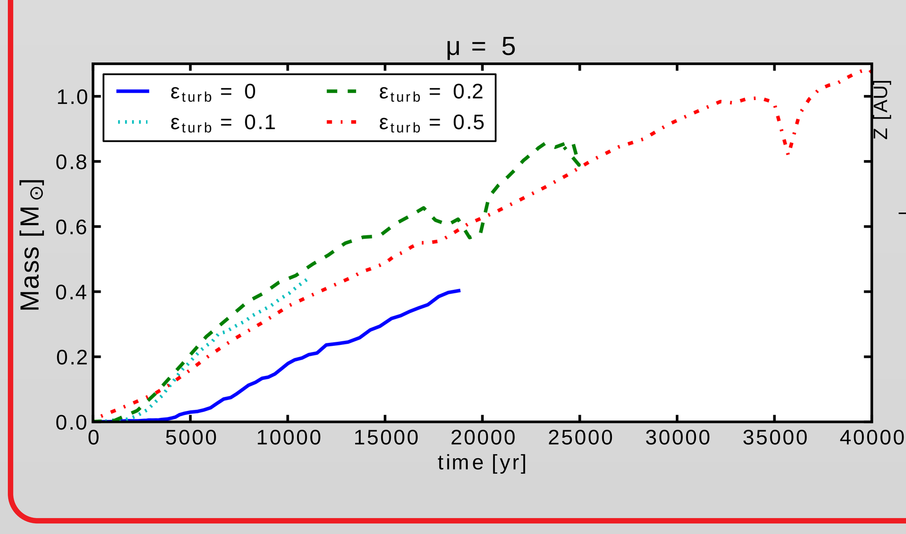
$$\mu(R) = \frac{M(R)}{\pi R^2 \langle \mathbf{B} \rangle} \Big/ \frac{1}{2\pi\sqrt{G}}$$

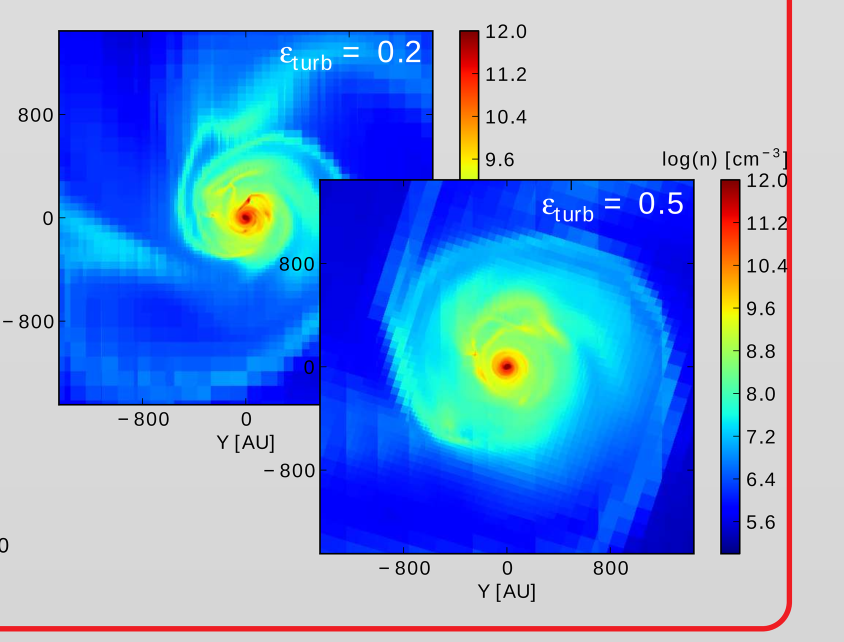






$\Rightarrow$ **Discs are more massive:**





Conclusions

At variance with earlier analyses, we show that the transport of angular momentum acts less efficiently in collapsing cores with non-aligned rotation and magnetic field. We also show that the turbulence is responsible for a misalignment between the rotation axis and the magnetic field and can diffuse out the magnetic field of the inner regions efficiently. The magnetic braking is therefore reduced, and massive discs can be built.
The early formation of massive discs can take place at moderate magnetic intensities if the rotation axis is tilted or in a turbulent environment, because of misalignment and turbulent diffusion.

References

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