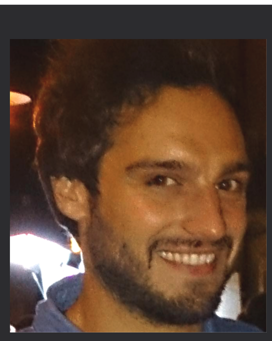
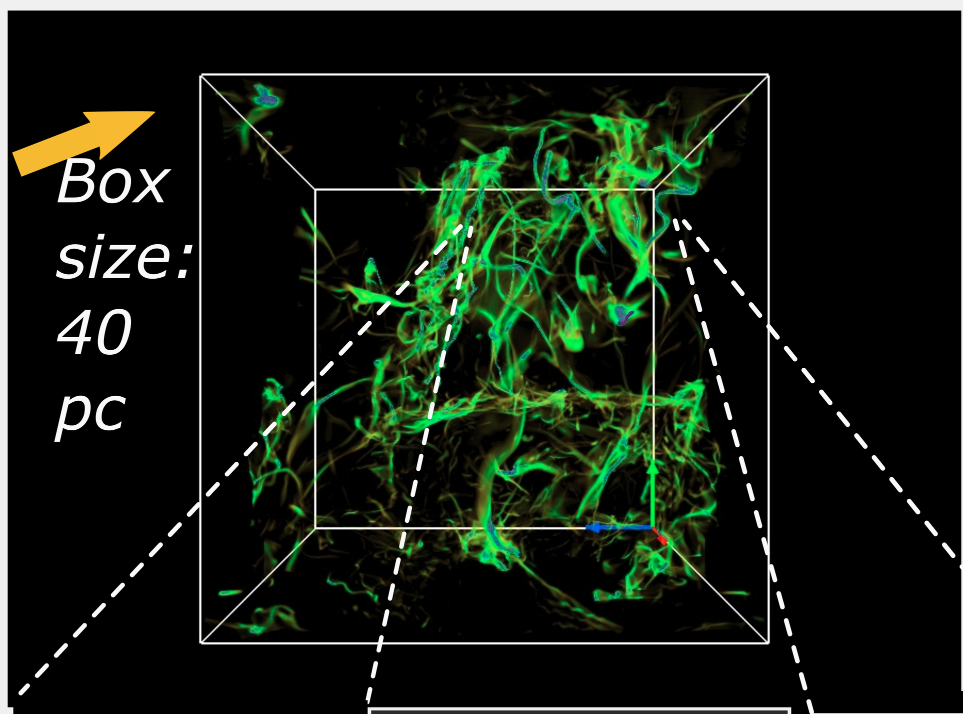


Zooming in on Protoplanetary Disk Formation

Michael Küffmeier [(1) (2)]
[(1)] Centre for Star and Planet Formation, University of Copenhagen, Denmark
[(2)] Niels Bohr Institute, University of Copenhagen, Denmark

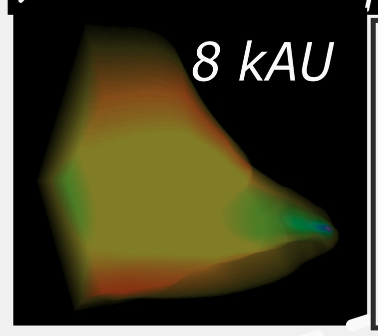
Motivation

Protoplanetary disks are a consequence of star formation and are considered as the region of planetary birth and evolution. While disk dynamics have been modeled for decades with a standard accretion disk approach considering a viscosity parameter α, the question of initial disk formation and the influence of the stellar environment has been ignored. However, stars have different environments. Taking this fact into account, we start from first principles, i.e.: from GMC collapse.

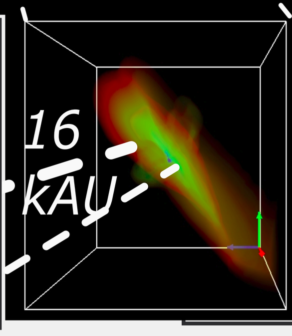


Code:

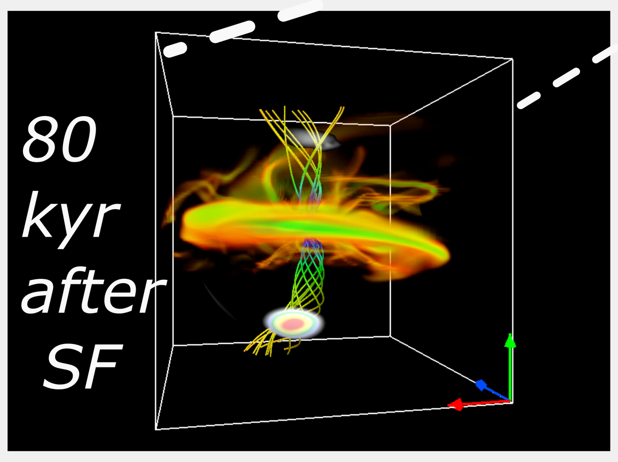
Modified version of AMR code RAMSES solving the equations of MHD



Pre-stellar cores can have different shapes, even for stars of similar masses.

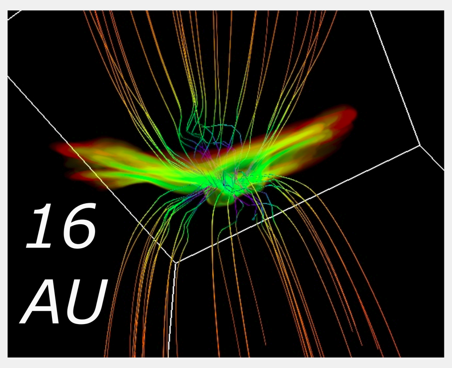


RAMSES code: R. Teyssier
Modifications: T. Haugbølle and Å. Nordlund



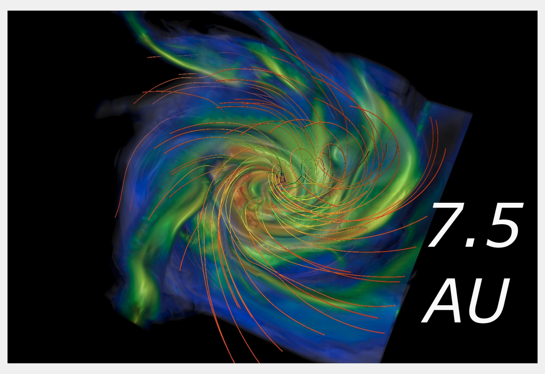
Magnetic Fields are anchored to large scales and cause Magnetic braking.
Magnetic towers collimate jets.
Magnetic field lines are bent, outflows are rather asymmetric due to turbulence.
No magnetic braking catastrophe!

5 kyr after SF



Hour-glass shaped

50 kyr after SF



Toroidal

Separation of scales due to Larson's velocity dispersion relation

$$\sigma \propto L^{0.4}$$

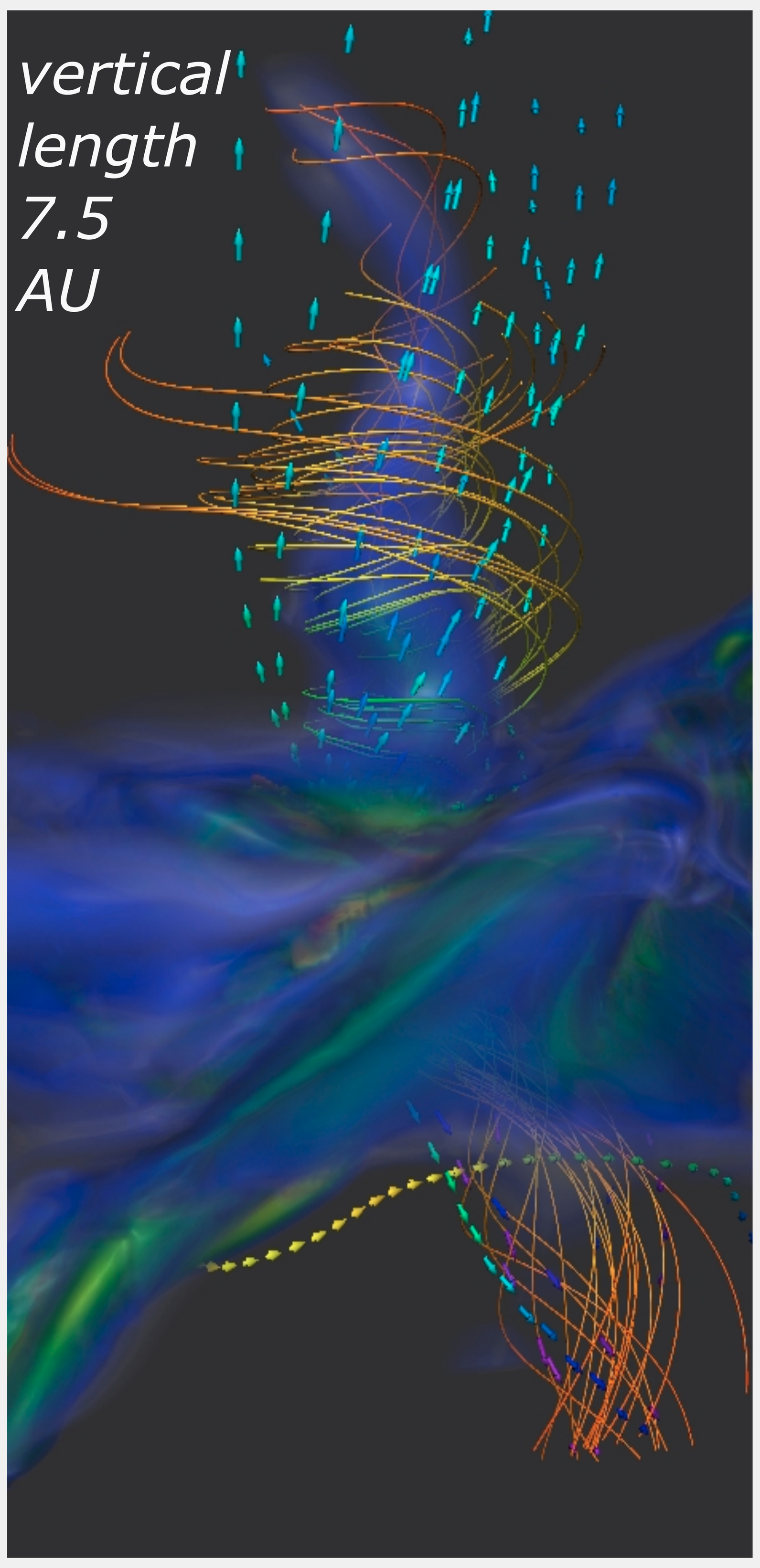
Larger spatial scales evolve on longer time scales

3 Steps of Zooming-in

1) Simulate the molecular cloud with highest refinement of 128 AU for a few million years to create a sample of sink particles

2) Pick out sinks to zoom-in with highest resolution of 2 AU and run for several time scales of stellar evolution of ~ 100 yrs

3) Increase the refinement to a minimum cell size of 0.016 AU => resolve inner disk profile for a few hundred years

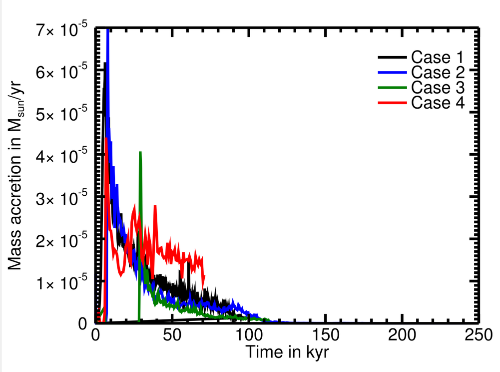


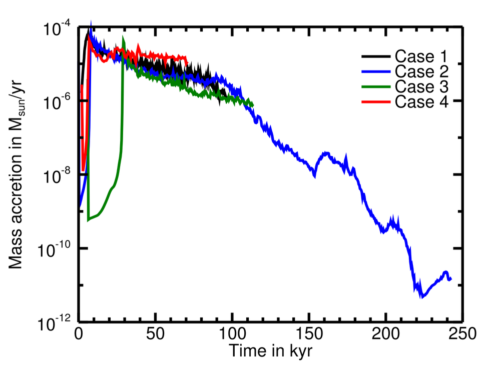
Massive outflow in a protostellar jet
The continuous color scheme represents density (roughly about 10^{-13} g/cm³ in the jet), the lines are the magnetic field lines and the arrows represent the velocity field. The outflow is launched with velocities of more than 200 km/s, while the magnetic field strength close to the star is tens to even more than 100 Gauss, though these magnetic values are probably overestimated due to the lack of non-ideal effects. Note that even for the lower resolution runs, outflows are launched, which are of lower velocity because of a larger launching radius and a corresponding lower Kepler speed.

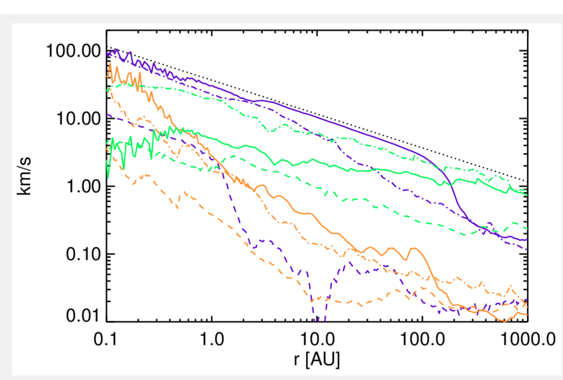
Want to see more?

Disk accretion process

- Accretion onto the disk is not homogeneous and occurs through filaments (cf. Seifried 2013)
- Accretion profiles can differ a lot for individual stars
- Typically, high initial phase of accretion, which quickly falls off after a few thousand years

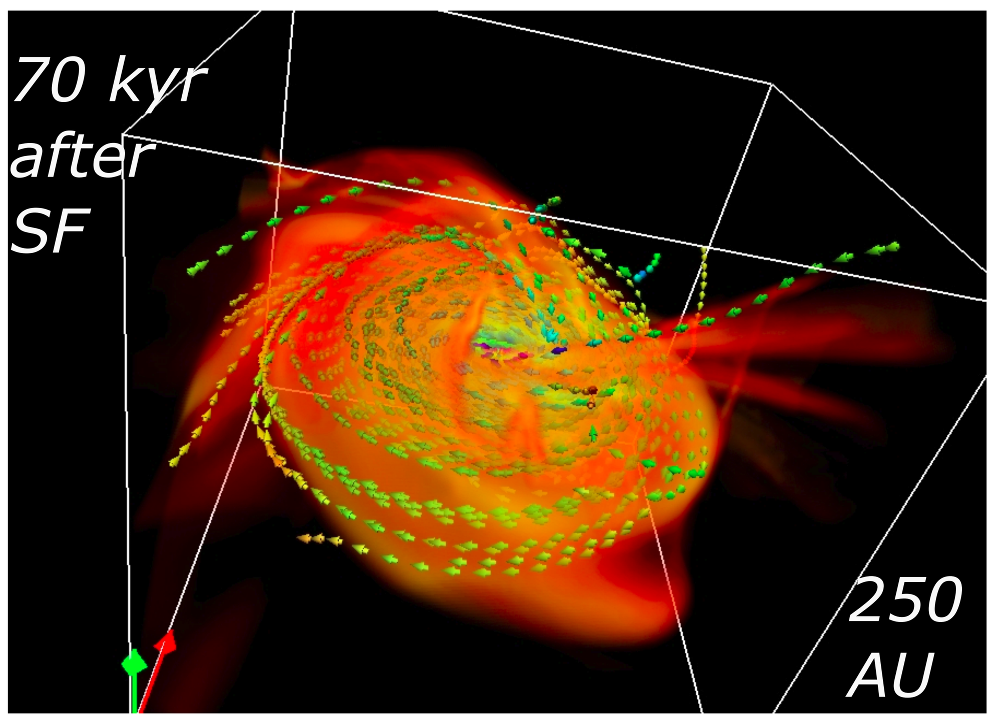






Radial profiles of characteristic velocities at three epochs; 2 kyr (dashed), 50 kyr (dot-dashed), and 100 kyr (full drawn). From top to bottom the three curves (blue, green and orange) for each epoch are: the mass weighted rotational velocity, the average Alfvén speed ($B_{rms}/\sqrt{4\pi\rho_{rms}}$), and the root mean square velocity dispersion. The dotted straight line (slope -1/2) shows the Keplerian rotation speed for the fully accreted star.

Outlook:
Implementatiton of radiative transfer (ray-tracing routine developed by T. Frostholm), chemical evolution network (KROME package by T. Grassi) and non-ideal MHD terms



Conveyor belt?
Since a lot of the stellar mass is ejected in protostellar outflows and replenishment times, i.e. the average time of the gas in the disk is rather short at most of the order of thousands of years, an explanation for chondrules with age differences of millions of years is challenging. A possible explanation could be to produce many chondrules in the disk, which are then ejected in outflows. Most of them will leave the system, but some will eventually be stored in the envelope and accrete back on the disk at a later stage of more evolved protoplanetary disk evolution.

Summary

Protoplanetary disk formation depends on stellar environment and varies for each individual star

Accretion onto the disk is inhomogeneous and happens through accretion channels

Angular momentum is reduced due to magnetic braking induced by magnetic fields anchored to larger scales

Magnetic fields launch jets and outflows

Inherited large-scale turbulence leads to "chaotic" process =>
The old scenario is SAD, however the solution is CiMBLE (Chaotic Magnetic Braking by Large-scale Effects)