# Star-disk magnetospheric interaction in 3D with tilted stellar field

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# Outline

- Introduction
- Star-disk magnetospheric interaction simulations
- A simple setup for complicated 3D MHD simulations with PLUTO
- Summary

# Introduction: need for a simple tool for complicated 3D MHD simulations

"Numerical experiments" in astrophysics are different than their technical, engineering counterpart, mostly because of immense distance and time scales involved. Assumptions used in numerical simulations in astrophysics are often outrageously simplified, because of technical limitations. The laboratory check is often impossible,  for many problems we can not produce the needed conditions in the lab. Scaling of the results from matchbox dimensions to stellar or galactic dimensions is rather usual approximation. The proverbial "sanity check" in many cases is pure insanity.

1D simulations are, in this respect, less dangerous, as their claims are modest, necessarily resorting to height and volume-averaging in comparisons with the full 3D description. In the simplest-but important-cases like shocks in the flows they work perfectly and as such are used in the standard tests of codes.

2D simulations produce visually more realistic results, but often qualitatively differ from reality-just think of the problem of rotating flow, with whirls and spirals, or the long-standing problem of magnetic reconnection, which still puts a question mark above most of the magnetic results in astrophysical simulations. So called 2.5D simulations, which are axisymmetric 2D simulations, are usually well motivated in astrophysics, but… rarely enough.

Full 3D simulations are a must, and today we reached the technical possibility of conducting them at our desktops or laptops. Research can be done on the state of the art facilities, but for teaching it we need simple and reliable tools. I will present one such setup for star-disk magnetospheric interaction with the publicly available code PLUTO.

# State of the art in star-disk simulations

More than 20 years ago (2002) A. Koldoba from Keldysh Institute in Moscow made a setup with cubed sphere grid for the group of Marina Romanova in Cornell University. They started producing results for star-disk magnetospheric interaction with this setup, which set a challenge to other groups.

Papers were many, but problem was that the code was not publicly available.

My goal was to make something with publicly available code, with the simpler setup than their cubed sphere, but also powerful enough to simulate young stars with multipole magnetic fields or neutron stars with the magnetic dipole (or multipole) tilted with respect to the stellar rotation axis, which is a challenging demand.

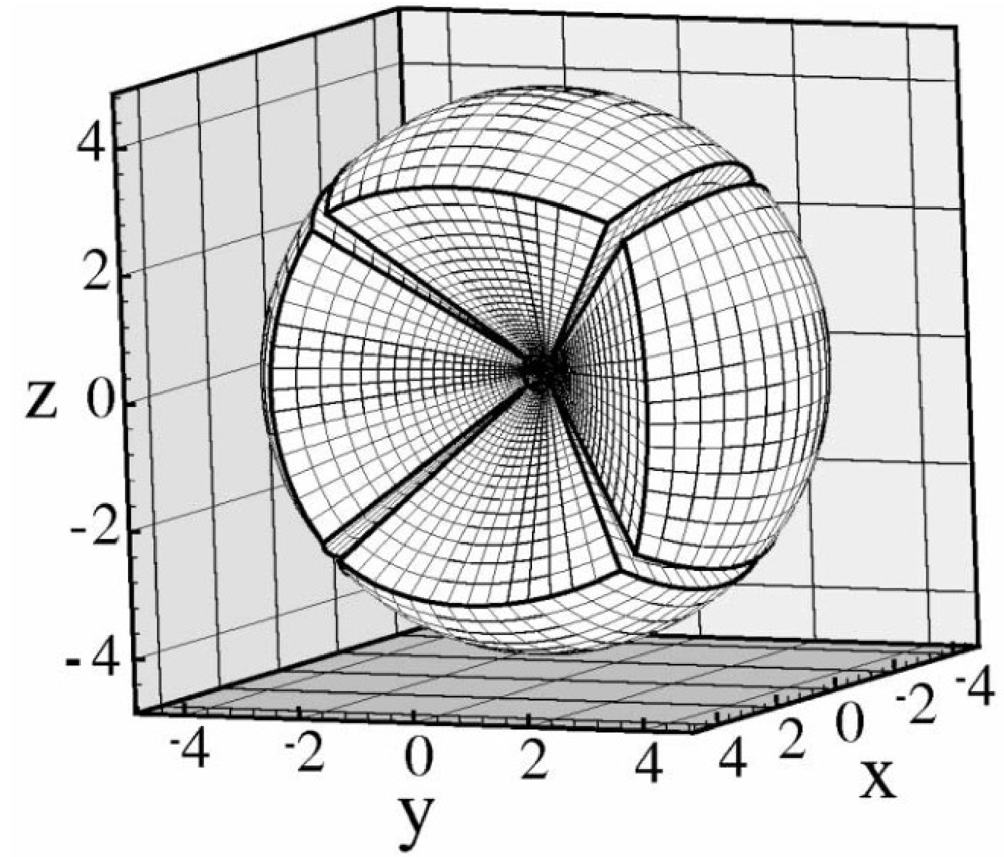



FIG. 1.—Cubed sphere grid, which consists of six sectors. The $+x$ sector is omitted in order to show the inner structure of the grid. Grid is inhomogeneous in the $R$-direction in such a way that the cells are roughly cubical independent of $R$.

# Results of the Marina Romanova group

Using the cubed sphere setup, M. Romanova reported results at ALMA meeting more than decade ago:

# Results of the Marina Romanova group

Through the years, their group made many contributions:

3050 *A. K. Kulkarni and M. M. Romanova*

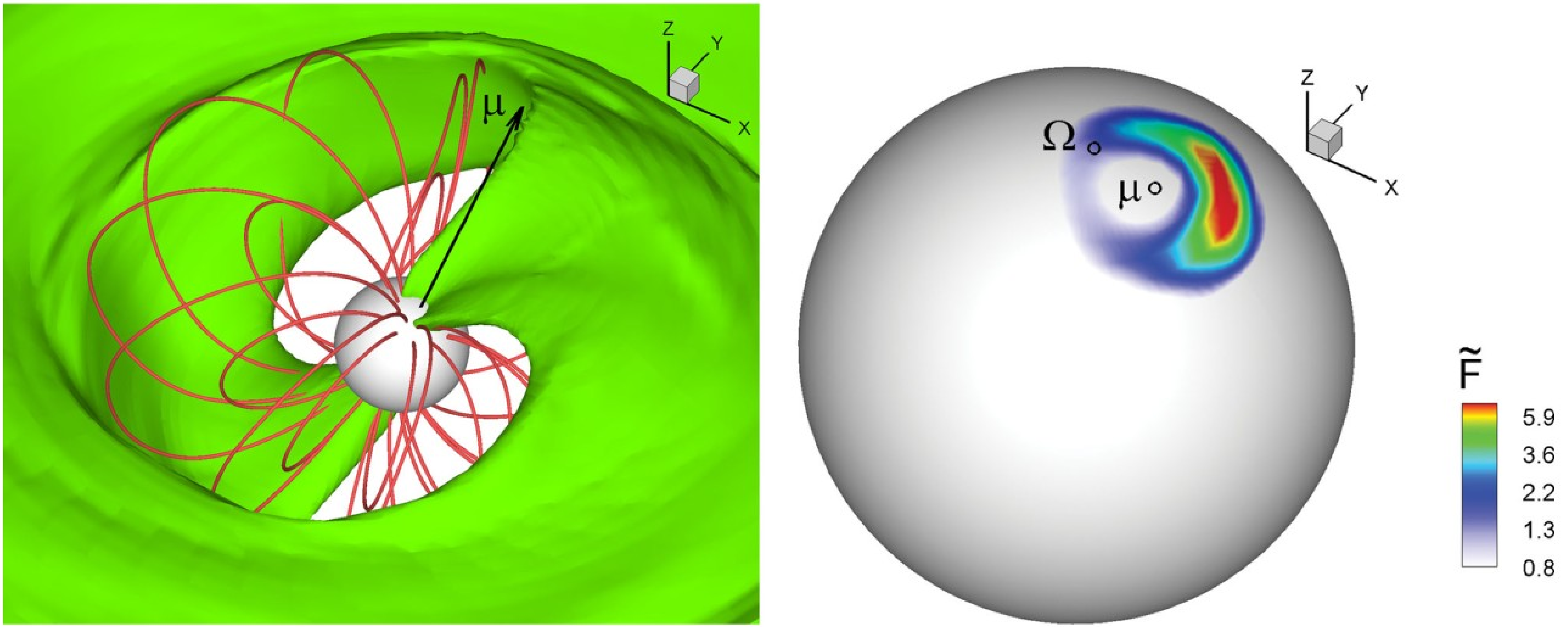
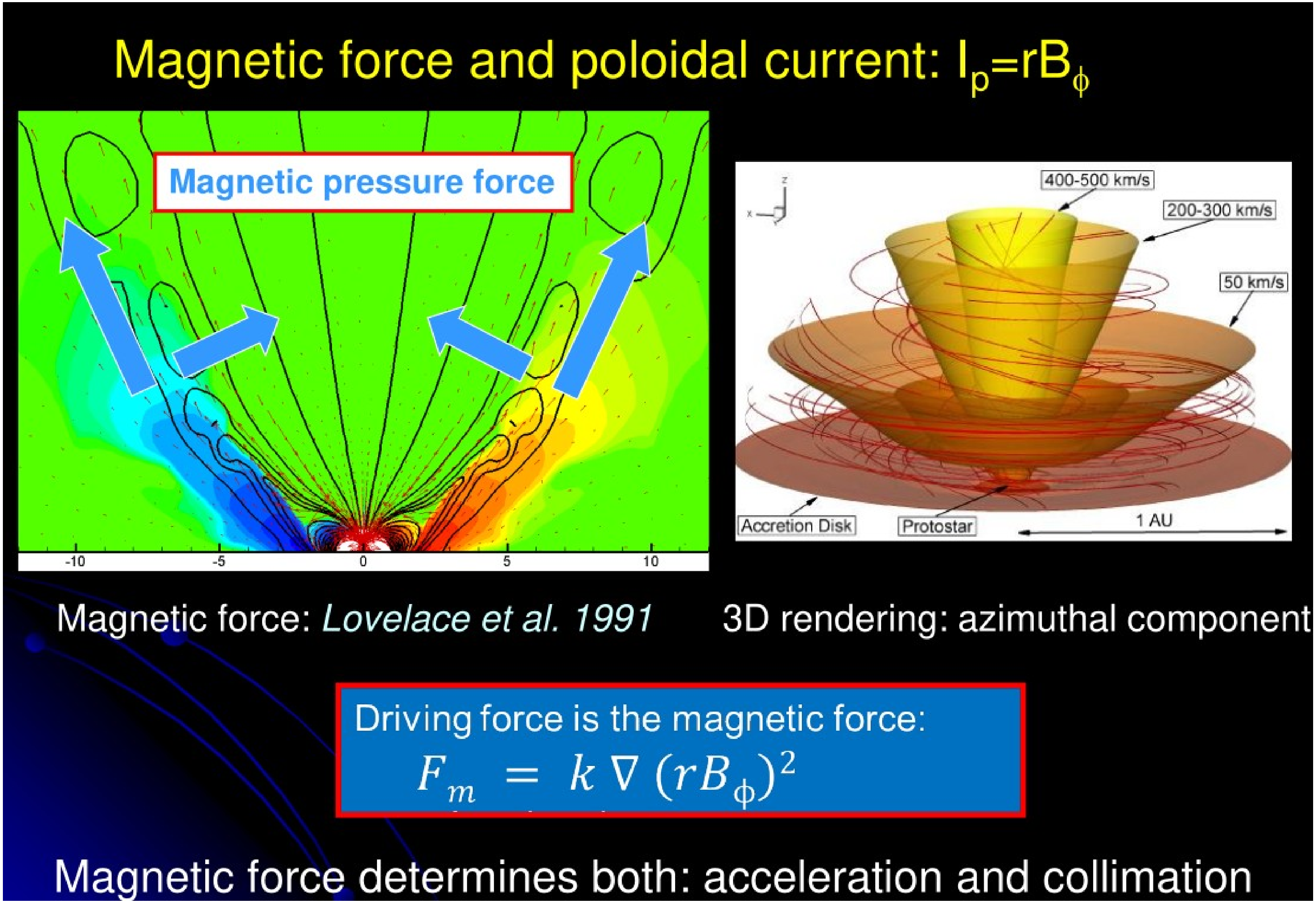



**Figure 1.** Left-hand panel: a 3D view of the funnel flow from the disc to a magnetized star, where the dipole moment $\mu$ is tilted by $\Theta = 20^\circ$ about the rotational axis. One of the density levels is shown in green; sample field lines are shown in red. Right-hand panel: the energy flux distribution on the surface of the star. The circles show the position of the magnetic ($\mu$) and rotational ($\Omega$) axes, respectively. Other parameters are $\tilde{\mu} = 2$ and $r_c = 2$.

# Results of the Marina Romanova group

They also did a lot of good physics there:



# A simple tool in PLUTO for complicated 3D MHD simulations

Problem was, again, with the fact that the code used by MR group is not publicly available and others with Newtonian codes somehow did not follow-up at that time.

Meantime, in GR community simulations went far into 3D, while in star formation (YSOs) and white dwarfs we still lacked a simple setup capable of delivering similar simulations. I hoped that someone will provide it, but e.g. with PLUTO there was no such development, and other codes somehow were not following.

In a paper with Tomek Bulik, (way) back in 1998, I had this less-than-spectacular drawing of a pulsar:

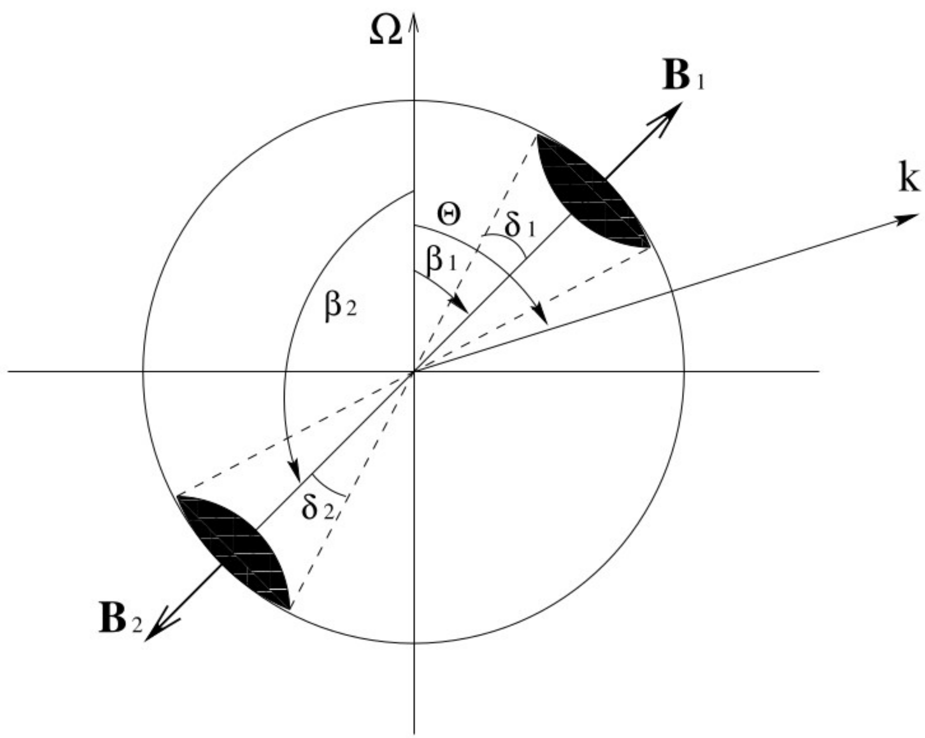
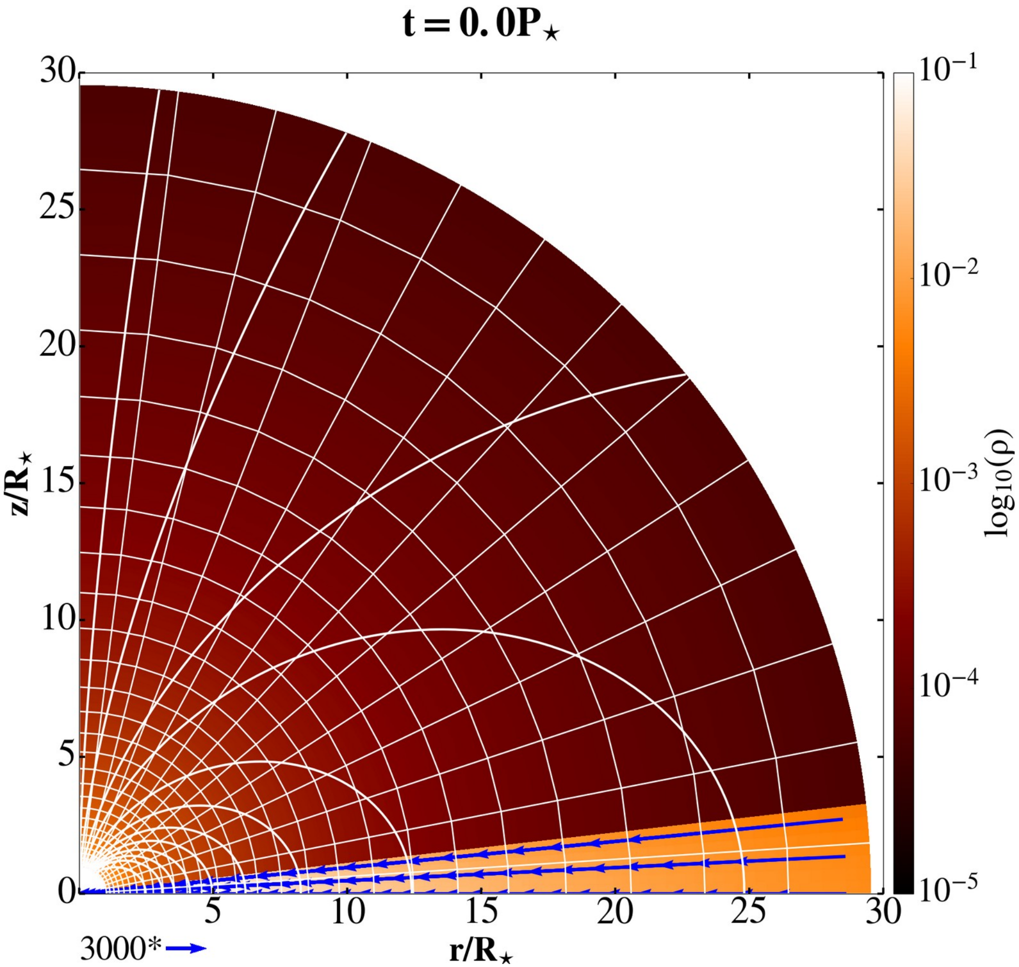
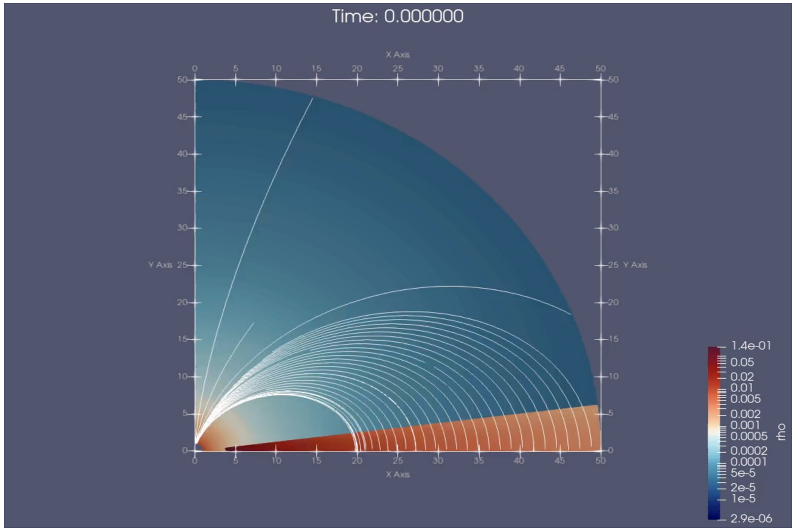


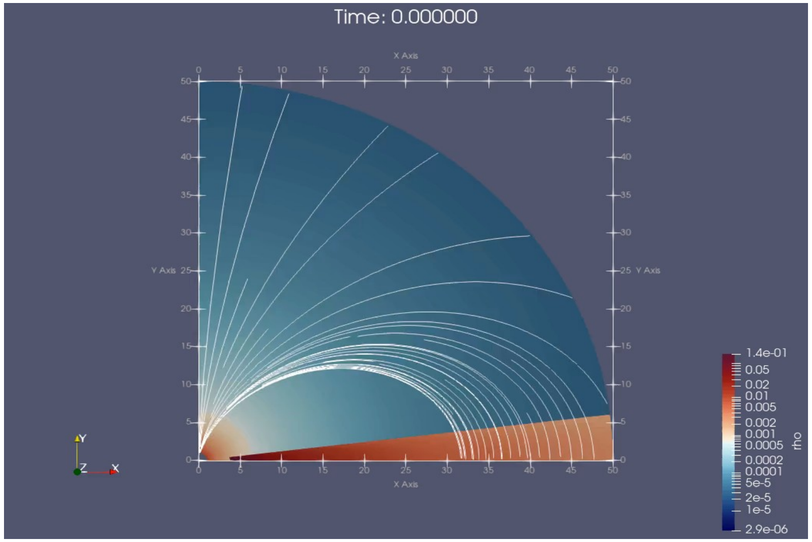

Fig. 1. Geometry of emission from a rotating neutron star.

Then, like the rest of the community, for some years I was busy with parameter studies of YSOs and various other cases in 2.5 D setup-results of which I was presenting in previous meetings here.

# Star-disk simulations in 2.5D with disk midplane as boundary condition

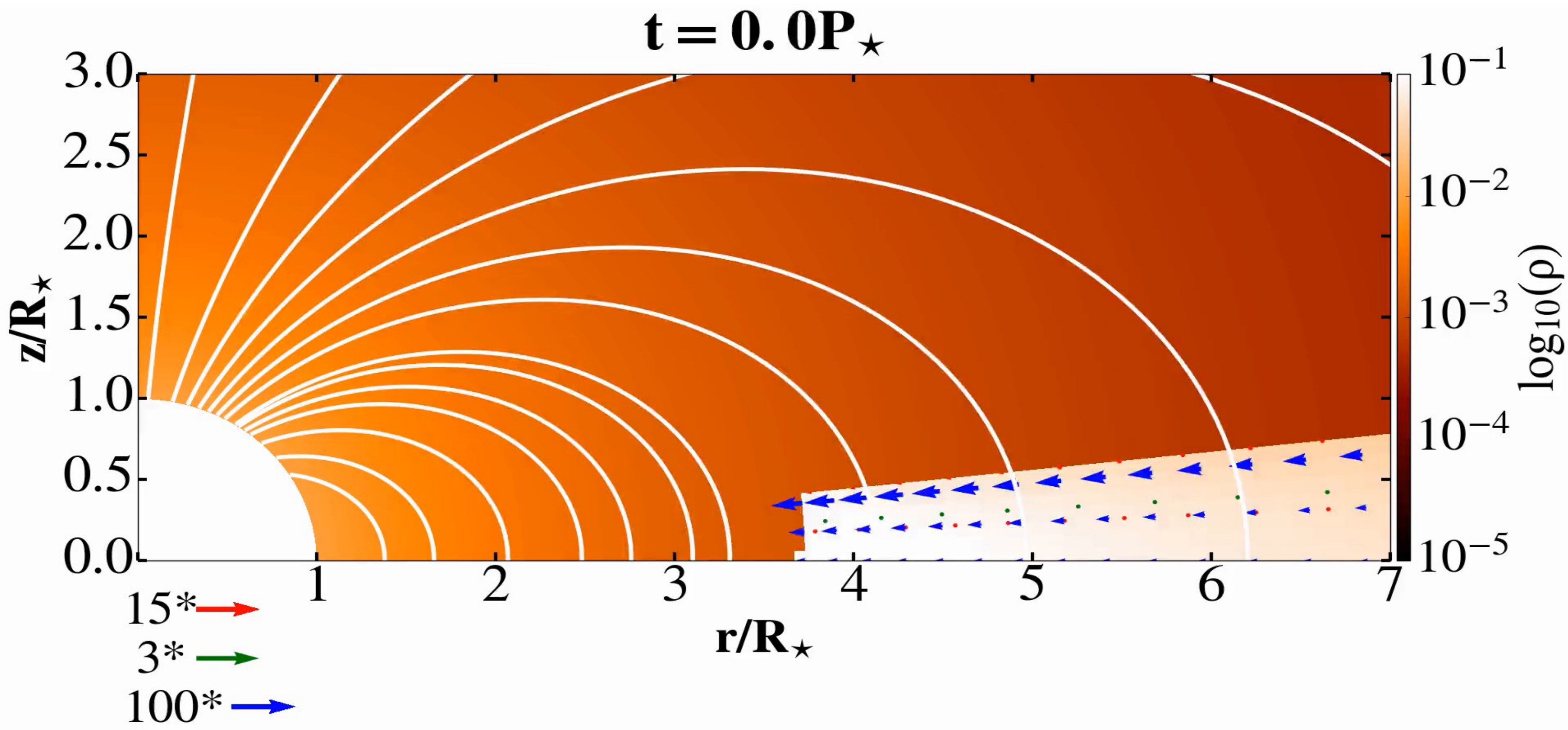


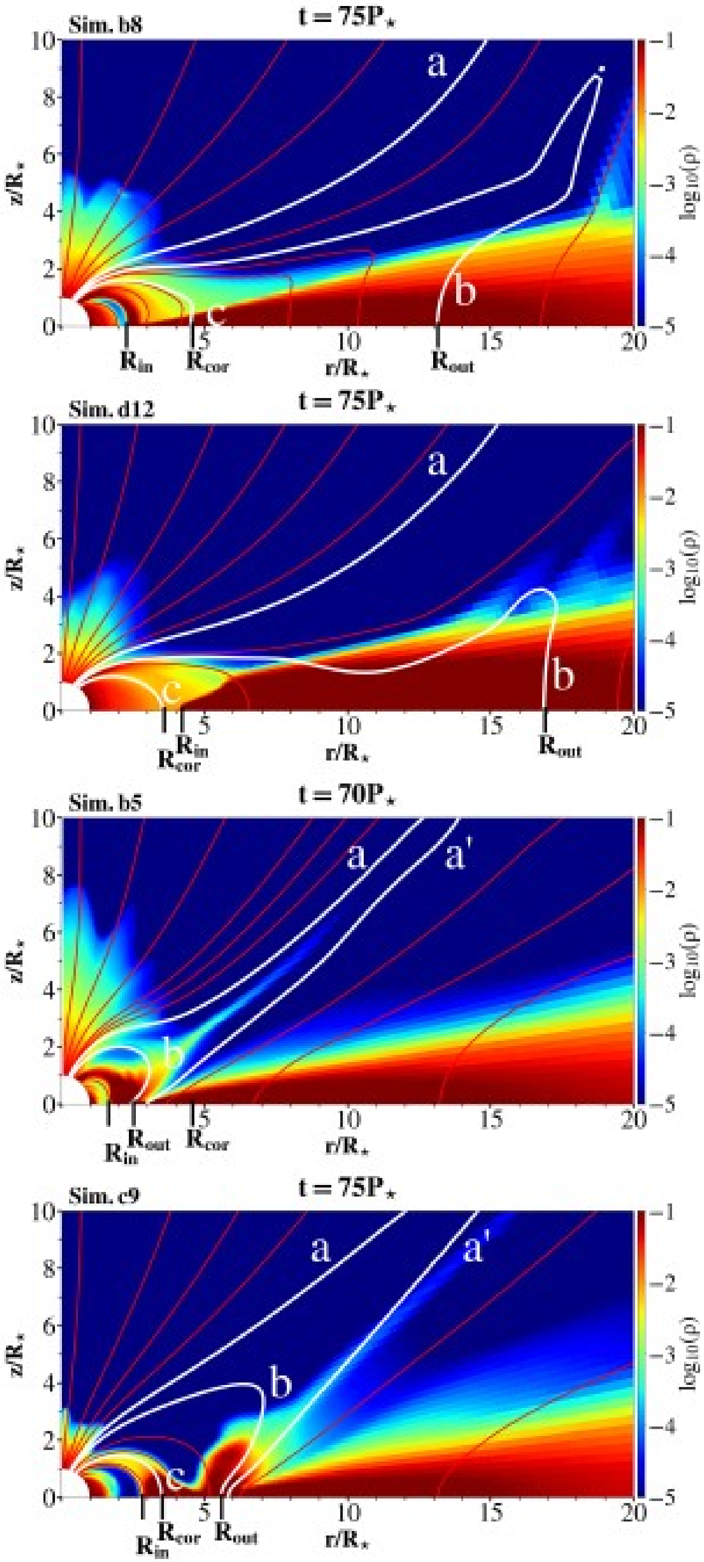




- We add the magnetic field to the HD solution
- Stellar surface is a rotating boundary condition at the origin of the spherical computational domain. We assume the star to be a magnetized rotator. The initially non-rotating corona is in a hydrostatic balance.

# Accretion column in 2.5D axisymmetric solution with disk midplane as b.c.



# Types of star-disk solutions




- Solutions in simulations with the dipolar stellar field in 2.5D result in 4 different cases, depending on the position of Rcor(otation) with respect to the disk truncation radius Rin.

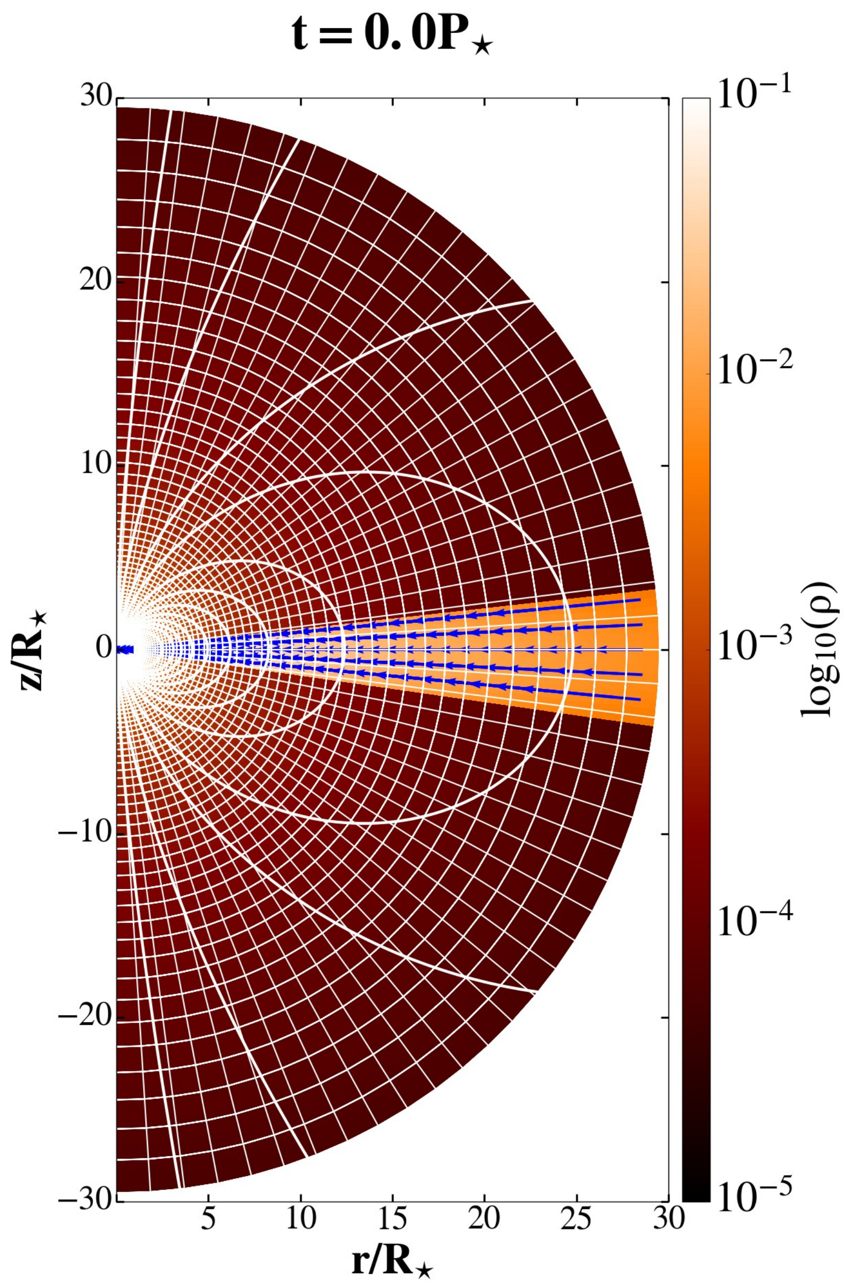
- In general, faster stellar rotation in combination with larger stellar magnetic field prevents the accretion column formation.

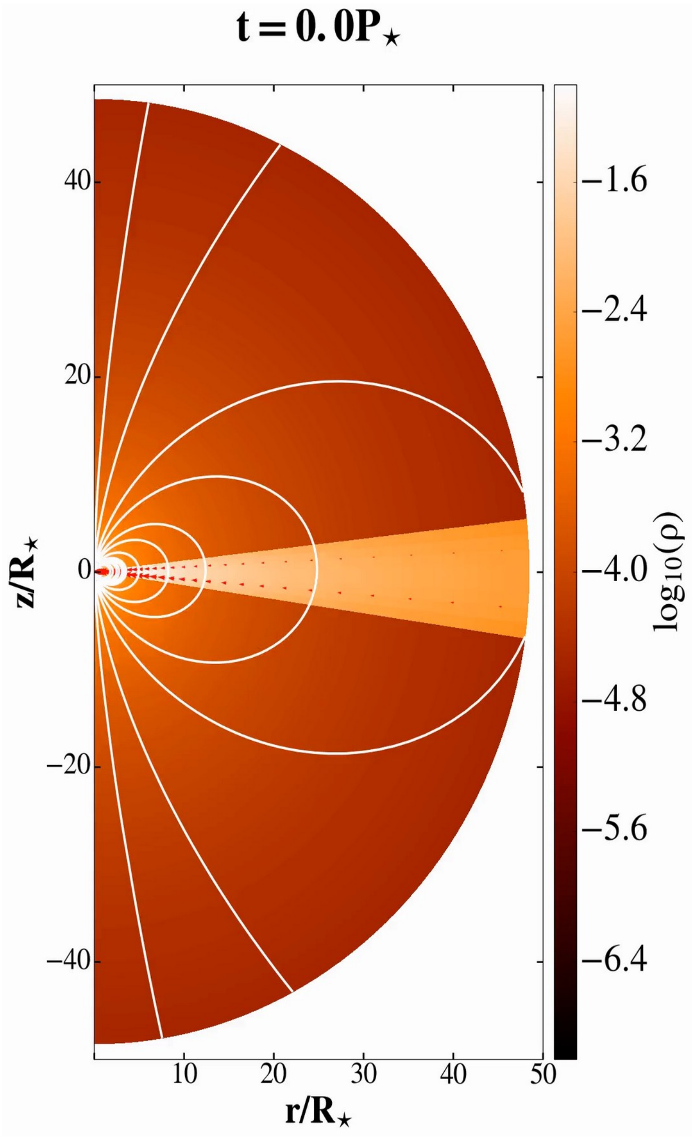
- In the two bottom panels, with resistivity $\alpha_m$=0.1 and $\Omega_{star}$=0.1, a conical outflow is formed.

How this holds in 3D? With the same parameters, solutions are, as could be expected, different.

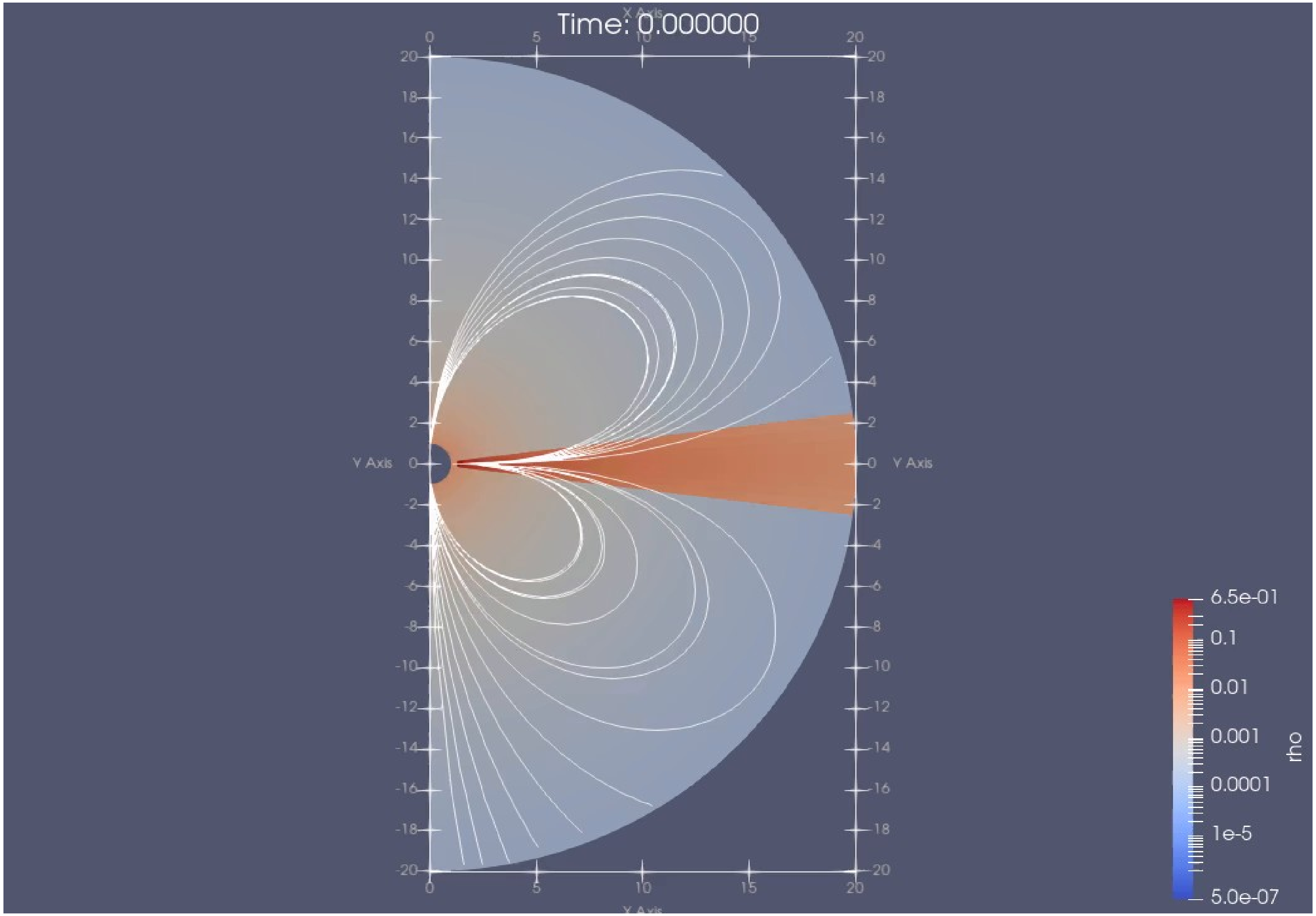
# Star-disk simulations in 2.5D without disk equatorial boundary





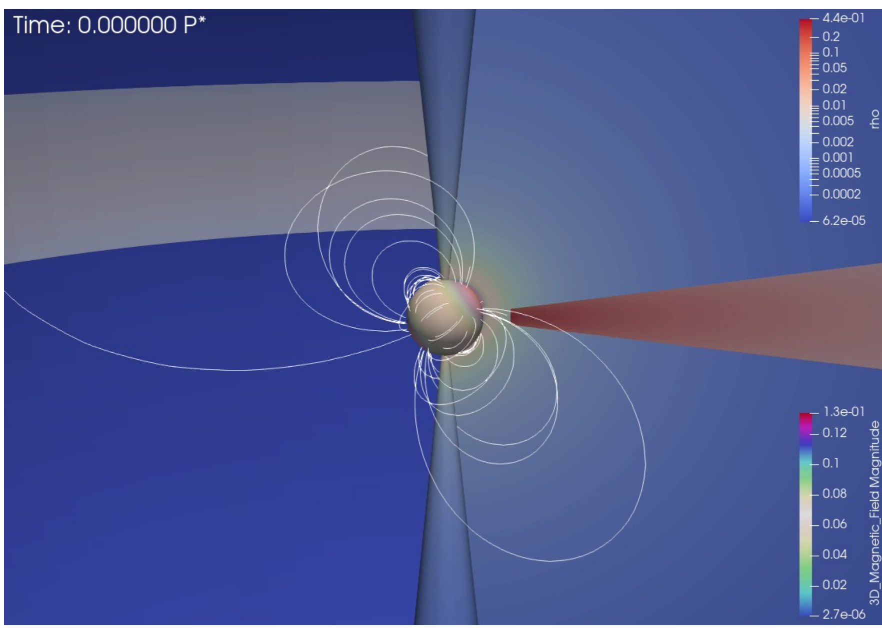



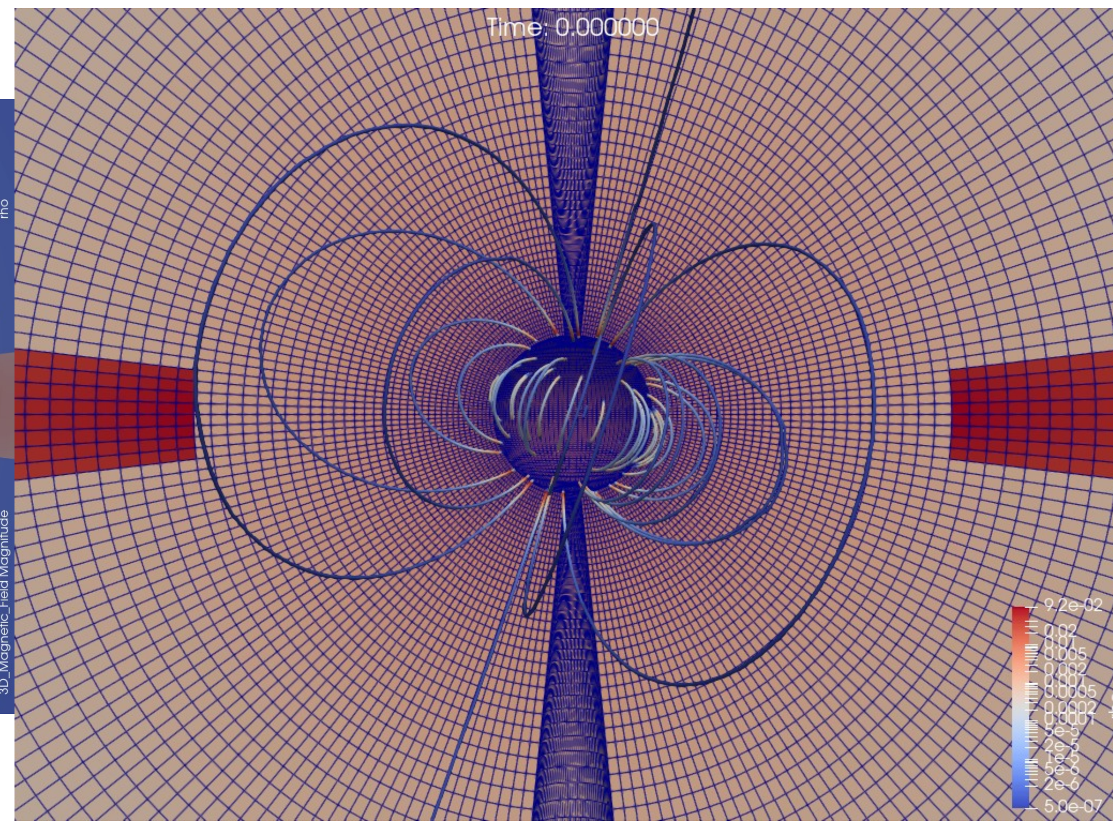
# Simulations of thin disk with quadrupole magnetic field



During the last year, with PhD student in Warsaw, Sukalpa Kundu, we developed a simple full, nonaxisymmetric 3D MHD setup for thin accretion disk with the newest version of PLUTO code. As in my previous work, all the viscous and resistive dissipative heat is assumed to be radiated away, so this setup is for a cold, thin accretion disk. The cooling term exactly removes heat in the energy equation:

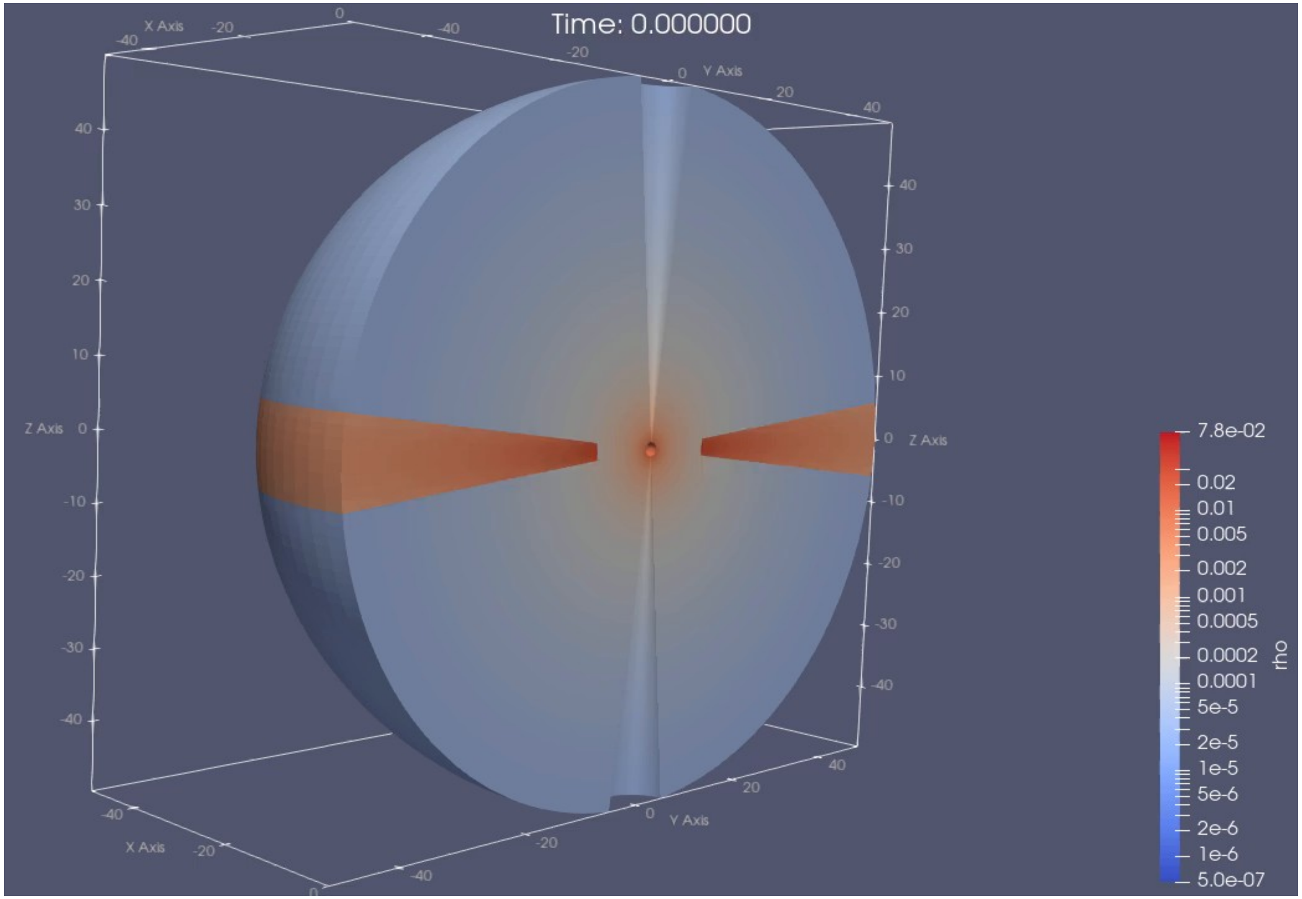
$$\frac{\partial E}{\partial t} + \nabla \cdot \left[ \left( E + P + \frac{\mathbf{BB}}{8\pi} \right) \mathbf{v} - \frac{(\mathbf{v}\cdot\mathbf{B})\mathbf{B}}{4\pi} \right] + \nabla \cdot \left[ \underbrace{\eta_{\mathrm{m}} \frac{\mathbf{J}\times\mathbf{B}}{4\pi} - \mathbf{v}\cdot\tilde{\tau}}_{\text{heating terms}} \right] = \rho \mathbf{g}\cdot\mathbf{v} - \underbrace{\Lambda}_{\text{cooling}}$$



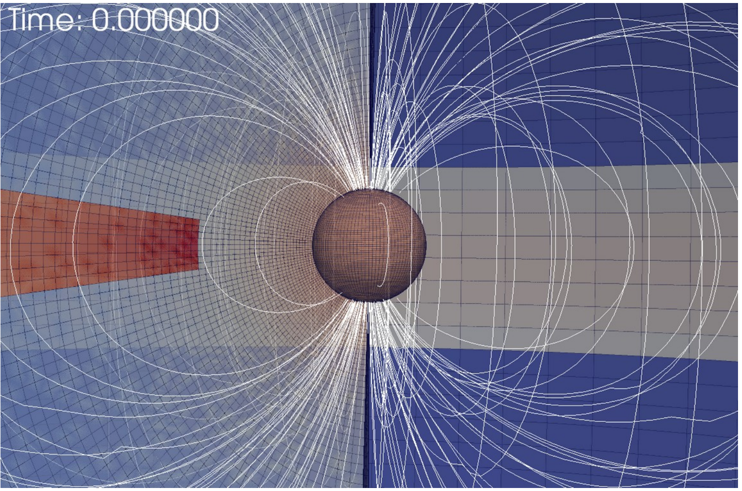
# 3D simulations of thin disk without mag. field

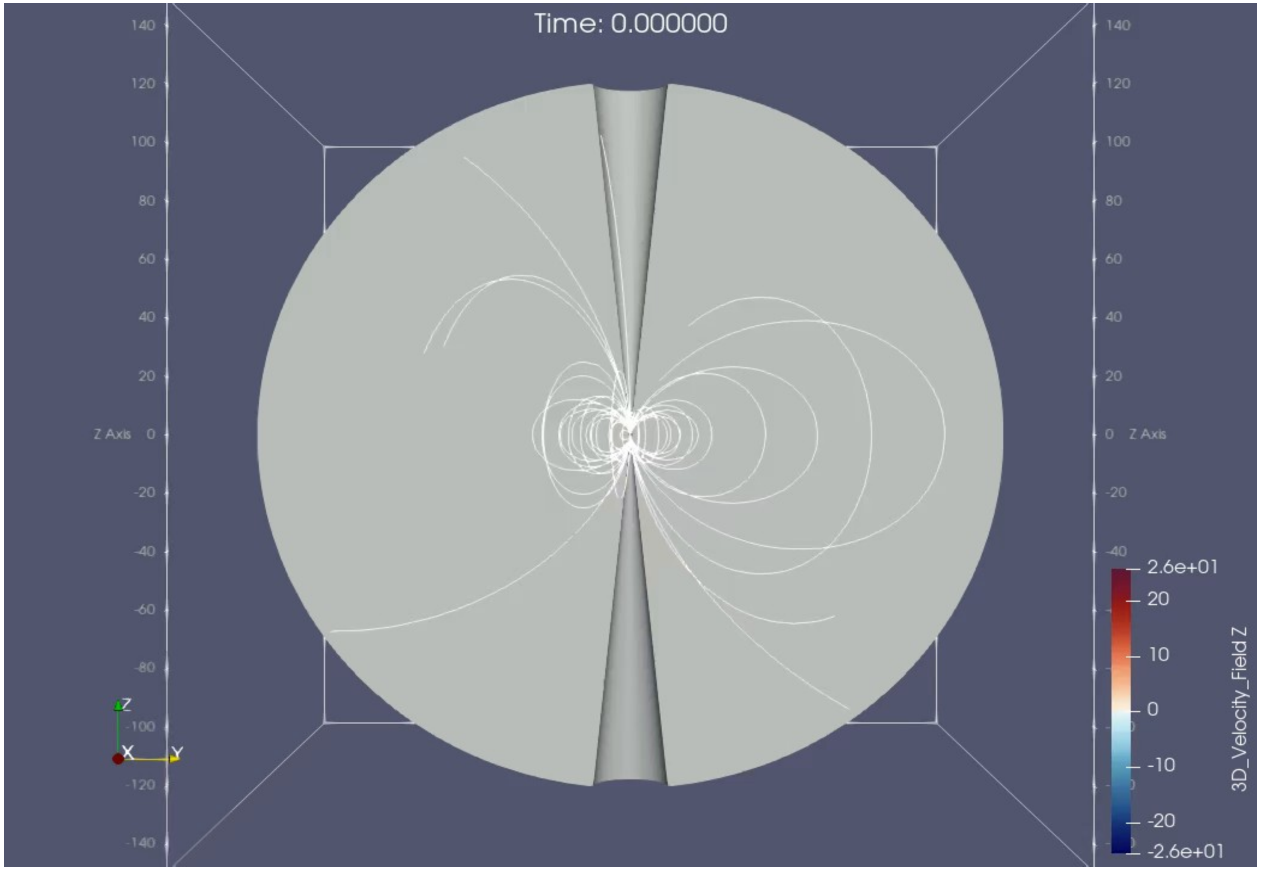
- The first step towards the full 3D is to perform the axisymmetric 3D simulations without and with magnetic field. The purely HD thin disc, providing that you have a good cooling of the disk, is easy and fast. Minimal resolution? The rule of thumb is that one needs to have a grid cell for each independent variable in the code; in PLUTO it means density, pressure and 3 velocity components, so at least 5 grid cells for a feature you wish to resolve.



# 3D simulations, case with magnetic field aligned with rotation

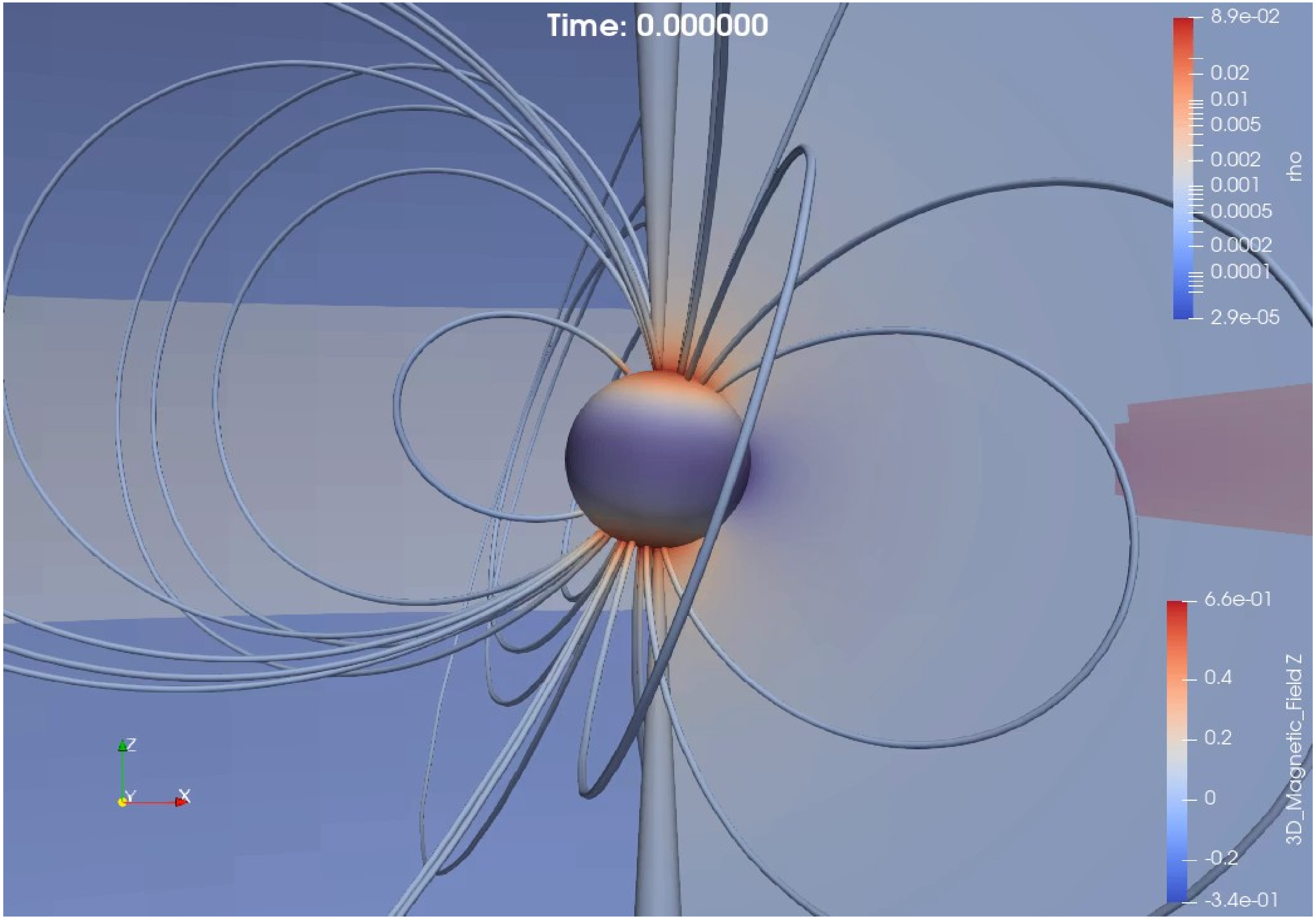
In the magnetic case, with the magnetic field aligned with the rotation axis, we already get the foretaste of differences with 2D: computational cost is immense, both in the sense of the computational time and memory: instead of few MB, we now easily have output files of 100 MB and larger. By the rule of thumb for resolution, the 3 components of magnetic fields are added to the 5 in the HD case, making it 8 grid cells per feature we want to resolve.



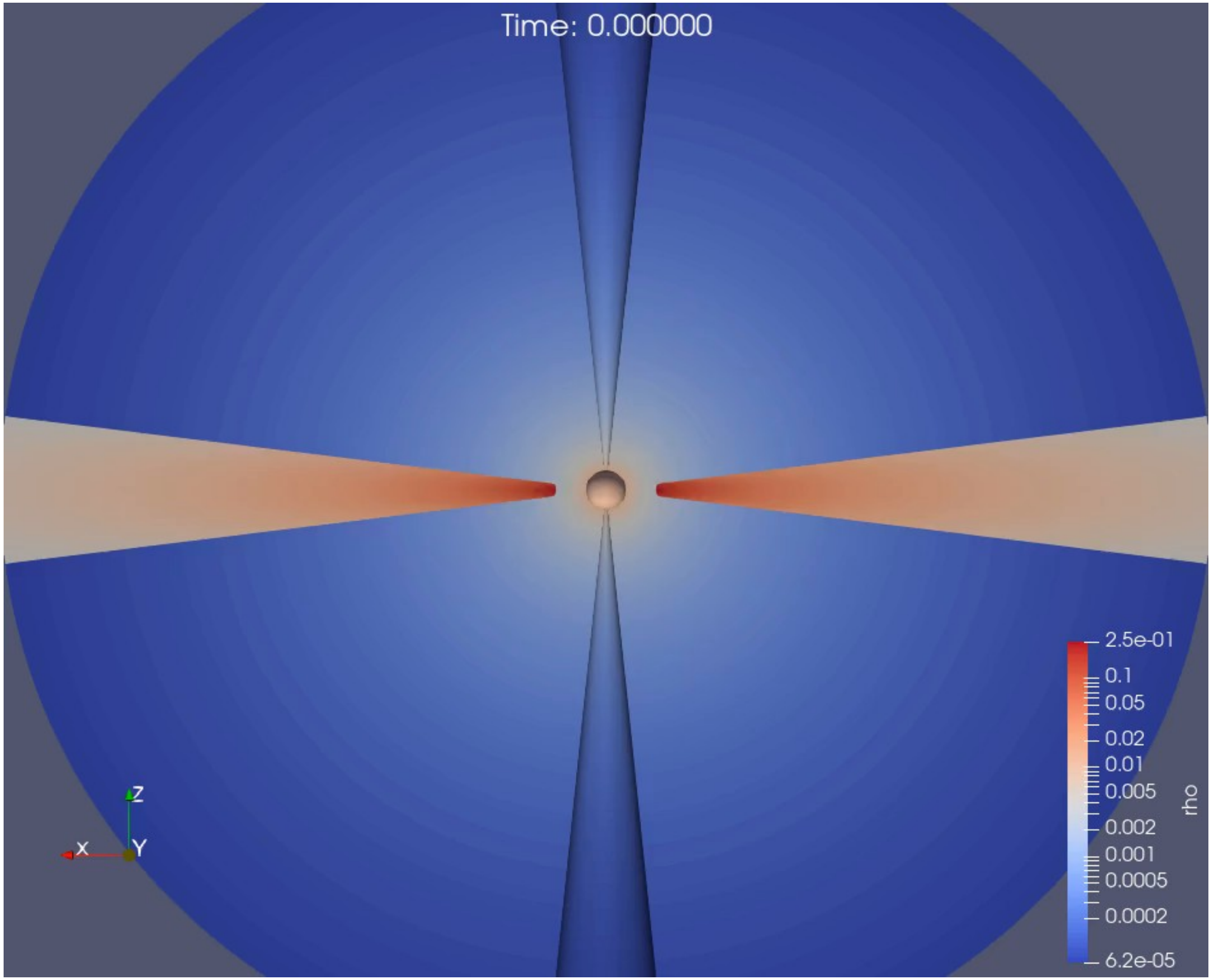




Zoom into the vicinity of the star. Top panel: inner boundary condition at T=0; right panel: animation of vertical velocity component.

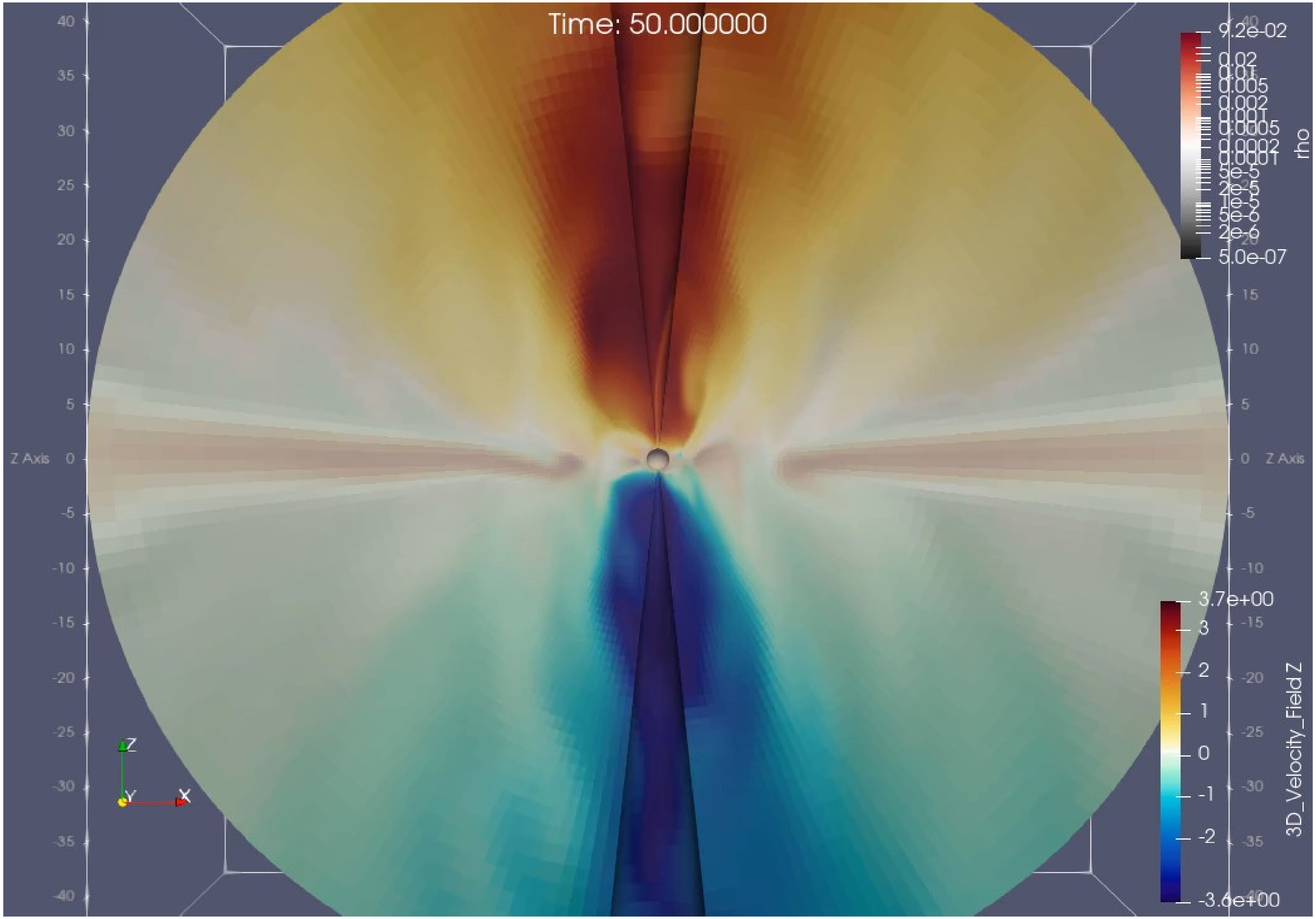
To keep things clear, we do not use corotating frame. A zoom is the first stellar rotation:



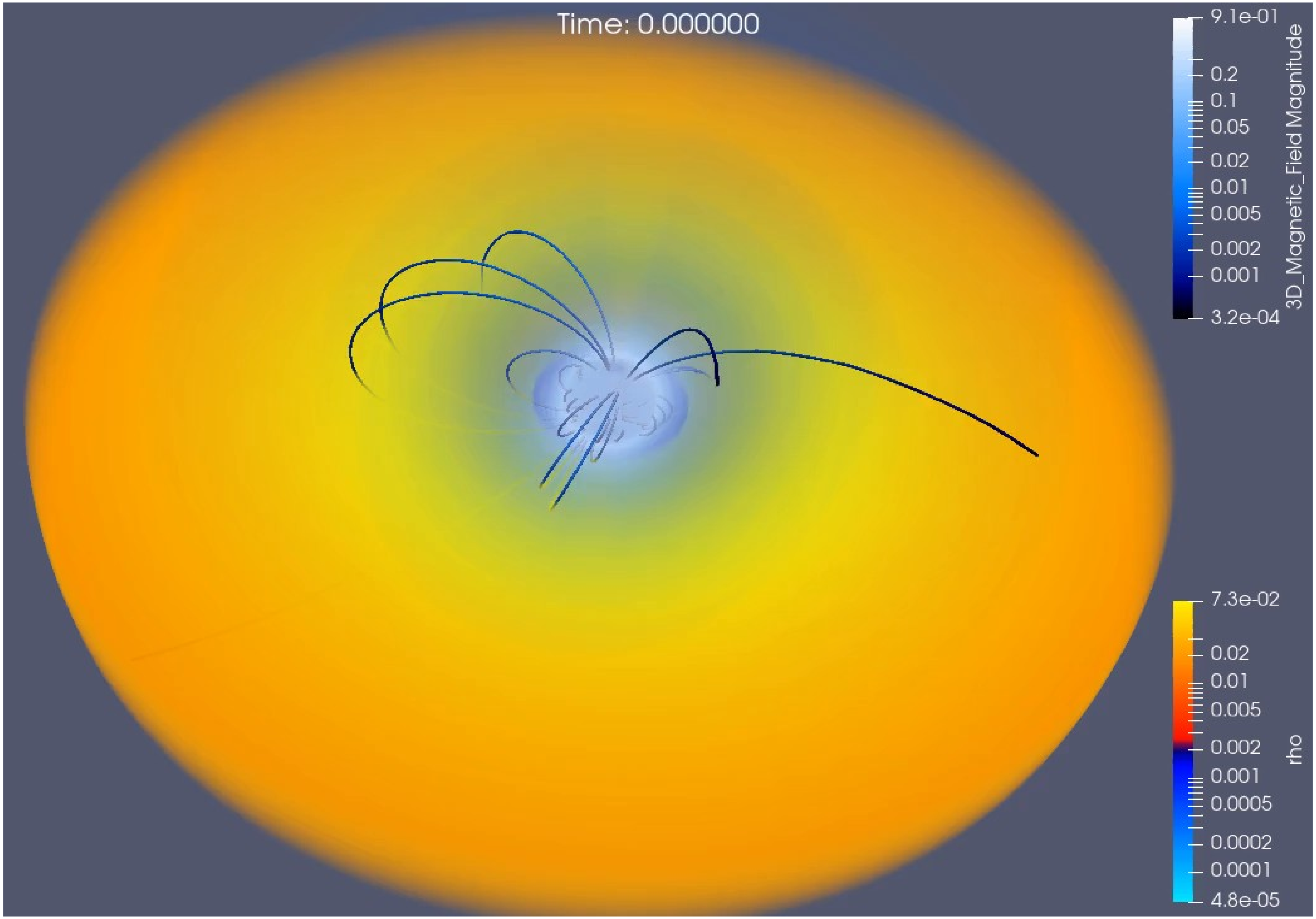
About 60 stellar rotations with moderate magnetic field (150 G for YSO, $8\text{x}10^8$ G for NS):



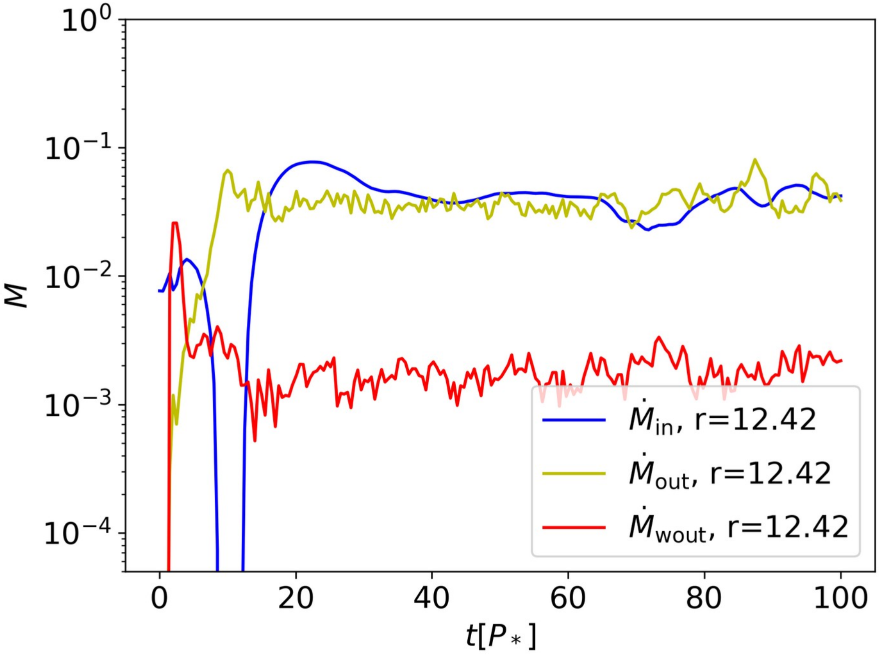
# Axial outflows in 3D simulations with tilted field

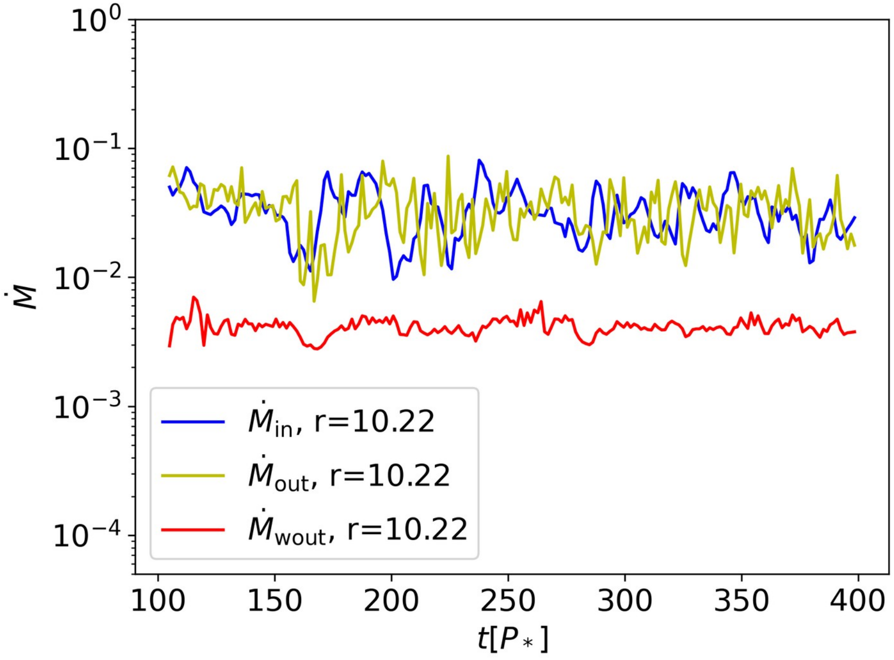


# Near-propeller regime



# Mass fluxes in near-propeller regime in 3D




Mass fluxes in two cases in 3D shown in the previous slides when the system is near the propeller regime. There is no accretion onto the star.

Next star-disk simulations with PLUTO will include radiative transfer. As usual, I will put the setup to my webpage, feel free to use it.

# Summary

- Simulations of star-disk magnetospheric interaction for thin accretion disk in 3D have been done since two decades, it is time to make them more readily available.

- Usually 3D demands state of the art resources. For initial research and teaching purposes, we need something faster.

- PLUTO code offers publicly available platform, but we did not have the setup for global simulations of thin disc with tilted magnetic field yet, so we created it.

- Most of this work, with detailed instructions, is already available online on my webpage, feel free to use it.

THANK YOU!