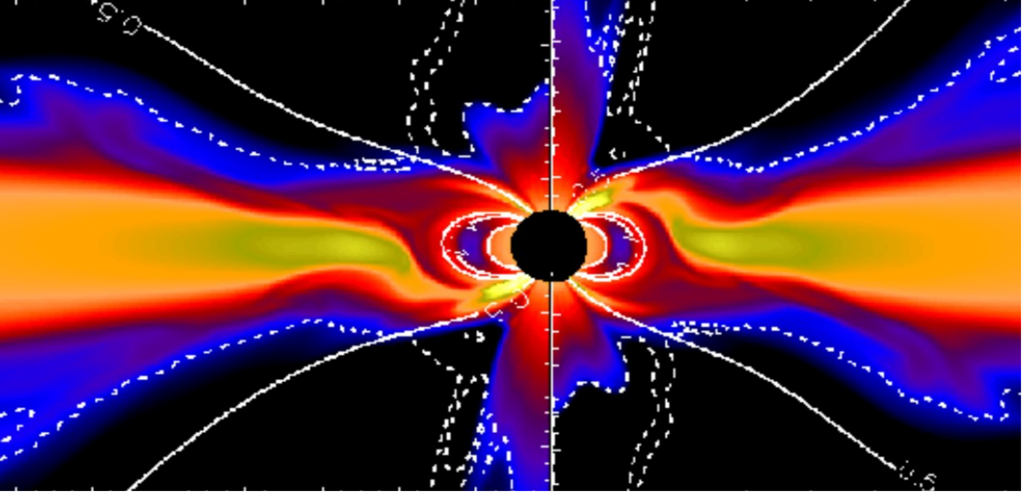

Simulations of young and not so young stars with accretion discs and outflows

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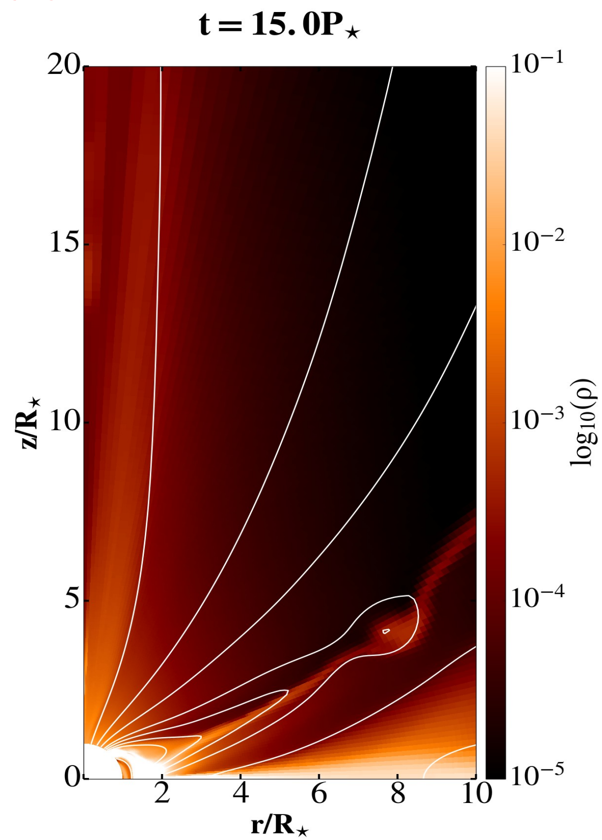

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- Axial and conical jets
- Different geometries of magnetic field
- Connection to observations
- Dust and the disk
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Introduction

•Using the PLUTO code, I perform the long-lasting simulations of accretion disks, which reach a quasi-stationary state.

•With PLUTO I solve 2D axi-symmetric viscous & resistive MHD equations.

•We neglect Ohmic and viscous heating in the energy equation-we still include viscosity and resistivity in the equation of motion and in the induction equation.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0$$

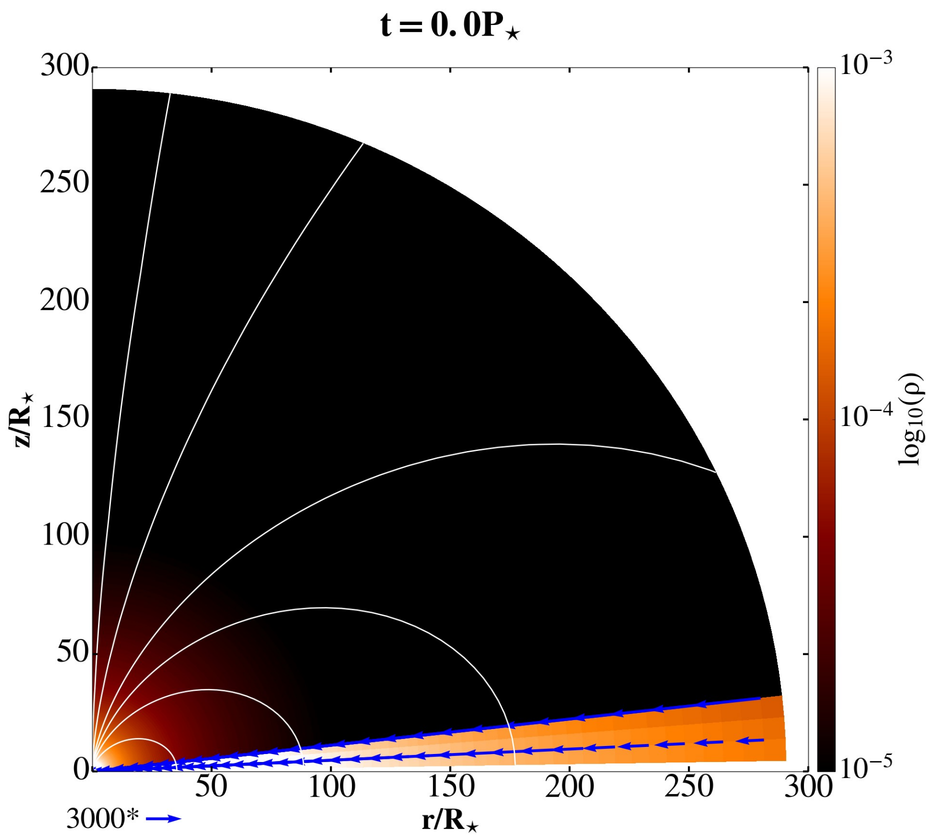
$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{u}\boldsymbol{u} + \left(P + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi} \right) \boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} - \boldsymbol{\tau} \right] = \rho \boldsymbol{g}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{\boldsymbol{B}\cdot\boldsymbol{B}}{8\pi} \right) \boldsymbol{u} - \frac{(\boldsymbol{u}\cdot\boldsymbol{B})\,\boldsymbol{B}}{4\pi} \right] + \nabla \cdot \left[\eta_{\mathrm{m}} \boldsymbol{J} \times \boldsymbol{B}/4\pi - \boldsymbol{u}\cdot\boldsymbol{\tau} \right] = \rho \boldsymbol{g}\cdot\boldsymbol{u} - \Lambda_{\mathrm{cool}}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \times (\boldsymbol{B} \times \boldsymbol{u} + \eta_{\mathrm{m}} \boldsymbol{J}) = 0.$$

Solutions in Young Stellar Objects case

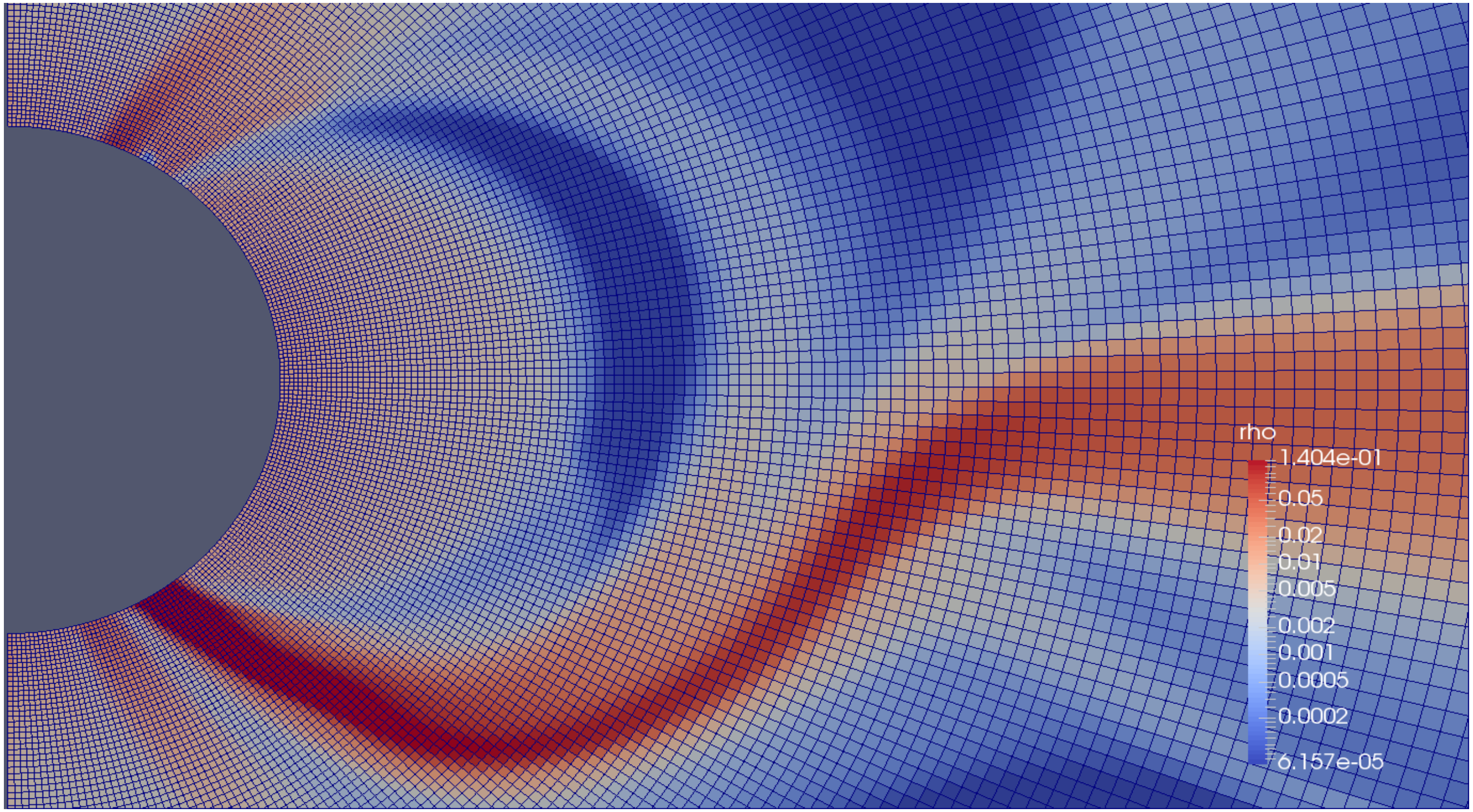
All the simulations start with the same initial and boundary conditions, the Kluźniak & Kita (2000) solution for the full 3D hydro-dynamical disk, with the added initially non-rotating corona and the stellar dipole field.



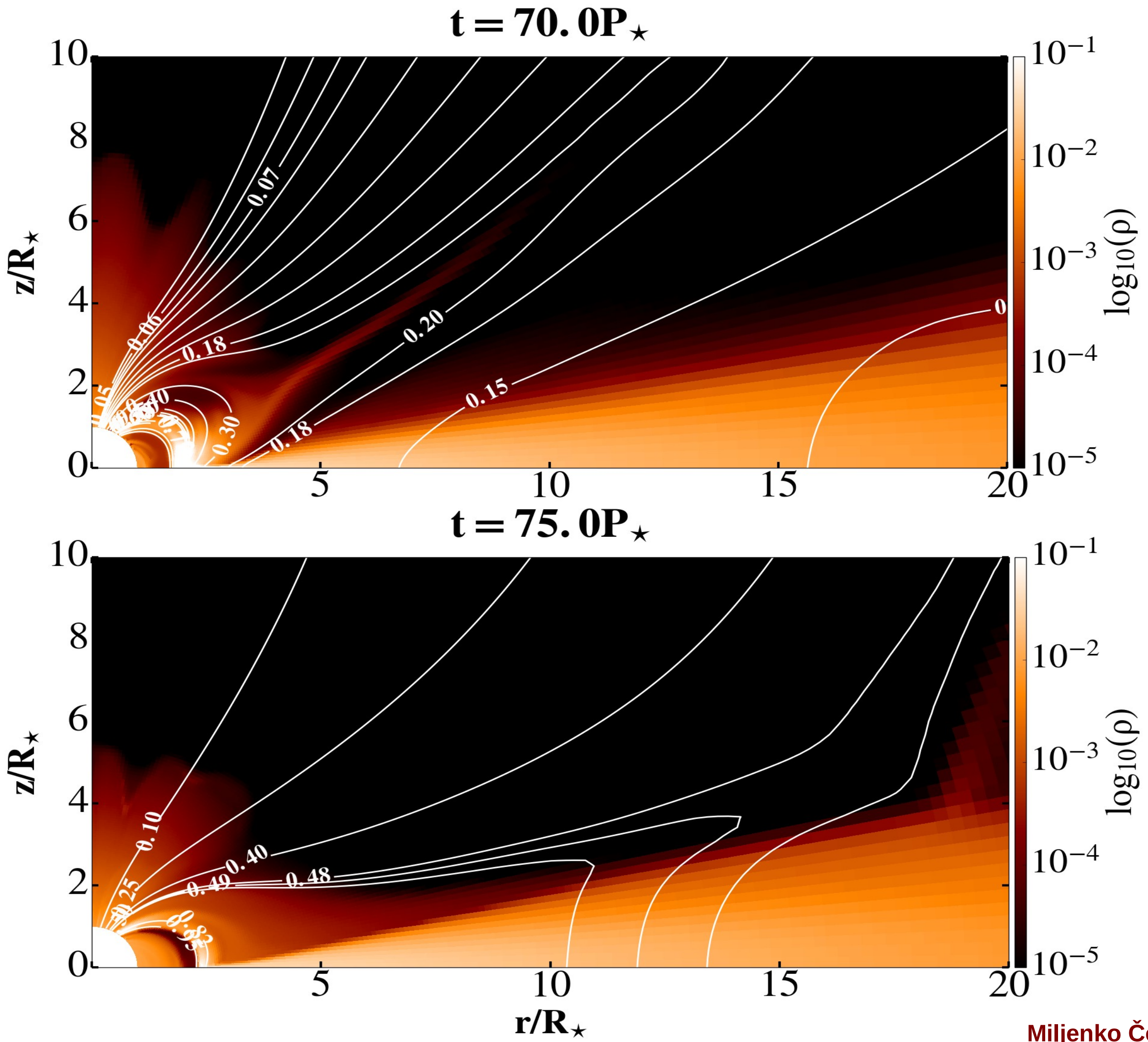
I performed a systematic study with magnetic star-disk numerical simulations where the disk quasi-stationarity is reached.

Star-disk simulation setup

- Resolution is Rxϑ=[217x200] grid cells in ϑ=[0,π], with a logarithmic grid spacing in the radial direction. The accretion column is well resolved.
- Star typically rotates at about 1/10 of the breakup rotational velocity.



Solution with 0.5 kG, Ω_s=0.1, α_v=1: α_m=0.1 and α_m=1

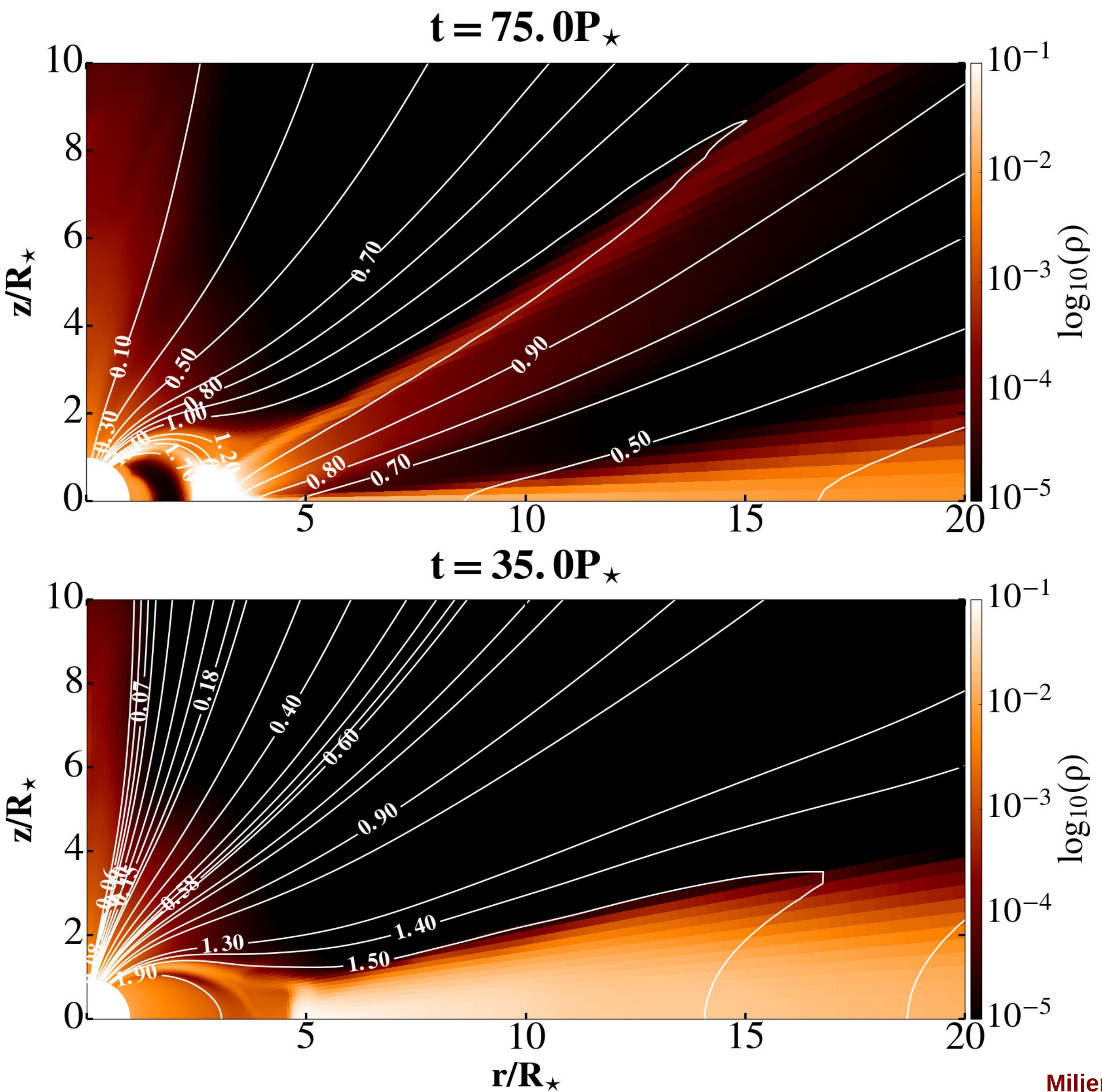


In my simulations I observe few types of solutions, which depend on the stellar rotation, strength of the magnetic field and amount of the resistivity in the simulation.

In all the simulations with α_m=0.1 a conical jet is launched.

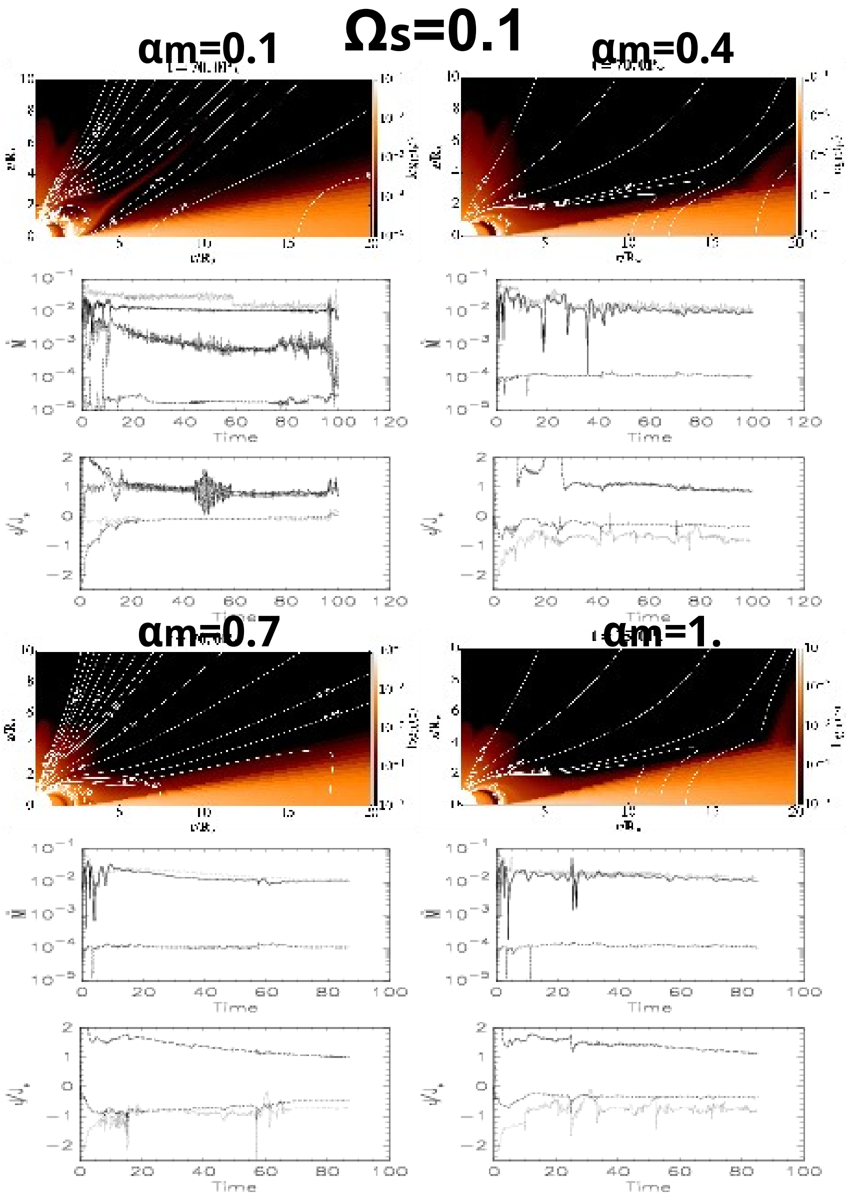
I investigate how far in the disk is the stellar magnetic field still penetrating the disk. This determines the transport of the angular momentum in the system and if the star is spun up or slowed down.

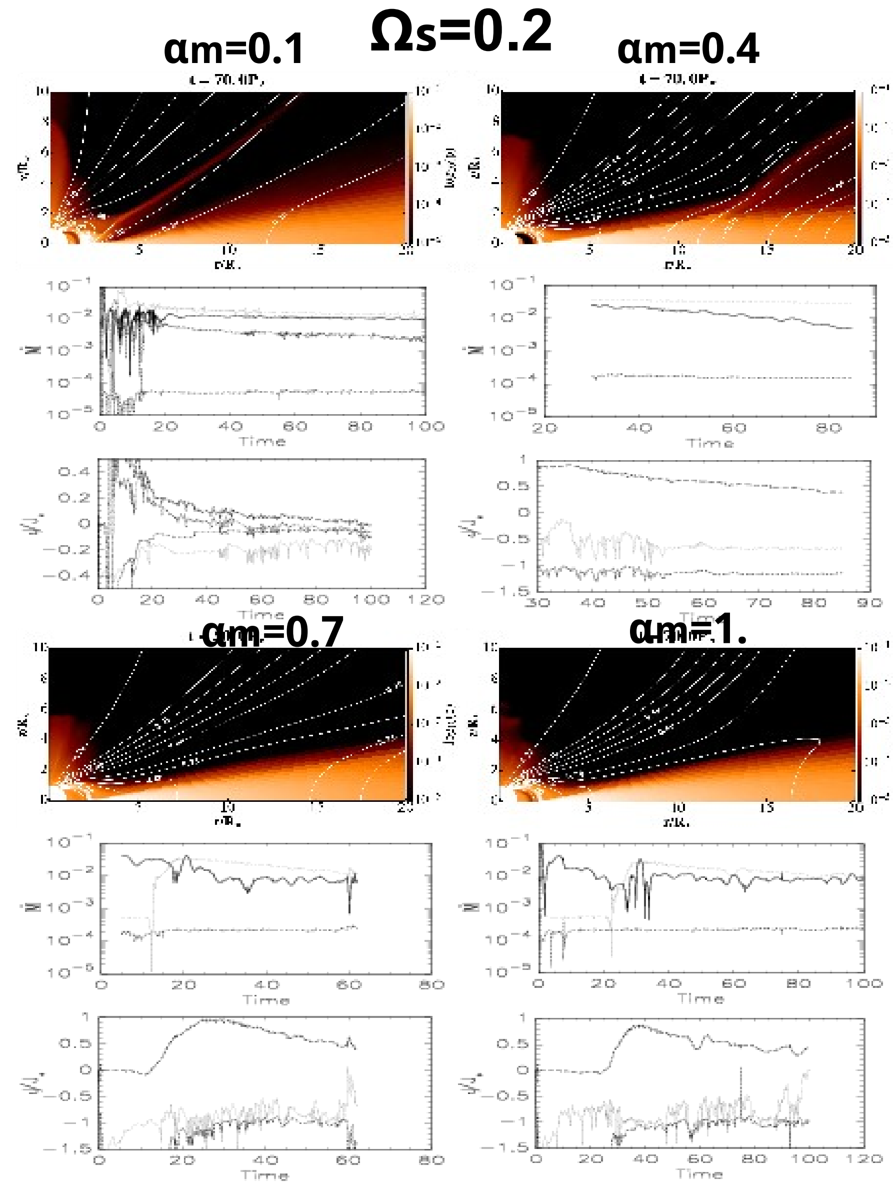
Solution with 1. kG, Ω_s=0.2, α_v=1: α_m=0.1 and α_m=1



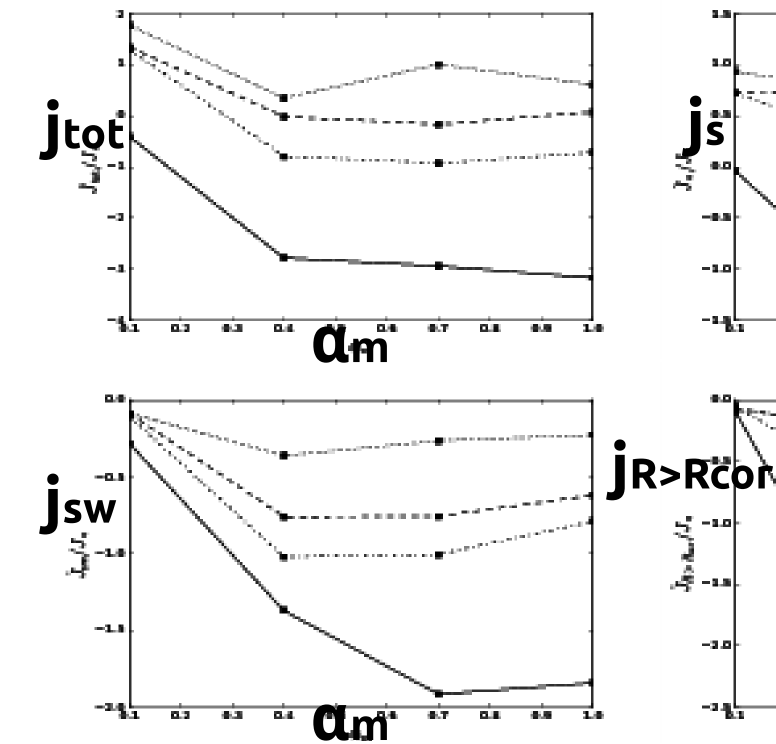
With larger magnetic field, the disk inner radius is pushed away from the star. This changes the geometry of solutions.

Part of the “Atlas” of solutions in Bs=0.5 kG case



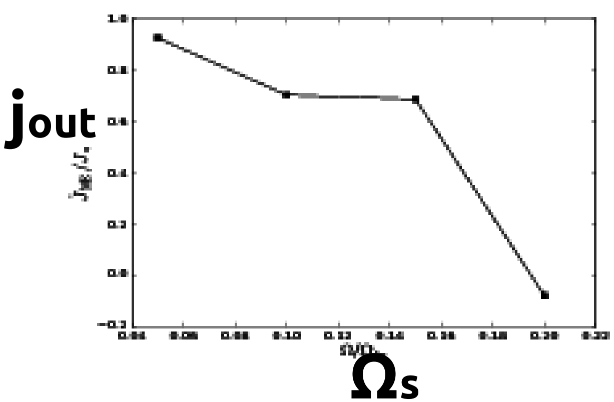


Trends in YSO solutions with Bstar=0.5 kG



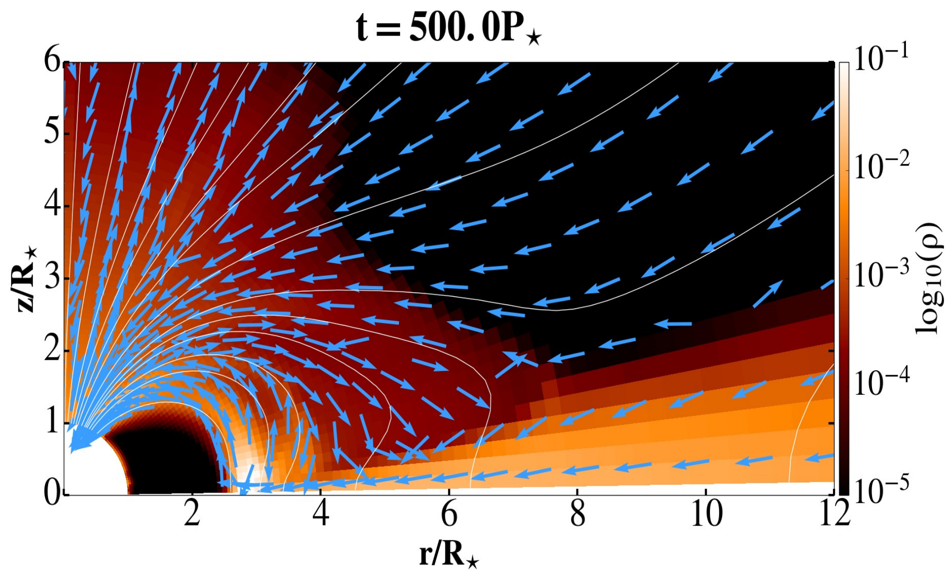
Shown is the average angular momentum flux change with resistivity (α_m) in various components of the system, normalized to the stellar angular momentum. Dotted, dashed, dot-dashed and solid lines represent fluxes in Ω_s=0.05, 0.1, 0.15 and 0.2 cases. We are interested in trends. Compared with observations, this will be used to improve the stellar models.

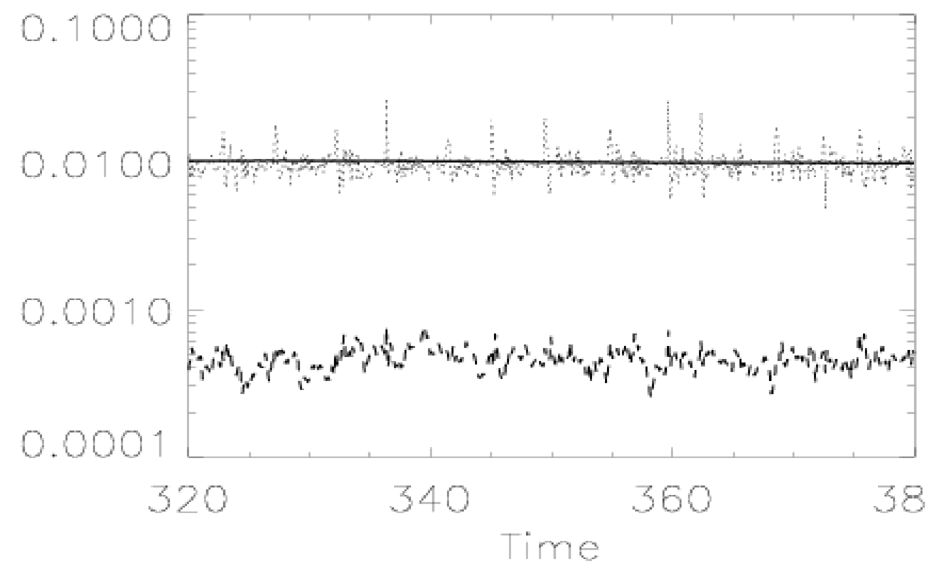
We are also working on the magnetic extension of the Kluźniak & Kita disk in the asymptotic approximation. Results from the "Atlas" will be used to validate the results.



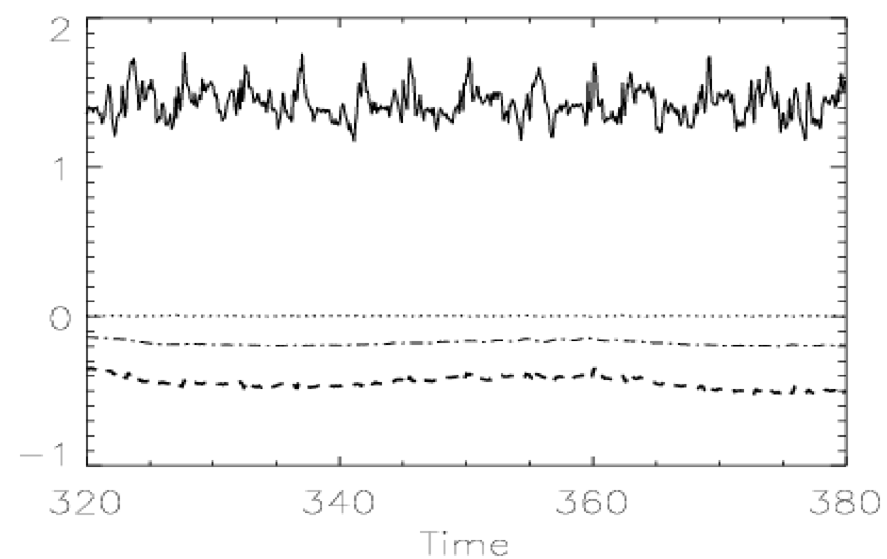
←-- Here is shown angular momentum flux change with Ω_s, in the conical outflow case (with α_m=0.1).

Reincarnated stars: Star-disk simulations of millisecond pulsars





Zoom into the central part of the system after 500 pulsar rotations to visualize the accretion column and the magnetic field lines connected to the disk beyond the corotation radius Rcor=4.65 Rs.

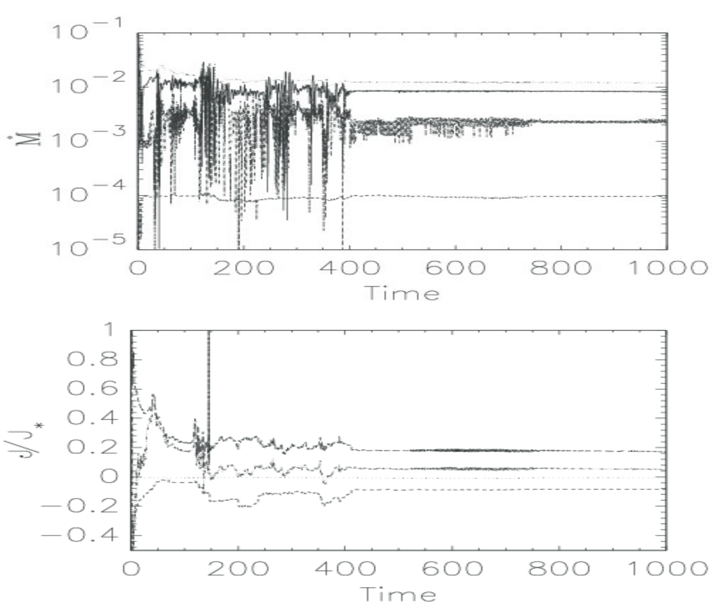


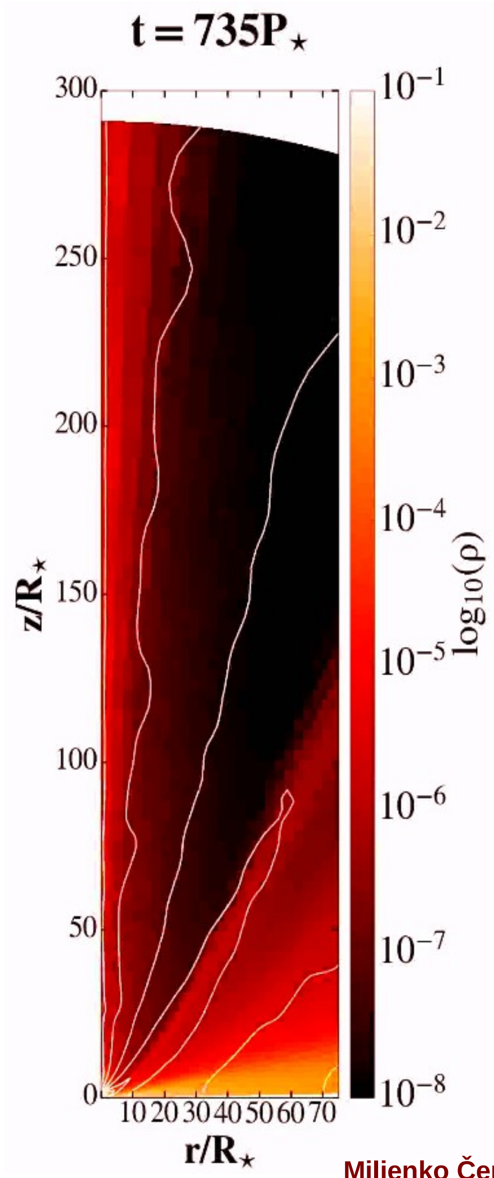
Right top panel: Mass flux in time. Dotted and solid lines show the flux onto the star and through the disk at R=12. Dashed line shows the mass flux in the stellar wind. Right bottom panel: Angular momentum flux in time. Dotted and dot-dashed lines show the negligible kinetic flux and the stellar wind flux. Solid and dashed lines show the flux from the matter falling onto the star from the disk inside the Rcor and beyond Rcor. Negative flux slows down the star.

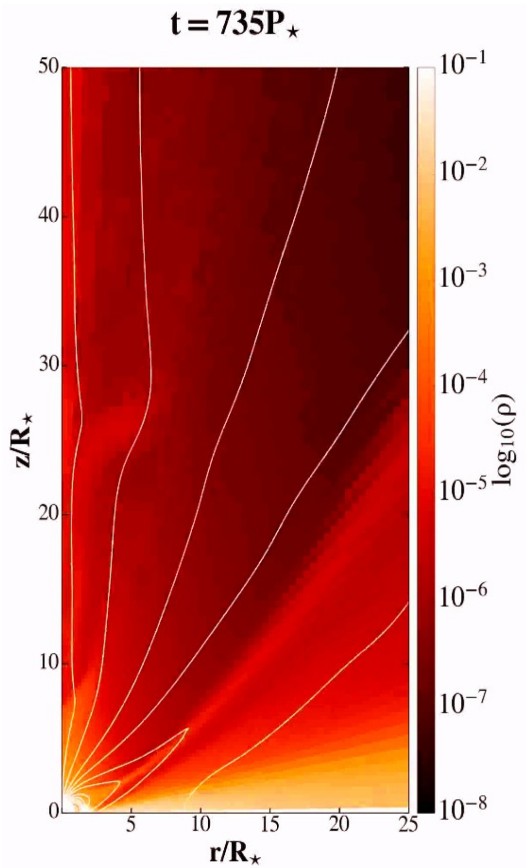
The jet launching

I also obtained a continuous launching of an axial jet from the star-disk magnetosphere.

The axial jet and the conical outflow are launched after the relaxation from the initial conditions. They are similar to the results in Romanova et al. (2009) and Zanni & Ferreira (2013).



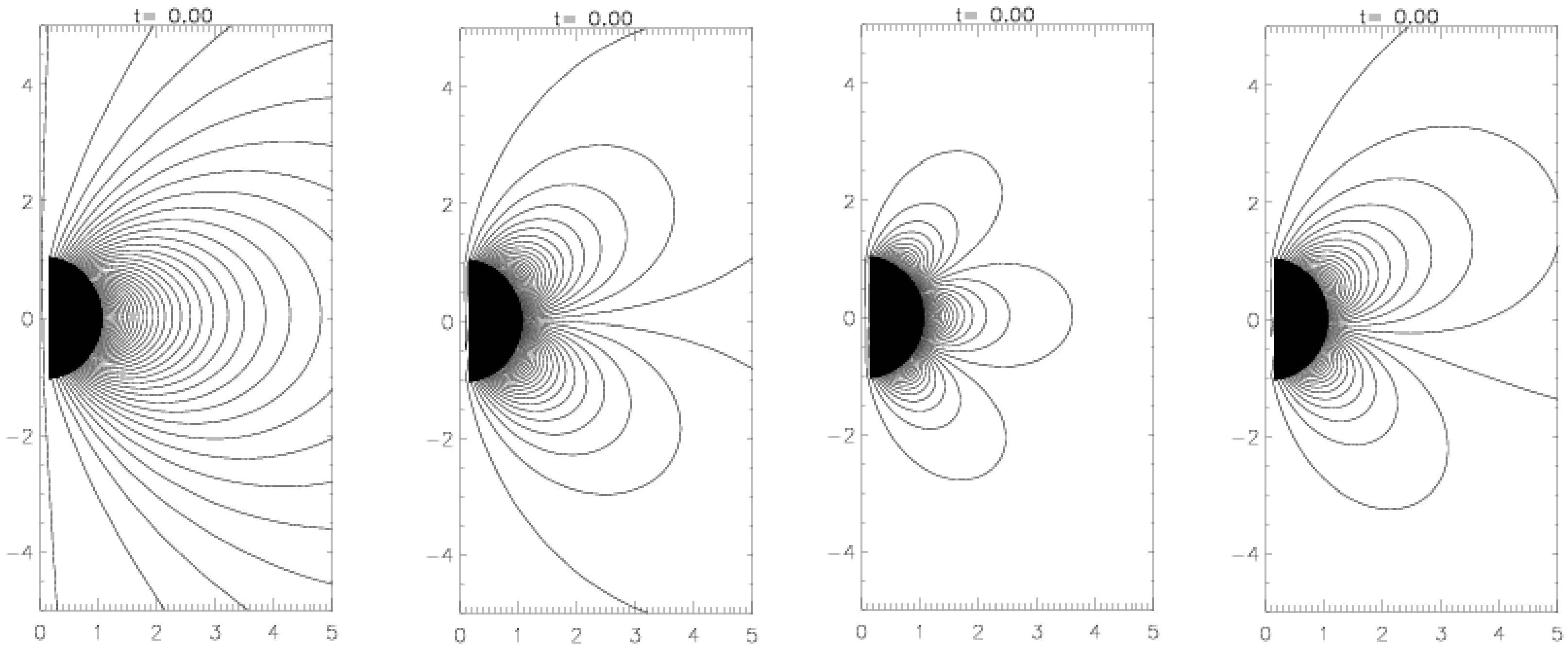




Zoom into the launching region.

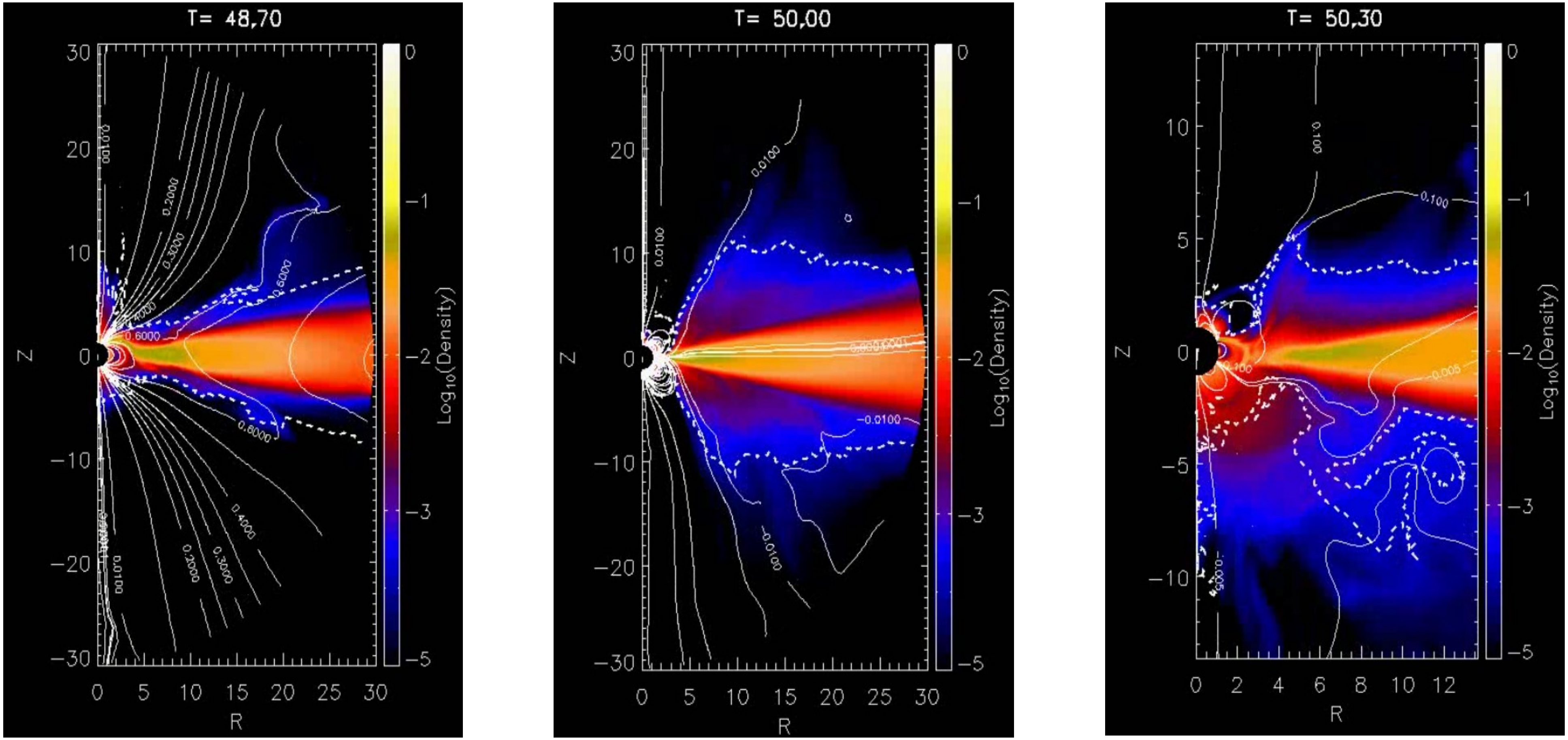
Different geometries of magnetic field

I performed simulations with the different geometries of a stellar magnetic field: dipole, quadrupole, octupole and combinations of those (multipole).

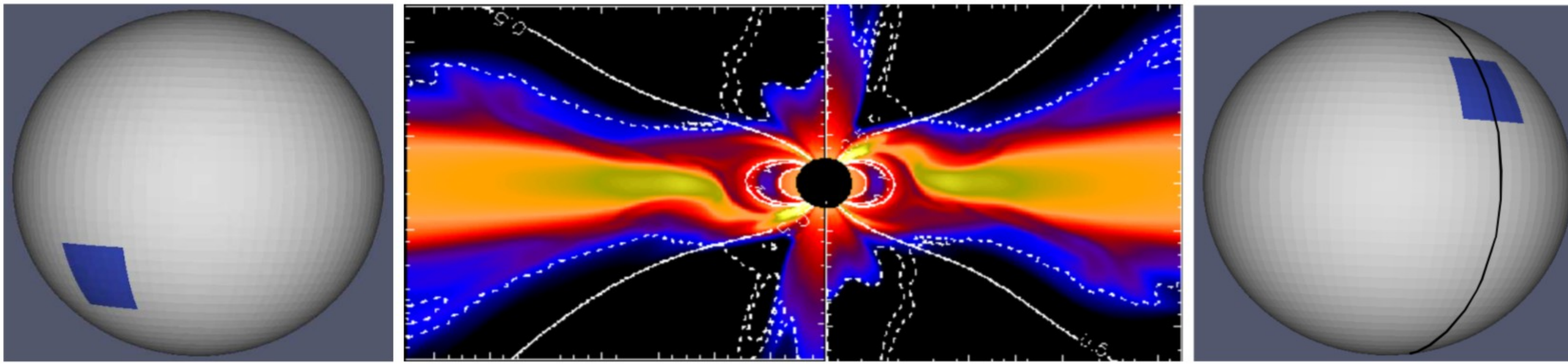


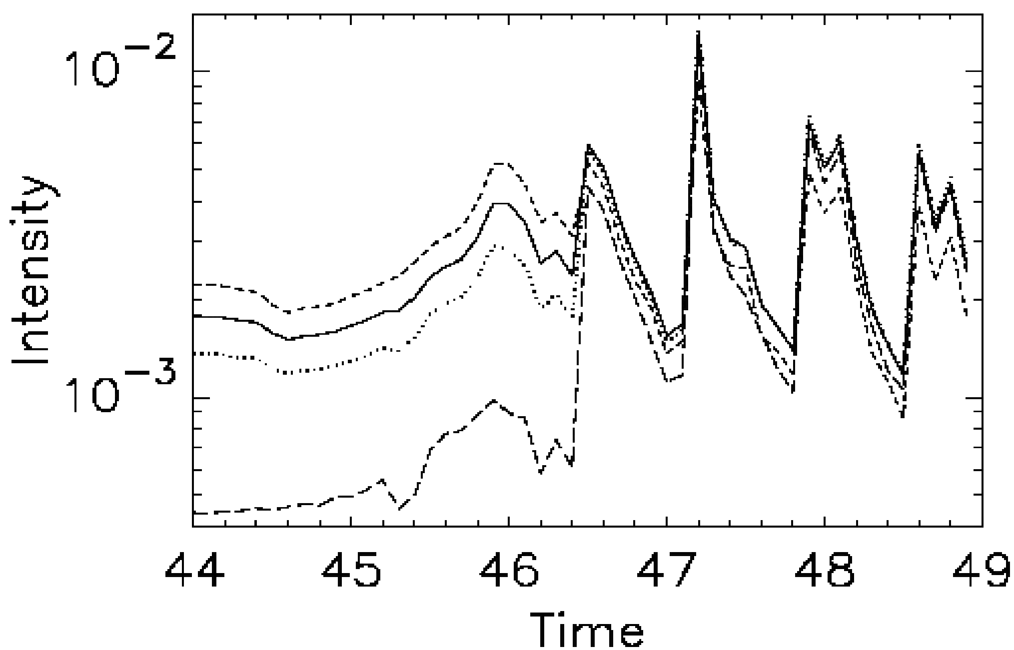
Results with the different geometries of the stellar magnetic field

- Shown are simulation results for YSOs with the dipole, quadrupole and octupole, in a full half-plane.



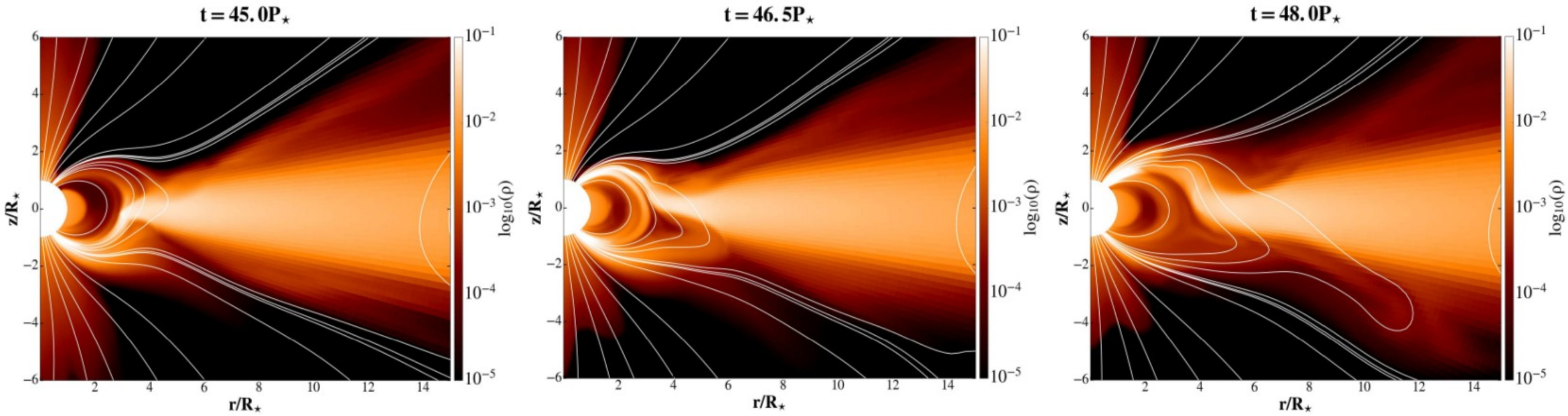
Connection to observations 1: 2D model for 3D light curve

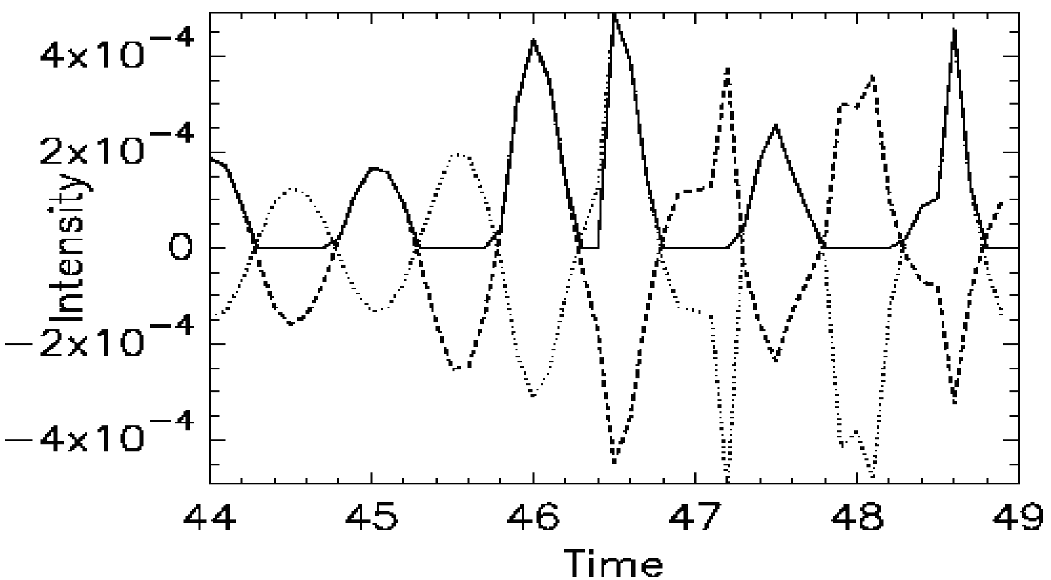




The emission integrated along the stellar rim one grid cell thick in the azimuthal direction. The solid, dotted, long-dashed and short-dashed lines represent the intensities for an observer positioned at a co-latitudinal angle θ =15, 30, 60 and 165 degrees, respectively.

Connection to observations 1: 2D model for 3D light curve



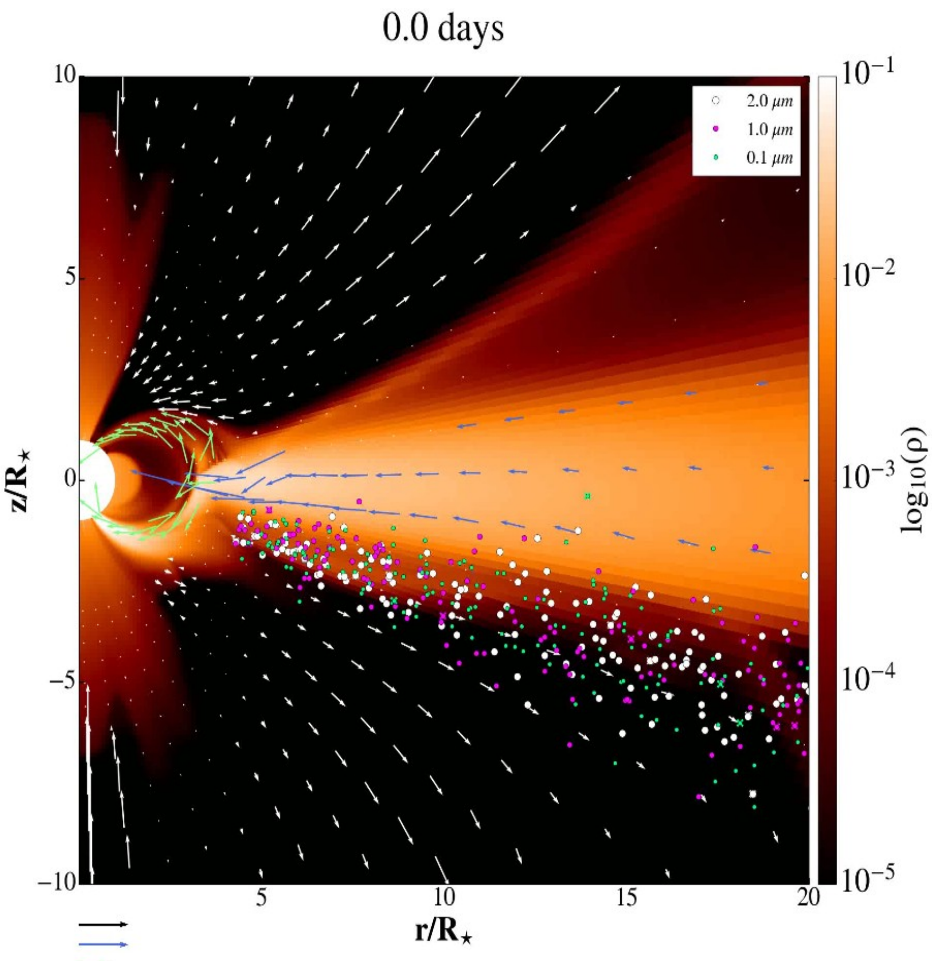


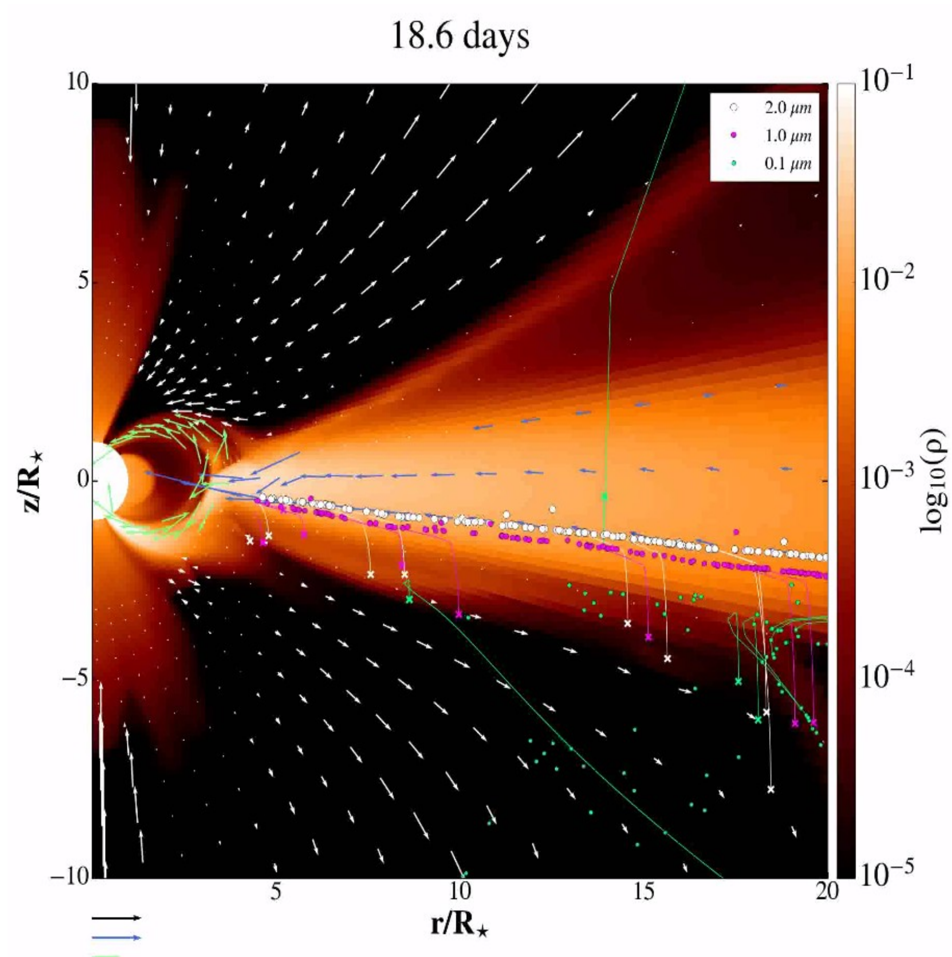
The dotted and dashed lines show the intensity for modeled hot spots as seen from the co-latitude angles of θ =15 and θ =165 degrees. Intensity is negative when the spot is not visible from a given position. In solid line is shown the total intensity for an observer with θ =165. Switching of the accretion column from the southern to northern hemisphere produces a phase shift in the observed intensity peak as the star rotates.

Connection to observations 2: Dusty disk in Young Stellar Objects

We also investigate the results of the impact of the disk with another material which does not influence the disk.

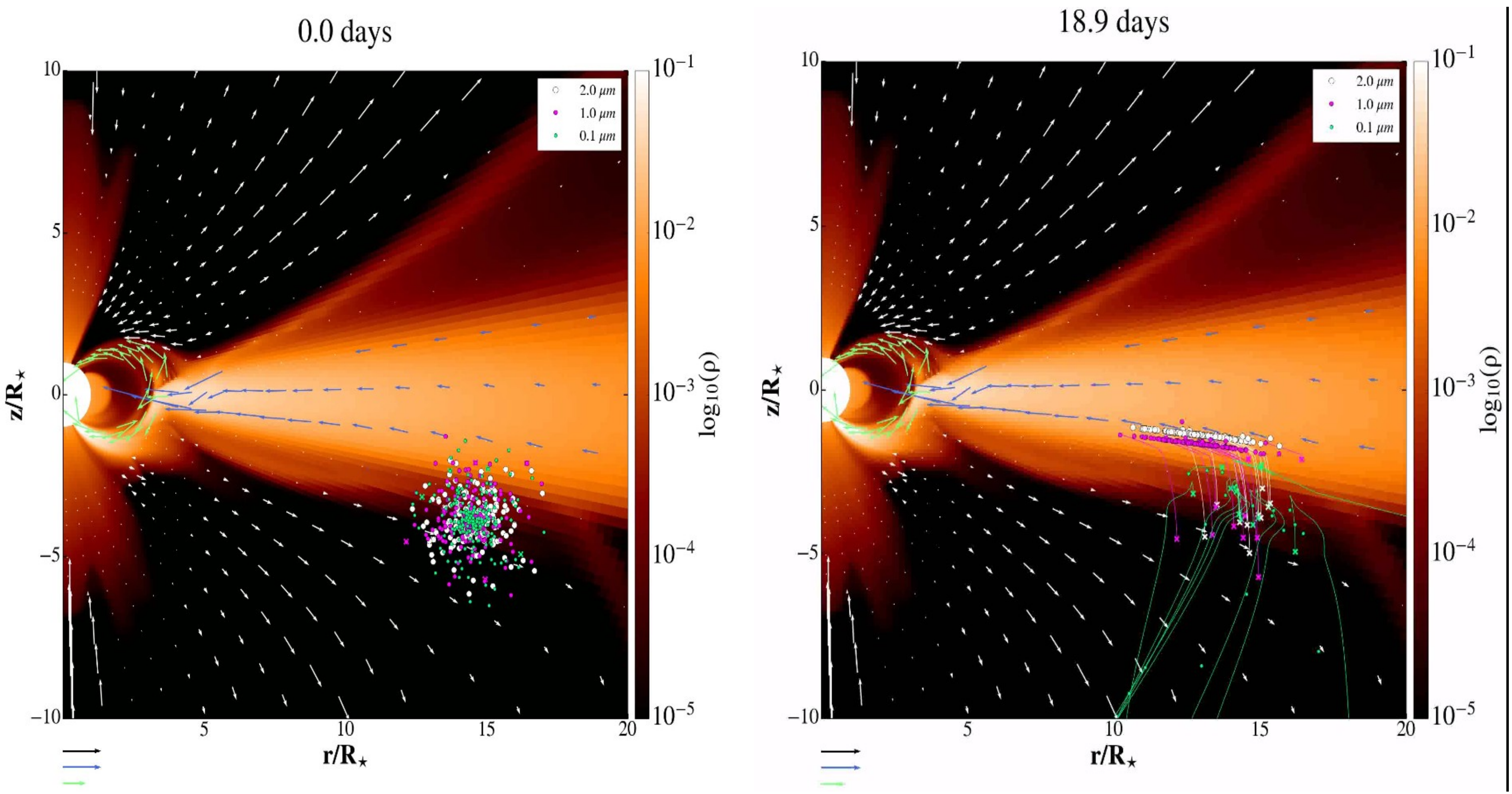
In a Summer Program project in 2017, Cezary Turski wrote the Python script for post-processing of the quasi-stationary results in my solutions. He added the dust particles and computed their movement in and above the disk as a background. The results will be used to improve the model of dust distribution in the disk.





Connection to observations 2: Dusty disk in Young Stellar Objects

A case of an impact with a more compact distribution of particles.



Summary

-In Young Stellar Objects case, I obtained solutions in the different points in the parameter space, to find trends in solutions.

-I performed long-lasting star-disk simulations for millisecond pulsars

-Axial (and conical) jets in YSO and NS cases obtained.

-Solutions with different geometry of magnetic field obtained.

-2D model for 3D light curve developed, to help connecting models and observations.

-Dusty Disk in Young Stellar Objects (C. Turski)