SILESIAN UNIVERSITY IN OPAVA

Numerical simulations with PLUTO code

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General outline

- **PART I:** General introduction to PLUTO code and its physics modules, installation of the code, testing of the installation with Sod shock tube test in 1D, visualization with gnuplot.
- **PART II:** Setup of 2D simulation from Test Problem template: Orszag-Tang test in 2D. Detailing of the setup and used files. Visualization of HD results with Paraview & VisIt. Animation of the results.
- **PART III:** Introduction to accretion disk. Setup of HD disk in axisymmetric 2D. Initial and boundary conditions, numerical methods and tricks. Shortcut to MHD setup.
- **PART IV:** Details of star-disk magnetospheric interaction simulations, with some examples. Setup of axisymmetric 2D setup with dipole and multipole magnetic field. Visualization of magnetic field lines with Paraview and Python.
- **PART V:** Full 3D setup: Orszag-Tang test in 3D. HD and then magnetic accretion disk. Restart and initialization from (modified) files. Running on Linux cluster. Visualization of 3D results. Various uses of the results: light-curves for comparison with observations, post-processing of the results (PLUTO+DUSTER): radiative effects in motion of dust grains. Concluding remarks.

  -Check webpage https://web.tiara.sinica.edu.tw/~miki/mikipluto.html

  Required packages: PLUTO source code, C-compiler (+MPI), Python (matplotlib, NumPy), Gnuplot, Paraview, VisIt.

Outline, Part I

- “Simulations” ver. “computations”.
- PLUTO physics modules.
- Documentation, test problems, templates.
- Practical part: installing the code.
- Testing with the use of 1D Sod shock tube test provided with the code.
- Visualization with gnuplot.

Simulation ver. computation

- Computation is actually an evaluation: you plug the numbers in a known algorithm and obtain the result. For this, you need to know the analytical expression. You still can use calculator or a computer to actually obtain numbers and plot e.g. trajectory of a bullet, but you **do** know the equation for the solution.

- Simulation is when you do not know the equation for the solution. You set the governing equations, e.g. differential equations, and use a numerical method to find the solutions. This is usually done in time steps, and we obtain the solution to some precision. We do not know the analytical expression for the solution, we just have numbers=numerical simulation.

- Why PLUTO? I used other codes, but PLUTO is constantly evolving (and is used in variety of problems) **and** the development is followed in the manual-which is not so often the case in the coding world. It gives chance to students to go through the-still steep-learning curve in the shortest possible time. Check also Doxygen html files in PLUTO/Doc .

PLUTO physics modules, equations

6.1 The HD Module

The HD module may be used to solve the Euler or the Navier-Stokes equations of classical fluid dynamics. The relevant source files and definitions for this module can be found in the Src/HD directory.

With the HD module, **PLUTO** evolves in time following system of conservation laws:

$$\frac{\partial}{\partial t}\begin{pmatrix} \rho \\ \boldsymbol{m} \\ E_t + \rho\Phi \end{pmatrix} + \nabla \cdot \begin{pmatrix} \rho\boldsymbol{v} \\ \boldsymbol{m}\boldsymbol{v} + p\mathsf{I} \\ (E_t + p + \rho\Phi)\boldsymbol{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ -\rho\nabla\Phi + \rho\boldsymbol{g} \\ \boldsymbol{m}\cdot\boldsymbol{g} \end{pmatrix} \tag{6.1}$$

where ρ is the mass density, $\boldsymbol{m} = \rho\boldsymbol{v}$ is the momentum density, $\boldsymbol{v}$ is the velocity, p is the thermal pressure and E_t is the total energy density:

$$E_t = \rho e + \frac{\boldsymbol{m}^2}{2\rho}\,. \tag{6.2}$$

An equation of state provides the closure $\rho e = \rho e(p, \rho)$.

The source term on the right includes contributions from body forces and is written in terms of the (time-independent) gravitational potential Φ and and the acceleration vector $\boldsymbol{g}$ (§5.4).

6.2 The MHD Module

The MHD module is suitable for the solution of ideal or resistive (non-relativistic) magnetohydrodynamical equations. Source and definition files are located inside the Src/MHD directory.

With the MHD module, **PLUTO** solves the following system of conservation laws:

$$\begin{aligned}
&\frac{\partial \rho}{\partial t} &&+ \quad \nabla\cdot(\rho \boldsymbol{v}) &&= \quad 0 \\
&\frac{\partial \boldsymbol{m}}{\partial t} &&+ \quad \nabla\cdot\left[\boldsymbol{m}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathsf{I}\left(p + \frac{\boldsymbol{B}^2}{2}\right)\right]^T &&= \quad -\rho\nabla\Phi + \rho\boldsymbol{g} \\
&\frac{\partial \boldsymbol{B}}{\partial t} &&+ \quad \nabla\times(c\boldsymbol{E}) &&= \quad 0 \\
&\frac{\partial (E_t + \rho\Phi)}{\partial t} &&+ \quad \nabla\cdot\left[\left(\frac{\rho \boldsymbol{v}^2}{2} + \rho e + p + \rho\Phi\right)\boldsymbol{v} + c\boldsymbol{E}\times\boldsymbol{B}\right] &&= \quad \boldsymbol{m}\cdot\boldsymbol{g}
\end{aligned} \tag{6.4}$$

where ρ is the mass density, $\boldsymbol{m} = \rho\boldsymbol{v}$ is the momentum density, $\boldsymbol{v}$ is the velocity, p is the gas (thermal) pressure, $\boldsymbol{B}$ is the magnetic field[2] and E_t is the total energy density:

$$E_t = \rho e + \frac{\boldsymbol{m}^2}{2\rho} + \frac{\boldsymbol{B}^2}{2}\,. \tag{6.5}$$

where an additional equation of state provides the closure $\rho e = \rho e(p,\rho)$ (see Chapter 7). The source term on the right includes contributions from body forces and is written in terms of the (time-independent) gravitational potential Φ and and the acceleration vector $\boldsymbol{g}$ (see §5.4).

In the third of Eq. (6.4), $\boldsymbol{E}$ is the electric field defined by the expression

$$c\boldsymbol{E} = -\boldsymbol{v}\times\boldsymbol{B} + \frac{\eta}{c}\cdot\boldsymbol{J} + \frac{\boldsymbol{J}}{ne}\times\boldsymbol{B} \qquad \left(\boldsymbol{J} = c\nabla\times\boldsymbol{B}\right) \tag{6.6}$$

where the first term is the convective term, the second term is the resistive term (η denotes the resistivity tensor, see §8.2) while the third term is the Hall term (§8.1). Note that the speed of light c never enters

6.3 The RHD Module

The RHD module implements the equations of special relativistic fluid dynamics in 1, 2 or 3 dimensions. Velocities are always assumed to be expressed in units of the speed of light. The special relativistic module comes with 2 different equations of state, and it also works in curvilinear coordinates. Gravity in Newtonian approximation can also be incorporated. The relevant source files and definitions for this module can be found in the Src/RHD directory.

The special relativistic module evolves the conservative set $\boldsymbol{U}$ of state variables

$$\boldsymbol{U} = \Big(D,\ m_1,\ m_2,\ m_3,\ E_t\Big)^T$$

where D is the laboratory density, $m_{x1,x2,x3}$ are the momentum components, E_t is the total energy (including contribution from the rest mass). The evolutionary conservative equations are

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \boldsymbol{m} \\ E_t \end{pmatrix} + \nabla\cdot\begin{pmatrix} D\boldsymbol{v} \\ \boldsymbol{m}\boldsymbol{v} + p\mathsf{I} \\ \boldsymbol{m} \end{pmatrix}^T = \begin{pmatrix} 0 \\ \boldsymbol{f}_g \\ \boldsymbol{v}\cdot\boldsymbol{f}_g \end{pmatrix}$$

where $\boldsymbol{v}$ is the velocity, p is the thermal pressure. Primitive variables $\boldsymbol{V}$ always include the rest-mass density ρ, three-velocity $\boldsymbol{v} = (v_{x1}, v_{x2}, v_{x3})$ and pressure p. With **PLUTO** 4.4, the acceleration term $\boldsymbol{f}_g$ is treated consistently[3] with the formalism of [Tau48]. If $\boldsymbol{a}$ is the acceleration vector,

$$\boldsymbol{f}_g = \rho\gamma^2\left[\gamma^2\boldsymbol{v}\,(\boldsymbol{v}\cdot\boldsymbol{a}) + \boldsymbol{a}\right]. \tag{6.12}$$

6.4 The RMHD Module

The RMHD module implements the equations of (ideal) special relativistic magnetohydrodynamics in 1, 2 or 3 dimensions. Velocities are always assumed to be expressed in units of the speed of light. Source and definition files are located inside the Src/RMHD directory.

The RMHD module solves the following system of conservation laws:

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \boldsymbol{m} \\ E_t \\ \boldsymbol{B} \end{pmatrix} + \nabla\cdot\begin{pmatrix} D\boldsymbol{v} \\ w_t\gamma^2\boldsymbol{v}\boldsymbol{v} - \boldsymbol{b}\boldsymbol{b} + \mathsf{I}p_t \\ \boldsymbol{m} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ \boldsymbol{f}_g \\ \boldsymbol{v}\cdot\boldsymbol{f}_g \\ \boldsymbol{0} \end{pmatrix} \tag{6.13}$$

where D is the laboratory density, $\boldsymbol{m}$ is the momentum density, E is the total energy (including contribution from the rest mass) while $\boldsymbol{f}_g$ is an acceleration term (see 6.3).

Primitive variables are similar to the RHD module but they also contain the magnetic field, $\boldsymbol{V} = (\rho, \boldsymbol{v}, p, \boldsymbol{B})$. The relation between $\boldsymbol{V}$ and $\boldsymbol{U}$ is

$$\begin{aligned} D &= \gamma\rho \\ \boldsymbol{m} &= w_t\gamma^2\boldsymbol{v} - b^0\boldsymbol{b} \\ E_t &= w_t\gamma^2 - b^0 b^0 - p_t \end{aligned} \quad , \quad \begin{cases} b^0 = \gamma\boldsymbol{v}\cdot\boldsymbol{B} \\ \boldsymbol{b} = \boldsymbol{B}/\gamma + \gamma(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{v} \\ w_t = \rho h + \boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2 \\ p_t = p + \dfrac{\boldsymbol{B}^2/\gamma^2 + (\boldsymbol{v}\cdot\boldsymbol{B})^2}{2} \end{cases}$$

PLUTO physics modules, equations

A note on public vs. non-public modules.

Besides the official code release, a few modules have not yet been made available with the standard public version, as they are still under active development or testing stage. In other circumstances, a private module may have been implemented under specific collaboration policies, which do not grant its public distribution. These non-offical modules include:

- Lagrangian Particle Module
  (Developers: B. Vaidya [*bvaidya@iiti.ac.in*], D. Mukherjee [*dipanjan@iucaa.in*]);
- Dust Module
  (Developers: A. Mignone [*mignone@to.infn.it*], M. Flock [*flock@mpia.de*]);
- Relativistic Resistive MHD
  (Developers: A. Mignone [*mignone@to.infn.it*], G. Mattia [*mattia@mpia.de*]);

Distribution, private sharing and usage of these modules is permitted only in the form of a collaboration between our partner institutions network, requiring co-authorship from at least one of the module developers.

6.5 The Resistive RMHD (*ResRMHD*) Module

Note: This module is not part of the public code release, see "Terms & Conditions of Use" at the beginning of this guide

The ResRMHD module deals with the non-ideal relativistic MHD equations using the approaches discussed in [MMBD19]. Source and definition files are located inside the Src/ResRMHD directory.

The set of resistive relativistic equations arising from the time and space split of the covariant are, in vectorial form,

$$\begin{aligned}
&\frac{\partial D}{\partial t} + \boldsymbol{\nabla}\cdot(D\boldsymbol{v}) = 0,\\
&\frac{\partial \boldsymbol{m}}{\partial t} + \boldsymbol{\nabla}\cdot(w\boldsymbol{u}\boldsymbol{u} + p\mathsf{I} + \mathsf{T}) = 0,\\
&\frac{\partial \mathcal{E}}{\partial t} + \boldsymbol{\nabla}\cdot\boldsymbol{m} = 0,\\
&\frac{\partial \boldsymbol{B}}{\partial t} + \boldsymbol{\nabla}\times\boldsymbol{E} = 0,\\
&\frac{\partial \boldsymbol{E}}{\partial t} - \boldsymbol{\nabla}\times\boldsymbol{B} = -\boldsymbol{J},
\end{aligned} \tag{6.14}$$

where I is the identity matrix and the fluid conserved variables are the density $D = \rho\gamma$ as measured in the laboratory frame, the total momentum density $\boldsymbol{m} = w\gamma\boldsymbol{u} + \boldsymbol{E}\times\boldsymbol{B}$, and the total energy density

$$\mathcal{E} = w\gamma^2 - p + \mathcal{P}_{\rm EM}\,. \tag{6.15}$$

In the expressions above, $w = \varepsilon + p$ is the specific enthalpy and $\mathcal{P}_{\rm EM} = (E^2 + B^2)/2$ denotes the EM energy density. Finally,

$$\mathsf{T} = -\boldsymbol{E}\boldsymbol{E} - \boldsymbol{B}\boldsymbol{B} + \tfrac{1}{2}(E^2 + B^2)\mathsf{I} \tag{6.16}$$

7. Equation of State

In the current implementation, **PLUTO** describes a thermally ideal gas obeying the *thermal* Equation of State (EOS)

$$p = nk_BT = \frac{\rho}{m_u\mu}k_BT \tag{7.1}$$

where p is the pressure, n is the total particle number density, k_B is the Boltzmann constant, T is the temperature, ρ is the density, m_u is the atomic mass unit and μ is the mean molecular weight. The thermal EOS describes the thermodynamic state of a plasma in terms of its pressure p, density ρ, temperature T and chemical composition μ. Eq. (7.1) is written in CGS physical units. Using code units for p and ρ while leaving temperature in Kelvin, the thermal EOS is conveniently re-expressed as

$$p = \frac{\rho T}{\mathcal{K}\mu} \qquad \Longleftrightarrow \qquad T = \frac{p}{\rho}\mathcal{K}\mu \qquad \left(\text{where} \quad \mathcal{K} = \frac{m_u v_0^2}{k_B}\right) \tag{7.2}$$

where $\mathcal{K}$ is the **KELVIN** macro which depends explictly on the value of `UNIT_VELOCITY`.

8. Nonideal Effects

In this chapter we give an overview of the code capabilities for treating dissipative (or diffusion) terms which, at present, include

- Hall MHD (MHD), described in §8.1;
- Resistivity (MHD), described in §8.2;
- Thermal conduction (HD, MHD), described in §8.3;
- Viscosity (HD, MHD), described in §8.4;

Each modules can be individually turned on from the physics sub-menus accessible via the Python script.

PLUTO documentation, templates and test examples

- PLUTO is freely available. Source files of the code are downloadable from http://plutocode.ph.unito.it/

- After unpacking, the source code is in PLUTO directory. In PLUTO/Doc is the manual, userguide.pdf. Follow the “Quick start” at the beginning of the document to **install and test the code. Produce the gnuplot output specified in the manual, to verify if the setup works.**

- The code comes with templates of subroutines which are usually changed. They are given in the PLUTO/Src/Templates

- Test examples, under /PLUTO/Test_Problems, are basic versions of setups used in previous versions of the code, during the developments of the setups for simulations presented In publications by various groups. It is a good library of examples for faster start of one’s own project.

- I will provide the setup for HD and MHD accretion disk for this lectures.

Shell variable setup, aliases

- We follow the “Quick start” from the beginning of the PLUTO/Doc/userguide.pdf

- Instead of every time after login repeating
  export PLUTO_DIR=/home/user/PLUTO # in bash shell
  Create in .bash_aliases (or .bashrc) a shell variable with path to PLUTO:
  export PLUTO_DIR="/home/miki/PLUTO"

- Also, it is useful to create an alias (shortcut) for running the setup.py, e.g.:
  alias pls='python $PLUTO_DIR/setup.py'

- For runs on multiple processors on laptop, useful is alias like:
  alias plutorun6='mpirun -np 6 ./pluto'

Hands-on introduction: PLUTO/setup.py

miki@petri: ~/Applics/PLUTO44

```
    I A  setup.py (python)  import os  Row 1    Col 1    9:35  Ctrl-K H
import os
import sys
import shutil

try:
  os.environ['PLUTO44_DIR']
except KeyError:
  print('PLUTO44_DIR not defined. Setting it to the Current Directory')
  pluto_directory = os.getcwd()
  pass
else:
  pluto_directory = os.environ['PLUTO44_DIR']

sys.path.append(pluto_directory + '/Tools/Python/')
import menu
import configure
from make_problem import MakeProblem


def PlutoInterface(pluto_dir, do_auto_update = False):
  work_dir = os.getcwd()
  interface_optval = ''
** Joe's Own Editor v4.1 ** (utf-8) ** Copyright © 2015 **
```

Hands-on introduction: PLUTO/Config/Linux.mpicc.defs

miki@petri: ~/Applics/PLUTO44

```
    IW   Config/Linux.mpicc.defs        Row 1    Col 1    9:
#############################################################
#
#     Configuration file for mpicc (parallel)
#
#############################################################

CC       = mpicc
CFLAGS   = -c -O3 -Wundef
LDFLAGS  = -lm

PARALLEL = TRUE
USE_HDF5 = FALSE
USE_PNG  = FALSE

########################################
# MPI additional spefications
########################################

ifeq ($(strip $(PARALLEL)), TRUE)
endif

########################################
#    HDF5 library options
########################################

ifeq ($(strip $(USE_HDF5)), TRUE)
INCLUDE_DIRS +=/usr/local/lib/HDF5-parallel/include
LDFLAGS +=/usr/local/lib/HDF5-parallel/lib -lz -lm -lhdf5
endif

########################################
#     PNG library options
########################################

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```

Test problem: Sod shock tube in 1D-use #04 if problems with #01

0.2 Running a simple shock-tube problem

PLUTO can be quickly configured to run one of the several test problems provided with the distribution. Assuming that your system satisfies all the requirements described in the next chapter (i.e. C compiler, Python, etc..) you can quickly setup **PLUTO** in the following way:

1. Change directory to any of the test problems under PLUTO/Test_Problems, e.g.

   ```
   ~> cd $PLUTO_DIR/Test_Problems/HD/Sod
   ```

2. Copy the header and initialization files from a configuration of our choice (e.g. #01):

   ```
   ~/PLUTO/Test_Problems/HD/Sod> cp definitions_01.h definitions.h
   ~/PLUTO/Test_Problems/HD/Sod> cp pluto_01.ini pluto.ini
   ```

3. Run the Python script using

   ```
   ~/PLUTO/Test_Problems/HD/Sod> python $PLUTO_DIR/setup.py
   ```

   and select "Setup problem" from the main menu, see Fig. 1.2. You can choose (by pressing Enter) or modify the default setting using the arrow keys.

4. Once you return to the main menu, select "Change makefile", choose a suitable makefile (e.g. Linux.gcc.defs) and press enter.

   All the information relevant to the specific problem should now be stored in the four files init.c (assigns initial condition and user-supplied boundary conditions), pluto.ini (sets the number of grid zones, Riemann solver, output frequency, etc.), definitions.h (specifies the geometry, number of dimensions, reconstruction, time stepping scheme, and so forth) and the makefile.

5. Exit from the main menu ("Quit" or press 'q') and type

   ```
   ~/PLUTO/Test_Problems/HD/Sod> make
   ```

   to compile the code.

6. You can now run the code by typing

   ```
   ~/PLUTO/Test_Problems/HD/Sod> ./pluto
   ```

   At this point, **PLUTO** reads the initialization file pluto.ini and starts integrating. The run should take a few seconds (or less) and the integration log should be dumped to screen.

Files for setup and their modifications

- The PLUTO original source will not be changed, for our simulations we just append to it our version of some files in a pre-compiling step.
- The changed version of a file in the work directory (for which I suggest the name /home/Pluto) has, by default in PLUTO, priority to the original version in PLUTO/Src directory.

- The files to be copied into the work directory from the working version into a new setup are **init.c, pluto.ini, definitions.h**, (+userdef_output.c, res_eta.c, visc_nu.c for the accretion disk setup).

- The file definitions.h is the only *.h file changed in the work directory. All the other *.h files are to be changed directly in PLUTO/Src directory.

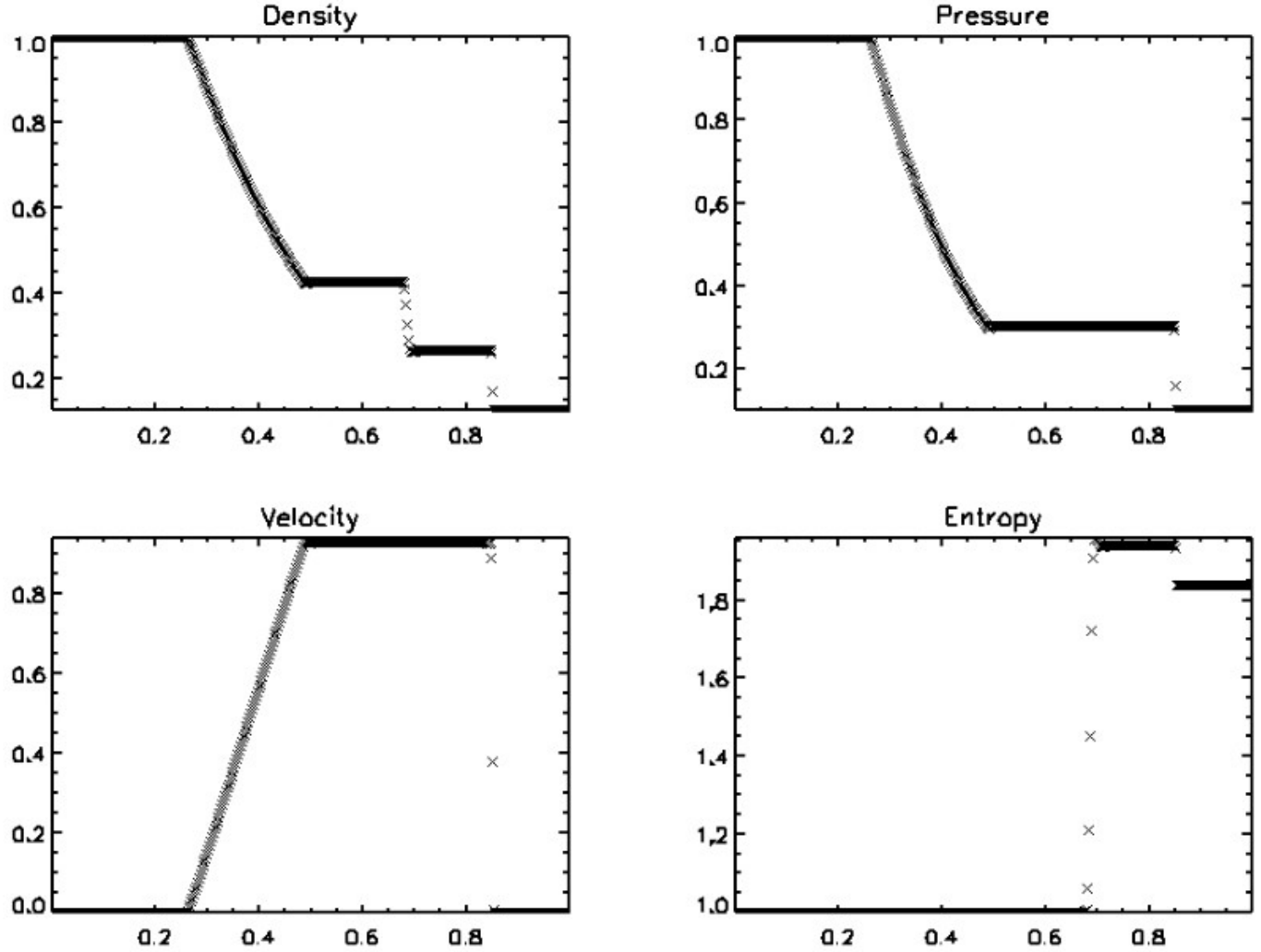
- In the file **pluto.ini** are defined the grid, solvers and run parameters.
- Most of the entries in **definitions.h** are done through the python environment during the setup of the run, but some entries are to be done by hand editing the definitions.h file, prior to compilation.
- In the file **init.c** is defined the physics setup.

Test problem: Sod shock tube in 1D

Detailed Description **from Doxygen file:** The Sod shock tube problem is one of the most used benchmark for shock-capturing schemes. It is a one-dimensional problem with initial condition given by a discontinuity separating two constant states:

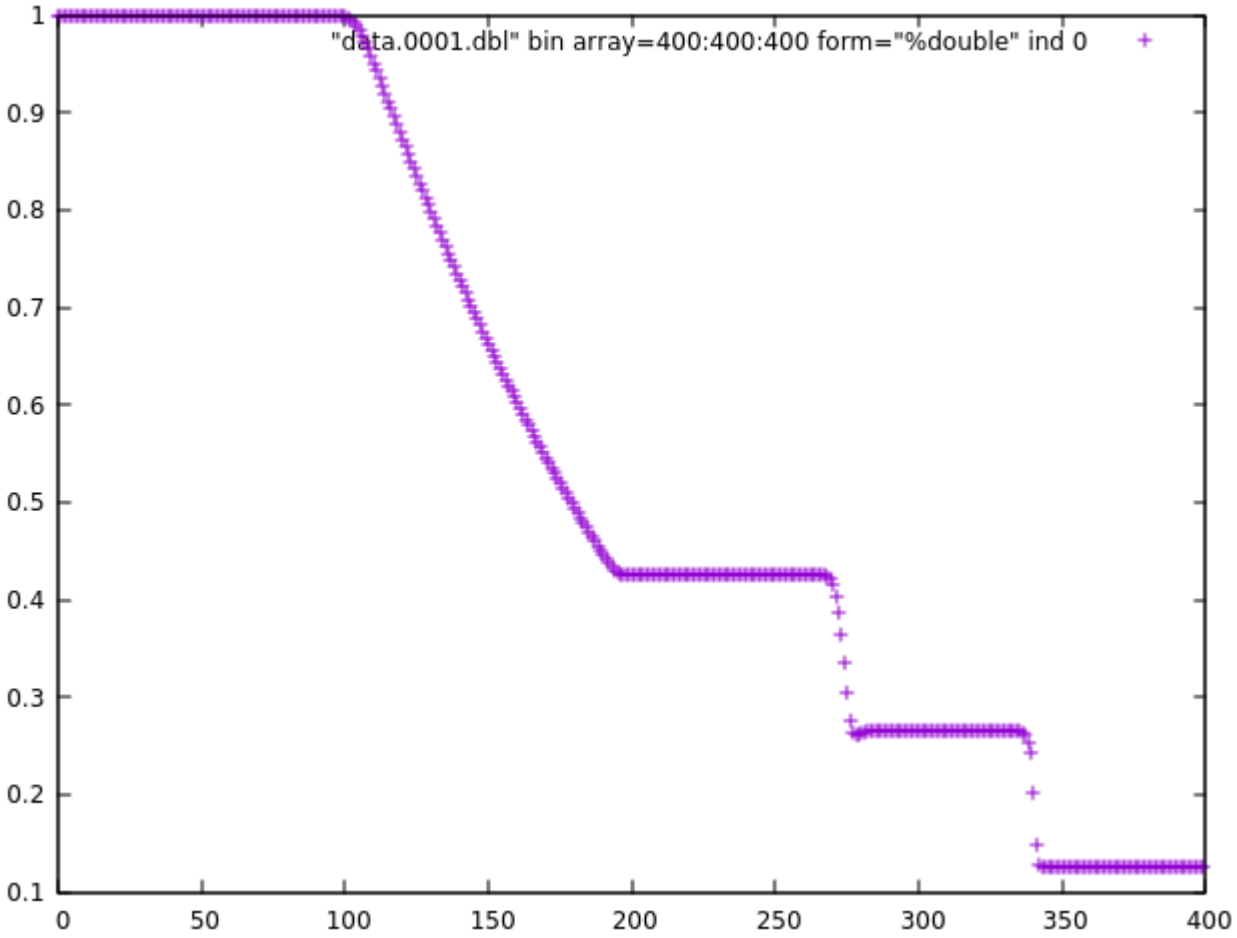
$$(\rho, v_x, p)_L = (1, 0, 1) \quad \text{for} \quad x < 0.5$$
$$(\rho, v_x, p)_R = \left(\tfrac{1}{8}, 0, \tfrac{1}{10}\right) \quad \text{for} \quad x > 0.5$$

The evolved structured at t=0.2 is shown in the panels below and consists of a left-going rarefaction wave, a right-going contact discontinutity and a right-going shock wave. The results shown here were carried with PARABOLIC interpolation, CHARACTERISIC_TRACING time stepping and the two_shock Riemann solver on 400 zones (**configuration #04**).



Test problem: Sod shock tube in 1D

Typing in terminal:
gnuplot> plot "data.0001.dbl" bin array=400:400:400 form="%double" ind 0
You should obtain:



Summary of the Part I

- We got acquainted with PLUTO and its physics modules.
- I show where to find documentation, test problems and templates.
- Practical part: we went through the code installation.
- We tested the setup using the 1D Sod shock tube test provided with the code.
- We used visualization of the results with gnuplot.

Outline, Part II

- Initial and boundary conditions setup for 2D Orszag-Tang test.
- Hands-on introduction to setup files of PLUTO.
- Output formats & files which we should save for later analysis.
- Visualization of the results with Paraview and VisIt.
- Movies time: animation and saving of the movie.

2D test problem: Orszag-Tang

0.3 Running the Orszag-Tang MHD vortex test

1. Change directory to PLUTO/Test_Problems/MHD/Orszag_Tang.
2. Choose a configuration (e.g. #02) and copy the corresponding configuration files, i.e.,

```
~/PLUTO/Test_Problems/MHD/Orszag_Tang> cp definitions_02.h definitions.h
~/PLUTO/Test_Problems/MHD/Orszag_Tang> cp pluto_02.ini pluto.ini
```

3. Run the Python script:

```
~/PLUTO/Test_Problems/MHD/Orszag_Tang> python $PLUTO_DIR/setup.py
```

   select "Setup problem" and choose the default setting by pressing enter;

4. Once you return to the main menu, select "Change makefile" and choose a suitable makefile (e.g. Linux.gcc.defs) and press enter.
5. Exit from the main menu ("Quit" or press 'q'). Edit pluto.ini and, under the *[Grid]* block, lower the resolution from 512 to 200 in both directions (`X1-grid` and `X2-grid`). Change `single_file`, in the "dbl" output under the *[Static Grid Output]* block, to `multiple_files`. Finally, edit definitions.h and change `PRINT_TO_FILE` from *YES* to *NO*.
6. Compile the code:

```
~/PLUTO/Test_Problems/MHD/Orszag_Tang> make
```

7. If compilation was successful, you can now run the code by typing

```
~/PLUTO/Test_Problems/MHD/Orszag_Tang> ./pluto
```

   At this point, **PLUTO** reads the initialization file pluto.ini and starts integrating. The run should take a few minutes (depending on the machine you're running on) and the integration log should be dumped to screen.

Orszag-Tang I.C. & B.C.

For each simulation we need to define **initial** and **boundary** conditions.

I introduce some numerical simulations terminology here in ***bold***:

We set velocity and magnetic field in a 2D Cartesian coordinates, in a ***computational box*** with (x,y,0)=(256x256x0) grid cells and a ***physical domain*** x,y=[0,2*pi]

Velocity components: v = (-sin y, sin x, 0)

Magnetic field: B = (-sin y, sin 2x, 0)

Density: rho = 25/9

Pressure: p = 5/3

Orszag-Tang I.C. & B.C.

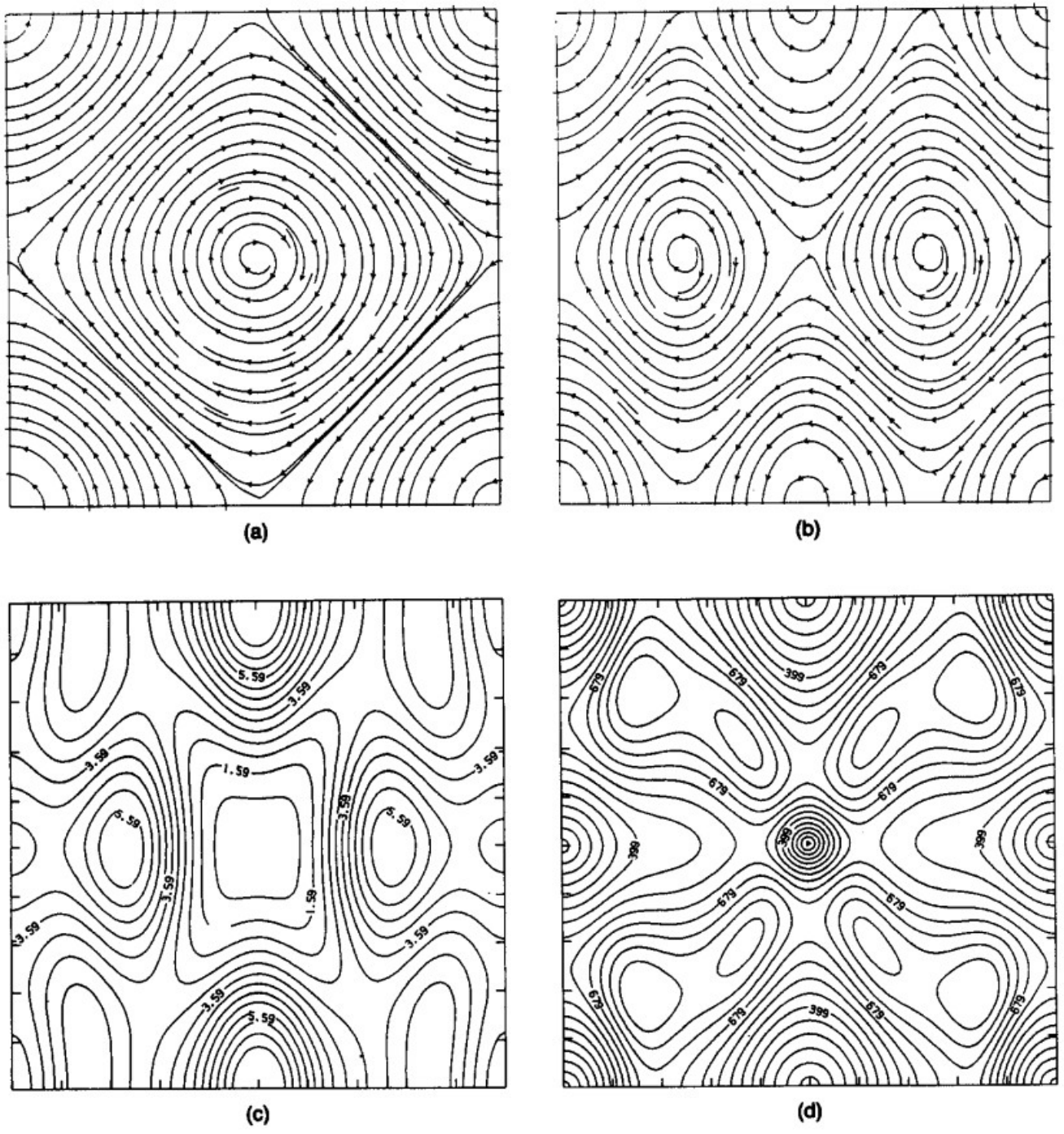
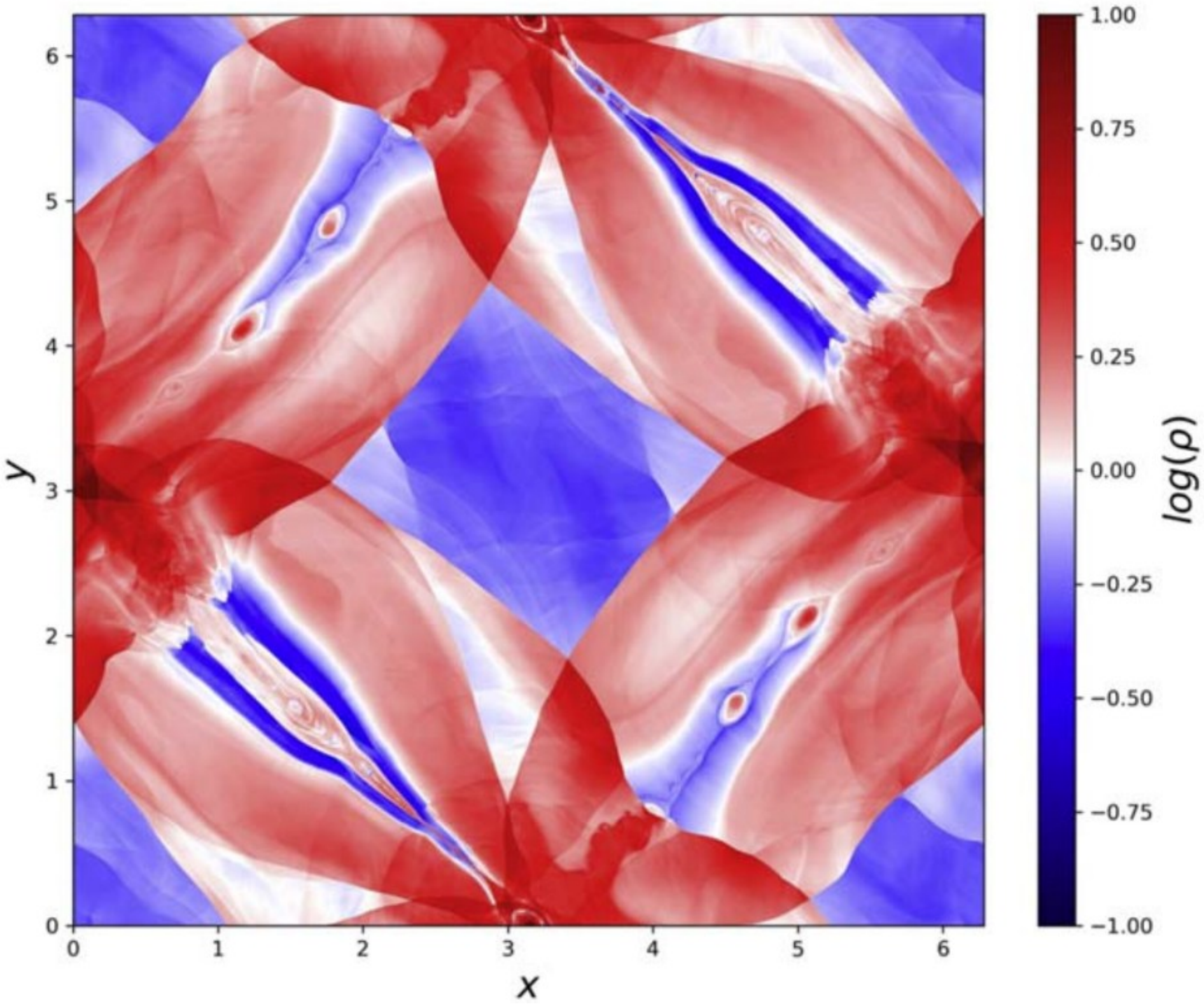


FIG. 1. Initial conditions: (a) velocity field; (b) magnetic field; initial conditions specific to the $M = 0.6$ case: (c) thermal pressure field; (d) local Mach number. Minimum and maximum values are 0.73 and 7.9 for thermal pressure and 0.0 and 0.97 for local Mach number.

OT, standard test but not so standard results



OT, standard test but not so standard results

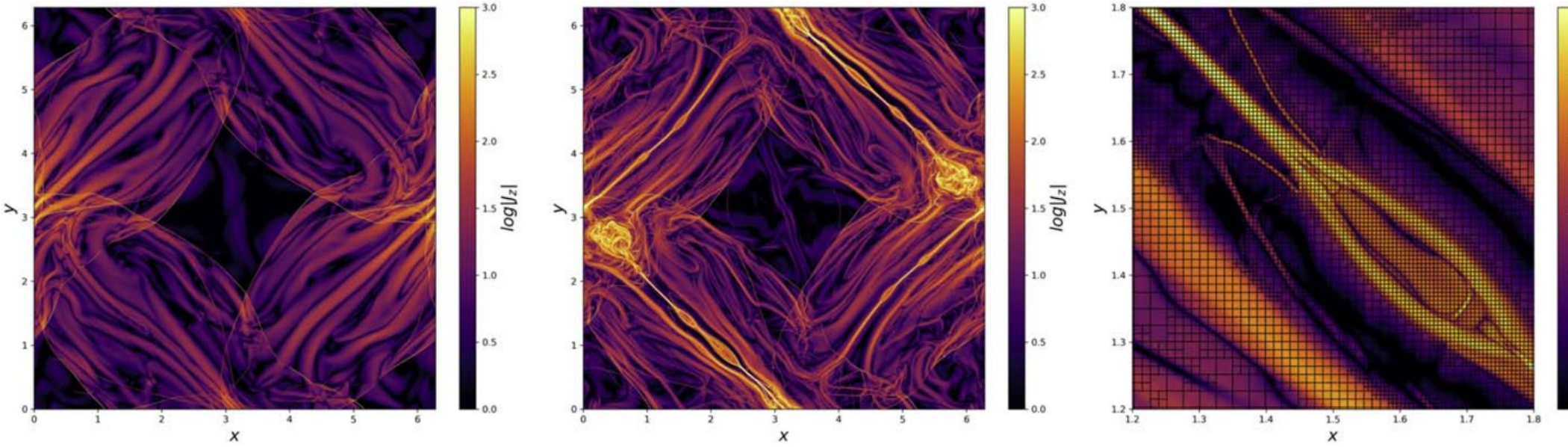


Figure 2. Logarithm of the out-of-plane current density magnitude $|J_z|$ at $t = 10t_c$ for $S = 2 \times 10^3$ (left), $S = 2 \times 10^4$ (middle), and a zoom into the current she
$S = 2 \times 10^4$ showing the AMR grid blocks (right), each consisting of 8×8 cells, in black. Both cases have an effective resolution of 8192^2 cells in the domain
plasmoid-unstable current sheet on the right is captured by more than 10 cells over its width.

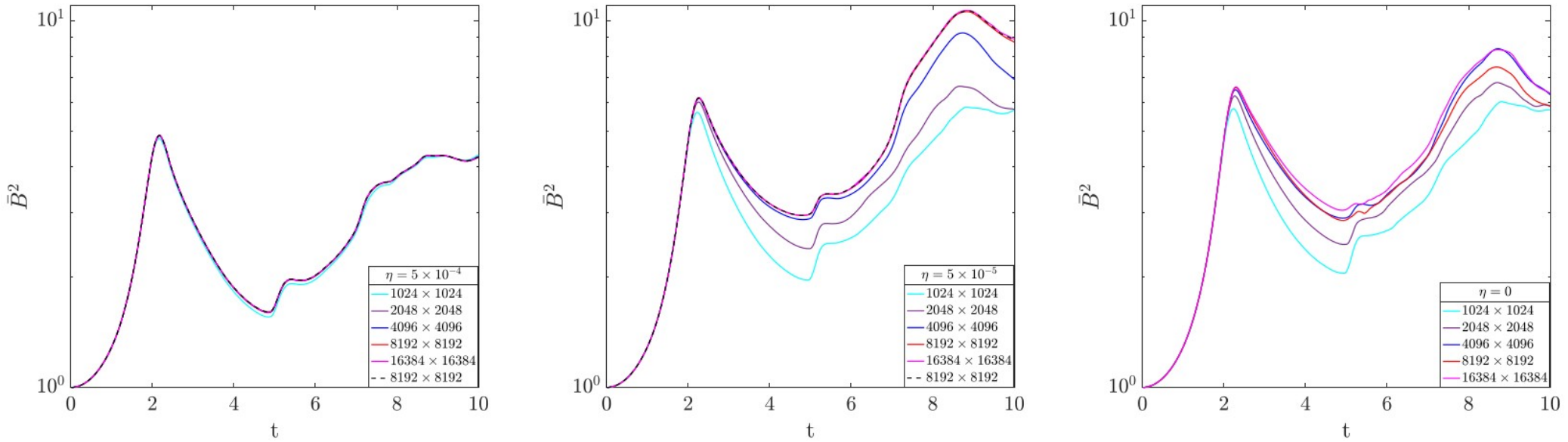


Figure 3. Evolution of the domain-averaged magnetic energy density $\bar{B}^2$ for $S = 2 \times 10^3$ (left), $S = 2 \times 10^4$ (middle), and the ideal case $\eta = 0$ (right) for all resolutions considered.

Hands-on introduction to setup files of PLUTO

- Guided tour through the source files:

  -pluto.ini contains definition of:
  grid, solver, choice of boundary conditions, output steps, parameters.

  -Definition of output formats.

  -Output files, files to save for later analysis and eventual restart.

  -definitions.h: macros setting.

  -init.c: physical setup, equations for **initial** and **boundary** conditions.

Hands-on introduction: pluto.ini

miki@petri: ~/Pluto44/OTang2D

```
   I    pluto.ini (ini)
[Grid]

X1-grid    1    0.0    200    u    6.28318530717959
X2-grid    1    0.0    200    u    6.28318530717959
X3-grid    1    0.0    1    u    1.0

[Chombo Refinement]

Levels           4
Ref_ratio        2 2 2 2 2
Regrid_interval  2 2 2 2
Refine_thresh    0.3
Tag_buffer_size  3
Block_factor     4
Max_grid_size    32
Fill_ratio       0.75

[Time]

CFL                    0.8
CFL_max_var    1.1
tstop            3.1
first_dt             1.e-4

[Solver]

Solver         hll

[Boundary]
```

miki@petri: ~/Pluto44/OTang2D

```
   I    pluto.ini (ini)
[Boundary]

X1-beg          periodic
X1-end          periodic
X2-beg          periodic
X2-end          periodic
X3-beg          periodic
X3-end          periodic

[Static Grid Output]

uservar    0
dbl        10.31  -1   single_file
flt        -1.0   -1   single_file
vtk        0.31   -1   single_file
tab        -1.0   -1
ppm        -1.0   -1
png        -1.0   -1
log         1
analysis   -1.0   -1

[Chombo HDF5 output]

Checkpoint_interval  -1.0  0
Plot_interval         1.0  0

[Parameters]

SCRH                          0
```

Output formats & files to save

- In pluto.ini we defined which output
- data.xxxx.dbl files – viewing, processing with Python, idl etc. packages.
  -also, for restart, together with restart.out.
- Data.xxxxdbl.h5 - hdf5 files-need to set the flag in /PLUTO/Config/*.defs file
- data.xxxx.vtk files – for viewing with Paraview, VisIt.
- Together with data.xxxx.dbl and .vtk files, always save also, in the same directory with the results, pluto.ini, definitions.h. init.c, grid.out, dbl.out, restart.out, to know which setup produced the files, and also for some analysis and plotting packages, which might need them.
- grid.out files defines the geometry, dbl.out lists the output variables

Hands-on introduction: definitions.h

```
miki@petri: ~/Pluto44/OTang2D
   I A  definitions.h (c)                                        Row 1
#define  PHYSICS                         MHD
#define  DIMENSIONS                      2
#define  GEOMETRY                        CARTESIAN
#define  BODY_FORCE                      NO
#define  COOLING                         NO
#define  RECONSTRUCTION                  LINEAR
#define  TIME_STEPPING                   HANCOCK
#define  NTRACER                         0
#define  PARTICLES                       NO
#define  USER_DEF_PARAMETERS             1

/* -- physics dependent declarations -- */

#define  EOS                             IDEAL
#define  ENTROPY_SWITCH                  NO
#define  DIVB_CONTROL                    EIGHT_WAVES
#define  BACKGROUND_FIELD                NO
#define  AMBIPOLAR_DIFFUSION             NO
#define  RESISTIVITY                     NO
#define  HALL_MHD                        NO
#define  THERMAL_CONDUCTION              NO
#define  VISCOSITY                       NO
#define  ROTATING_FRAME                  NO

/* -- user-defined parameters (labels) -- */

#define  SCRH                            0

/* [Beg] user-defined constants (do not change this line) */

#define  LIMITER                         MC_LIM
```

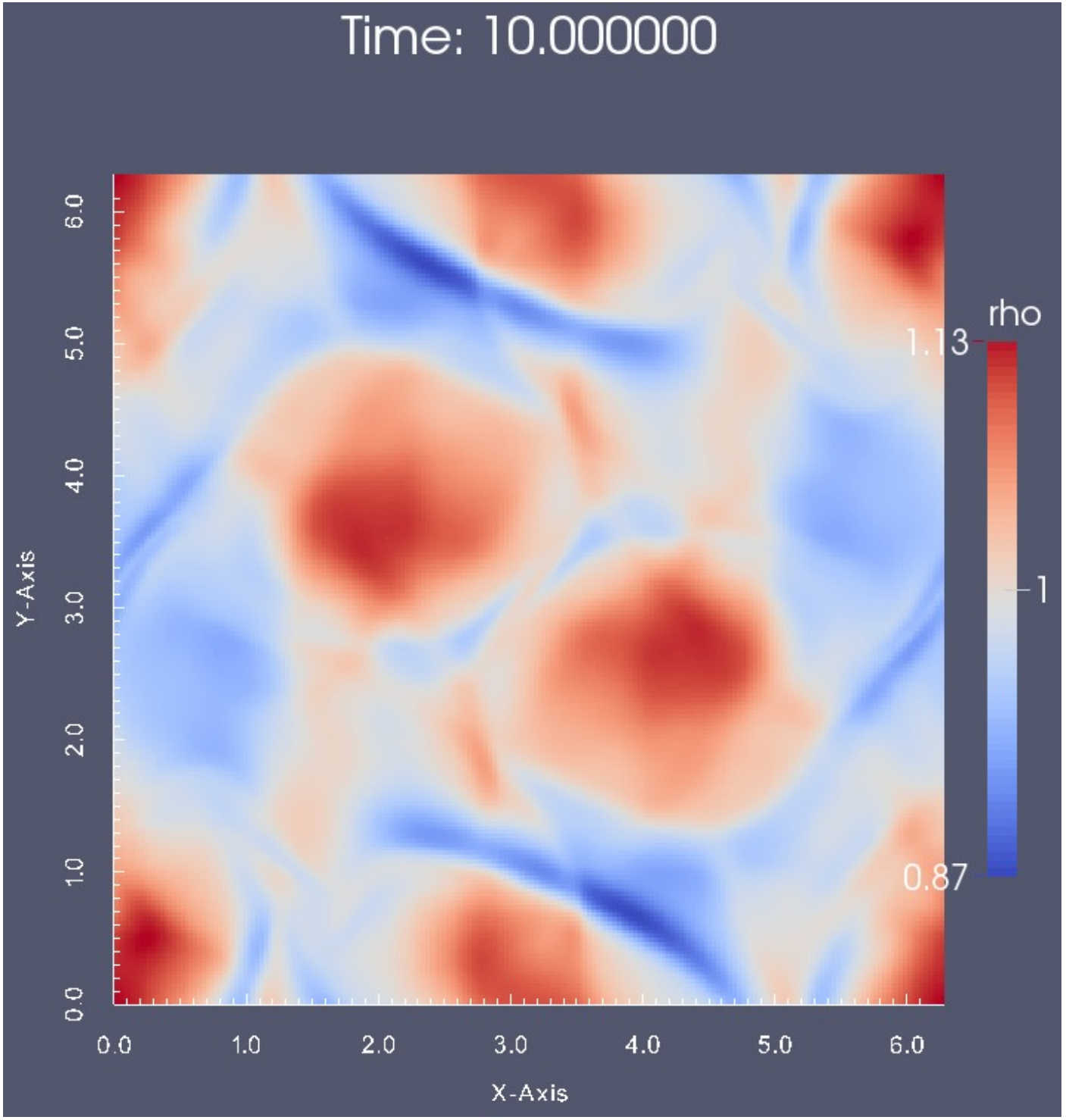
Hands-on introduction: init.c

- Note that at the beginning of each file in PLUTO is a brief description about what it does. It is a very good practice, follow it.

```
miki@petri: ~/Pluto44/OTang2D
   I A  init.c (c)  void Init (double *us, double x1,
/* ************************************************************
void Init (double *us, double x1, double x2, double x3)
/*
 *
 ************************************************************
{
  double x=x1, y=x2 ,z=x3;
  g_gamma = 5./3.;//g_inputParam[GAMMA];

  us[VX1] = -0.7* sin(y);
  us[VX2] =  0.7* sin(x);
  us[VX3] = 0.0;
  us[BX1] = - sin(y);
  us[BX2] =   sin(2.0*x);
  us[BX3] = 0.0;
  us[RHO] = 1.;
  #if EOS != ISOTHERMAL && EOS != BAROTROPIC
   us[PRS] = 10.0;
  #endif
  us[TRC] = 1.0;

  us[AX1] = 0.0;
  us[AX2] = 0.0;
  us[AX3] = cos(y) + 0.5 * cos(2.0*x);

 #if DIMENSIONS == 3 && ROTATE == -1
 {
   double c0 = 0.8;
   us[VX2] = - sin(z);
   us[VX3] =   sin(y);
   us[VX1] =   0.0;

   us[BX2] = c0*( - 2.0*sin(2.0*z) + sin(x));
   us[BX3] = c0*(       sin(x) + sin(y));
   us[BX1] = c0*(       sin(y) + sin(z));
```

```
miki@petri: ~/Pluto44/OTang2D
   I A  init.c (c)                    Row 27   Col 1   12:55  Ctrl-K H for
/* ////////////////////////////////////////////////////////////////////////// */
/*!
  \file
  \brief Orszag-Tang MHD vortex.

  The Orszag Tang vortex system describes a doubly periodic fluid
  configuration leading to two-dimensional supersonic MHD turbulence.
  Although an analytical solution is not known, its simple and reproducible
  set of initial conditions has made it a widespread benchmark for
   inter-scheme comparison.

  The computational domain is the periodic box \f$[0,2\pi]^D\f$ where
  \c D is the number of spatial dimensions.
  In 2D, the initial condition is given by
  \f[
     \vec{v} = \left(-\sin y,\, \sin x, 0\right) \,,\qquad
     \vec{B} = \left(-\sin y,\, \sin 2x, 0\right) \,,\qquad
     \rho = 25/9\,,\qquad
     p    = 5/3
  \f]

  This test problem does not have any input parameter.

  A snapshot of the solution on a \c 512x512 grid is shown below.

  \image html mhd_ot.02.jpg "Density at t=3.1 (configuration #02)."

  \author A. Mignone (mignone@ph.unito.it)
  \date   April 13, 2014

  \b References
     - "Comparison of some Flux Corrected Transport and TVD numerical
        schemes for hydrodynamic and magnetohydrodynamic problems",
        Toth & Odstrcil, JCP (1996) 128, 82
     - "High-order conservative finite difference GLM-MHD schemes for
```

Visualization and animation with Paraview, VisIt



Summary of the Part II

- We described and set the 2D Orszag-Tang test.
- I detailed the setup files of PLUTO.
- We learned which are the output formats.
- We learned to use Paraview and VisIt for 2D results.
- We learned how to animate results with Paraview.

Outline, Part III

- A very brief introduction to history of accretion disk numerics.
- Introduction to HD accretion disk simulation.
- Setup of axisymmetric 2D(=2.5D) HD disk.
- Introduction to star-disk magnetospheric interaction simulations.
- Setup of axisymmetric 2D setup with dipole magnetic field.
- Visualization of magnetic field lines with Paraview.

Introduction of accretion disk simulations

- First numerical solution of (HD) accretion disk was by Prendergast & Burbidge (1968) (no pics!)
- Analytical solution was given by Shakura & Sunyaev (1973), with alpha-viscosity prescription.
- From that time to the 1990-ies many developments and models, with different approximations.
- In Kluźniak & Kita (2000) was given a solution of the HD disk in the full 3D. It was obtained by the method of asymptotic approximation (Taylor expansion).
- In 2009, numerical simulations of star-disk magnetospheric interaction were done in 2D-axisymmetric simulations, by Romanova et al. (2009, 2013, with non-public code), Zanni & Ferreira (2009, 2013, with modification of a publicly available code PLUTO v. 3.0).
- Development of disk simulations in the direction of MRI in the disk (Flock et al.), but nothing much in star-disk magnetospheric simulations for a decade.
- In Čemeljić et al. (2017) and Čemeljić (2019, "Atlas" paper), the first repeating of Zanni et al. (2009, 2013) axi-symmetric viscous & resistive MHD simulations in 2D with PLUTO code, v.4.1. The results are similar to Romanova et al., obtained with their (non-public) code with entropy conservation, not energy.
- In "Atlas" paper I performed a parameter study to investigate the influence of different parameters. This publication, especially its Appendix, is used here as a guide through setup and numerical methods.

Normalization in the code

Code works in the normalized units. For translating into other units, one needs to multiply with the corresponding scaling factors. When using Cooling, one needs to define units in definitions.h subroutine.

Table A.1. Typical values and scaling for different central objects.

	YSOs	WDs	NSs
$M_\star (M_\odot)$	0.5	1	1.4
$R_\star$	$2R_\odot$	5000 km	10 km
$P_\star$	4.6 d	6.1 s	0.46 ms
$B_\star$ (G)	500	5×10^5	10^8
ρ_{d0} (g cm^{-3})	1.2×10^{-10}	9.4×10^{-9}	4.6×10^{-6}
v_0 (km s^{-1})	218	5150	136 000
$\dot{M}_0 (M_\odot$ yr$^{-1})$	5.7×10^{-7}	1.9×10^{-9}	10^{-9}
B_0 (G)	200	5×10^4	2.93×10^7

Equations solved by the code

- Code I used in "Atlas" is PLUTO (v.4.1) by Mignone et al. (2007, 2012). We will do it in v.4.4
- We will perform simulations of a thin accretion disk.
- If the disk is to reach the quasi-stationary state, the Ohmic and viscous heating in the energy equation should be balanced with the source term. In such a case, we effectively neglect the dissipative terms in the energy equation-this is equal to the assumption that all the heat is radiated away from the disk.

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

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

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{8\pi} \right) \boldsymbol{v} - \frac{(\boldsymbol{v} \cdot \boldsymbol{B}) \boldsymbol{B}}{4\pi} \right]$$

$$+ \nabla \cdot \left[\underbrace{\eta_{\mathrm{m}} \boldsymbol{J} \times \boldsymbol{B}/4\pi - \boldsymbol{v} \cdot \boldsymbol{\tau}}_{\text{heating terms}} \right] = \rho \boldsymbol{g} \cdot \boldsymbol{v} - \underbrace{\Lambda}_{\text{cooling}}$$

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

the gravity acceleration is $\boldsymbol{g} = -\nabla \Phi_{\mathrm{g}}$, where the gravitational potential of the star with mass $M_\star$ is equal to $\Phi_{\mathrm{g}} = -GM_\star/R$. Then $g_{\mathrm{R}} = -1.0/R^2$ in the code units.

- Viscosity and resistivity are still affecting the solution, in the equation of motion and in the induction equation.

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + \frac{\boldsymbol{B} \cdot \boldsymbol{B}}{8\pi} \right) \boldsymbol{u} - \frac{(\boldsymbol{u} \cdot \boldsymbol{B})\, \boldsymbol{B}}{4\pi} \right]$$

$$+ \nabla \cdot \left[\eta_{\mathrm{m}} \boldsymbol{J} \times \boldsymbol{B}/4\pi - \boldsymbol{u} \cdot \boldsymbol{\tau} \right] = \rho \boldsymbol{g} \cdot \boldsymbol{u} - \Lambda_{\mathrm{cool}}$$

Practical part: init.c file, Hydro-dynamical star-disk setup

The initial disk was set with the initial density b
a self-similar profile and the aspect ratio ϵ:

$$\rho_{\rm d} = \rho_{\rm d0}\left\{\frac{\gamma-1}{\gamma\epsilon^2}\left[\frac{R_*}{R}-\left(1-\frac{\gamma\epsilon^2}{\gamma-1}\right)\frac{R_\star}{R\sin\theta}\right]\right\}^{1/(\gamma-1)}$$

$$= \rho_{\rm d0}\left\{\frac{2}{5\epsilon^2}\left[\frac{R_\star}{R}-\left(1-\frac{5}{2}\epsilon^2\right)\frac{R_\star}{R\sin\theta}\right]\right\}^{3/2}.$$

The pressure was

$$P_{\rm d} = \epsilon^2\rho_{\rm d0}v_{\rm K\star}^2\left(\frac{\rho_{\rm d}}{\rho_{\rm d0}}\right)^\gamma =$$

$$= \frac{\rho_{\rm d0}v_{\rm K\star}^2}{\epsilon^3}\left\{\frac{2}{5}\left[\frac{R_\star}{R}-\left(1-\frac{5\epsilon^2}{2}\right)\frac{R_\star}{R\sin\theta}\right]\right\}^{5/2}$$

The initial disk velocity profile is, following KK00:

$$v_{Rd} = -\alpha_{\rm v}\epsilon^2\left[10-\frac{32}{3}\Lambda\alpha_{\rm v}^2-\Lambda\left(5-\frac{1}{\epsilon^2\tan^2\theta}\right)\right]\sqrt{\frac{GM_*}{R\sin^3\theta}},$$

$$v_{R\varphi} = \left[\sqrt{1-\frac{5\epsilon^2}{2}}+\frac{2}{3}\epsilon^2\alpha_{\rm v}^2\Lambda\left(1-\frac{6}{5\epsilon^2\tan^2\theta}\right)\right]\sqrt{\frac{GM_*}{R\sin\theta}} \quad \text{(A.10)}$$

where

$$\Lambda = \frac{11}{5}\Big/\left(1+\frac{64}{25}\alpha_{\rm v}^2\right). \quad \text{(A.11)}$$

In the corona, density and pressure are:

$$\rho_{\rm c} = \rho_{\rm c0}(R_\star/R)^{1/(\gamma-1)},$$

$$P_{\rm c} = \rho_{\rm c0}\frac{\gamma-1}{\gamma}\frac{GM_\star}{R_\star}\left(\frac{R_\star}{R}\right)^{\gamma/(\gamma-1)}$$

Viscosity tensor is given by Landau-Lifshitz def:

$$\boldsymbol{\tau} = \eta_{\rm v}\left[(\nabla\boldsymbol{v})+(\nabla\boldsymbol{v})^T-\frac{2}{3}(\nabla\cdot\boldsymbol{v})\boldsymbol{I}\right], \quad \text{(A.7)}$$

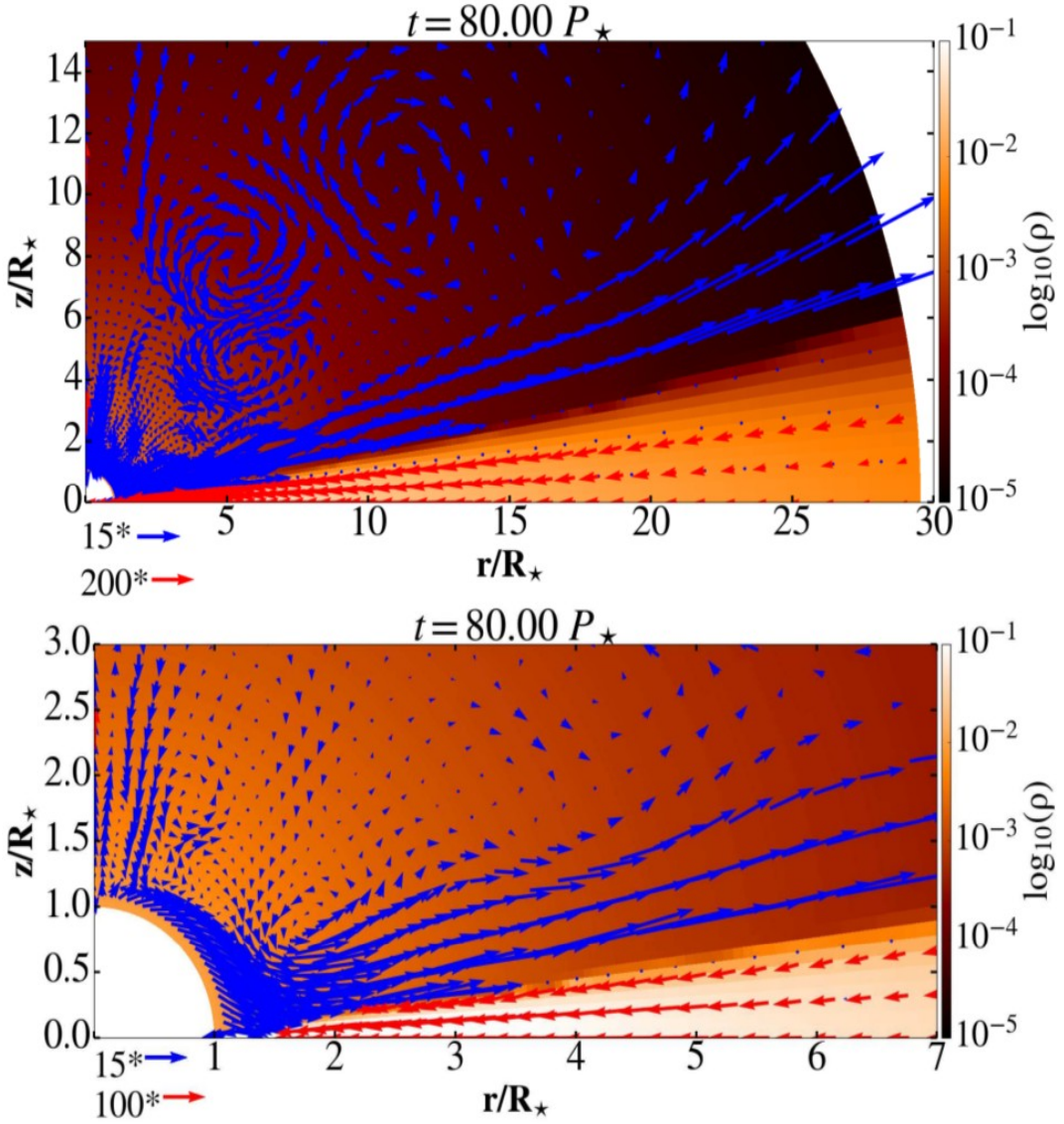
with the dynamic viscosity $\eta_{\rm v} = \rho\nu_{\rm v}$ given with

$$\eta_{\rm v} = \frac{2}{3}\rho\alpha_{\rm v}\left[c_{\rm s}^2(r)|_{z=0}+\frac{2}{5}\left(\frac{GM_\star}{R}-\frac{GM_\star}{r}\right)\right]\sqrt{\frac{r^3}{GM_\star}}, \quad \text{(A.8)}$$

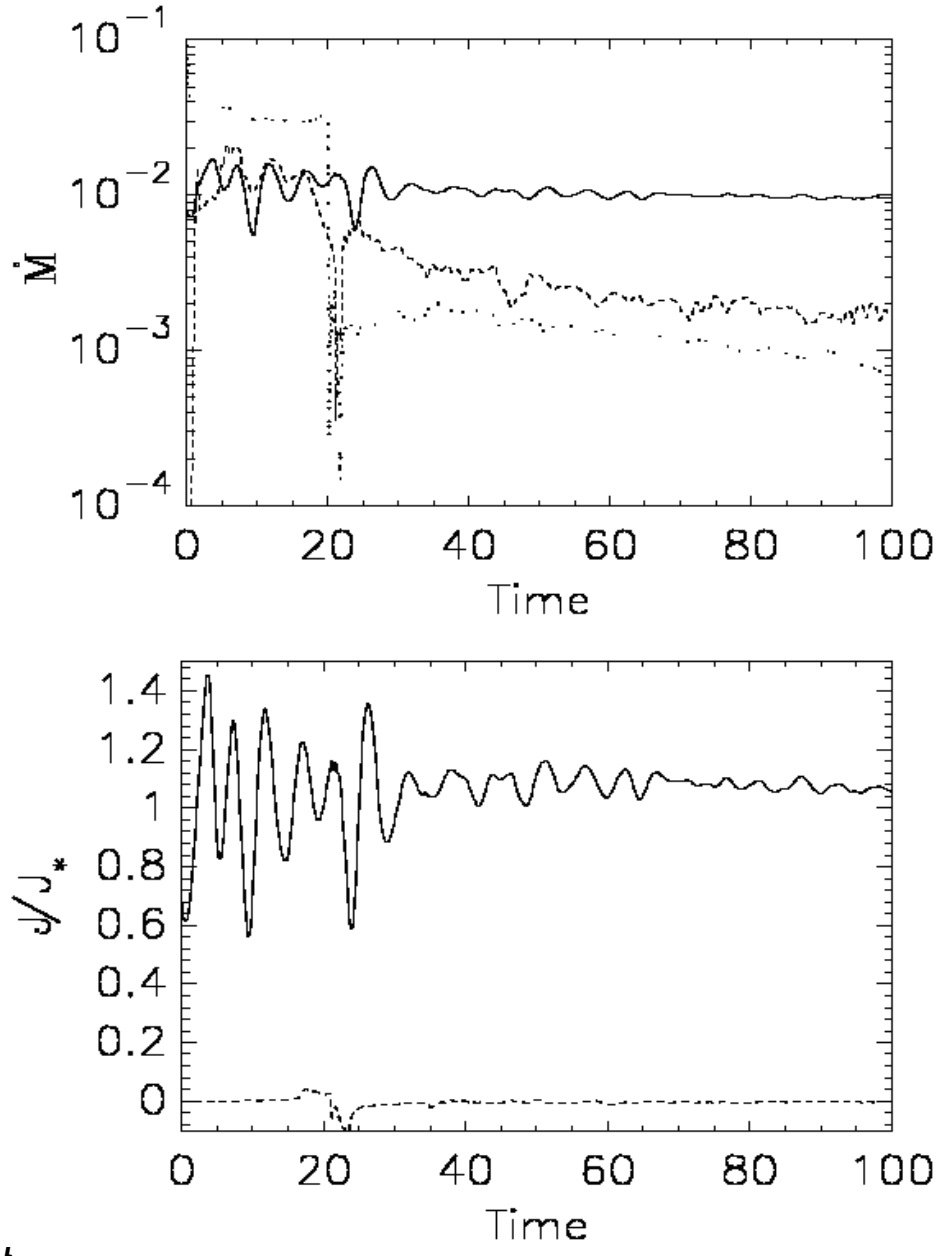
where $\nu_{\rm v}$ is the kinematic viscosity. The magnetic diffusivity was assumed proportional to the viscosity, with the free parameter

$$\nu_{\rm m} = \frac{3}{2}\alpha_{\rm m}\frac{\nu_{\rm v}}{\alpha_{\rm v}},$$

Practical part: results in Hydro-dynamical star-disk simulations



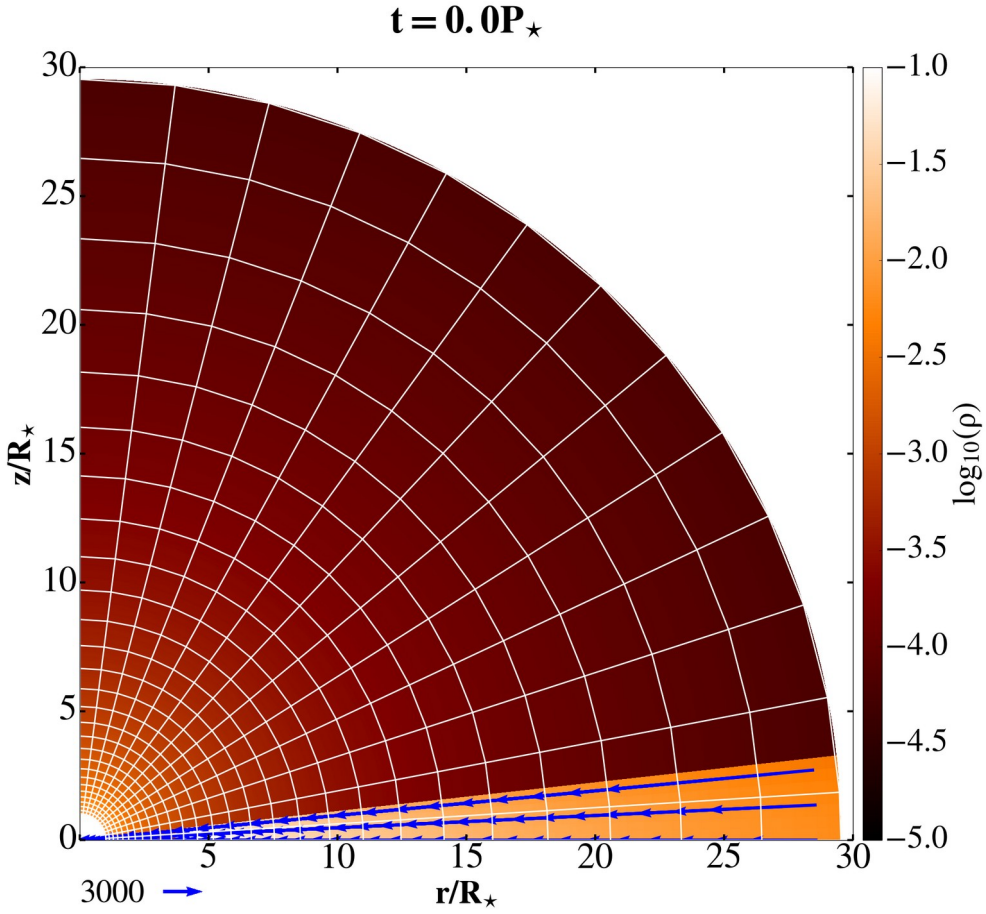
Ideally, this is what we wish to obtain. Computational bc and a zoom closer to the star after 80 stellar rotations. In color is shown the density, and vectors show velocity, with the different normalization in the disk and stellar wind.



Time dependence of the mass and angular momentum fluxes in the various components in our simulations.

Star-disk simulations setup

- The Kluźniak-Kita (2000) analytical solution is purely HD.
- We will start with the HD disk, and then add the magnetic field.
- Stellar surface is a rotating boundary around the origin of the spherical computational domain. In the non-magnetic setup, it is just a simple setup with “absorption” of the flow atop the stellar surface-we assume the star to be a (differentially) rotating magnetized rotator.
- The initial corona is a non-rotating corona in a hydrostatic balance with the 100 times denser disk below it. After short relaxation, lasting for the few stellar rotations, corona starts rotating, following the disk.



Logarithmic grid in a star-disk simulations setup

Pluto44usgui.pdf

31 (32 of 151) 202.59%

In practice, the mesh spacing in the *1+* grid is obtained by reversing the spacing in the *1−* grid.

Note: The interval should not include the origin when using a logarithmic grid.

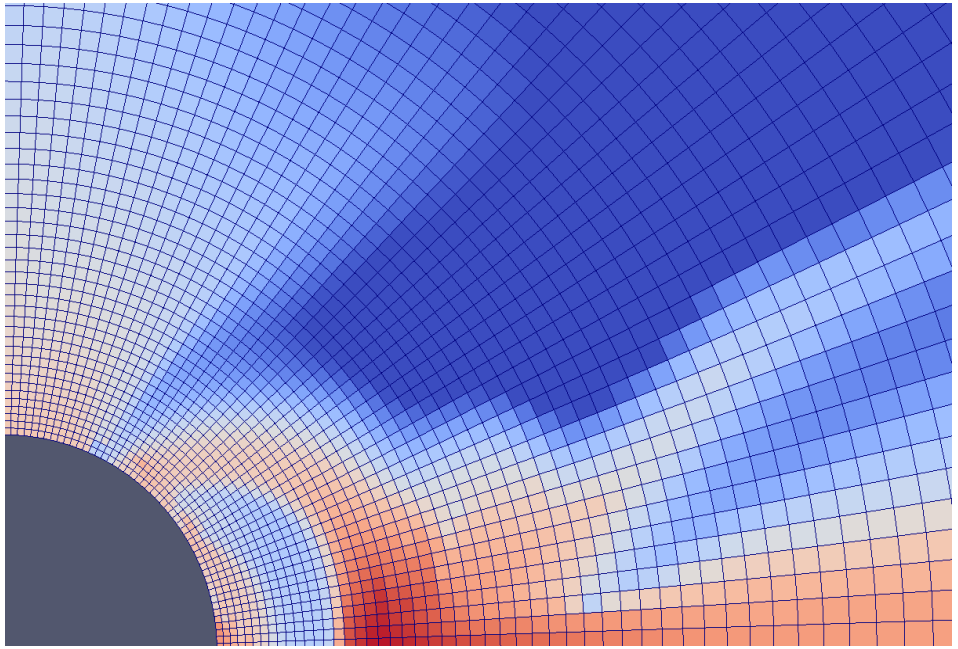
In *CYLINDRICAL* or *SPHERICAL* coordinates, a radial logarithmic grid has the advantage of preserving the cell aspect ratio at any distance from the origin. In addition, the condition to obtain approximately squared cells (aspect ratio ≈ 1) is $\Delta r_1 \approx r_1 \Delta\phi$ where $\Delta r_1 = r_L \left(e^{\Delta\xi} - 1\right)$ is the radial spacing of the first active computational zone. This condition can be be used to determine either the number of points in the radial direction or the endpoint:

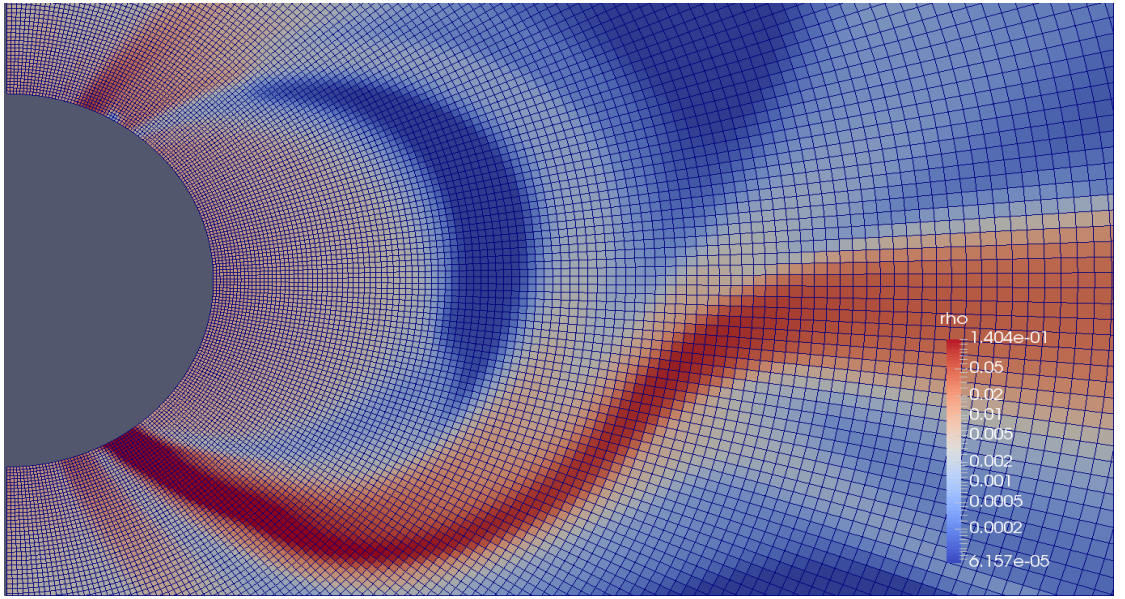
$$\log_{10} \frac{r_R}{r_L} = N_r \log_{10} \frac{2 + \Delta\phi}{2 - \Delta\phi} .$$

Beware that non-uniform grids may introduce extra dissipation in the algorithm. Changes in the grid spacing are correctly accounted for when RECONSTRUCTION is set to either *LINEAR*, *PARABOLIC* or *WENO3*.

Resolution needed in a setup

- Resolution in my production runs is Rxϑ=[217x100] grid cells in ϑ=[0,π/2], with a logarithmic grid spacing in the radial direction. For testing I also use Rxϑ=[109x50] grid cells, which gives qualitatively correct results.
- The accretion column is well resolved if a rule of thumb is satisfied that there is at least that many grid cells how many there is independent variables (5 in HD case, 8 in MHD case in our setups: density, pressure, 3 components of **v** and **B**).
- Star rotates at about 1/10 of the breakup rotational velocity.
- I did also ϑ=[0,π] cases in Rxϑ=[217x200] grid cells, as well as Rxϑ=[109x100] grid cells. Now there is no need to define the equatorial boundary condition, the simulation self-consistently computes across the domain. This case usually leads to an asymmetry with respect to the equatorial plane-I will show more on this in the last lecture.





Star-disk: pluto.ini

```
   I    pluto.ini (ini)                                  Row 22   Col 1    2:51  Ctrl-K H for help
[Grid]

X1-grid    1    1.0    109    l+   30.
X2-grid    1    0.0    50     u    1.570796327
X3-grid    1    0.0    1      u    1.0

[Chombo Refinement]

Levels           4
Ref_ratio        2 2 2 2 2
Regrid_interval  2 2 2 2
Refine_thresh    0.3
Tag_buffer_size  3
Block_factor     8
Max_grid_size    64
Fill_ratio       0.75

[Time]

CFL              0.4
CFL_max_var      1.2
tstop            628.0
first_dt         1.e-6

[Solver]

Solver         roe

[Boundary]

X1-beg         userdef
X1-end         userdef
X2-beg         axisymmetric
** Joe's Own Editor v4.1 ** (utf-8) ** Copyright © 2015 **
```

```
   I    pluto.ini (ini)                                  Row 57   Col 1    2:52  Ctrl-K H for help
X2-end         eqtsymmetric
X3-beg         outflow
X3-end         outflow

[Static Grid Output]

uservar    3 nu num Te
dbl       6.279 -1   single_file
flt       -1.0  -1   single_file
vtk       6.279  -1   single_file
tab       -1.0  -1
dbl.h5     -6.279  -1
ppm       -1.0  -1
png       -1.0  -1
log        100
analysis  -1.0  -1

[Chombo HDF5 output]

Checkpoint_interval  -1
Plot_interval       1.0

[Parameters]

ALPHAM                      0.4
MU                          0.1
TEMPF                       300.0
RHOC                        0.01
RD                          1.7
EPS                         0.1
OMG                         0.1
ALPHAV                      1.0
DFLOOR                      5.e-7
```

Star-disk: definitions.h

```
   I A  definitions.h (c)                                    Row 3    Col 1    2:53  Ctrl-K H for help
#define  PHYSICS                     HD
#define  DIMENSIONS                  2
#define  COMPONENTS                  3
#define  GEOMETRY                    SPHERICAL
#define  BODY_FORCE                  VECTOR
#define  FORCED_TURB                 NO
#define  COOLING                     NO
#define  RECONSTRUCTION              LINEAR
#define  TIME_STEPPING               RK2
#define  DIMENSIONAL_SPLITTING       NO
#define  NTRACER                     1
#define  USER_DEF_PARAMETERS         9

/* -- physics dependent declarations -- */

#define  DUST_FLUID                  NO
#define  EOS                         IDEAL
#define  ENTROPY_SWITCH              NO
#define  THERMAL_CONDUCTION          NO
#define  VISCOSITY                   EXPLICIT
#define  ROTATING_FRAME              NO

/* -- user-defined parameters (labels) -- */

#define  ALPHAM                      0
#define  MU                          1
#define  TEMPF                       2
#define  RHOC                        3
#define  RD                          4
#define  EPS                         5
#define  OMG                         6
#define  ALPHAV                      7
#define  DFLOOR                      8
** Joe's Own Editor v4.1 ** (utf-8) ** Copyright © 2015 **
```

```
   I A  definitions.h (c)                                    Row 18   Col 1    2:53  Ctrl-K H for help
#define  DUST_FLUID                  NO
#define  EOS                         IDEAL
#define  ENTROPY_SWITCH              NO
#define  THERMAL_CONDUCTION          NO
#define  VISCOSITY                   EXPLICIT
#define  ROTATING_FRAME              NO

/* -- user-defined parameters (labels) -- */

#define  ALPHAM                      0
#define  MU                          1
#define  TEMPF                       2
#define  RHOC                        3
#define  RD                          4
#define  EPS                         5
#define  OMG                         6
#define  ALPHAV                      7
#define  DFLOOR                      8

/* [Beg] user-defined constants (do not change this line) */

#define  WARNING_MESSAGES            NO
#define  INTERNAL_BOUNDARY           YES
#define  SHOCK_FLATTENING            MULTID
#define  CT_EN_CORRECTION            YES
#define  UNIT_DENSITY                8.5e-11
#define  UNIT_LENGTH                 1.392e11
#define  UNIT_VELOCITY               2.1839e7
#define  VTK_VECTOR_DUMP             YES
#define  CT_EMF_AVERAGE              ARITHMETIC
#define  LIMITER                     VANLEER_LIM

/* [End] user-defined constants (do not change this line) */
```

Star-disk: init.c

```
   I A  init.c (c)                                                    Row 1    Col 1    2:55  Ctrl-K H for help
/* ///////////////////////////////////////////////////////////////////// */
/*!
  \file
  \brief Contains basic functions for problem initialization.

  The init.c file collects most of the user-supplied functions useful
  for problem configuration.
  It is automatically searched for by the makefile.

  \author A. Mignone (mignone@ph.unito.it)
  \date   Sep 10, 2012

 \modified by M. Cemeljic (miki@camk.edu.pl)
 \date July 2020
 Below is given Miki's stripped, minimal version of the setup in ideal MHD,
 for teaching purpose in SHAO. It is not meant to produce quasi-stationary
 or any publication-worth result, but to provide a platform for teaching.
 It is based on the setup described in Appendix of "Atlas" paper,
 Cemeljic, 2019, A&A, 624, A31.
*/
/* ///////////////////////////////////////////////////////////////////// */
#include "pluto.h"


/* ********************************************************** */
void Init (double *v, double x1, double x2, double x3)
/*
 *
 ********************************************************** */
{
 double coeff, eps2, pc, rcyl;
 double br,bth;
 double lambda;
 double xhi2, Rco;
```

```
   I A  init.c (c)  void Init (double *v, double x1, double x2, double x3)      Row 36   Col 1    2:56  Ctrl-K H for help
 rcyl=x1*sin(x2);
 eps2=g_inputParam[EPS]*g_inputParam[EPS];
 coeff=2./5./eps2*(1./x1-(1.-5./2.*eps2)/rcyl);
 lambda=11./5./(1.+64./25.*g_inputParam[ALPHAV]*g_inputParam[ALPHAV]);

/* initial non-rotating adiabatic corona in hydrostatic equilibrium  */
 v[RHO] = g_inputParam[RHOC]*pow(x1,-3./2.);
 v[PRS] = 2./5.*g_inputParam[RHOC]*pow(x1,-5./2.);

 pc=v[PRS];

  v[VX1] = 0.0;
  v[VX2] = 0.0;
  v[VX3] = 0.0;

/* Keplerian adiabatic disk in vertical pressure equilibrium with the
   adiabatic corona, as given by Kluzniak & Kita (2000) */

  v[PRS]=eps2*pow(coeff,5./2.);

    if (v[PRS] >= pc && rcyl > g_inputParam[RD])
      {v[RHO] = pow(coeff,3./2.);
       v[VX1] = -g_inputParam[ALPHAV]/sin(x2)*eps2*(10.-32./3.
       *lambda*g_inputParam[ALPHAV]*g_inputParam[ALPHAV]
       -lambda*(5.-1./(eps2*tan(x2)*tan(x2))))/sqrt(rcyl);
       v[VX3] = (sqrt(1.-5./2.*eps2)+2./3.*eps2
       *g_inputParam[ALPHAV]*g_inputParam[ALPHAV]
       *lambda*(1.-6./(5.*eps2*tan(x2)*tan(x2))))/sqrt(rcyl);
       v[TRC] = 1.0;     /* Track the disc material */
      }
    else
      {
       v[PRS]=2./5.*g_inputParam[RHOC]*pow(x1,-5./2.);
       v[TRC] = 0.0;     /* Track the corona */
```

Summary of the Part III

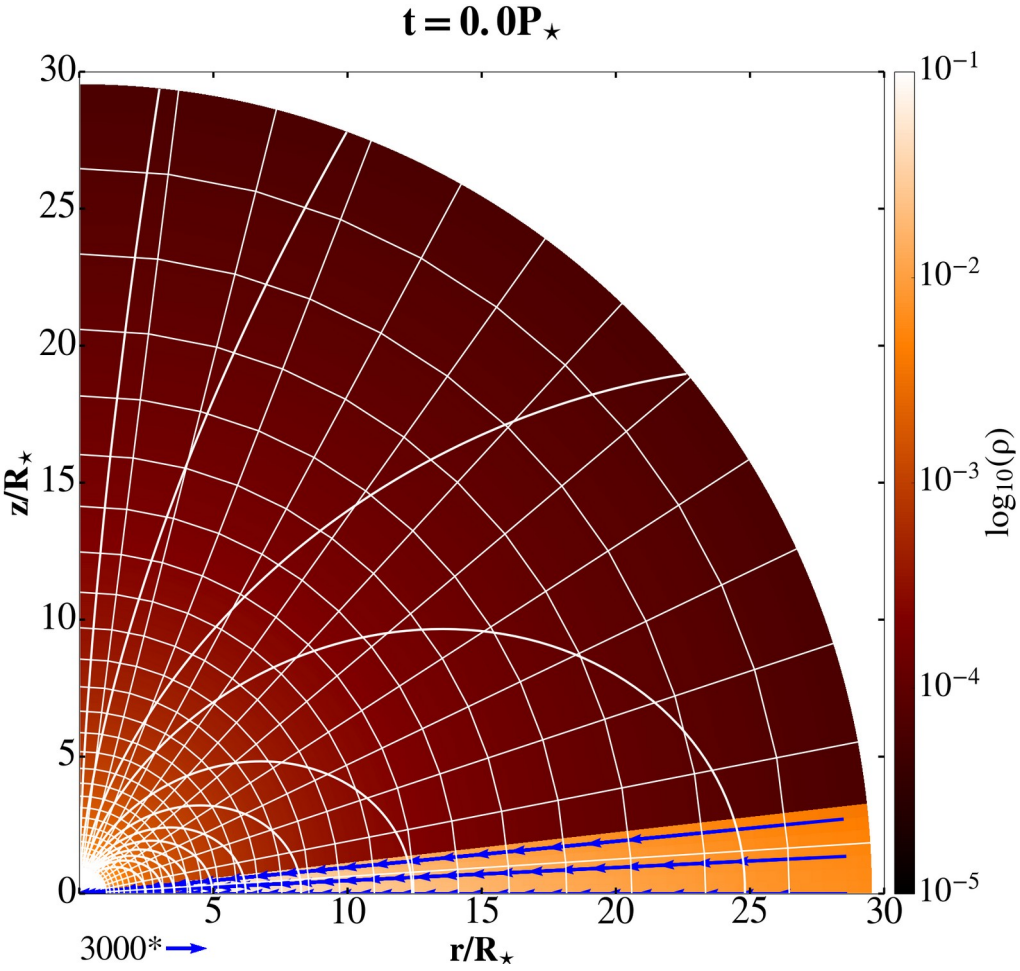
- A very brief introduction to history of accretion disk numerics.
- Introduction to HD accretion disk simulation.
- Setup of axisymmetric 2D(=2.5D) HD disk.
- Details of the HD setup in pluto.ini, definitions.h and init.c
- Shortcut to star-disk magnetospheric interaction simulations as just an extension of HD setup.

Outline, Part IV

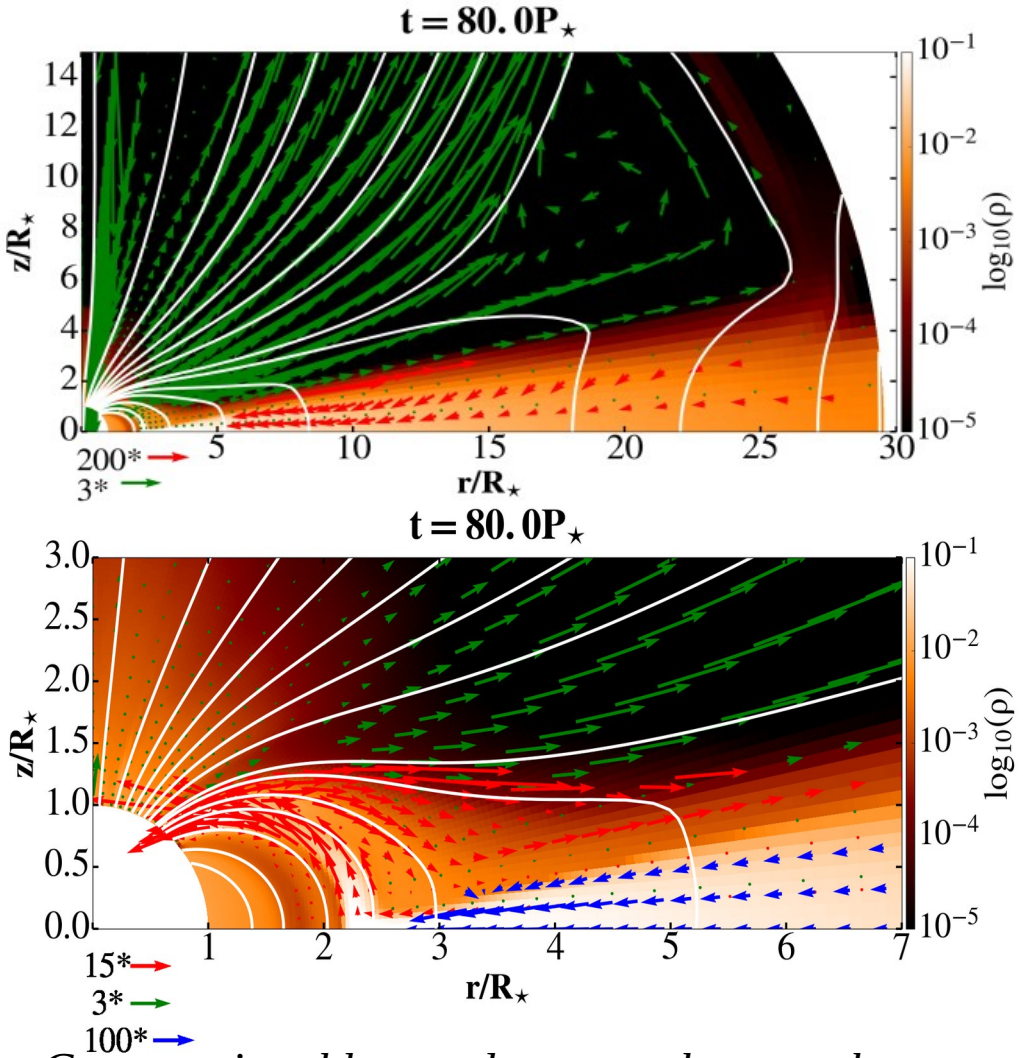
- Star-disk magnetospheric interaction simulations.
- Setup of axisymmetric 2D setup with dipole magnetic field.
- Visualization of magnetic field lines with Paraview.
- Simulations in 2.5D with an axial outflow.
- Python scripts for visualization.
- Setup of full 3D HD disk.
- Setup of full 3D magnetic disk with dipole magnetic field.
- Restart and initialization from (modified) file.
- Visualization of 3D solutions with Paraview

Setup of magnetic star-disk interaction

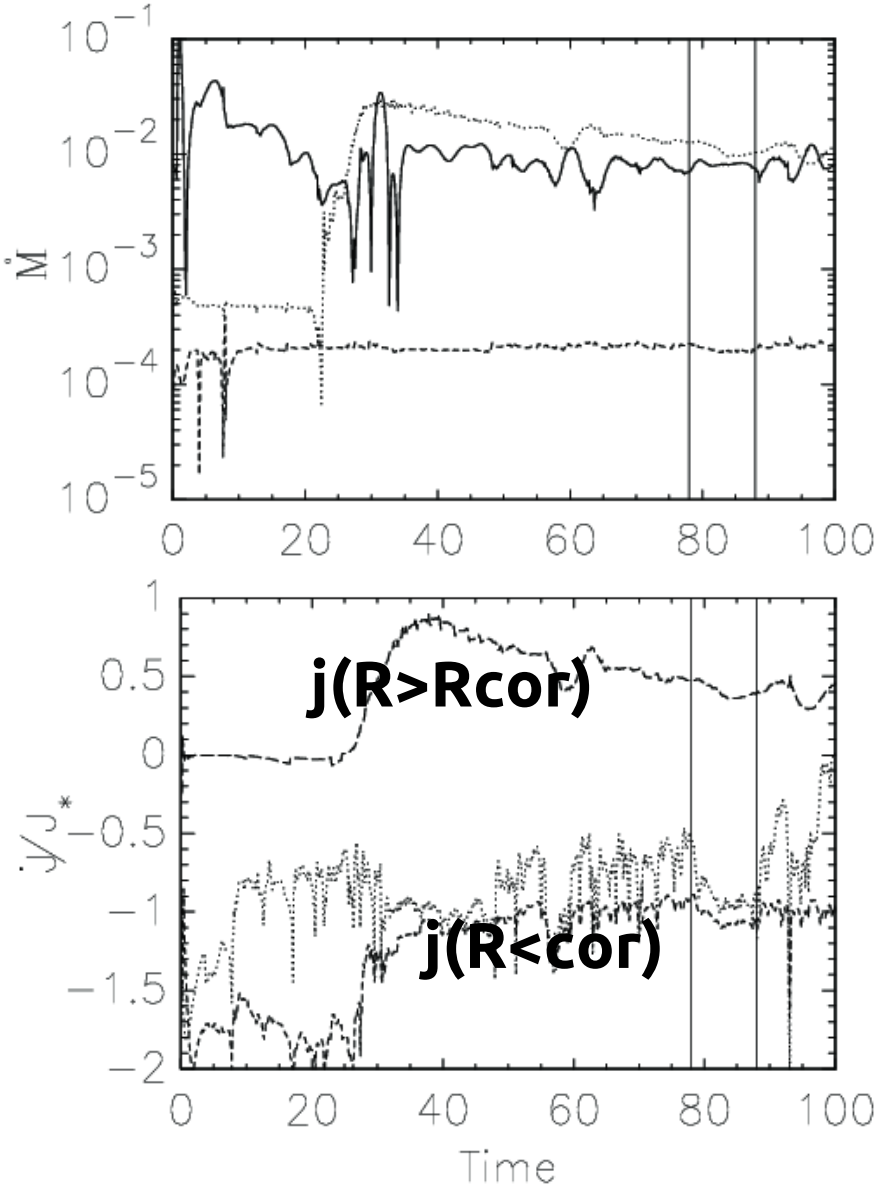
- The Kluźniak-Kita (2000) analytical solution is purely HD. We now add the stellar dipole magnetic field, with the axis matching the stellar rotation axis, so that the axi-symmetry would be preserved. Later we will set the simulations with quadrupole, octupole and mixed, multipole field.
- Stellar surface is a rotating boundary around the origin of the spherical computational domain. In the magnetic setup, it is **not** a simple setup with “absorption” of the flow atop the stellar surface-we assume the star to be a (differentially) rotating magnetized rotator. The initial corona is a non-rotating corona in a hydrostatic balance. After short relaxation, lasting for the few stellar rotations, corona starts rotating, following the disk.



Results in star-disk magnetospheric interaction simulations

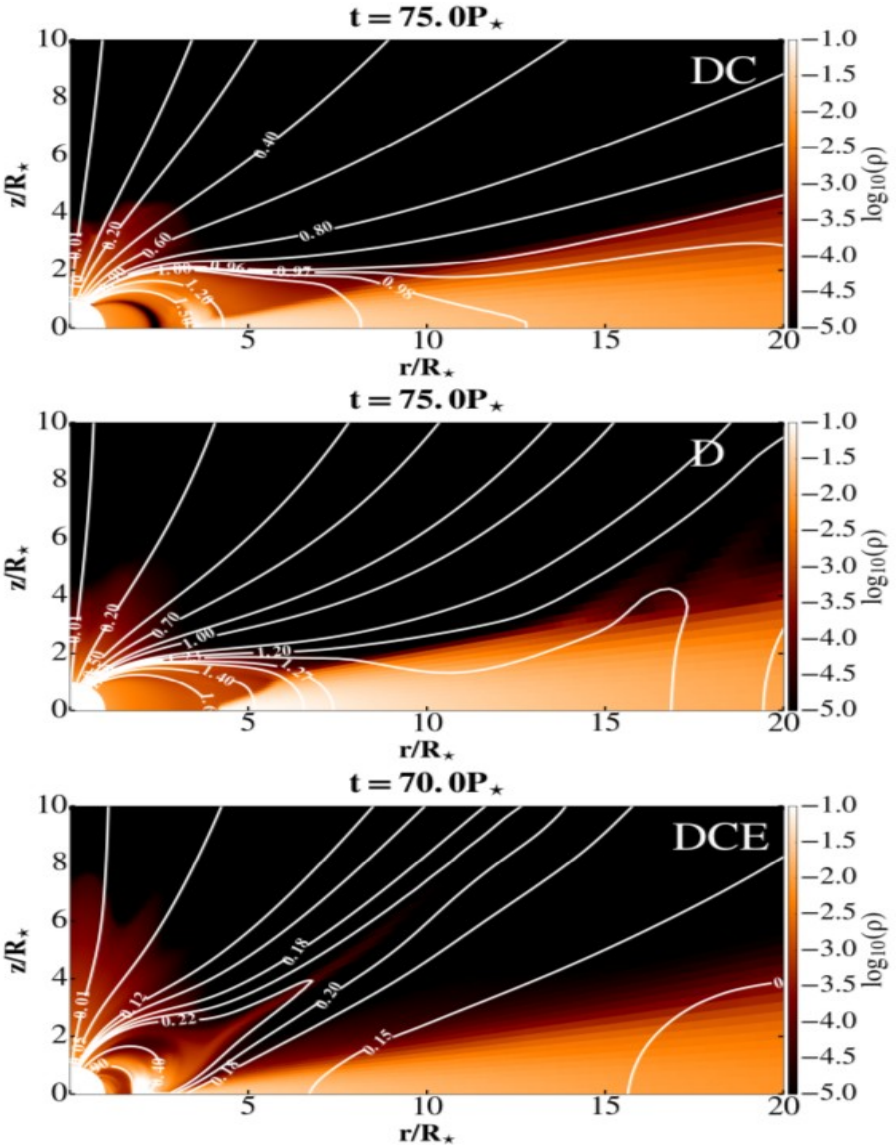


Computational box and a zoom closer to the star after 80 stellar rotations, to visualize the accretion column and the magnetic field lines (white solid lines) connected to the disk beyond the corotation radius Rcor=2.92 Rs. In color is shown the density, and vectors show velocity, with the different normalization in the disk, column and stellar wind.



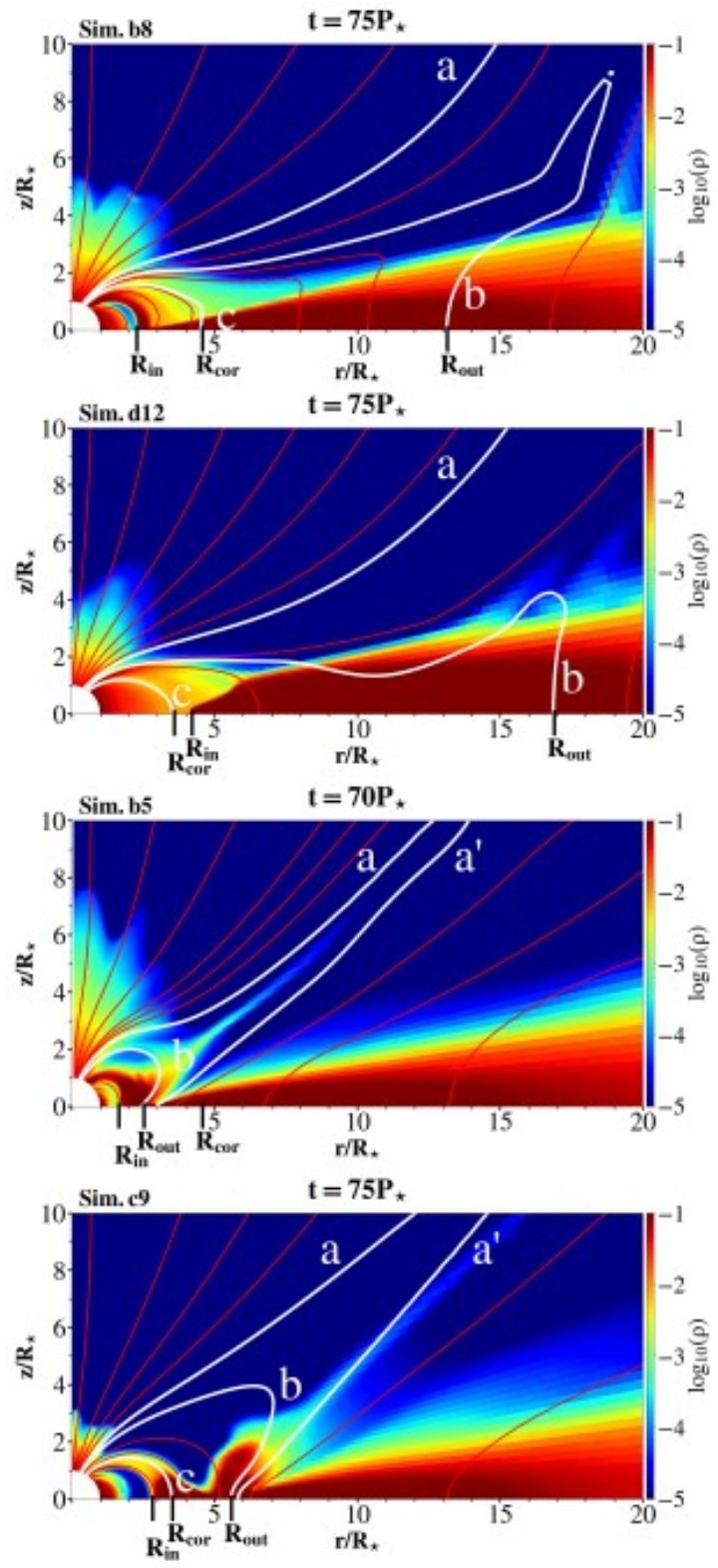
Time dependence of the mass and angular momentum fluxes in the various components in our simulations with marked time interval in which the average value during the quasi-stationarity is computed.

Types of solutions for slowly rotating stars in “Atlas”



Three different cases of geometry in the results. In the top and middle panels are shown B=1 kG and the resistivity αm=1, in the cases with Ωs=0.1 (top panel) and Ωs=0.15 (middle panel). Faster stellar rotation prevents the accretion column formation. In the bottom panel is shown the third case, with B=0.5kG, resistivity αm=0.1 and Ωs=0.1, where a conical outflow is formed.

α_m =	0.1	0.4	0.7	1
$\Omega_\star/\Omega_{br}$				
		$B_\star$ = 250 G		
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
		$B_\star$ = 500 G		
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
		$B_\star$ = 750 G		
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	DC	DC	DC
0.2	DCE	DC	DC	DC
		$B_\star$ = 1000 G		
0.05	DCE	DC	DC	DC
0.1	DCE	DC	DC	DC
0.15	DCE	D	D	D
0.2	DCE	D	D	D

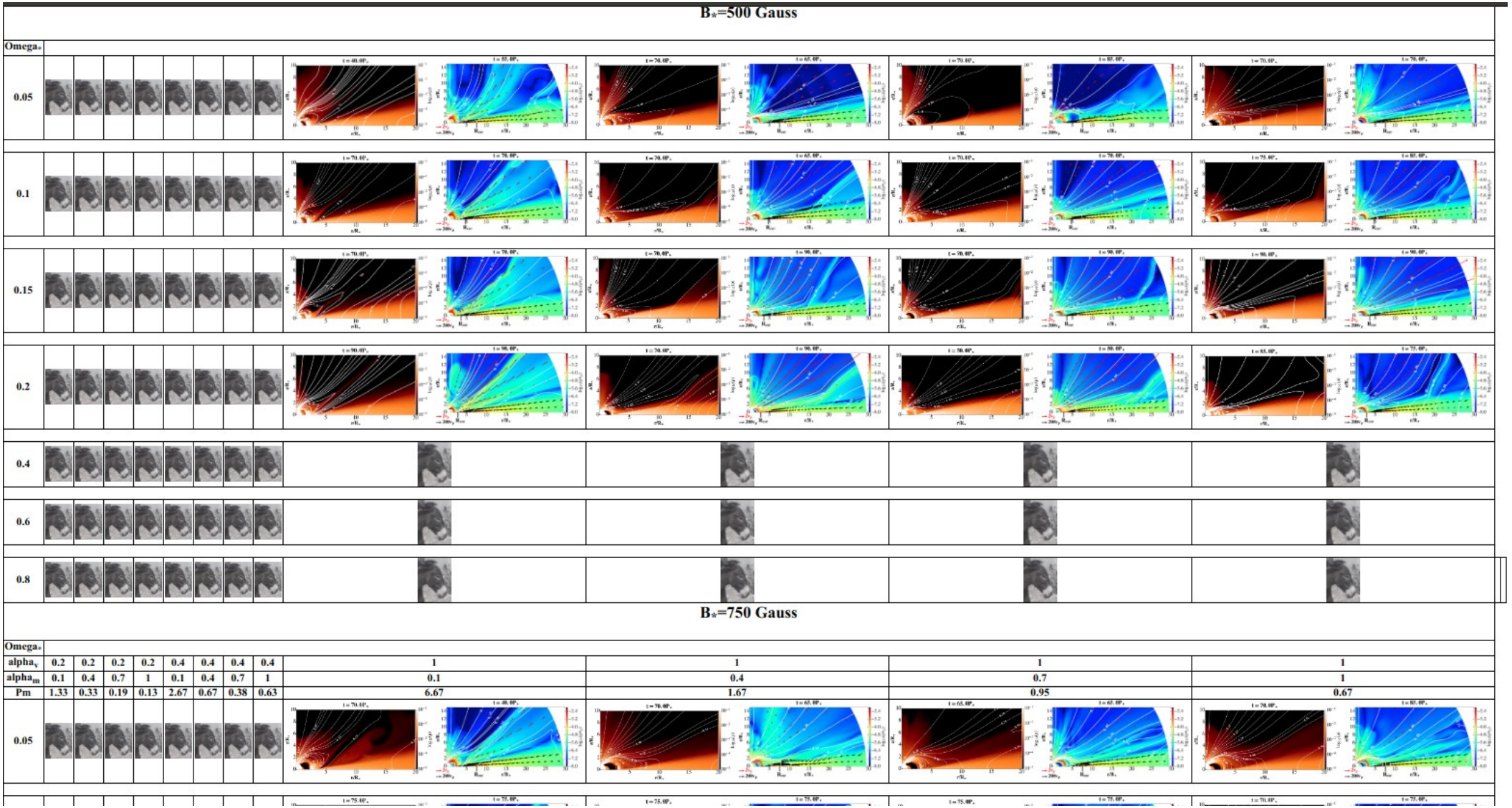


Configurations of solutions in “Atlas”

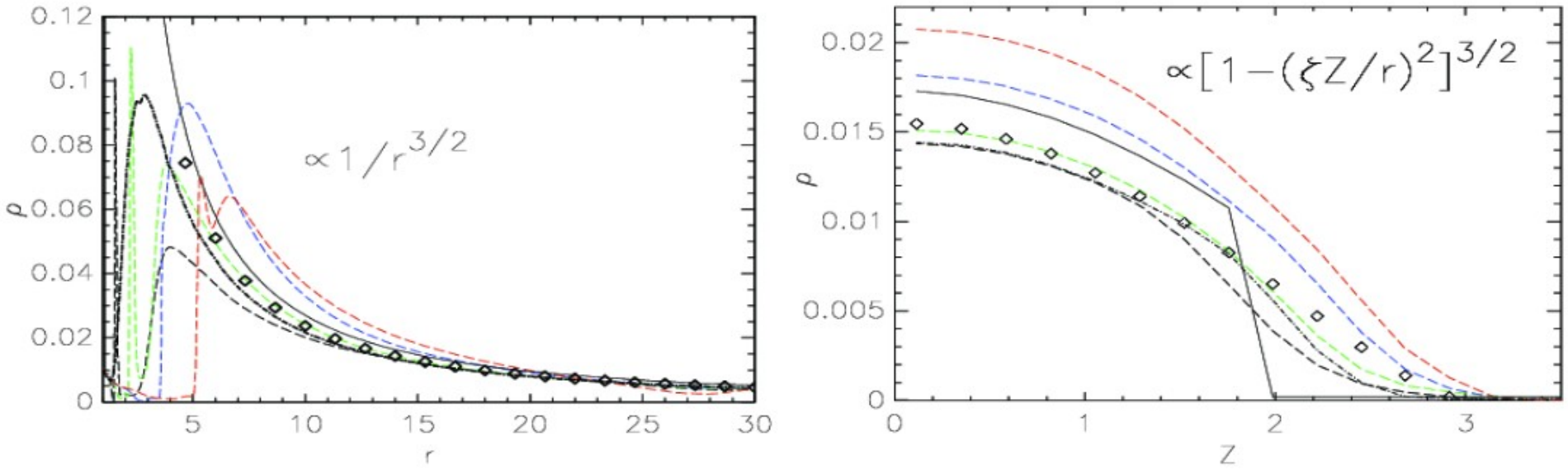
- 4 different cases if we consider the position of Rcor in the case with conical outflow.
- In general, faster stellar rotation prevents the accretion column formation.
- In the bottom panels resistivity α_m=0.1 and Ω_s=0.1, a conical outflow is formed.

“Atlas” of results in star-disk magnetospheric interaction simulations

- In “Atlas” paper I performed a systematic study, 64 simulations with magnetic star-disk numerical simulations, for slowly rotating star (up to 20% of the breakup velocity of the star). Cases with faster rotating star are currently investigated in work with students. It is only with dipole stellar field, it would be interesting also to do with other geometries.



Comparison of results with increasing mag. Field strength



Matter density in the initial set-up (thin solid line) with the quasi-stationary solutions in numerical simulations in the HD (dot-dashed line) and the MHD (long-dashed line) cases. In black, green blue and red colors are the results in the MHD cases with the stellar magnetic field strength 0.25, 0.5, 0.75 and 1.0 kG, respectively. The closest match to the 0.5 kG case is depicted with the diamond simbols. In the left panel is shown the radial dependence nearby the disk equatorial plane, and in the right panel the profiles along the vertical line at r=15.

Similar plots for other quantities reveal trends on the solutions with the increasing magnetic field, stellar rotation rate or dissipation coefficients.

Trends in the “Atlas” results

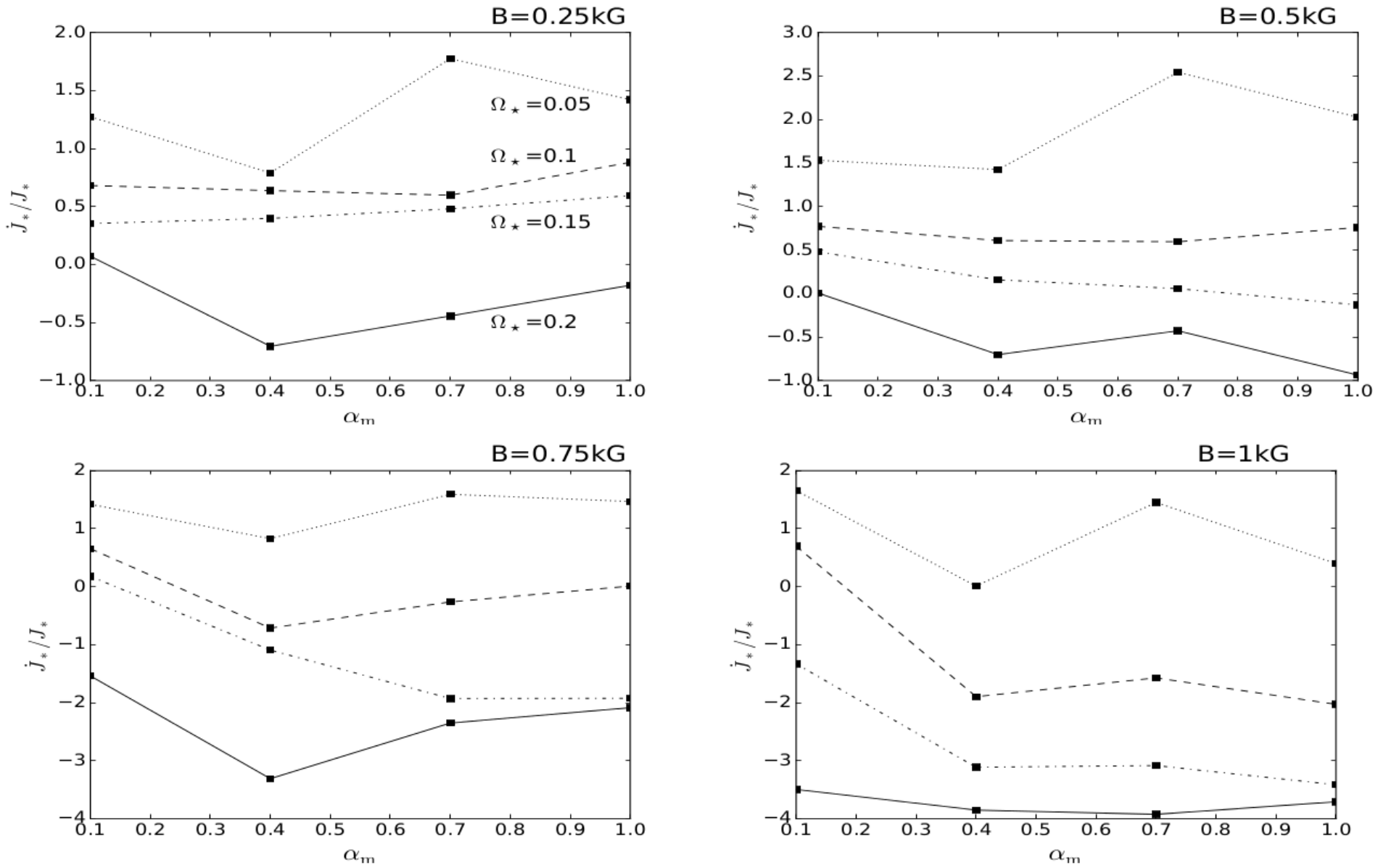


Fig. 4. Average angular momentum flux transported onto the stellar surface by the matter in-falling from the disk onto the star through the accretion column. Each panel shows a set of solutions with one stellar magnetic field strength and varying stellar rotation rate and resistivity. Results with $\Omega_\star/\Omega_{\rm br} = 0.05$ (dotted), 0.1 (dashed), 0.15 (dash-dot-dotted), and 0.2 (solid) are shown in units of stellar angular momentum $J_\star = k^2 M_\star R_\star^2 \Omega_\star$ (with $k^2 = 0.2$ for the typical normalized gyration radius of a fully convective star). A positive flux spins the star up, a negative flux slows it down. With the increase in stellar rotation rate, spin-up of the star by the infalling matter decreases and eventually switches to spin-down.

Trends in the “Atlas” results

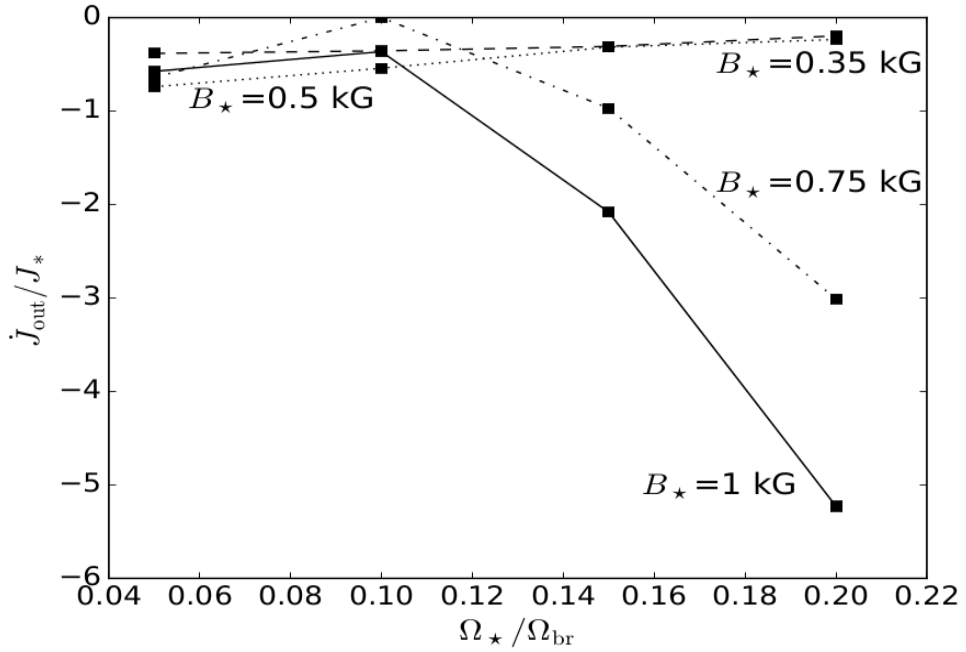
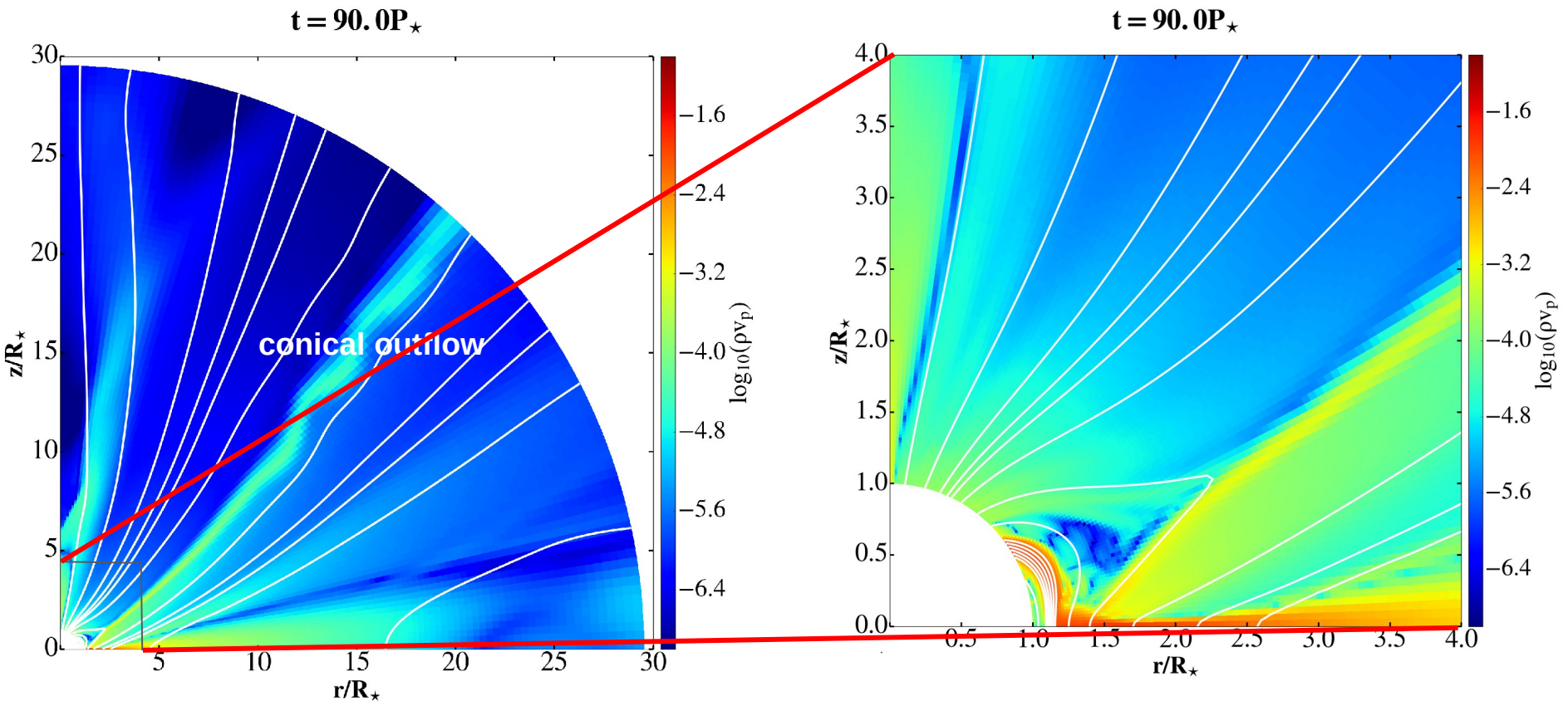


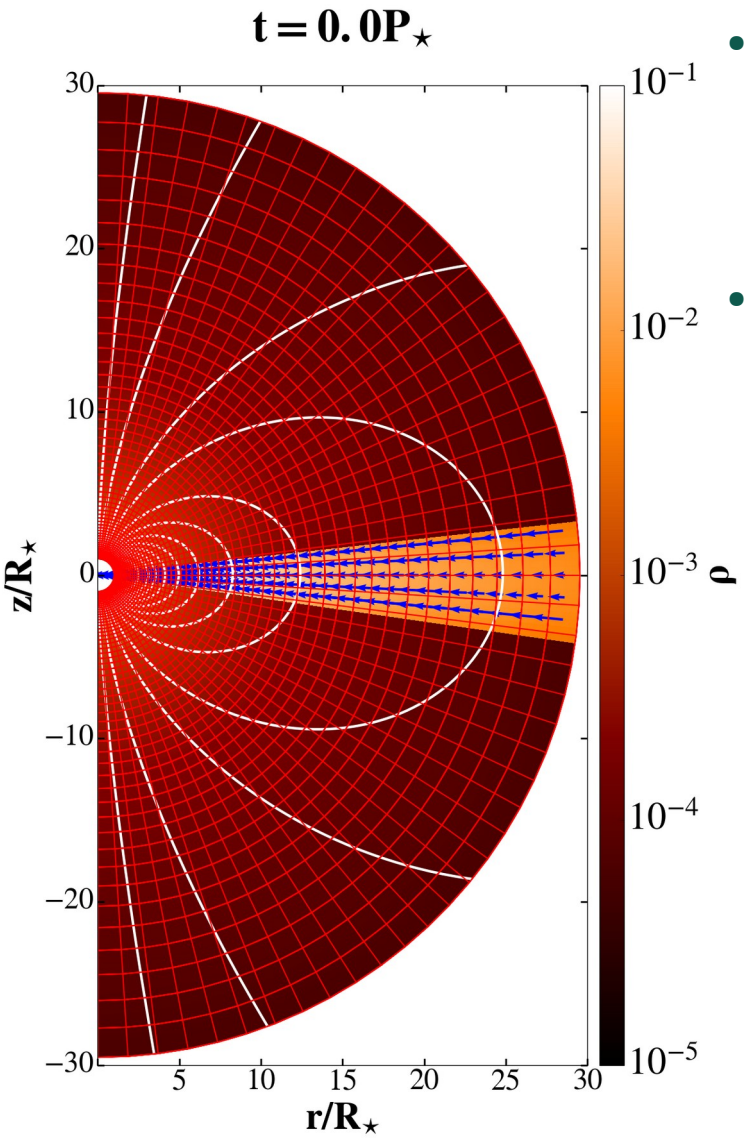
Fig. 5. Average angular momentum flux in the outflow that forms for $\alpha_{\rm m} = 0.1$. It is computed at $R = 12R_\star$ for different stellar rotation rates. Normalization is the same as in Fig. 4. Fluxes in $B_\star = 0.25$ (dotted), 0.5 (dash-dotted), 0.75 (dashed) and 1 kG (solid) are shown.

Magnetospheric launching of conical outflow



Color shows **momentum** in the MHD simulation in the young stellar object with conical outflow, lines are the magnetic field lines. Right panel is a zoom into the left panel close to the star, to show the closest vicinity of the star.

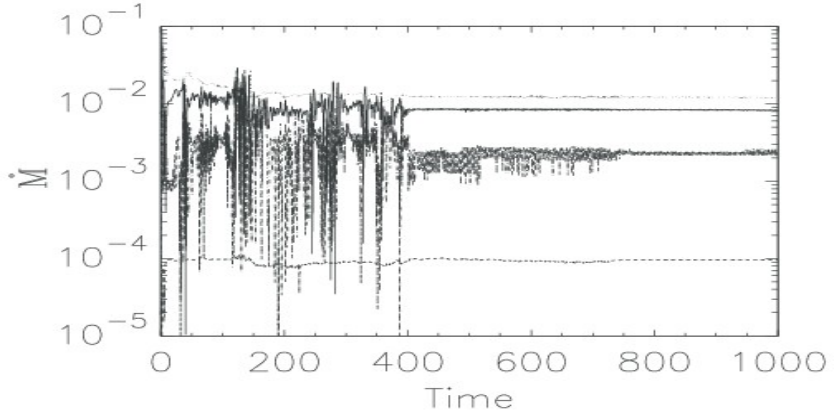
Setup in a complete co-latitudinal plane

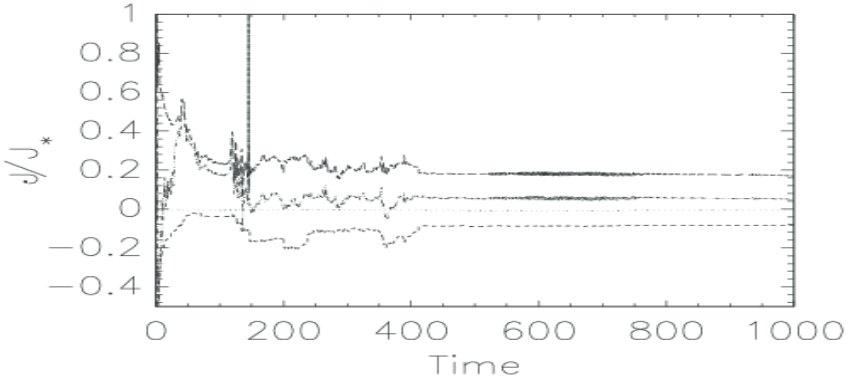


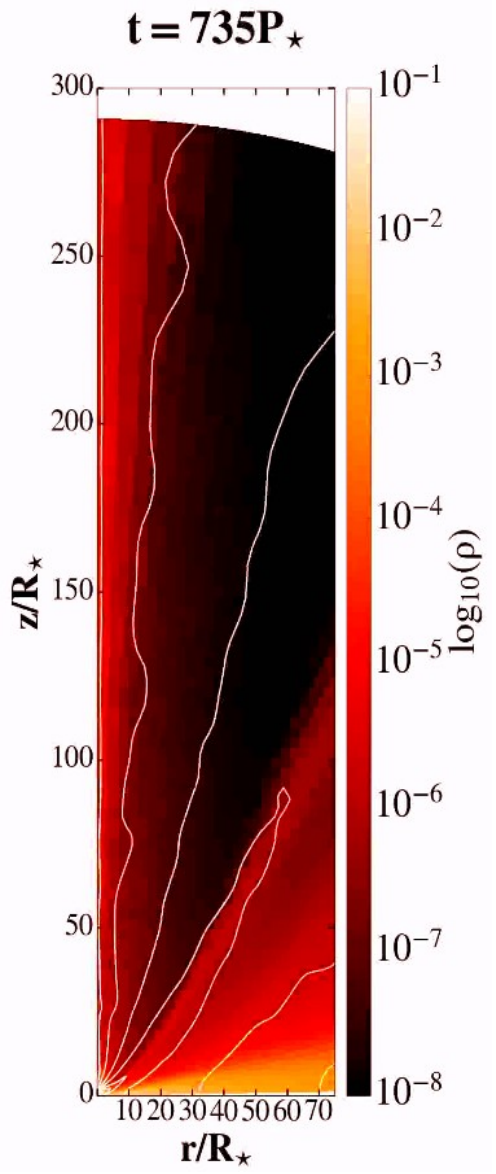
- I did also Rxϑ=[217x200] grid cells in a complete co-latitudinal plane ϑ=[0,π], here is shown the case with dipole stellar field.
- Now there is no meridional plane boundary condition, so that the flow is not constrained at that plane.

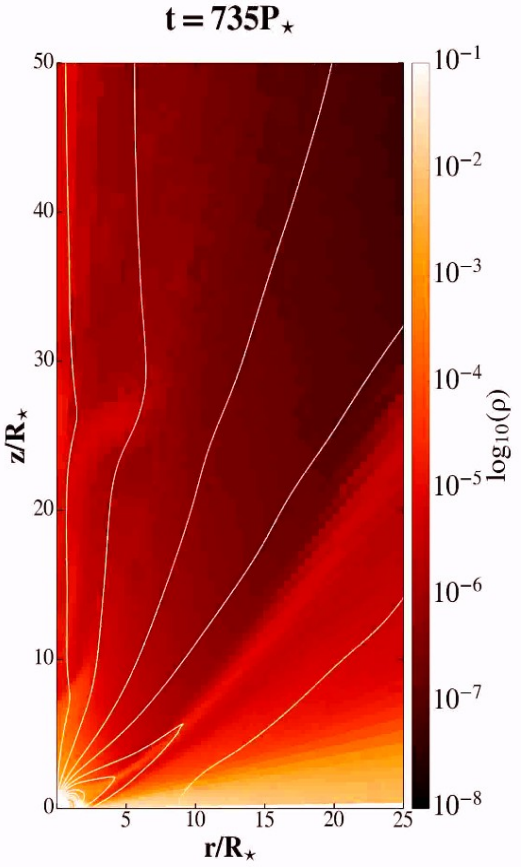
The axial outflow ("jet") launching

- In a part of the parameter space, there is a continuous launching of an axial outflow from the star-disk magnetosphere. In my simulations, it showed that one has to wait until few hundreds of rotations of the star.
- The axial 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).



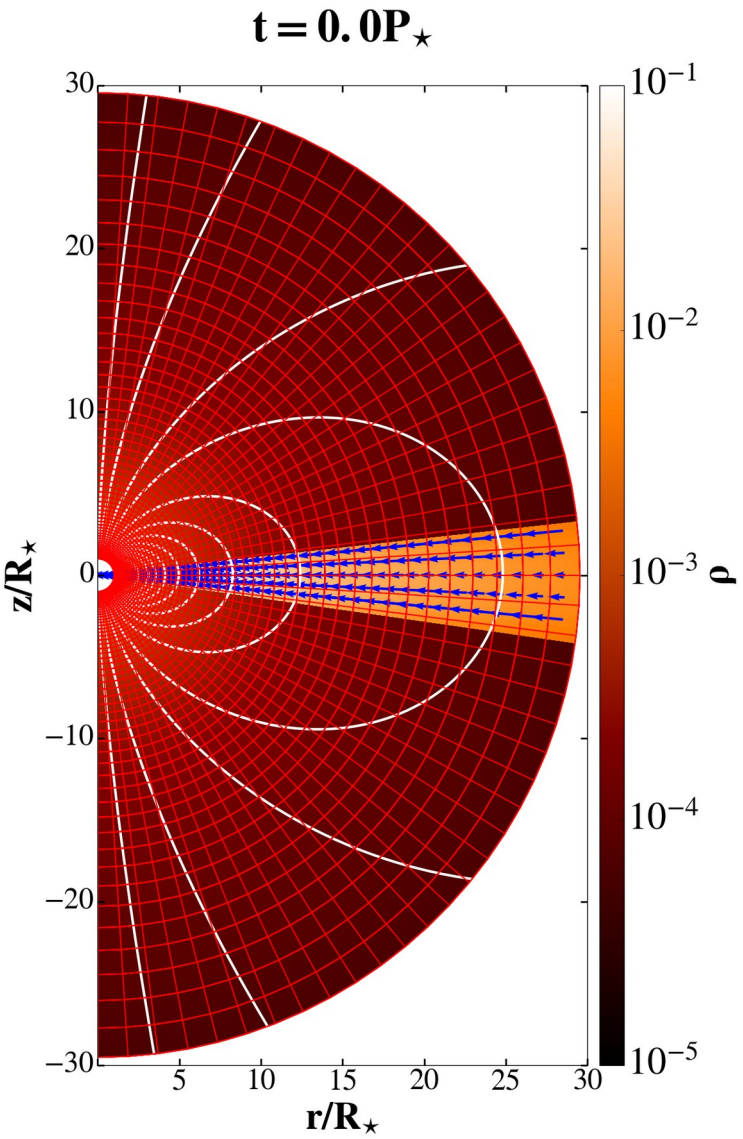




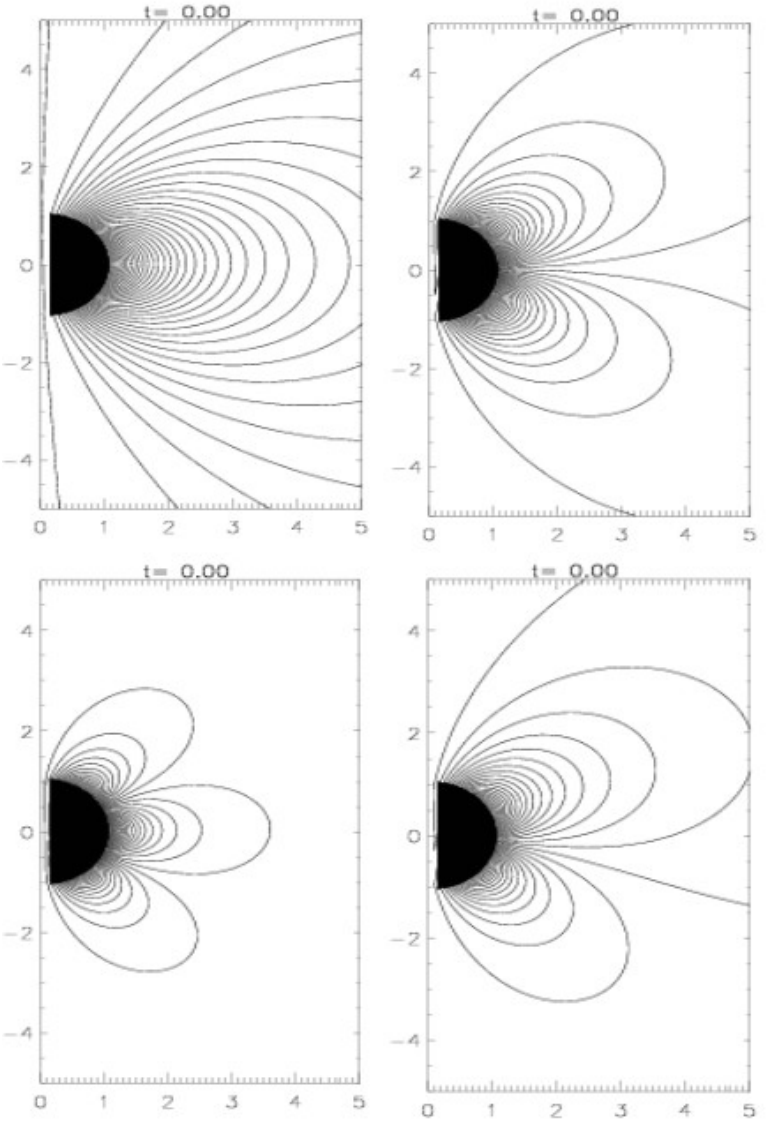


Zoom into the launching region.

Setup with different geometries of initial magnetic field



- I did also setups with different initial geometries of magnetic field than dipole: a quadrupole, octupole and mixed multipole.



Results with different geometries of initial magnetic field

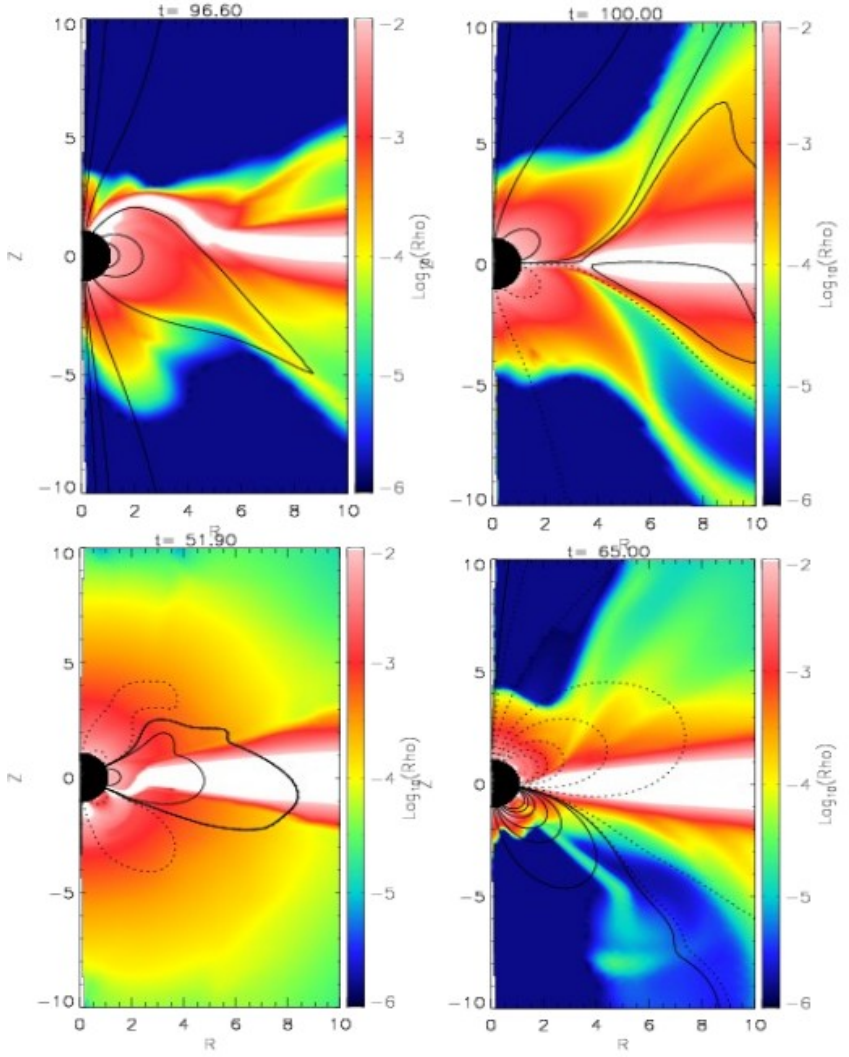


Figure 2: *Stable solutions in our SDI simulations, for the different geometries of the magnetic field, with time t given in stellar rotations. The matter density distribution is shown in logarithmic color grading, with the poloidal magnetic field shown in solid and dashed lines, depending on the direction of the field. We sampled the magnetic field lines to leave the density distribution close to the star visible. The results for dipole, quadrupole, octupole and mixed multipole cases are shown from left to right, top to bottom, respectively.*

Numerical methods in PLUTO for star-disk interaction

•I already showed, and will show again where is definition of each of the setup entries in the code, here is an example of what you can usually read in the description of a setup:

-Simulations were performed using the second-order piecewise linear reconstruction.

-Van Leer limiter, which is more diffusive and enhances stability, is used in density and magnetic field and a minmod (monotonized central differences) limiter in pressure and velocity.

-An approximate Roe solver (hlld in the pluto options) was used, with a modification in the flag_shock subroutine: flags were set to switch to more diffusive hll solver when the internal energy was lower than 1% of the total energy, instead of switching in the presence of shocks.

-The second-order time-stepping (RK2) was employed.

-$\nabla \cdot \mathbf{B} = 0$ was maintained by the constrained transport method.

-The magnetic field was evolved with the split-field option, so that only changes from the initial stellar magnetic field were evolved in time. This means that in the final results, one has to add magnetic dipole (or other initial field) to the solution from the code.

-The power-law cooling is introduced to account for the disk dissipative heating. Physically it is good enough to represent bremsstrahlung. There are other cooling functions in PLUTO, one can also import a table of values, not necessarily a function.

Setup of magnetic runs-changes in pluto.ini and definitions.h

```
   I    pluto.ini (Modified)(ini)                                  Row 27   Col 19   1:29  Ctrl-K H for help

Solver        hll

[Boundary]

X1-beg        userdef
X1-end        userdef
X2-beg        axisymmetric
X2-end        eqtsymmetric
X3-beg        outflow
X3-end        outflow

[Static Grid Output]

uservar    3 nu num Te
dbl       6.279 -1   single_file
flt       -1.0  -1   single_file
vtk       6.279  -1   single_file
tab       -1.0  -1
dbl.h5     -6.279  -1
ppm       -1.0  -1
png       -1.0  -1
log        100
analysis  -1.0  -1

[Chombo HDF5 output]

Checkpoint_interval  -1
Plot_interval       1.0

[Parameters]

ALPHAM                      0.4
MU                          0.07
```

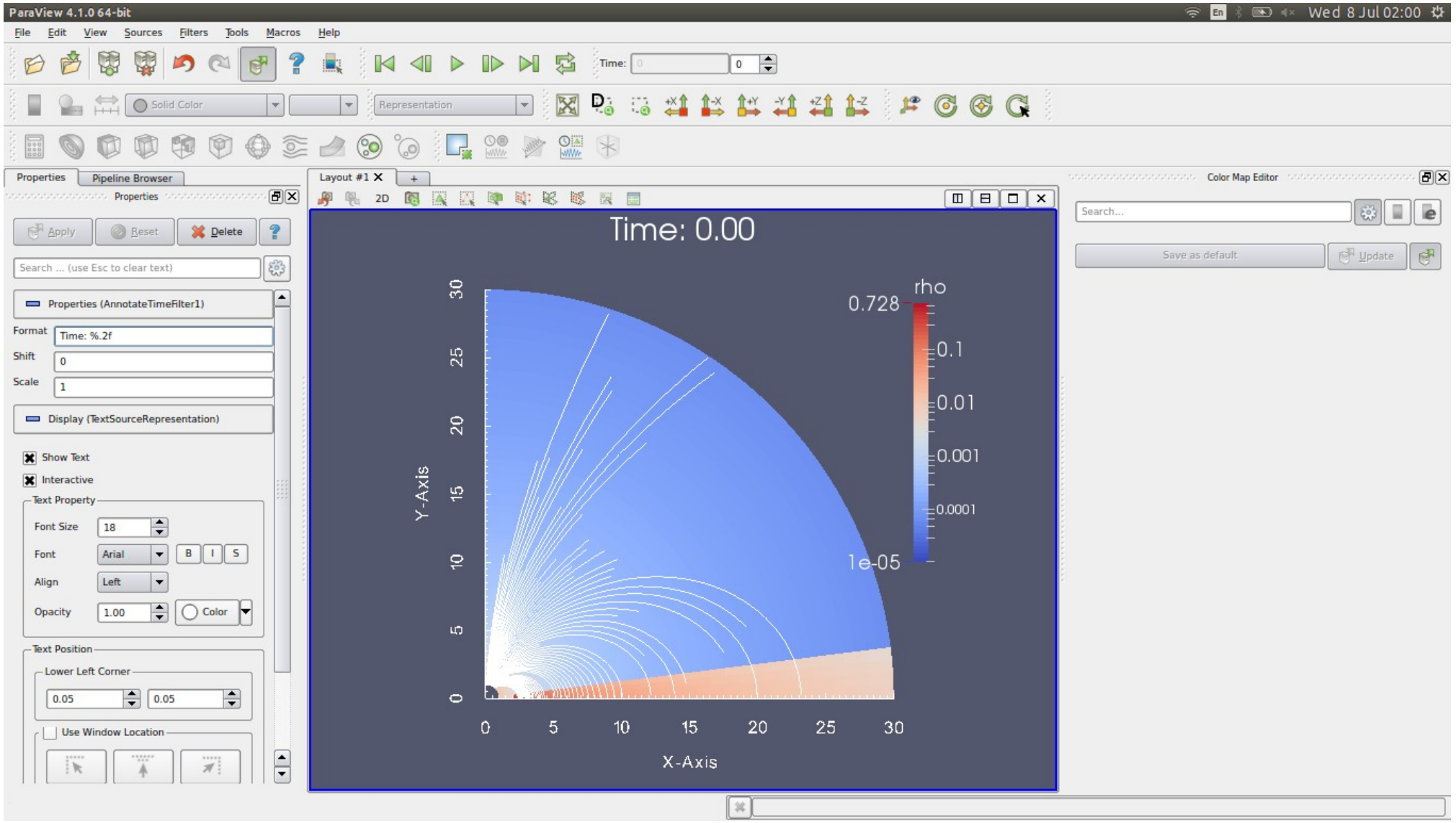
```
   I A  definitions.h (c)                                        Row 1    Col 1    1:30  Ctrl-K H for help
#define  PHYSICS                     MHD
#define  DIMENSIONS                  2
#define  COMPONENTS                  3
#define  GEOMETRY                    SPHERICAL
#define  BODY_FORCE                  VECTOR
#define  FORCED_TURB                 NO
#define  COOLING                     NO
#define  RECONSTRUCTION              LINEAR
#define  TIME_STEPPING               RK2
#define  DIMENSIONAL_SPLITTING       NO
#define  NTRACER                     1
#define  USER_DEF_PARAMETERS         9

/* -- physics dependent declarations -- */

#define  EOS                         IDEAL
#define  ENTROPY_SWITCH              NO
#define  DIVB_CONTROL                CONSTRAINED_TRANSPORT
#define  BACKGROUND_FIELD            YES
#define  AMBIPOLAR_DIFFUSION         NO
#define  RESISTIVITY                 NO
#define  HALL_MHD                    NO
#define  THERMAL_CONDUCTION          NO
#define  VISCOSITY                   EXPLICIT
#define  ROTATING_FRAME              NO

/* -- user-defined parameters (labels) -- */

#define  ALPHAM                      0
#define  MU                          1
#define  TEMPF                       2
#define  RHOC                        3
#define  RD                          4
#define  EPS                         5
```

Setup of magnetic dipole and multipoles in init.c

```
   I A  init.c (c)  void UserDefBoundary (const Data *d, RBox *box, int side,   Row 146  Col 1    4:22  Ctrl-K H for help
#if PHYSICS == MHD
/* ********************************************************************* */
void BackgroundField (double x1, double x2, double x3, double *B0)
/*
 *
 * PURPOSE
 *
 *   Define the component of a static, curl-free background
 *   magnetic field.
 *
 *
 * ARGUMENTS
 *
 *   x1, x2, x3  (IN)    coordinates
 *
 *   B0         (OUT)    vector component of the background field.
 *
 *
 ********************************************************************* */
{
/* dipole */
   B0[0] = 2.*g_inputParam[MU]*cos(x2)/(x1*x1*x1);
   B0[1] = g_inputParam[MU]*sin(x2)/(x1*x1*x1);
   B0[2] = 0.0;

}
#endif
```

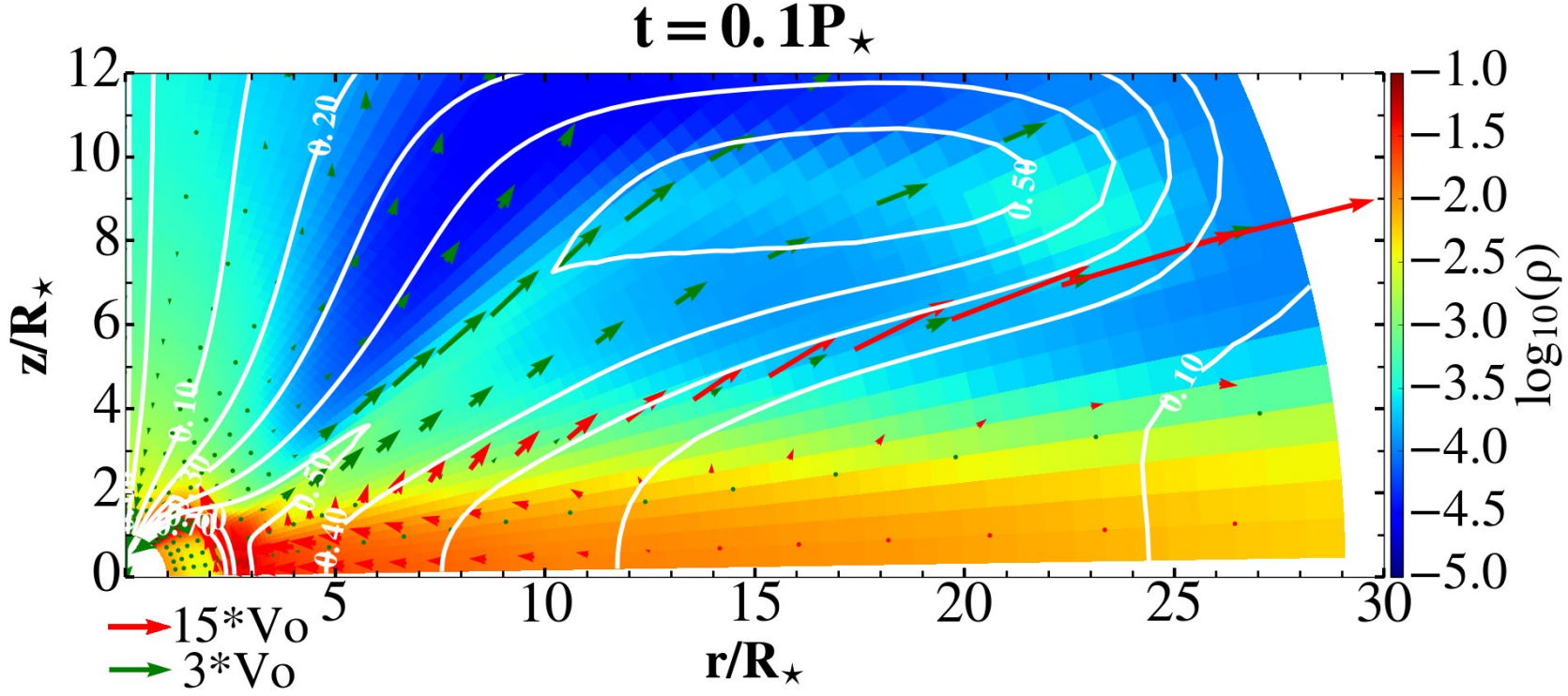
```
{
/* dipole */
   B0[0] = 2.*g_inputParam[MU]*cos(x2)/(x1*x1*x1);
   B0[1] = g_inputParam[MU]*sin(x2)/(x1*x1*x1);
   B0[2] = 0.0;
/* */
/* quadrupole
  B0[0] = 3.0/2.0*g_inputParam[MU]*(3.0*cos(x2)*cos(x2)-1.0)/(x1*x1*x1*x1);
  B0[1] = 3.0*g_inputParam[MU]*cos(x2)*sin(x2)/(x1*x1*x1*x1);
  B0[2] = 0.0;
*/

/* octupole
  B0[0] = 2.0*g_inputParam[MU]*(5.0*cos(x2)*cos(x2)*cos(x2)-3.0*cos(x2))/(x1*x1*x1*x1*x1);
  B0[1] = 0.5*g_inputParam[MU]*(15.0*cos(x2)*cos(x2)*sin(x2)-3.0*sin(x2))/(x1*x1*x1*x1*x1);
  B0[2] = 0.0;
 */
}
```

Visualization of Bp lines with Paraview



Python script for visualization

- mc_veloclect.py , python ver.3.5 and newer.
- Density in logarithmic color grading.
- Vectors of velocity. Remember to show normalization, I normalize to Keplerian velocity at the stellar equator (R=1).
- Magnetic field lines-plots with A_phi isocontours-they are parallel to B_p field lines. Magnetic field lines could be plotted also with B_p streamlines, but I did not do it here.



Summary of the Part IV

- I introduced star-disk magnetospheric interaction simulations.
- We learned setup of axisymmetric 2D setup with dipole magnetic field.
- Visualization of magnetic field lines with Paraview.
- Python script for visualization of mag. field lines and velocity vectors.

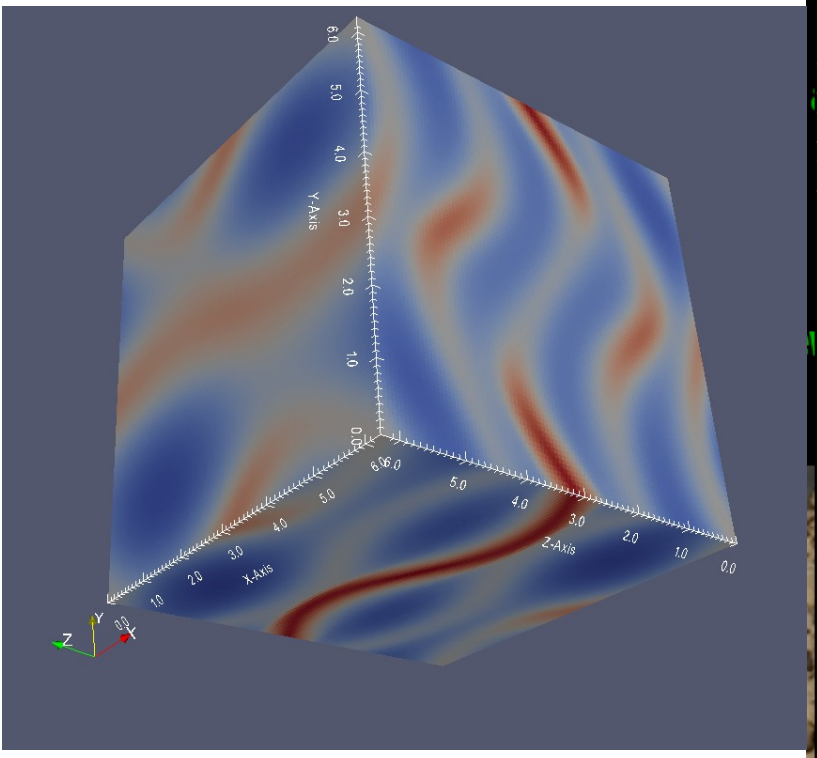
Outline, Part V

- Setup of 3D simulation: Orszag-Tang test in 3D.
  -plotting of the 3D results in Paraview.
- Setup of HD disk in full 3D.
- How about MHD? 3D MHD disk with the dipole magnetic field.
- Restart and initialization from (modified) file.
- Running a job on Linux cluster or supercomputer.
- Examples of the code uses:
  -comparison with observations: light curve
  -post-processing (PLUTO + DUSTER): influence of the radiative pressure on the motion of dust grain particles

- Concluding remarks

Setup of 3D simulation, Orszag-Tang test in 3D

- Simple, just copy one of 3D setups from PLUTO/Test_Problems/MHD/Orszag_Tang, perform a setup.py (made a pls alias?) to pre-set a 3D run, and add copy the corresponding pluto.ini (e.g. _07).
- Visualisation of the result in 3D with Paraview:



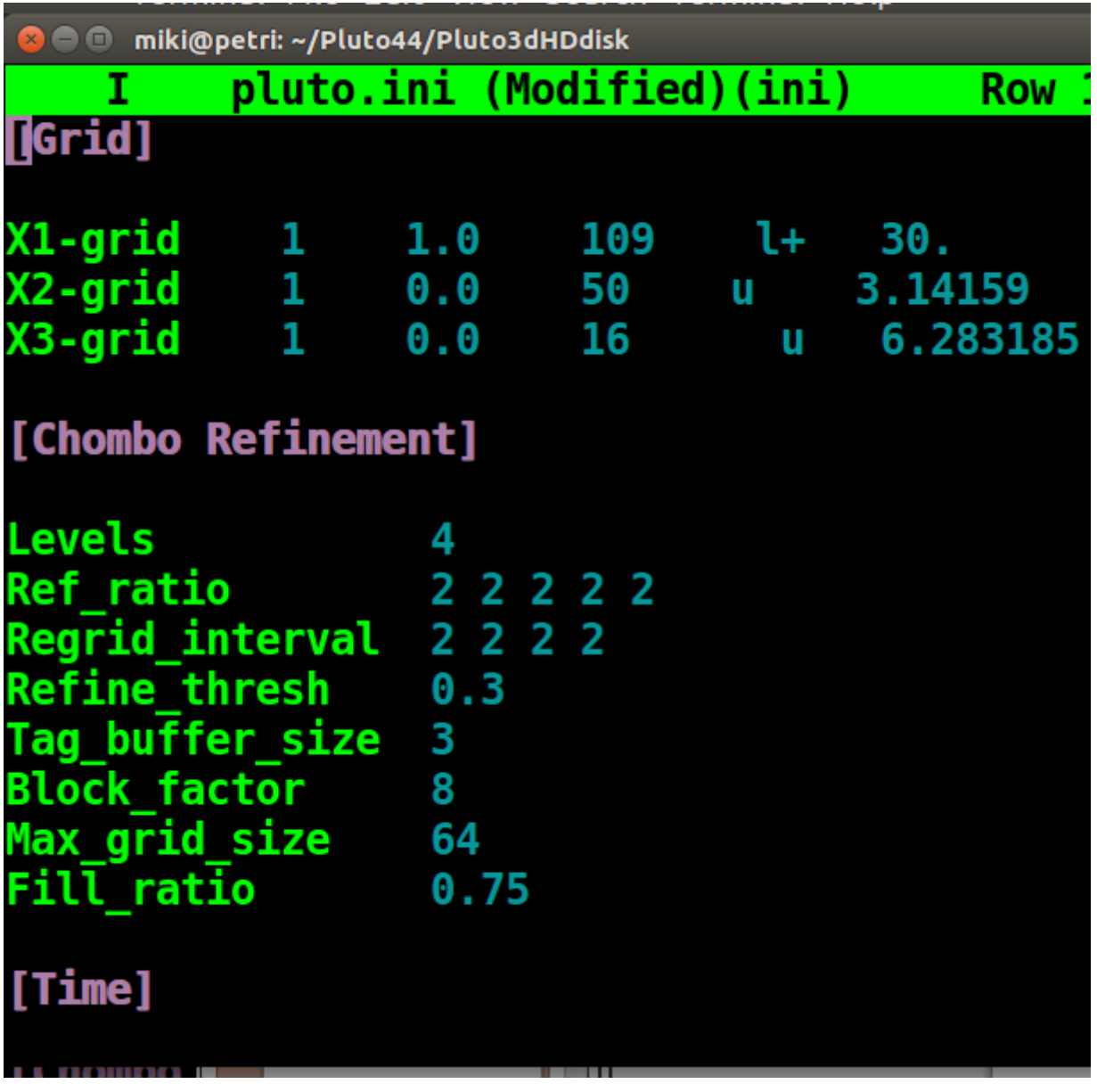
miki@petri: ~/Pluto44/OTang3D

```
    I    pluto.ini (ini)                    Row 20   Col 1
[Grid]

X1-grid    1    0.0    100    u    6.28318530717959
X2-grid    1    0.0    100    u    6.28318530717959
X3-grid    1    0.0    100    u    6.28318530717959

[Chombo Refinement]

Levels           4
Ref_ratio        2 2 2 2 2
Regrid_interval  2 2 2 2
Refine_thresh    0.3
Tag_buffer_size  3
Block_factor     4
Max_grid_size    32
Fill_ratio       0.75

[Time]

CFL                     0.8
CFL_max_var    1.1
tstop            3.1
** Joe's Own Editor v4.1 ** (utf-8) ** Copyright © 20
```

Setup of 3D simulation of accretion disk in HD case

- Should be simple, just define the whole Kluźniak-Kita solution, which is HD and axisymmetric, so we just set the same in each azimuthal plane.
- We need theta=[0,PI] version of the setup now, so boundaries will be different.

- Can be useful to create the initial condition for other runs.



Restart of simulation from a (modified) file

- Setup of 3D run: change to 3D in definitions.h (or through python setup) and change the pluto ini grid accordingly in pluto.ini file, change the boundary condition (usually“periodic”).
- Restart from a file is one of the options in PLUTO.
- One can start completely new simulation from a (modified) file. Previous result, with eventual modifications, is now used as an initial condition for new simulation.
- You can create a 3D initial condition from the result of 2D simulation.

```
   I A  init.c (c)  }
/* ************************************************************************
void InitDomain (Data *d, Grid *grid)
/*!
 * Assign initial condition by looping over the computational domain.
 * Called after the usual Init() function to assign initial conditions
 * on primitive variables.
 * Value assigned here will overwrite those prescribed during Init().
 *
 *
 ************************************************************************
{
  int i,j,k,id;
  double *x1 = grid->x[IDIR];
  double *x2 = grid->x[JDIR];
  double *x3 = grid->x[KDIR];
  double r;
  double coeff, eps2, pc, rcyl;
  double br,bth;
  double lambda;
  double xhi2, Rco;

  rcyl=x1[i]*sin(x2[j]);
  eps2=g_inputParam[EPS]*g_inputParam[EPS];
  coeff=2./5./eps2*(1./x1[i]-(1.-5./2.*eps2)/rcyl);
  lambda=11./5./(1.+64./25.*g_inputParam[ALPHAV]*g_inputParam[ALPHAV]);

  id = InputDataOpen ("./Adata.0045.dbl","grid.out"," ", 0, CENTER);
  TOT_LOOP(k,j,i){
    d->Vc[RHO][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[PRS][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[VX1][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[VX2][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[VX3][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[BX1][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
```

```
   I A  init.c (c)  void InitDomain (Data *d, Grid *grid)
    d->Vc[RHO][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[PRS][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[VX1][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[VX2][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[VX3][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[BX1][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[BX2][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[BX3][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
    d->Vc[TRC][k][j][i] = InputDataInterpolate(id,x1[i],x2[j],x3[k]);
     }
  InputDataClose(id);
/**/
  TOT_LOOP(k,j,i){
//    pc=2./5.*g_inputParam[RHOC]*pow(x1[i],-3./2.);
    if (d->Vc[RHO][k][j][i] >= pc){
//    if (d->Vc[TRC][k][j][i] >= 0.5) {
     }
    else
      {
       d->Vc[RHO][k][j][i] = g_inputParam[RHOC]*pow(x1[i],-3./2.);
       d->Vc[PRS][k][j][i] = 2./5.*g_inputParam[RHOC]*pow(x1[i],-5./2.);
       d->Vc[VX1][k][j][i] = 0.0;
       if (x2[j] < CONST_PI/2./20.) d->Vc[VX1][k][j][i] = 0.001;
       d->Vc[VX2][k][j][i] = 0.0;
       d->Vc[VX3][k][j][i] = 0.0;
       d->Vc[TRC][k][j][i] = 0.0;     // Track the corona
      }
} /**/

}

/* ********************************************************************* */
void Analysis (const Data *d, Grid *grid)
/*
```

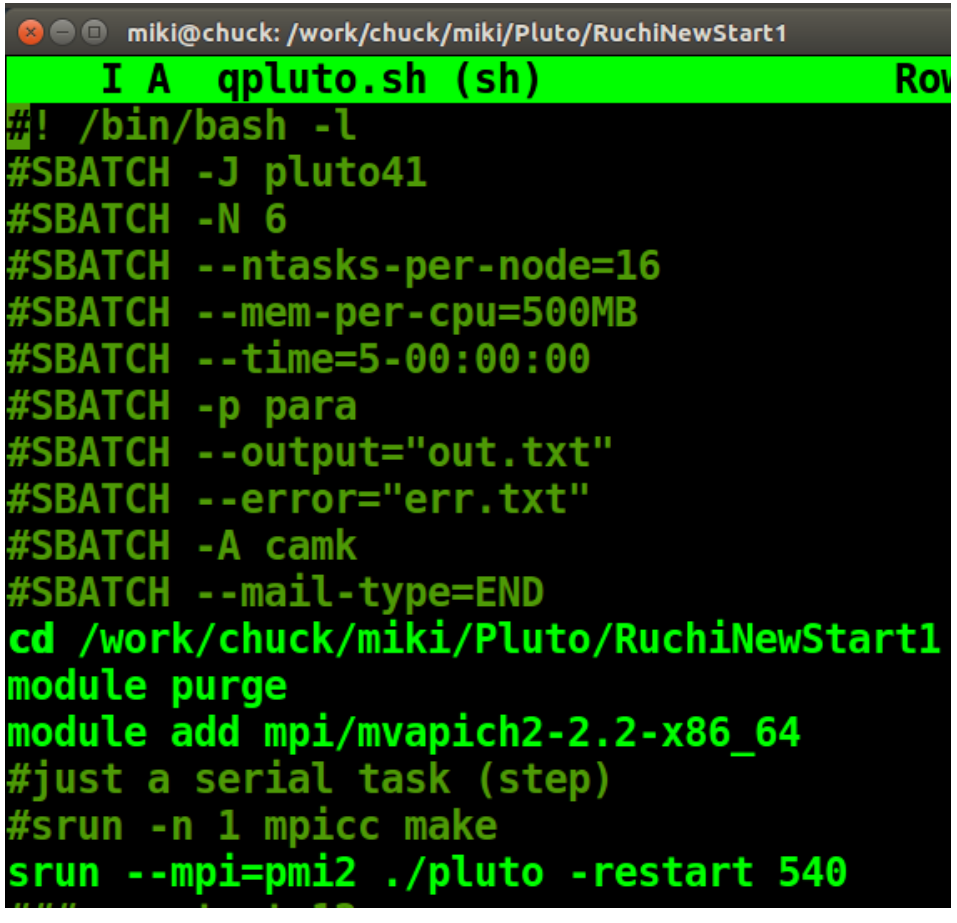
Running on a Linux cluster

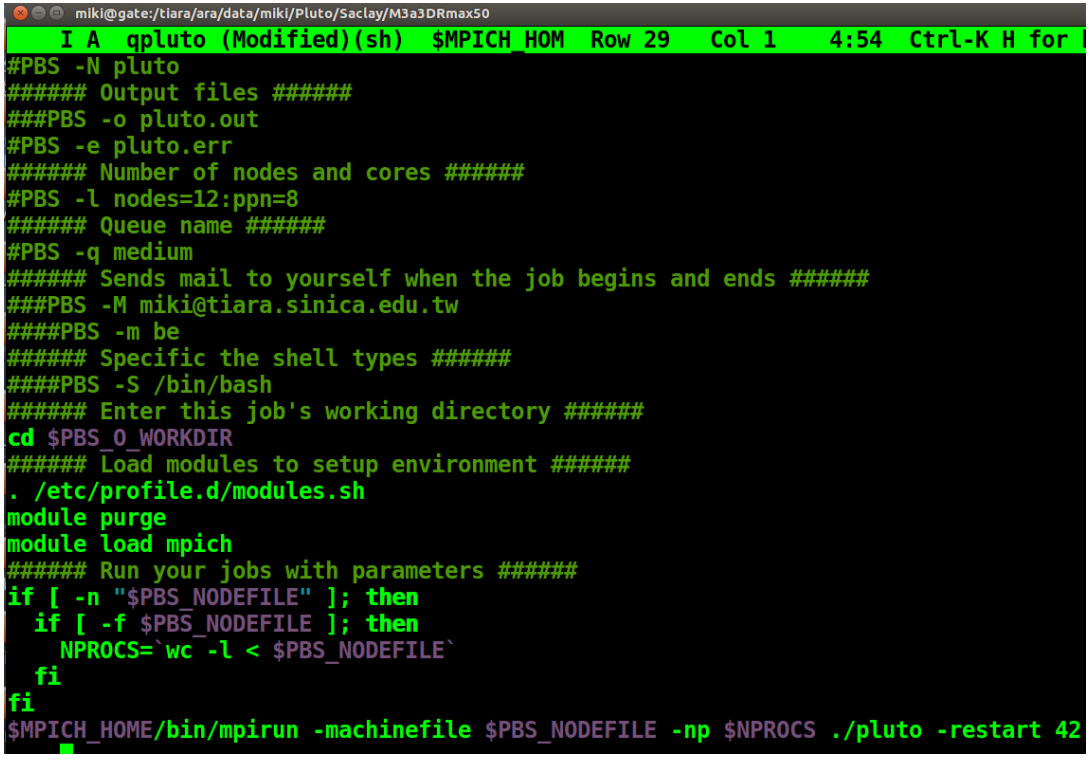
- Usually Linux clusters and supercomputers use management and queuing system. I will describe two of them, which work in a similar way. Think of them just as an expanded command for running your job.

  - **SLURM** - a free one, became quite reliable so one does not need to pay for management, which could come with a significant cost. After creating a slurm_job_file, execute sbatch slurm_job_file . Most often used commands: sbatch, squeue, scancel.

  - **PBS** – (Portable Batch System), there are Open (free) and Pro (not free) versions, also very similar is its fork, **TORQUE.** After creating a PBS or TORQUE job script pbs_job_file, execute in terminal: qsub pbs_job_file.

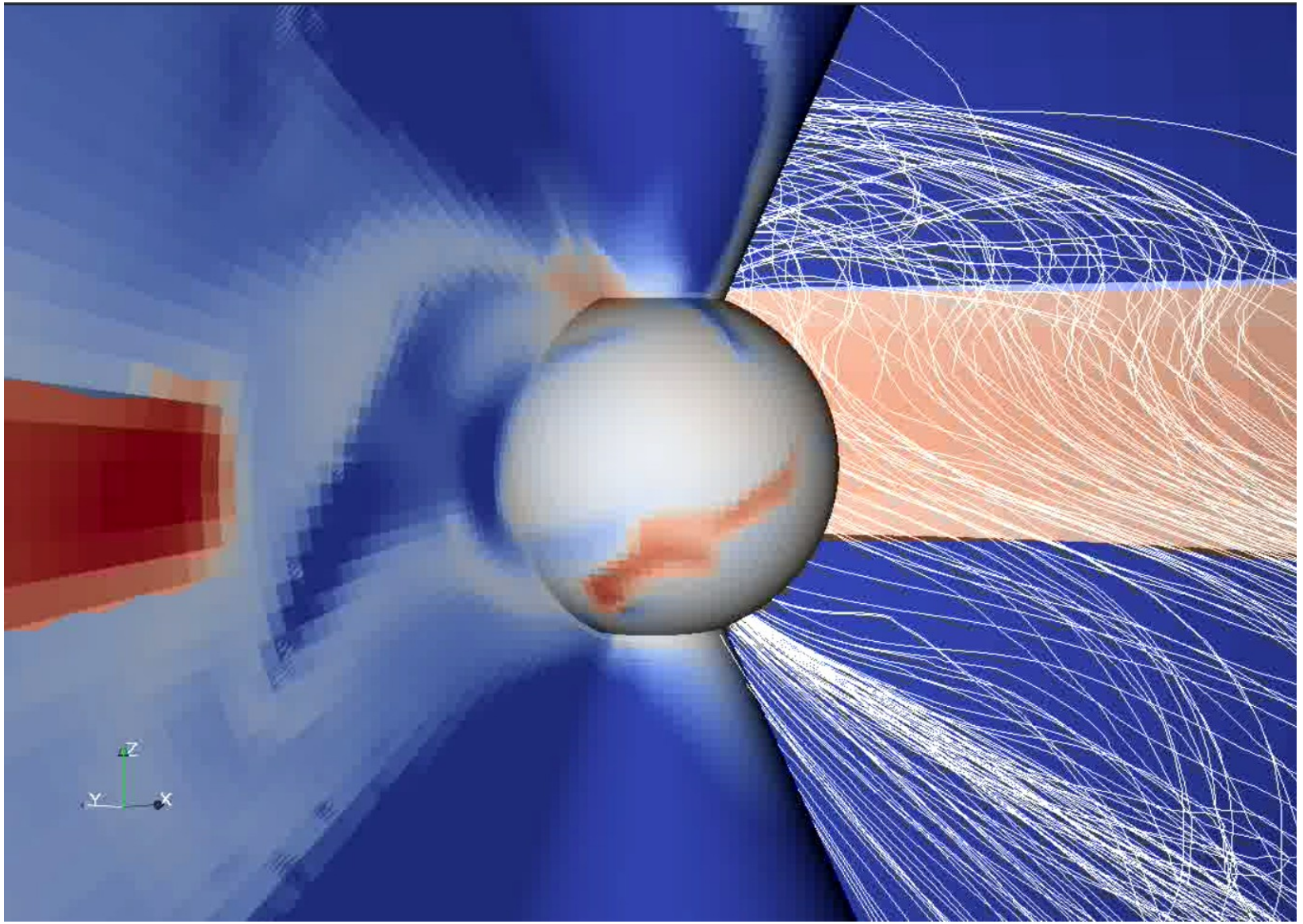
  Most often used commands are: qsub, qstat, qdel, qmgr and xpbs, pbsjobs (located in /home/Tools/bin) for additional detail about queued and running jobs.





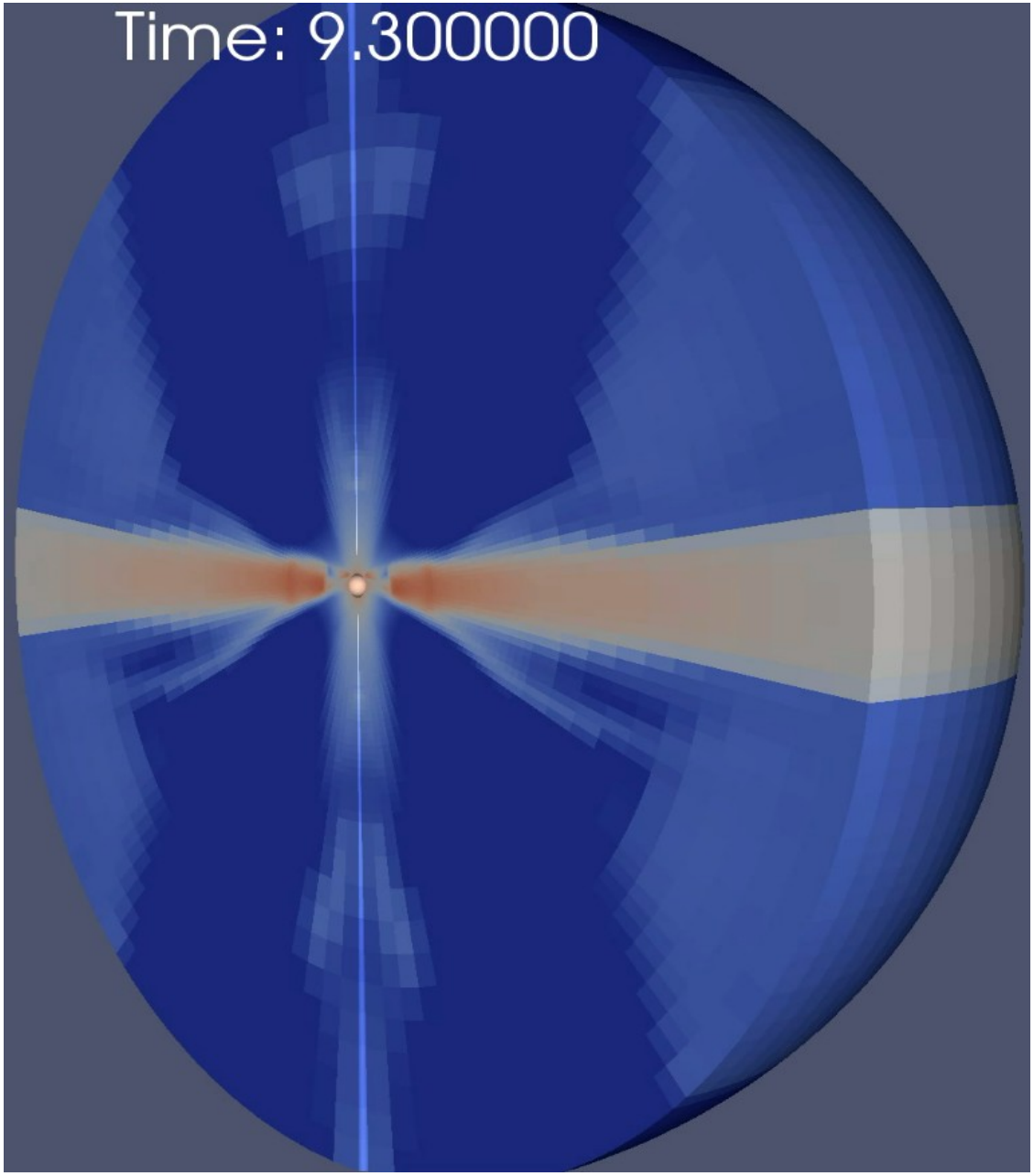
3D simulations, tilted magnetic field case

- The magnetic field in this case is not aligned with the rotation axis.
- Still in development-I have a setup, but not a stable run, yet.



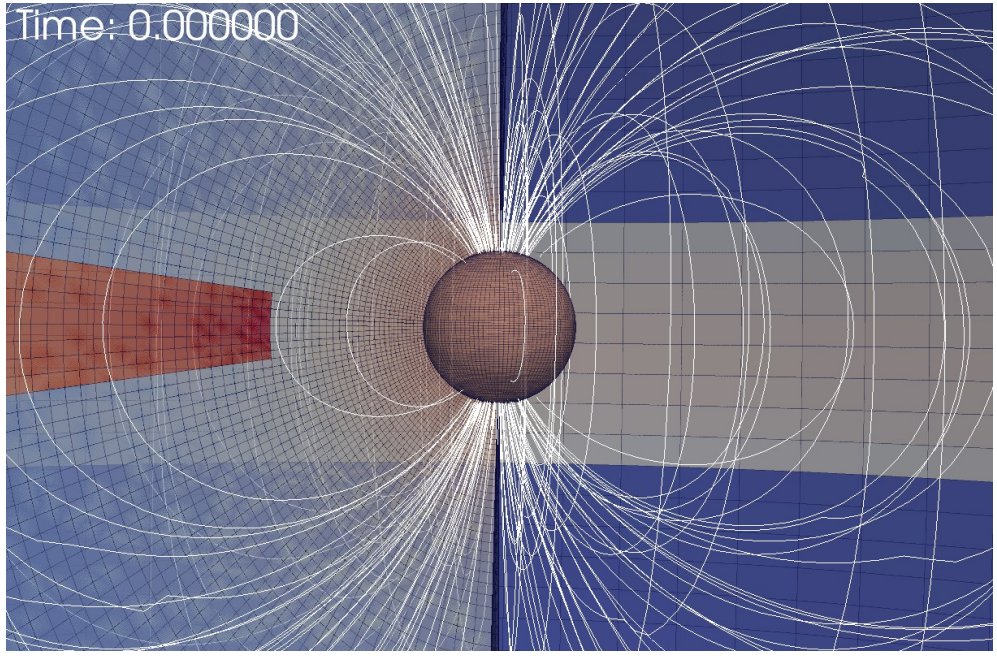
The asymmetric jet launching in 3D simulations

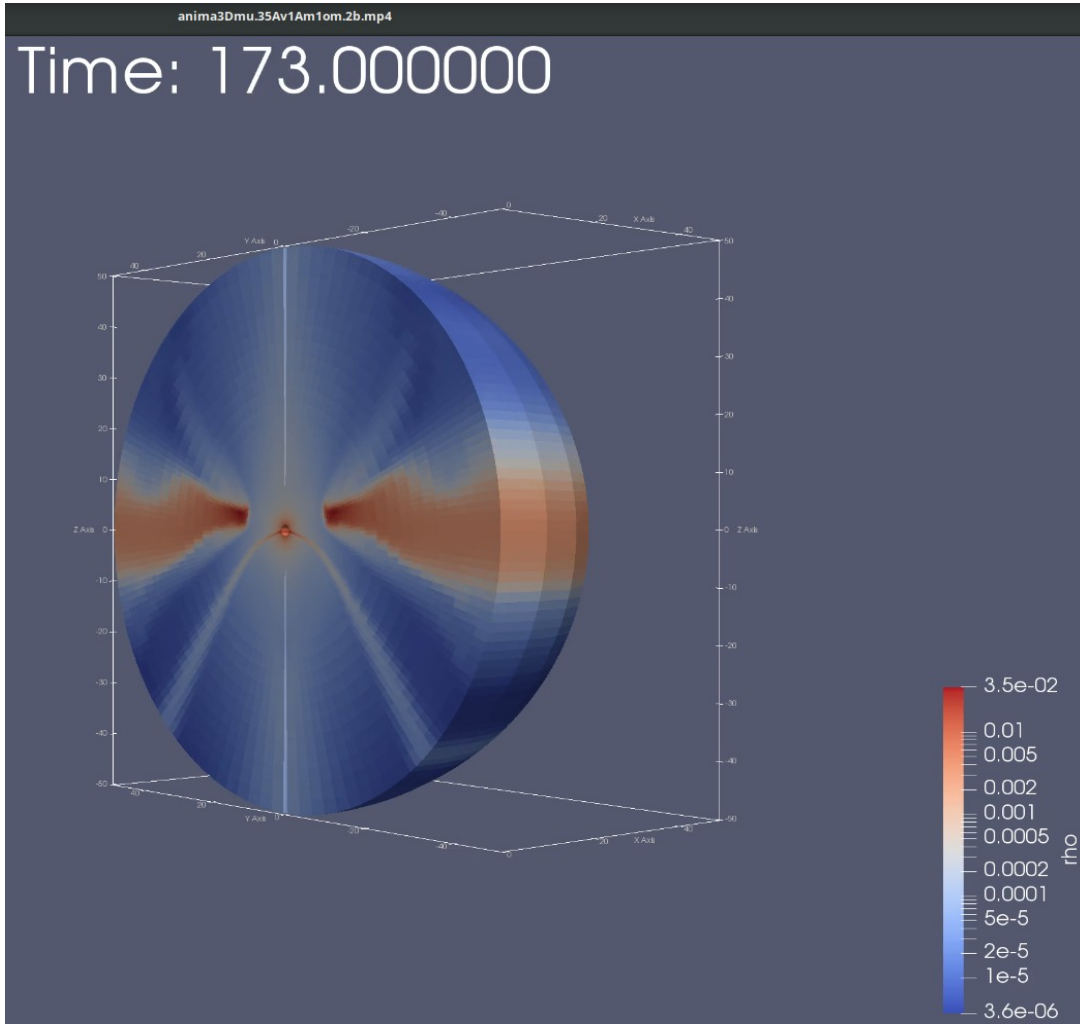
- In full 3D simulations I obtain asymmetric jets.



3D simulations, case with magnetic field aligned with rotation

- The first step here is to perform the axisymmetric 3D simulation. I use the spherical grid. The magnetic field in this case is aligned with the rotation axis.
- Zoom into the vicinity of the star=inner boundary condition at T=0 and at T=173 (2.5 stellar rotations only, for now.





Comparison with observations, “hiccups” in light curves

- A curious case with switching of the hemisphere to which the column is attached (Čemeljić & Siwak, 2020) .

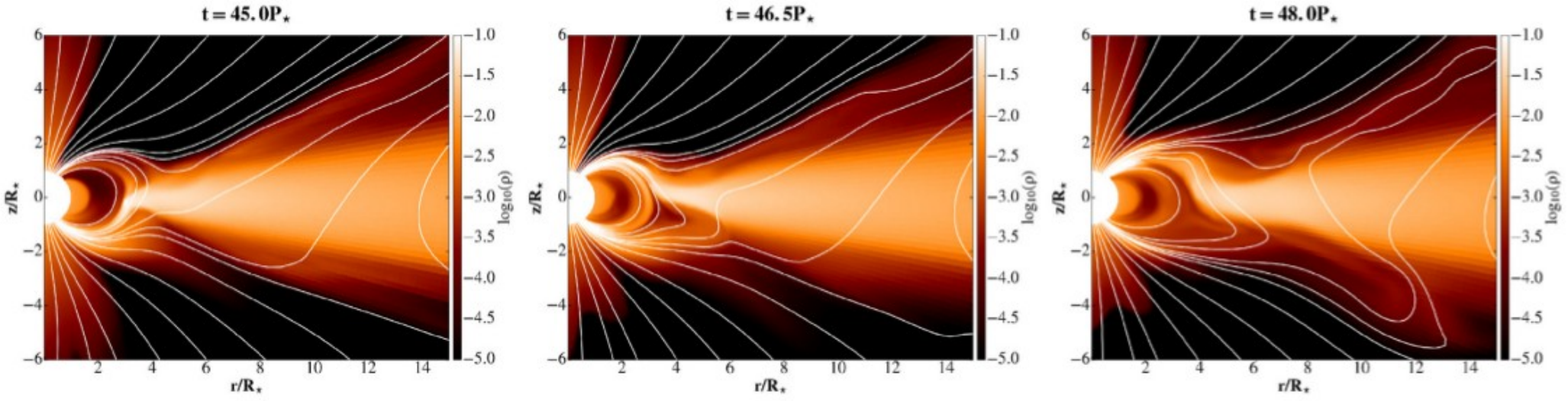
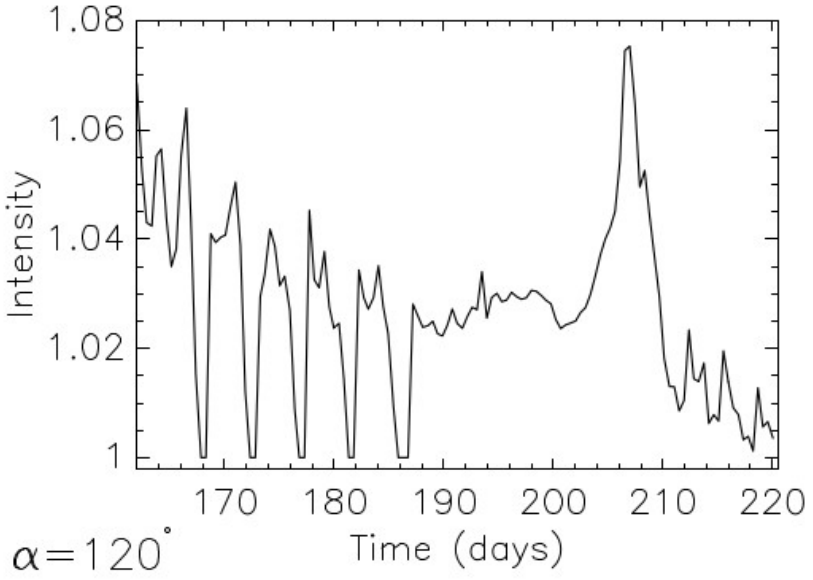


Figure 4. A sequence of snapshots from the results in the interval when switching of the accretion column from the Southern to the Northern hemisphere occurs.

Comparison with observations, “hiccups” in light curves

- Such switching could explain some of the cases of aperiodicity in the Young Stellar Objects.



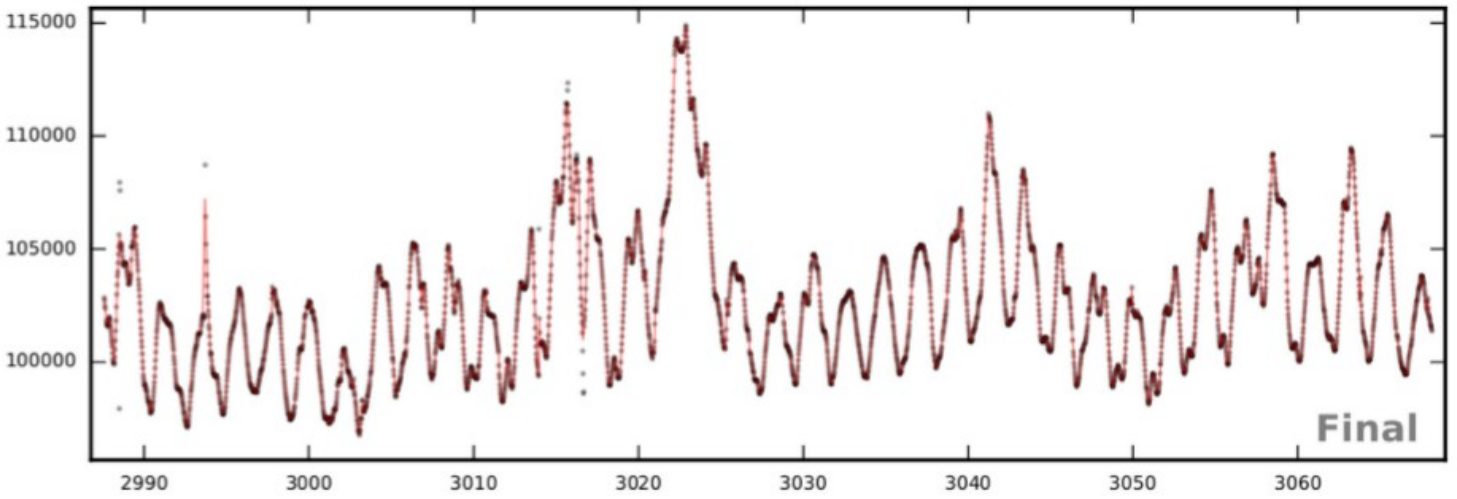
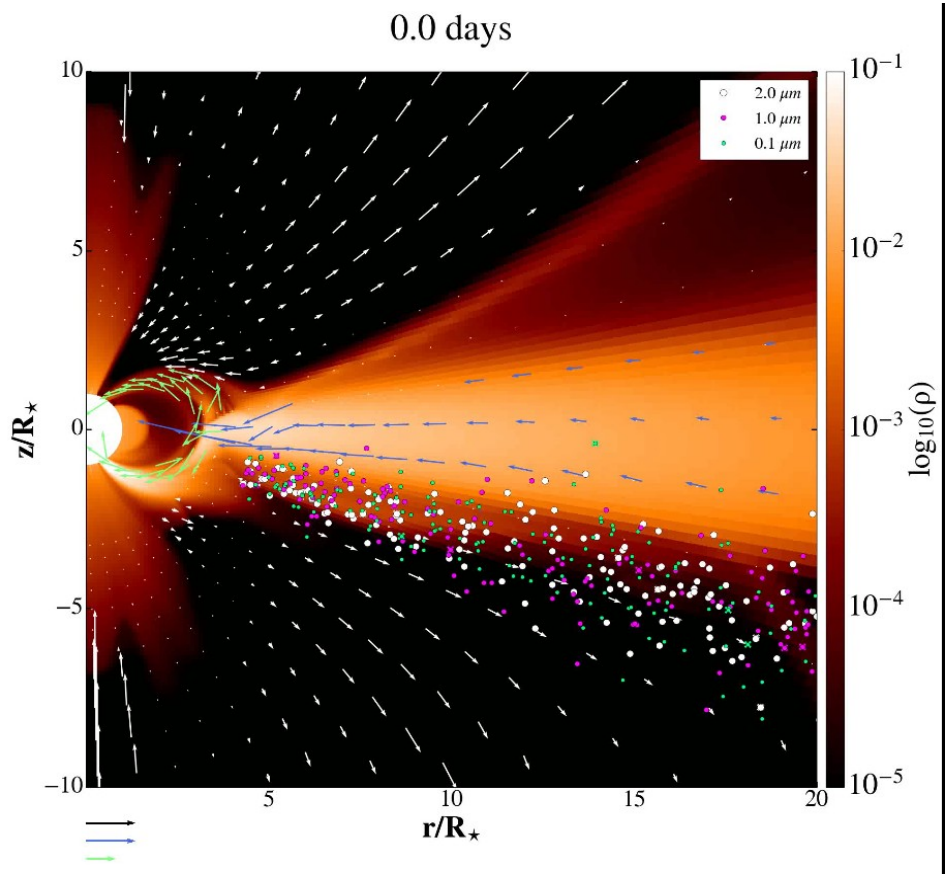
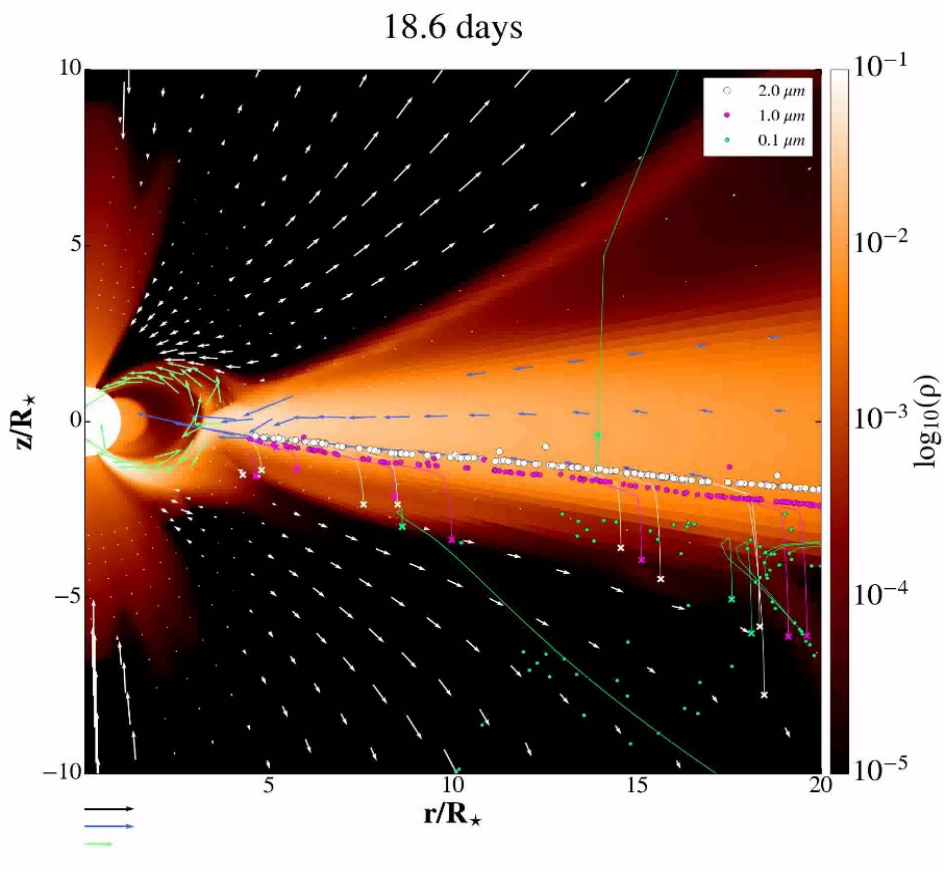


Figure 8. Top panel: intensity in a 3D model made from the longer time sequence than shown in Fig. 7. Shifts in the phase of the observed light (‘hiccups’) occur during the switch of the accretion column from the southern to northern stellar hemisphere between the 190 and 210 d. Bottom panel: light curve from the *Kepler* observation of V1000 Tau in which part of the contribution could occur because of the column switching. Time in the abscissa is annotated in Julian days.

"STARDUST": Dusty disk in Young Stellar Objects

During a Summer Student Program, C. Turski wrote the Python script "DUSTER" for post-processing of the quasi-stationary results in my star-disk solutions. He added the dust particles and computed their movement in the disk-corona solution as a background. The results are used to model dust distribution in the disk.





$$\ddot{\vec{r}} = -G\frac{M_\star}{r^3}\vec{r} - \frac{\rho_{gas}}{\rho_{gr}}\frac{c_s}{a}(\dot{\vec{r}} - \vec{v}_{gas}) + \vec{\beta}G\frac{M_\star}{r^2}$$

$$\beta = 0.4\frac{L_\star}{L_\odot}\frac{M_\odot}{M_\star}\frac{3000\frac{kg}{m^3}}{\rho_{gr}}\frac{\mu m}{a}, \quad R_{in} = 0.0344\Psi\left(\frac{1500K}{T_{gr}}\right)^2\sqrt{\frac{L_{tot}}{L_\odot}}[\mathrm{AU}],$$

Summary, Part V

- Setup of 3D simulation: Orszag-Tang test, HD and MHD disk in 3D.
- Plotting of the 3D results in Paraview.
- Restart and initialization from (modified) file.
- Running a job on Linux cluster or supercomputer.
- Examples of the code uses: light curve, post-processing (PLUTO + DUSTER): motion of dust grain particles

Lectures summary & Concluding remarks

-In 5 lectures, I presented the PLUTO code, in hands-on approach. I chose PLUTO because it is well used (=tested and updated) in the astrophysics community, is user-friendly (good documentation) and very well written (good tool for hands-on learning of C programming language).

- We started with general description and followed with a standard Orszag-Tang test in 2D. This brought us to the thin disk setup in HD. With addition of the stellar dipole magnetic field, we obtained MHD setup for a star-disk magnetospheric interaction for a thin accretion disk in 2D axisymmetric simulations.

- Along the way, we learned different ways of visualization: Paraview, VisIt, Python

- I detailed the 3D setup of magnetic star-disk simulations, ab initio and from the already evolved setup, restarting/initializing simulations from a (modified) previous result file. I also showed usual scripts for running on the linux clusters or supercomputers.
- I described the use of results in post-processing, to create a light curve, compute the dust settling or radiative pressure effects on the dust.

Thank you and Good Luck!

This was an express course in PLUTO. I hope it will be of use to you. For me, PLUTO is 15 years in places like my home island in Croatia, and the cities: Athens, where I learned it first, and then Taipei, Paris and Warsaw: