Collimation of outflows in moderately magnetized neutron stars

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Outline

- ULXs
- KORAL code
- Recent results with KORAL
- A simple tool for complicated 3D MHD simulations with PLUTO
- Papers I added to ISSI #495 “Feeding the spinning top” count of publications

ULXs for numerical simulators

ULXs are extragalactic ultra-luminous X-ray sources emitting above 10^{39} erg/s if assumed isotropic. It is less than the luminosity of AGNs, but far surpassing the Eddington luminosity for a typical stellar-mass black hole (of mass ∼ 10 $M_\odot$) or a neutron star.

Such extraordinary luminosity may be produced in binary systems where the accretor is a stellar-mass black hole or a neutron star that apparently emits beyond its Eddington limit.

Among explored possibilities were:

-sub-Eddington accretion in intermediate mass BHs (10^2-10^4 $M_\odot$)

-photon-bubble instability of stellar mass BHs-but this can not produce more than $3x10^{40}$ erg/s without beaming

ULXs

Our simulations support the third scenario, proposed by King et al. (2001):

- a super-Eddington accretion onto compact objects in intermediate and high mass X-ray binaries and emission geometrically beamed by outflows close to the accretor, that create a funnel-like optically thin region.

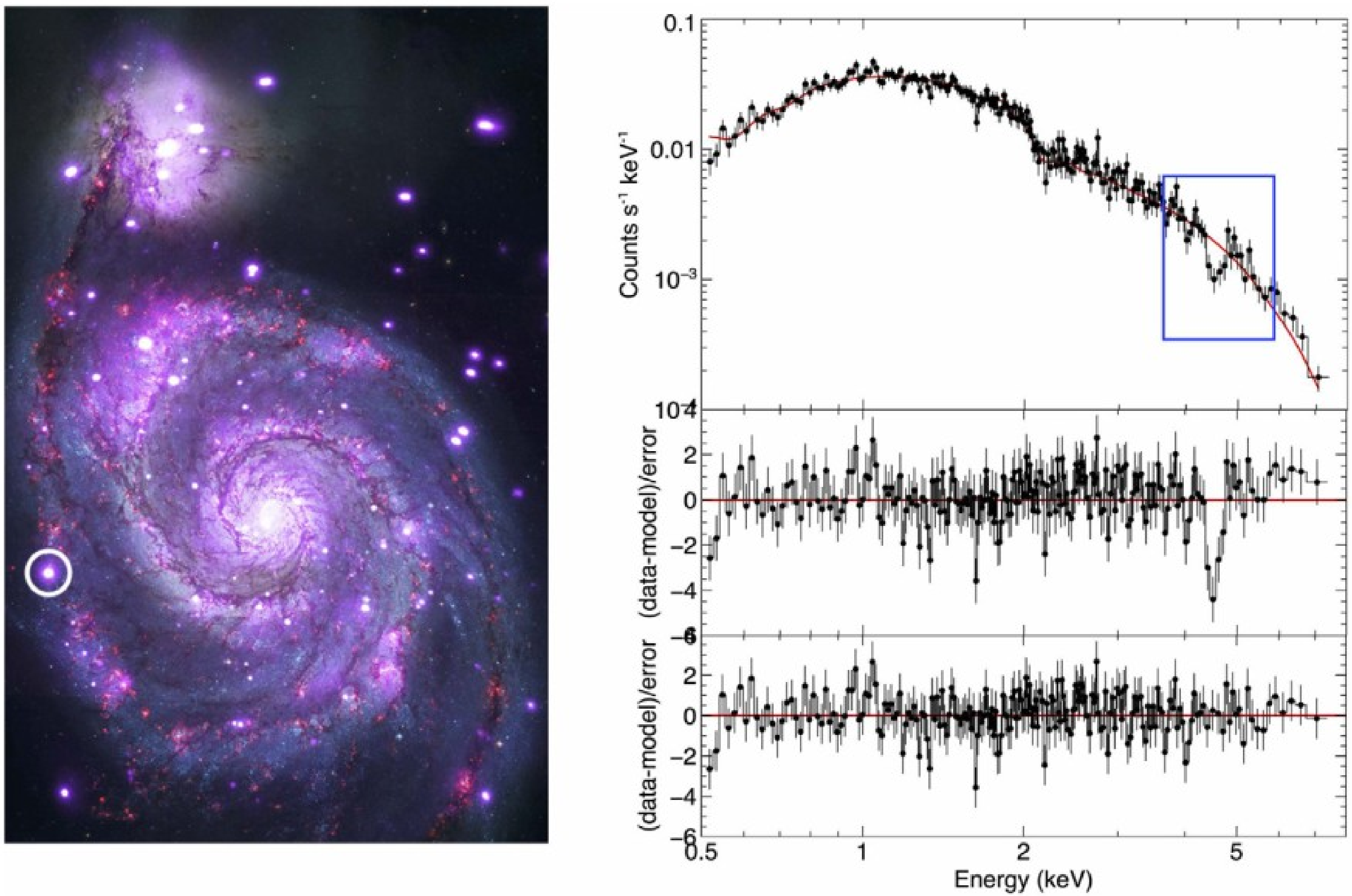
Radiation can reach the observer through the funnel, which is a fraction $b \lll 1$ of the solid angle of the sphere. Such an observer overestimates the true luminosity L by a beaming factor b related to the apparent ("isotropic") luminosity; $L_{iso} \sim L/b$.

We know about 1800 ULXs until now (Walton et al., 2022). Several have $L_X >$ 10^{41}–10^{42} erg s^{-1} . Almost all are in other galaxies, but they are not located in their centers, so they are not accreting supermassive black holes.

NS ULXs are of particular interest because here the mass of the central object is known, which means one wildly unknown parameter less in models.

An example of observation: ULX-8

In strong magnetic fields, electron and proton orbits are quantized into Landau levels. Depending on the quantum mechanical cross section, they can resonantly scatter incident photons of sufficient energy and leave cyclotron resonance scattering features (CRSFs) visible in the spectrum. The transition energy of such lines is related to the magnetic field strength and particle type:



$$\Delta E_{e^-} = \frac{11.6}{(1+z)}\left(\frac{B}{10^{12}G}\right)\ \mathrm{keV}$$

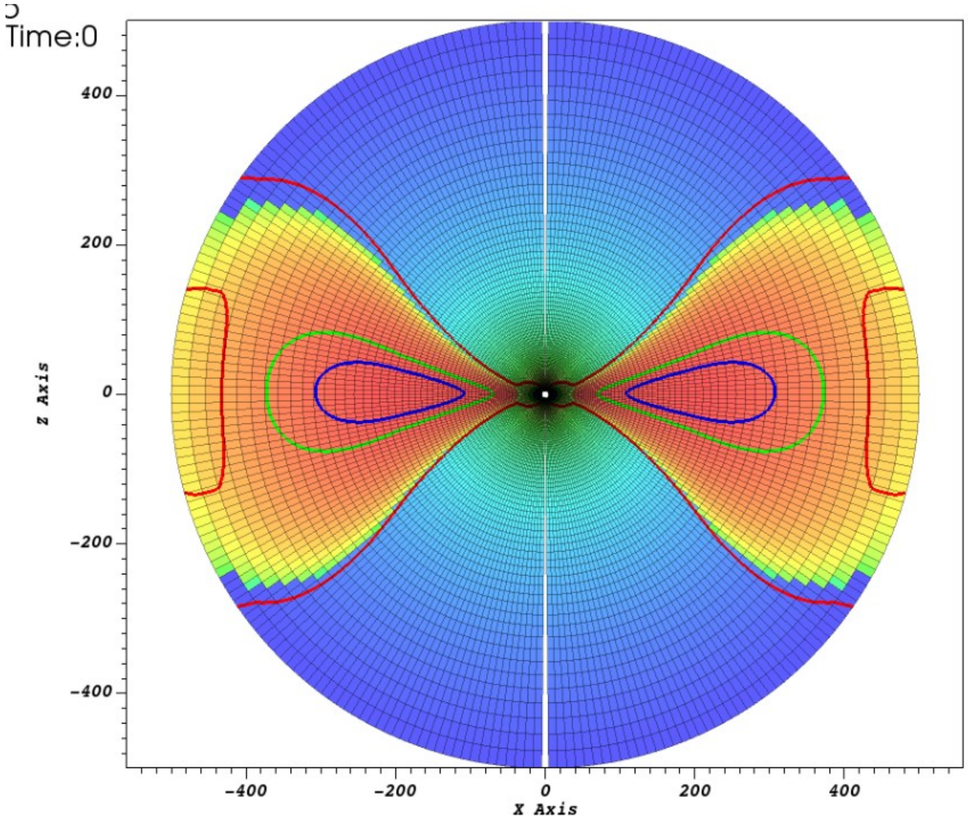
$$\Delta E_{p^+} = \frac{6.3}{(1+z)}\left(\frac{B}{10^{15}G}\right)\ \mathrm{keV}$$

where z is the gravitational redshift

$$z = \left(1 - \frac{2GM}{r_{cyc}c^2}\right)^{-1/2} - 1$$

Figure from Brightman et al. (2018) showing the location of ULX-8 in M51 and the the first reported cyclotron resonance scattering feature (CRSF) at ∼4.5 keV in a Chandra observation. They concluded it is a proton CRSF. Constraints from spectral fitting suggest that the dipole field is likely weak, and the CRSF is the result of higher order multipole, like quadrupole, closer to the neutron star. In the case of Swift J0243.6+6124 Kong et al. (2022) found a similar situation.

KORAL Simulations setup



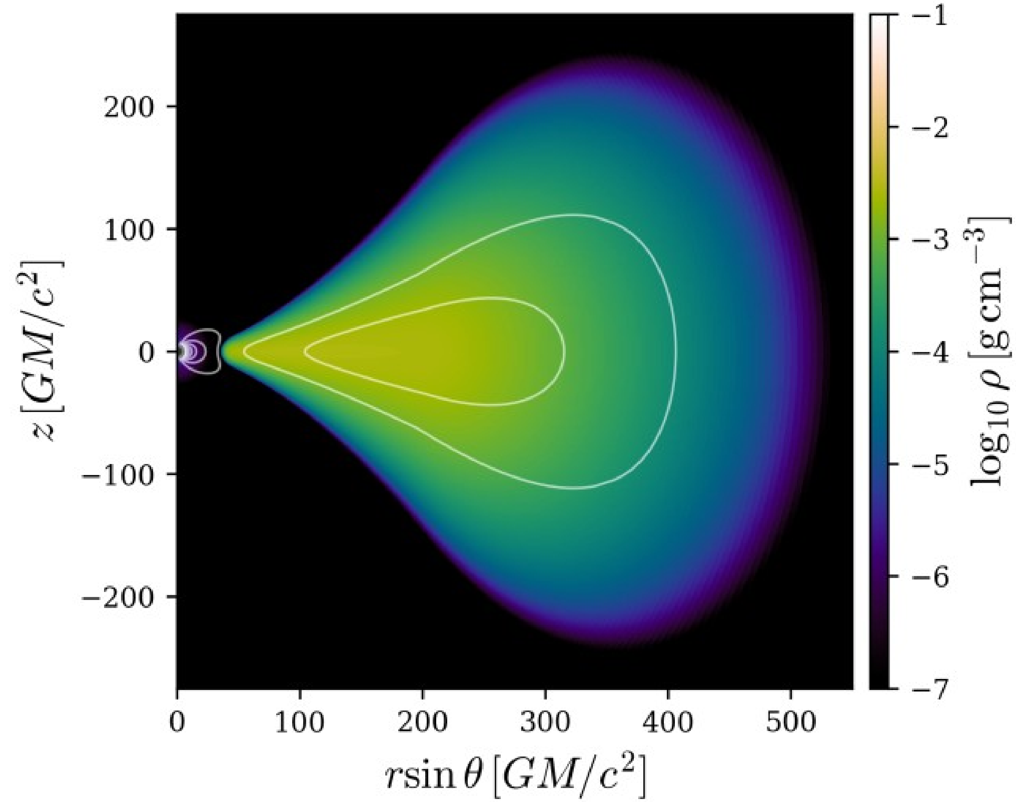
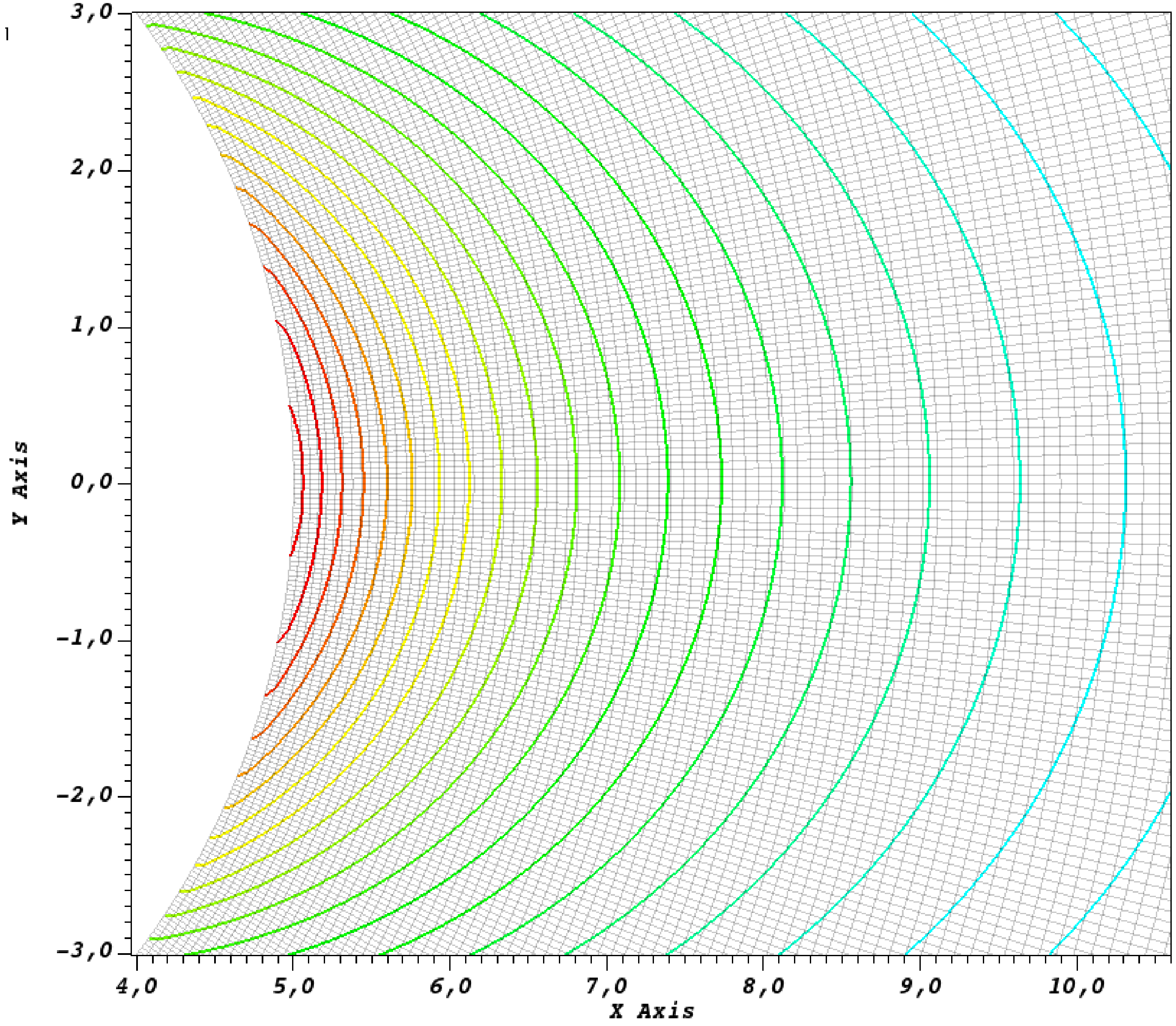


Figure 1. The initial rest mass density ρ in the fluid frame, shown with logarithmic color grading. Solid lines indicate the isocontour lines of the vector potential A_ϕ, which in our setup are parallel to the magnetic field lines. The surface magnetic field strength of dipole is 10^{11} G.

KORAL Simulations setup



The grid is precise enough to resolve the field lines close to the star.

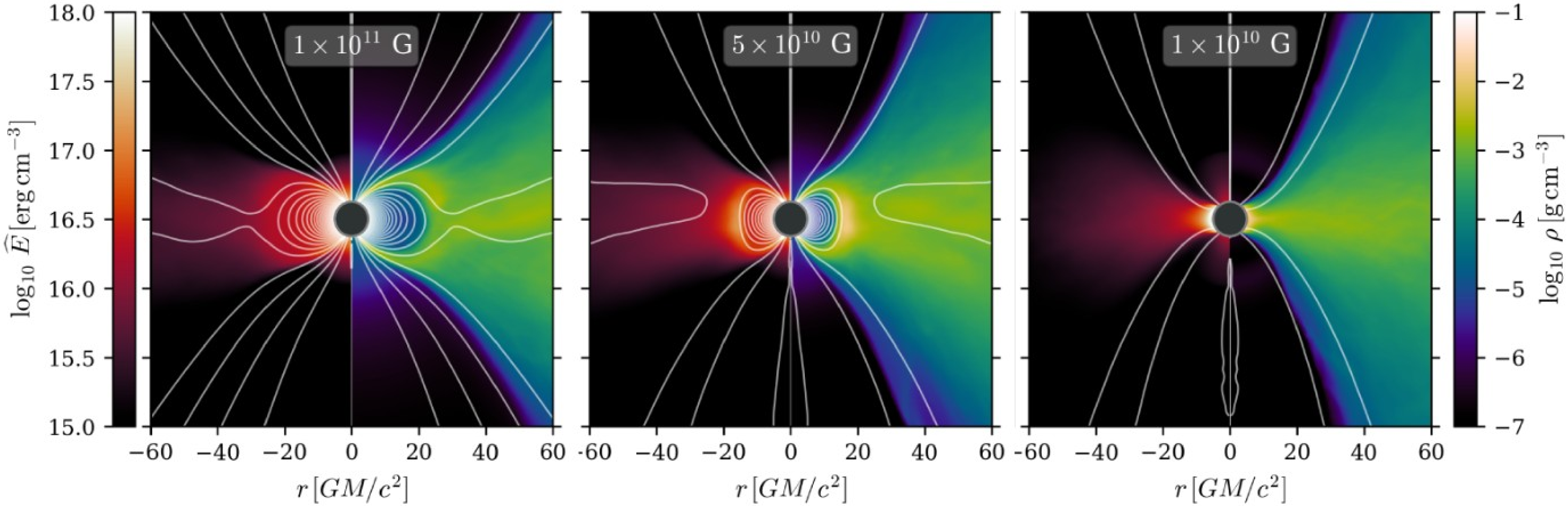


Figure 2. Our simulation results in the cases with stellar dipoles of 10^{11} G (*left panel*), and 10^{10} G (*right panel*). The left half of the panels shows the radiation energy density $\hat{E}$ and the right half the rest-mass density ρ. Magnetic field lines are plotted as isocontours of the vector potential, A_ϕ. Note that the rarefied cones above and below the star are much wider for the 10^{11} G case. The plots are produced using the time-averaged data.

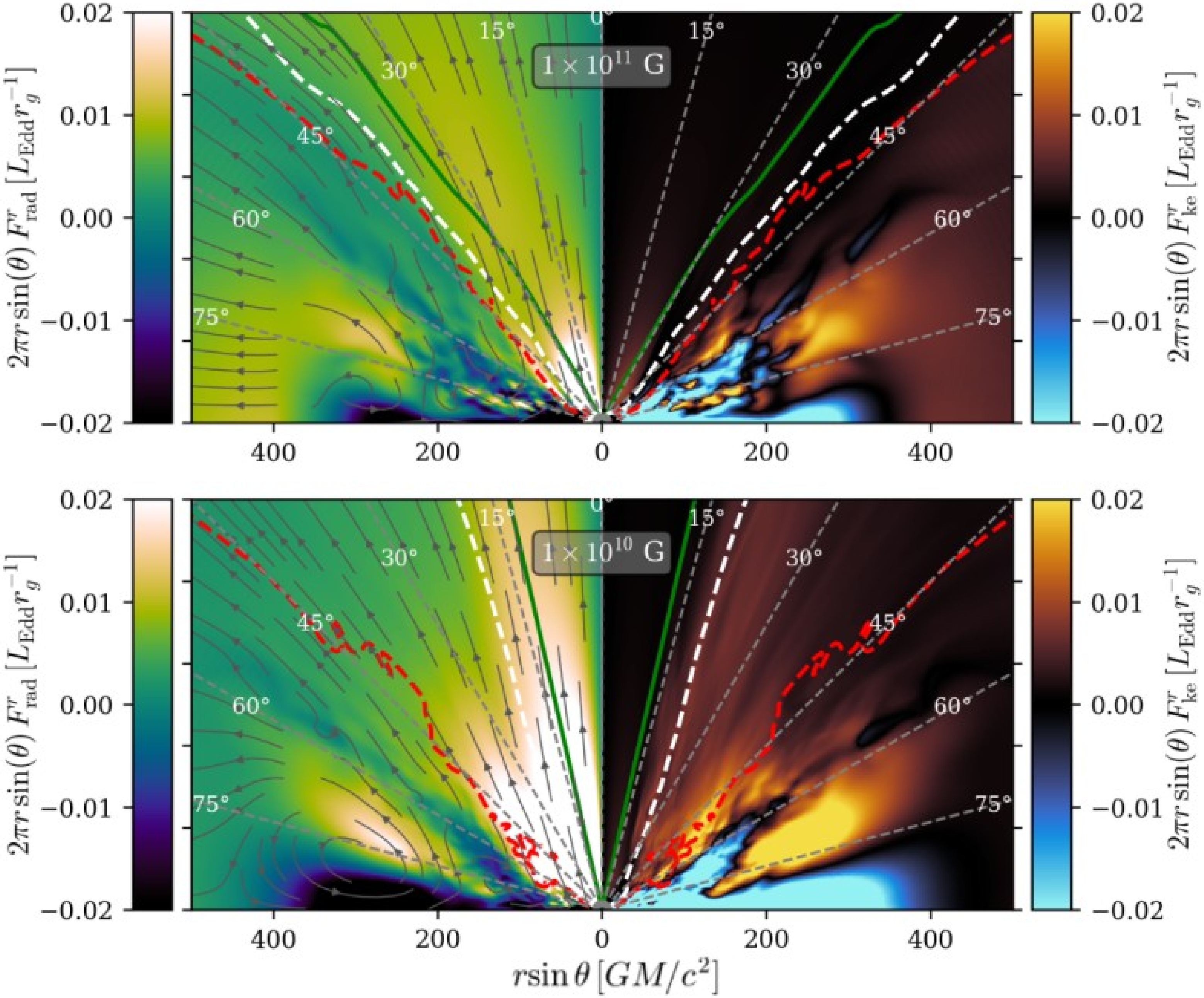
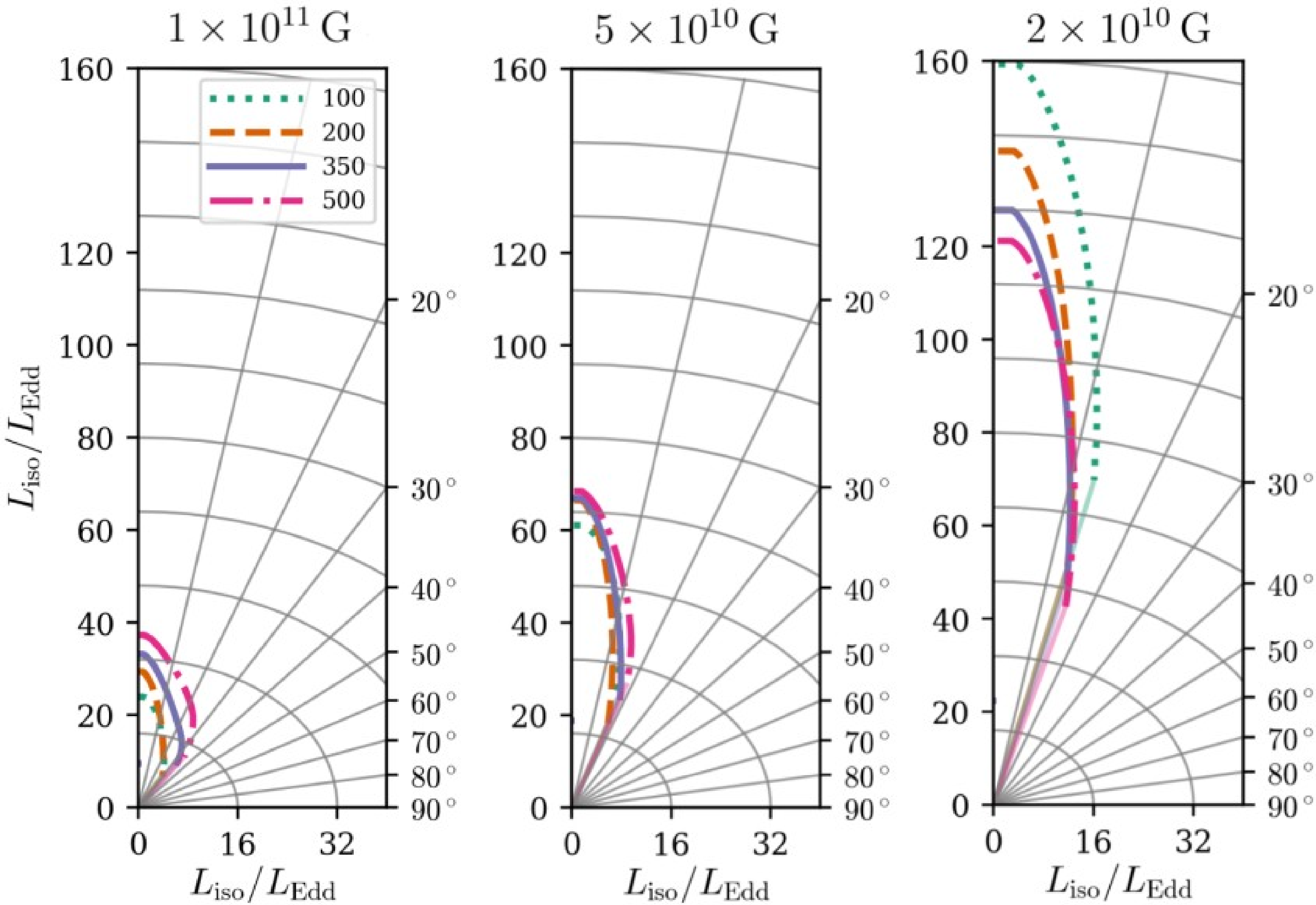


Figure 3. The radiation and kinetic fluxes in our simulations with the neutron star dipole 10^{11} G (*top panel*) and 10^{10} G (*bottom panel*) are shown in the left and right halves of each panel, respectively. The negative values indicate the direction towards the neutron star (inflow), while the positive values indicate outflow. The red dashed contour represents the zero Bernoulli surface. The white dashed and solid green contours depict photospheres $\tau_\theta = 1$ and $\tau_r = 1$, respectively. The dashed grey lines show the viewing angles as labeled. The grey streamlines in the left half panels follow the radiation flux and indicate its direction. The plots are produced using the time-averaged data.



Isotropic luminosity as a function of the viewing angle, at various distances, 100-500 r_g.

Conclusion

We conclude that ultraluminous X-ray sources are most likely powered by neutron stars with a dipolar magnetic field in order of 10^{10} G than with a stronger magnetic field.

Needed: a simple tool in PLUTO for complicated 3D MHD simulations

After some years, I finally developed a tool which can serve multiple roles: as a teaching and visualisation tool, but also as a serious simulations tool.

Goal was to make something with publicly available code, with the most simple setup, but also powerful enough to simulate e.g. NSs with the magnetic dipole (or multipole) tilted with respect to the stellar rotaion axis.

We remember that more than 20 years ago A. Koldoba made a setup for the group of Marina Romanova:

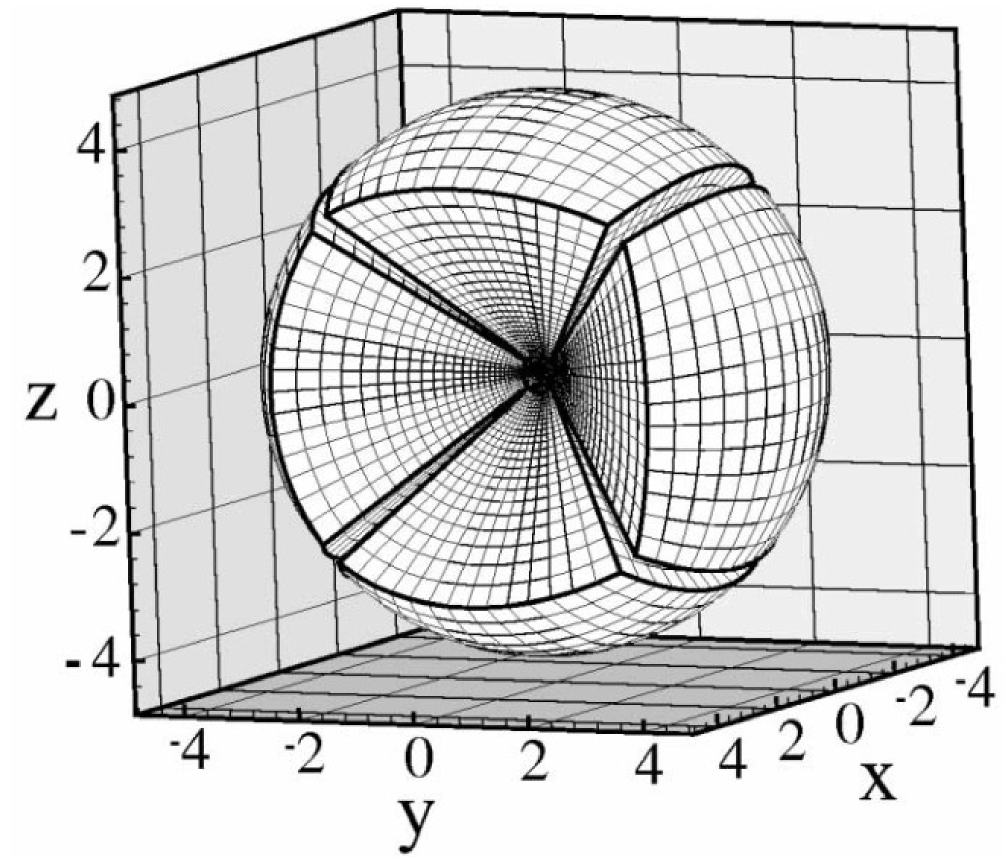


FIG. 1.—Cubed sphere grid, which consists of six sectors. The $+x$ sector is omitted in order to show the inner structure of the grid. Grid is inhomogeneous in the R-direction in such a way that the cells are roughly cubical independent of R.

Marina Romanova group

Actually MR once reported it at ALMA meeting exactly 23 years ago:

Marina Romanova group results

They made many beautiful contributions:

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

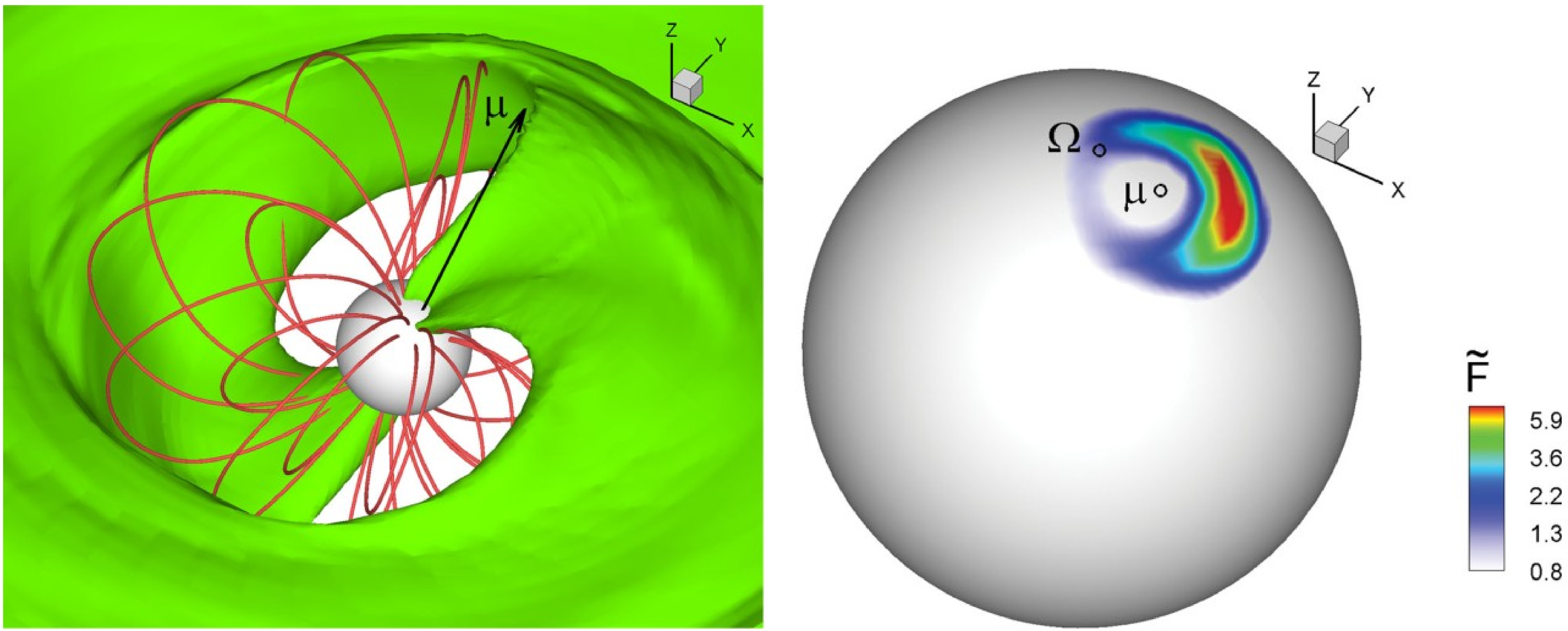
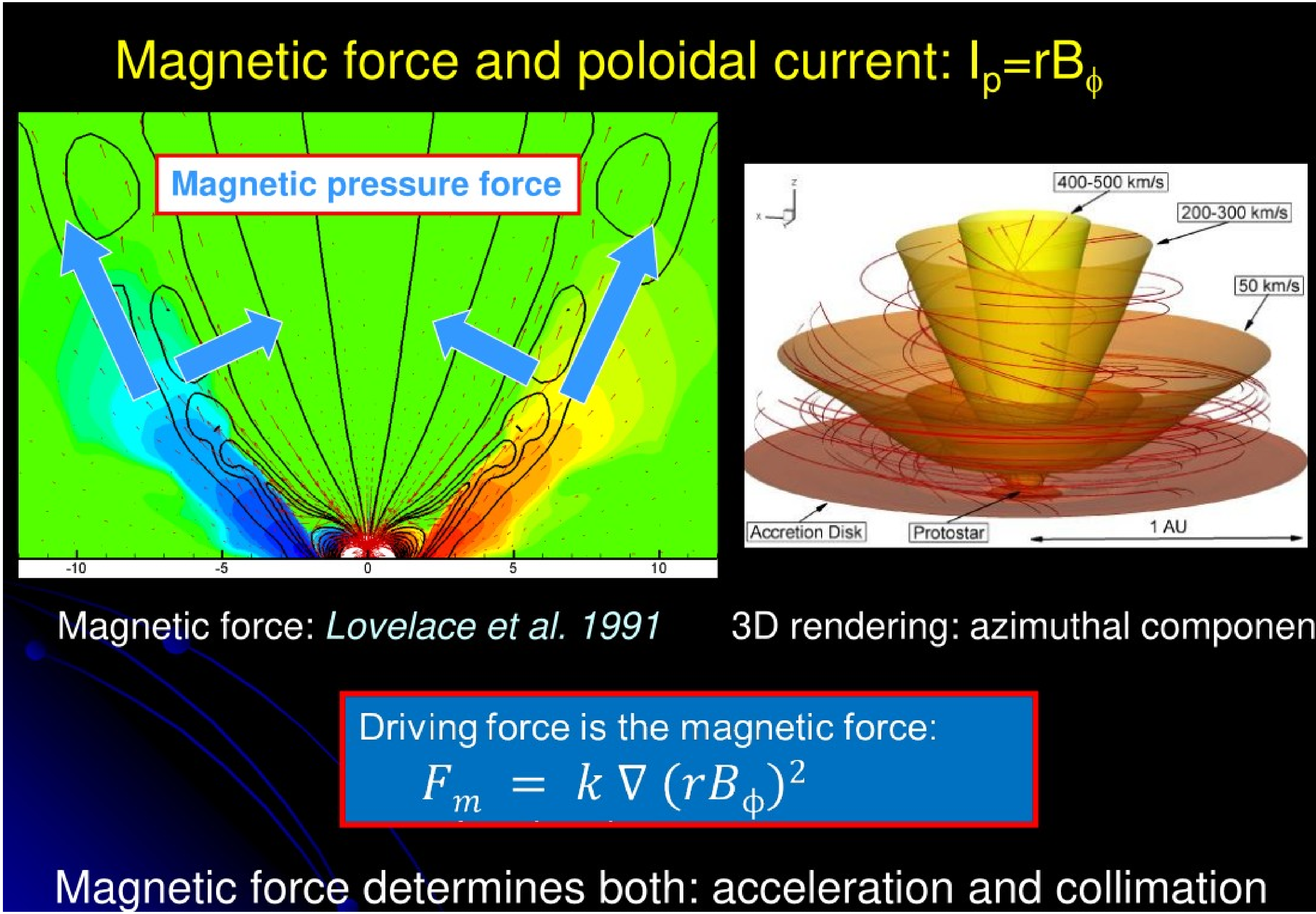


Figure 1. Left-hand panel: a 3D view of the funnel flow from the disc to a magnetized star, where the dipole moment μ is tilted by $\Theta = 20^\circ$ about the rotational axis. One of the density levels is shown in green; sample field lines are shown in red. Right-hand panel: the energy flux distribution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

Marina Romanova's group results

They also did a lot of good physics there:



A simple tool in PLUTO for complicated 3D MHD simulations

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

Meantime, in GR community simulations went far into 3D, while in star formation (YSOs) and white dwarfs we still lacked a simple setup capable of delivering similar simulations. I hoped that someone will provide it, but e.g. with PLUTO there was no such.

In 1998, in my first paper I had this non-spectacular drawing:

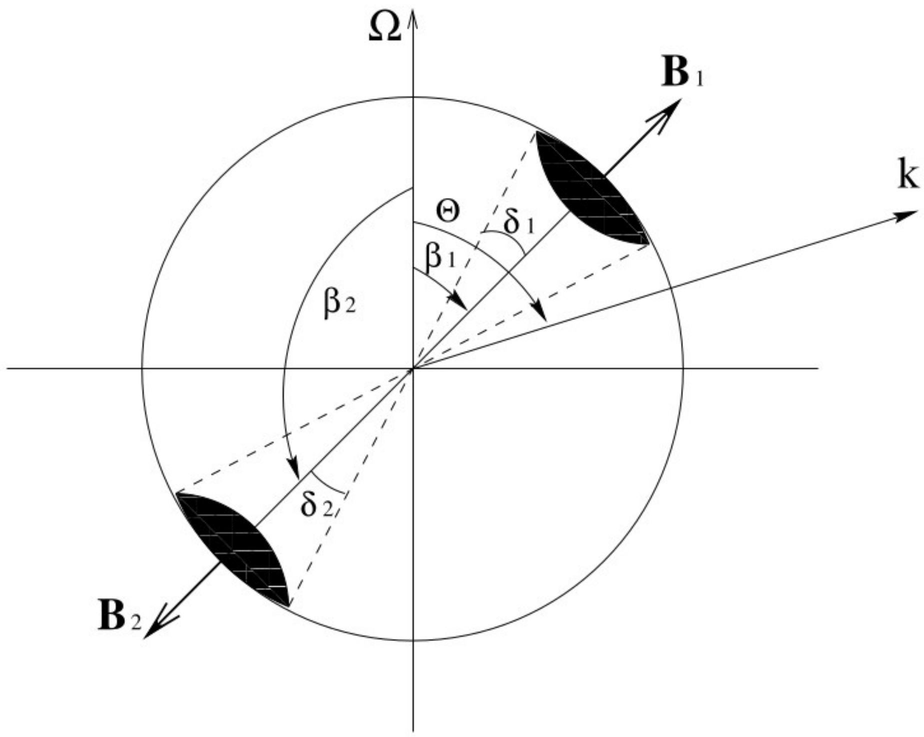
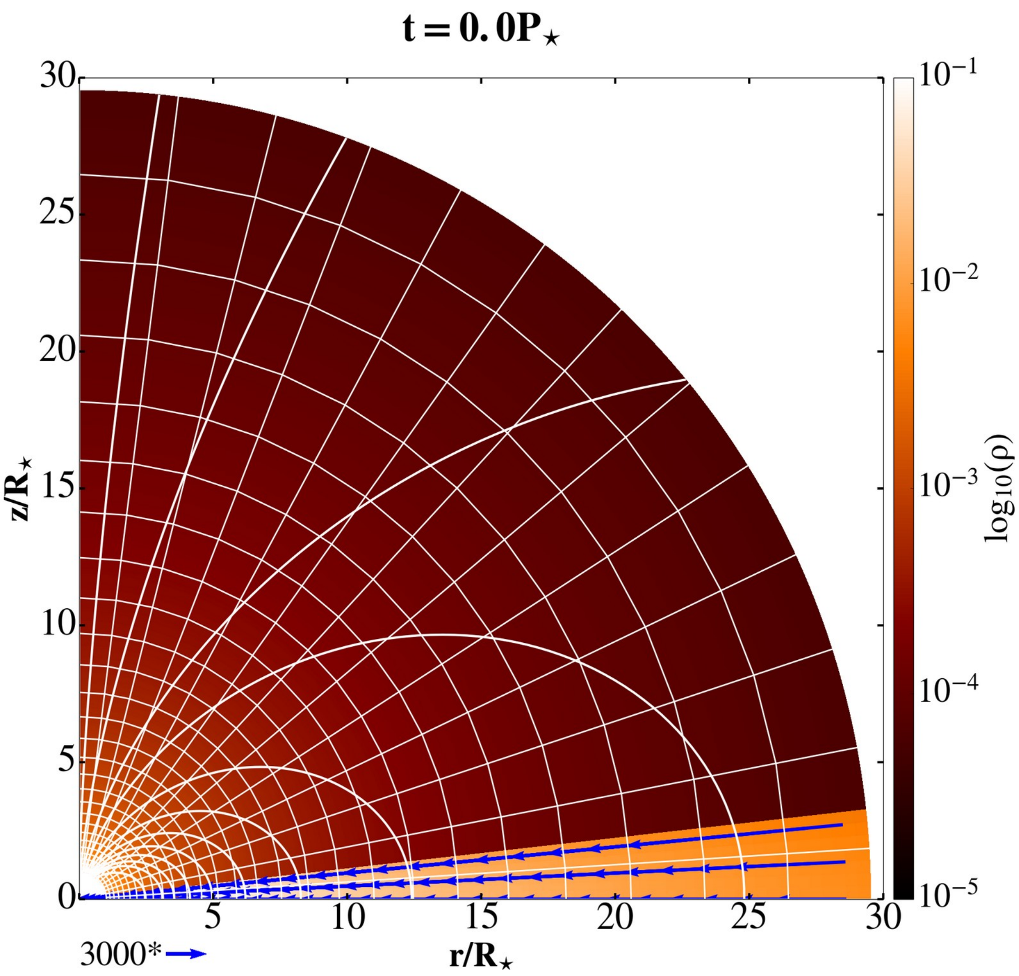
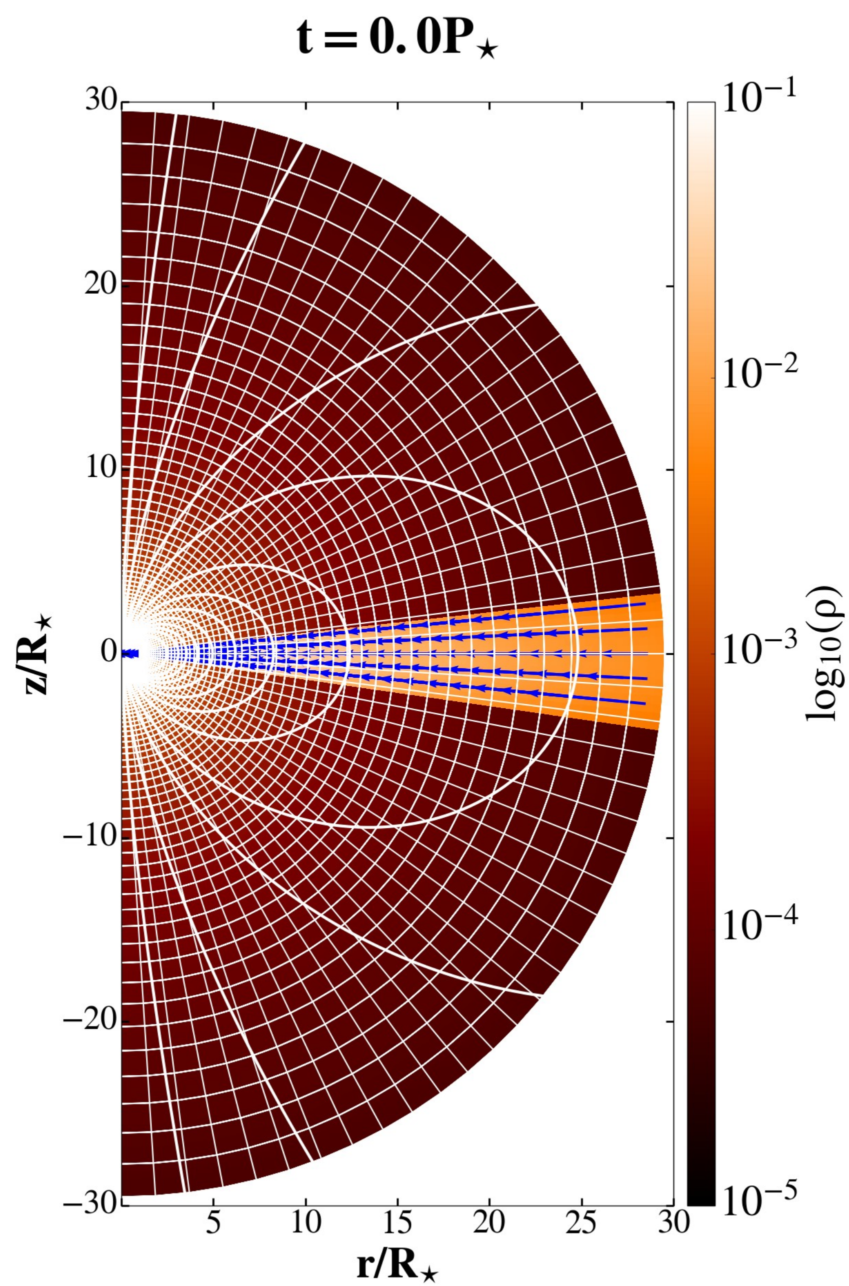


Fig. 1. Geometry of emission from a rotating neutron star.

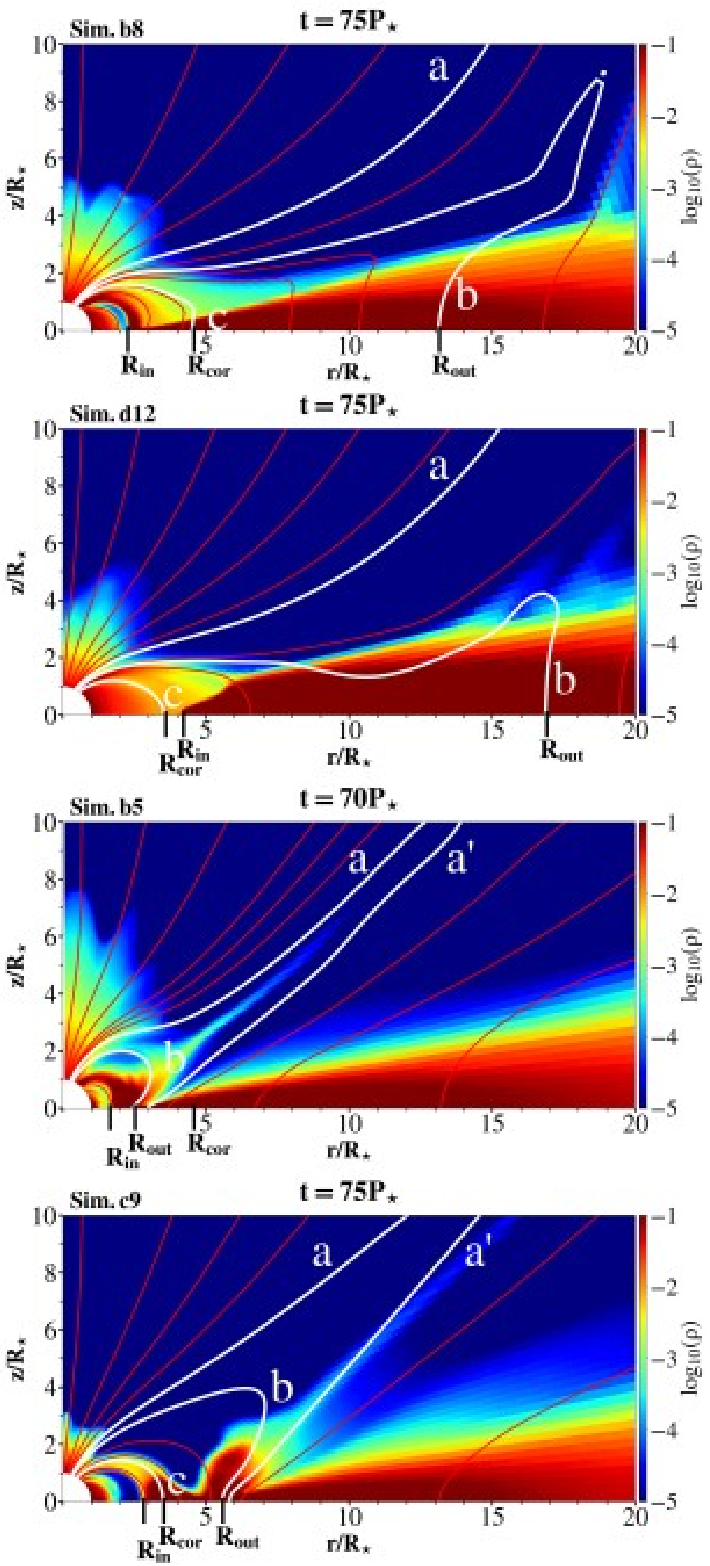
Then, like the rest of the community, for some years I was busy with parameter studies of YSOs and various other cases in 2.5 D setup-results of which I was presenting in previous ISSI meetings:

Star-disk simulations with magnetic field





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

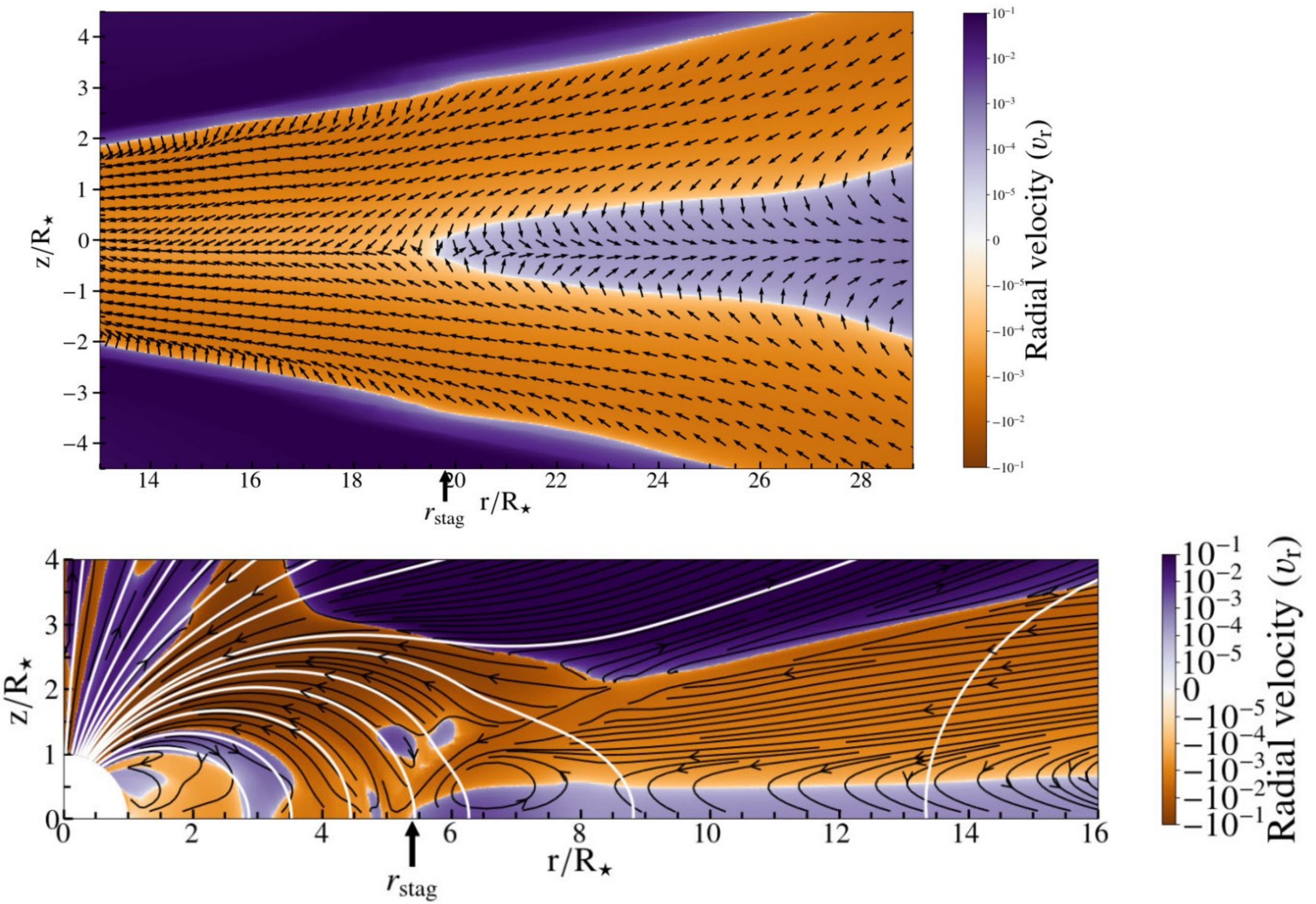


Configurations of solutions in “Atlas” paper

- 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.

Midplane backflow in thin accretion disk

4710 *R. Mishra, M. Čemeljić and W. Kluźniak*



We showed that in 2.5D setup a midplane backflow in thin accretion disk exists in both the HD and MHD simulations.

Light curve hiccups

1060 *M. Cemeljić and M. Siwak*

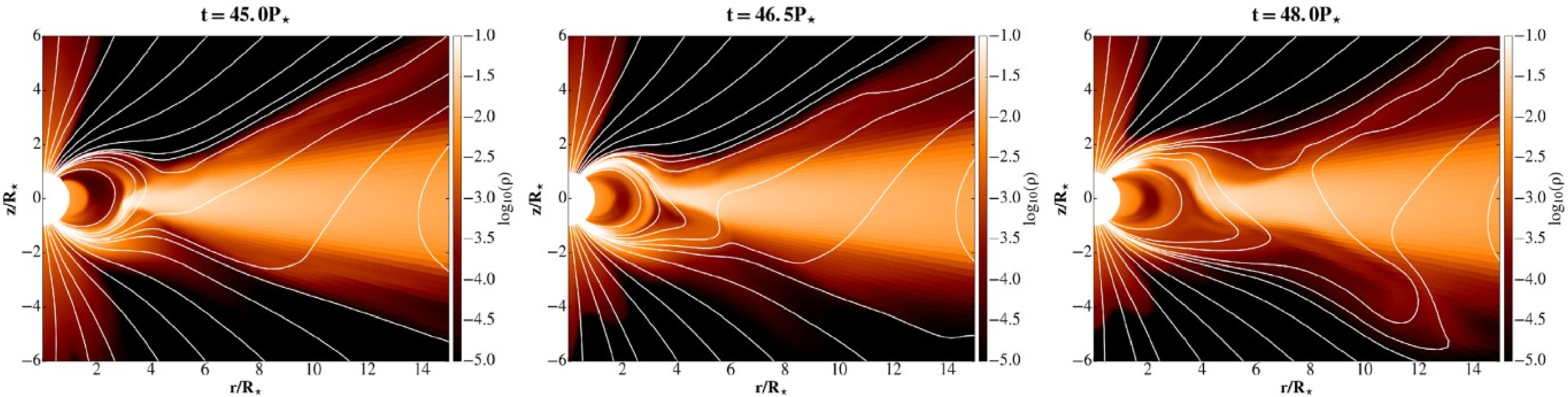
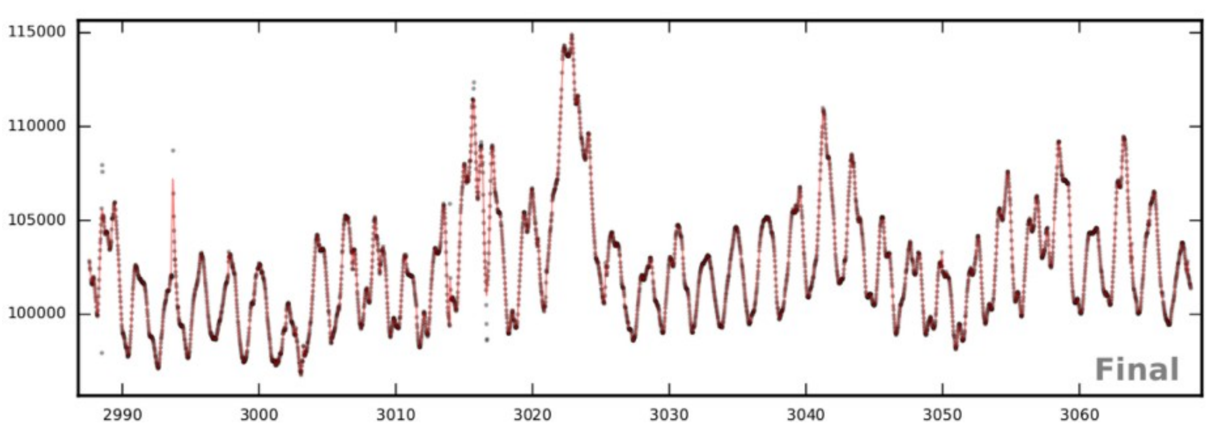
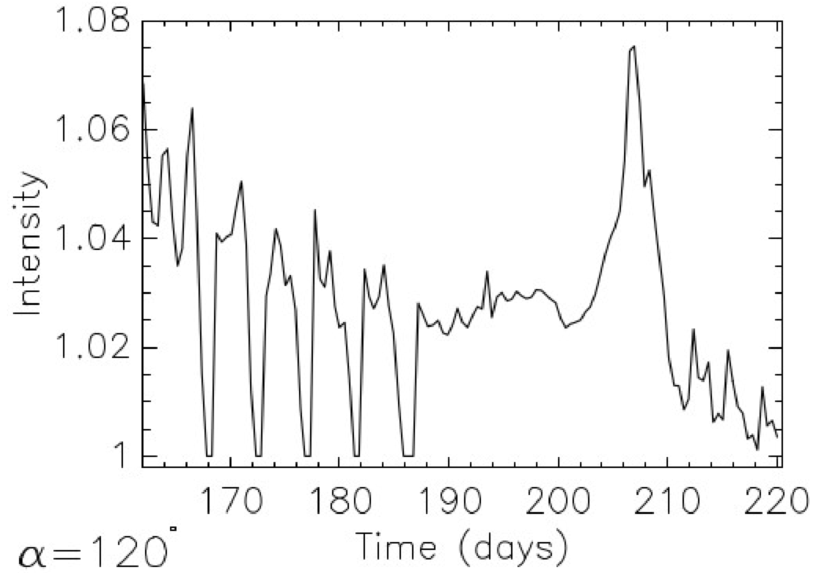
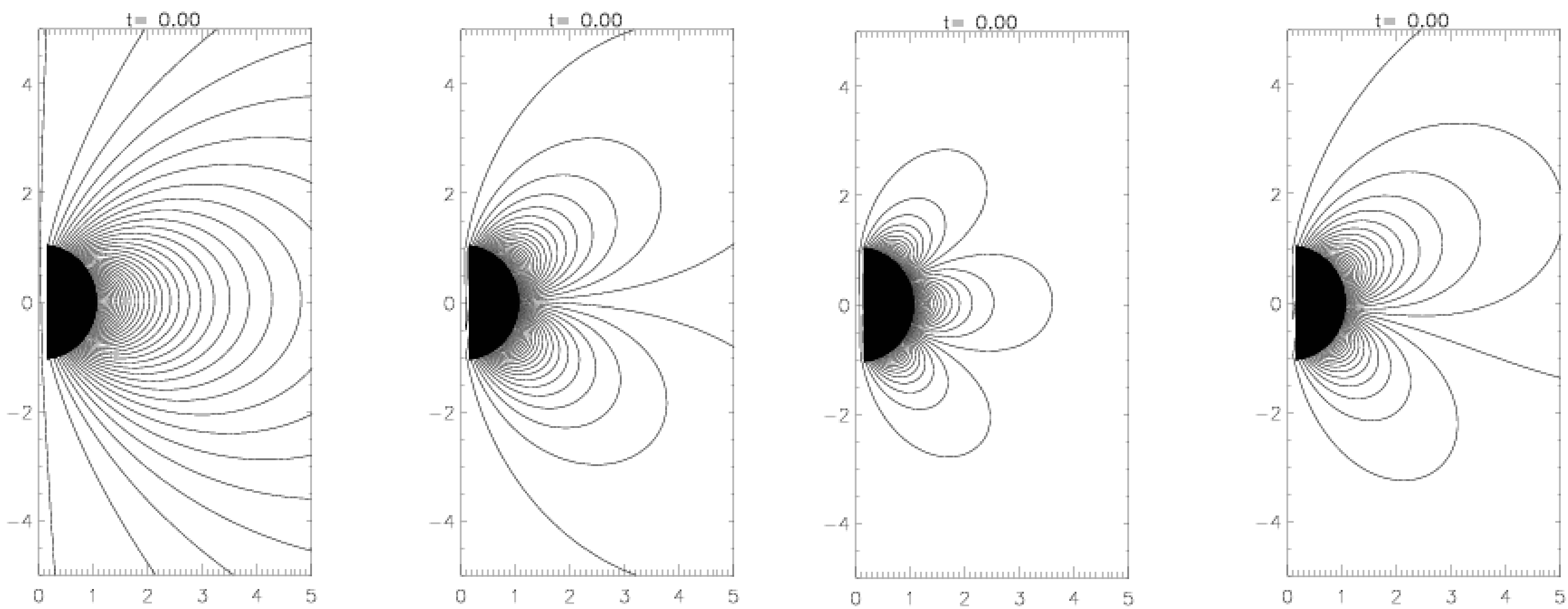


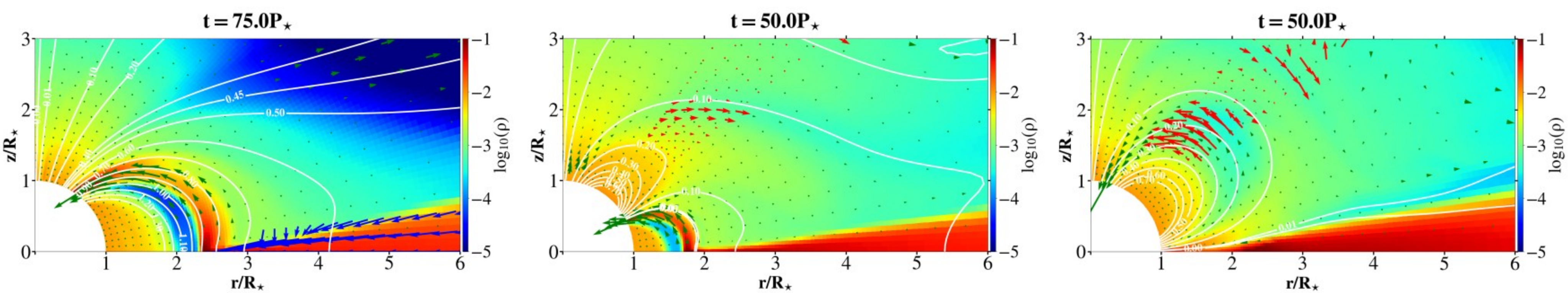
Figure 4. A sequence of snapshots from the results in the interval when switching of the accretion column from the Southern to the Northern hemisphere occurs.





Star-disk interaction with other geometries of the magnetic field



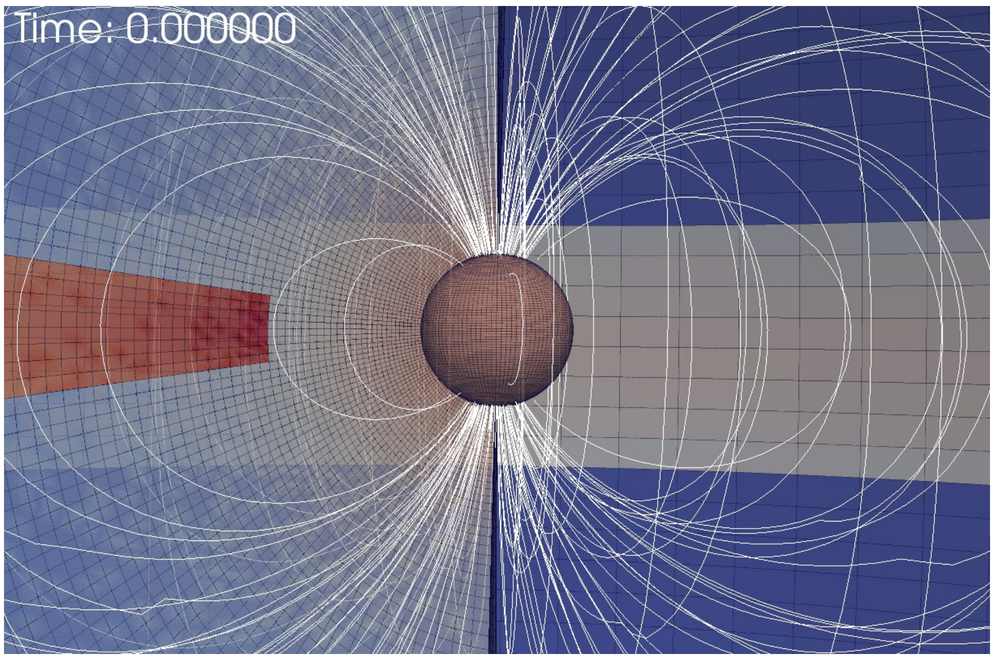


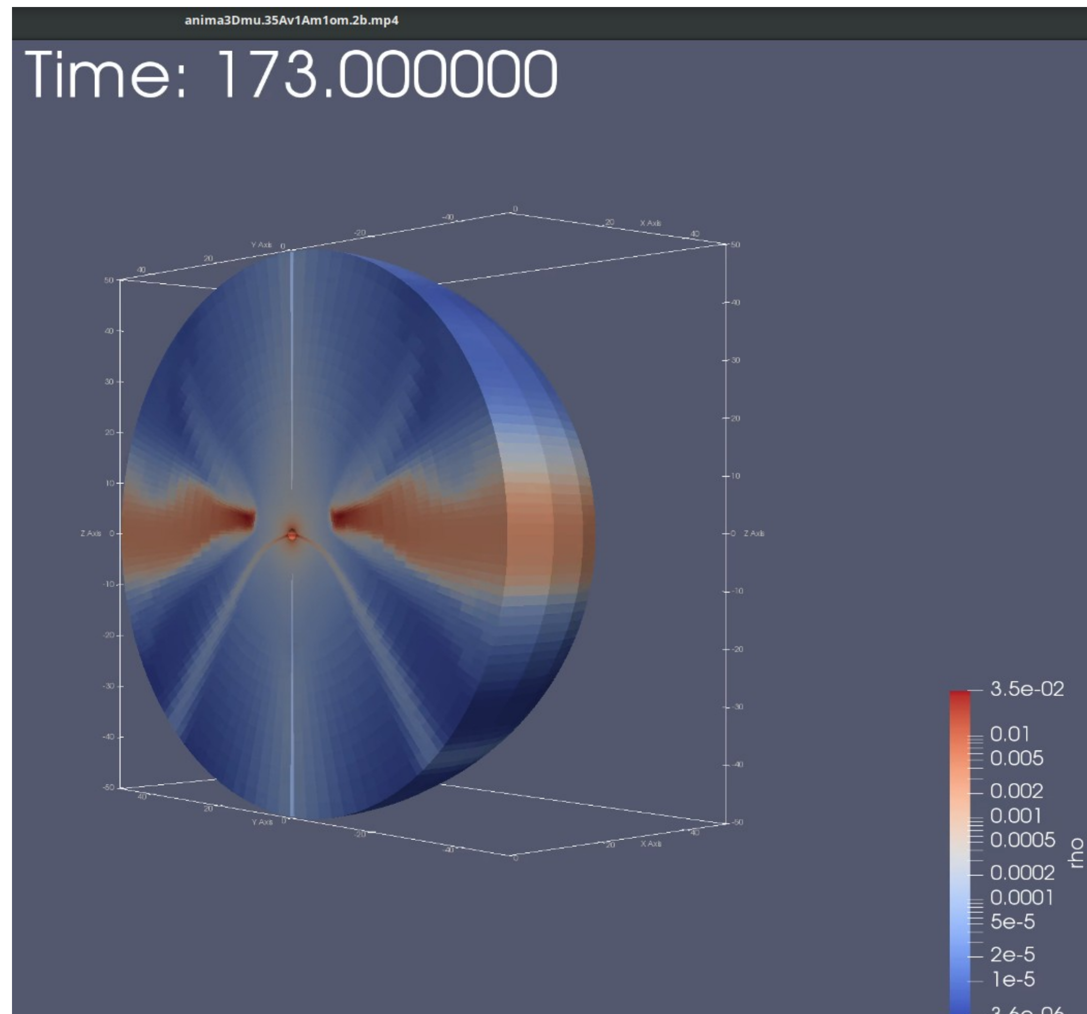
- In addition to the stellar dipole field,we also performed simulations with quadrupole, octupole and multipole fields.

- There were also some odd uses of the setup in its pseudo-Newtonian reincarnations in simulations with black holes and naked singularities.

3D simulations, case with magnetic field aligned with rotation

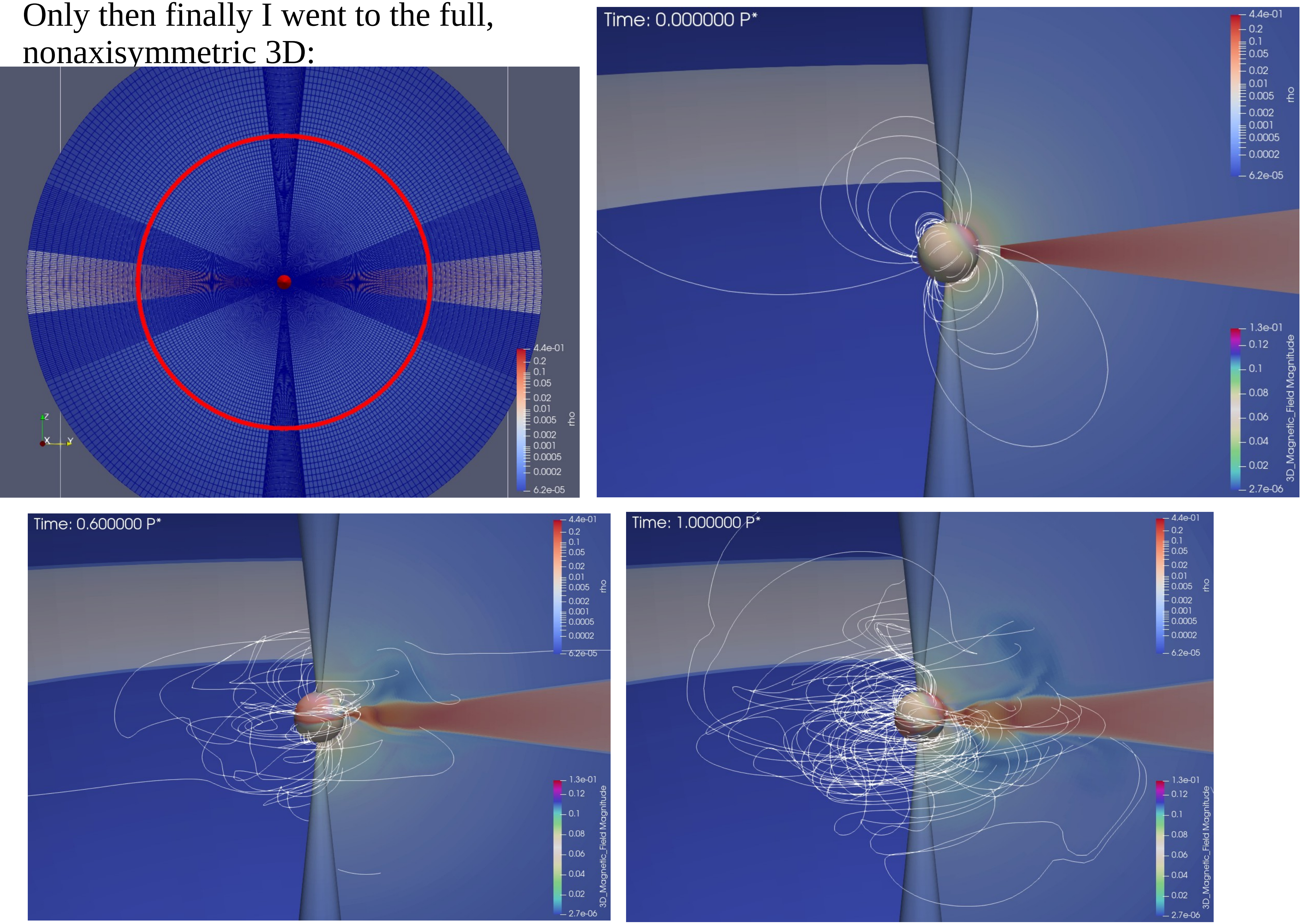
- The first step towards full 3D is to perform the axisymmetric 3D simulation. I used the spherical grid. The magnetic field in this case is aligned with the rotation axis.
- Zoom into the vicinity of the star=inner boundary condition at T=0 and at T=173 (2.5 stellar rotations) only, this setup runs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





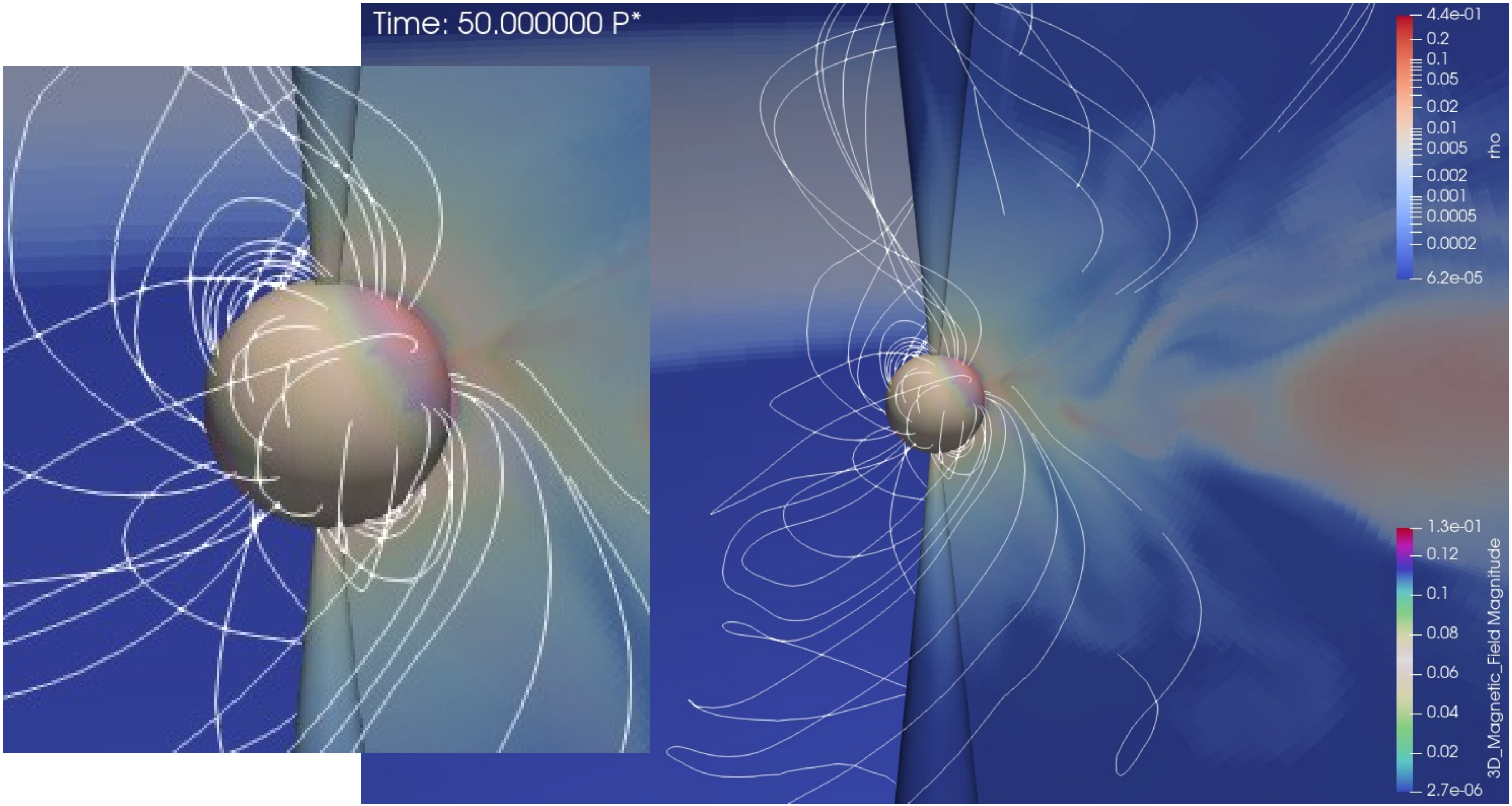
A simple tool in PLUTO for complicated 3D MHD simulations

Only then finally I went to the full, nonaxisymmetric 3D:



A simple tool in PLUTO for complicated 3D MHD simulations

After 50 stellar rotations with not too strong field (50 G for YSO, 8×10^{8} G for NS):



The 3D journey for star-disk simulations with PLUTO just started. As usual, I will put the setup to my webpage, feel free to use it.

Publications with ISSI #495 acknowledgement published/accepted up to now

A&A 678, A57 (2023)
https://doi.org/10.1051/0004-6361/202140637

Astronomy & Astrophysics

Magnetically threaded accretion disks in resistive magnetohydrodynamic simulations and asymptotic expansion

M. Čemeljić[1,2,3], W. Kluźniak[2,1], and V. Parthasarathy[4]

A&A 679, A16 (2023)
https://doi.org/10.1051/0004-6361/202243517

Astronomy & Astrophysics

Trends in torques acting on the star during a star-disk magnetospheric interaction

M. Čemeljić[1,2,3] and A. S. Brun[4]

The Astrophysical Journal Letters, 959:L13 (6pp), 2023 December 10
https://doi.org/10.3847/2041-8213/ad0f1f

Auroras on Planets around Pulsars

Ruchi Mishra[1], Miljenko Čemeljić[1,2,3], Jacobo Varela[4], and Maurizio Falanga[5,6]

The Astrophysical Journal, 981:69 (7pp), 2025 March 1
https://doi.org/10.3847/1538-4357/adb421

Pseudo-Newtonian Simulation of a Thin Accretion Disk Around a Reissner–Nordström Naked Singularity

Miljenko Čemeljić[1,2,3,4], Włodek Kluźniak[2], Ruchi Mishra[1,2], and Maciek Wielgus[5]
[1] Nicolaus Copernicus Superior School, College of Astronomy and Natural Sciences, Gregorkiewicza 3, 87-100, Toruń, Poland; miki@camk.edu.pl

ULX collimation by outflows in moderately magnetized neutron stars

Fatemeh Kayanikhoo[1,2], Włodek Kluźniak[1] and Miljenko Čemeljić[3,2,1,4]

Thank you!

Polish goodie with coffee today: Bird's milk

My Croatian island view in winter time.