# Relativistic low angular momentum accretion

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## Abstract

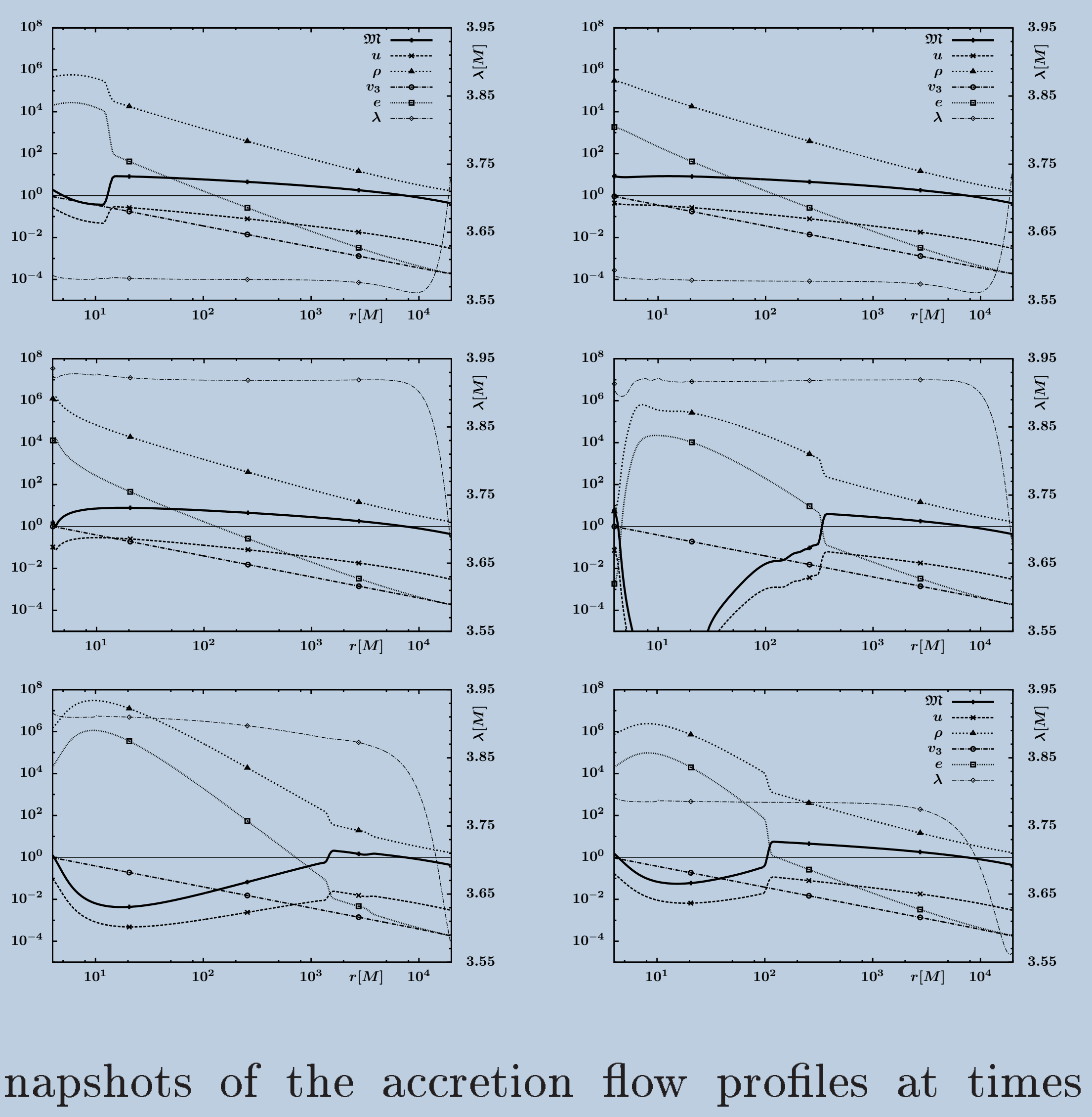
We study accretion of matter onto Schwarzschild or Kerr black hole using fully relativistic description with the presence of magnetic field, using the non-axisymmetric numerical simulations.

## Motivation

We focus on the interplay between the value of angular momentum and magnetic field strength, when driving the evolution of the flow. We also investigate the possible existence of standing shocks in such flows. Our computations are relevant in the case, when the sub-Keplerian component is important for explaining the properties of the accretion flow and at the same time non-negligible magnetic field interacts with the gas. Example of such system is e.g. the behavior of active galaxies. Magnetic field and its mutual interplay with strong gravity is critical for determining the structure of accretion flows in these objects. In particular, the interstellar magnetic field is present in the central region of the Milky way. In the diffuse intercloud medium, the observations indicate for the large-scale poloidal magnetic field, with the strength reaching $\sim 1mG$. Another physical set-up suitable for our computations are the microquasars, in which two component advective model together with Propagating Oscillatory Shock model was used for describing the evolution of the source and the frequency of its QPOs during outburst. The magnetic field initially coming from the companion star is likely to be amplified in the innermost region of the accretion flow due to compression of the magnetic field lines, thus playing important dynamical role in the accretion process.

## 1D Pseudonewtonian simulations

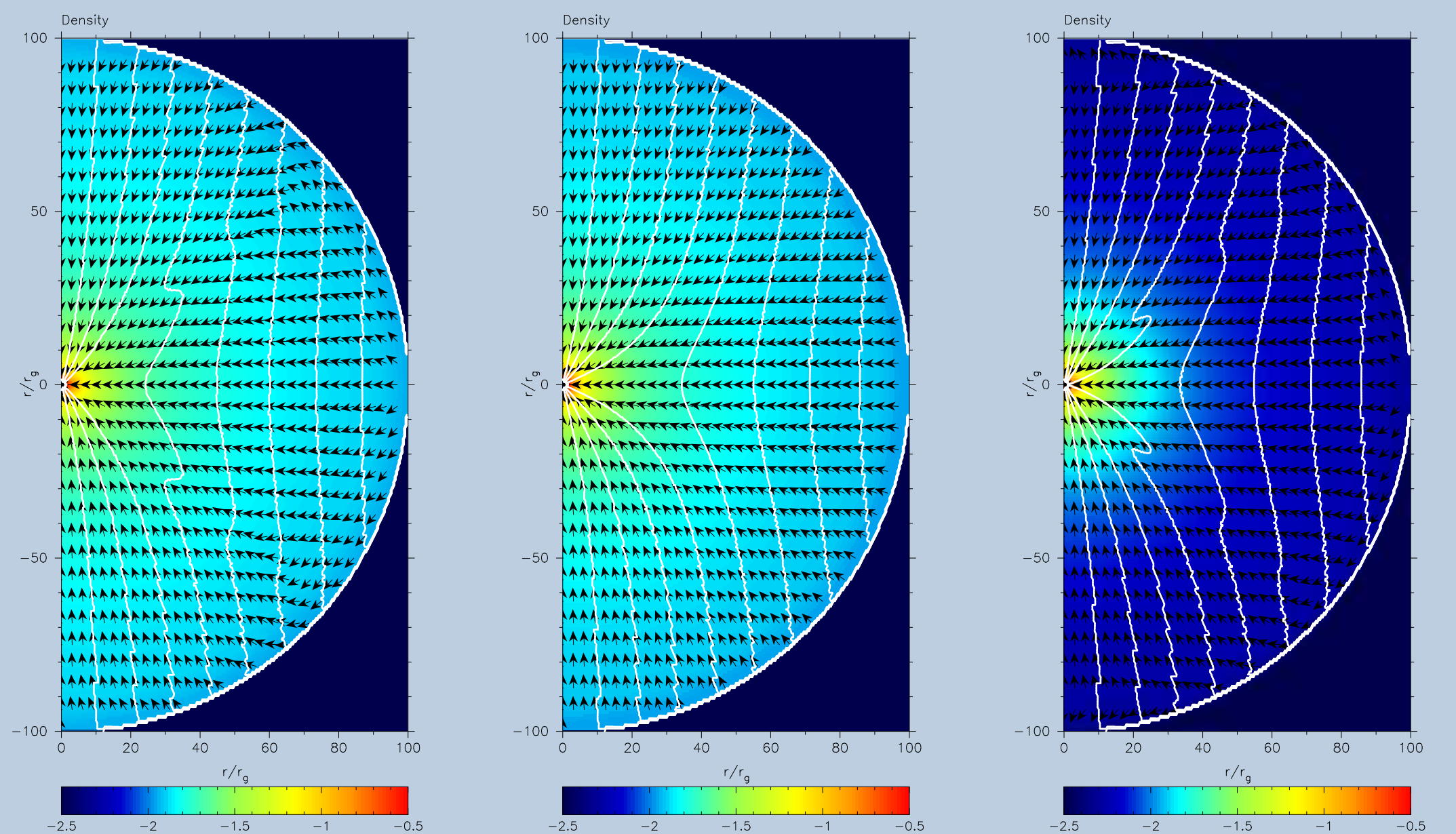
As a first step we carried out the 1D simulations of low angular momentum accretion of gas onto the Schwarszchild black hole described by the Paczynski-Wiita potential. The domain of these simulations spans over large radial distance with logarithmic grid spacing. The simulations have been run for long physical time up to hundred millions of M. We have found the shock solutions for certain subset in the parameter space. We also run simulations with the angular momentum of the incoming matter through the inner boundary changing periodically with time. In this case we observed repeated creation and disappearance of the shock front. During the evolution the density of gas in the innermost region, which emits the substantial fraction of the outgoing emission, has changed significantly.



Snapshots of the accretion flow profiles at times when the shock position is moving due to che changing angular momentum in the flow.

## Numerics 2D

For 2D simulations we use HARM code, which is conservative, shock-capturing scheme for evolving the equations of general relativistic magnetohydrodynamics [2]. Below we present three example results of HARM simulations with the presence of vertical magnetic field. In the first and third case the gas initially rotates. Snapshots are at $t = 88M$ showing 2-D density maps and velocity fields (normalized to 1), $\beta = 100$, $r_s = 8M$ (sonic radius) and $\dot{M} = 1$.

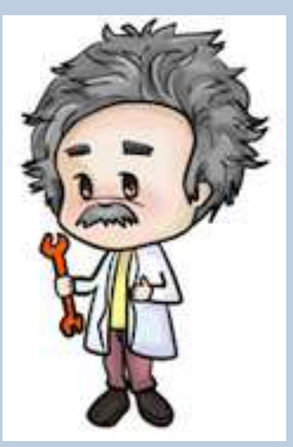


$\gamma = \frac{4}{3}$ with rotation

$\gamma = \frac{4}{3}$ no rotation

$\gamma = \frac{5}{3}$ with rotation

## Numerics 3D



For 3D simulations we use the **Einstein Toolkit** computational package [3]. The background spacetime is stationary Kerr solution. Currently unified rectangular 3D grid is used, but we plan to use refined grid in order ro resolve the region near the event horizon with better resolution. In case of nonrotating accretion initial conditions are set according to analytical Bondi solution. For low angular momentum accretion these conditions are modified by adding a nonzero $\phi$ component to the velocity of the gas in some confined region inside the computational domain (for some section of $\theta$ angles around the equatorial plane, and some interval of radii). The code generating rotating initial condition is still in development stage.

The evolution of the gas is simulated by the thorn called GRHydro delivered in Einstein Toolkit. It is a fully relativistic code for magnetohydrodynamics equipped with shock-capturing routines.

It solves the evolution equation $\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}^i}{\partial x^i} = \mathbf{S}$, where

$$\mathbf{F}^i = \alpha \begin{bmatrix} D\tilde{v}^i \\ S_j \tilde{v}^i + \sqrt{\gamma} P^* \delta^i_j - b_j \mathcal{B}/W \\ \tau \tilde{v}^i + \sqrt{\gamma} P^* v^i - \alpha b^0 \mathcal{B}^i / W \\ \mathcal{B}^k \tilde{v}^i - \mathcal{B}^i \tilde{v}^k \end{bmatrix},$$

$$\mathbf{S} = \alpha\sqrt{\gamma} \begin{bmatrix} 0 \\ T^{\mu\nu}\left(\frac{\partial g_{\nu j}}{\partial x^\mu} - \Gamma^\lambda_{\mu\nu} g_{\lambda j}\right) \\ \alpha\left(T^{\mu 0}\frac{\partial \ln \alpha}{\partial x^\mu} - T^{\mu\nu}\Gamma^0_{\mu\nu}\right) \\ 0 \end{bmatrix}$$

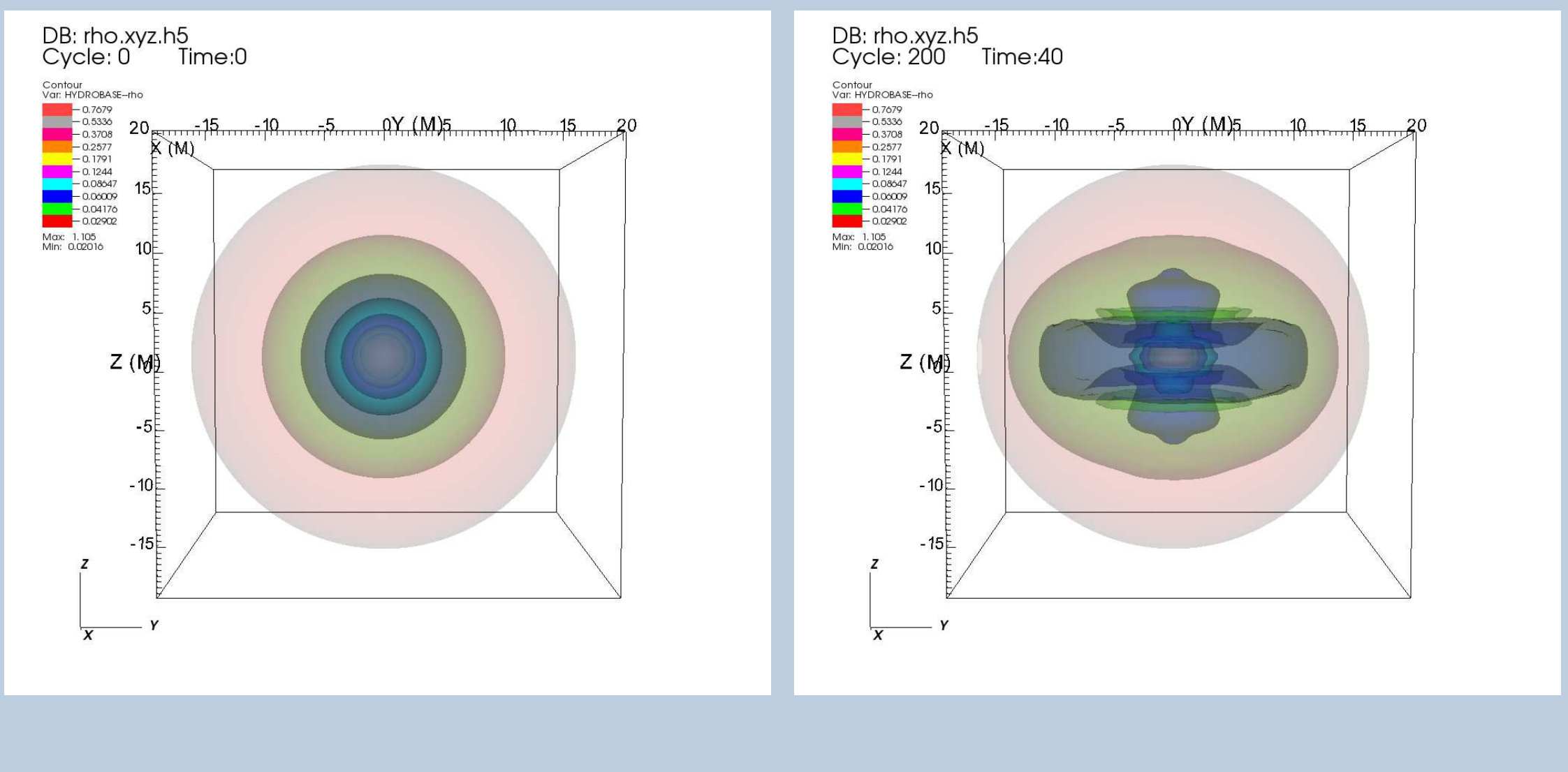
and $\mathbf{U} = \left[D, S_j, \tau, \mathcal{B}^k\right]$ are the conserved variables defined in terms of the primitive variables by

$$D = \sqrt{\gamma}\rho W, \quad S_j = \sqrt{\gamma}\left(\rho h^* W^2 v_j - \alpha b^0 b_j\right),$$

$$\mathcal{B}^k = \sqrt{\gamma} B^k, \quad \tau = \sqrt{\gamma}\left(\rho h^* W^2 - P^* - (\alpha b^0)^2\right) - D,$$

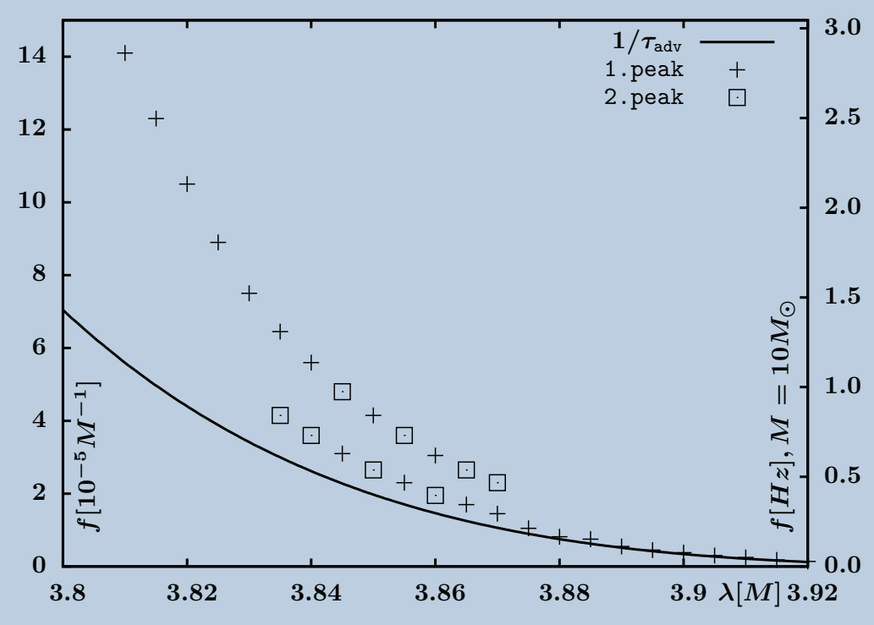
where $h^* = 1 + \epsilon + (P + b^2)$ is modified enthalpy and $W$ is Lorentz factor.

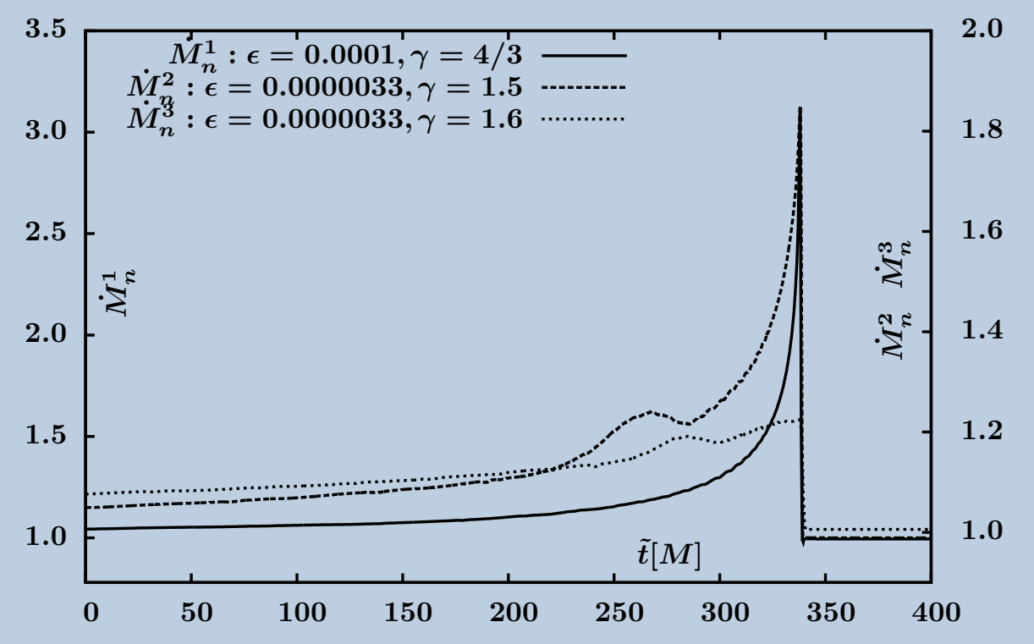
Fully relativistic 3D simulations are in preliminary stage. Here we present the plot of density of matter at initial state of simulation and evolved state of the gas inside the cubic computational domain.



## Discussion

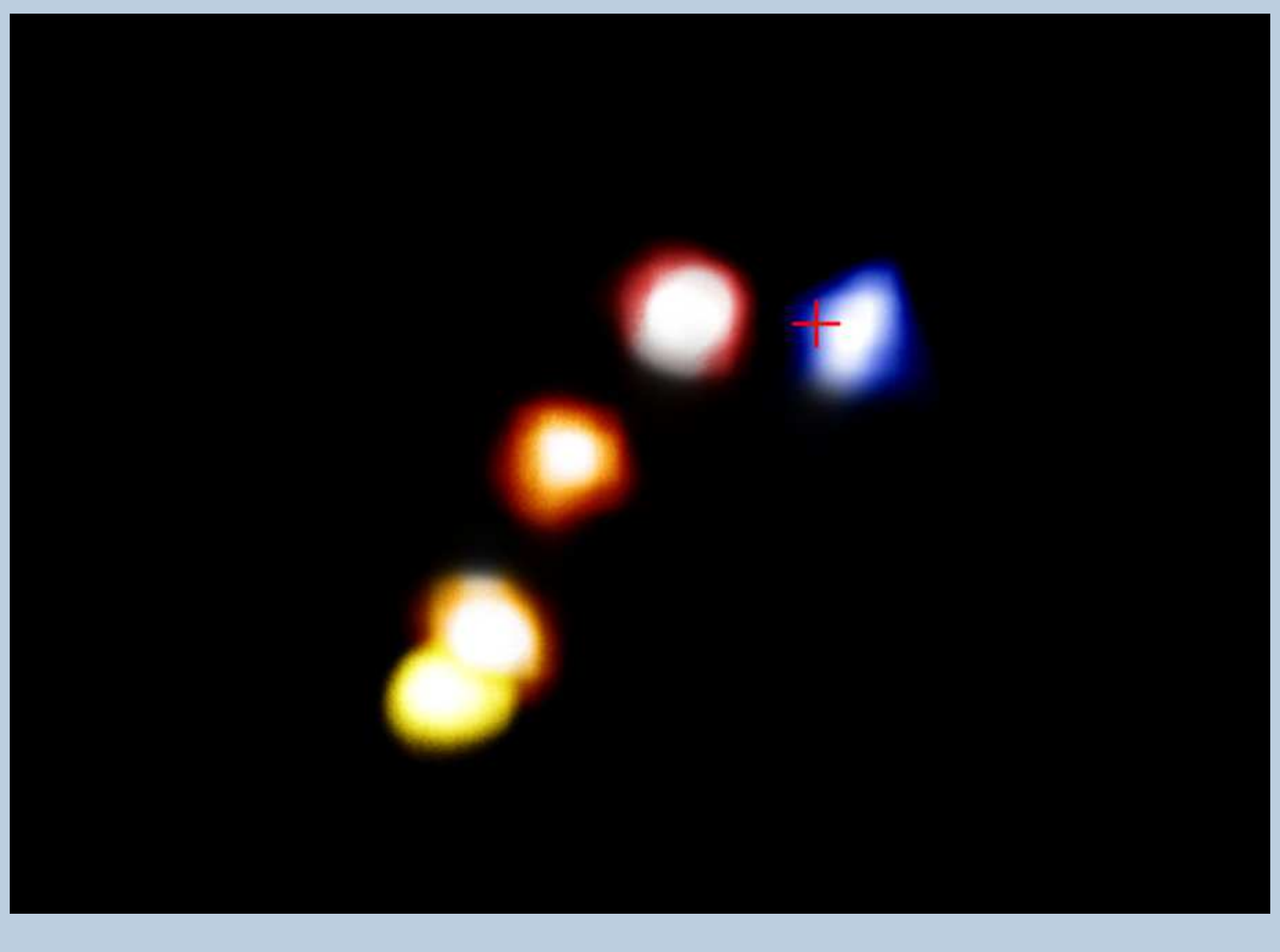
We have carried out simulations of one-dimensional hydrodynamical model of shocked quasi-spherical accretion flow, which confirm the shape of the steady solution and also the dependence of this solution on the leading parameters (angular momentum $\lambda$, energy $\epsilon$ and adiabatic index $\gamma$). The simulations yield the shock front unstable for a subset of parameters which leads to oscillation of the shock front around the position given by the steady solution with frequency depending on the distance to the center [1], which is in turn dependent on the value of angular momentum (see left figure). We expect, that the shock position and frequency of oscillations will be influenced by the magnetic field. Since the shock front is thought to be the source of radiation, this mechanism could be connected with the QPOs with evolving frequency reported from several microquasars (e.g. GX 339-4 [4] or XTE J1550-564 [5]).





Moreover, we also show the evolution of the flow with changing angular momentum and reported the repeating creation and disappearance of the shock front due to the hysteresis loop. We found out, that the disappearance of the shock is connected with peak in accretion rate onto the center, which timescale is given only by the last stable shock position given by the energy $\epsilon$ and adiabatic index $\gamma$ and most probably also by the strength of the magnetic field. The time scale of these peaks is in good agreement with the measured Sgr A* flares, ranging between $50M \sim 1000s$ to $250M \sim 5300s$ (see right figure ). Because of the very slow rise at the beginning of the peak, the moment when such increase could be observable depends also on other processes in the accretion region.

Observations of interstellar magnetic field present at the Galactic central region indicate for a large scale poloidal field, with a value close to $\sim 10\mu G$ on average, and reaching $\sim 1mG$ in dense clouds and localized filaments. The light curves of the flares observed from Galaxy center show quasi-periodic behavior caused by the orbital motion of hot gas near the last circular orbit around the supermassive black hole.



This composite image from ESO shows the motion of the dusty cloud G2 as it closes in on, and then passes, the supermassive black hole at the centre of the Milky Way.

## Bibliography

[1] P. Suková, A. Janiuk, *MNRAS* 2015 Vol. 447 1565-1579

[2] Gammie, Charles F.; McKinney, Jonathan C.; Tóth, Gábor, *The Astrophysical Journal*, Vol. 589, Issue 1, pp. 444-457

[3] http://www.einsteintoolkit.org
Löffler et al., Classical and Quantum Gravity 11, vol. 29, 2012

[4] A. Nandi, D. Debnath, S. Mandal, S. K. Chakrabarti A&A, 2012, vol. 542

[5] Chakrabarti, Sandip, Dutta, Broja, Pal, MNRAS 2009, vol. 394

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