General relativity M-hydrodynamics code GR-AMRVAC

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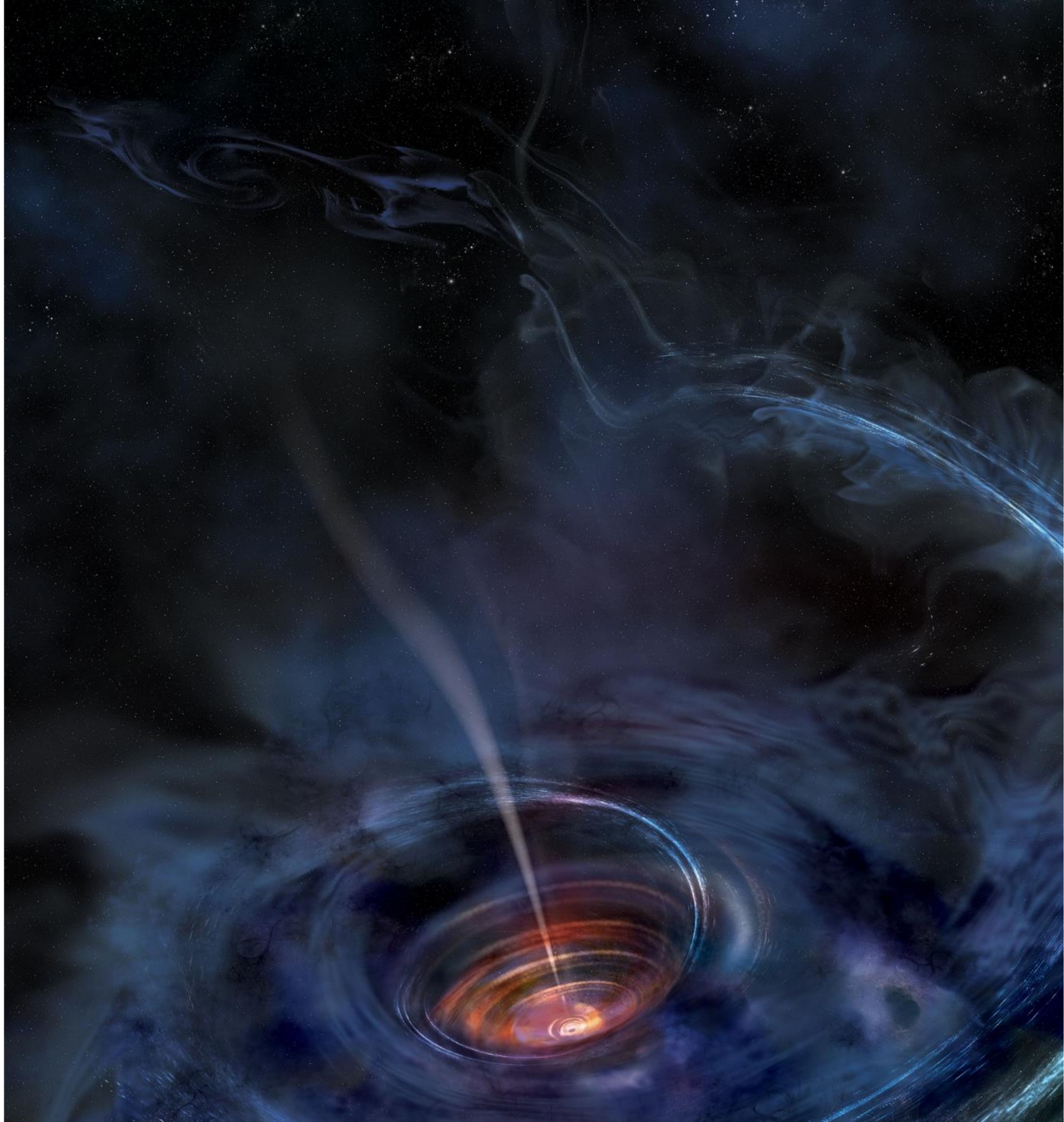
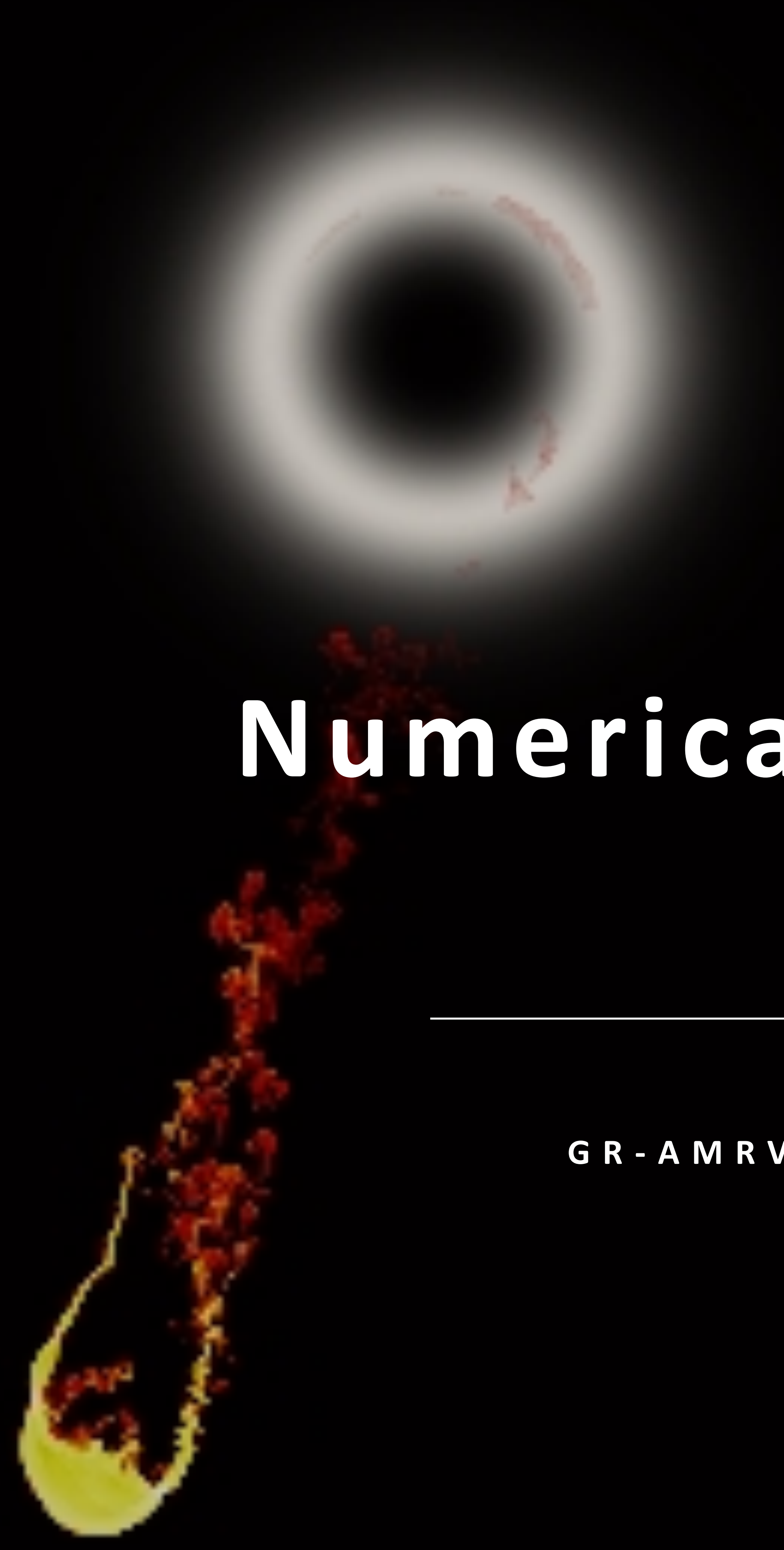
Outline

- Introduction
- Numerical tools
- Accretion disc
- Conclusions
- Projects



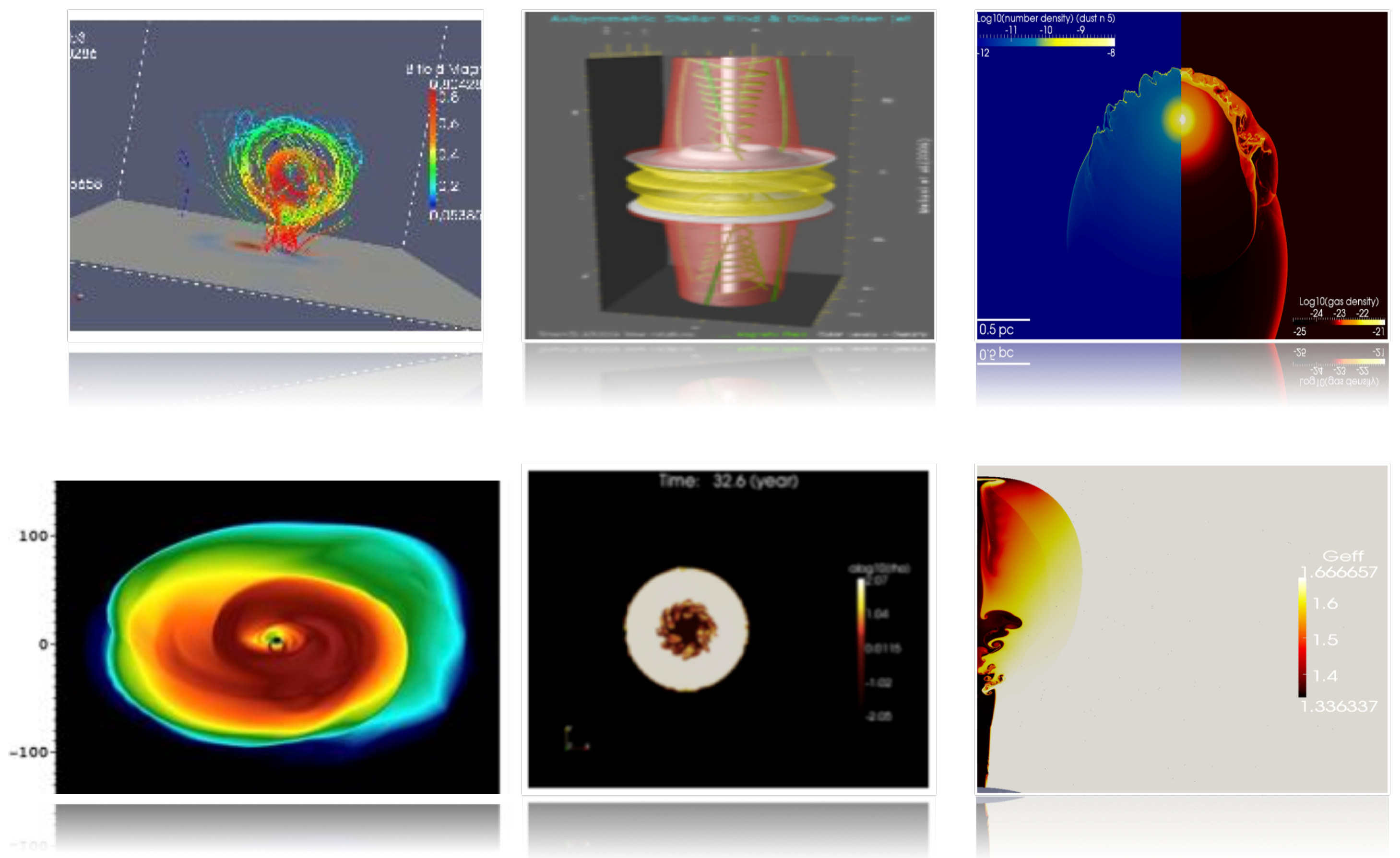


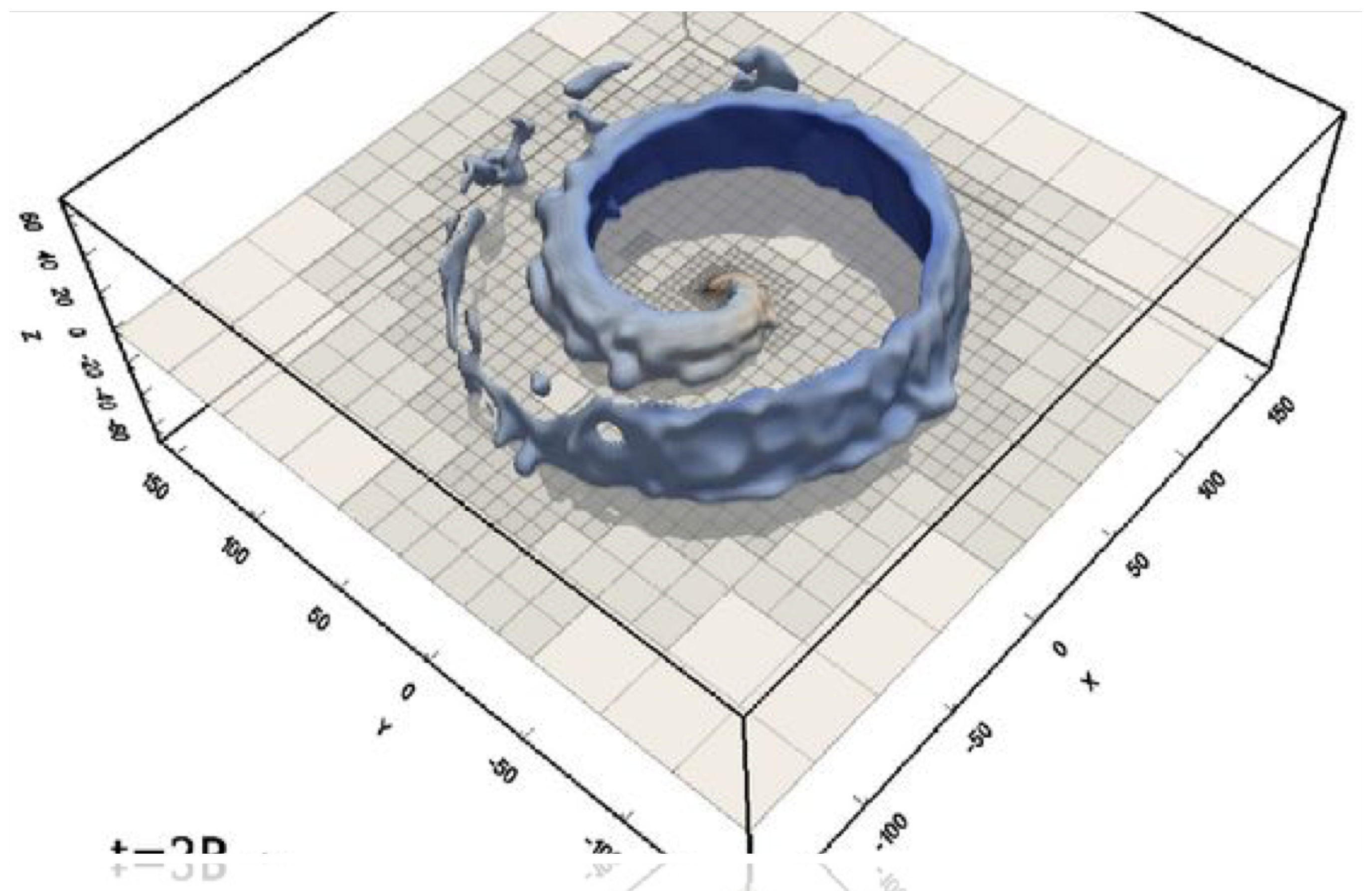
Numerical tools

GR-AMRVAC

Numerical tools

GR-AMRVAC code





Multi-physics

Hydrodynamic, magneto-hydrodynamic, special relativistic HD and MHD, General relativistic HD and MHD.

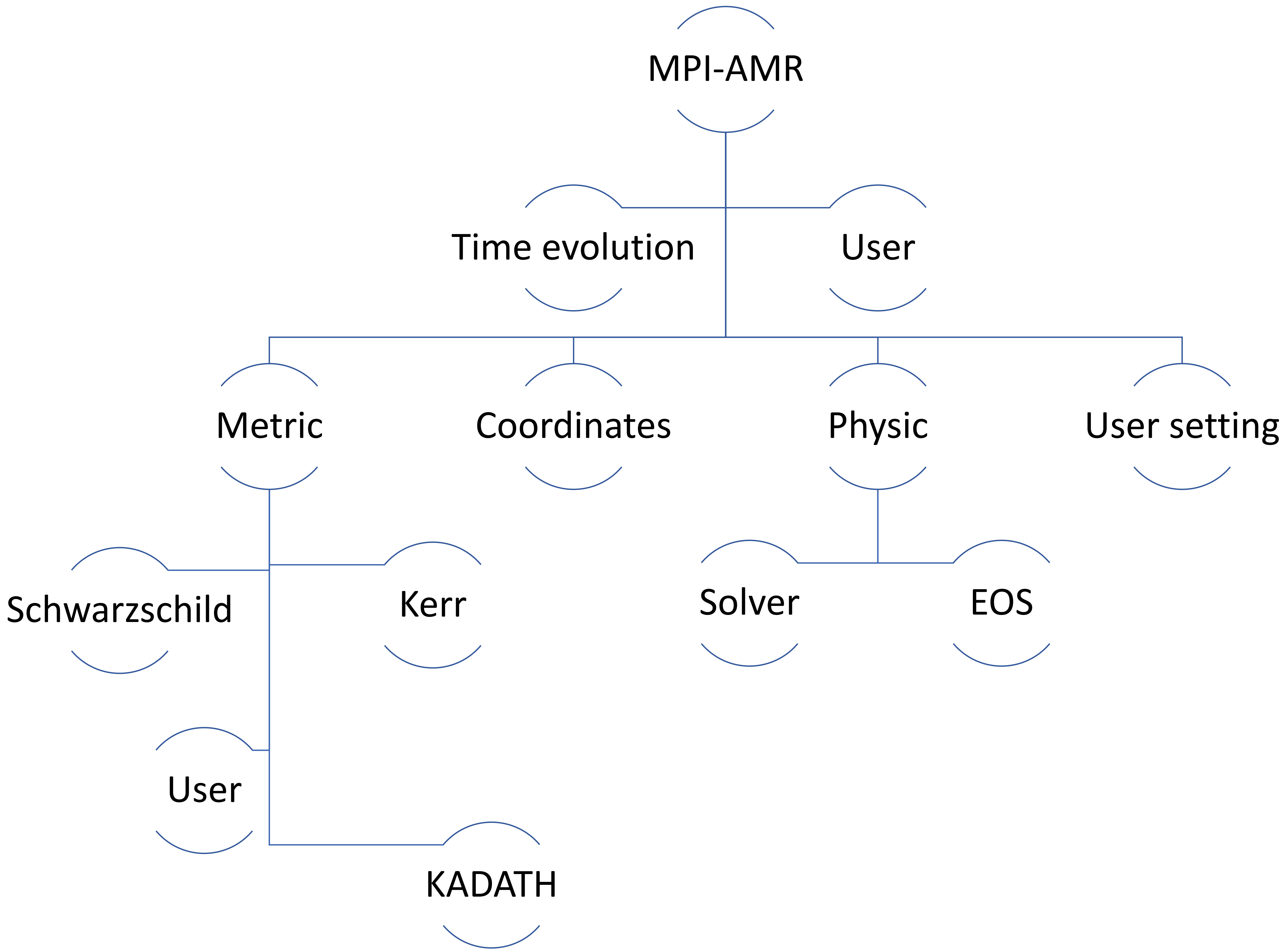
Adaptive Mesh refinement

Bloc-tree

Parallel

MPI parallelisation

Code structure



Equations

Equation of motion + Maxwell equations + Equation of state

Covariant approach

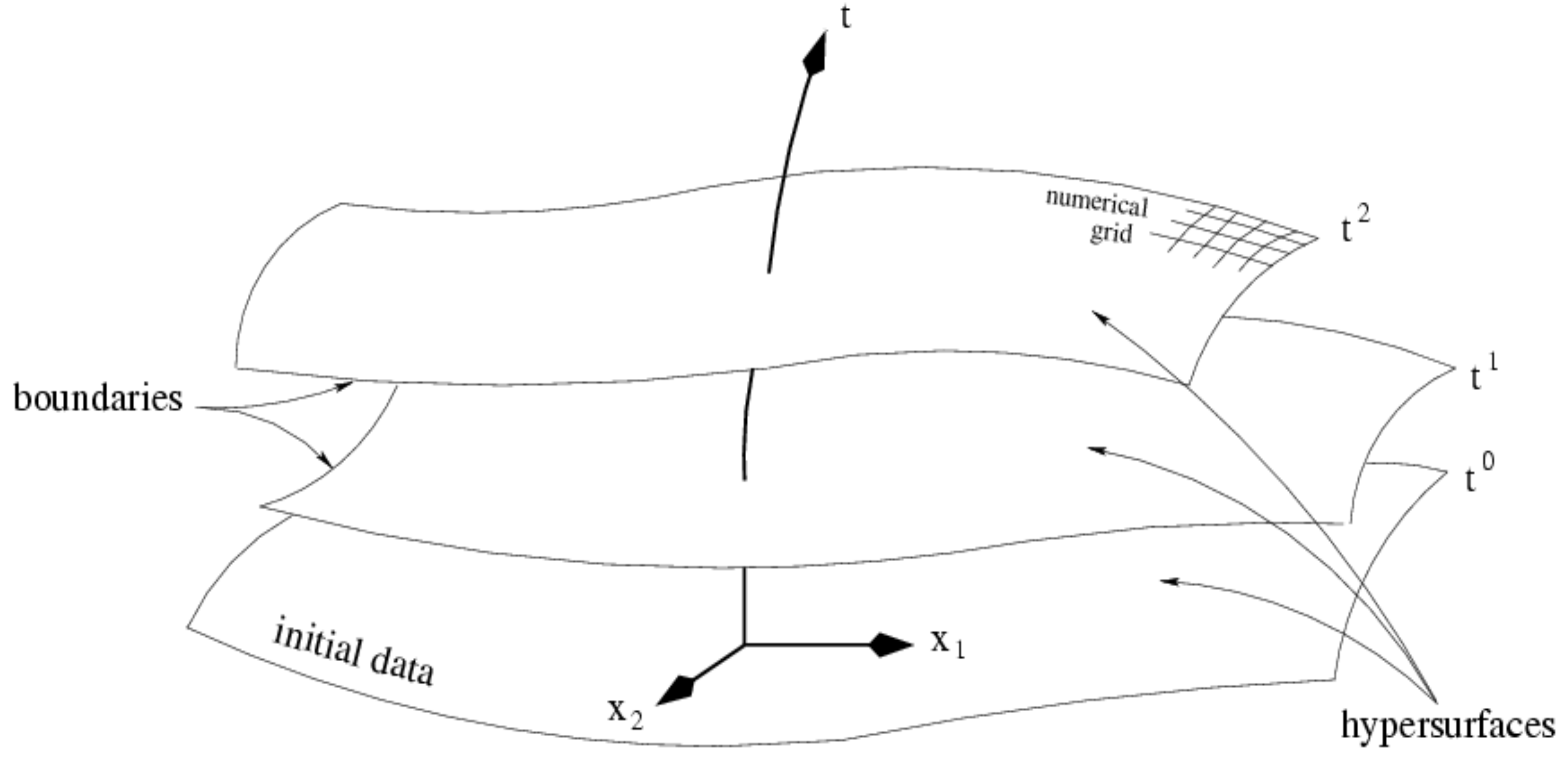
- $\nabla_\mu(\rho\, u^\mu) = 0$
- $\nabla_\mu(T^{\mu\nu}) = 0$
- $\nabla_\mu(F^{*\mu\nu}) = 0$
- $p = p(\rho, \varepsilon)$

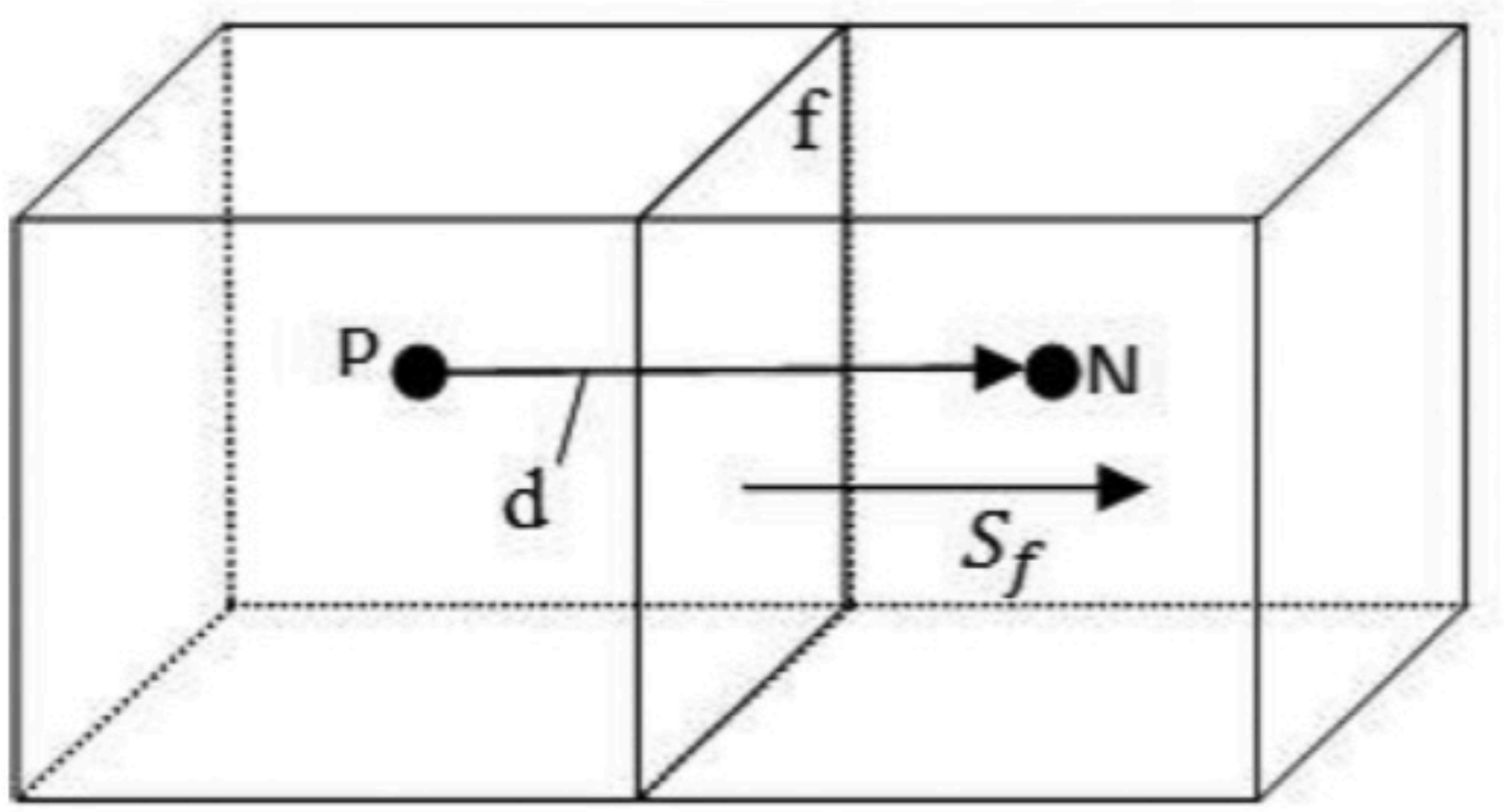
3+1 formulation

- $\frac{\partial}{\partial x^\mu}\left(\sqrt{-g}\rho\, u^\mu\right) = 0$
- $\frac{\partial}{\partial x^\mu}\left(\sqrt{-g}\, T^{\mu\nu}\right) = \sqrt{-g}\, \Gamma^\nu_{\mu\lambda} T^{\mu\lambda}$
- $\frac{\partial}{\partial x^\mu}\left(\sqrt{-g}\, F^{*\mu\nu}\right) = 0$
- $p = p(\rho, \varepsilon)$

- Martí, Ibáñez & Miralles (1991): 1+1, general EOS
- Eulderink & Mellema (1995): covariant, perfect fluid
- Banyuls et al (1997): 3+1, general EOS

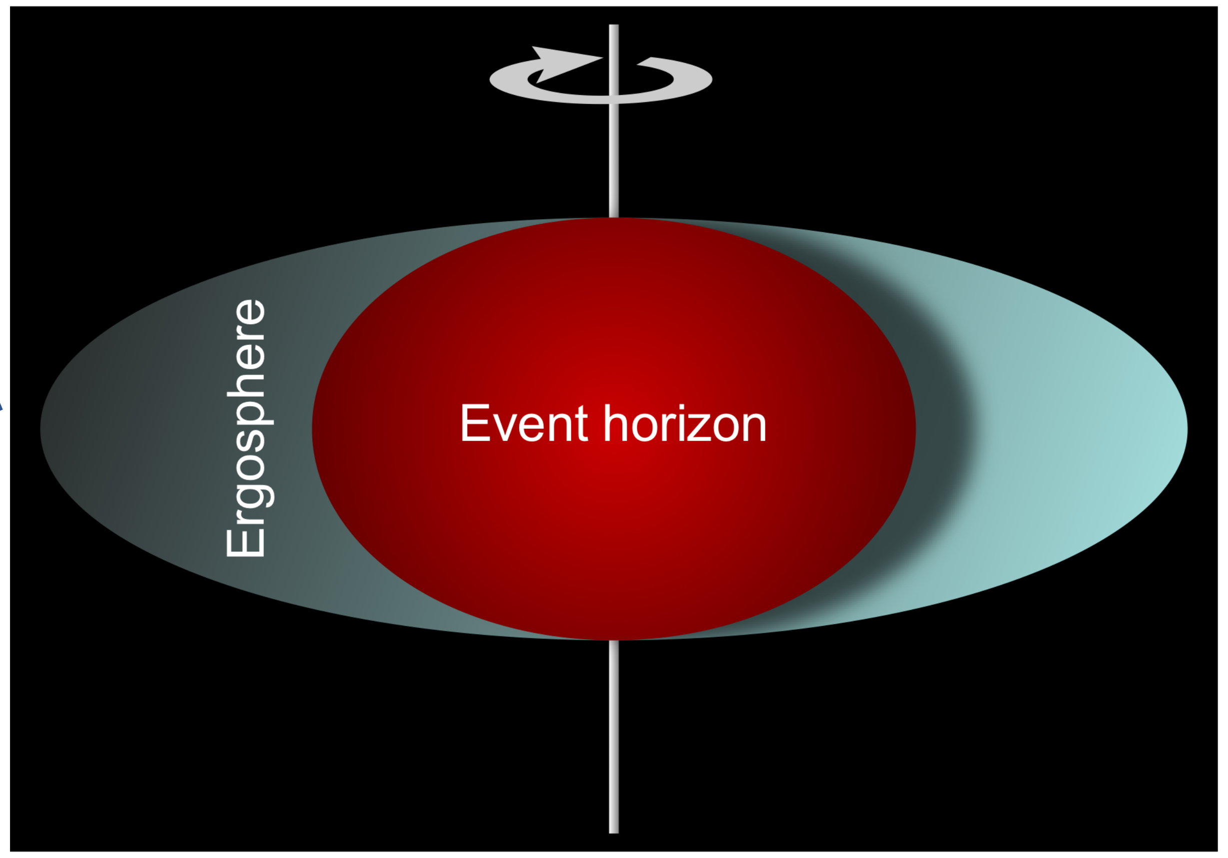
Foliate the spacetime with *t=const*



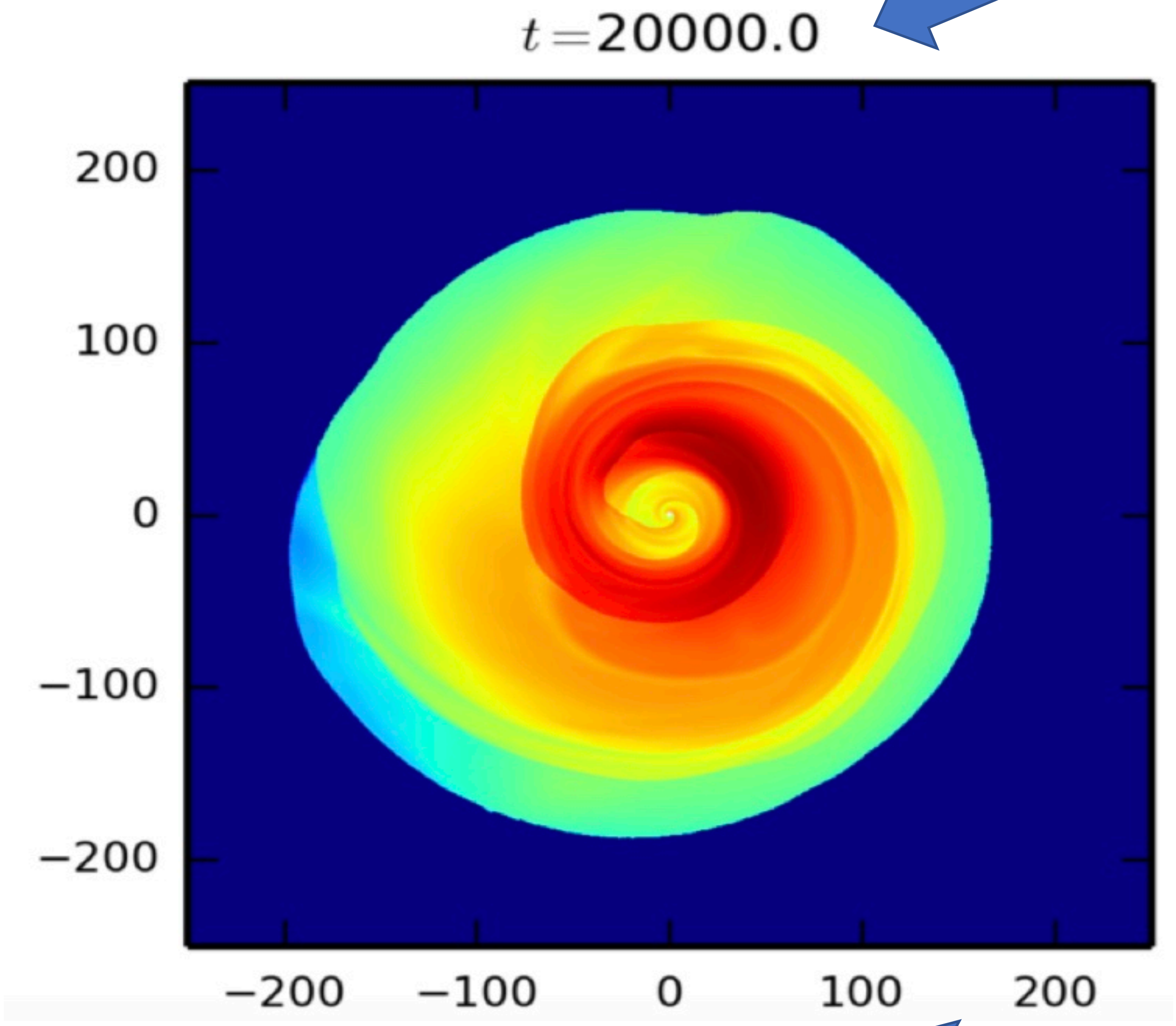


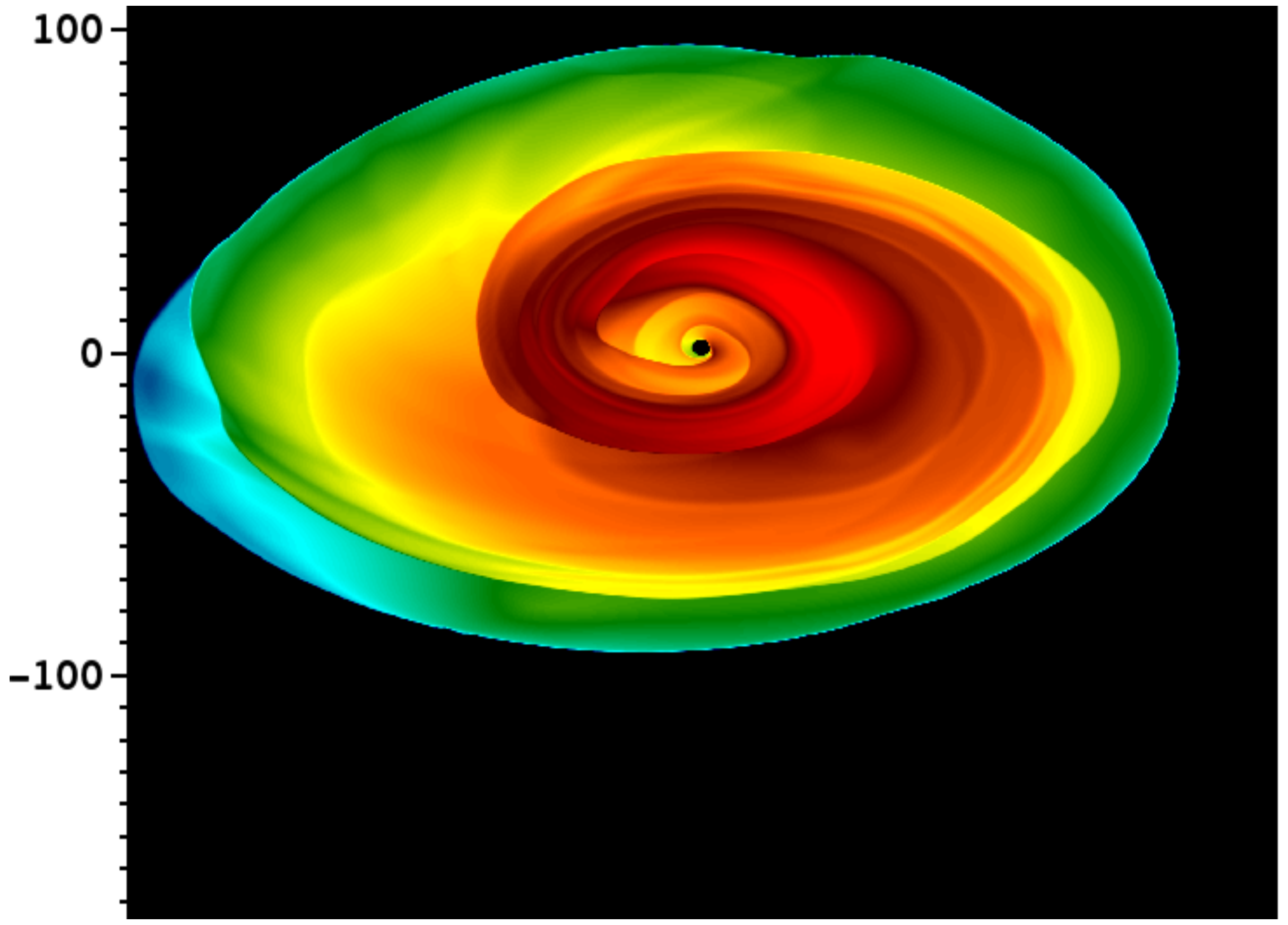
Finite volume

Analytical metric



Fuild s dynamics with.
GR-AMRVAC





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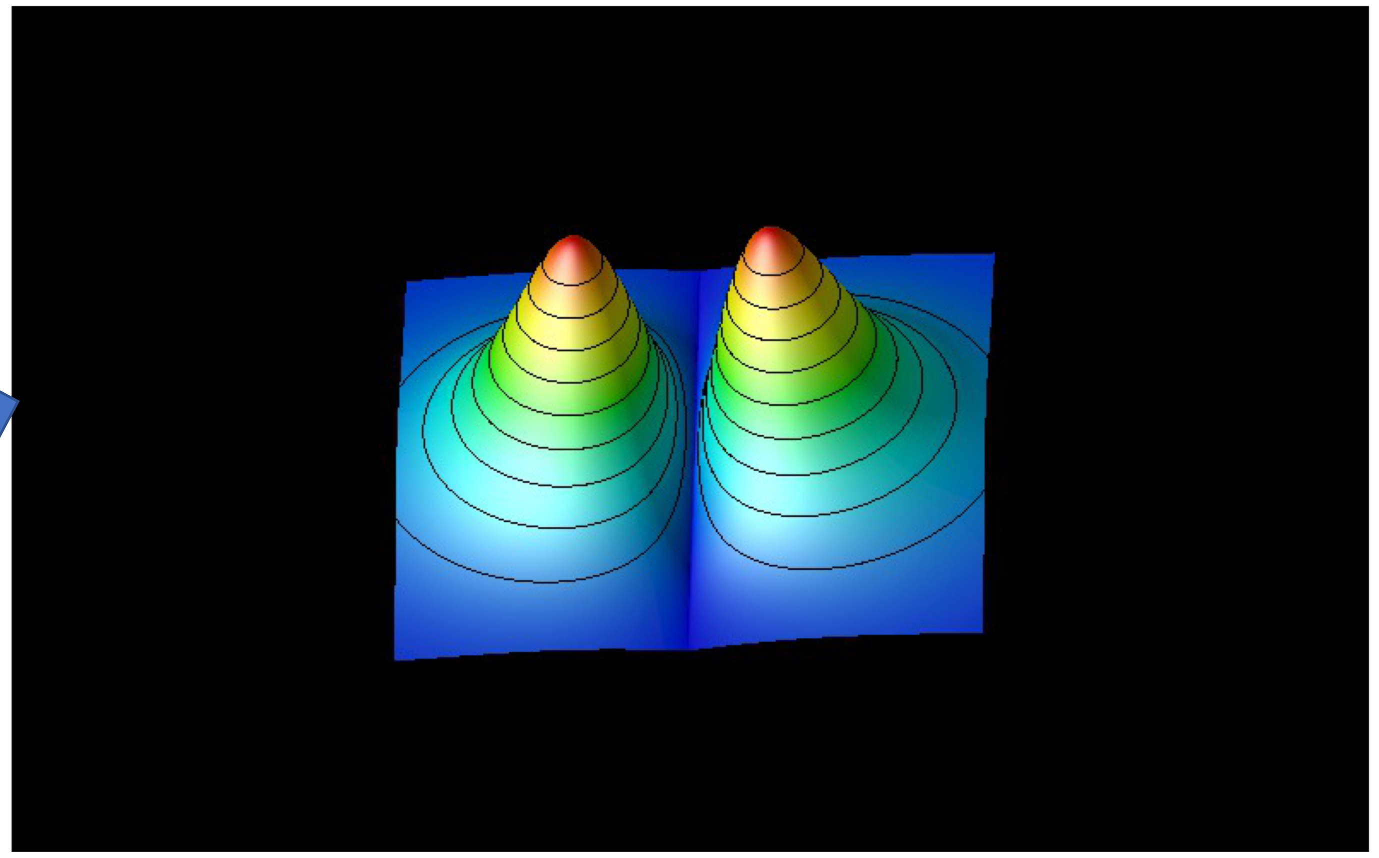
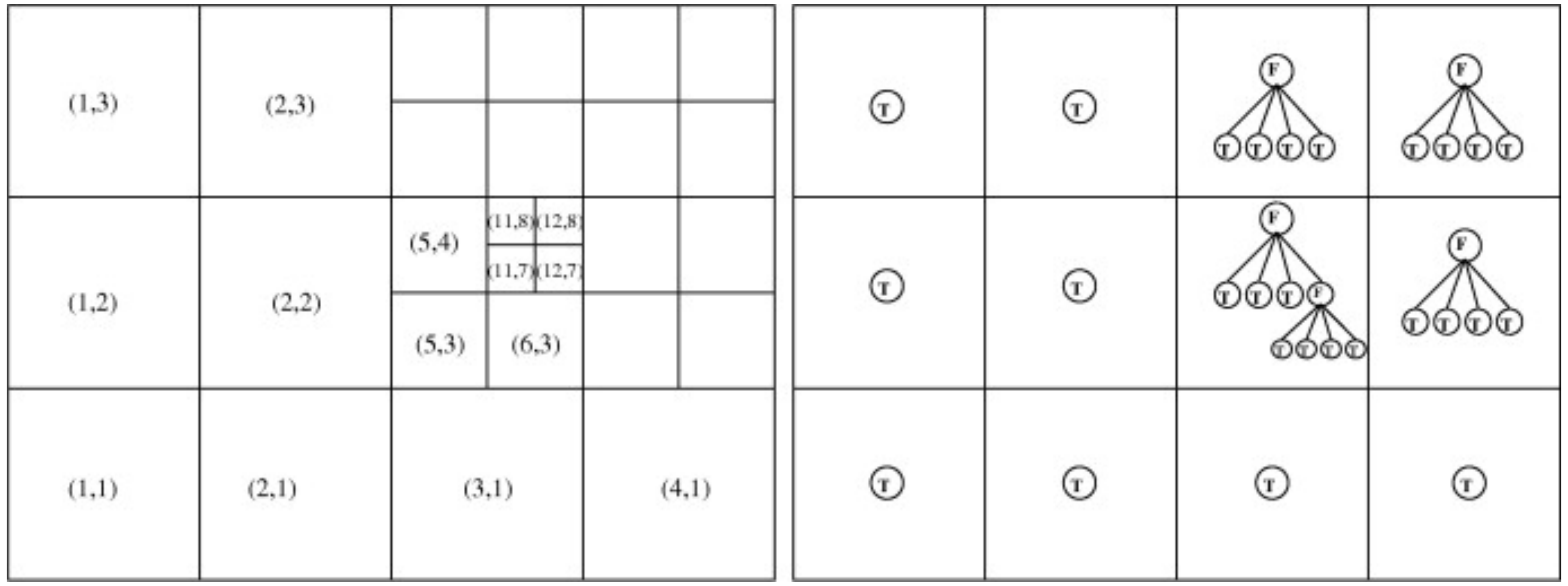


Numerical metric with KADTAH

Grid adaptation

- **subdivision of** blocks**, not zones**
- quad-tree **in 2D,** oct-tree **in 3D**
- **blocks distributed among processors for load-balancing**
- **neighbors may never differ by more than one level**
- **MPI- parallelization**



Refinement Criteria

- Choice of refinement criterion depends strongly on problem to be solved
- Default AMRVAC criterion is 2nd order error estimate (Löhner 1987).

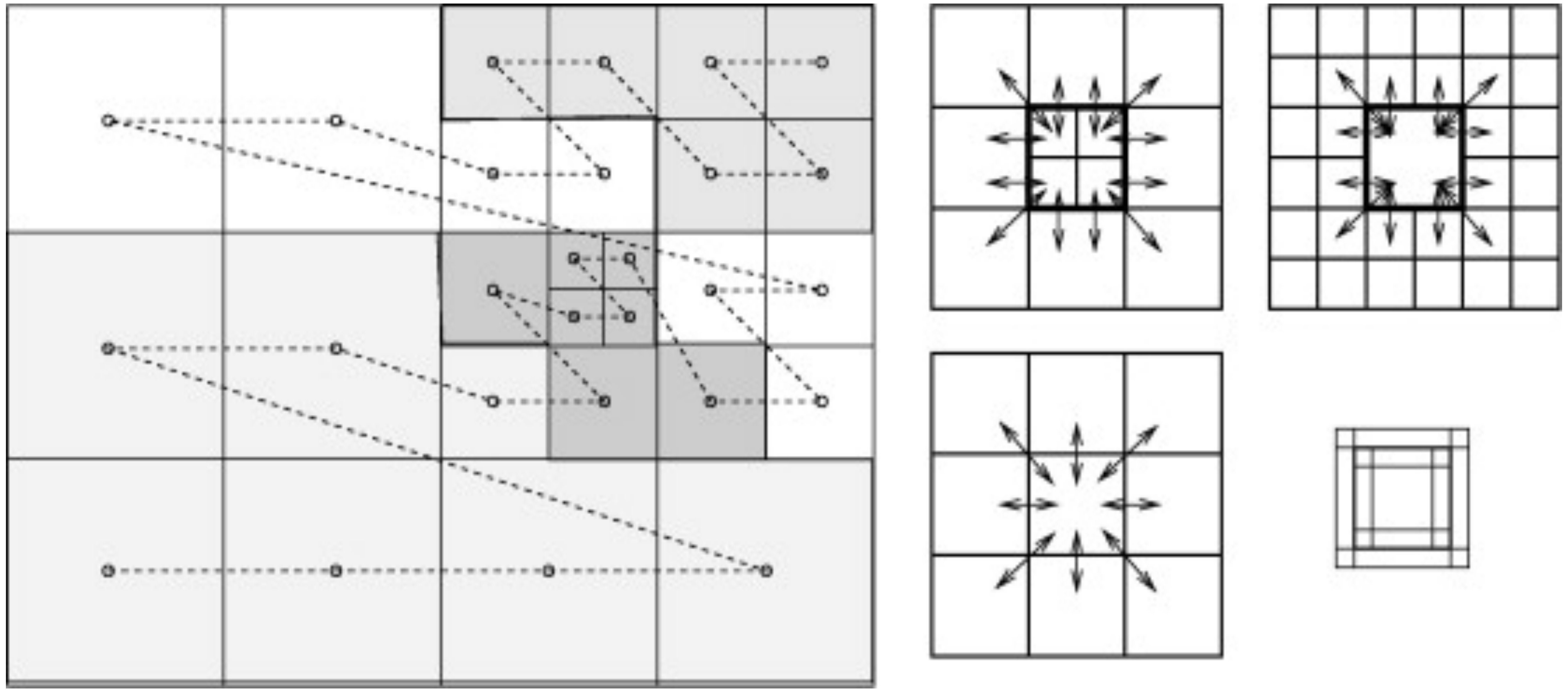
$$E = \frac{\sum (|\partial u|_{i+1/2} - |\partial u|_{i-1/2})^2}{\sum (|\partial u|_{i+1/2} + (|\partial u|_{i-1/2} + \varepsilon |u_{i-2} + u_{i-1} + u_{i+1} + u_{i+2}|)^2}$$

Load balance

Morton space-filling curve is passed through all the blocks in the tree

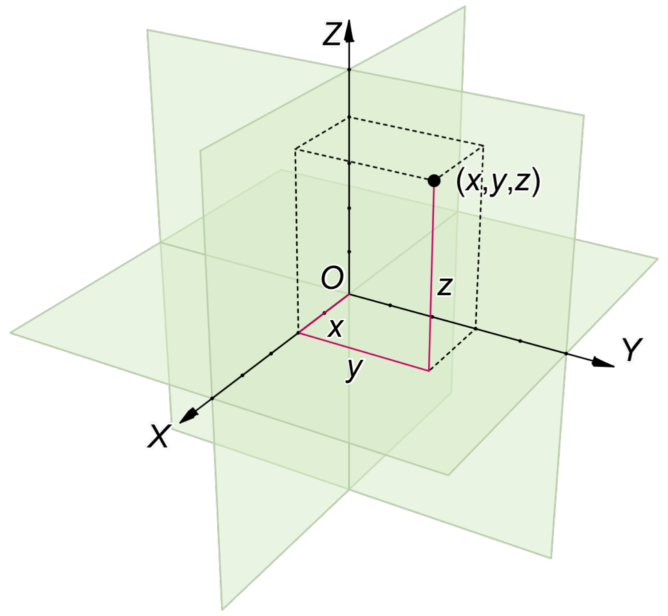
Blocks consecutively assigned to processors from list

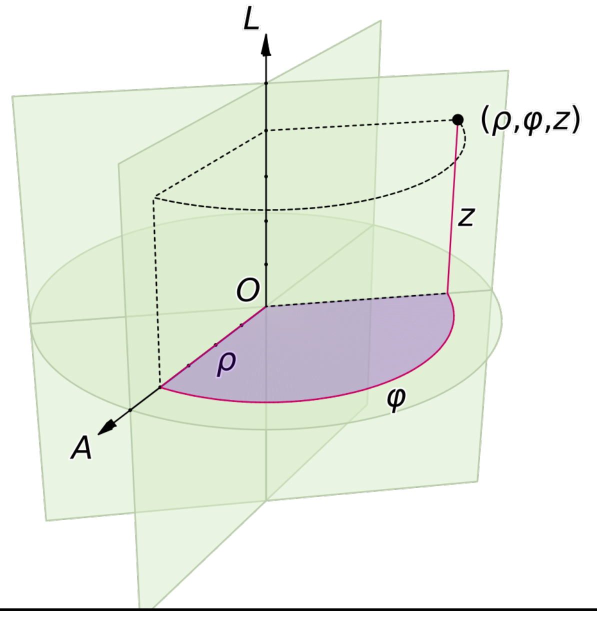
This increases chance of neighboring blocks being on same processor

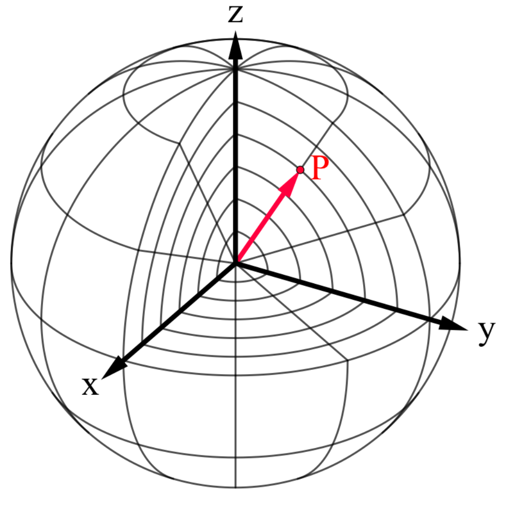


Metric implimentation

Cartesian coordinate — **Cylindrical coordinate** — **spherical coordinate**







Required:

- $$g_{\mu\nu} = \begin{pmatrix} N^2 - \beta^k\beta_k & \beta_j \\ \beta_i & \gamma_{ij} \end{pmatrix}$$

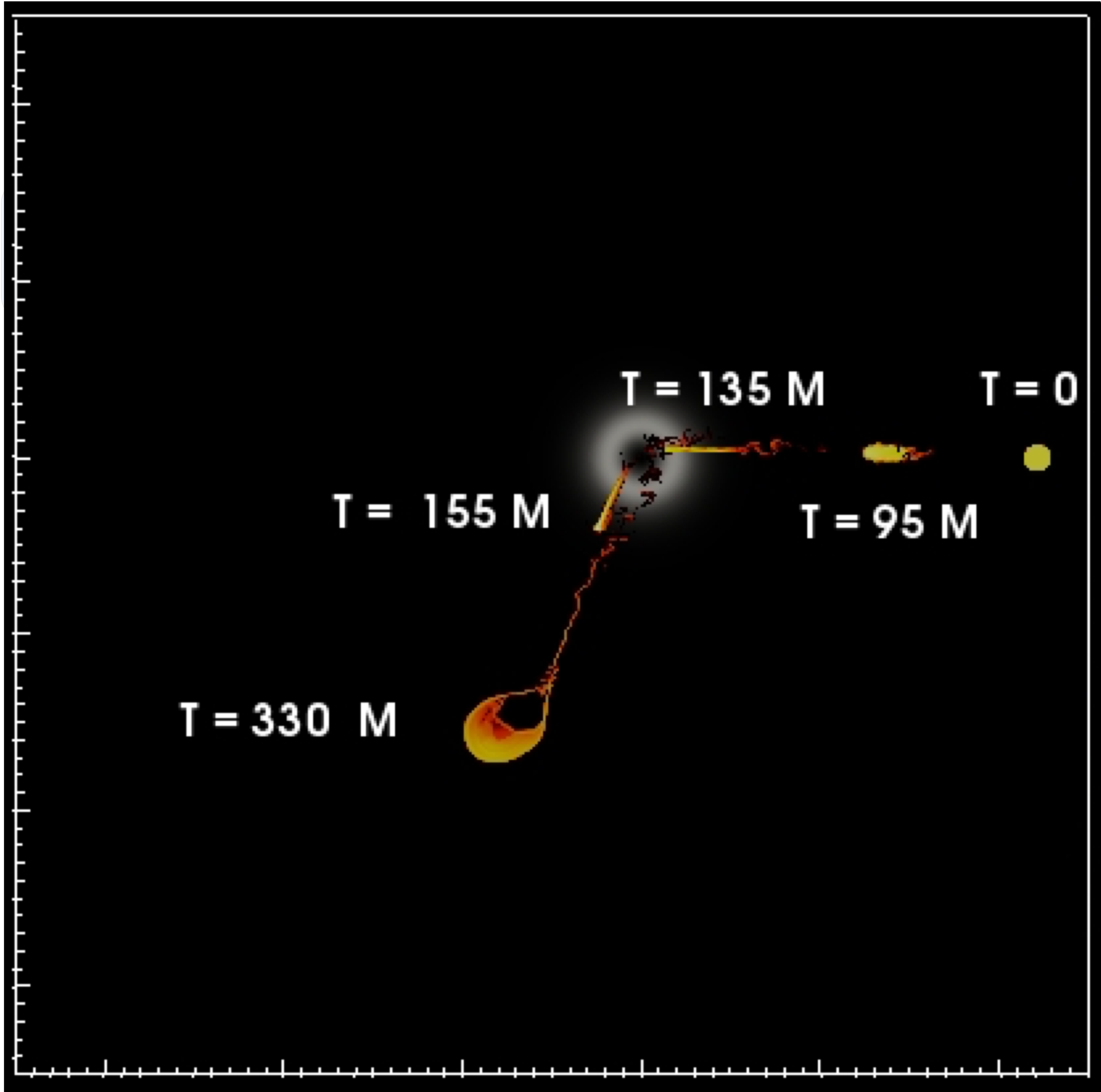
Shift vector

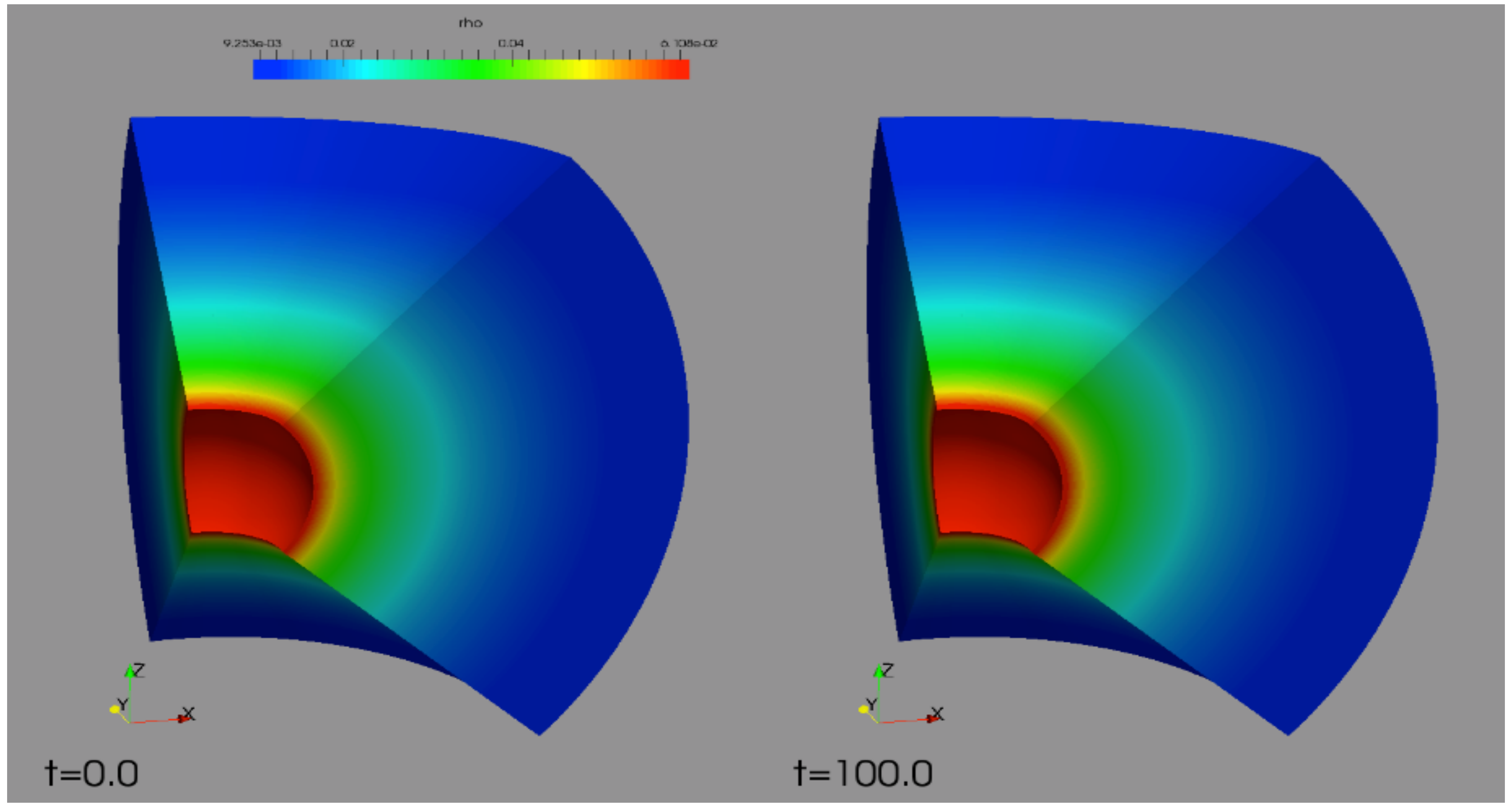
Laps

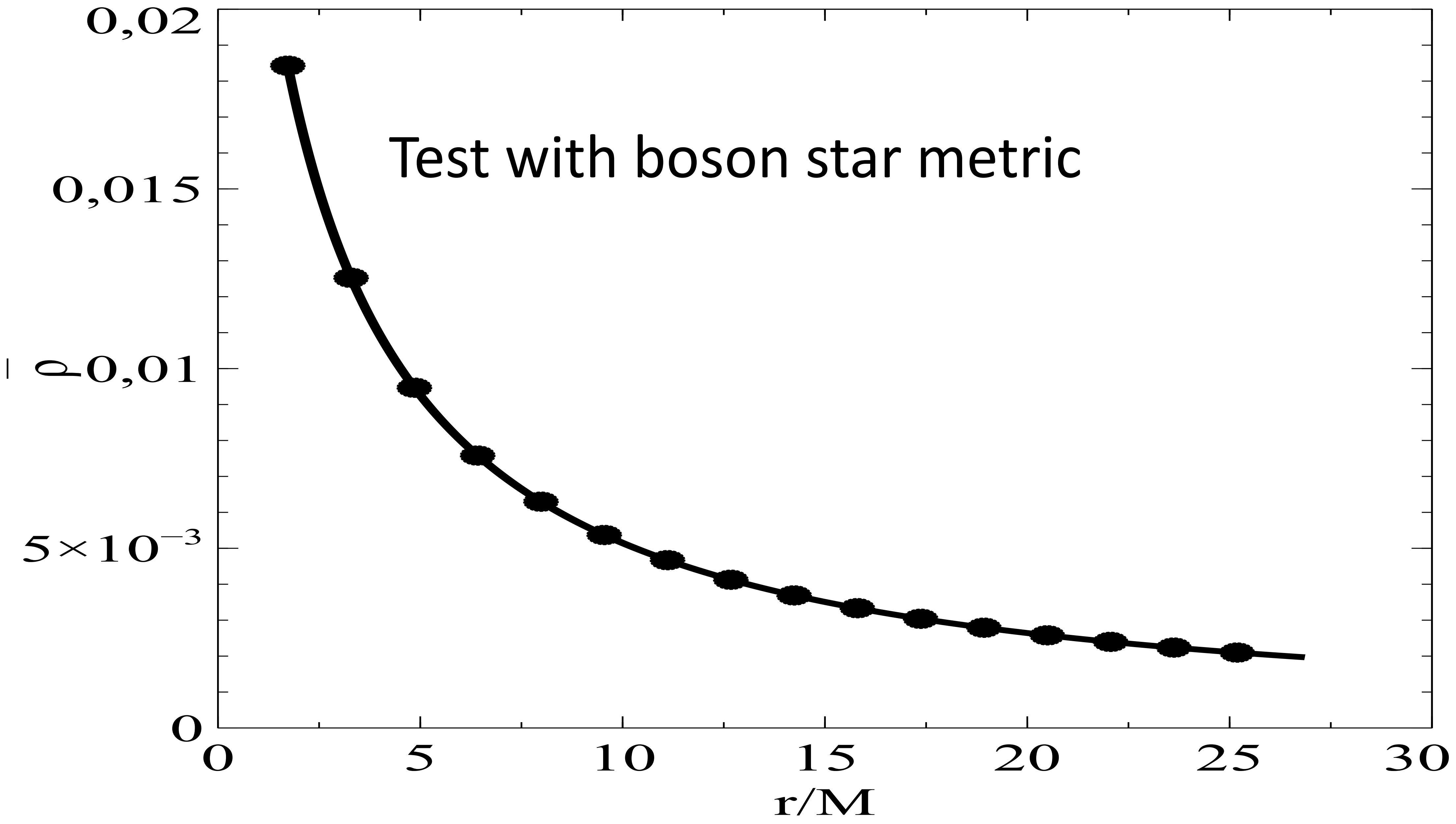
Spatial metric

Grid-Metric-Solver

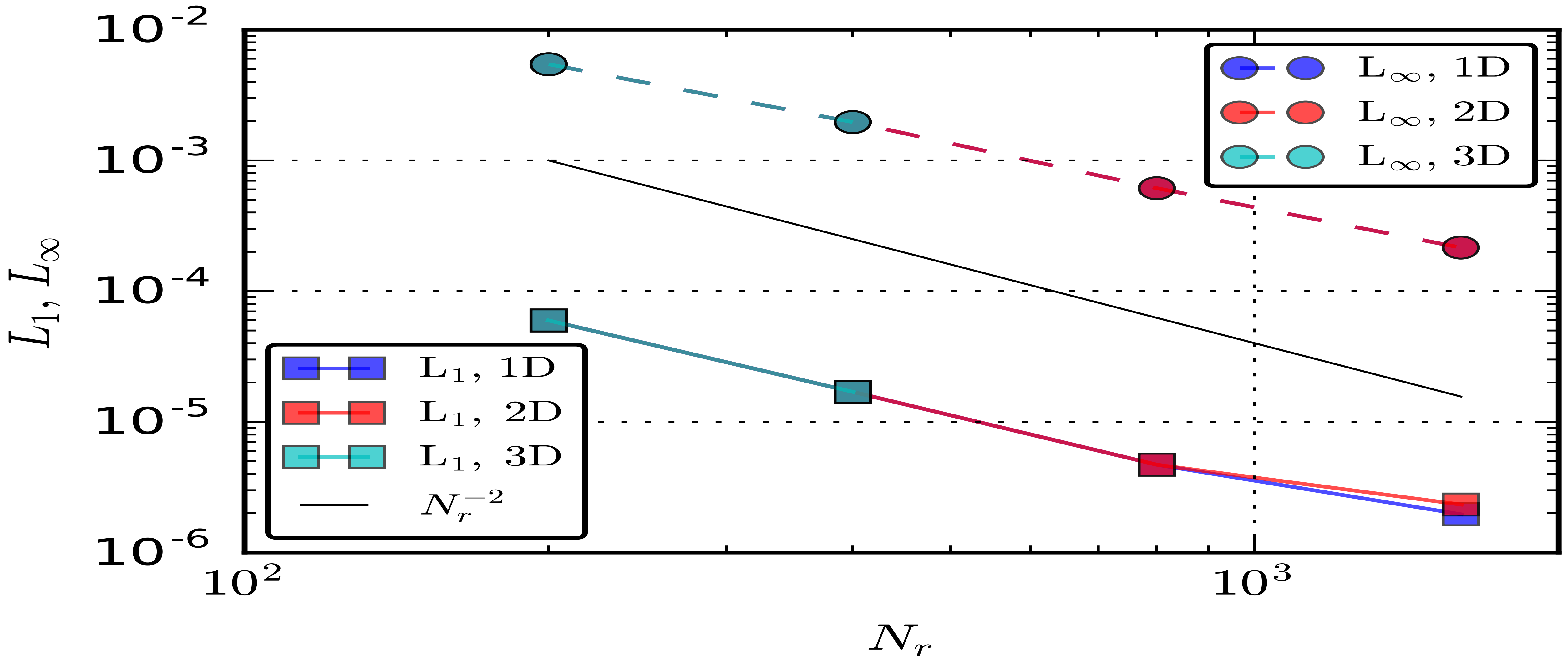
- Metric element is saved only in curved spacetime zone
- Numerical method is level and zone depending







Test with boson star metric



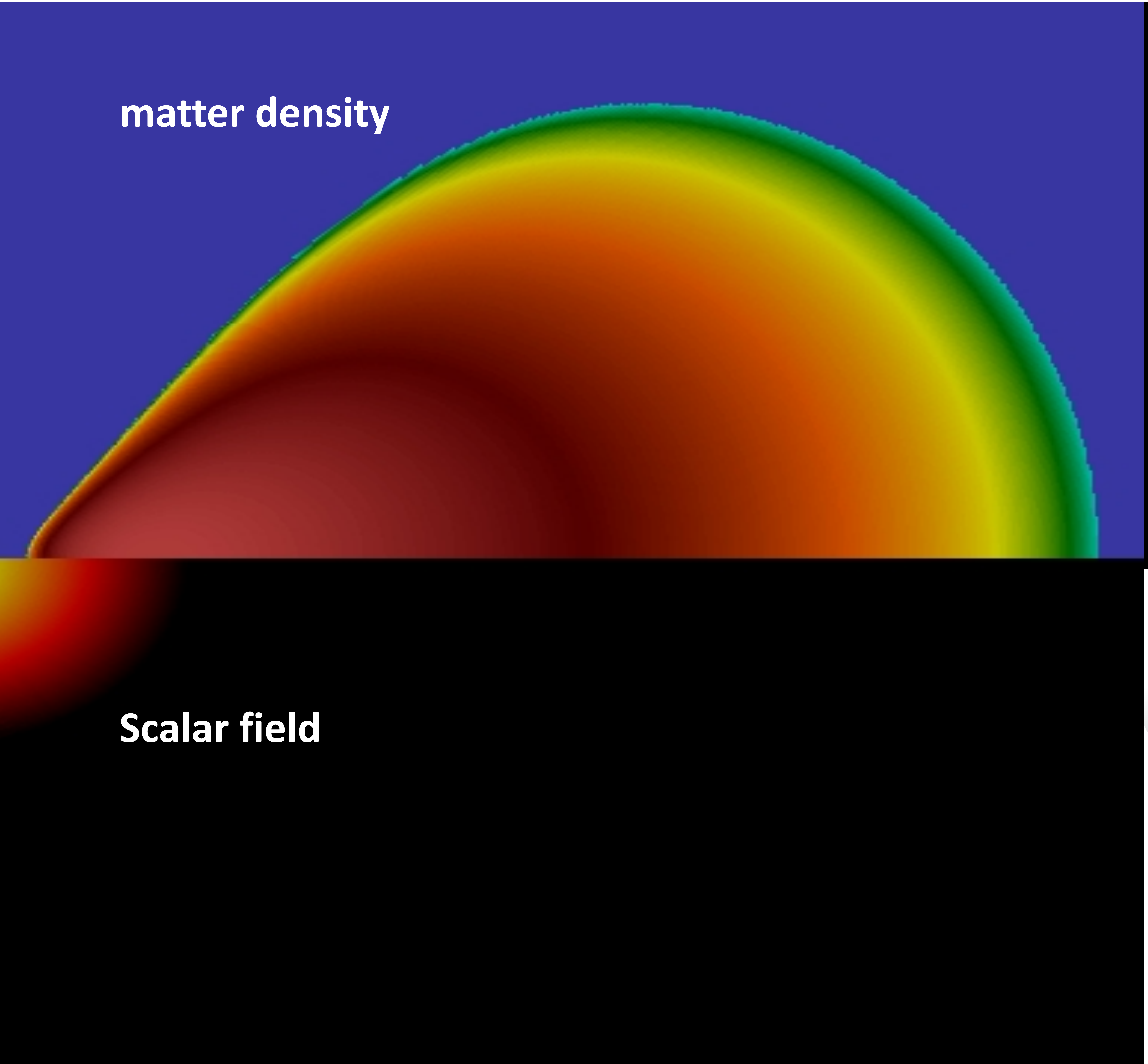
Test with Black hole metric

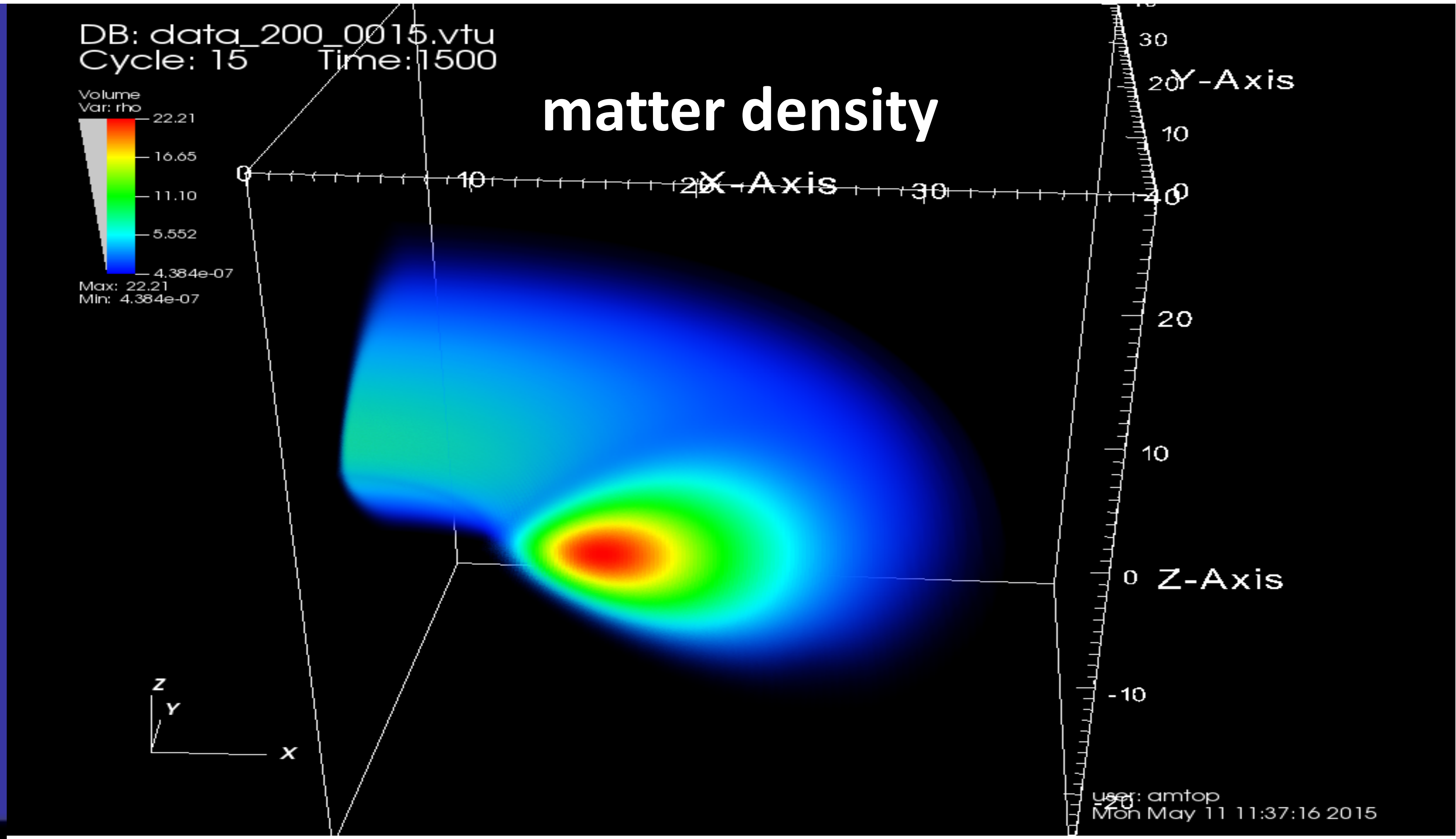
Code validations in GR (Bondi accretion)

- Second order convergence
- Treatment of numerical and analytical metric

Test with boson star metric

Test with Black hole star metric





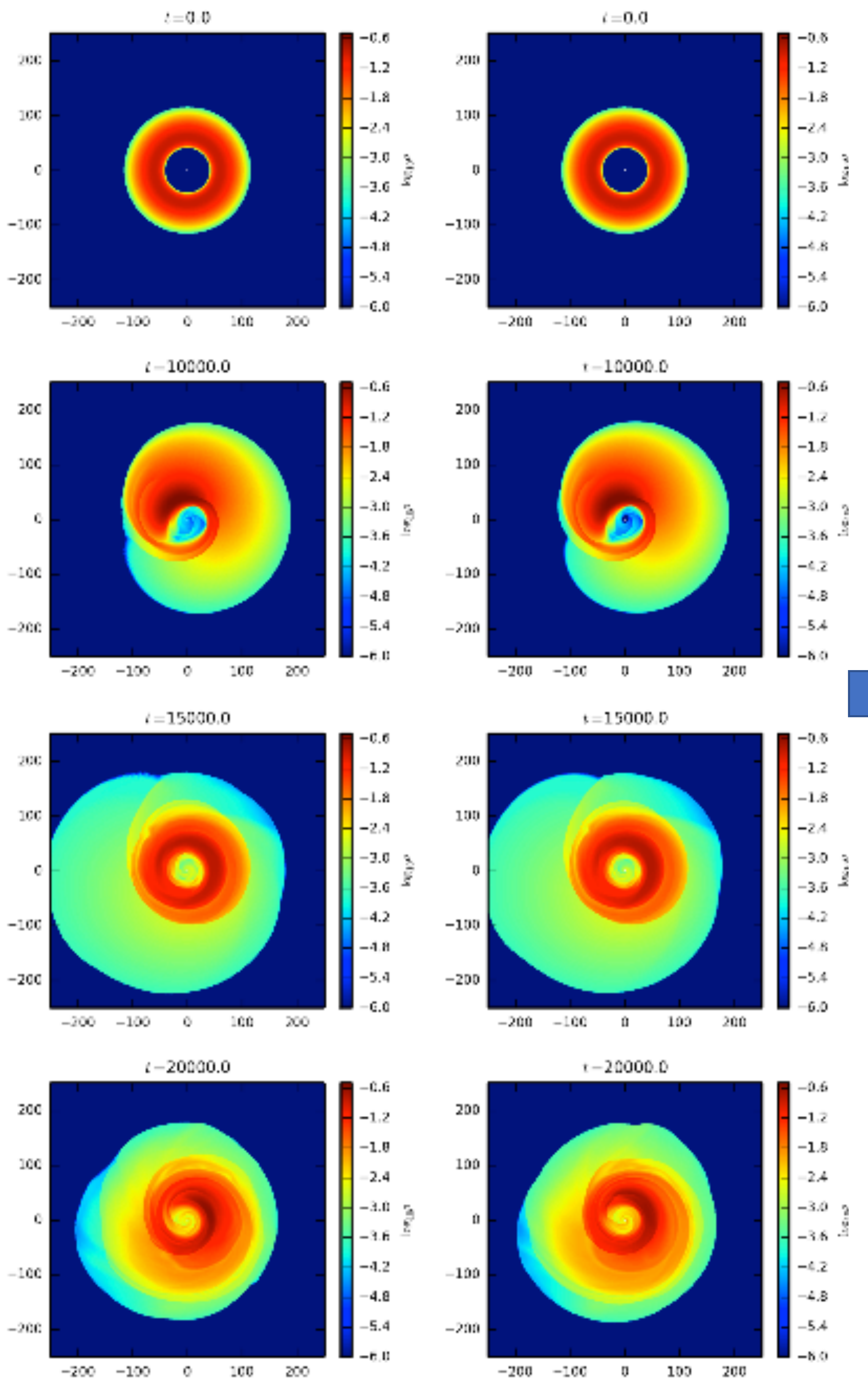
Code validations in GR (Stationary torus)

- Second order convergence
- Ability to treat inside Black –Hole and boson star torus

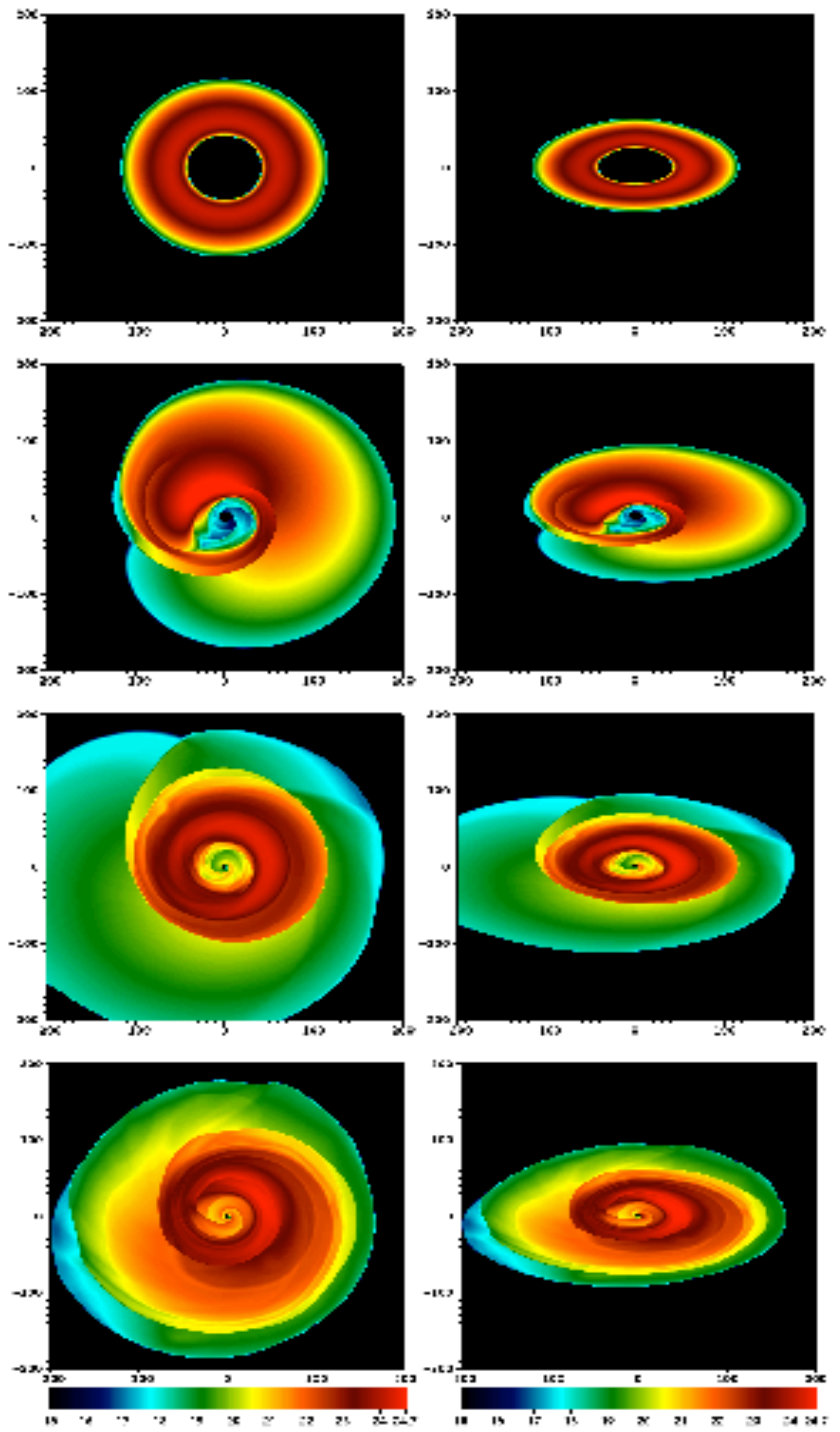

Accretion disc
Compact objects

Recoiling black hole

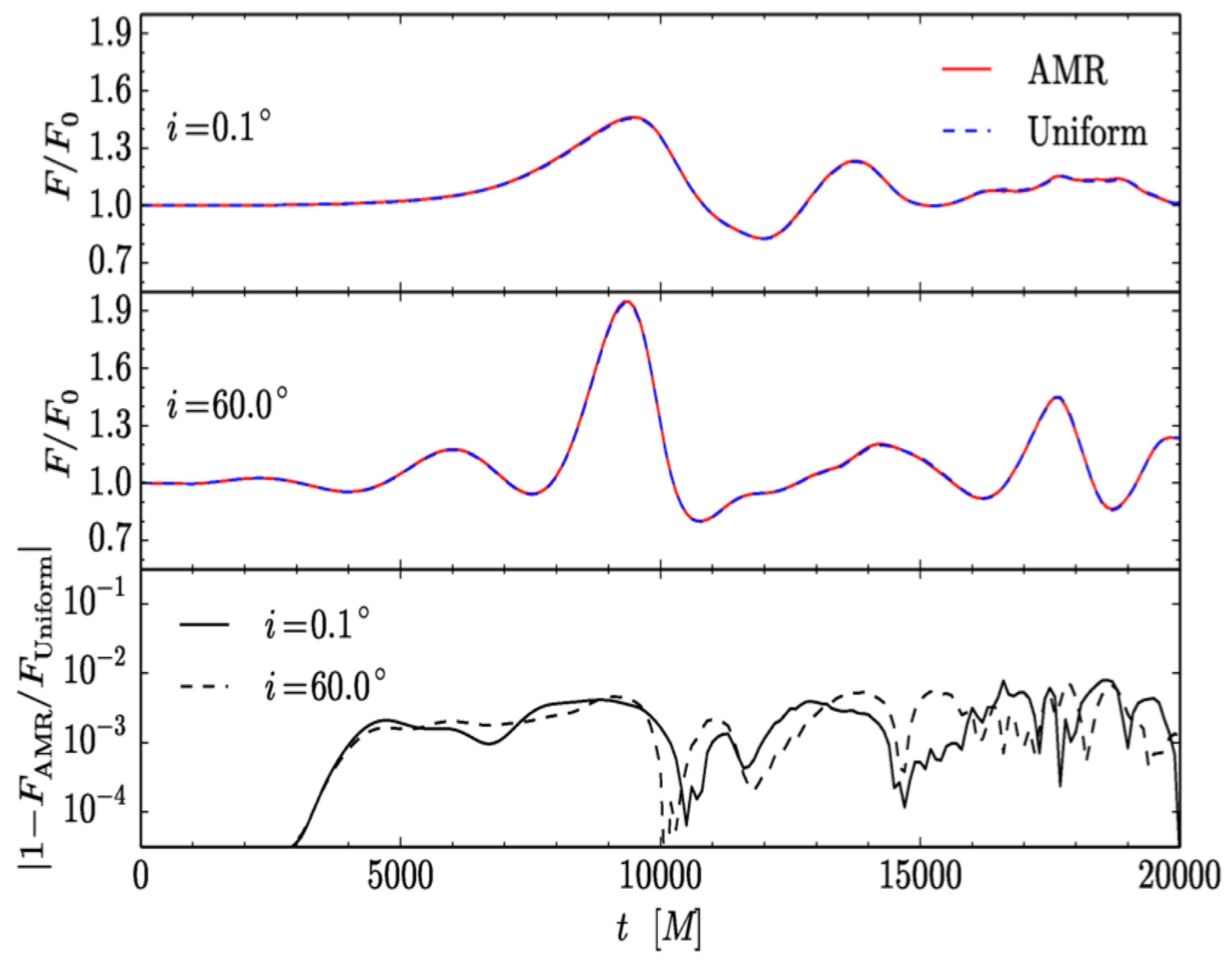
Density



Image



Light curve



Accretion in the vicinity of BH/Boson star

Why study flow in the vicinity of Boson star

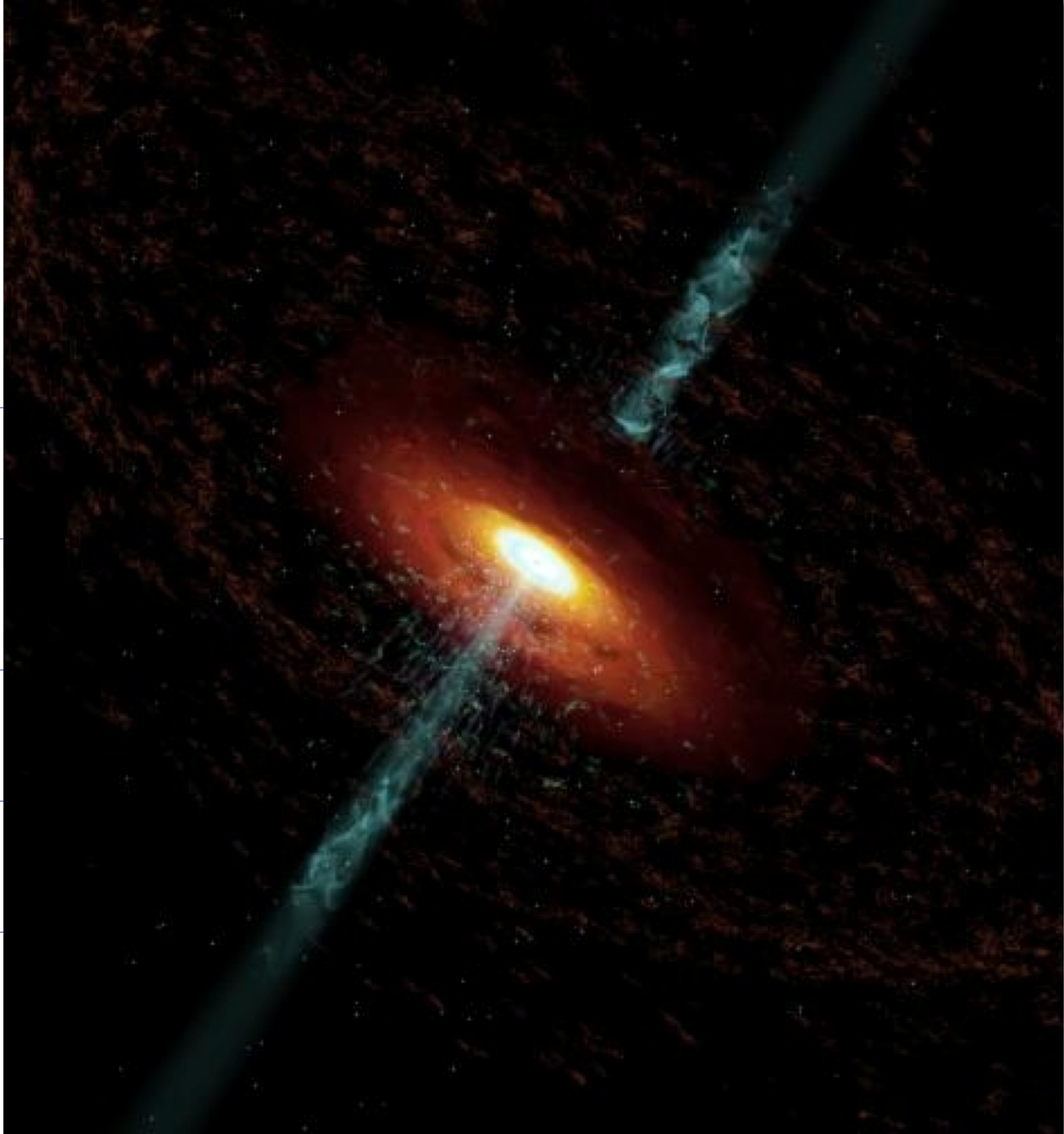
Boson exists

Mass of Boson star could reach Massive BHC?

Boson star can be BHC

New generation of instruments

Predict observational differences between Boson Star and BH as central object candidate

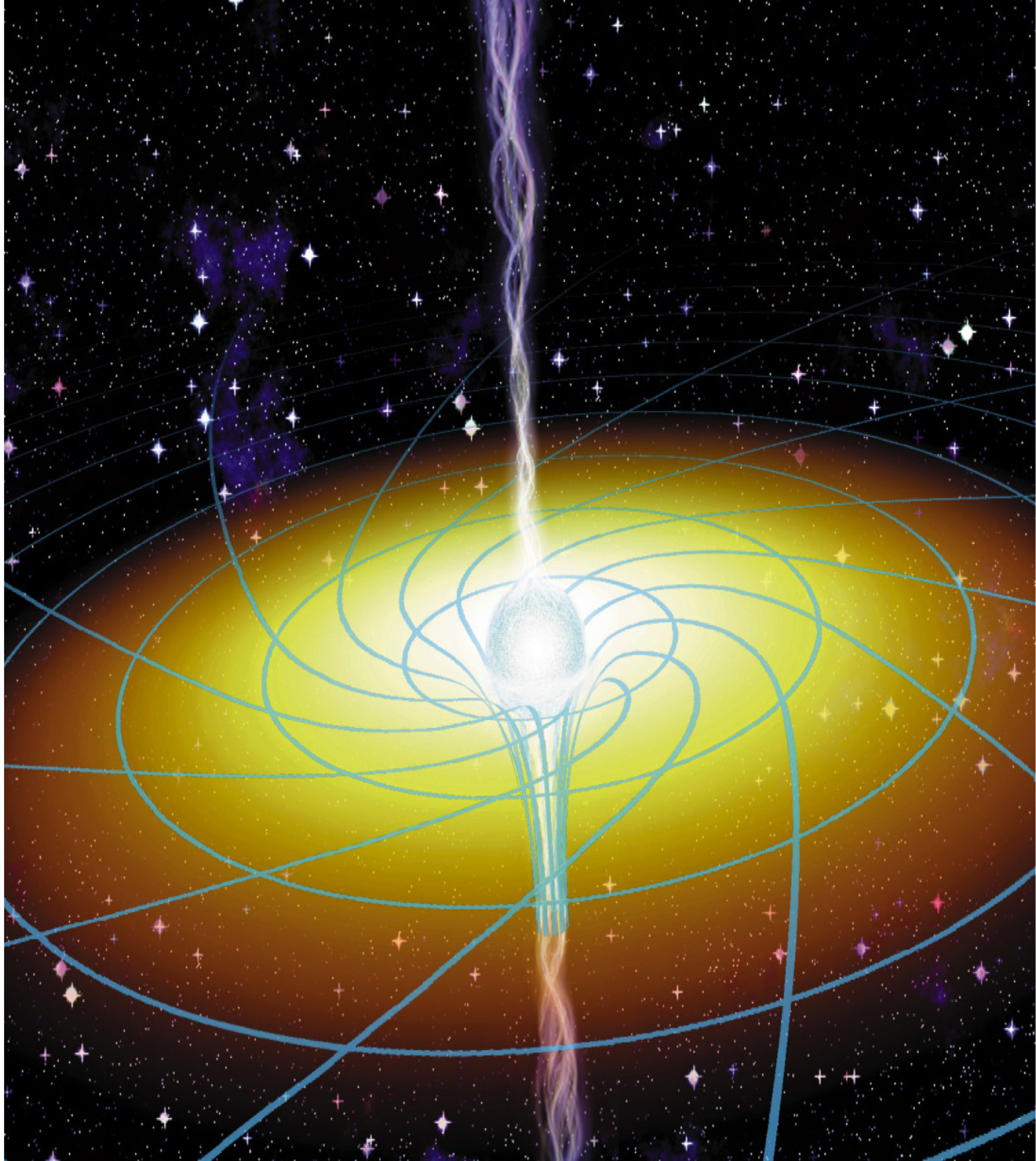


Differences Boson star/ Black Hole

Rotation
- Matter undergoes different Less-Thirring

Horizon
- Matter propagates inside/ouside

Shape
- Different geodesic



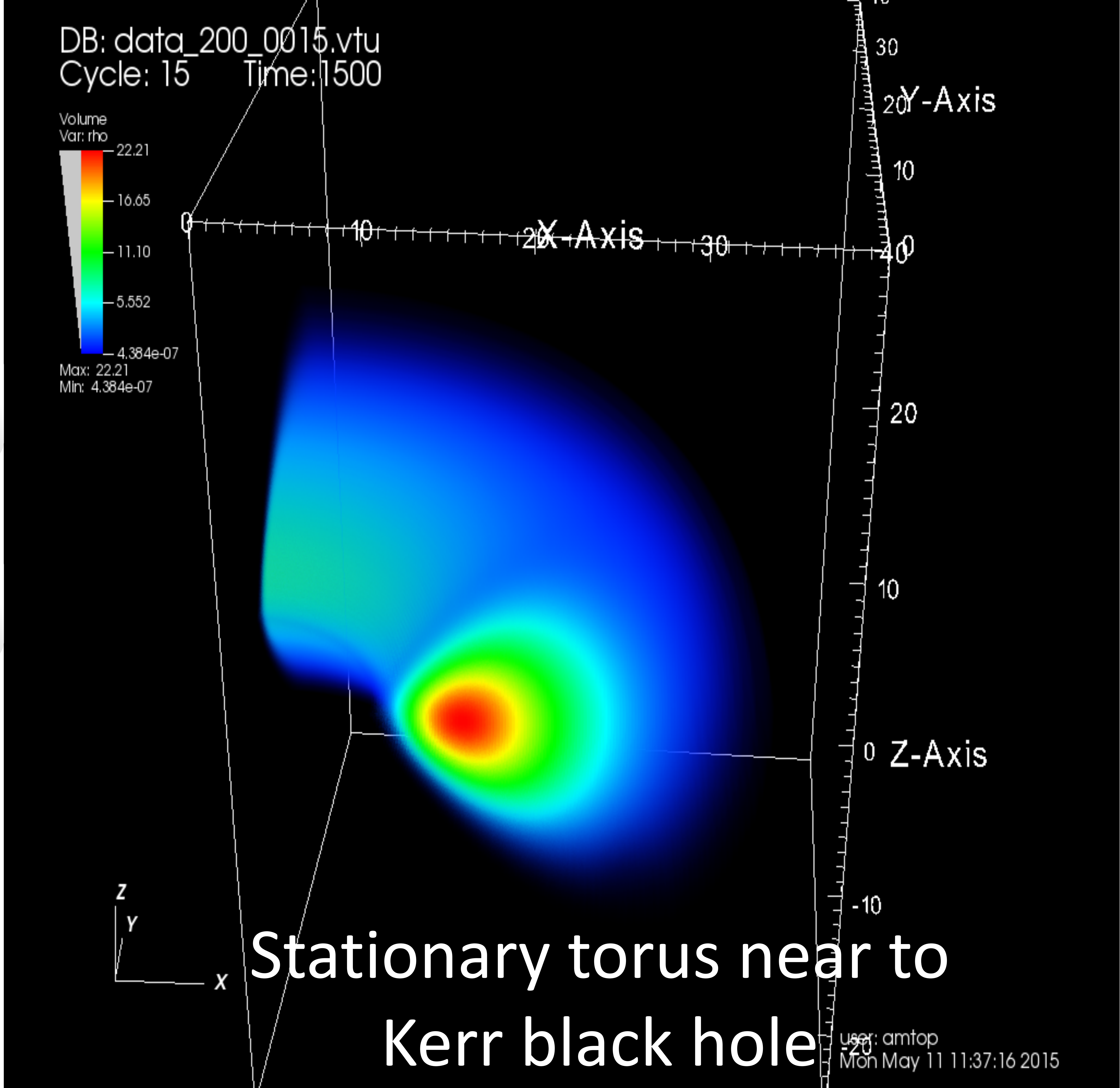
Torus model

Model of thick torus

- Propose : Abramowicz et al 1978

Characteristics:

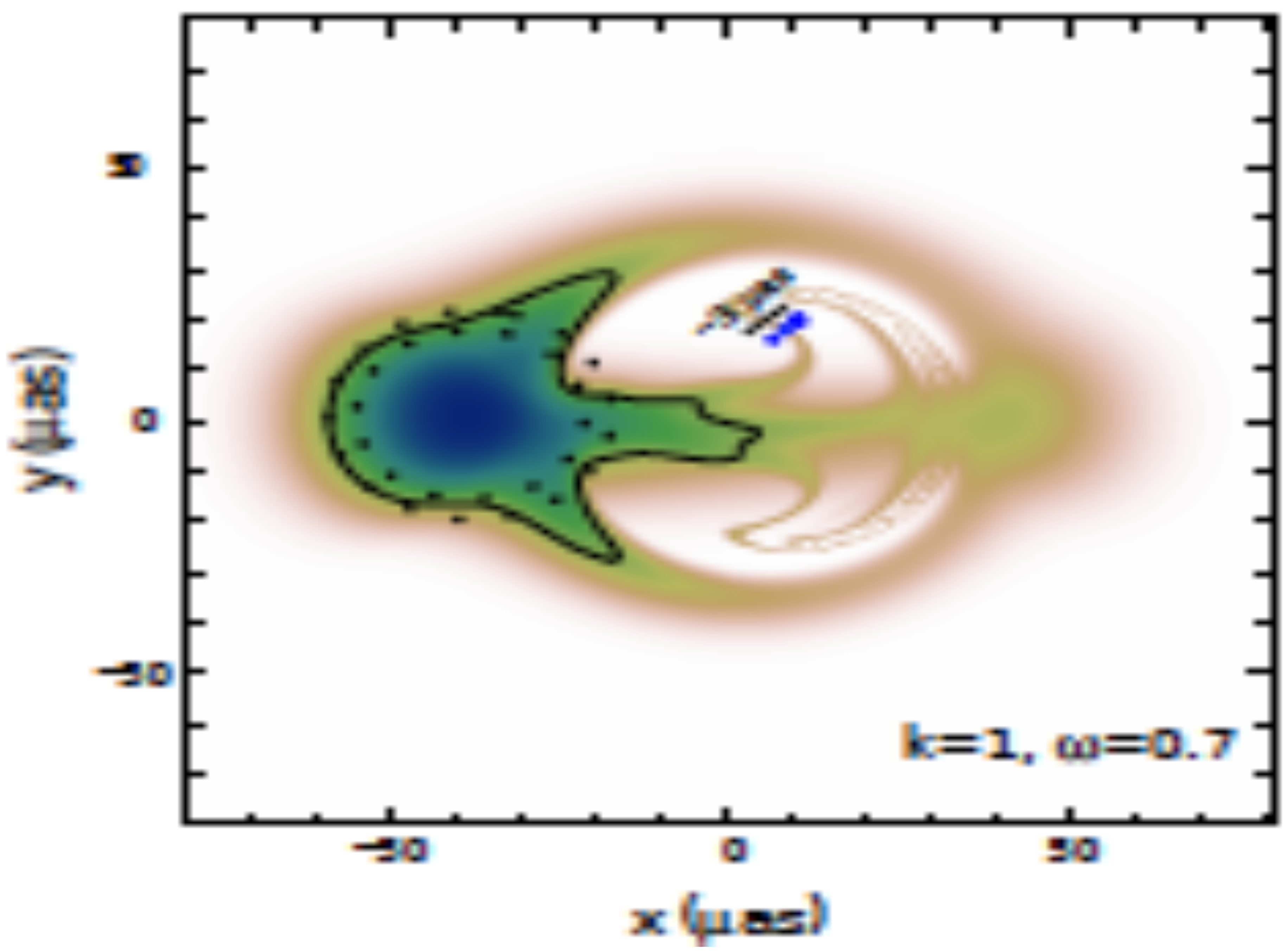
- Constant specific angular momentum
- Inner radius
- Cusp : accretion
- At center : Keplerian rotation



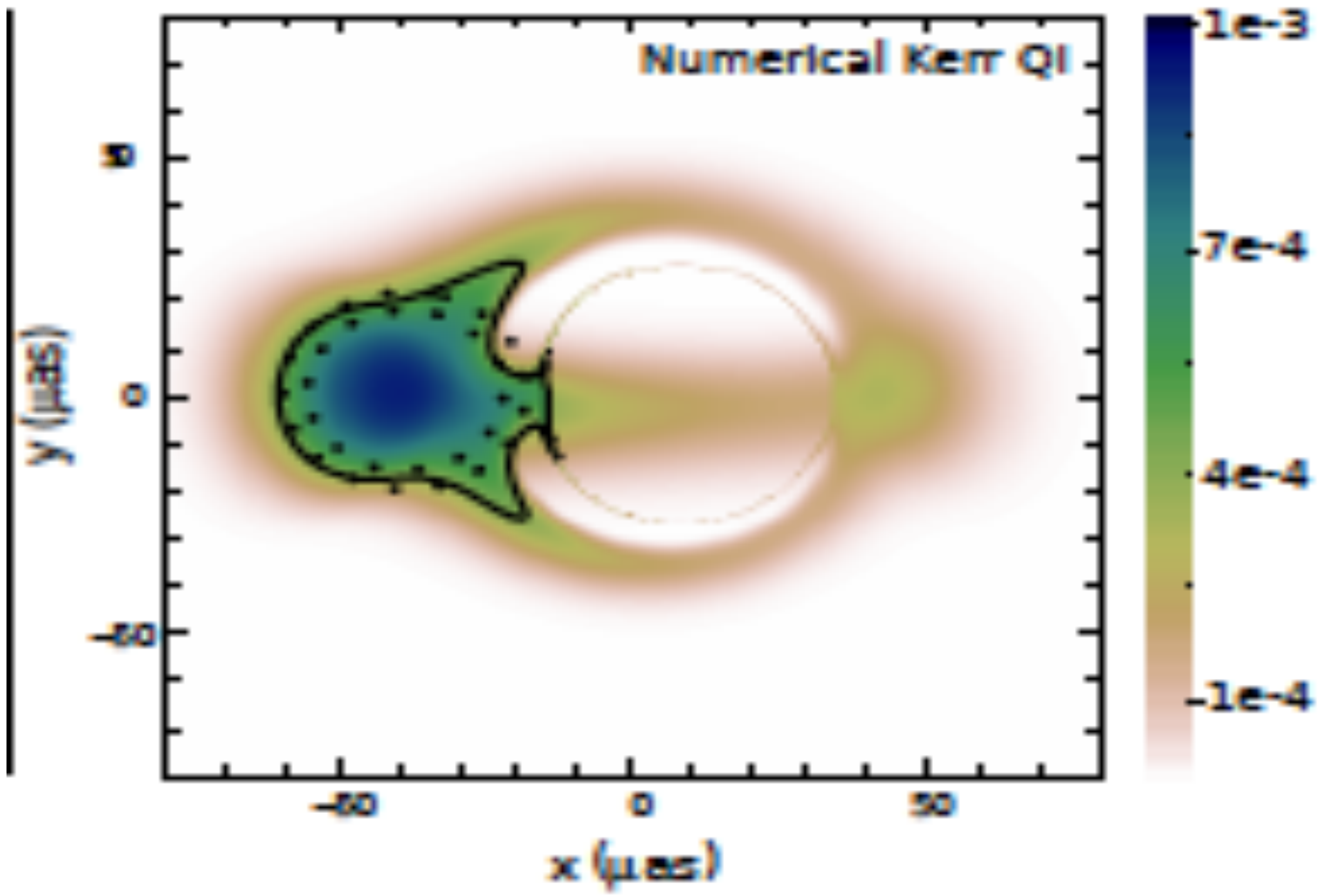
Stationary torus near to Kerr black hole

Shadow of Boson Stars/Kerr BH

Boson star – disk shadow

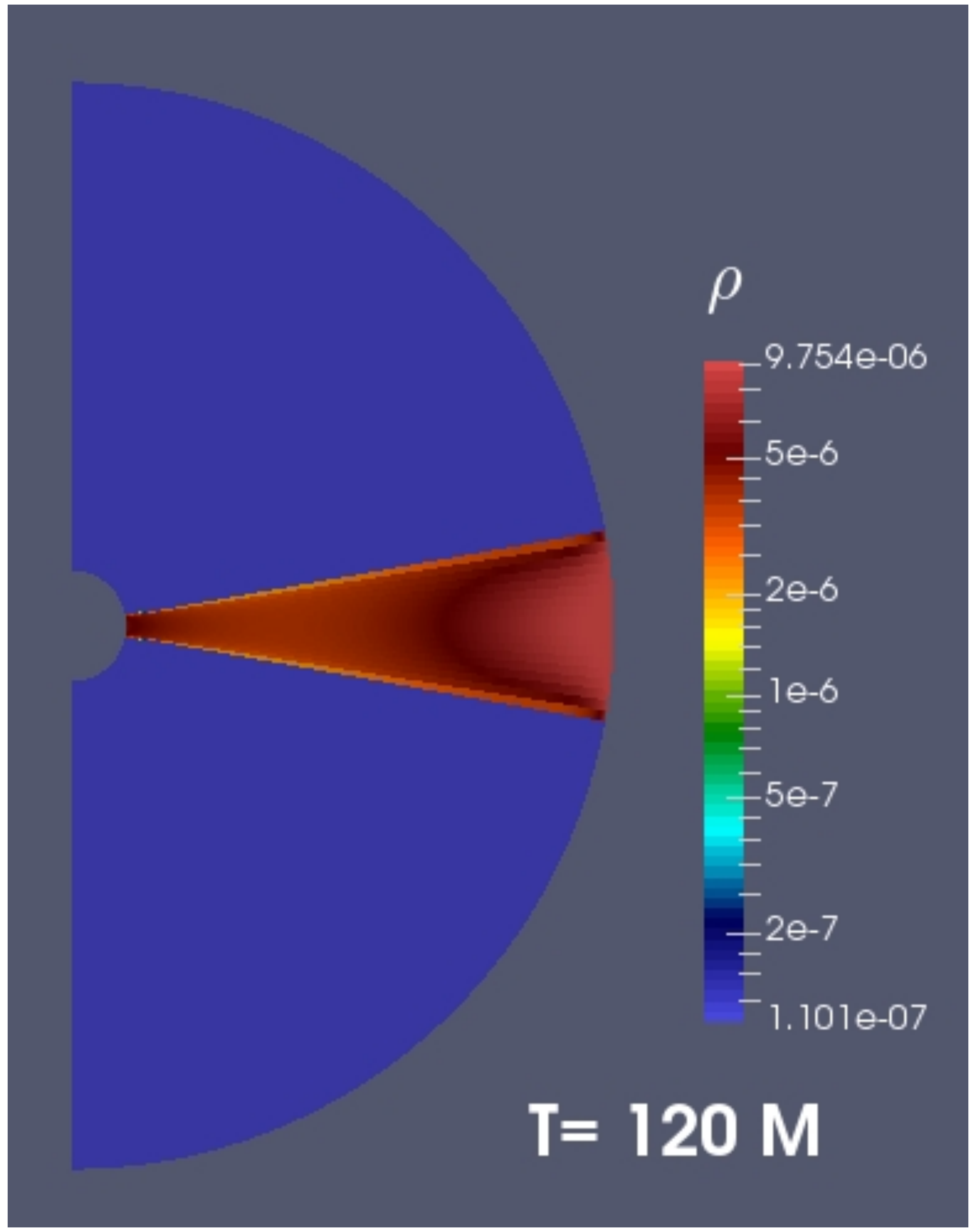


BH shadow

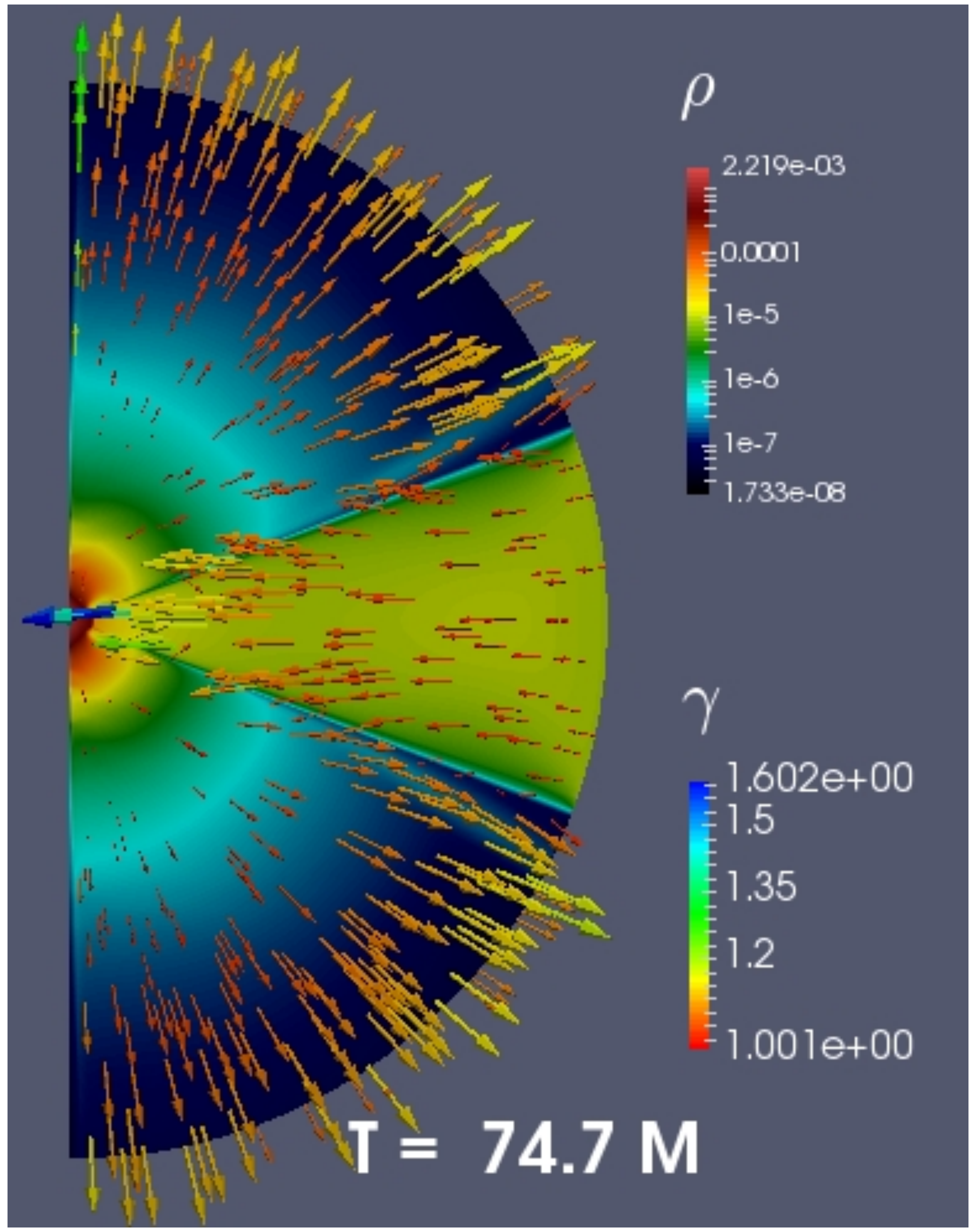


Accretion in BH /Boson star

Accretion in BH



Accretion – ejection in Boson star



Tidal disruption by Boson star

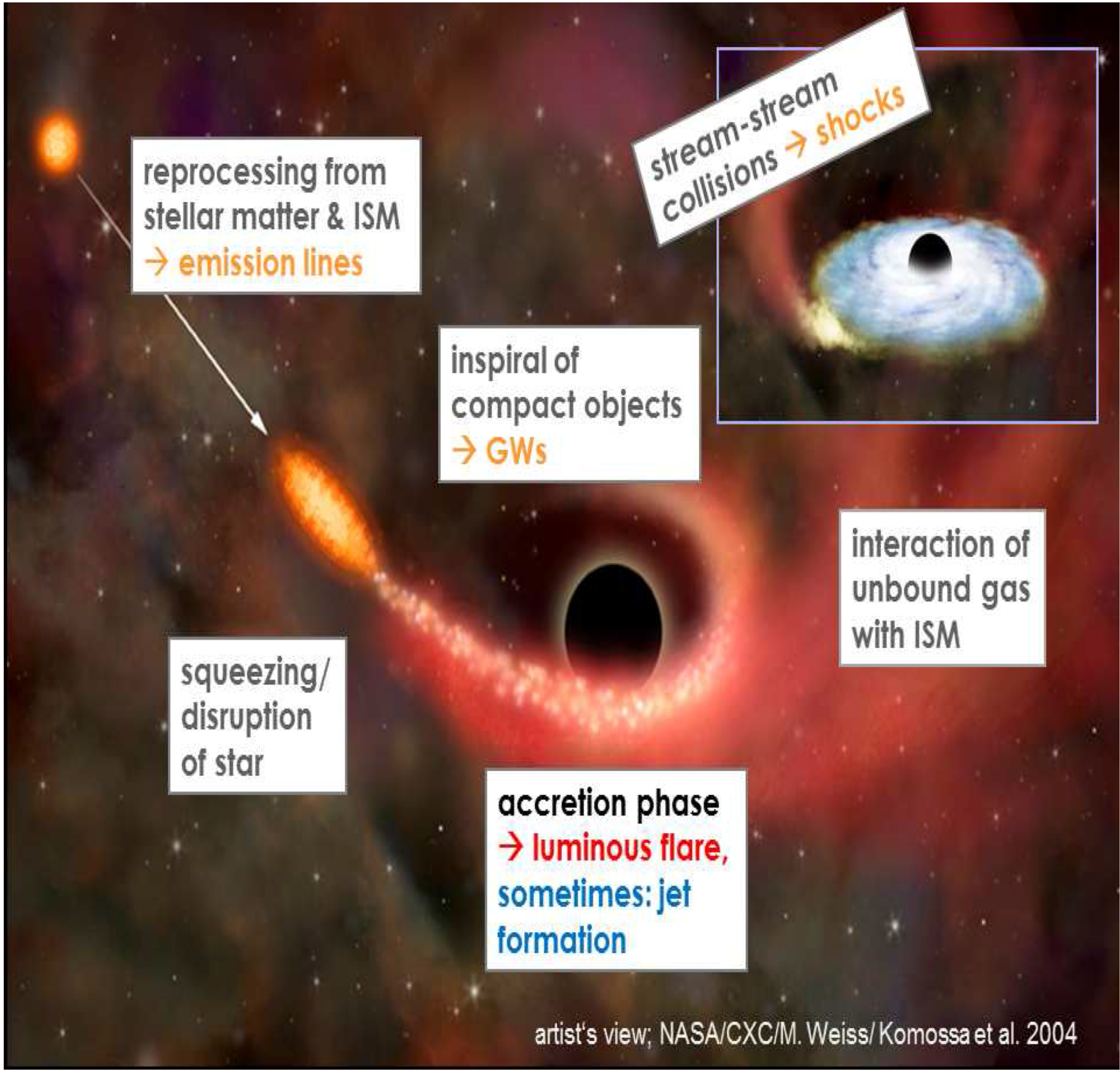
Tidal disruption of stars by BH

Theory 70-80

- Lacy et al 1982
- Luminet and Marck 1985
- …

Observation X-Ray

- Komossa and Bade 1999
- Merloni et al. 2015



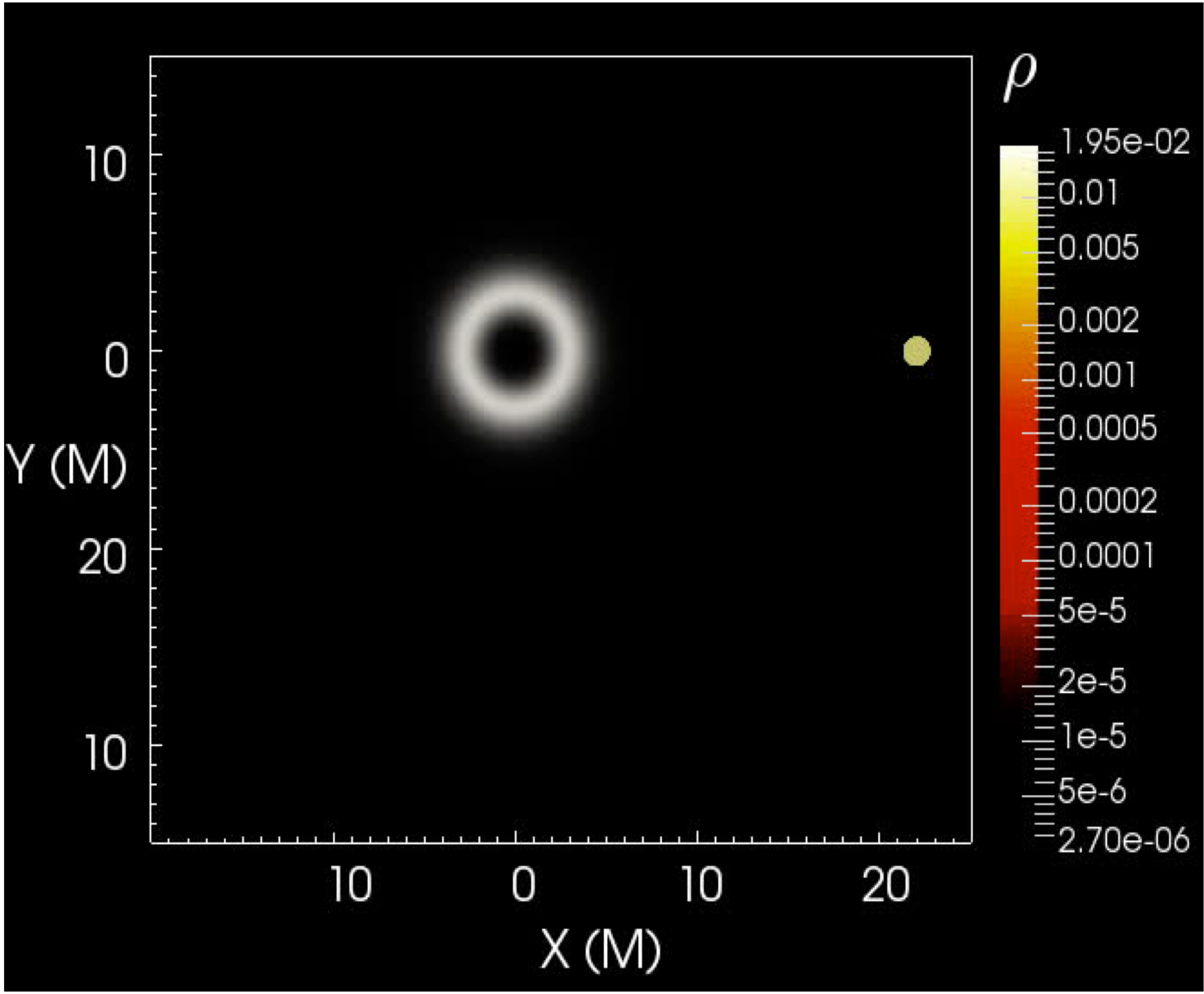
Tidal disruption with BS (Model)

Cloud

- Zero angular momentum
- Zero initial speed
- Uniform density
- Low pressure

External medium

- Low density
- Low pressure



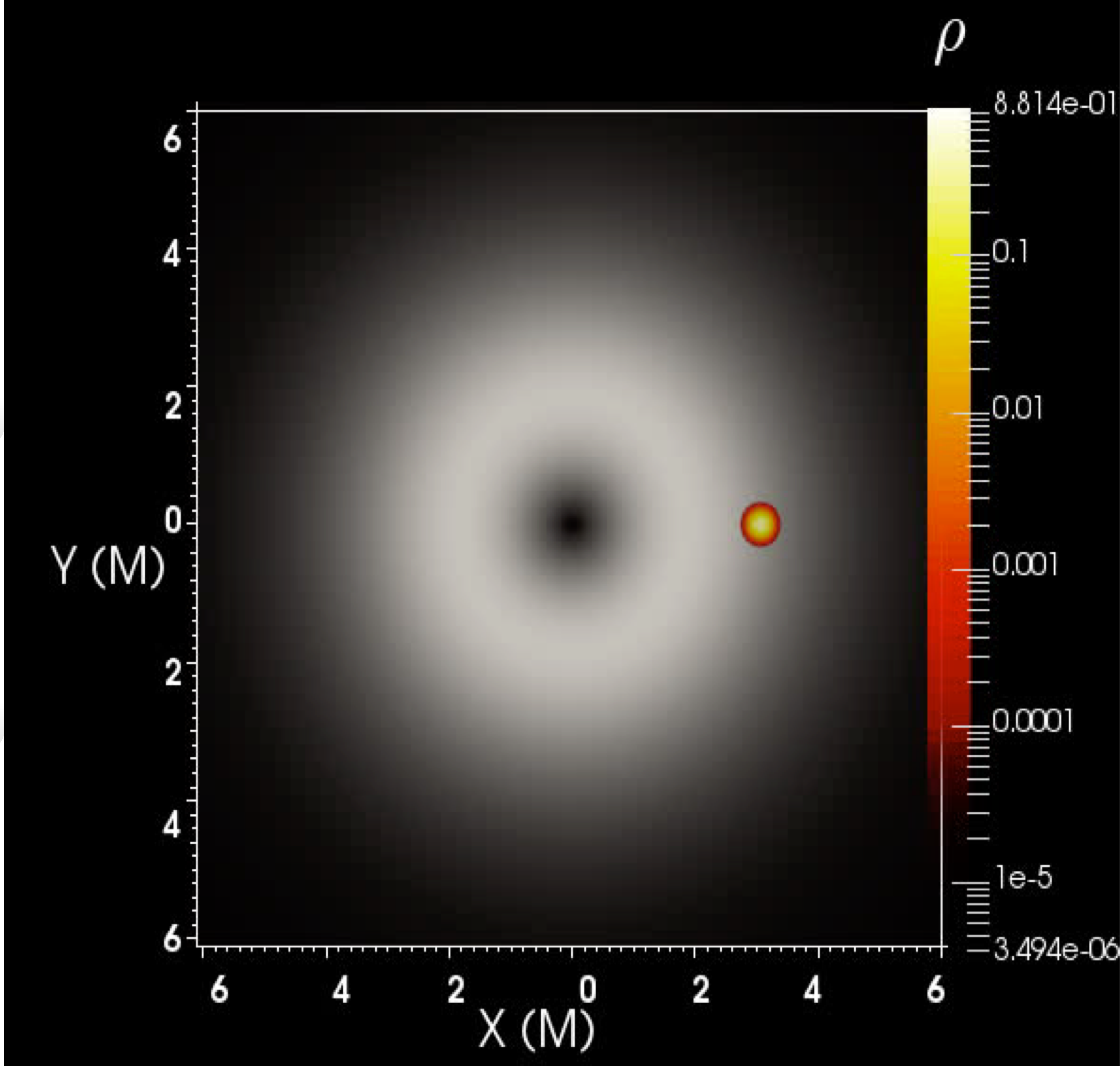
Cloud near BS

First phase

- Cloud oscillates in center
- Tidal disruption increases each time cloud cross the center

Last phase

- Disc formation



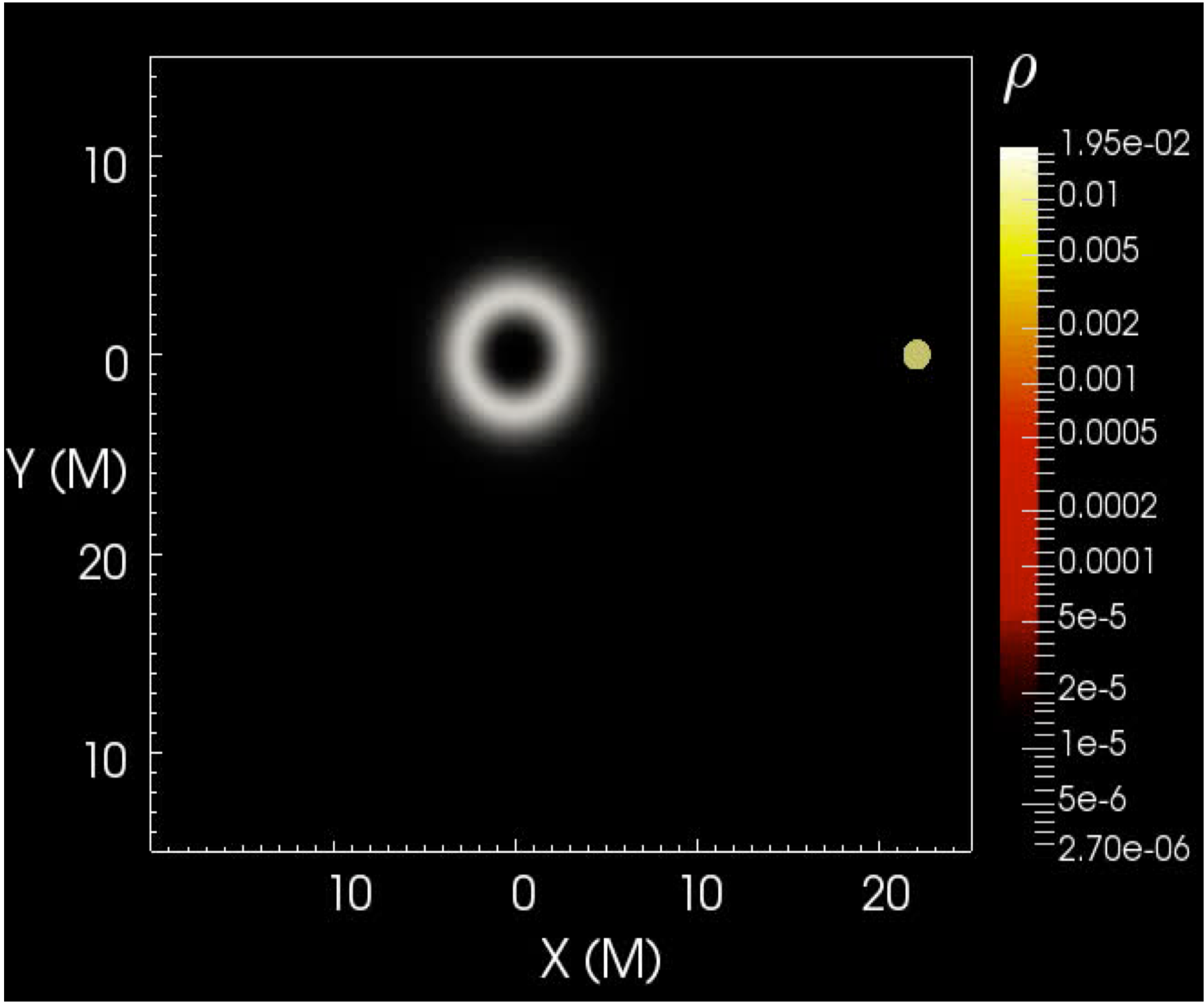
Tidal disruption with BS (cloud at larger distance)

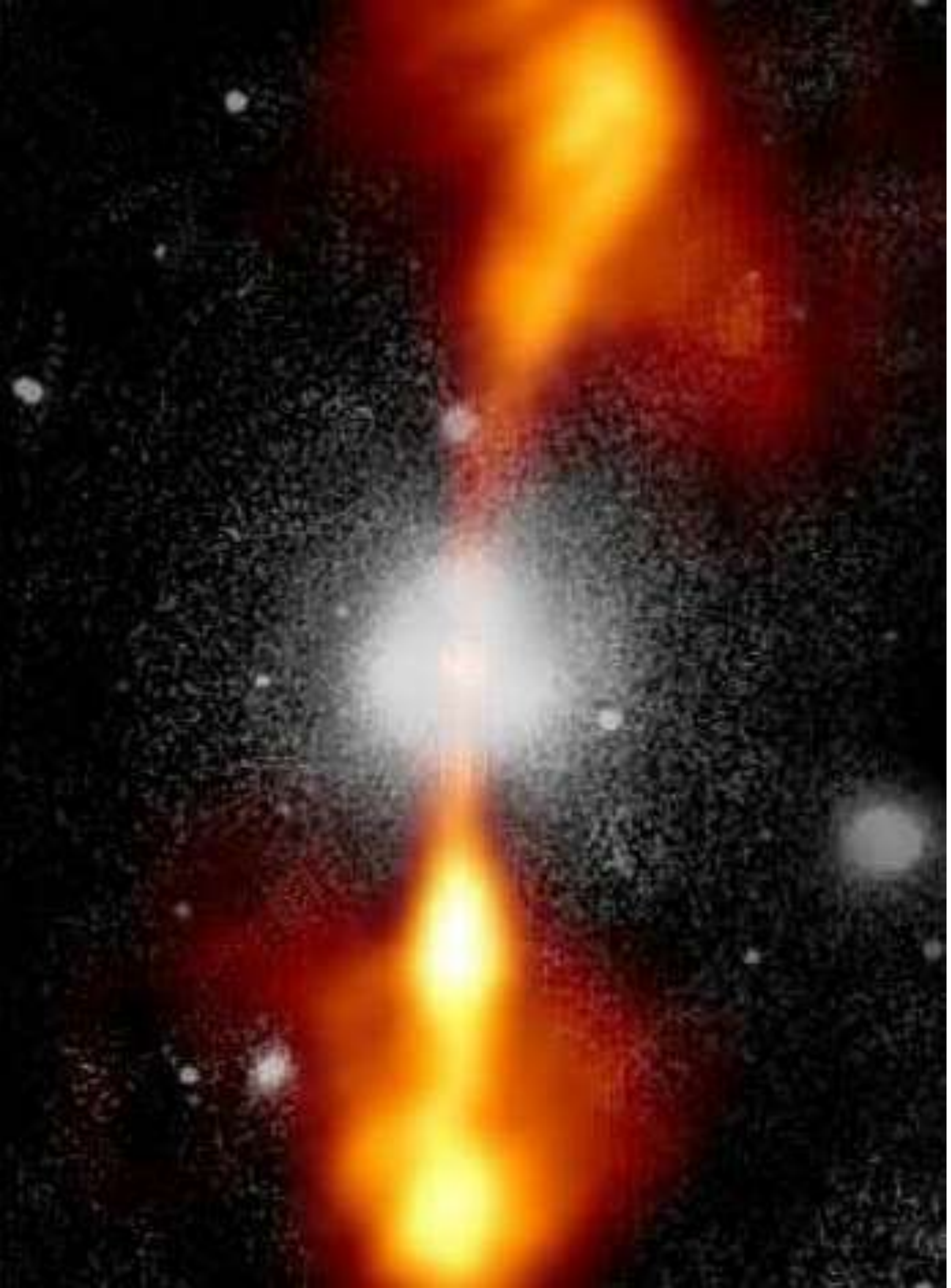
First phase

- The cloud accelerates to 0.5c
- Deflected by 120^{O}

Last phase

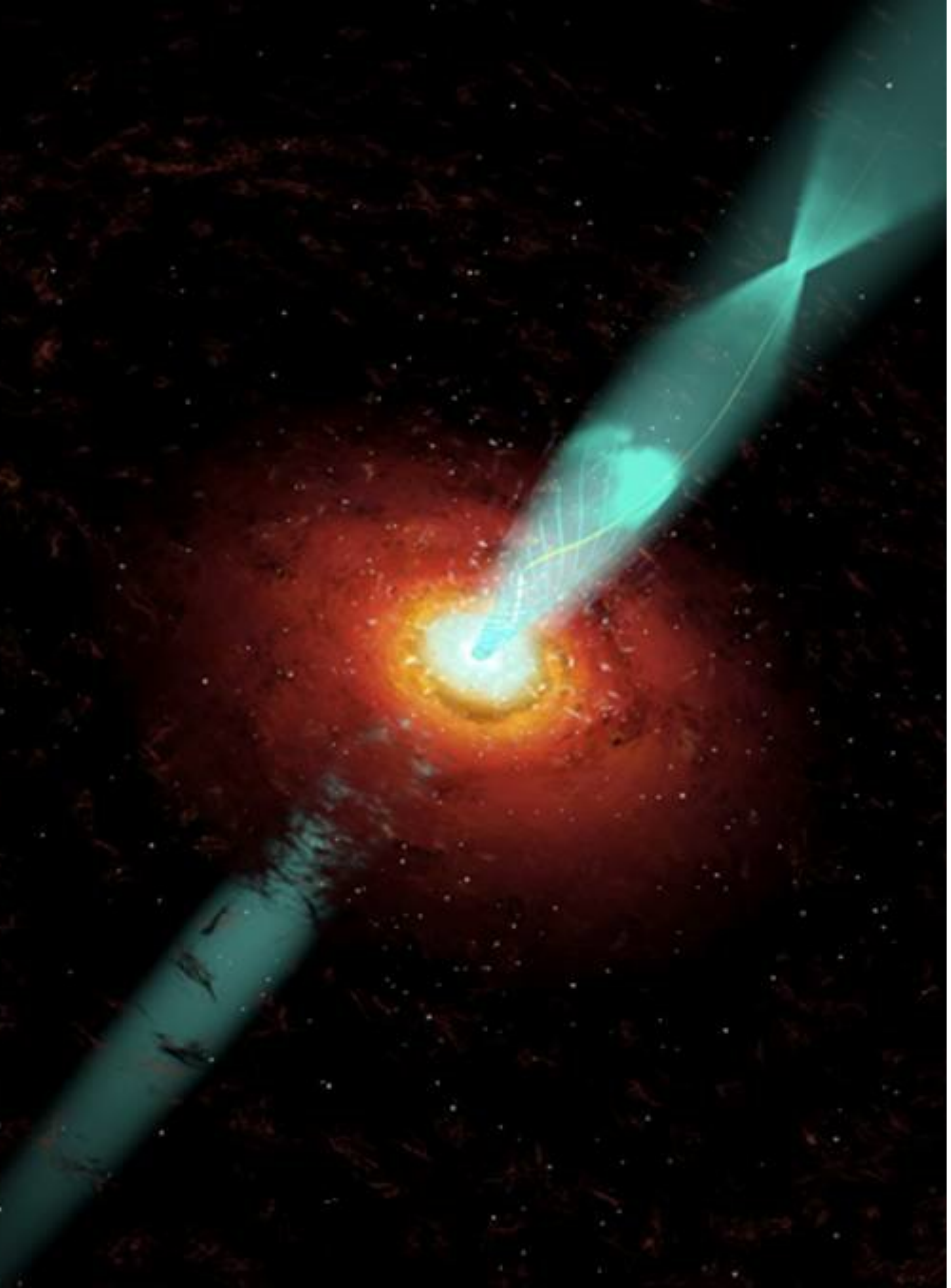
- Disc formation
- Vortex within torus





Conclusions

- Development of general relativistic code



Projects

- Time evolution of the space-time + GRMHD
- Particles acceleration + general relativistic magneto-hydrodynamic