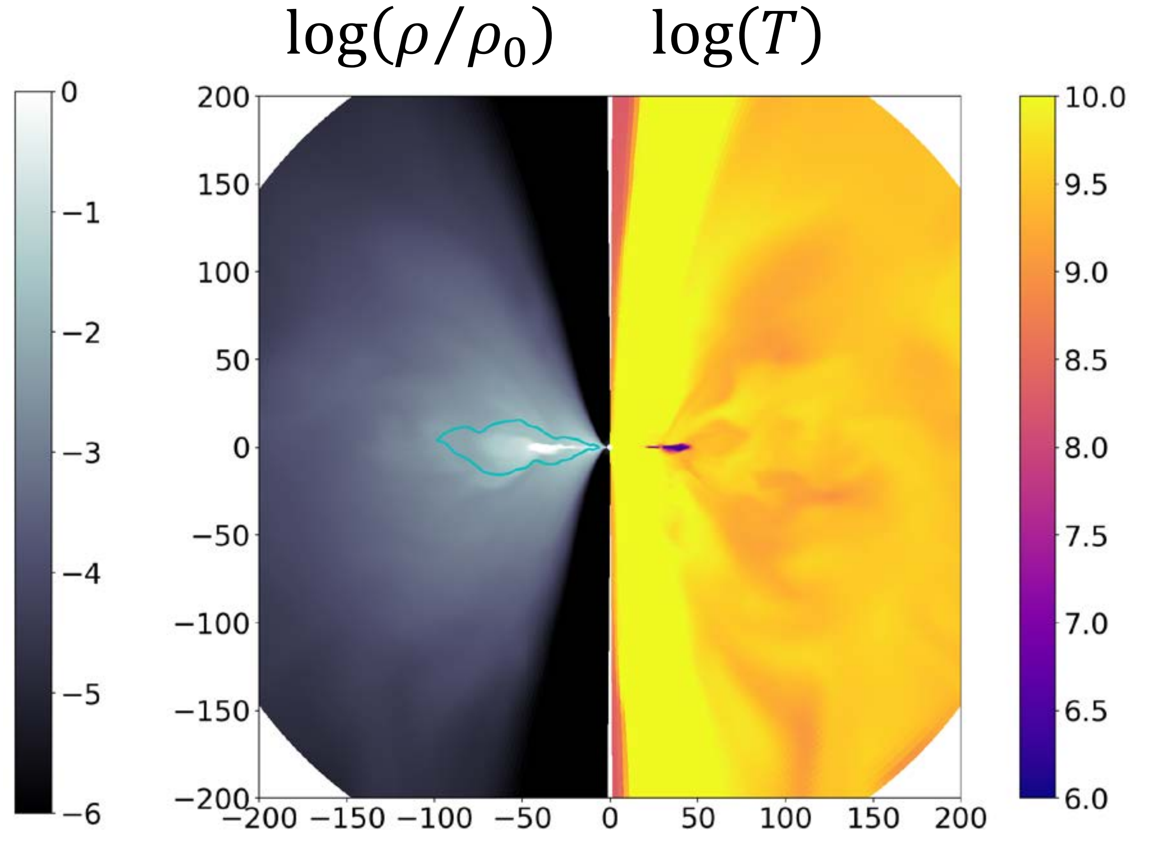
GRRMHD simulations of black hole accretion flows solving Boltzmann equation



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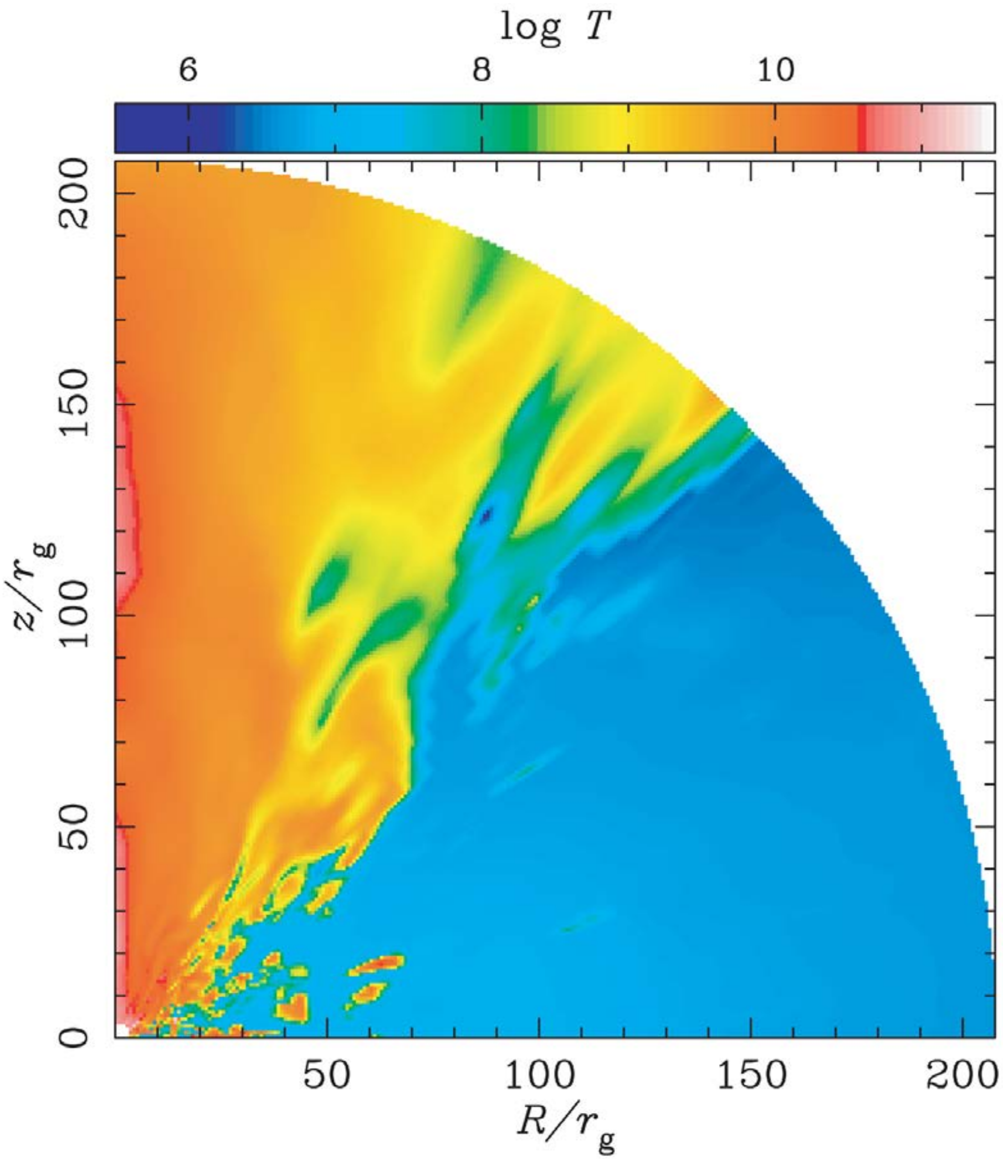
Radiation Hydrodynamics Simulations



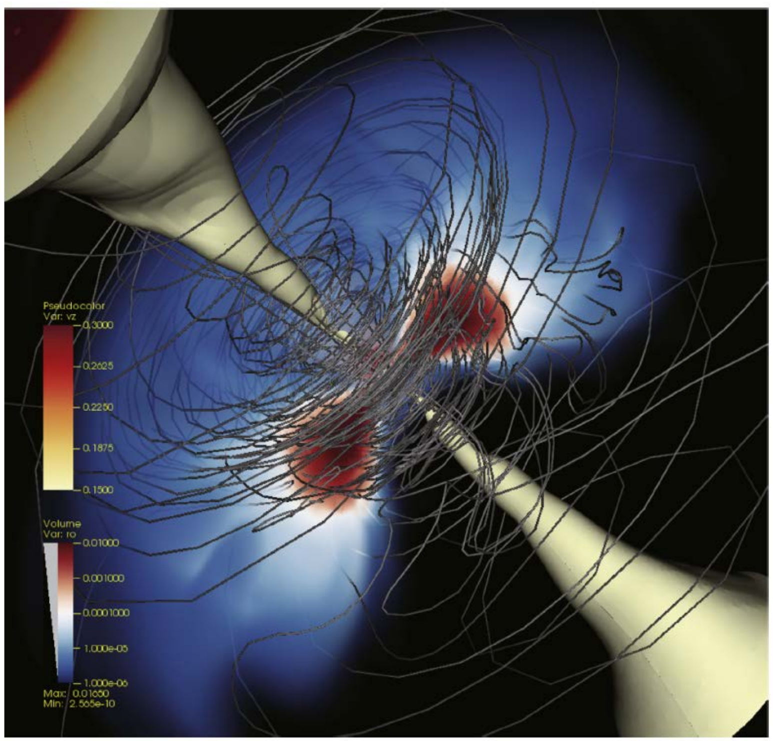
Ohsuga et al. (2005)

Ohsuga et al. (2005) conducted 2D radiation HD simulations of the supercritical accretion flows around a black hole

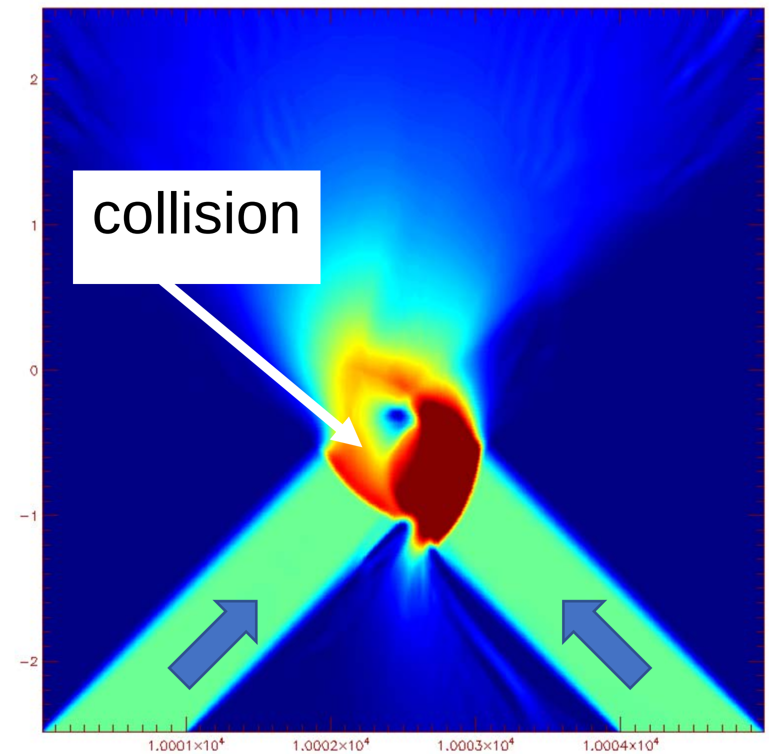
- Hot outflow with velocity of 0.1c is formed around the rotation axis by strong radiation pressure
- The radiation is important for the outflow formation and structure of the accretion flow

General Relativistic Radiation MHD Simulations (M1 method)

Takahashi et al. (2016) carried out 3D general relativistic radiation MHD simulations of accretion flows which is formed by the magnetorotational instability (MRI).
The jet is accelerated by the strong radiation pressure.



Takahashi et al. (2016)



M1 method

Boltzmann Equation for Radiation

$$\frac{\partial I}{\partial t} + \boldsymbol{n} \cdot \frac{\partial I}{\partial \boldsymbol{x}} = 0$$

$\times \int \mathrm{d}\Omega \Rightarrow$

$$\frac{\partial E_r}{\partial t} + \frac{\partial F^i}{\partial x^i} = 0$$

$\times \boldsymbol{n} \int \mathrm{d}\Omega \Rightarrow$

$$\frac{\partial F^i}{\partial t} + \frac{\partial P^{ij}}{\partial x^j} = 0$$

- In order to solve this equation, we need to obtain the radiation pressure $P^{ij} = \mathbb{D} E_r$
- M1 method assumes that the Eddington tensor is below in order to close these equations (Gonzalez et al. 2007)

$$\mathbb{D} = \frac{1-\chi}{2}\mathbb{I} + \frac{3\chi - 1}{2}\boldsymbol{n} \otimes \boldsymbol{n}, \quad \chi = \frac{3 + 4\|\boldsymbol{f}\|^2}{5 + 2\sqrt{4 - 3\|\boldsymbol{f}\|^2}}, \quad \boldsymbol{f} = \frac{\boldsymbol{F}_\mathrm{r}}{cE_\mathrm{r}}$$

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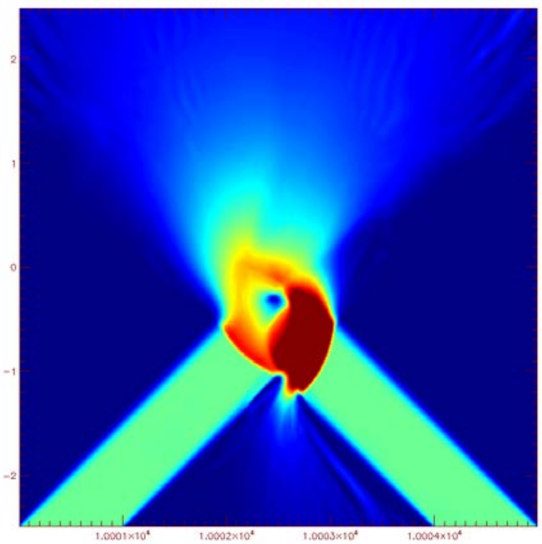
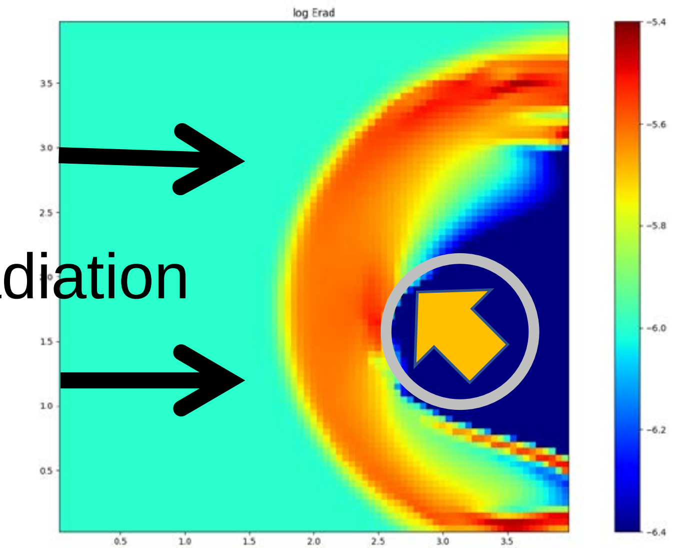
Demonstrations

Beam crossing test

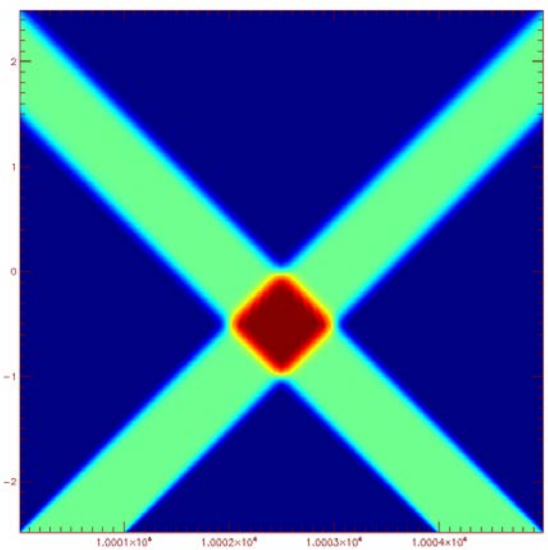
Interaction with optically thick cloud for scattering

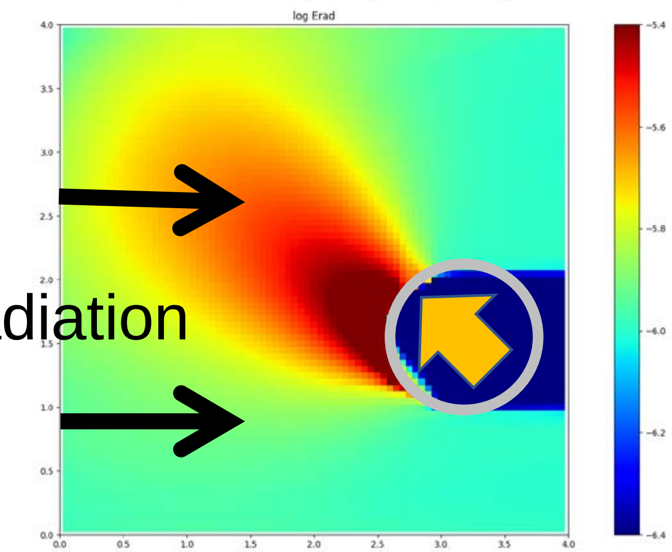
M1 method



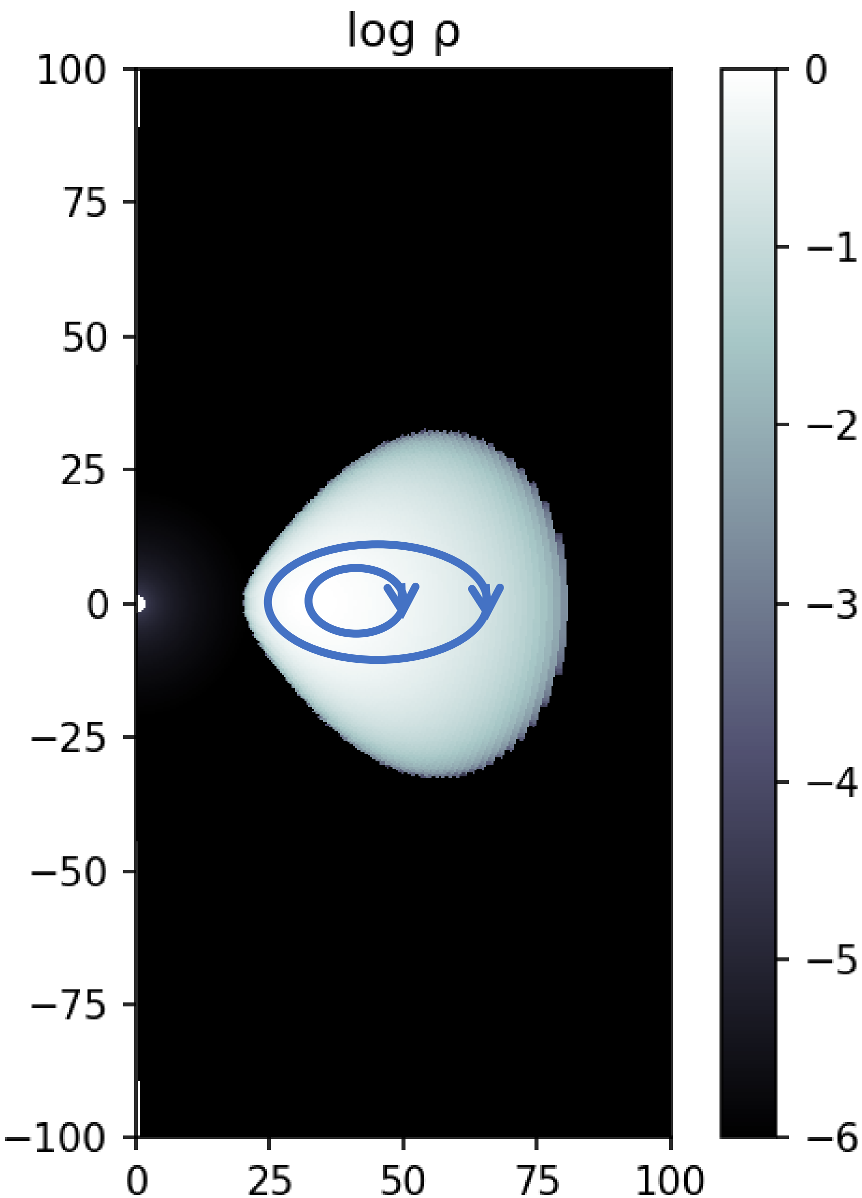


INAZUMA





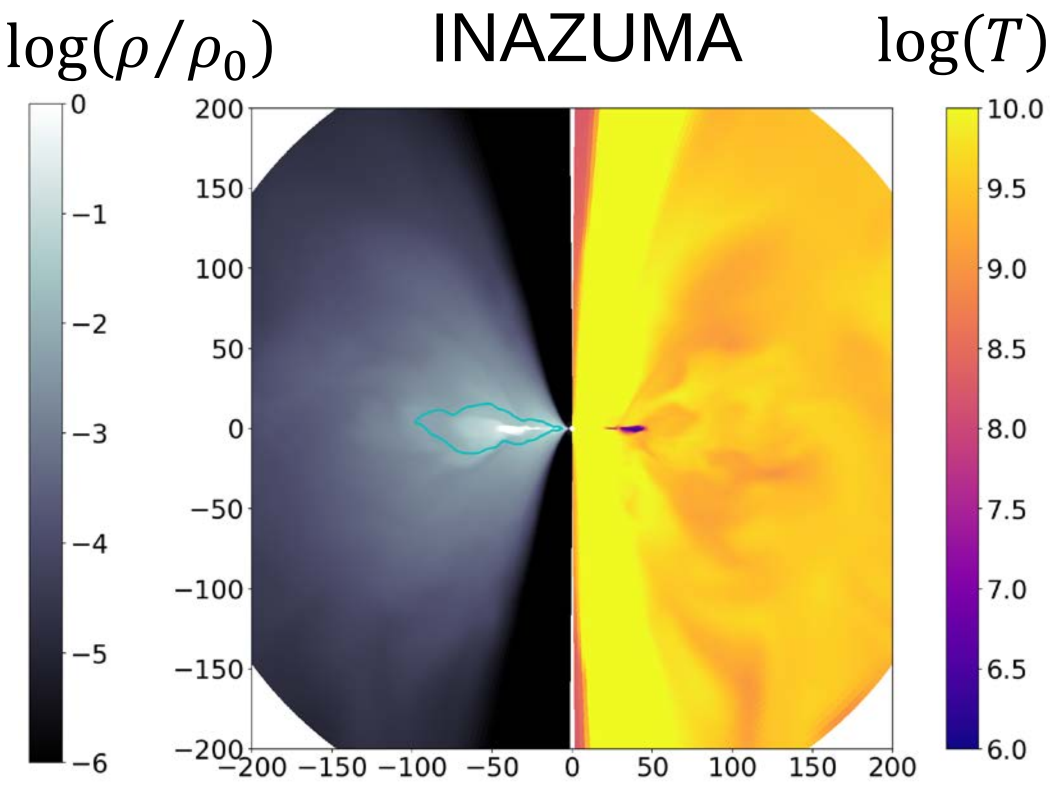
Initial Condition

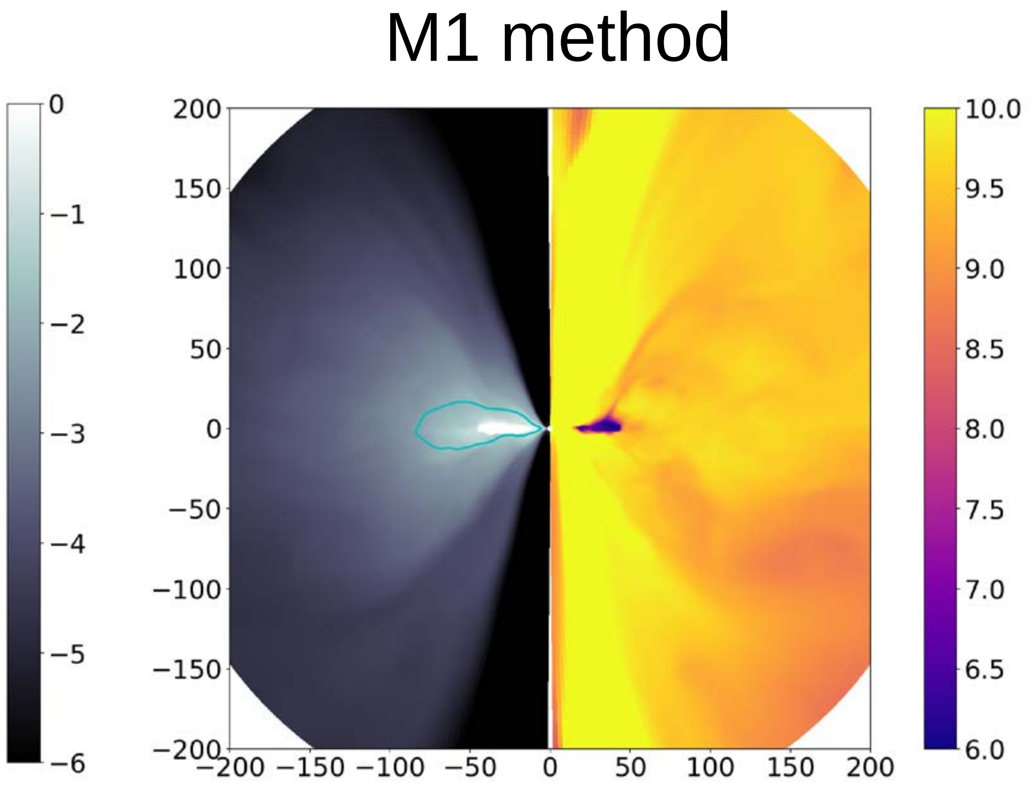


- We start simulations from an equilibrium torus given by Fishbone & Moncrief (1976)
- We simulate three models with the maximum density of the initial torus of $\rho_0=10^{-2}$, 10^{-4}, 10^{-5} g/cm^3
- We assume the weak poloidal magnetic field in the torus (blue curves)
- Free-free emission/absorption and isotropic electron scattering are considered
- Grid points

$(N_r, N_\theta, N_{\bar{\theta}}, N_{\bar{\varphi}}) = (300, 300, 8, 16)$

Density and Temperature Profiles ($\rho_0 = 10^{-5}$ g/cm^3)

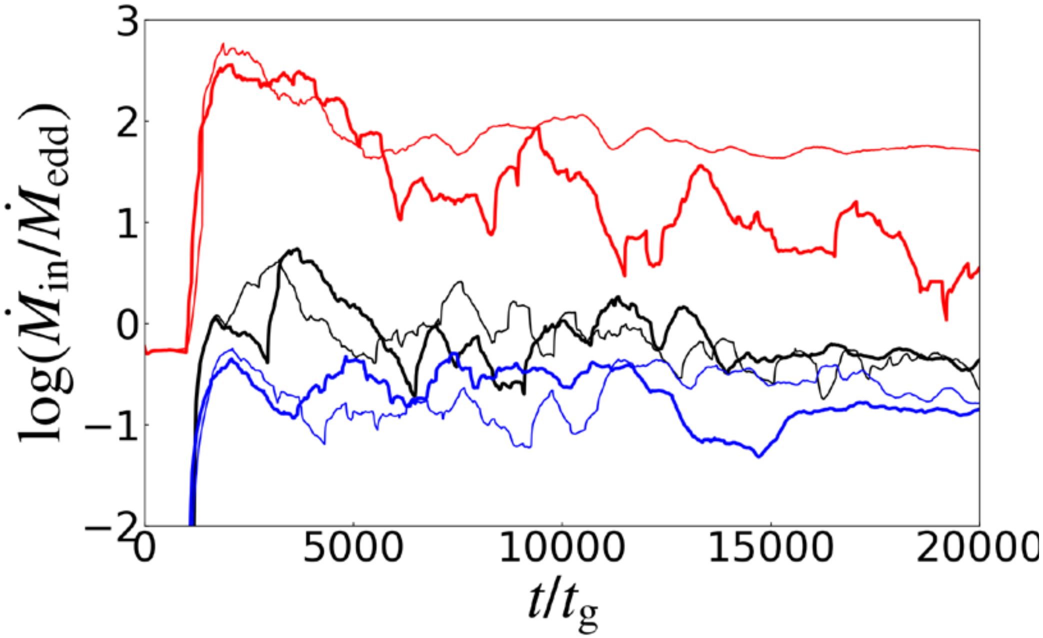


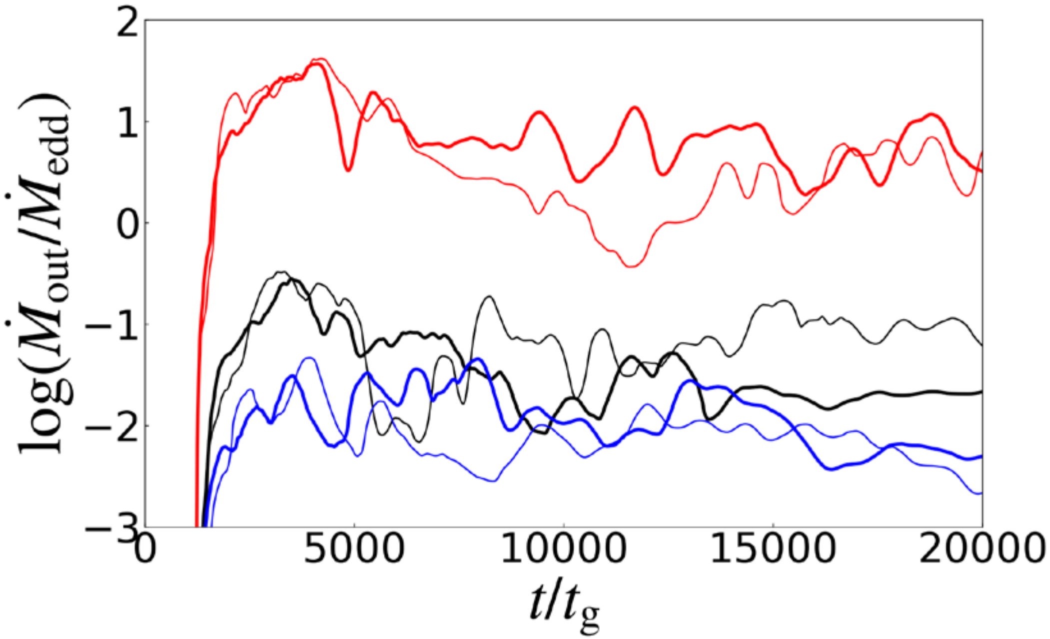


- The angular momentum transport occurs by the MRI and then the black hole accretion flow is formed in all models
- The density and temperature profiles are similar globally between M1 and INAZUMA in all models

Time Evolution of the Mass Accretion Rate and Outflow Rate

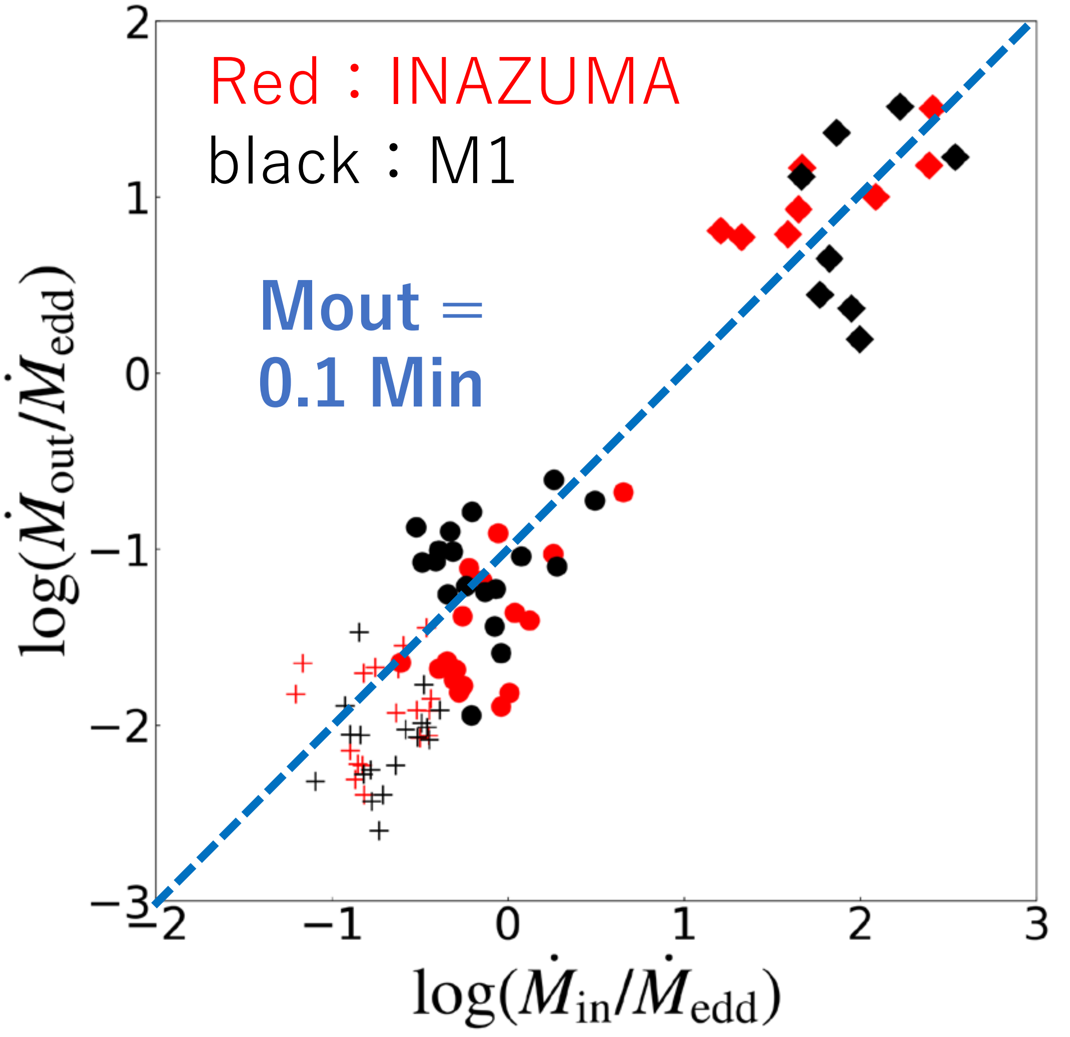
Red : $\rho_0=10^{-2}$	bold : INAZUMA
Black : $\rho_0=10^{-4}$	fine : M1
Blue : $\rho_0=10^{-5}$	





- The accretion rate is roughly similar for models except high accretion model
- The outflow rate is also similar between M1 and INAZUMA

Relation of the Accretion and Outflow

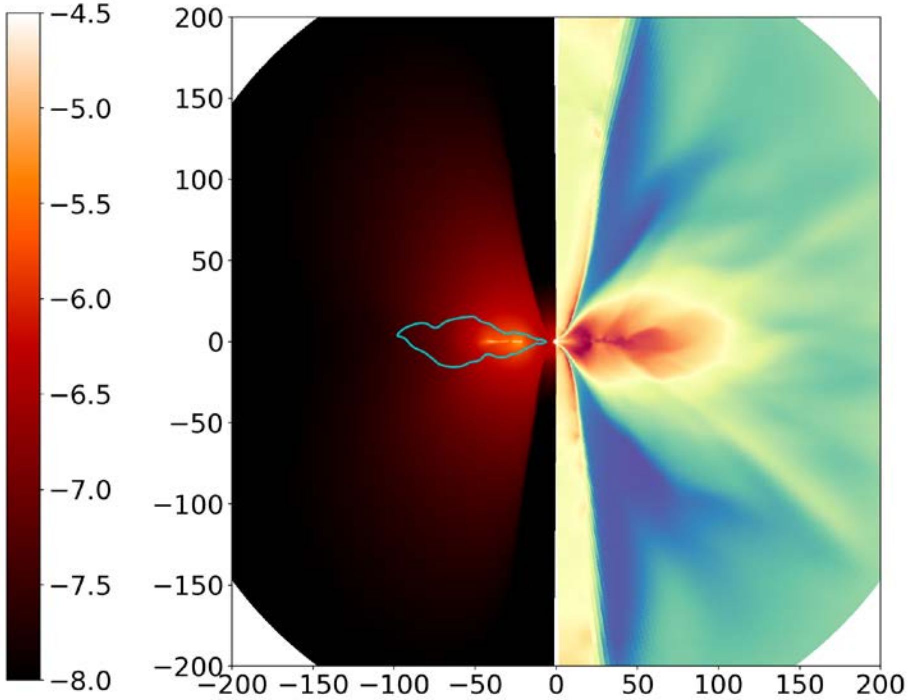


- This is the relation between the accretion rate and outflow rate averaged every 1000tg
- The outflow rate is roughly proportional to 10% of the accretion rate
- The tendency is similar between M1 and INAZUMA

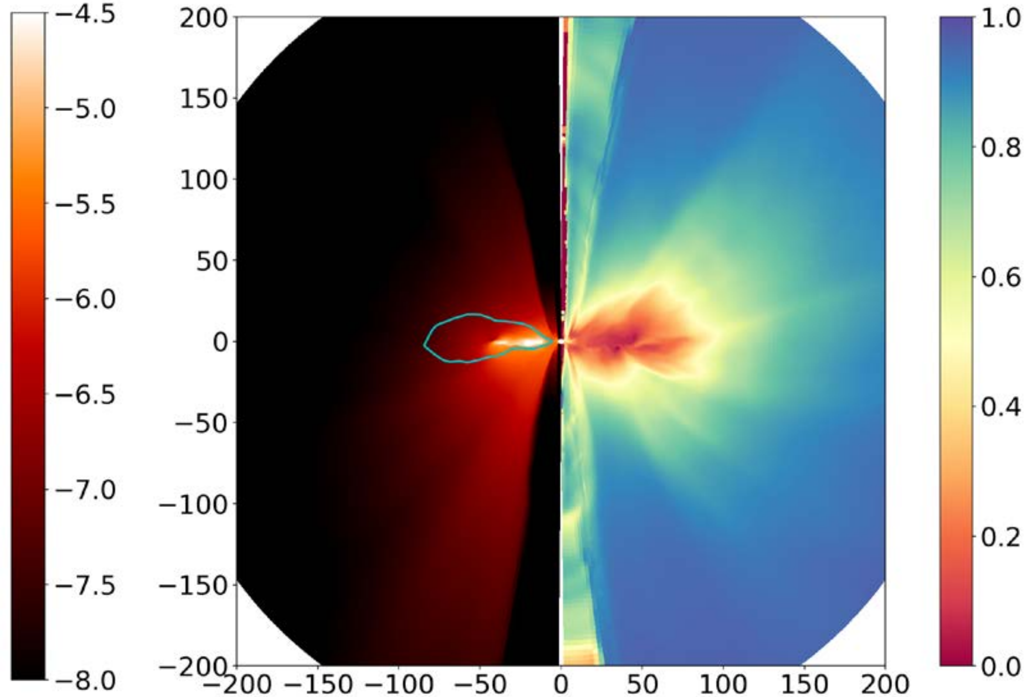
Application to Black Hole Accretion Flows

$\rho_0 = 1.0 \times 10^{-5}$ g/cm^3

$\log(E_{rad}/\rho_0)$ INAZUMA F_r/E_{rad}



M1 method

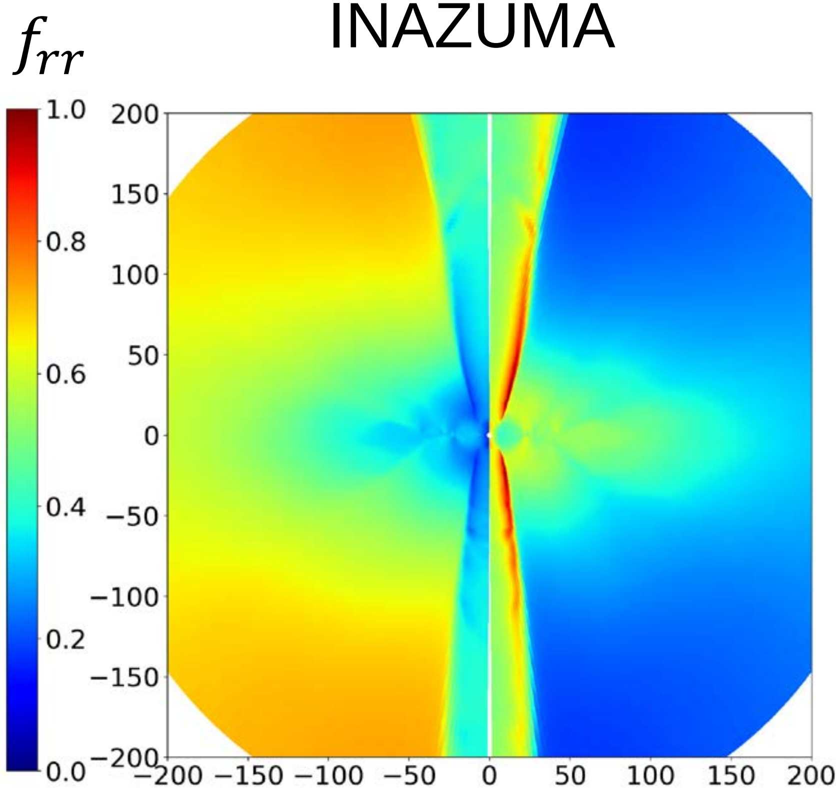


- The radiation energy density profiles are almost the same
- The radiation tends to propagate radially outward easily in the M1 method

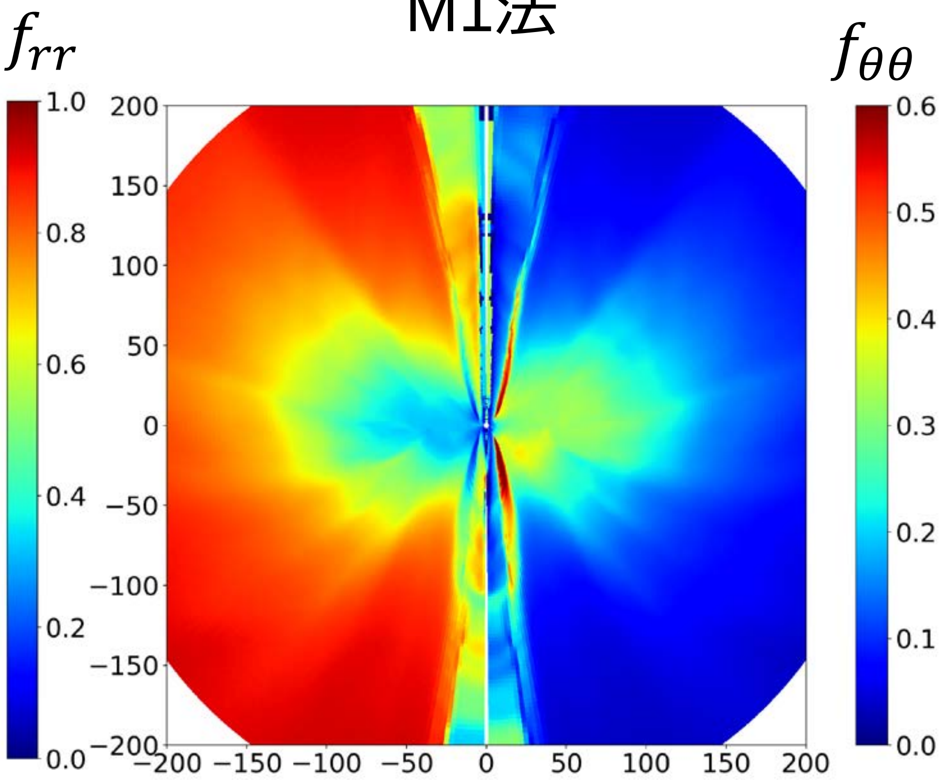
Comparison of the Eddington Tensor

ρ_0 = 1.0x10^{-5} g/cm^3

INAZUMA



M1法

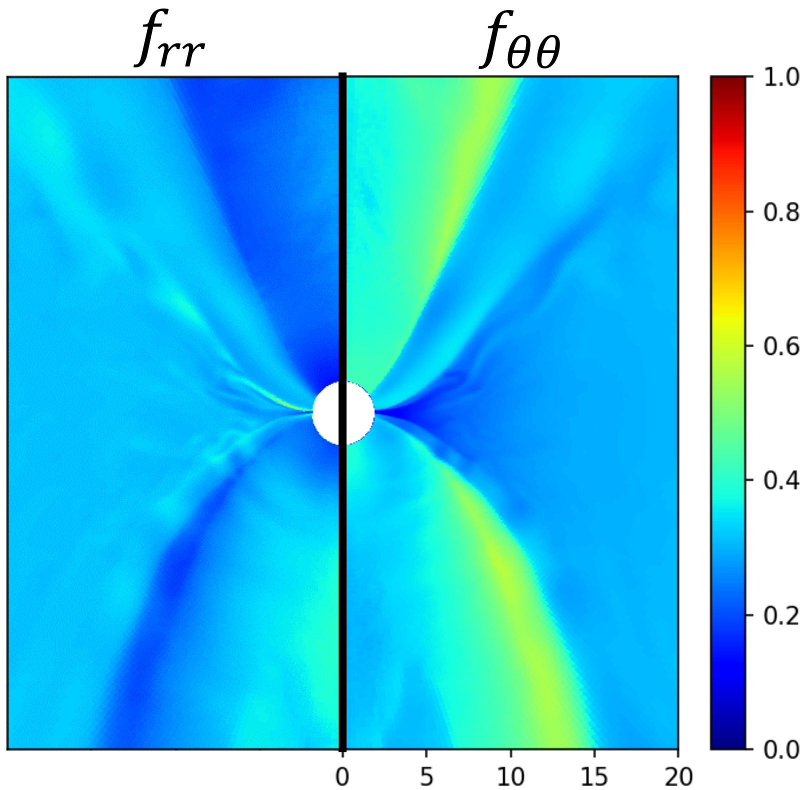


- The rr-component of the Eddington tensor becomes almost unity in the M1 method in the optically thin region far from the black hole while it becomes 0.6-0.7 in INAZUMA
- This means the radiation propagates only radially outward in M1

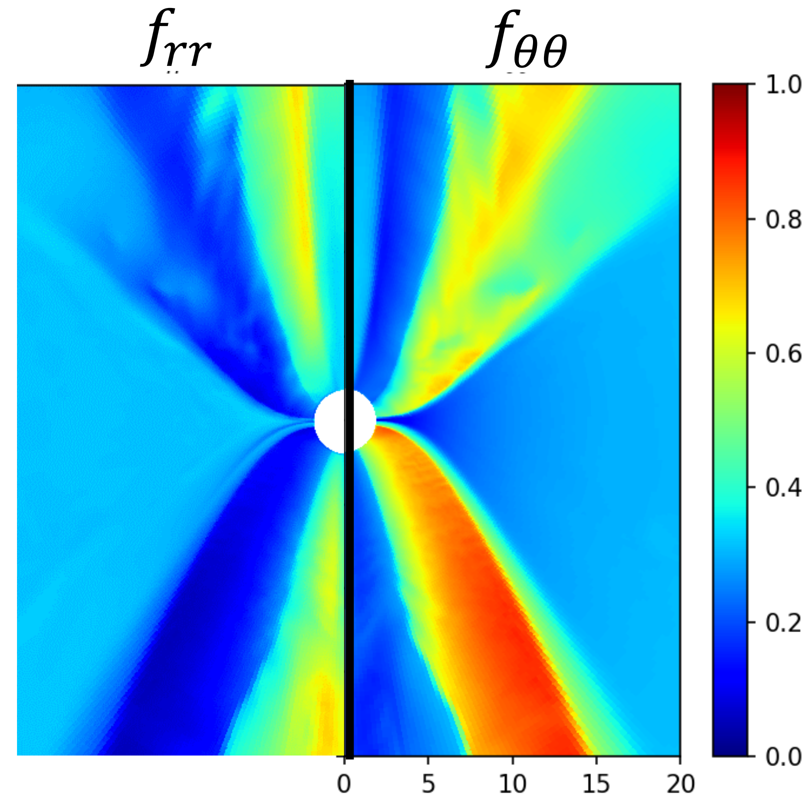
Unphysical Radiation Collision around the Rotation Axis

$\rho_0 = 1.0\text{x}10^{-2}$ g/cm^3

INAZUMA



M1



- The rr-component of the Eddington tensor around the rotation axis is smaller and θθ-component is larger in INAZUMA
- In M1 method, the unphysical radiation collision around the axis makes the rr-component larger and θθ-component smaller

Summary

- We developed the GR-RMHD code INAZUMA solving the time dependent radiation transfer equation
- We perform some test simulations and apply INAZUMA to the black hole accretion flow
- INAZUMA code can solve the radiative transfer in the optically thin region far from the black hole and around the rotation axis
- The mass accretion and outflow rate are similar between INAZUMA and M1 except high accretion model