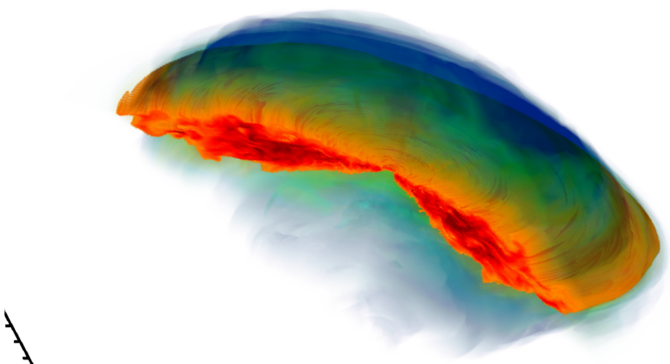
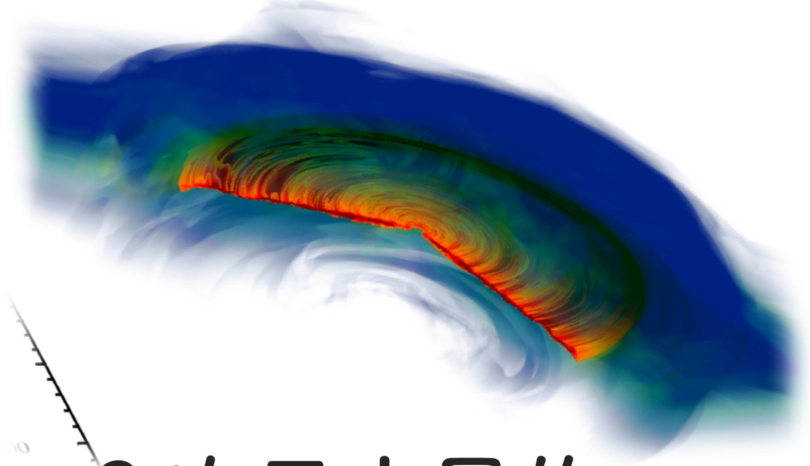




ブラックホール降着円盤の３次元大局的輻射磁気流体シミュレーション
Three-Dimentional Global Radiation MHD Simulations of Black Hole Accretion Disks

GRADUATE SCHOOL OF SCIENCE AND ENGINEERING ,CHIBA UNIVERSITY

TAICHI IGARASHI

COLLABOLATOR

YOSHIAKI KATO (RIKEN)

HIROYUKI TAKAHASHI (CHUBU UNIV.)

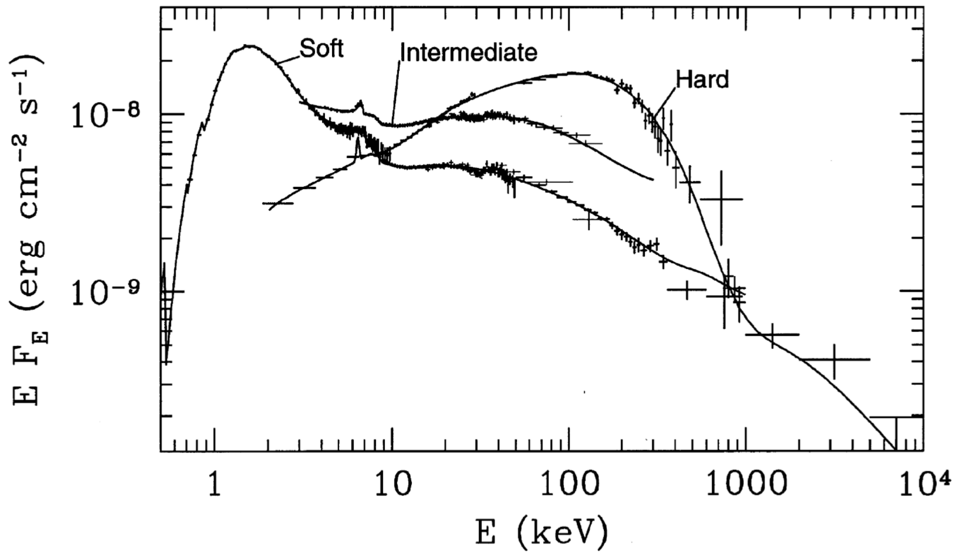
KEN OHSUGA (TSUKUBA UNIV.)

RYOJI MATSUMOTO (CHIBA UNIV.)

YOSUKE MATSUMOTO (CHIBA UNIV.)

Black Hole Accretion Disks

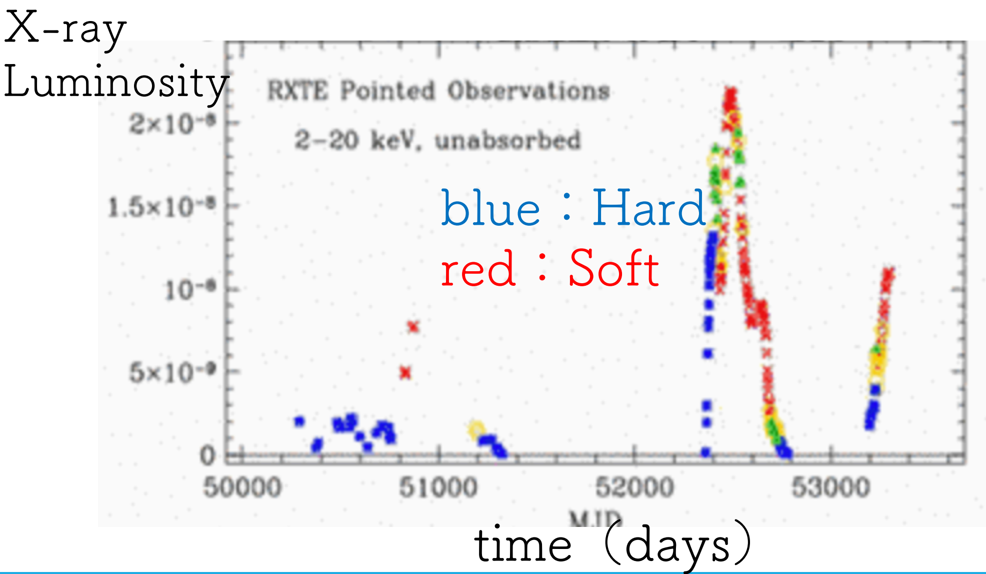
- When rotating gas accretes to a Black Hole , Accretion disks are formed
  - Binary BH candidates observed by X-ray.
    - Hard state : Hard X-ray dominant and faint.
    - Soft state : Soft X-ray dominant
    - Bright Hard state : Hard X-ray dominant and luminous.

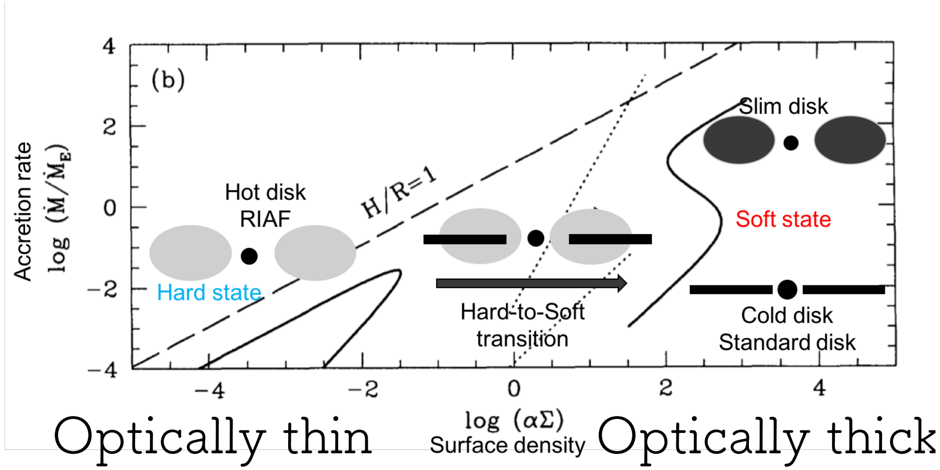


Cyg X-1 Gierlinski et al.1999

Hard-to-Soft Transition

- During an outburst of stellar mass ($\sim 10 M_{\odot}$) black hole candidates, state transitions are observed.
  - Bright hard state
  - Low frequency QPO(LFQPO) with peak frequency around 0.1~10 Hz.
  - Jet ejection
- The state transitions can be explained by using thermal equilibrium curve.





GX 339-4 Remillard 2005

Abramowicz et al.1995

MagnetoHydroDynamic Simulation

- Machida et al. 2006
  - MHD simulation of the cooling instability in initially optically thin hot accretion flow.
  - Radiative cooling is included after the magnetic turbulence driven by the MRI grows, so that the RIAF is formed.
  - When the density of the disk exceeds threshold for the onset of the cooling instability, the disk shrinks in the vertical direction by cooling and forms a magnetic pressure dominated disk.
  - ✓ Only considered optically thin radiative cooling.
  - ✓ Numerical oscillation in the low-β region.
- Compute more accurately in low-β region.
- Handle both optically thick and thin region.

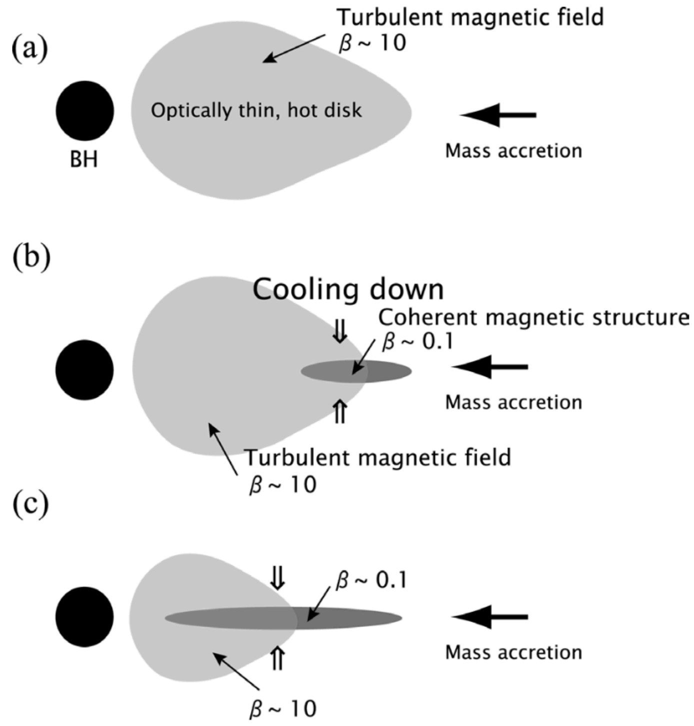


Fig. 7. Schematic picture of state transitions in black hole candidates. (a) Low/hard state, (b) onset of the cooling instability, (c) the transition radius between the hot disk and cool low-β disk moves inward as the accretion rate increases.

Machida et al.2006

Purpose of this study

- Investigate the time variabilities of accretion disks around a stellar mass Black Hole during hard-to-soft transition with moderately high accretion rate(~$0.1\dot{M}_{Edd}$) by global 3D Radiation MHD(RMHD) simulations.
  - Structure of the disk during hard-to-soft transition
  - Origin of QPO
  - Jet ejection

Numerical Method

- We apply non-relativistic version of the RMHD code developed by H.R.Takahashi and K.Ohsuga (2013)

- RMHD code CANS+R
  - Resistive-MHD part : CANS+(Matsumoto et al. 2016)
    - High order MHD code based on the HLLD approximate Riemann solver (Miyoshi and Kusano 2005)
    - 5^{th} order special accuracy is achieved by applying the MP5 scheme (Suresh & Huynh 1997)
    - Hyperbolic divergence cleaning
  - Radiation part : (Takahashi and Ohsuga 2013, Kobayashi et al. 2018)
    - Solve with 0^{th} and 1^{st} moments of time dependent , frequency averaged radiative transfer equation.
    - The equations are closed by M1-closure
    - Accurate to the order of v/c

Basic Equations of CANS+R

Resistive MHD

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

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + P\boldsymbol{I}) = \rho \nabla \phi_{PN} - \boldsymbol{S}(\mathbb{P}_r)$$

$$\frac{\partial E}{\partial t} + \boldsymbol{\nabla} \cdot [(E + P\boldsymbol{I})\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = -\nabla \cdot (\eta \boldsymbol{j} \times \boldsymbol{B}) + \rho \boldsymbol{v} \cdot \nabla \phi_{PN} - cS(E_r)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla} \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} + \psi \boldsymbol{I}) = -\boldsymbol{\nabla} \times (\eta \boldsymbol{j})$$

$$\frac{\partial \psi}{\partial t} + c_h^2 \boldsymbol{\nabla} \cdot \boldsymbol{B} = -\frac{c_h^2}{c_p^2}\psi$$

Source term

$$\boldsymbol{S}(\mathbb{P}_r) = \rho \kappa_{ff} \frac{\boldsymbol{v}}{c}(a_r T^4 - E_r) - \rho(\kappa_{ff} + \kappa_{es})\frac{1}{c}[\boldsymbol{F}_r - (\boldsymbol{v}\boldsymbol{E}_r + \boldsymbol{v} \cdot \mathbb{P}_r)]$$

$$S(E_r) = \rho \kappa_{ff}(a_r T^4 - E_r) + \rho(\kappa_{ff} - \kappa_{es})\frac{\boldsymbol{v}}{c} \cdot [\boldsymbol{F}_r - (\boldsymbol{v}\boldsymbol{E}_r + \boldsymbol{v} \cdot \mathbb{P}_r)]$$

Radiation

$$\frac{1}{c^2}\frac{\partial \boldsymbol{F}_r}{\partial t} + \boldsymbol{\nabla} \cdot \mathbb{P}_r = \boldsymbol{S}(\mathbb{P}_r)$$

$$\frac{\partial E_r}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{F}_r = cS(E_r)$$

Pseudo-Newtonian potential

$$\phi_{PN} = -\frac{GM}{R - r_s}$$

Electron Scattering Opacity

$$\kappa_{es} = \frac{\sigma_T}{m_p} = 0.4$$

Free-Free Absorption Opacity

$$\kappa_{ff} = 1.7 \times 10^{-25} m_p^{-2} \rho T_{gas}^{-3.5}$$

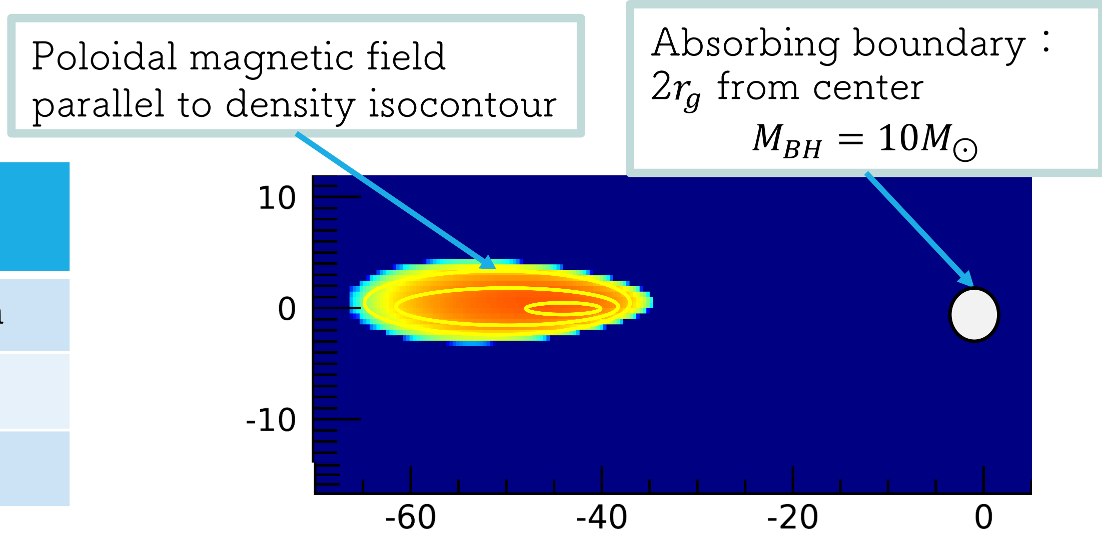
M1-closure

- $\mathbb{P} = \mathbb{D}E$
- Eddington tensor : $\mathbb{D}$
  - $\mathbb{D} = \frac{1-f}{2}\mathbb{I} + \frac{3f-1}{2}\boldsymbol{nn}$
- Eddington factor : f
  - $f = \frac{3+4\xi^2}{5+2\sqrt{4-3\xi^2}}$
  - $\xi = \frac{|\boldsymbol{F}|}{cE}$
  - $\boldsymbol{n} = \frac{\boldsymbol{F}}{|\boldsymbol{F}|}$

- Optically thick limit
  - $\xi = 0$
  - $\mathbb{D} = \frac{1}{3}\mathbb{I}$
- Optically thin limit
  - $\xi = 1$
  - $\mathbb{D} = \boldsymbol{nn}$

Simulation Set Up

normalization	
length	Schwarzschild radius: $r_g = 3\times10^6$ cm
velocity	Light speed: $c = 3\times10^{10}$ cm/s
Time	$t_0 = r_g/c = 1\times10^{-4}$ s



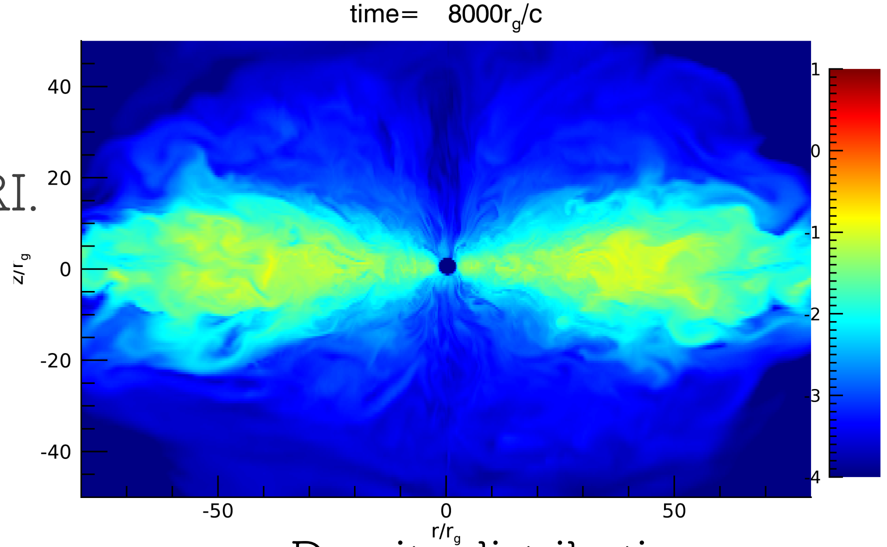
Initial density distribution

- 3D-cylindrical coordinate
  - 401*32*411 grids
  - $0 \le r \le 100r_g$
  - $\Delta r = 0.1r_g \ (0 \le r \le 20r_g)$
  - $-100r_g \le z \le 100r_g$
  - $\Delta z = 0.1r_g(-5rg \le z \le 5r_g)$

- Initial state
  - Equilibrium solution of rotating torus
  - Weak poloidal magnetic field.
  - At the density maximum of the torus ($r = 40r_g$)
    - Plasma β (P_{gas}/P_{mag})=10
    - Kepler rotation

Formation of RIAF

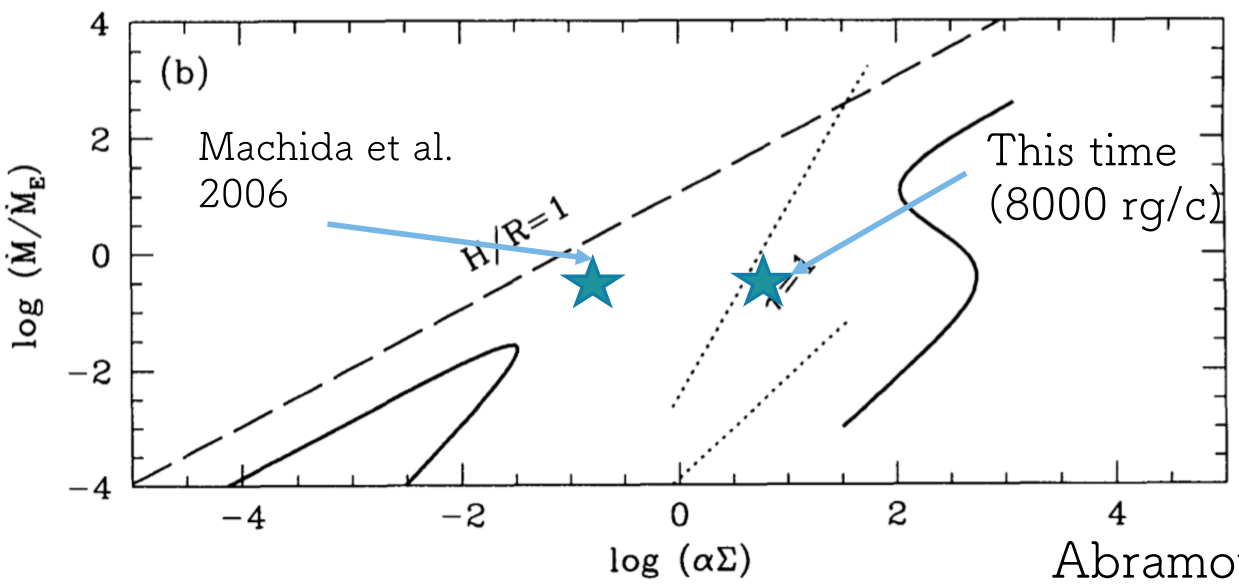
- MHD simulation is carried out without including radiation term until t=8000 r_g/c.
- The torus rotated 4times at 40r_g.
- Accretion is driven by the angular momentum transport by Maxwell stress enhanced by the growth of MRI.
- The disk becomes hot and expands due to the heating by magnetic dissipation.
- Density is ~$0.1\rho/\rho_0$ at mid-plane.
- Radiation term is switched on at t=8000 r_g/c.



Density distribution
@ 8000 r_g/c

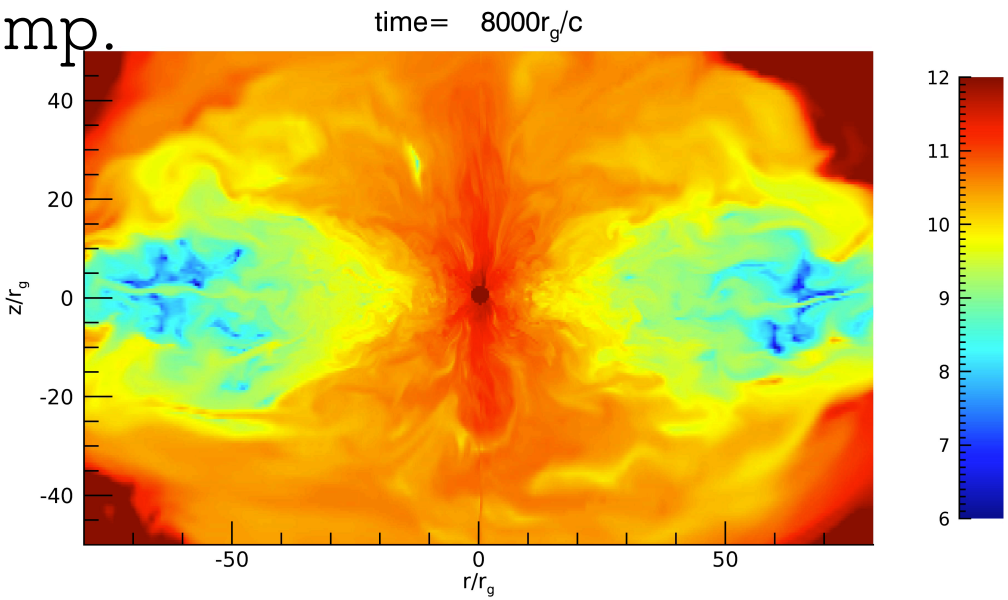
Initial State When Radiation is Switched on.

- Initial maximum density of the torus is : $\rho_0 = 1.0 \times 10^{-4}\ \mathrm{g}/cm^3$
  - Density of the non-radiative accretion flow : $1.0 \times 10^{-5}\ \mathrm{g}/cm^3$ at mid-plane.
  - The initial state is intermediate between optically thin disk and optically thick disk.

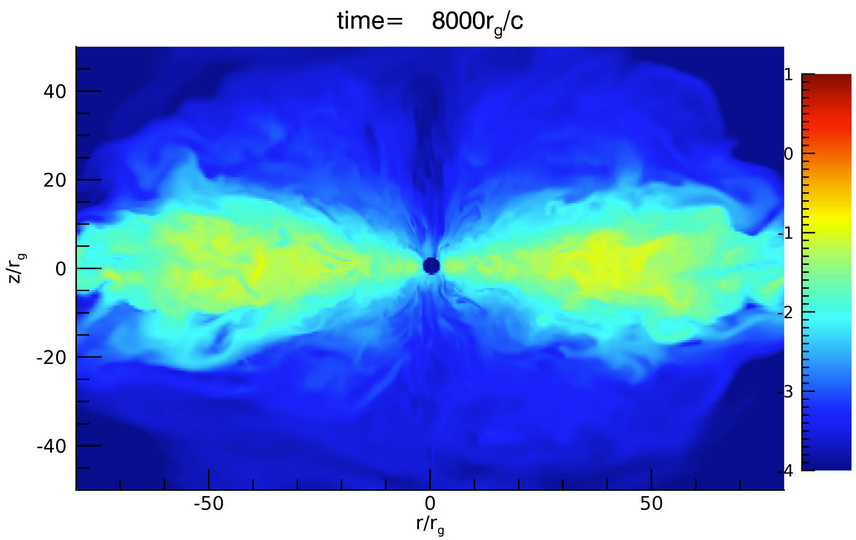


Abramowicz et al.1995

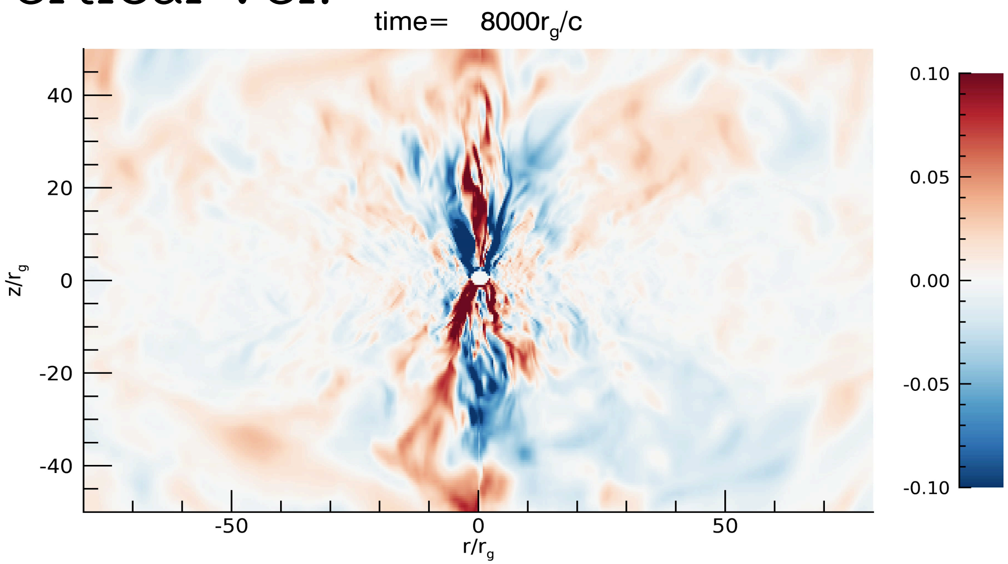
Temp.



Density



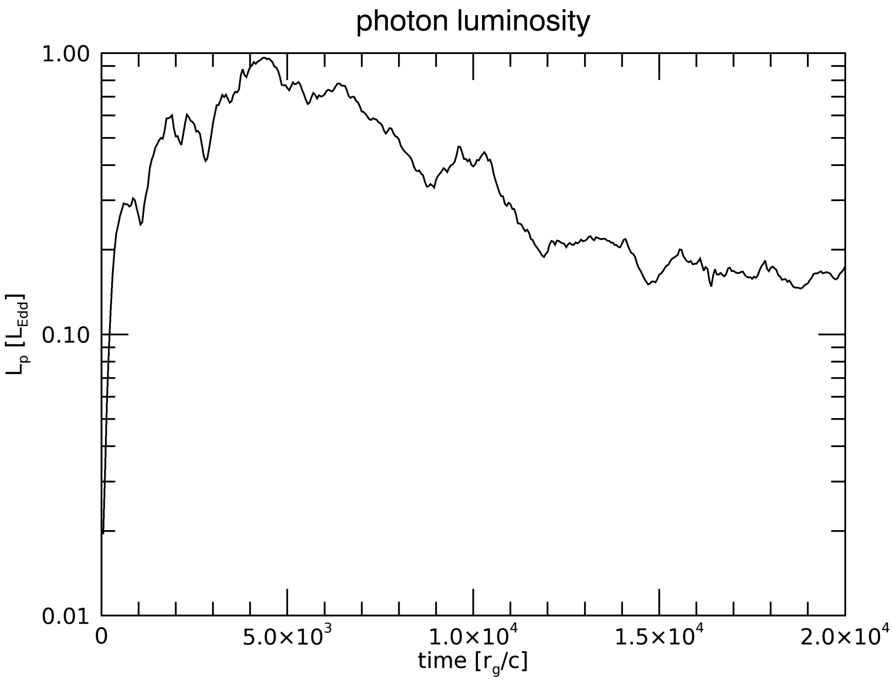
Vertical vel.



Luminosity

$1L_{Edd}$

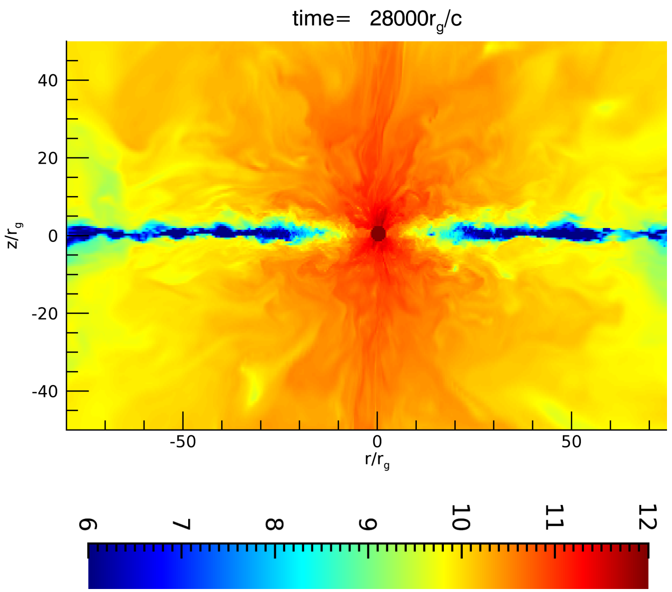
$0.11L_{Edd}$



- $L_{ph} = \int_{-25}^{25}\int_{0}^{2\pi} F_r(r=20) r d\varphi dz \ + \int_{0}^{20}\int_{0}^{2\pi} F_z(z=-25,25) r d\varphi d\mathrm{r}$
- Stationary around ~$0.1L_{Edd}$
  - Consistent with luminosity of bright hard state.

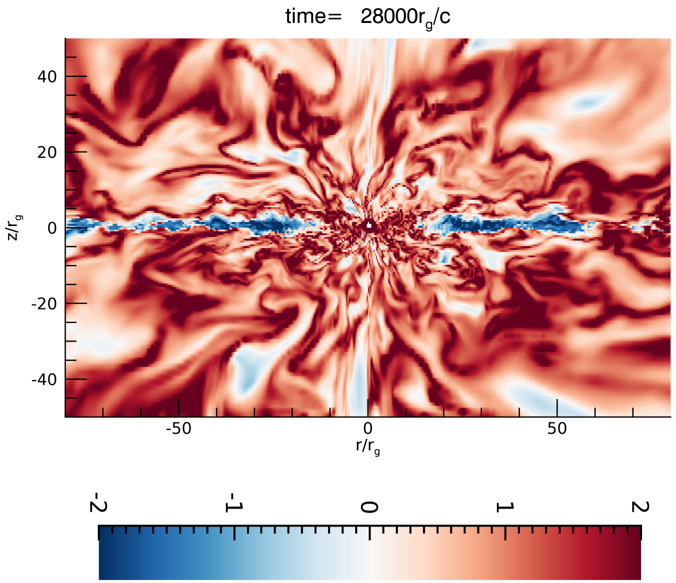
Snap Shot @28000 r_g/c

Temperature



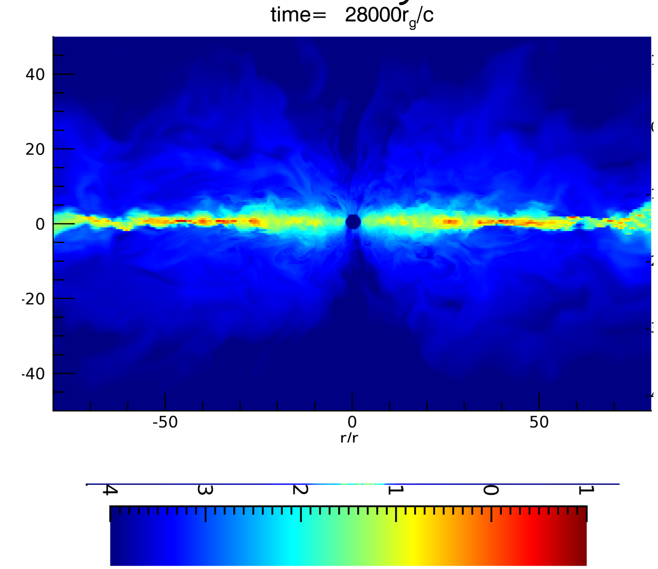
Log T

Plasma β



Log β

Density



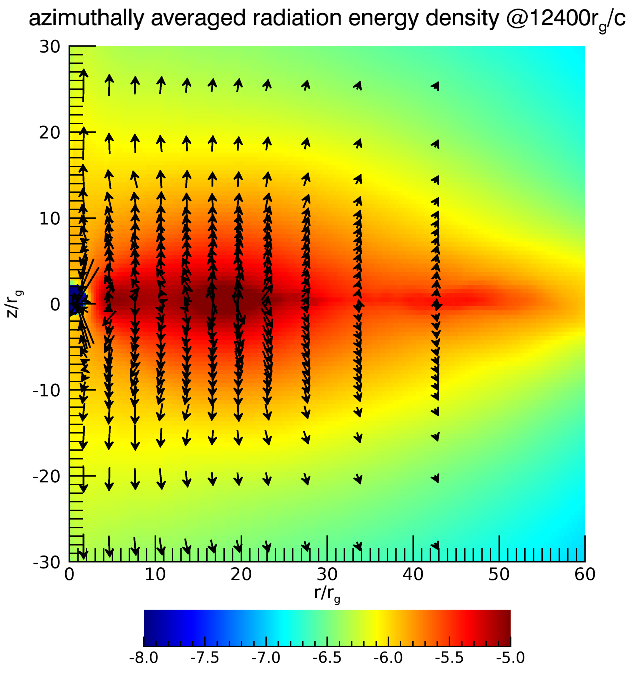
Log ρ/ρ_0

- Cold (~10^6 K),low-β ,geometrically thin disk formed in outer region($> 20r_g$)
- Hot(~10^{11} K),high-β ,geometrically thick disk formed in vicinity of BH($< 20r_g$)

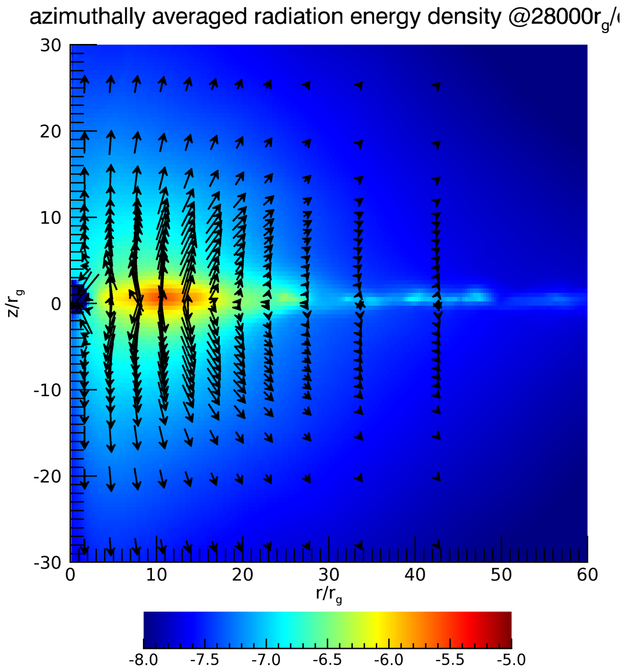
→ : rad flux of r-z plane
color : rad energy density

Radiation Energy Density

t=12400

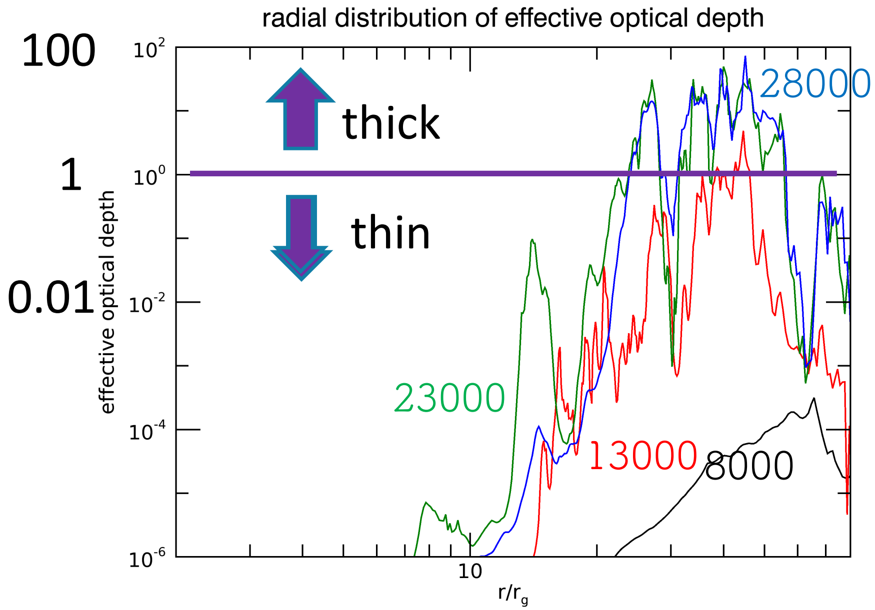


t=28000



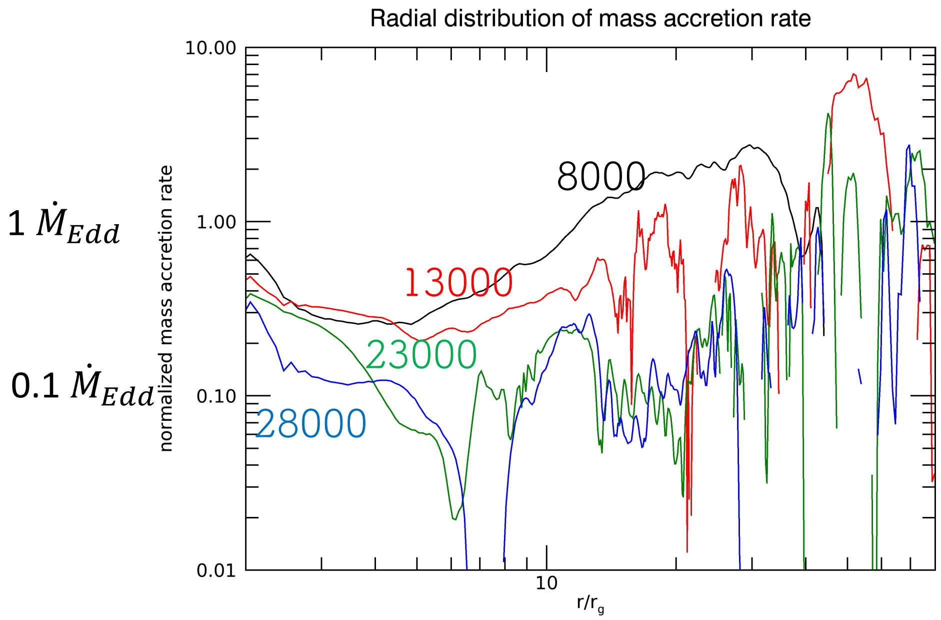
- Radiation energy is the largest around inner edge of the cool disk
- Radiation spectra is dominated by hard X-ray because most of the radiation is emitted in the optically thin region

Radial Distribution of Optical Depth



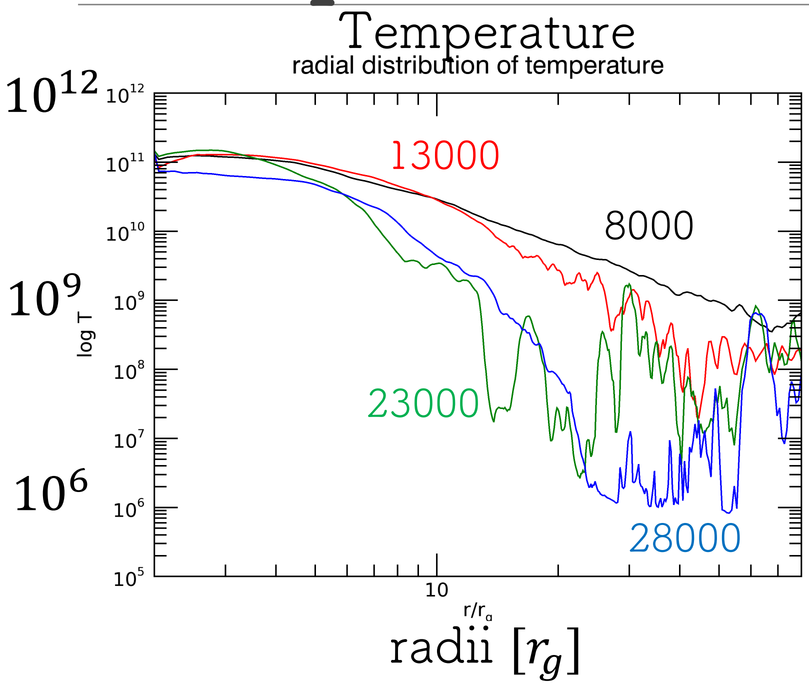
- Effective optical depth : $\tau_{eff} = \sqrt{\tau_{abs}(\tau_{sca} + \tau_{abs})}$
- Whole region is optically thin at the initial state when radiation term is switched on.
- Optical depth gradually increases and outer region become optically thick (τ_{eff}>1).
- But inner region stays optically thin.

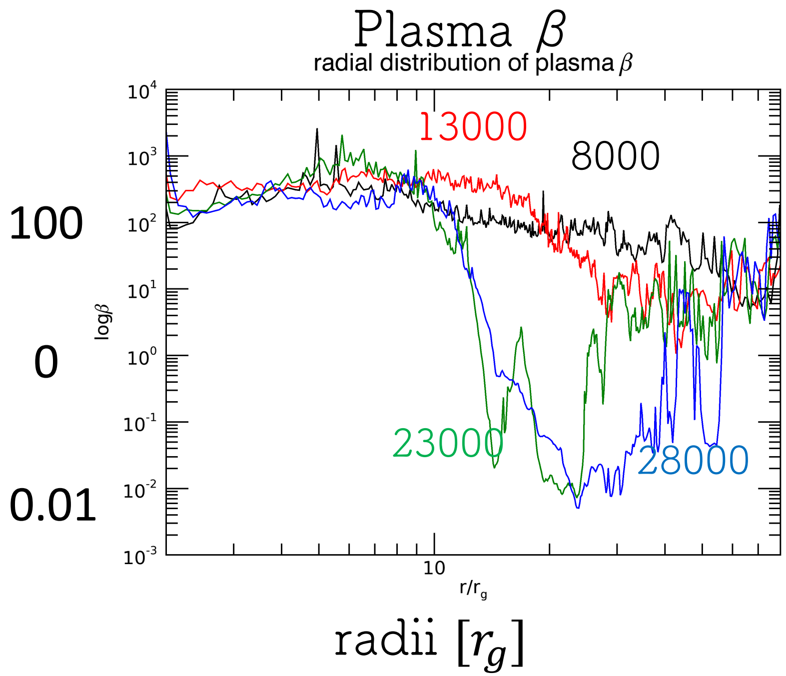
Radial Distribution of Net Mass Accretion Rate



- $\dot{M} = \int_{-H}^{H} \int_{0}^{2\pi} \rho v_r r d\varphi dz$ (H : disk thickness)
- Mass accretion rate is around $0.1\dot{M}_{Edd}$

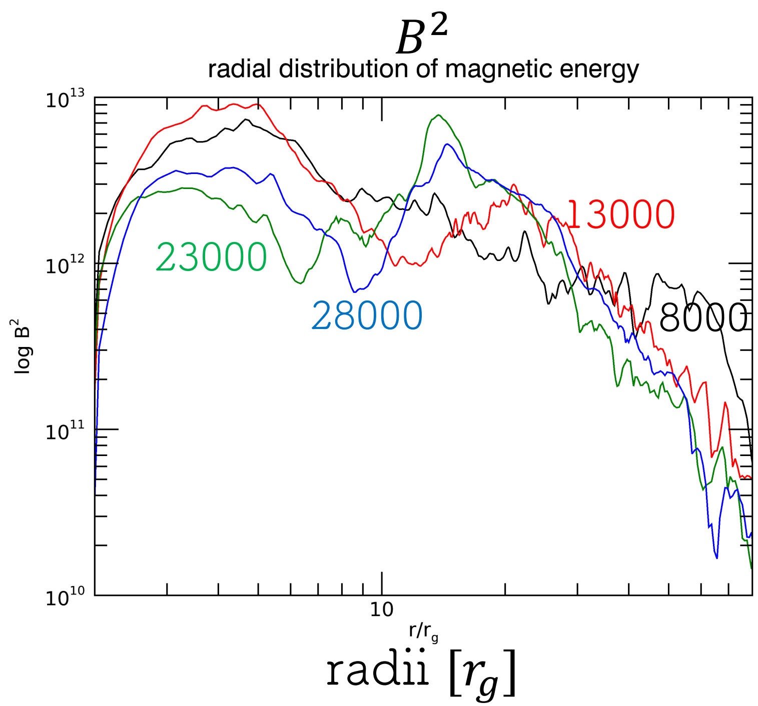
Radial Distribution of Temperature and Plasma β

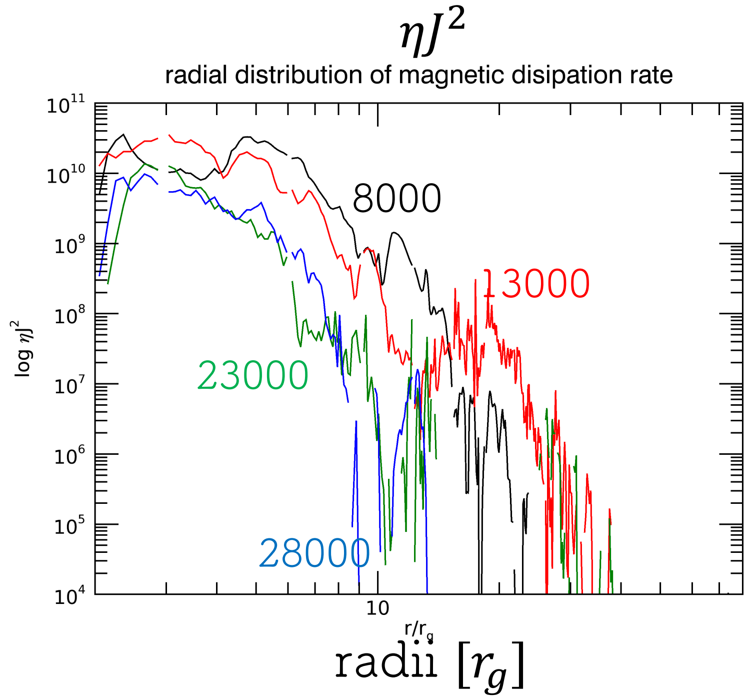




- Temperature decreases to 10^6K in the outer region
- The disk in the outer region is supported by magnetic pressure.
- Inner region stays in high-β , hot state
- Intermediate region between the hot disk and the cold disk appears around 10~20r_g
  - This radius is consistent with observation

Radial Distribution of Magnetic Energy and Joule Heating rate

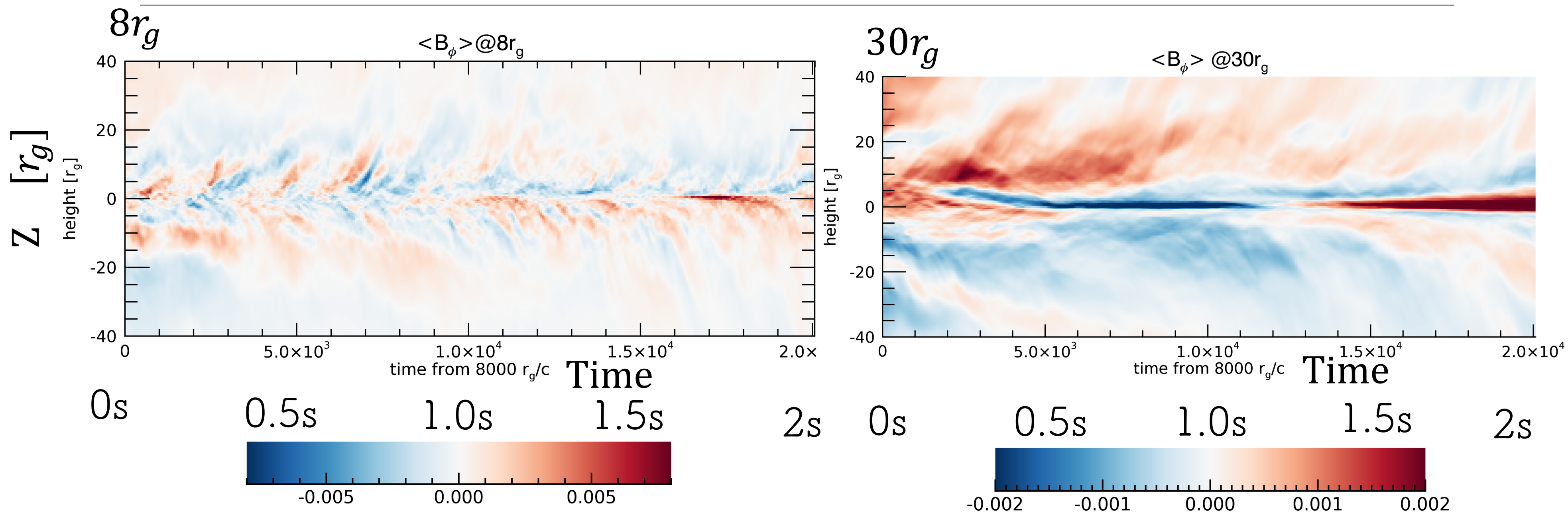




- The magnetic energy is largest around the inner edge of the cool disk where strong azimuthal magnetic field is formed by vertical contraction of the disk.

- Joule heating rate is largest in the inner hot disk.

Butterfly Diagram



- Azimuthal magnetic field reverse quasi periodically by disk dynamo at $8r_g$ (hot region)
  - The period of dynamo (0.1~0.3 s) is close to the frequency of LFQPO
  - The magnetic flux amplified in the disk buoyantly escape from the disk.
- Reversal of azimuthal magnetic field takes place even in the outer region where 30 r_g
  - In the outer region , disk dynamo reverses magnetic fields around the surface of the cool disk.

Summary

- We carried out RMHD simulations of hard-to-soft transitions in black hole candidates and showed that geometrically thin, optically thick cool disk in the outer region co-exist with the geometrically thick, hot, optically thin disk near the black hole.

- We carried out simulations for longer time than Takahashi et al. (2016) until field reversal takes place in the outer low-β region.

- In the inner hot disk , azimuthal magnetic field reverses quasi-periodically with frequency 5-10Hz. This frequency is close to the frequency of LFQPOs. The cyclic disk dynamo can be the origin of low-frequency QPOs observed during hard-to-soft transition.

- Magnetic energy is accumulated around the boundary between the hot disk and the cool disk.