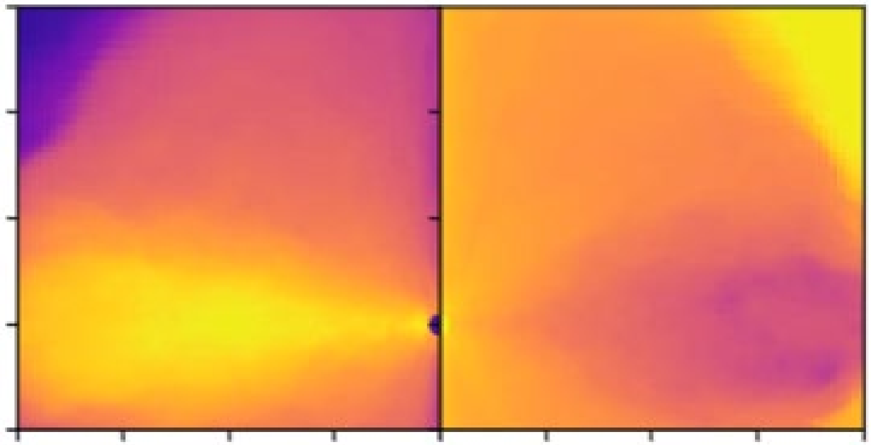
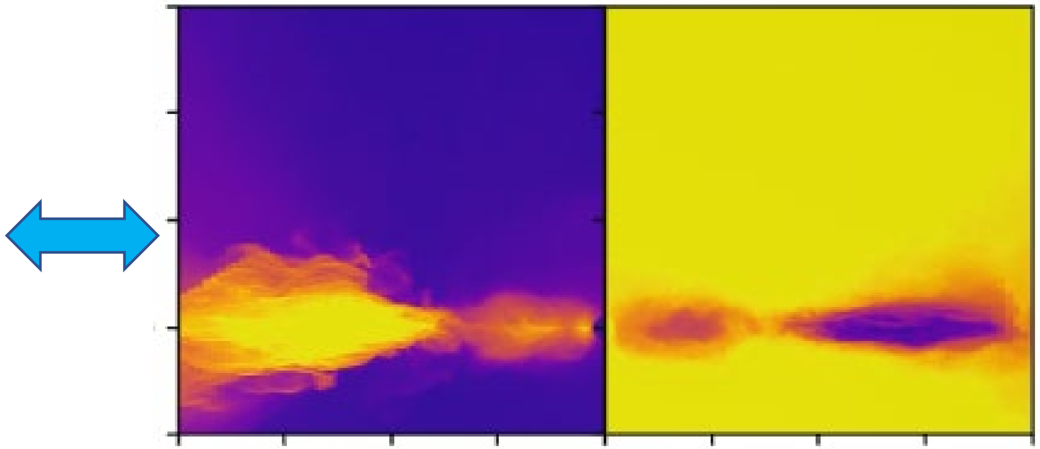
MAXI 15year Workshop Dec. 10-12, 2024 @Tokyo

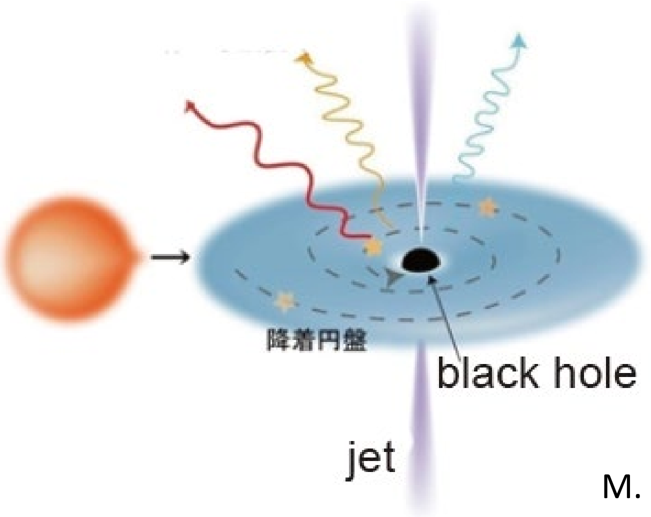
Magnetic Heating as the Origin of Bright Hard State in Black Hole Candidates



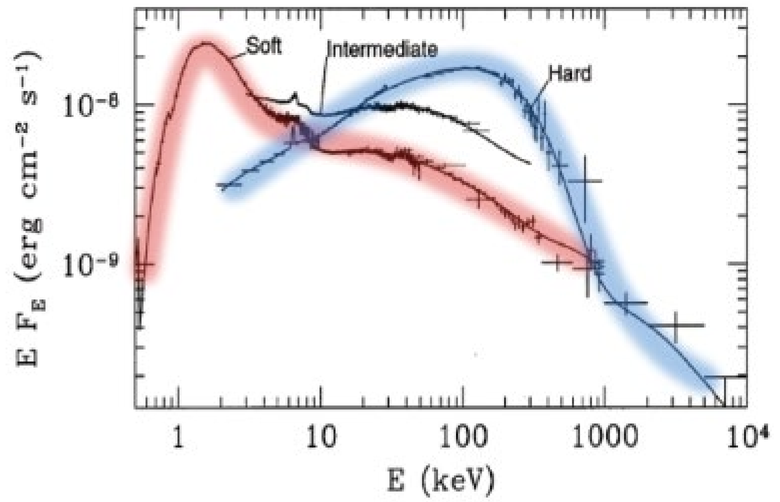


Ryoji Matsumoto (Chiba Univ.)
T. Igarashi (NAOJ/Rikkyo Univ), H.R. Takahashi (Komazawa Univ.),
T. Kawashima (ICRR, Univ. Tokyo), K. Ohsuga (Tsukuba Univ.),
and Y. Matsumoto (Chiba Univ.)

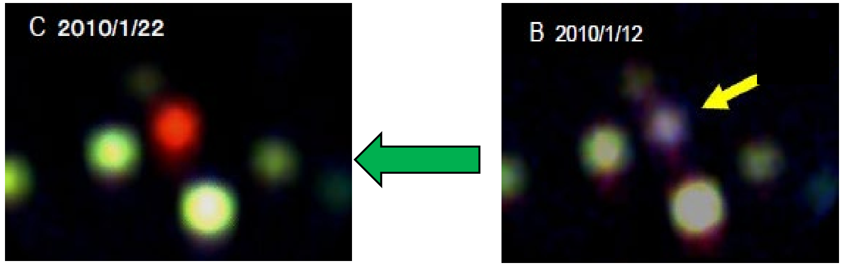
State Transitions of Black Hole Candidates



M. Machida



X-ray Spectrum of Cyg X-1（Gierlinski 1999）



State transition in XTE J1752-223

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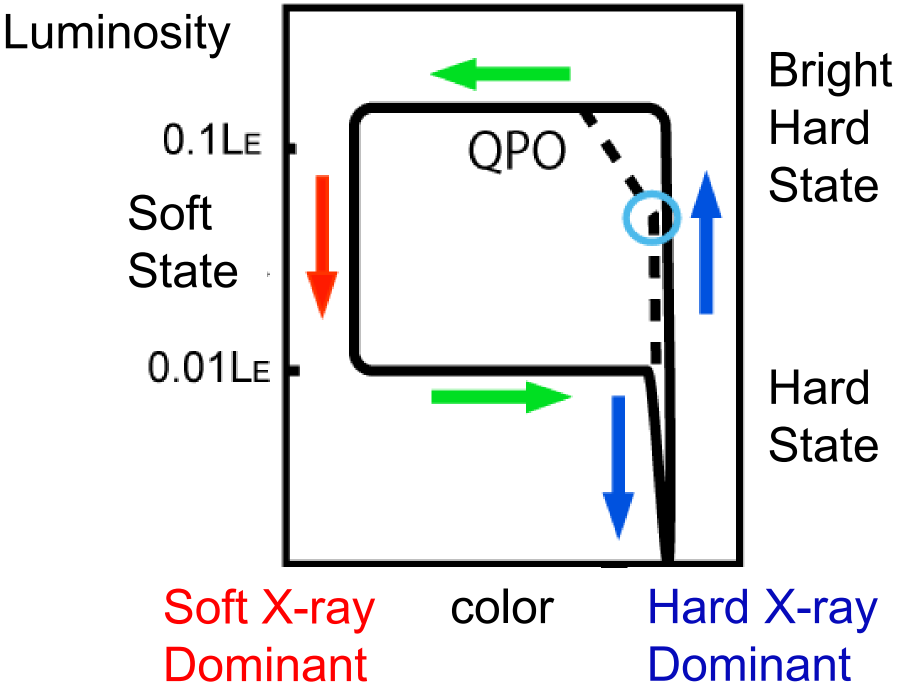
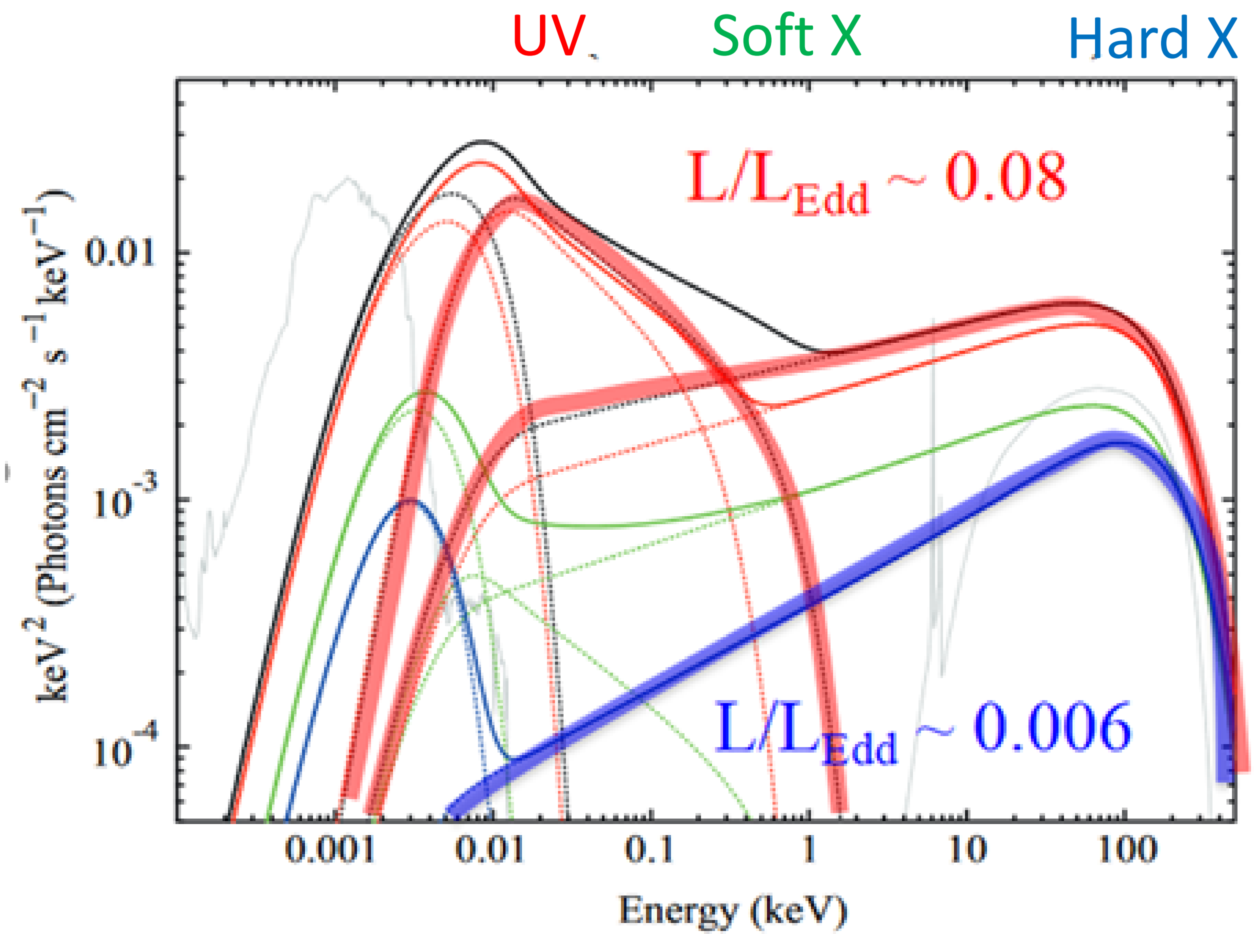


Evolution Track in Color-Luminosity Plane

X-ray Observation Revealed The Spectral Change during State Transition

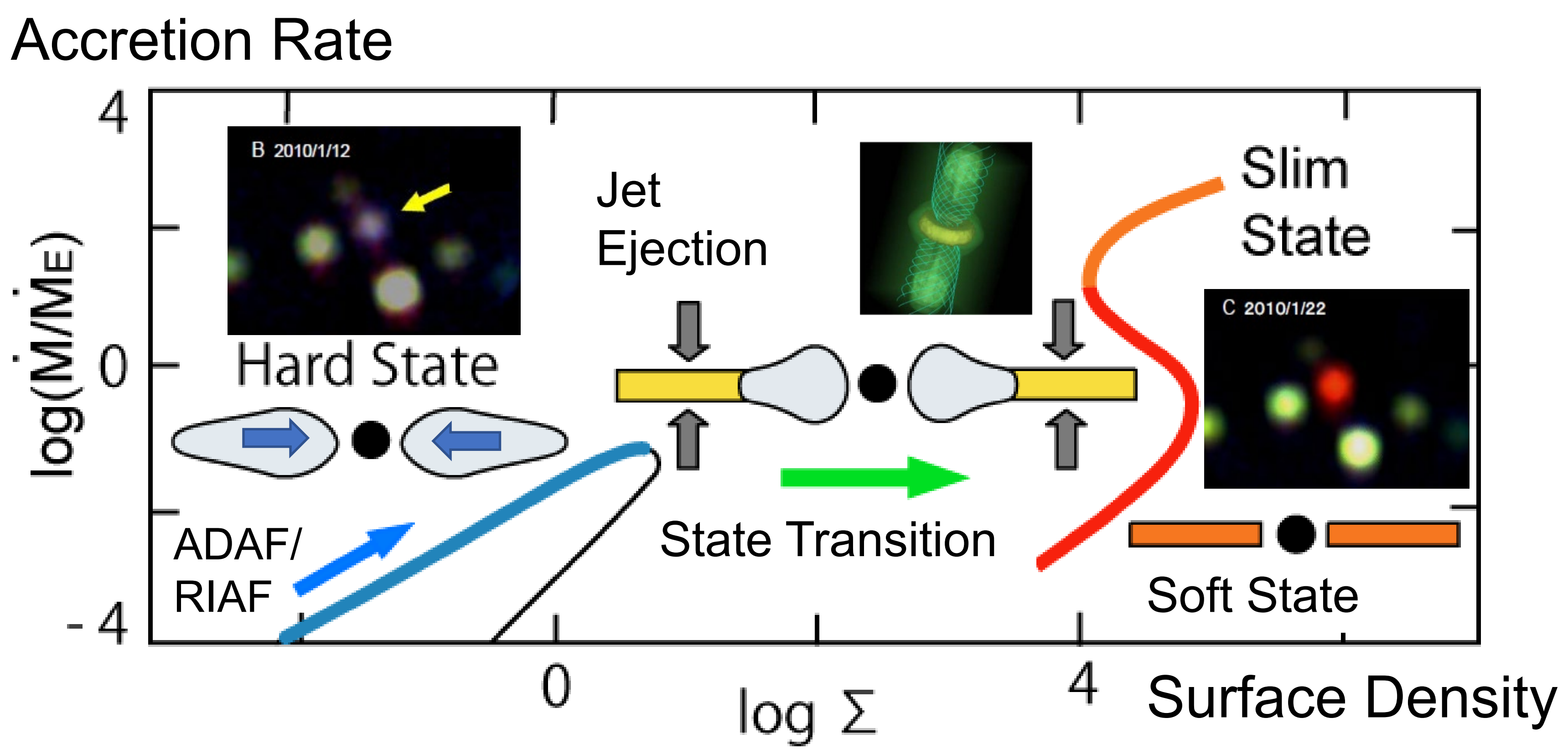


Soft X-ray Excess Appears during State Transition

Similar to the Hard-to-Soft State Transitions of Stellar Mass Black Hole Candidates

Radiation Spectrum of a changing look AGN Mrk1018 (Noda and Done 2018)

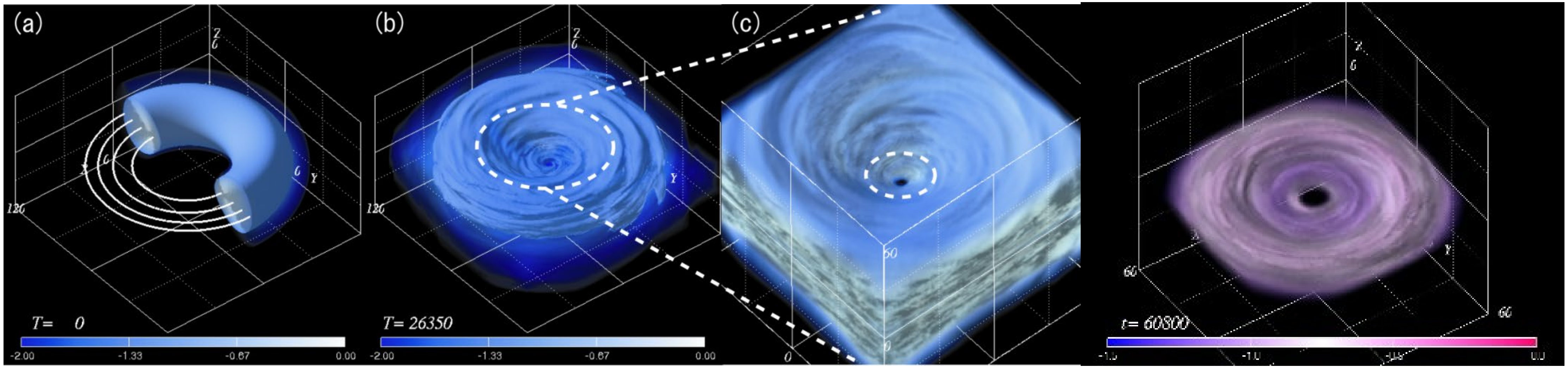
Theoretical Model of State Transitions



Optically Thin ⟵ ⟶ Optically Thick

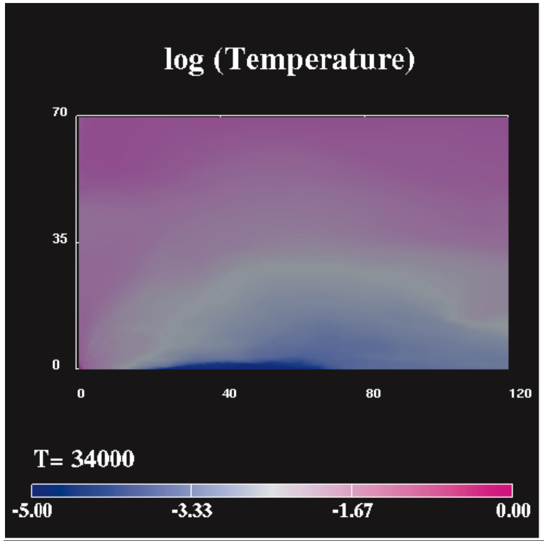
Thermal Equilibrium Curves of Accretion Flows
(Equilibrium Curves are from Abramowicz et al. 1995)

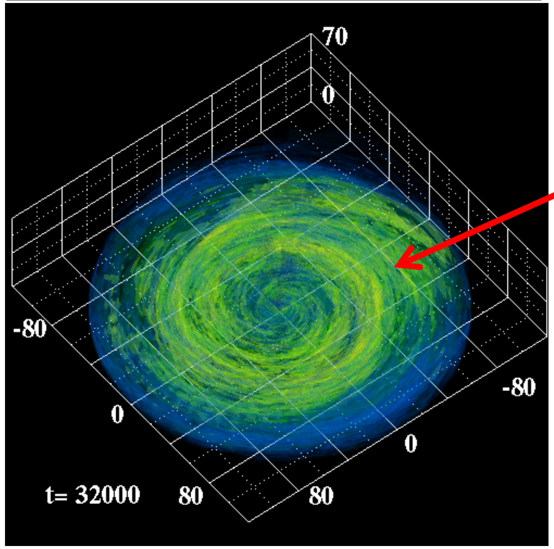
Global Three-Dimensional MHD Simulations of Radiatively Inefficient Black Hole Accretion Flows



Machida et al. 2003

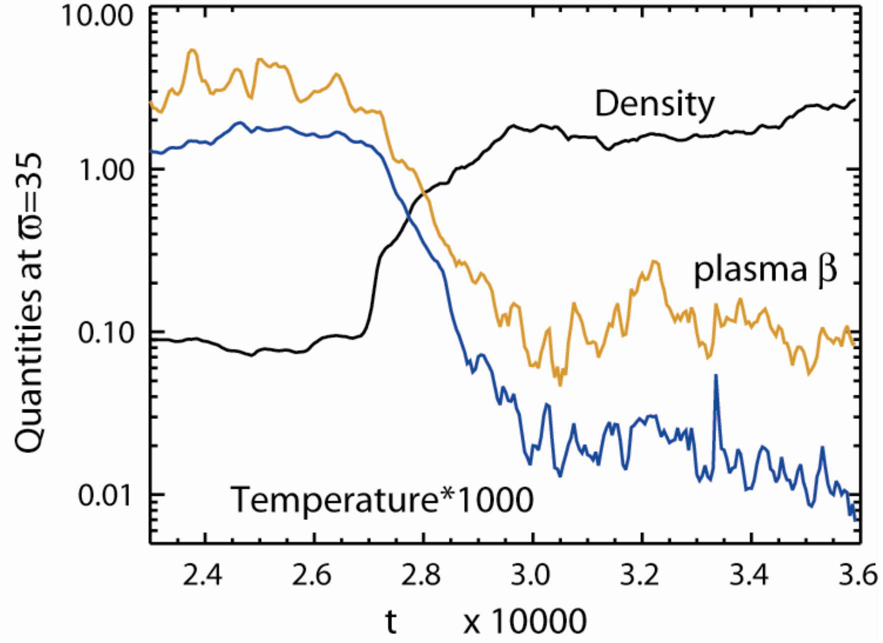
Global Three-dimensional MHD Simulation of State Transition

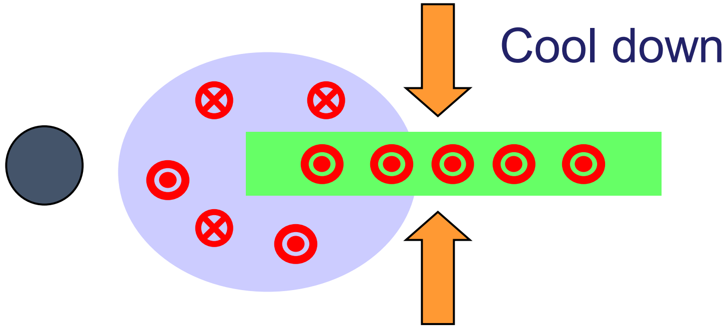




$\beta < 1$

3D MHD Simulation
including Cooling

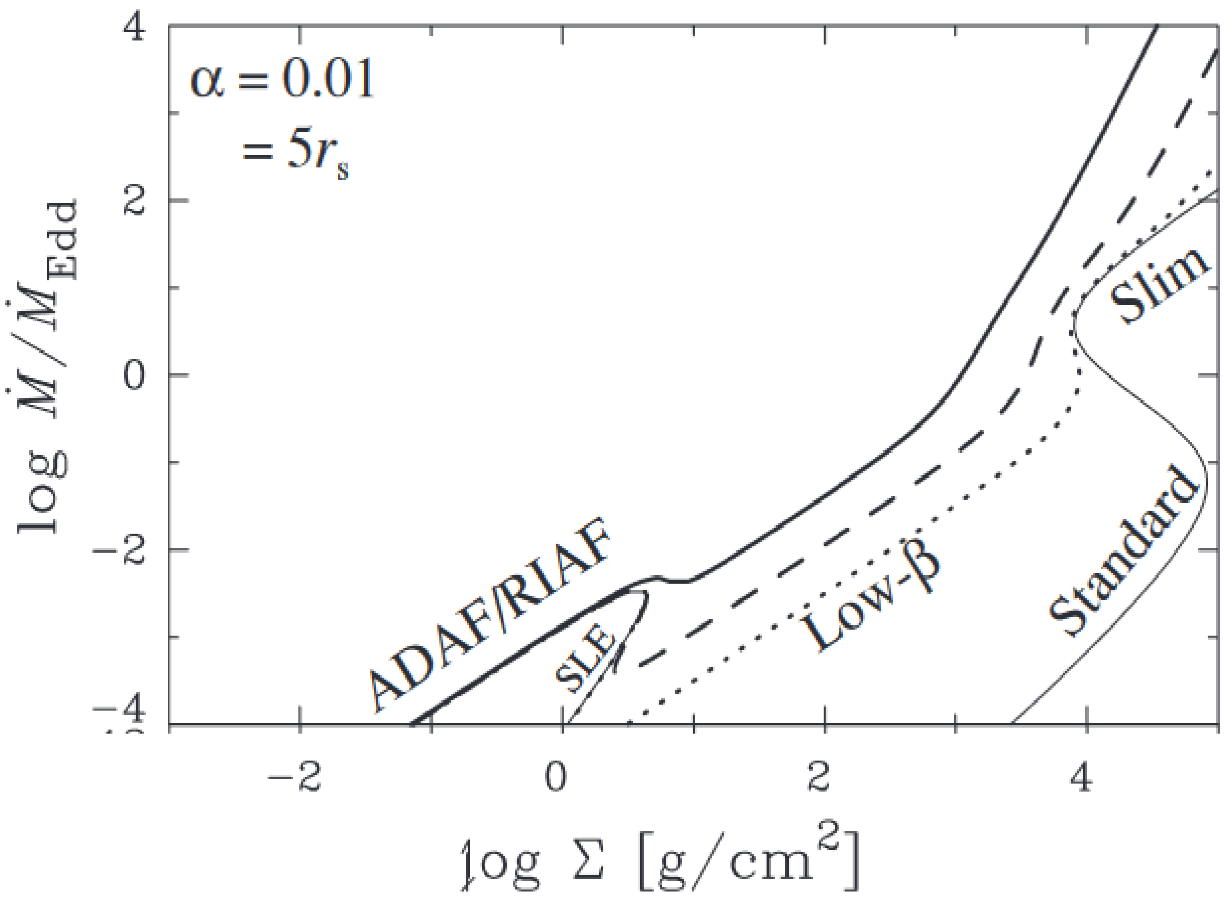




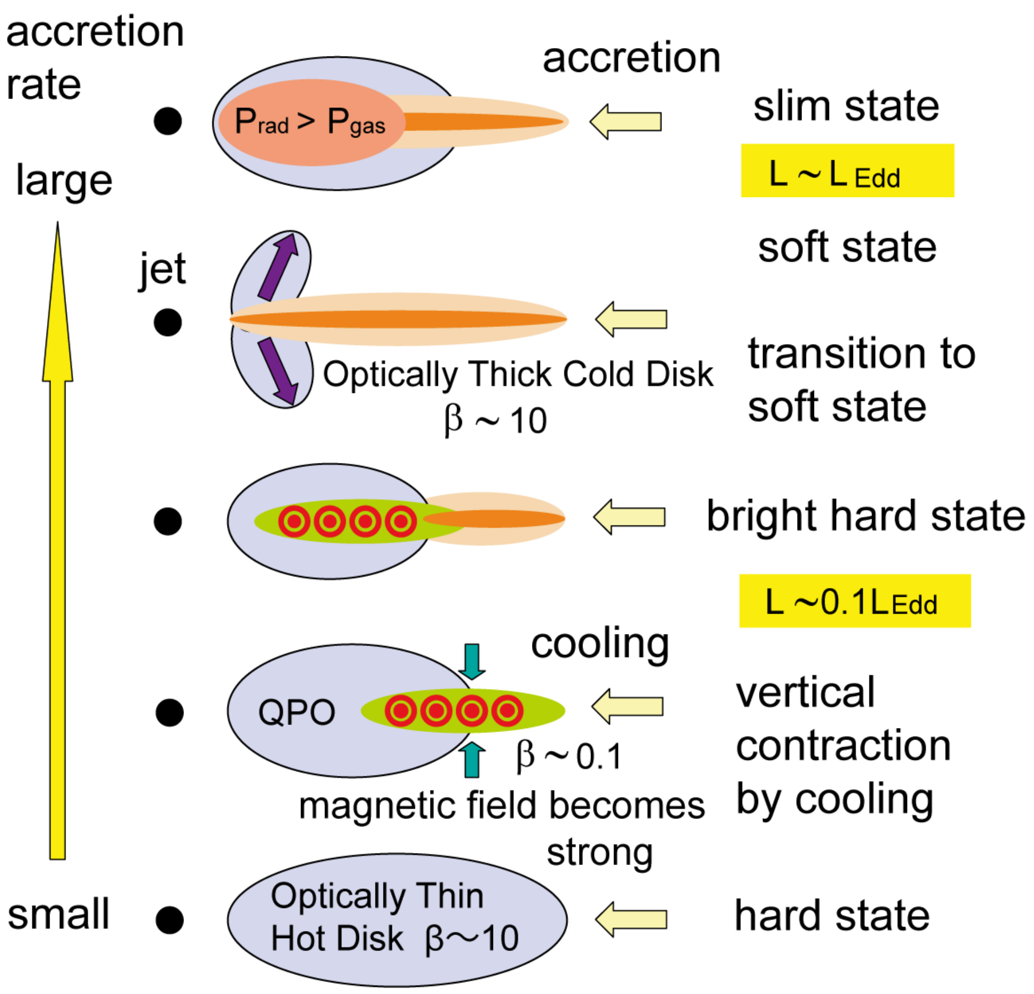
Toroidal
MAD ?

Machida et al. (2006)

Thermal Equilibrium Curve of Toroidal MAD and Schematic Picture of the Hard-to-Soft Transition.



Oda et al. 2009



For Luminous Accretion Flow, we need to carry out Radiation MHD Simulations

MHD

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

$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + p_{\mathrm{t}} I - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} \right] = -\rho \nabla \phi - \boldsymbol{S}$$

$$\frac{\partial E_{\mathrm{t}}}{\partial t} + \nabla \cdot \left[(E_{\mathrm{t}} + p_{\mathrm{gas}}) \boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{v} \cdot \boldsymbol{B})}{4\pi} \right] = -\rho \boldsymbol{v} \cdot \nabla \phi - \nabla \cdot \left(\frac{4\pi\eta}{c} \boldsymbol{j} \times \boldsymbol{B} \right) - cS_0$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{B}\boldsymbol{v} - \boldsymbol{v}\boldsymbol{B}) = -\nabla \times \left(\frac{4\pi\eta}{c} \boldsymbol{j} \right)$$

Source term

$$cS_0 = \rho \kappa_{\mathrm{ff}} c (4\pi B(T) - E) + \rho (\kappa_{\mathrm{ff}} - \kappa_{\mathrm{es}}) \frac{\boldsymbol{v}}{c} \cdot [\boldsymbol{F} - (\boldsymbol{v}E + \boldsymbol{v} \cdot \boldsymbol{P})] + \Gamma_{\mathrm{c}}$$

$$\boldsymbol{S} = \rho \kappa_{\mathrm{ff}} \frac{\boldsymbol{v}}{c} (4\pi B(T) - E) - \rho (\kappa_{\mathrm{ff}} + \kappa_{\mathrm{es}}) \frac{1}{c} [\boldsymbol{F} - (\boldsymbol{v}E + \boldsymbol{v} \cdot \boldsymbol{P})]$$

$$\Gamma_{\mathrm{c}} = \rho \kappa_{\mathrm{es}} c E_{\mathrm{r0}} \frac{4 k_{\mathrm{B}} (T_{\mathrm{e}} - T_{\mathrm{r}})}{m_{\mathrm{e}} c^2}$$

Compton Cooling

Pseudo Newtonian potential

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

Rad. Moment eq

$$\frac{\partial E}{\partial t} + \nabla \cdot \boldsymbol{F} = cS_0$$

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

Electron scattering opacity

$$\kappa_{\mathrm{es}} = \frac{\sigma_{\mathrm{T}}}{m_{\mathrm{p}}} = 0.4$$

Free-free opacity

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

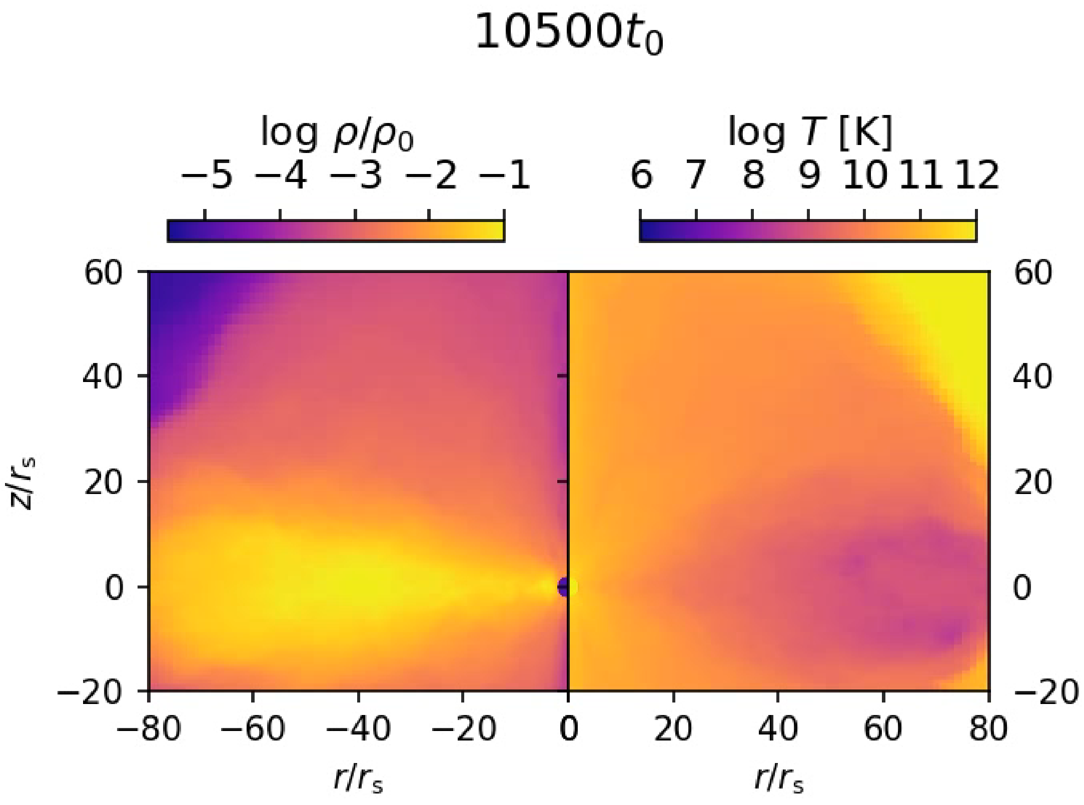
Simulation Code : CANS+R　MHD：CANS+(HLLD+MP5) (Matsumoto et al. 2019)
Rad： Non-relativistic version of M1-closure scheme (Takahashi & Ohsuga 2013)

Radiation MHD Simulation during Changing Look Phenomena in AGN (Igarashi et al 2024, ApJ 968, 121)

- $M_{BH} = 10^7 M_\odot$
- Unit Length $r_s = 3\times10^{12}$cm
- Unit time $t_0 = r_s/c = 100$sec
- Radiative cooling terms are turned on after RIAF is formed.
- Density is adjusted so that the accretion rate at this state is 10% of the Eddington accretion rate defined by

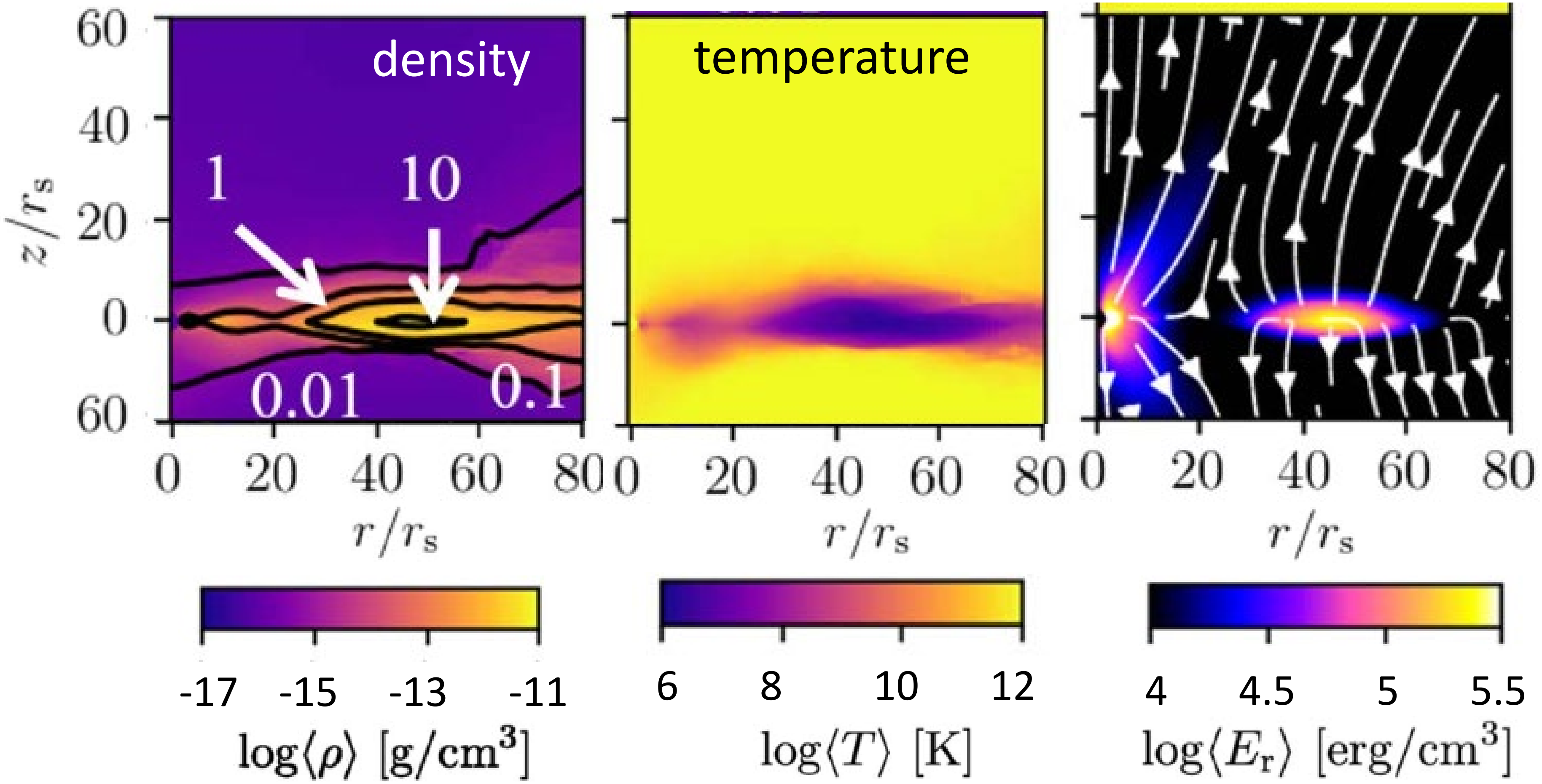
$$\dot{M}_{\rm Edd} = L_{\rm Edd}/c^2$$

- Number of grid points
  (N_r, N_φ, N_z)=(464.32.464)
  $\Delta r = \Delta z = 0.1 r_s$@ $r < 20$rs, $|z| < 5r_s$



Igarashi et al. 2024, ApJ

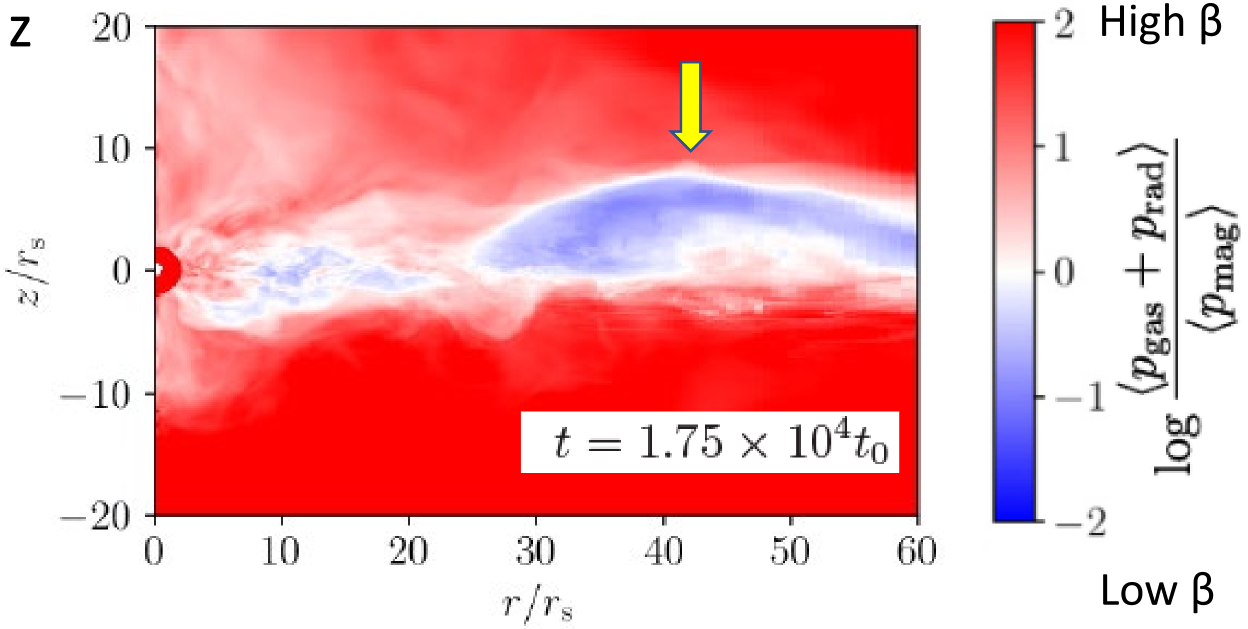
Distribution of Density, Temperature, and Radiation Energy Density averaged over $1.5<t/10^4 t_0<1.75$



Igarashi et al. 2024

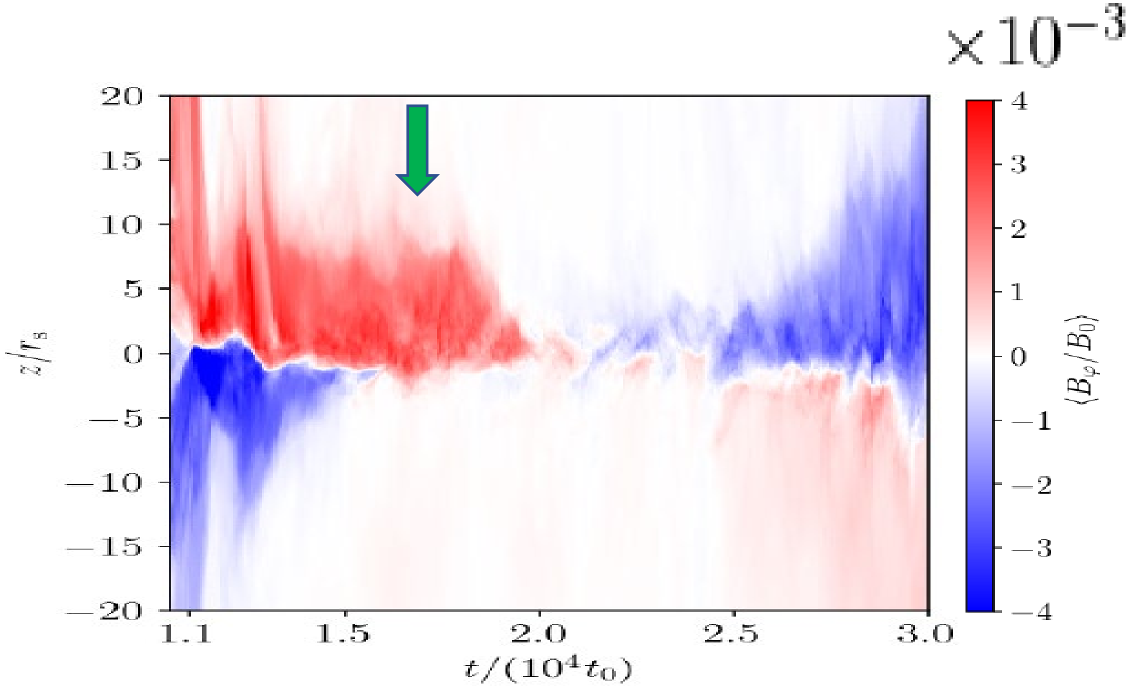
Formation of Low-β Region

Z



High β

Low β



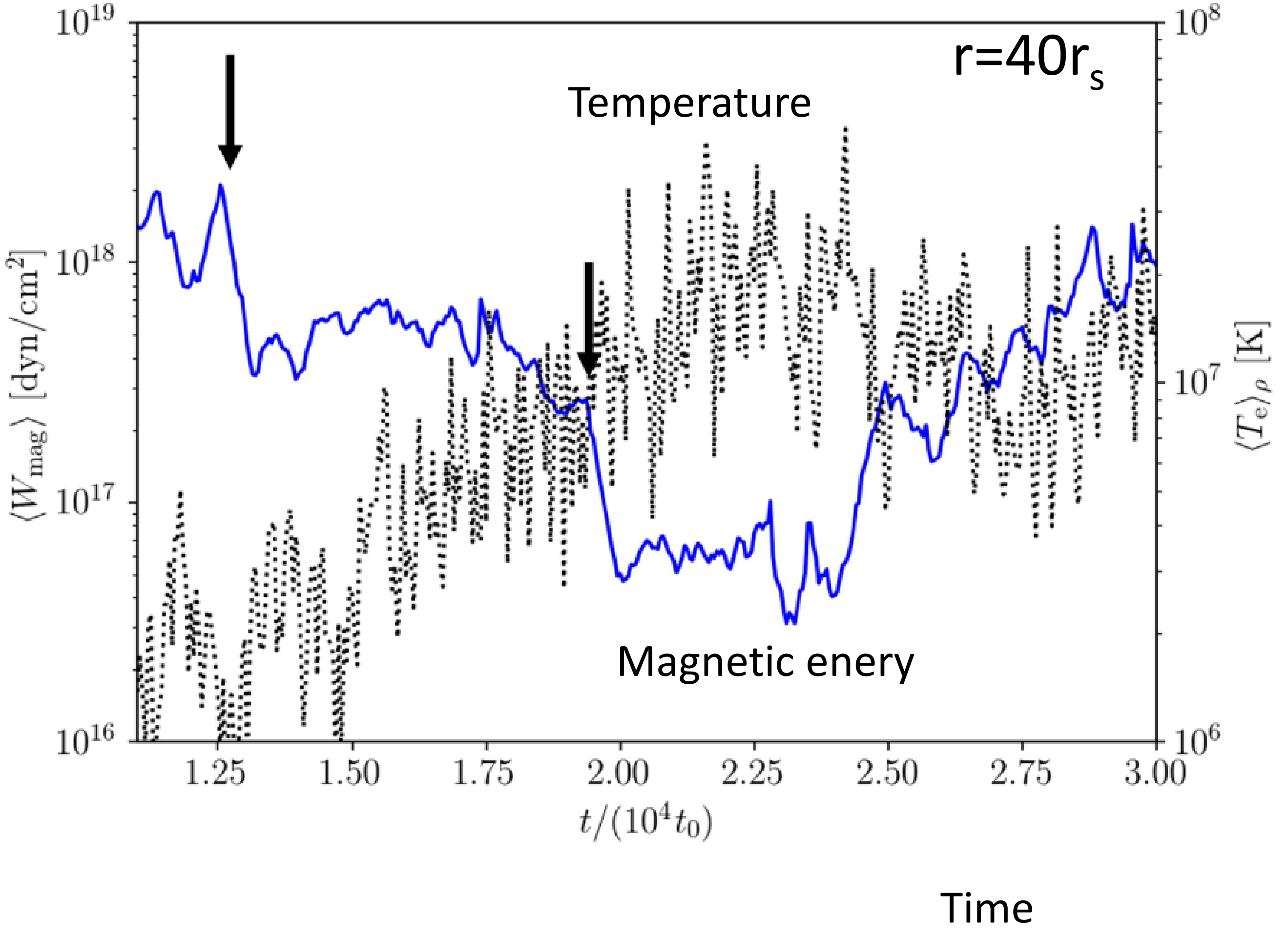
Time

Ratio of
(gas pressure + radiation pressure)/
Magnetic pressure

Butterfly Diagram of B_ϕ at $r=40r_s$

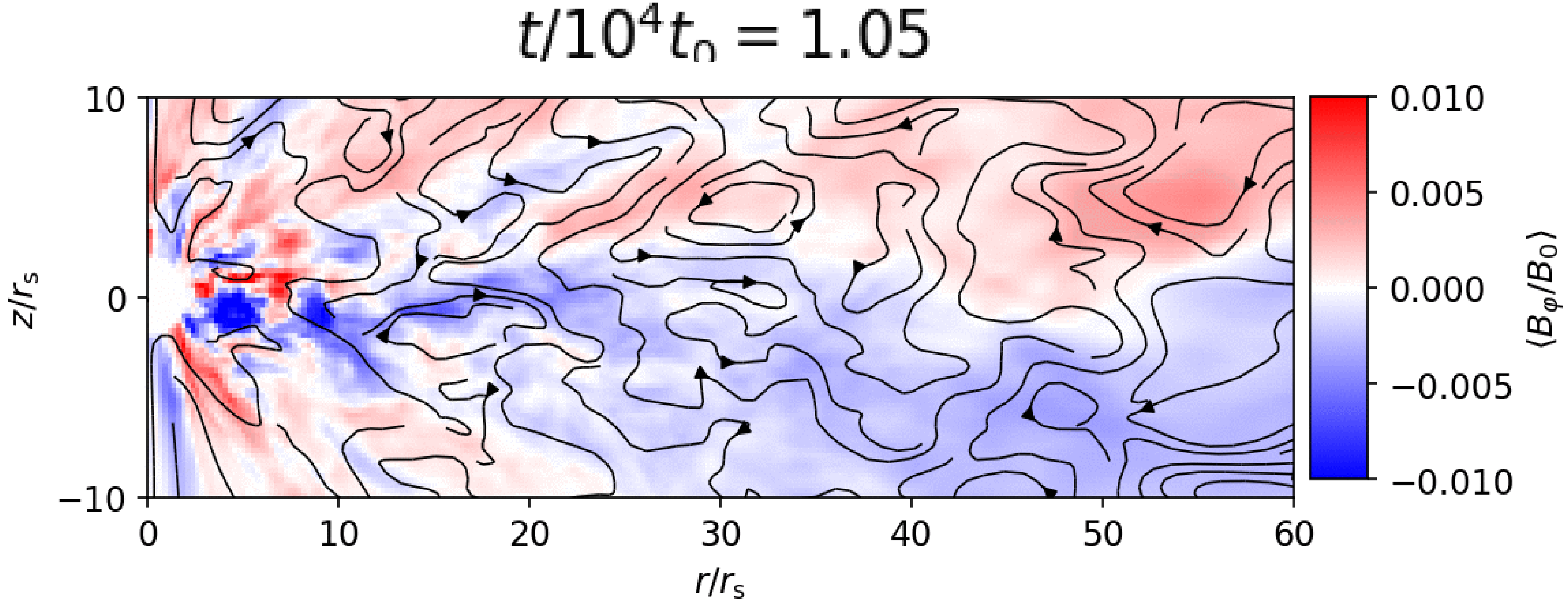
Magnetic Heating of the Warm Region

Vertically Integrated Magnetic Energy



Igarashi et al. 2024

Time Evolution of Toroidal Magnetic Field (Color) and Poloidal Magnetic Field (Solid Curves)



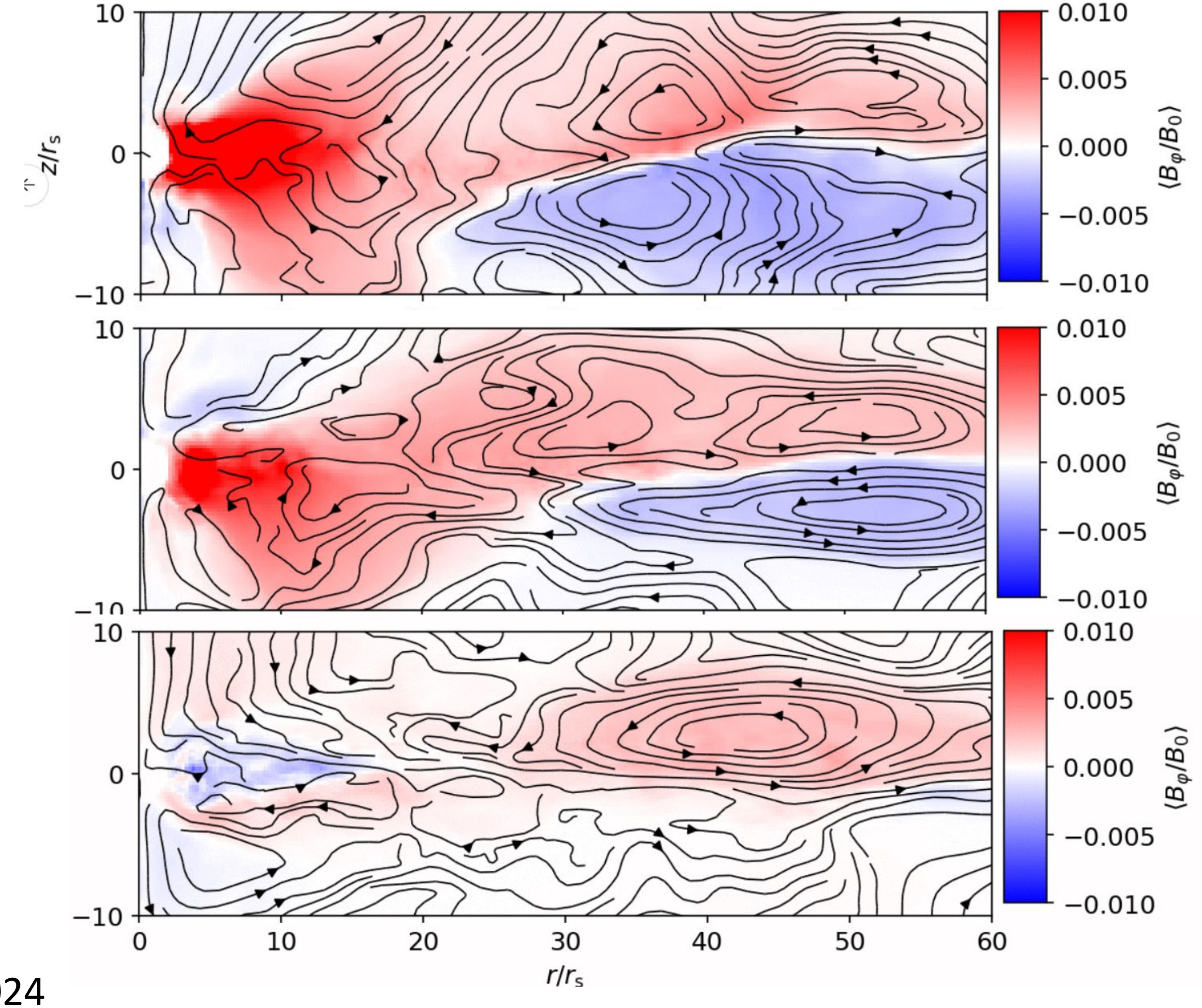
Igarashi et al. 2024

Merging of Toroidal Magnetic Flux Tubes

$t/t_0 = 1.3E4$

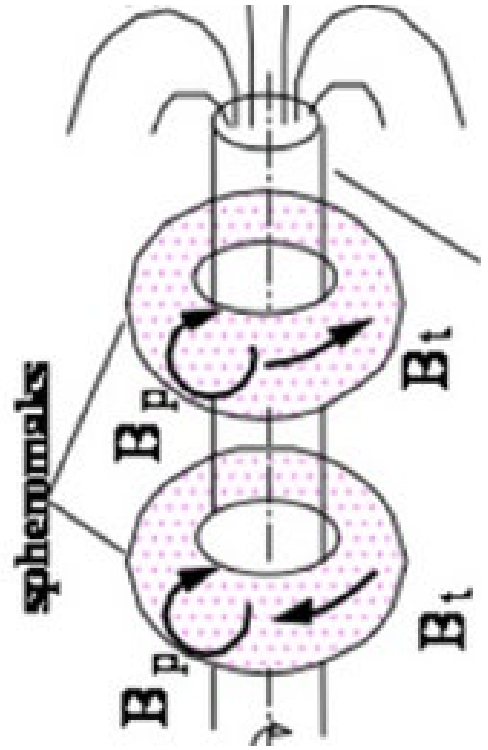
$t/t_0 = 1.4E0$

$t/t_0 = 1.7E4$

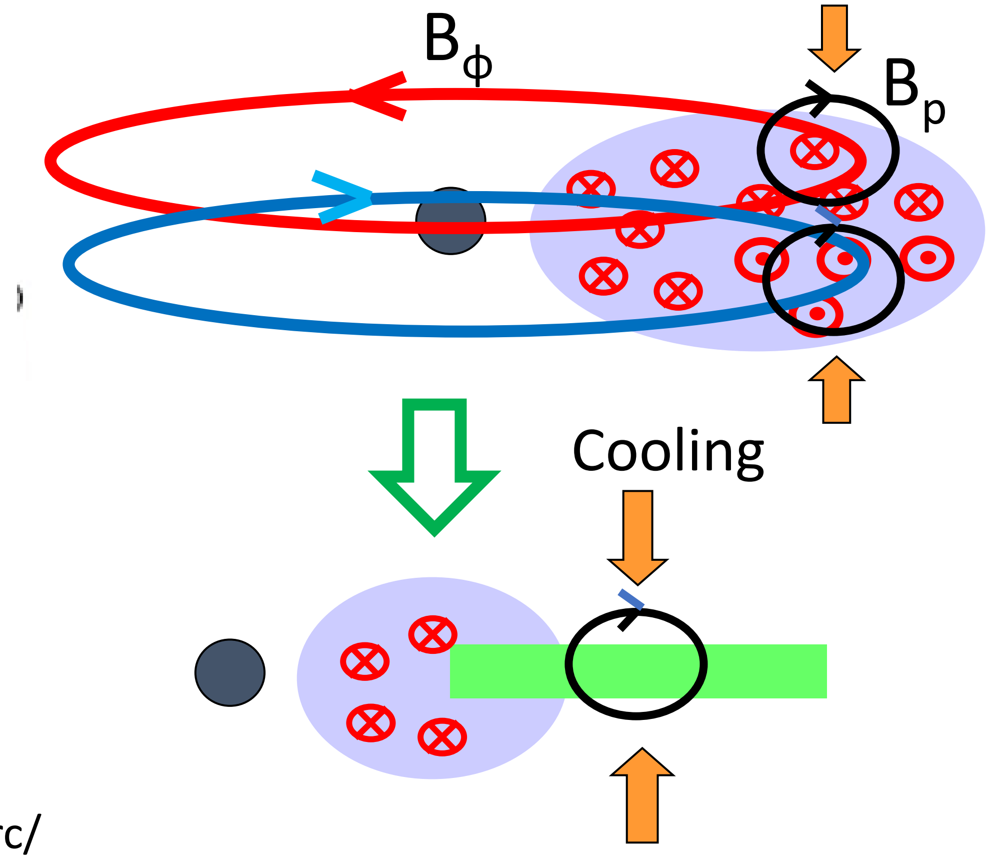


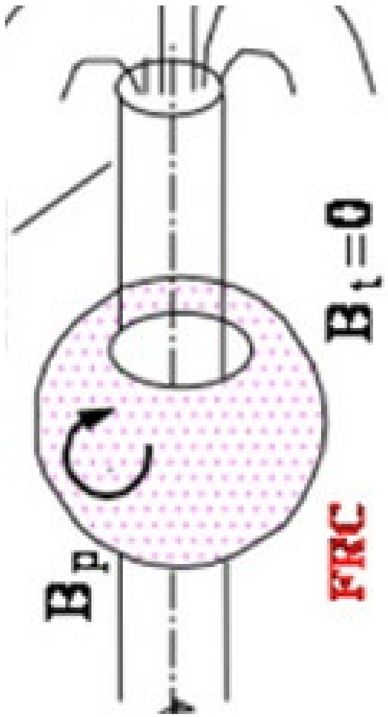
Igarashi et al. 2024

Similarity with the Merging of Spheromacs



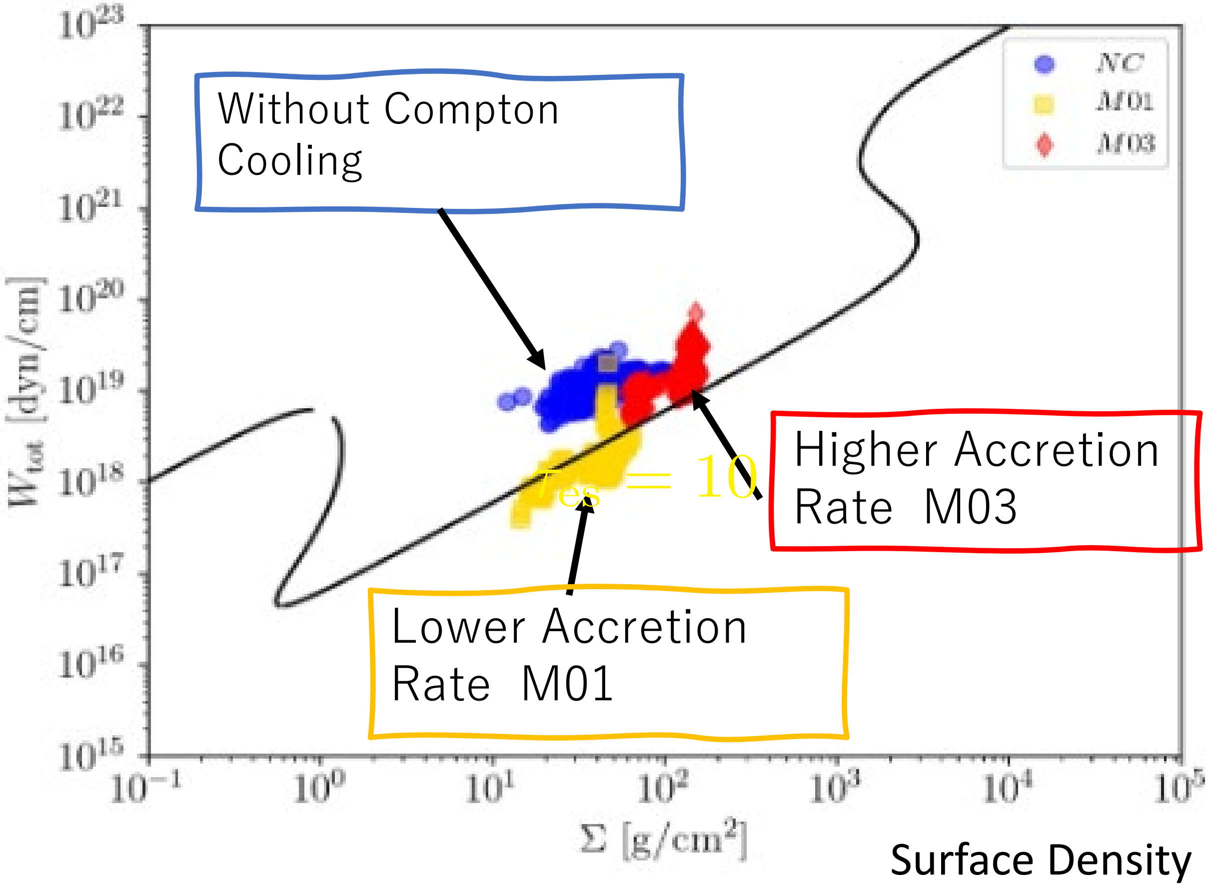
http://tanuki.t.u-tokyo.ac.jp/frc/



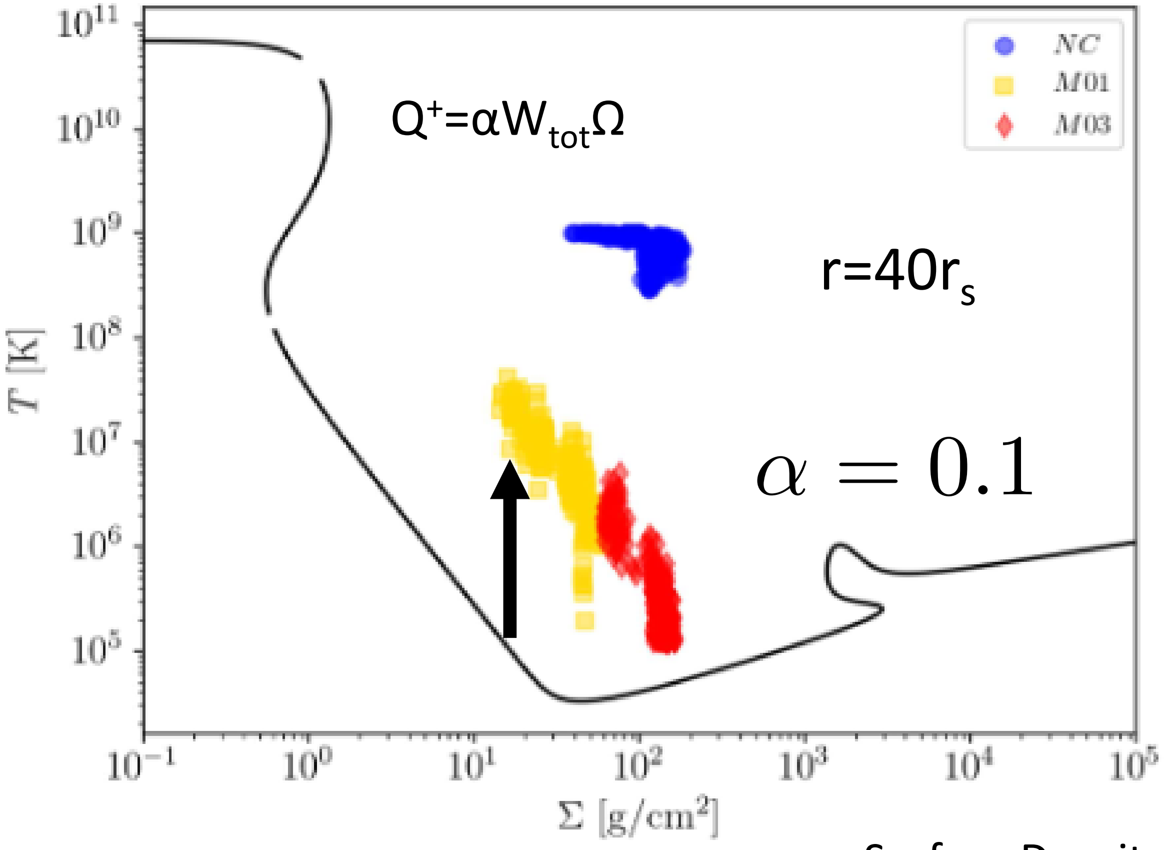


Comparison with Analytical Model by Oda et al. (2009)

W tot   r=40r_s $\alpha = 0.1$ $\Phi_0 = 3 \times 10^{16}$ Mx/cm $\Phi = \int B_\varphi dz = \Phi_0 \left(\frac{\Sigma}{\Sigma_0}\right)^\zeta$ $\zeta = 0.5$



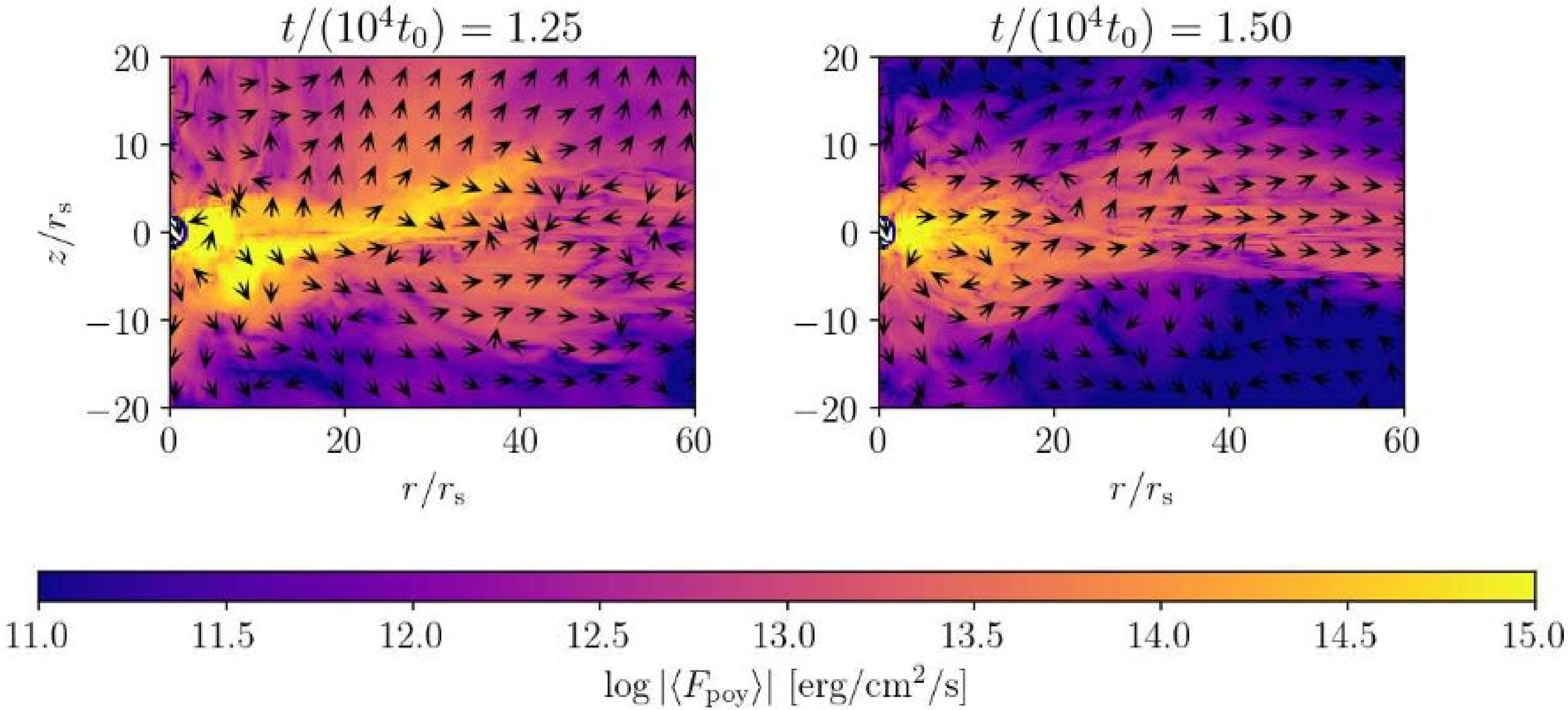
Surface Density



Surface Density

Igarashi et al. 2024

Transport of Poloidal Poynting Flux



Igarashi et al. 2024

Updated Analytical Model

Mass Conservation $\dot{M} = -2\pi r \Sigma v_r = \text{const.}$

Angular Momentum $\dot{M}\,(l - l_{\rm in}) = 2\pi r^2 \alpha W_{\rm tot}$

Total Pressure $W_{\rm tot} = W_{\rm gas} + W_{\rm rad} + W_{\rm mag}$

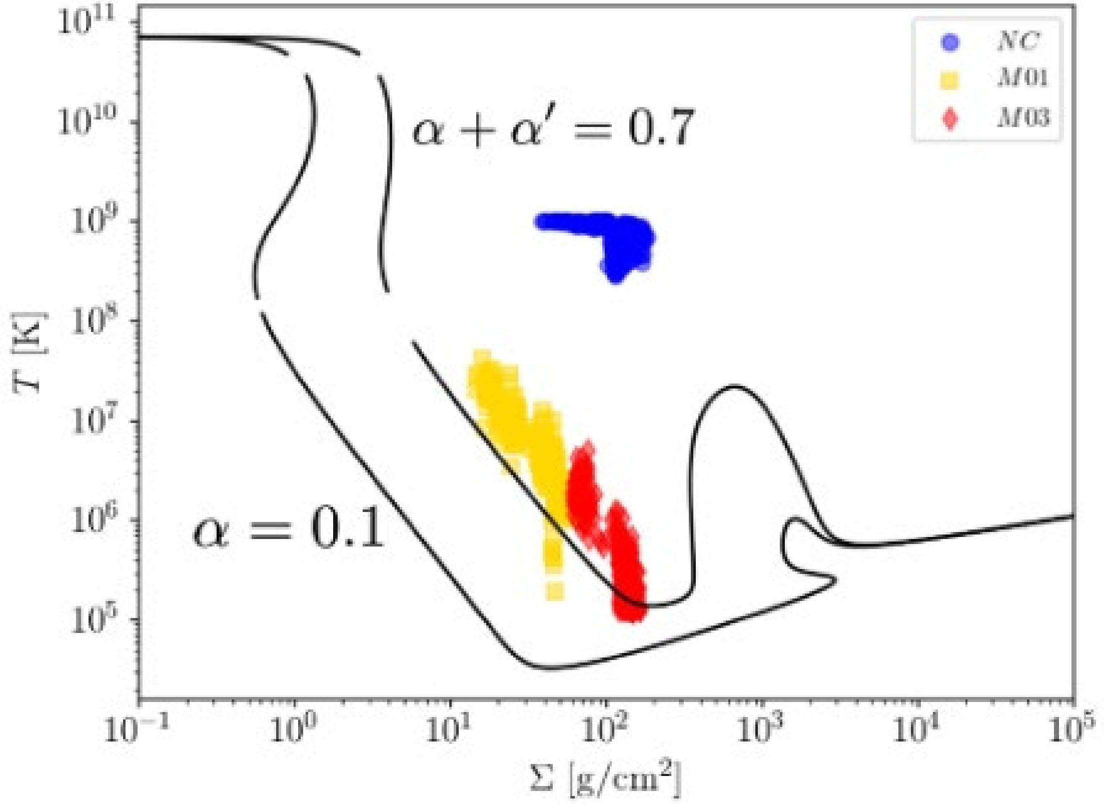
Energy Conservation $\dfrac{\dot{M}}{2\pi r^2}\dfrac{W_{\rm rad} + W_{\rm gas}}{\Sigma}\xi = \underline{Q^+} - \underline{Q^-},$

Heating Radiative Cooling

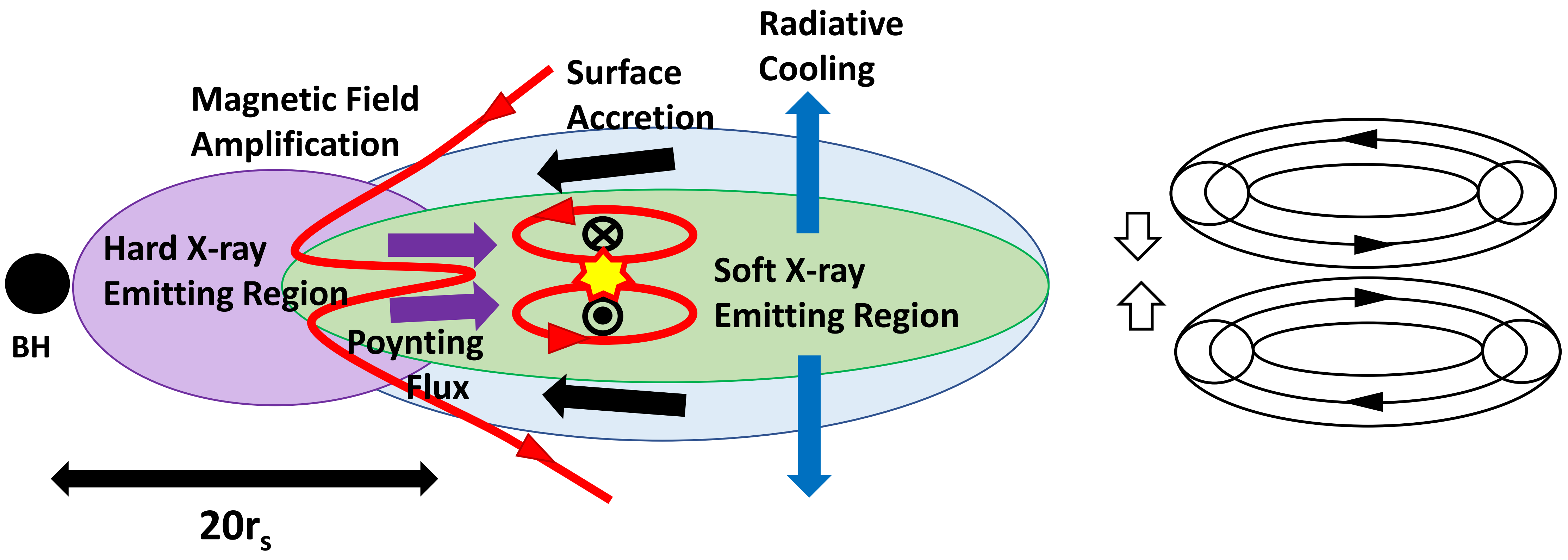
Classical Model $Q^+ = \alpha W_{\rm tot}\Omega$

Include Additional non-local Heating by Radial Poyinting Flux

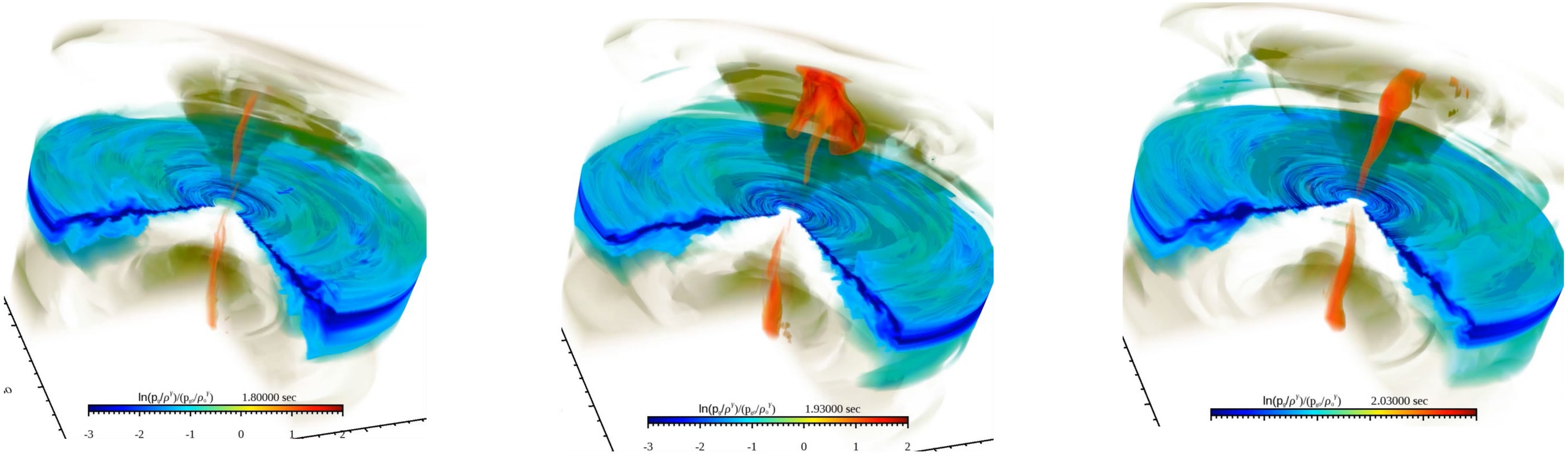
$Q^+ = (\alpha + \alpha')\, W_{\rm tot}\Omega$



A Schematic Picture of Numerical Results



Global 3D Radiation MHD Simulations of Stellar Mass Black Hole Accretion Flows during State Transition



Color: Entropy　(provided by Igarashi)

Igarashi et al. in prep.

Summary

- Global three-dimensional radiation MHD simulations showed that during a hard-to-soft state transition, hard X-ray emitting hot radiatively inefficient accretion flow near the black hole co-exists with the warm, radiatively cooled disk.
- The radiatively cooled region becomes supported by magnetic pressure because azimuthal magnetic field is enhanced due to the vertical contraction of the disk by radiative cooling.
- The equilibrium temperature of the warm region is higher than the model of the magnetically supported disk by Oda et al. (2009). The enhanced heating is due to the radial transport of the magnetic energy accumulated around the interface between RIAF and the warm disk.
- The magnetic energy transported to the warm region is released by merging of helical magnetic flux tubes, and heats the disk.

Than You for Your Attention !