輻射冷却を含めたブラックホール降着円盤のシミュレーション

町田　真美 (国立天文台)
中村　賢仁 (松江高専)
松元　亮治 (千葉大理)

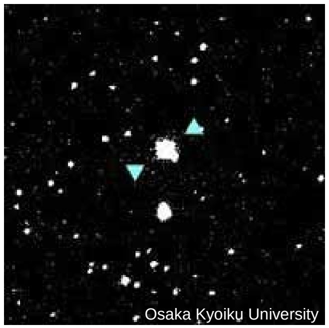
Contents

1. Introduction of state transition
2. Initial Model
3. Numerical Results
   - Temperature distribution
   - Evolution of magnetic field
4. Discussion
   - Application to the observation

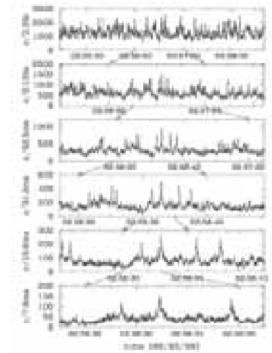
1. Introduction

What is the black hole X-ray binaries?

The most famous black hole candidates is Cyg X-1, which was found in 1971.

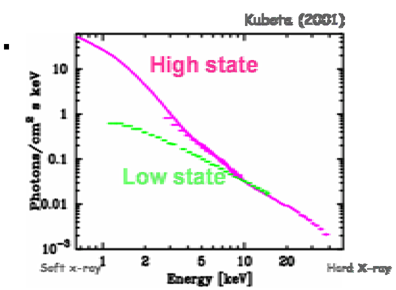


Properties of Cyg X-1 (Kato et al. 1998)
binary period 6.5017 day
Optical counterpart V = 9/O9.7Iab
Distance 2 kpc
Inclination angle 27 °
companion mass < 30 Mo
black hole mass < 15Mo



Recently, many other black hole candidates were observed.

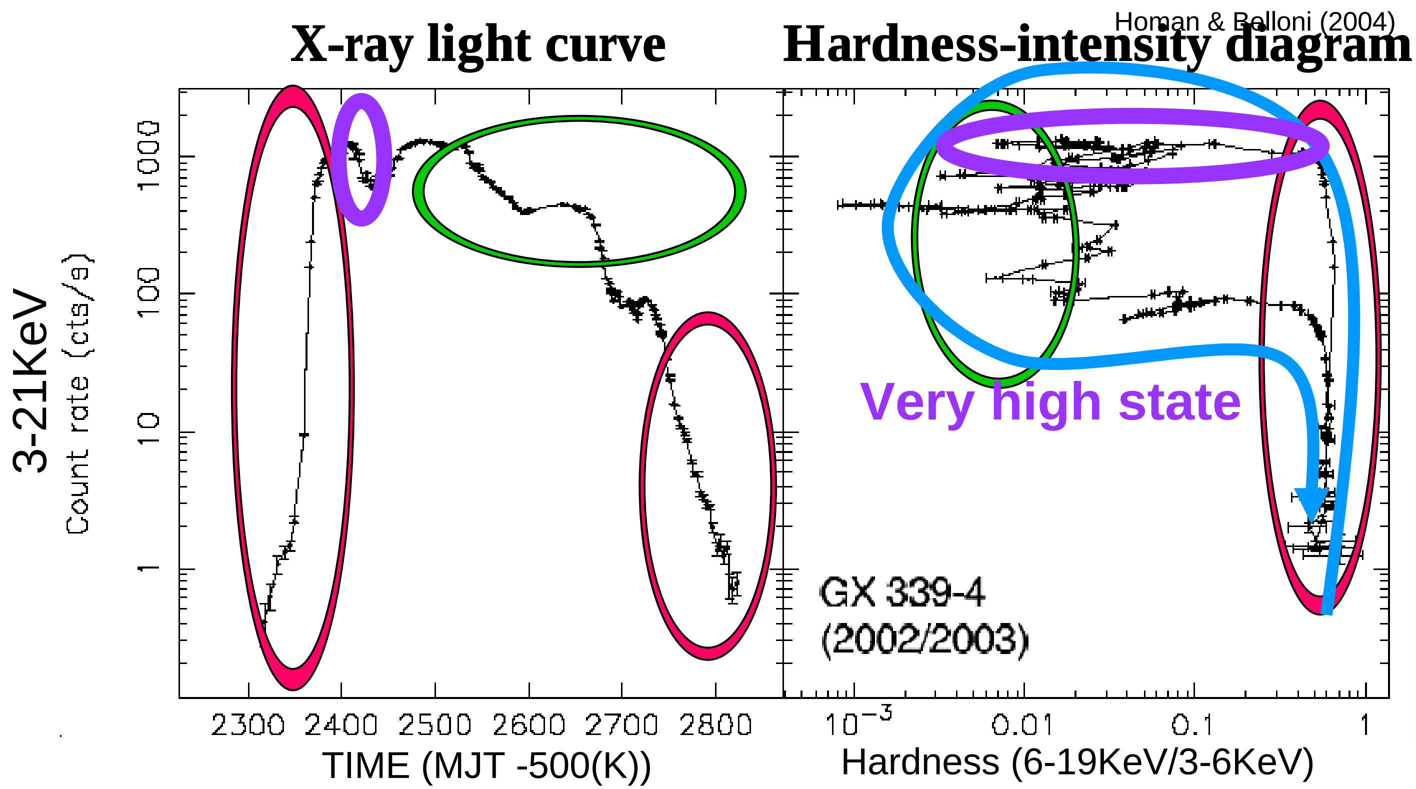
ex) Micro quasars (GRS 1915+105 …) , GX 339-4

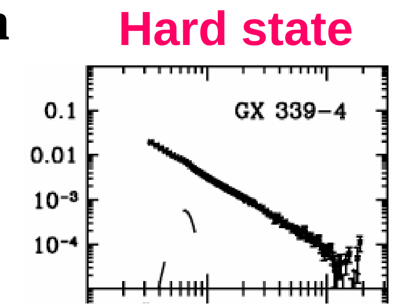


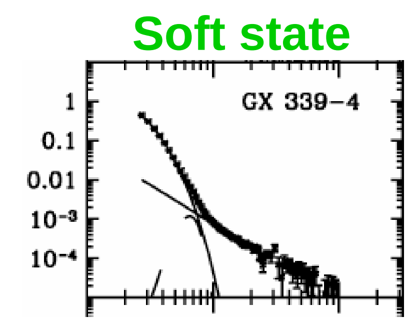
General properties of black hole binaries.

- The time variations of X-ray fluctuations seem to be chaotic/fractal.
- Two spectral type : high/soft state and low/hard state
- State transitions take place between high/soft state and low/hard state.

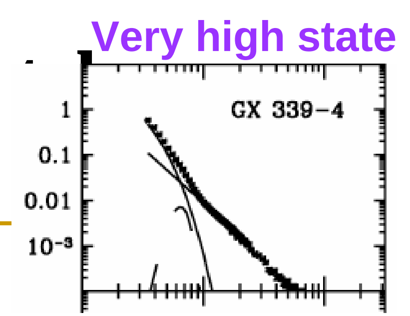
Activities of black hole candidates







McClintock & Remillard (2004)

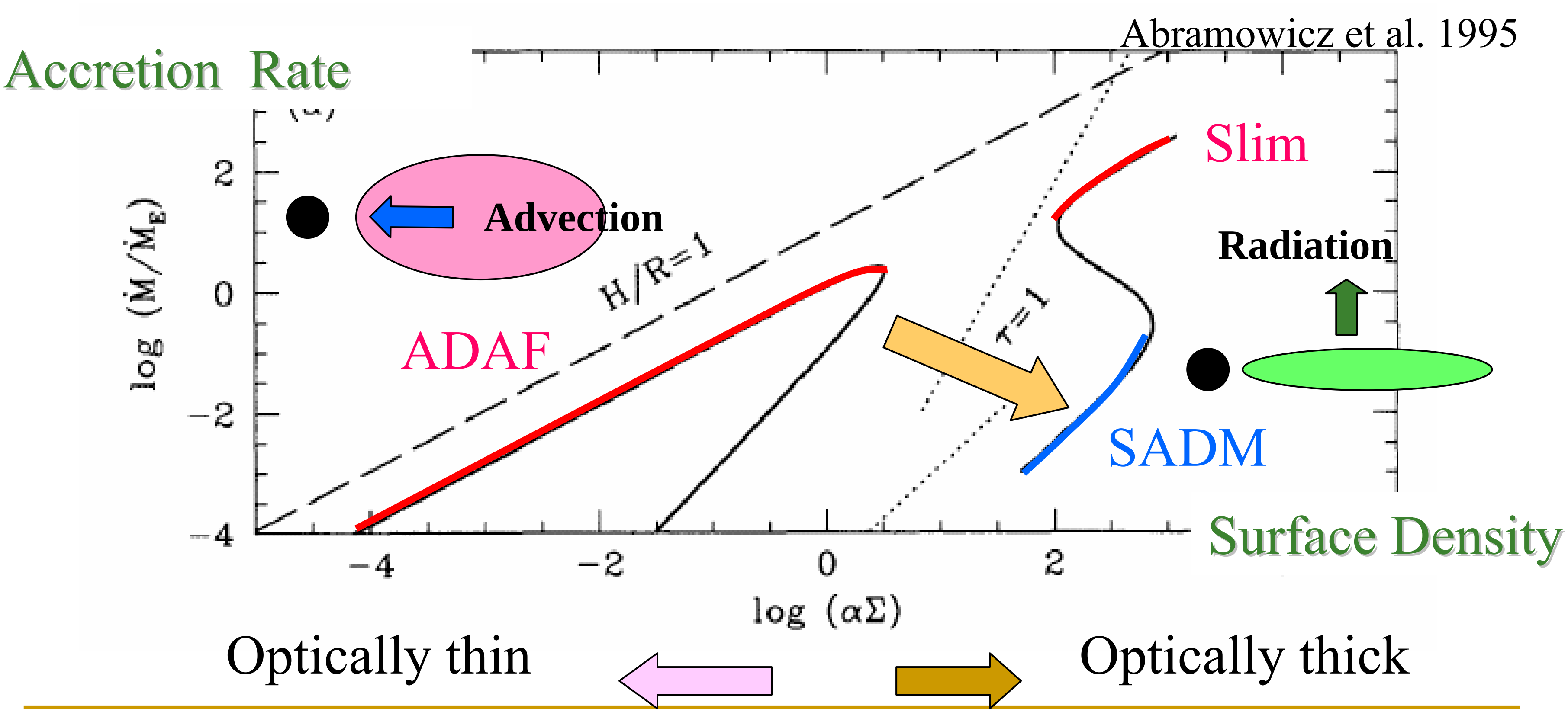


Hard → Soft and Soft → Hard transitions place within a single outburst.

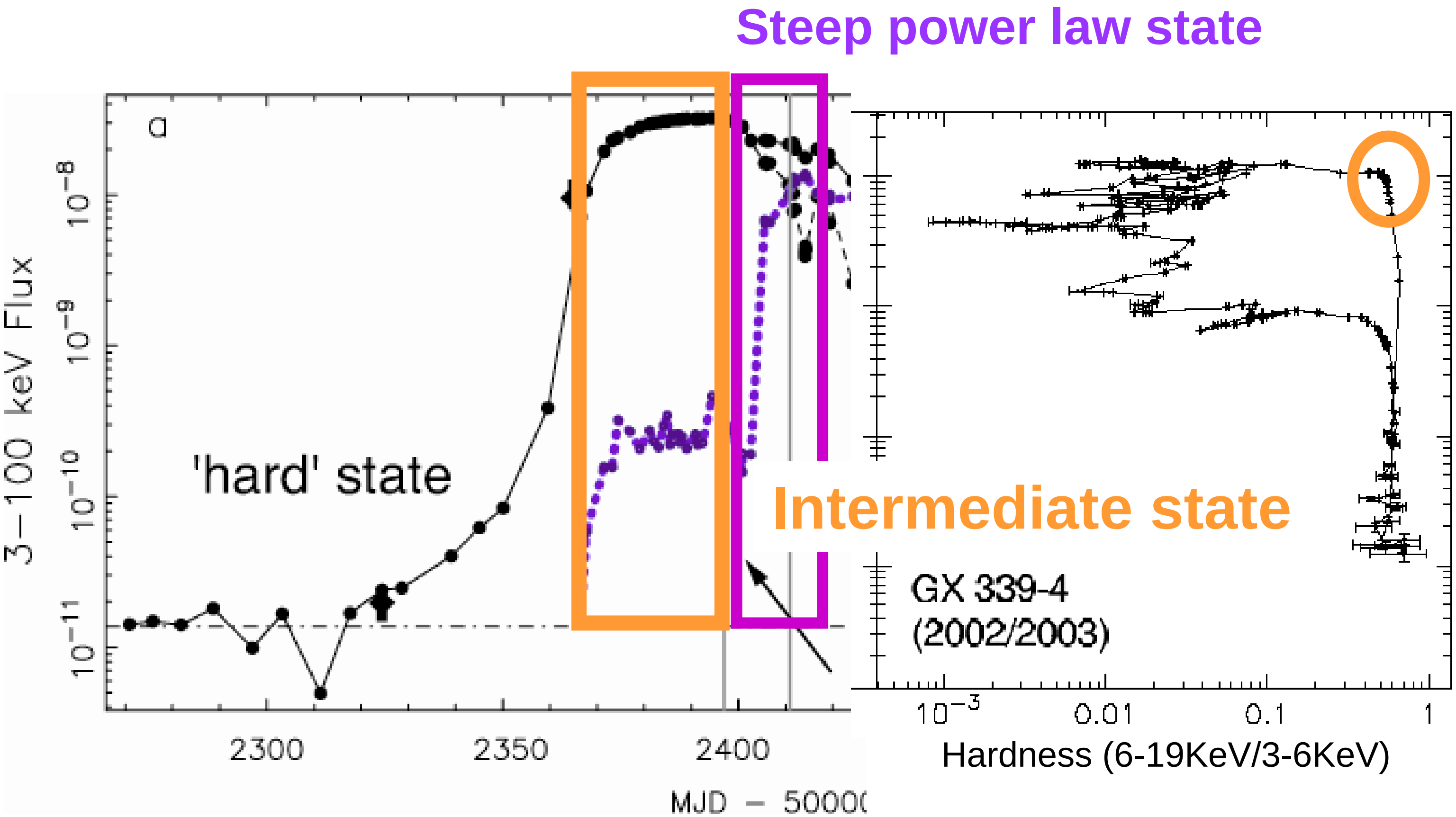
Thermal equilibrium curves of an accretion disk

Standard theory of accretion disks (Shakura and Sunyaev 1973) introduced phenomenological viscosity parameter α

Viscous stress: $T_{r\phi} = \alpha P$



Properties of very high state



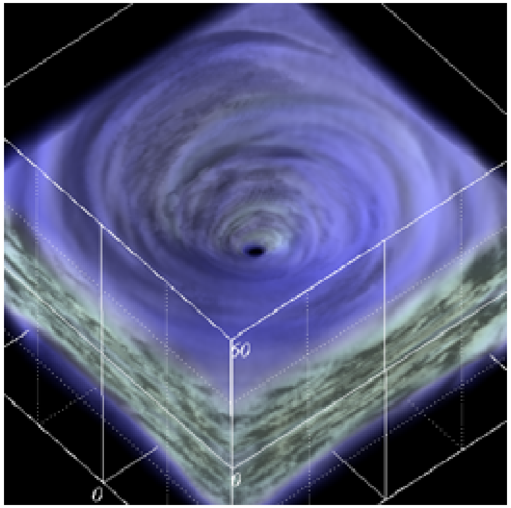
Intermediate state: **スペクトルがハードで, とても明るい**

光学的に薄く、high/soft stateと同程度に明るい状態にあるのか？

Purpose of this talk

Global 3D MHD simulations of black hole accretion disks have been carried out assuming radiatively inefficient disks

(e.g. : Hawley, Igumenshchev, Armitage, Matsumoto, Kato …)



Saturation level of plasma $\beta \sim 10$

Maxwell stress $\alpha_B \sim 0.01\text{-}0.1$

Machida & Matsumoto (2003)

However,

Radiative cooling is essential for state transitions !

We study the effect of radiative cooling on the evolution of initially optically thin, hot disk.

2.Basic equations and initial models

Basic equations

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

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \bullet \nabla)\mathbf{v} = - \nabla P + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi} - \rho \nabla \phi$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\frac{\partial \rho \varepsilon}{\partial t} + \nabla(\rho \varepsilon \mathbf{v}) + P \nabla \mathbf{v} = \eta J^2 - Q'_b \tau_0 \rho^2 T^{1/2}$$

Global Three-dimensional MHD Simulations of Black Hole Accretion Flows

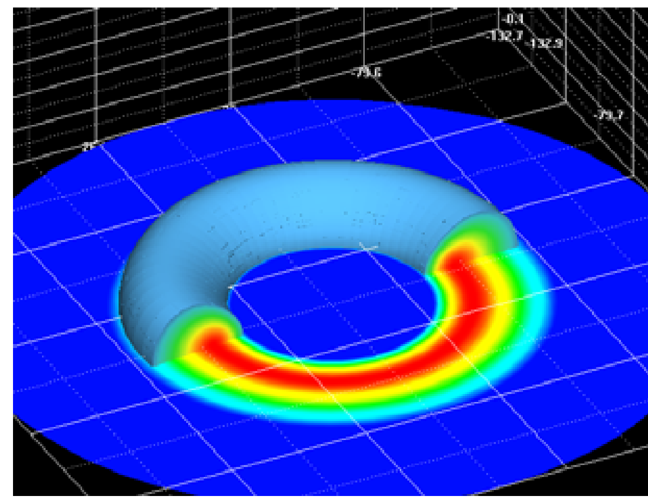
Gravitational potential : ϕ = - GM/(r-r_g)

Initial torus : constant angular momentum torus threaded by weak toroidal magnetic field

Pgas/Pmag = β = 100

Anomalous Resistivity

$$\eta = \max[(J/\rho)/v_c - 1, 0.0]^2 / \mathrm{R_m}$$



250*64*192mesh

Radiative cooling term

Cooling term is switched on after the accretion flow becomes quasi-steady.

We add the optically thin bremsstrahlung cooling term in the energy equation.

$$\rho T \frac{dS}{dt} = \eta J^2 - Q_b' \tau_0 \rho^2 T^{1/2}$$

$$Q_b' = 1.9 \times 10^{-4} A_F \left(\frac{T_e}{T}\right)^{1/2} \qquad \tau_0 = \kappa_{es} \rho_0 r_g = 1.2 \times 10^5 \rho_0 \left(\frac{M}{M_\odot}\right)$$

T_e: electron temperature
A_F: Compton amplification factor
τ_0: optical depth

Two temperature ADAF model

→ $T_e/T \sim 1/100$ and $A_F \sim 10$

→ $Q_b' = 1.9 \times 10^{-4}$ 、$\tau_0 = 0.3$

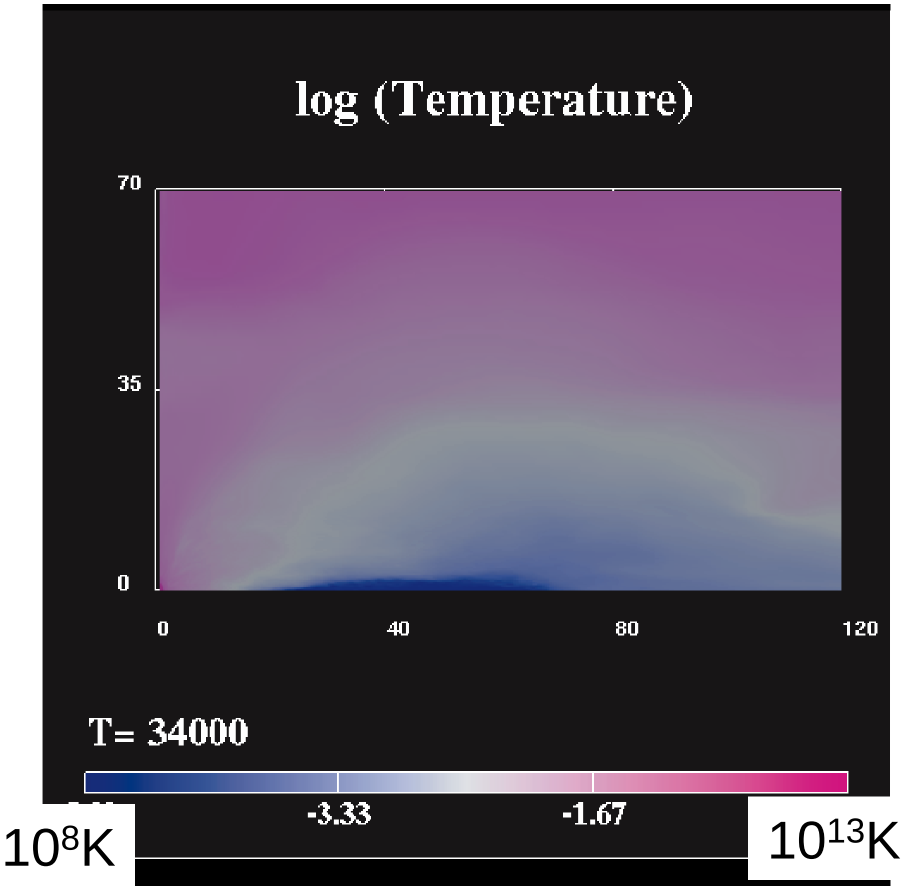
$M = 10\ M_{sun}$

model	plasma β	τ_0	Density ρ_0 (g/cm^3)	Switch on time
C100	100	0.6	4.8×10^{-7}	24,000
C50E	100	0.3	2.4×10^{-7}	14,000
C50	**100**	**0.3**	$\mathbf{2.4 \times 10^{-7}}$	**24,000**
C50L	100	0.3	2.4×10^{-7}	34,000
C10	100	0.06	4.8×10^{-8}	24,000
C1	100	0.006	4.8×10^{-9}	24,000

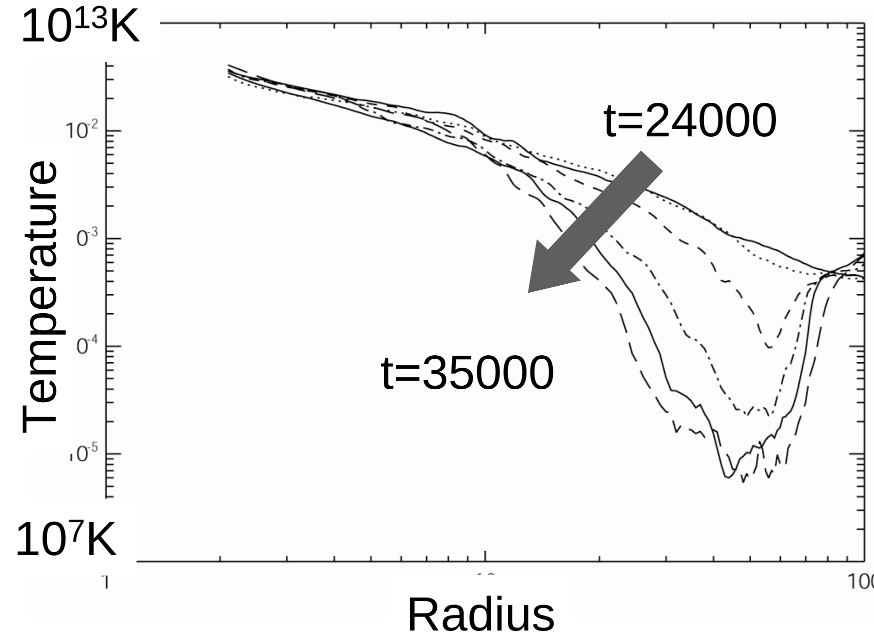
3 Numerical results

Transition to Cool Disk

Before Transition



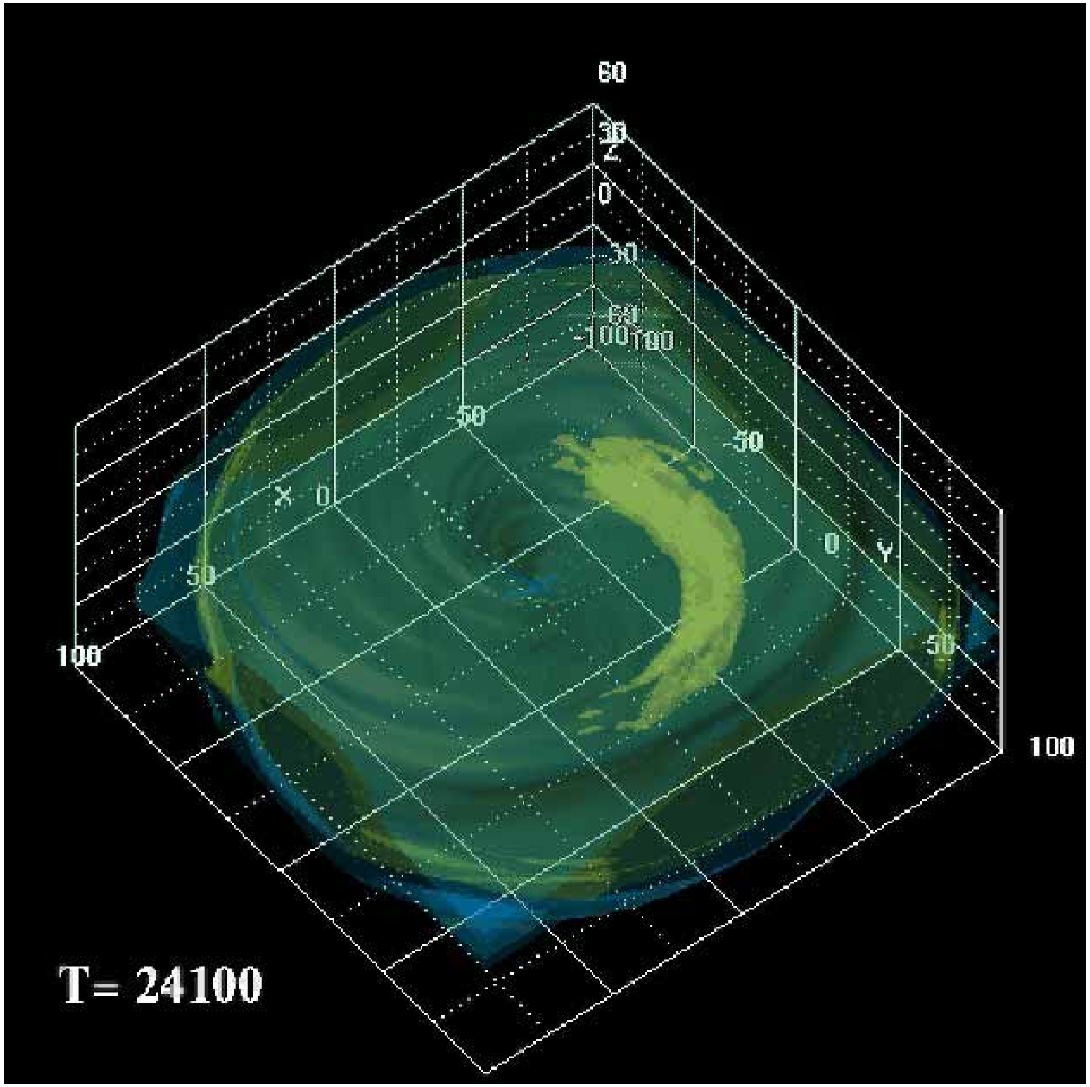
Temperature distribution



Cold region appears first around r~50 and propagates inward. The region inside 10 rg stays in the hot state throughout the simulation.

Cold, dense disk is formed in outer region!

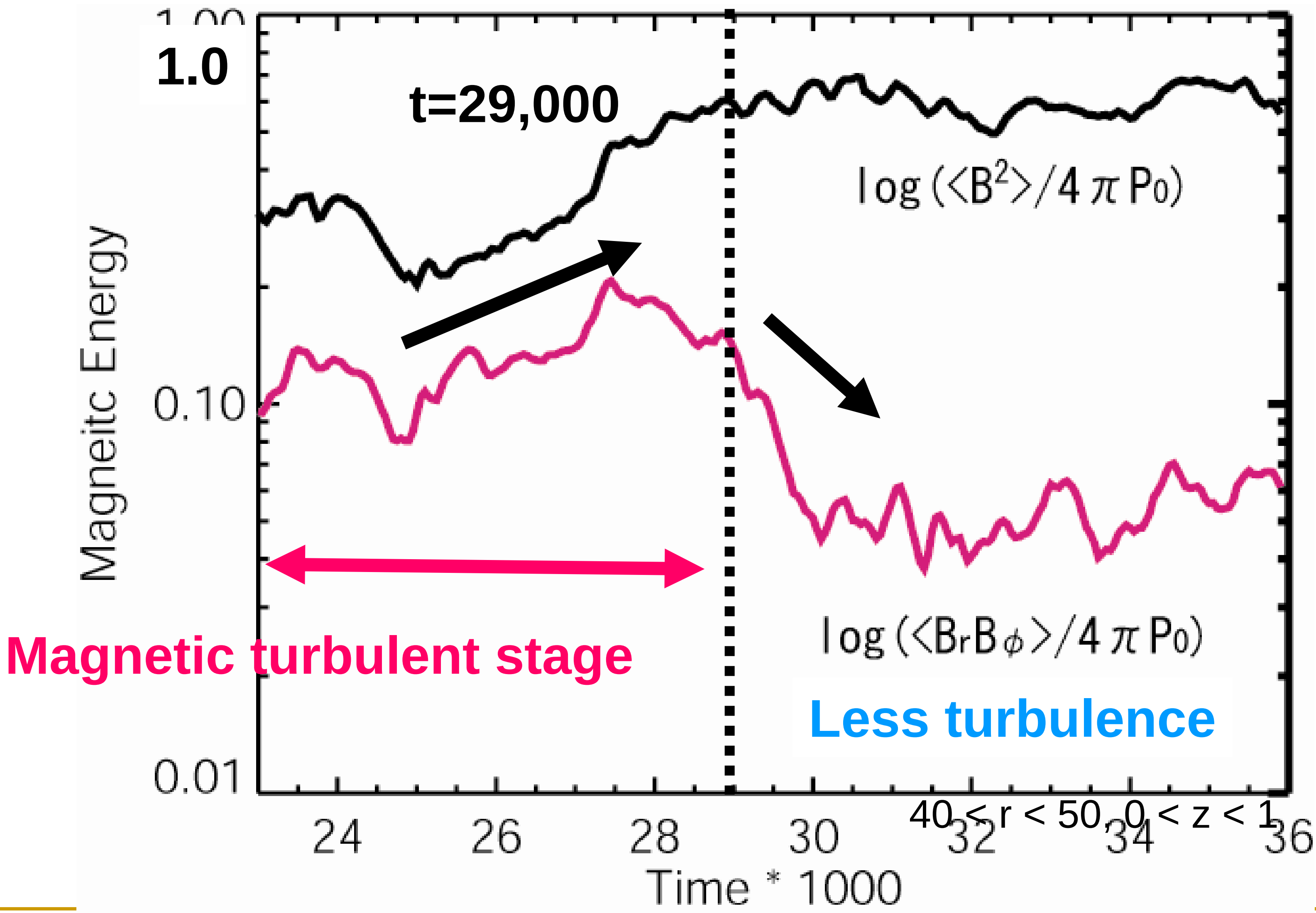
Formation of Low-β disk



Isosurface of plasma β
Yellow: 1
Green : 10
Blue : 100

Low-β disk is created!

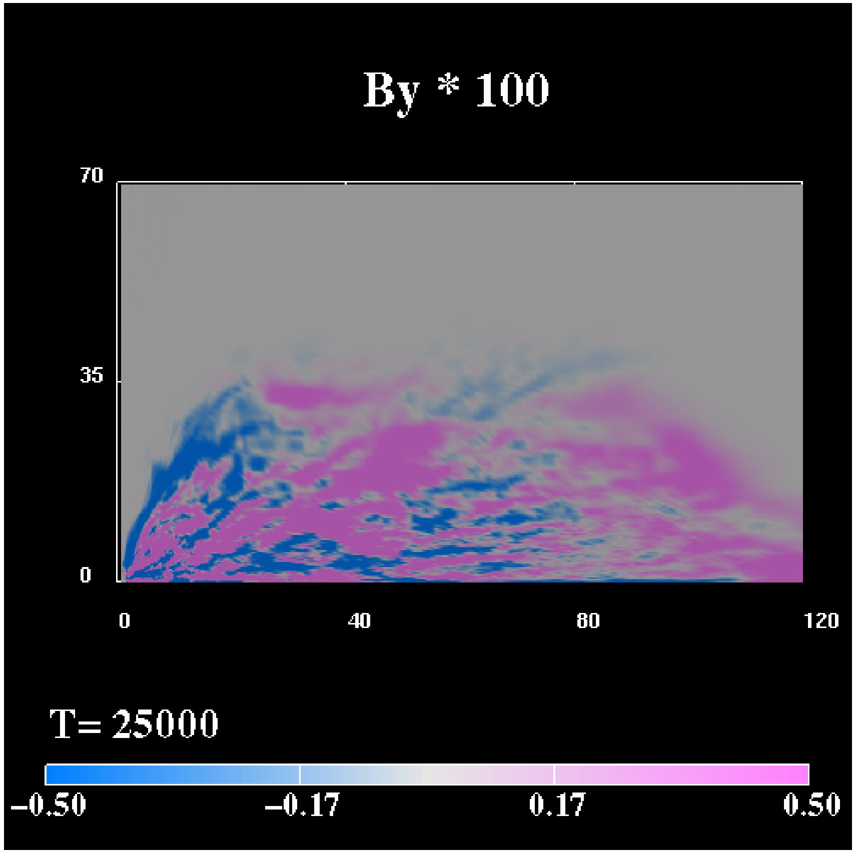
Time evolution of magnetic energy



Angular momentum transport becomes inefficient.

Azimuthal component of magnetic field

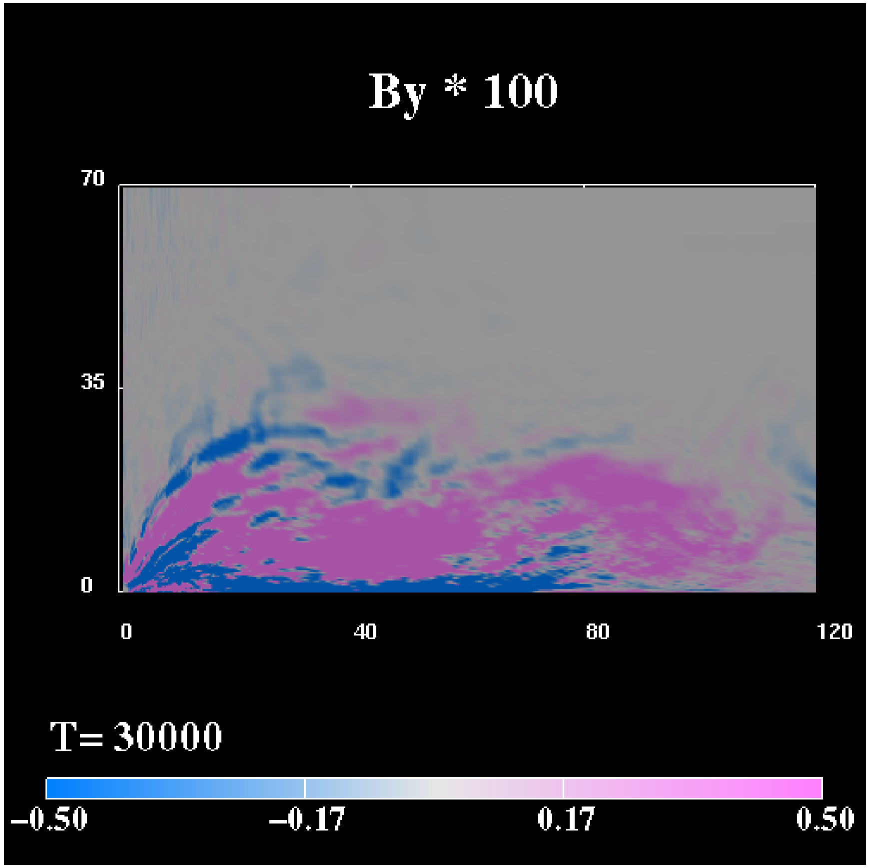
Before transition



magnetic turbulence dominates

B_ϕ component shows layered structure.

After transition

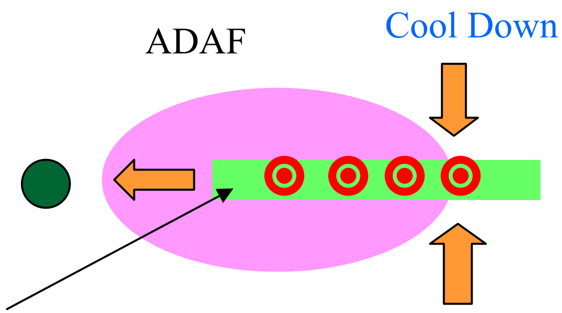


Turbulence suppressed

coherent negative B_ϕ dominated.

Strong toroidal magnetic fields suppress the growth of MRI.

磁気圧優勢円盤の安定性



光学的に薄い磁気圧優勢円盤の熱平衡曲線を求める。

1. **降着円盤は磁気圧優勢である.**

鉛直方向に積分した圧力

$W \approx B^2 H/(8\pi)$ Magnetic pressure dominated

鉛直方向の静水圧平衡

$W/(\Sigma H) \approx \Omega^2 H$

$W = PH$

$\Sigma = \rho H$

H : scale height

$\Omega = \Omega(r)$: angular velocity

2. **移流項は無視する.**

粘性加熱項

$Q^+ \propto \dot{M} \propto W$

放射冷却項

$Q^{rad} \approx \rho^2 T^{1/2} H$

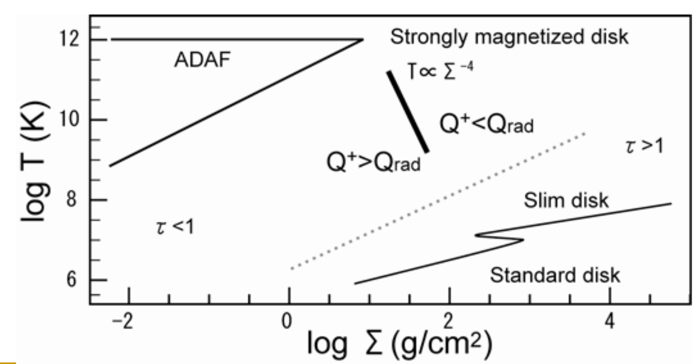
$\longrightarrow \quad \dot{M} \approx \Sigma^2 T^{1/2}/H$

3. **磁束の保存を仮定.**

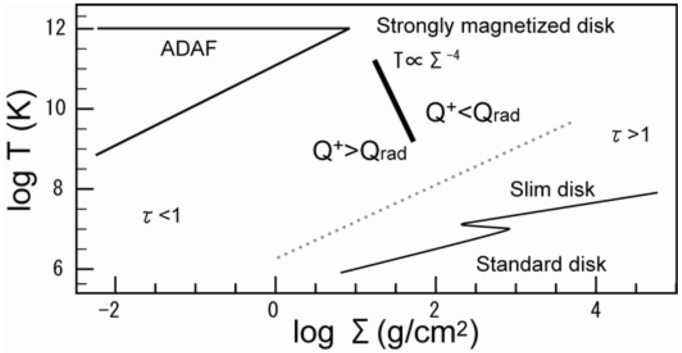
$$BH \cong \text{constant}$$

From these assumption,

$$\dot{M} \propto \Sigma^{1/3}, T \propto \Sigma^{-4}$$



計算結果と円盤モデルの比較

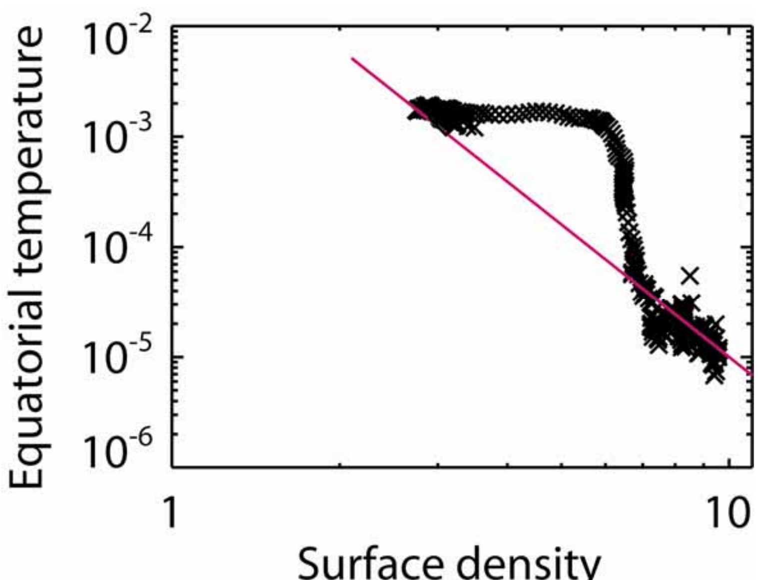


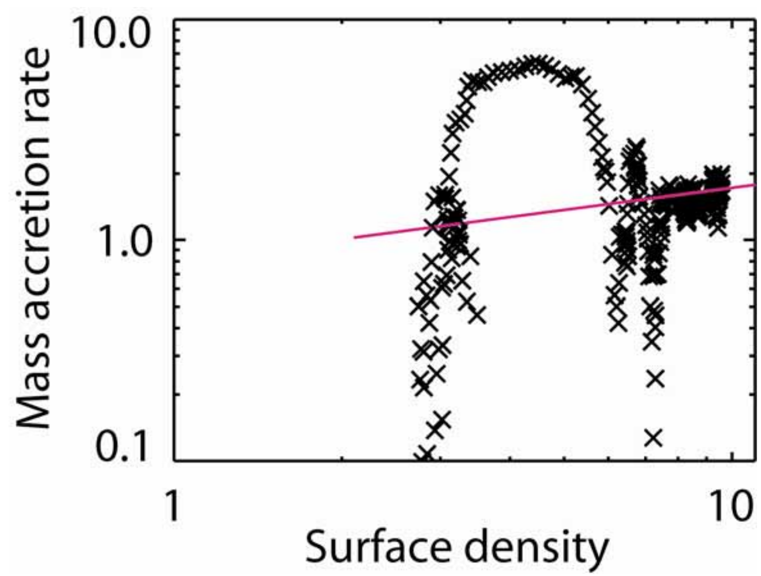
表面密度と赤道面温度の関係 (右)

表面密度と質量降着率の関係 (左)

ピンクの直線は磁気圧優勢円盤の熱平衡曲線

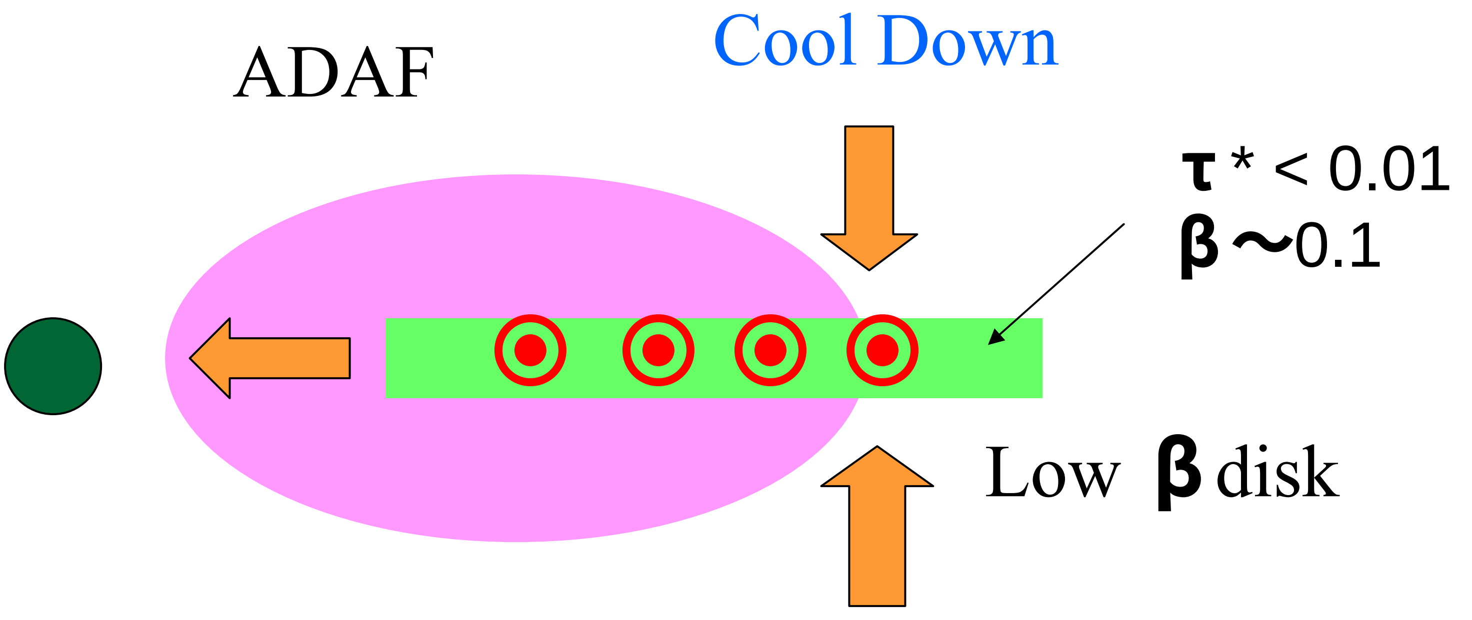
Surface density is integrated in $0<z<10r_g$.





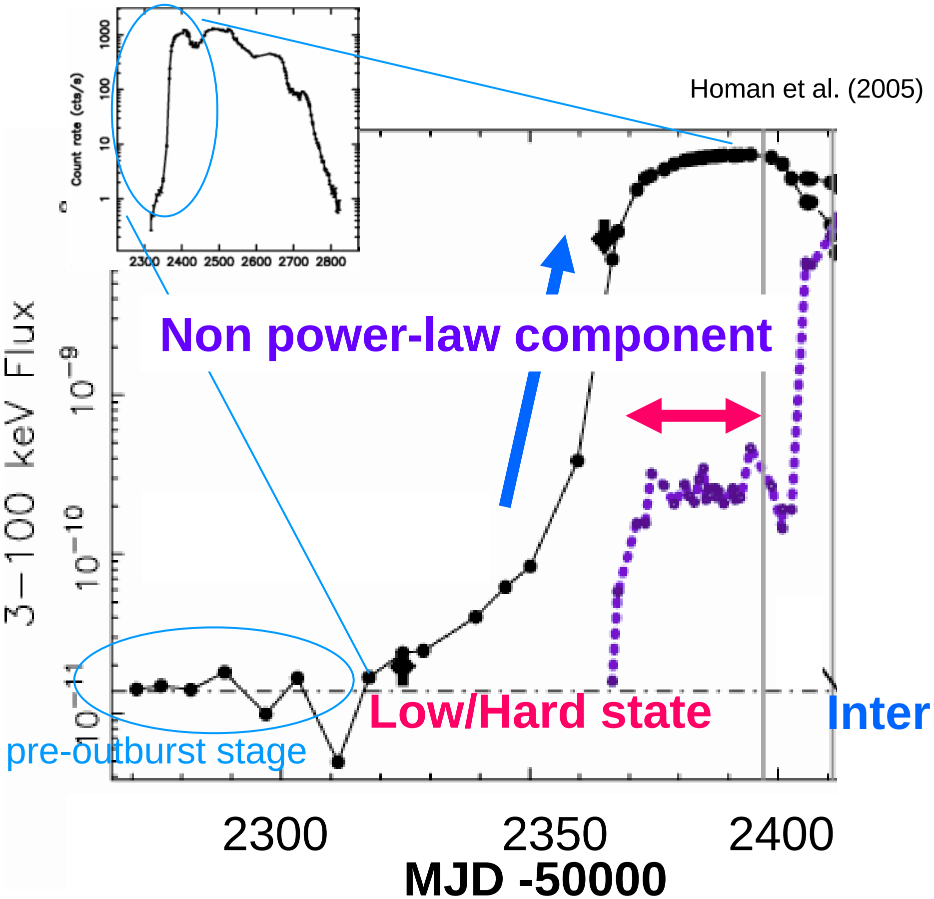
4. Discussion

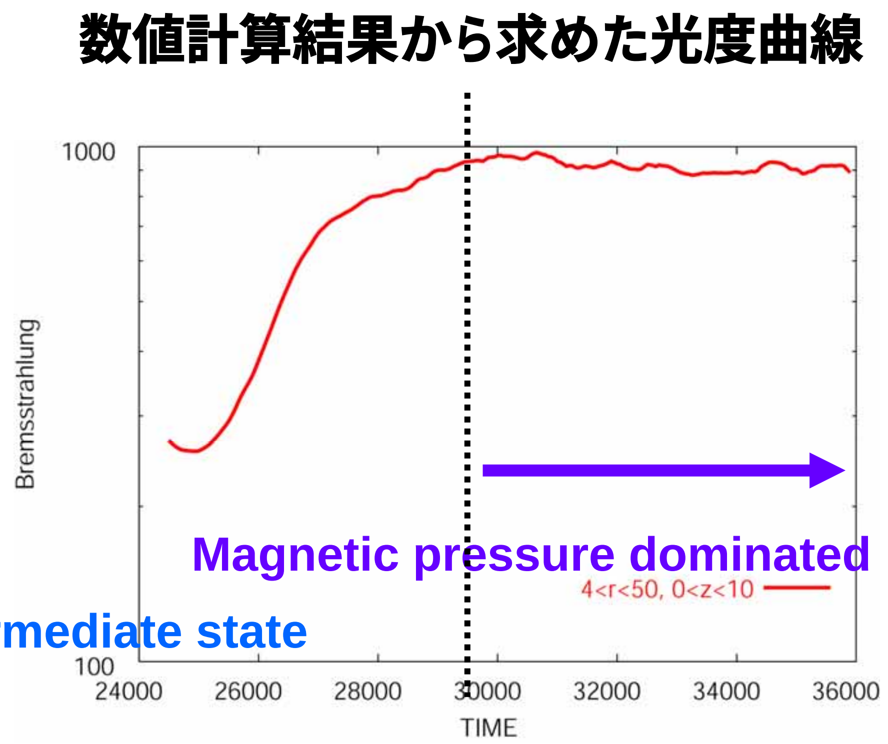
A schematic picture of simulation results



Time scale of radiative cooling becomes shorter than time scale of magnetic buoyancy. Therefore, the magnetically supported disk is created.

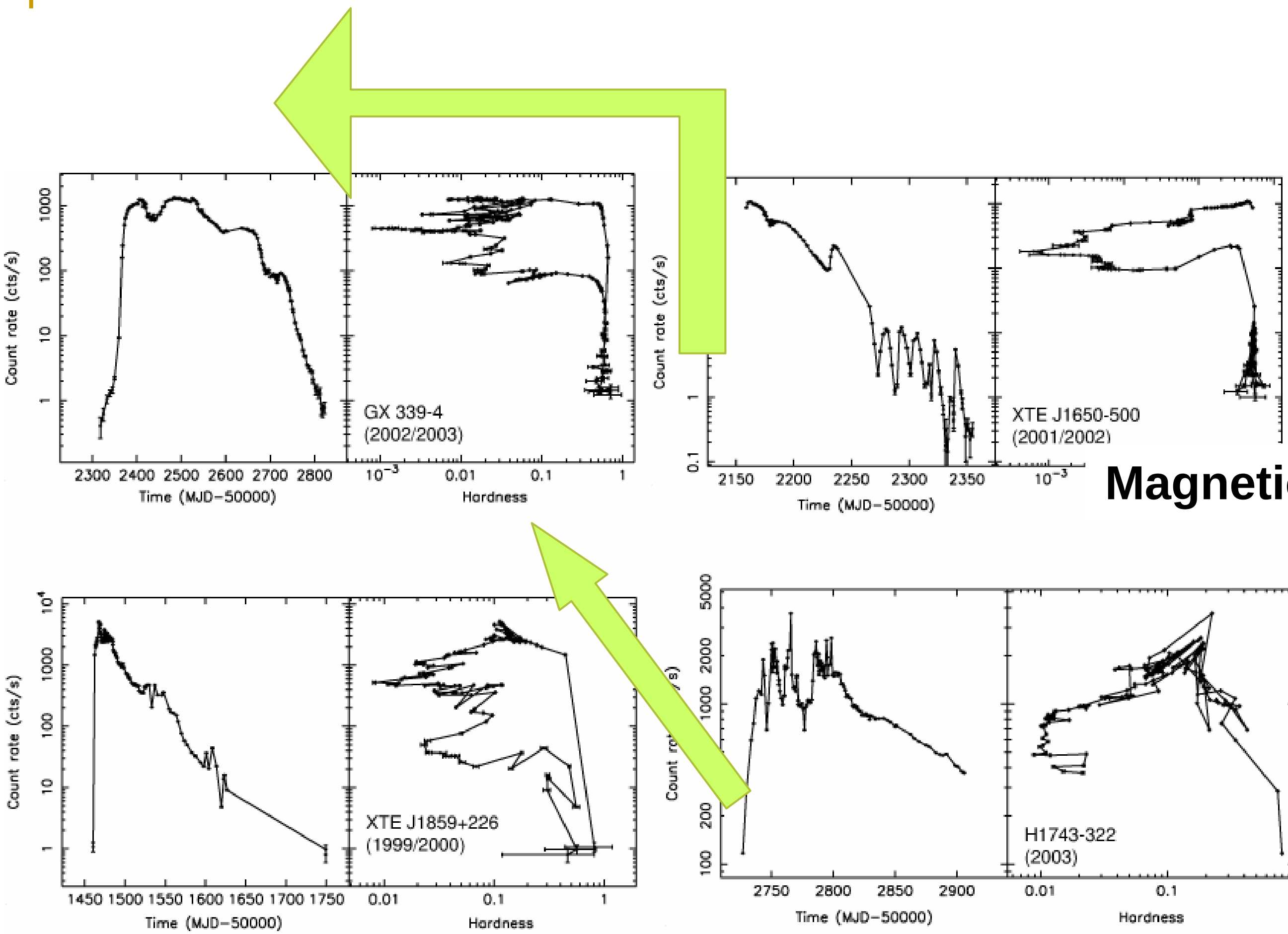
Application to the observation

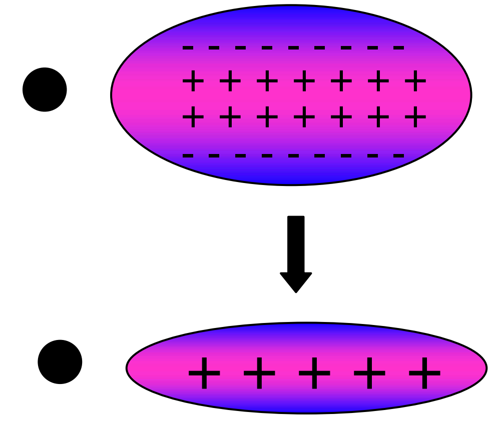




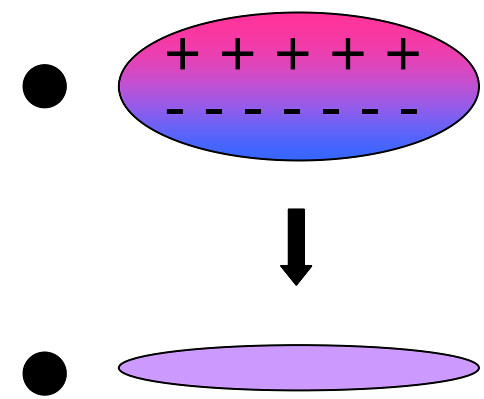
The thermal instability is the origin of the sudden increase of luminosity. Since magnetic pressure supports the disk, the cool disk does not become optically thick. Thus, soft component does not appear during this stage.

磁場構造の違いと観測





Magnetic field support the disk



Magnetic field dissipate and disk continue shrinking

大局的な磁場構造が状態遷移時の降着円盤の進化を決定する

Summary

1. 光学的に薄い放射冷却を加えることで、low/hard state からintermediate state への状態遷移の数値実験を行った。
2. この状態遷移によって降着円盤内部は磁気圧優勢になる。この磁気圧優勢円盤内部は、強い方位角方向磁場によって磁気乱流は抑えられる。
3. 数値計算から得られた磁気圧優勢円盤は降着円盤の熱平衡曲線上に新しく求められた新しい安定解に対応している。
4. 熱不安定性によって、光学的に薄い冷たい降着円盤からX線フラックスが急激に増加することを再現した。
5. 降着円盤は磁気圧優勢であるため、磁場散逸や磁気噴出などなんらかの現象によって磁気圧が減少しない限り、光学的に厚い降着円盤にまで遷移することはできない。