MHD Simulations of X-ray Flares in Black Hole Accretion Disks

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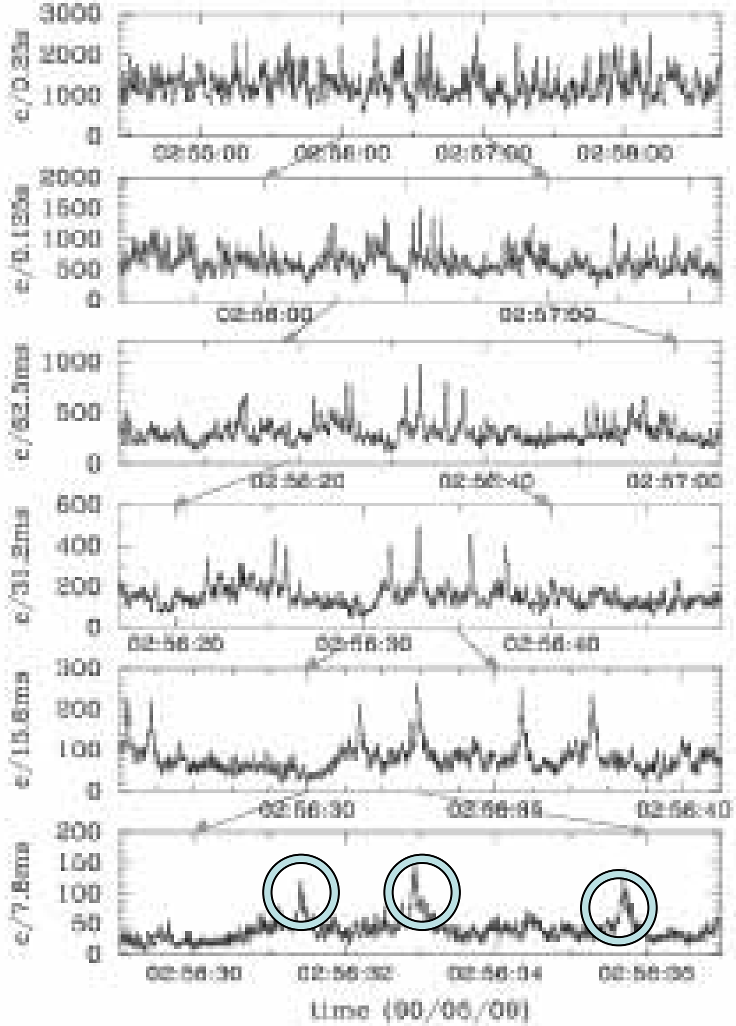
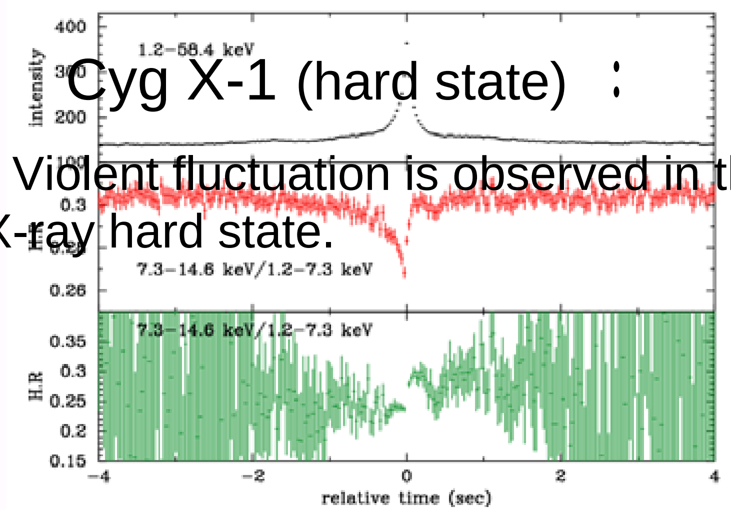
Introduction

X-ray Flares in Cyg X-1



X-ray counts from Cyg X-1 (**Negoro et al. 1995**)



Negoro et al. 2001

Cyg X-1 (hard state) :

Violent fluctuation is observed in the X-ray hard state.

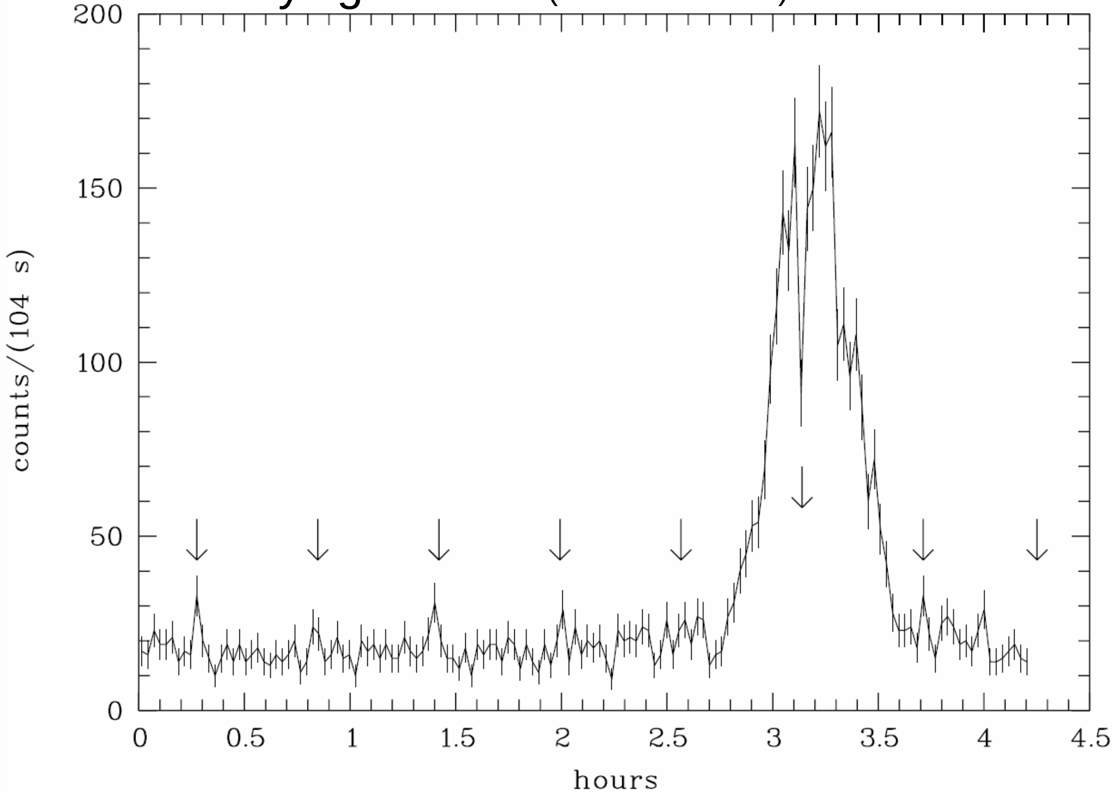
X-ray shot:

X-ray intensity increases exponentially.

Spectral softening is observed before the peak of the shot. The spectrum hardens within several milliseconds after the peak.

17 min Oscillation of Sgr A*

X-ray light curve (October 3 2002)



Aschenbach et al. (2004)

X-ray light curves of Sgr A* has almost same properties as galactic black hole candidate such as rapid X-ray variability and some peaks.

X-ray flux has some peaks,

~ 100s, 219s, 700s, 1150s, 2250s.

X-ray emissions are correlated with NIR and radio.

The Purpose of our Study

- The physical mechanism of X-ray flares
  – Magnetic energy release in radiatively inefficient accretion disks ?

    (⇒ Machida & Matsumoto 2003)
- Relation between X-ray flares and disk oscillations

NUMERICAL MODEL

Basic Equations

Equation of continuity

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

Equation of motion

$$\frac{\partial v}{\partial t} + v \cdot \nabla v = -\frac{1}{\rho}\nabla P + \frac{1}{4\pi\rho}\left(\nabla \times B\right) \times B - \nabla \phi$$

Induction equation

$$\frac{\partial B}{\partial t} = \nabla\left(v \times B\right) - \nabla \times \left(\eta \nabla \times B\right)$$

Equation of energy conservation

$$\frac{\partial \rho\varepsilon}{\partial t} + \nabla\left(\rho\varepsilon v\right) + P\nabla v = Q_j$$

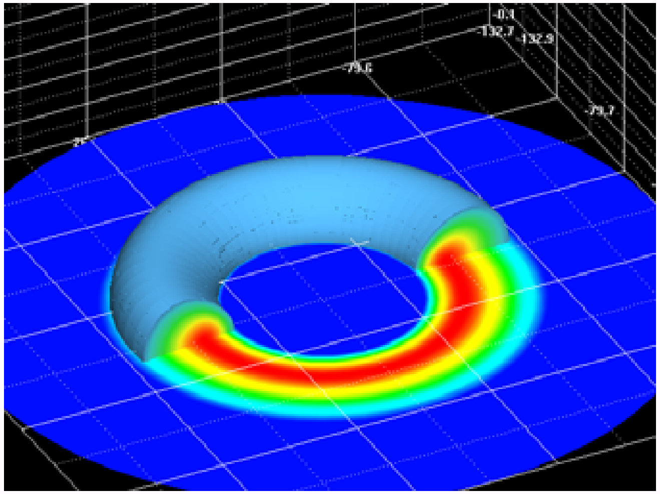
Anomalous resistivity

$$\eta = \begin{cases} \eta_0 \left(v_d - v_c\right)^2 & v_d > v_c \\ 0 & v_d < v_c \end{cases}$$

Initial Model & Simulation Parameters

Assumption

Gravitational potential $\phi = -GM/(r-r_g)$
Constant angular momentum torus
Anomalous resistivity
Ignored self gravity of disk



250*64*192 meshes

Unit

radius： $r_g=1$ r_g： Schwartzschild radius
velocity： c (light speed) =1
density： $\rho_0=1$

Parameter

The radius of pressure maximum $r_0 = 50\ r_g$
The ratio of gas pressure to magnetic pressure $\beta \equiv P_{gas}/P_{mag} = 100$ at $r=r_0$
Specific heat ratio $\gamma = 5/3$
Anomalous resistivity $\eta_0 = 5 \times 10^{-4}$
The ratio of initial halo density to the maximum equatorial density $\rho_{h0}/\rho_0 = 10^{-4}$
Critical ion-electron drift velocity $v_c = 0.9$

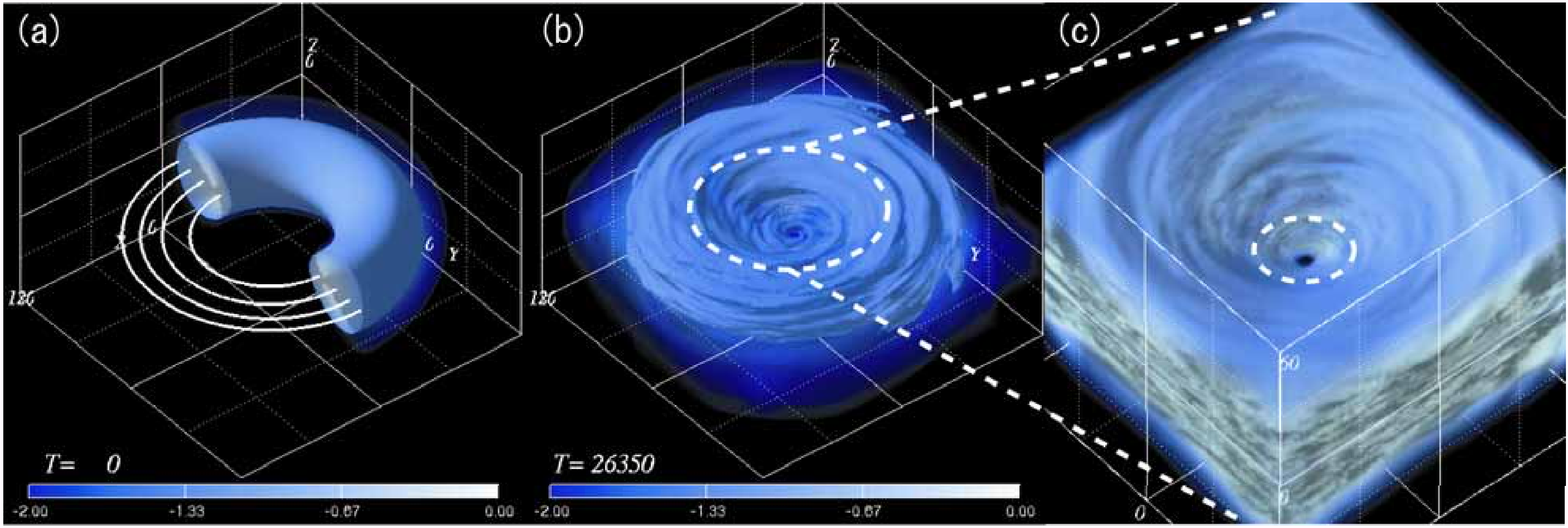
NUMERICAL RESULTS

Formation of an Accretion Disk

Initial model

t=26350

unit time t_0=rg/c

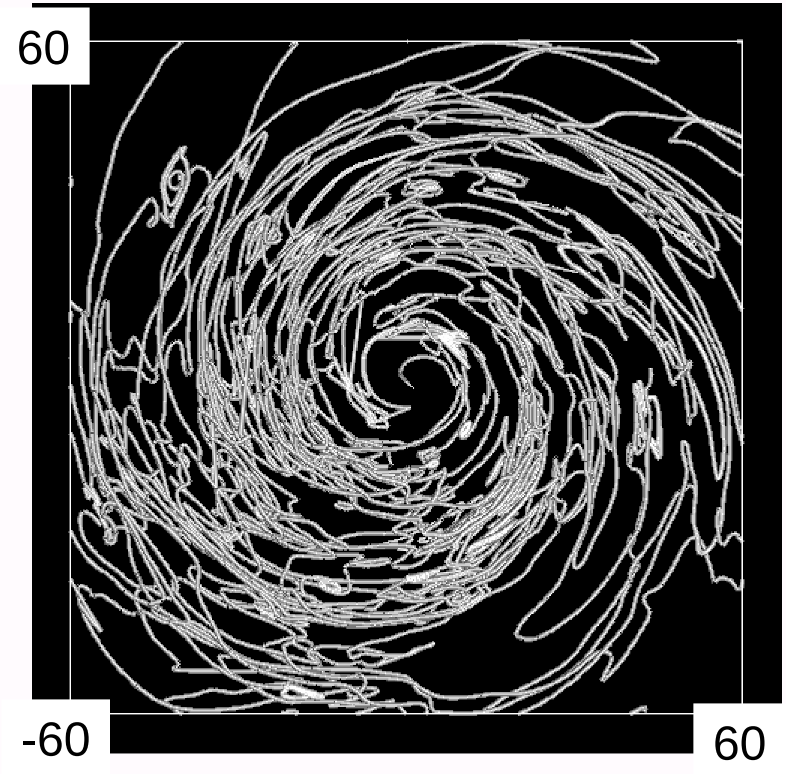


The equilibrium torus threaded by weak toroidal magnetic fields (β=100). Magnetic fields are amplified due to the magneto-rotational instability and saturates when plasma β is about 10. The MHD turbulence driven by MRI enhances the angular momentum transport rate and enables mass accretion.

Magnetic Field Lines

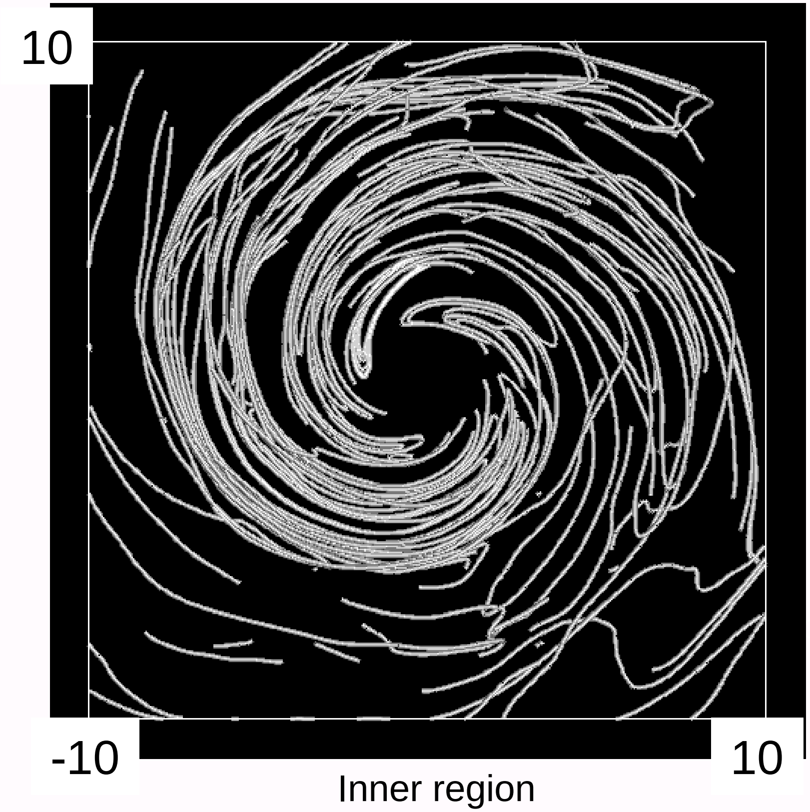
Magnetic field lines projected onto the equatorial plane

(-60 < x,y < 60)



Outer region

(-10 < x,y < 10)



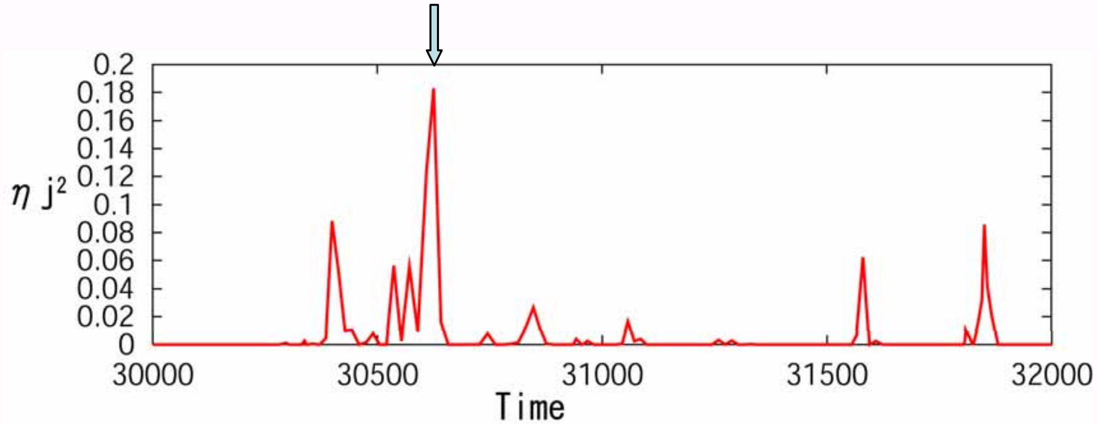
Inner region

Magnetic field lines are tightly wound.
⇒ Turbulent motions are dominant in the disk.

Magnetic field lines are less turbulent and globally show bisymmetric spiral shape (BSS).

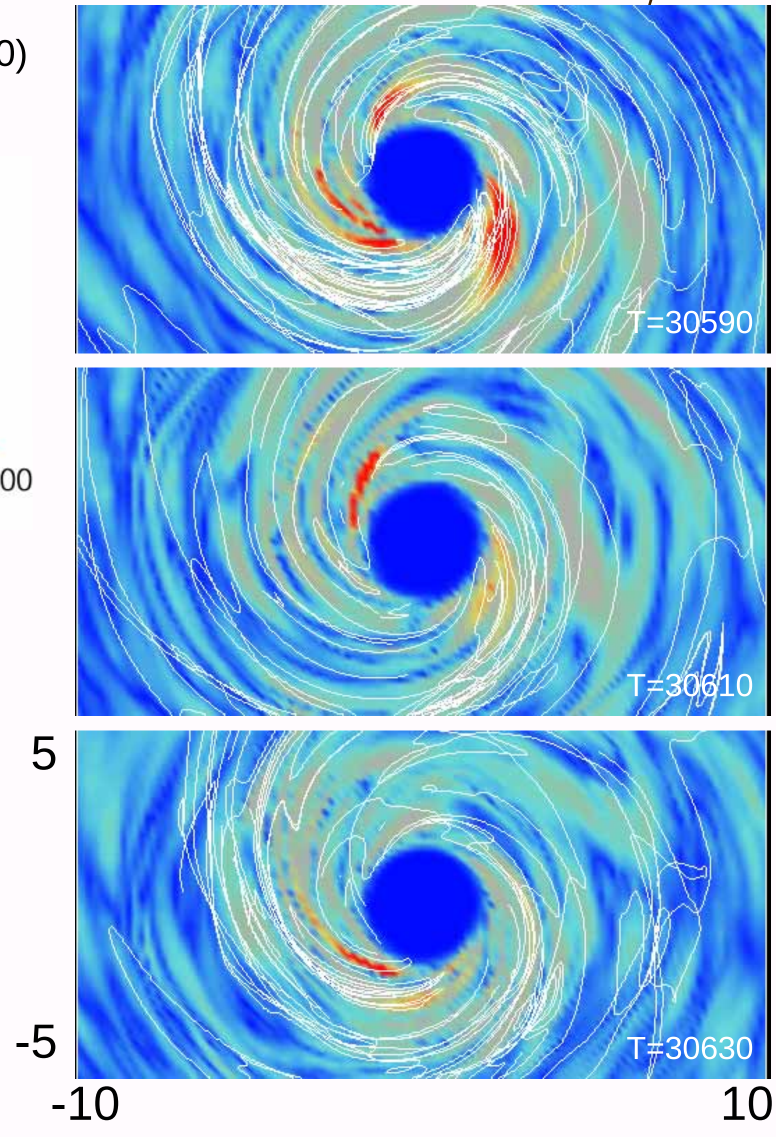
Magnetic Reconnection in the Innermost Region

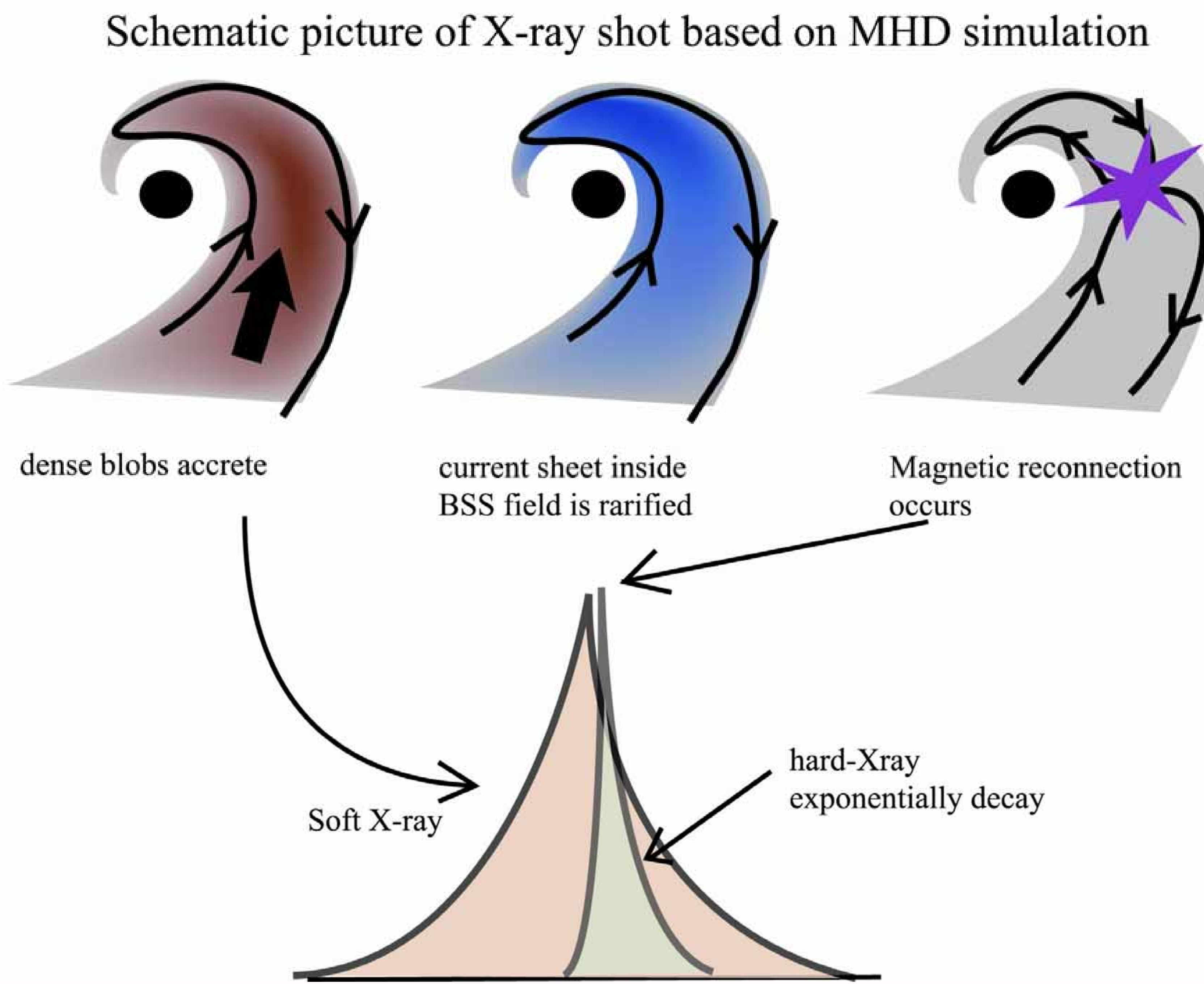
Volume integrated Joule heating rate $(2<\varpi<6, 0<\phi<2\pi, 0<z<10)$



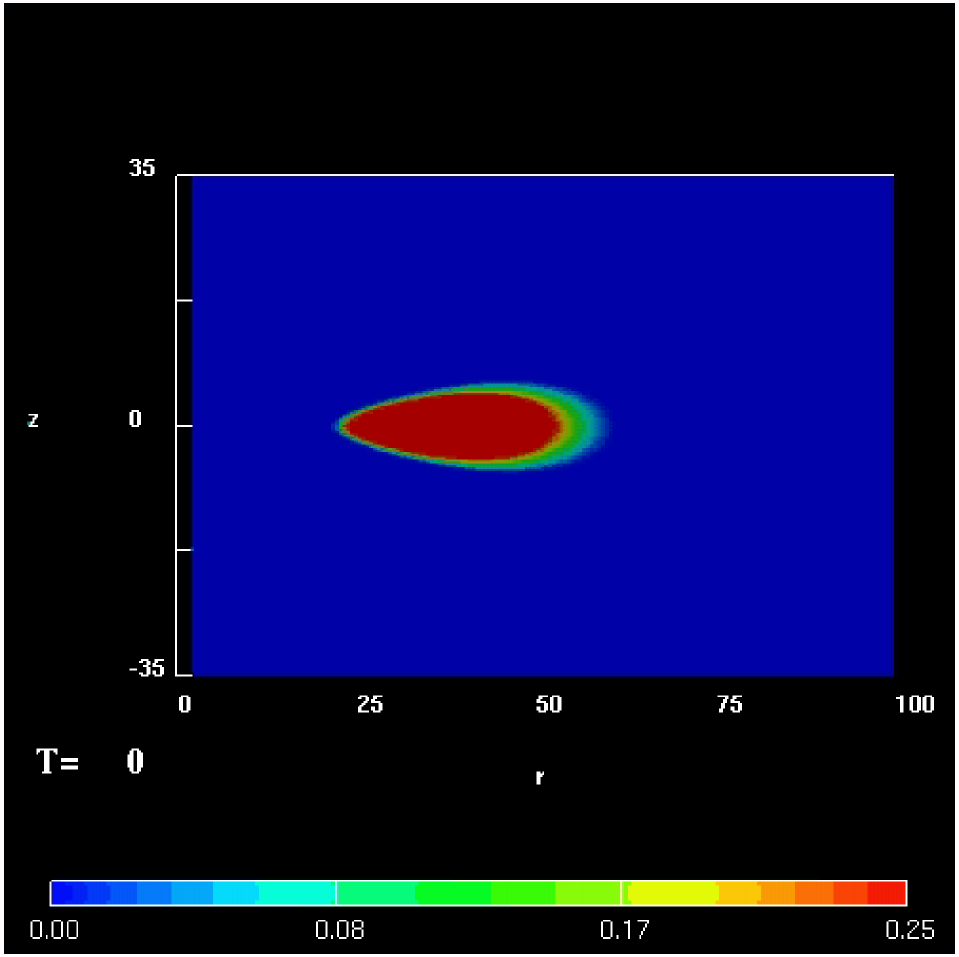
The above figure shows the time evolution of the volume integrated Joule heating rate. The arrow indicates the time when the largest magnetic reconnection takes place.

Right panels show the distribution of current density. The red region show the region where current density is high. The electric current dissipates as magnetic reconnection proceeds.



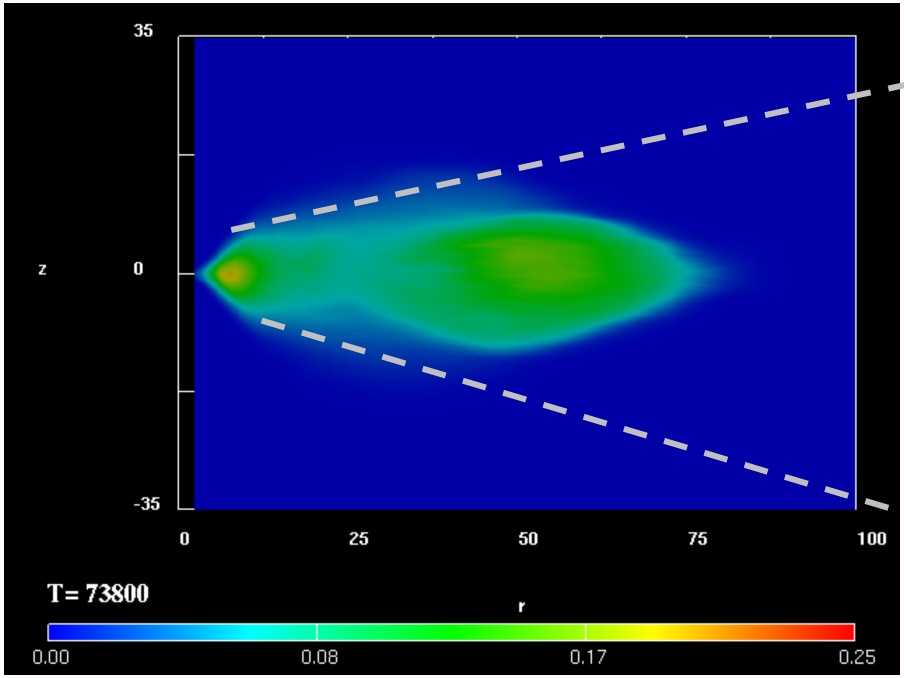

Schematic picture of X-ray shot based on MHD simulation
dense blobs accrete
current sheet inside
BSS field is rarified
Magnetic reconnection
occurs
hard-Xray
exponentially decay
Soft X-ray

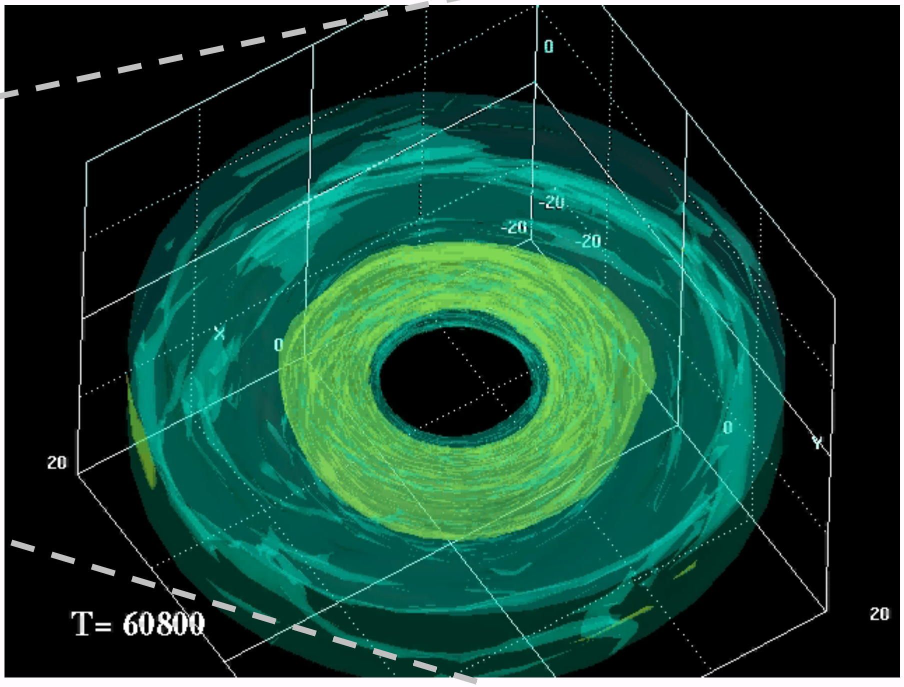
Longer Time Scale Simulation for Cooler Disk



Density distribution

Longer Time Scale Simulation for Cooler Disk

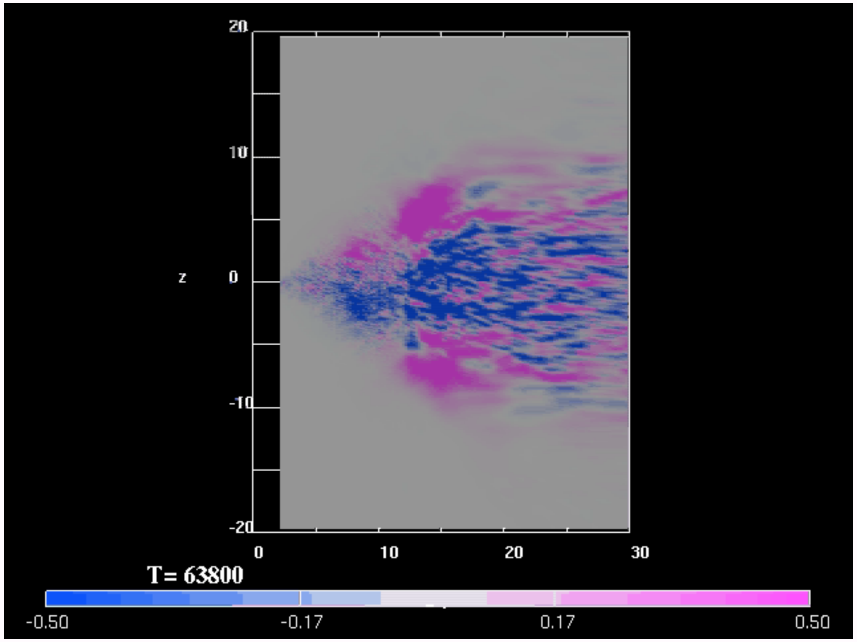




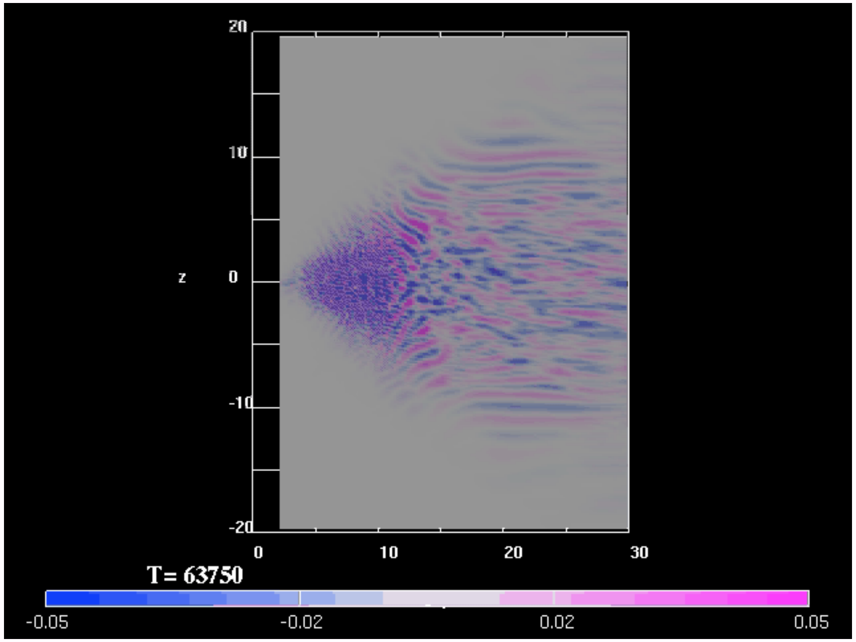
Yellow **ρ** =0.2
Green **ρ** =0.1

Distribution of Azimuthally Magnetic Field

Averaged toroidal magnetic field



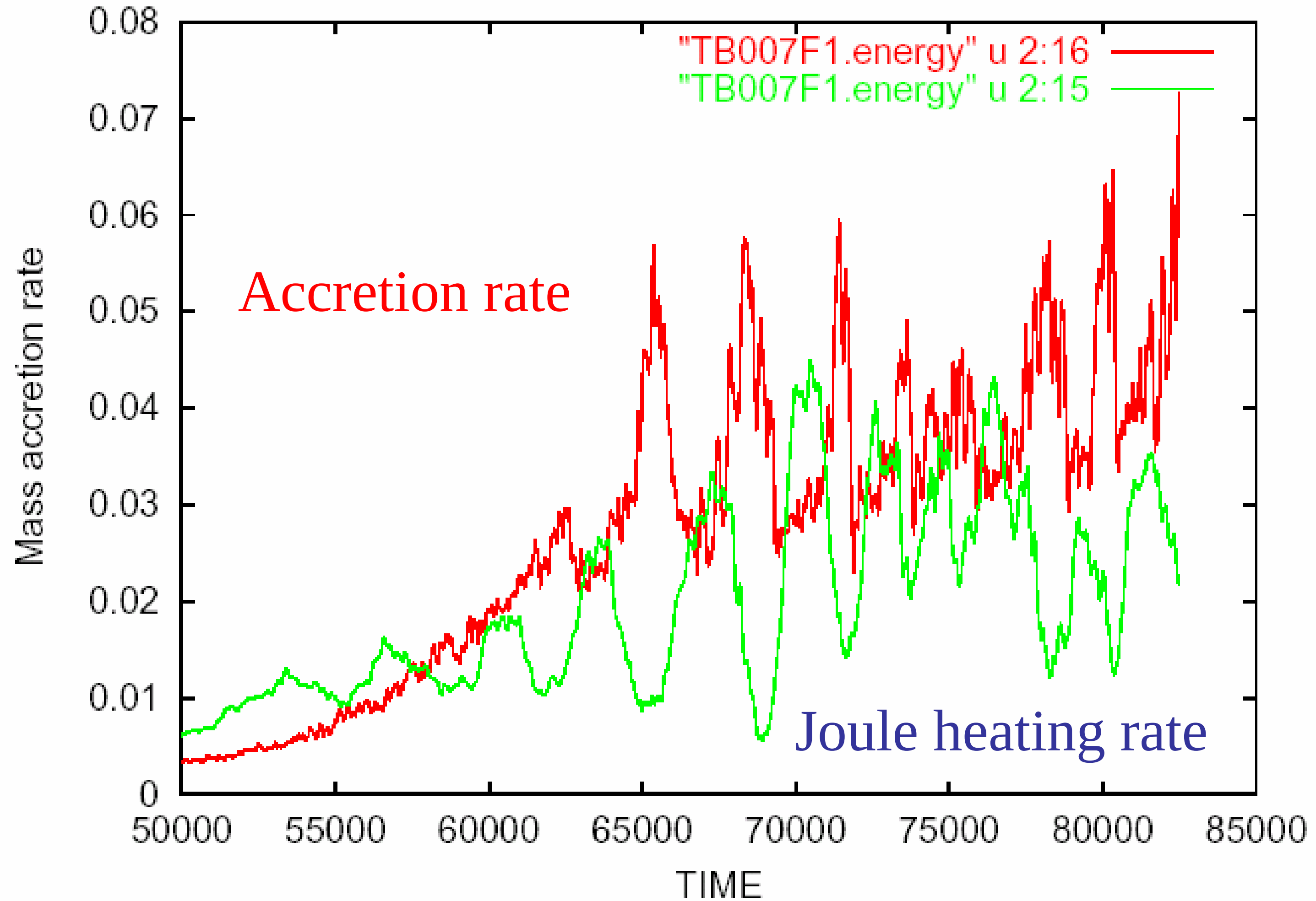
Non-averaged toroidal magnetic field



Sometimes, emergence of magnetic flux from the disk to its corona.

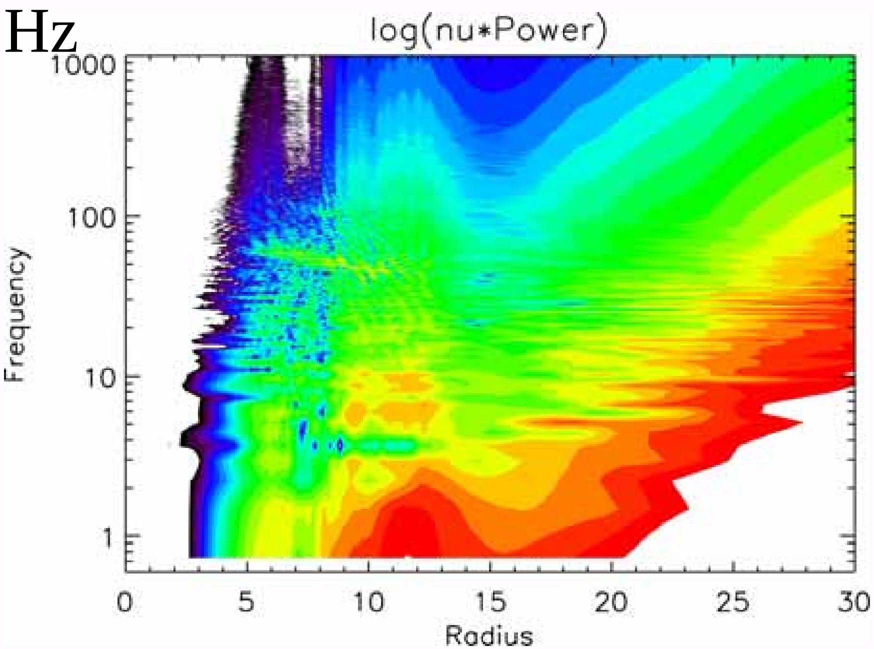
coherent oscillation pattern appears in the inner most region.

Sawtooth-like Oscillations in Accretion Disks

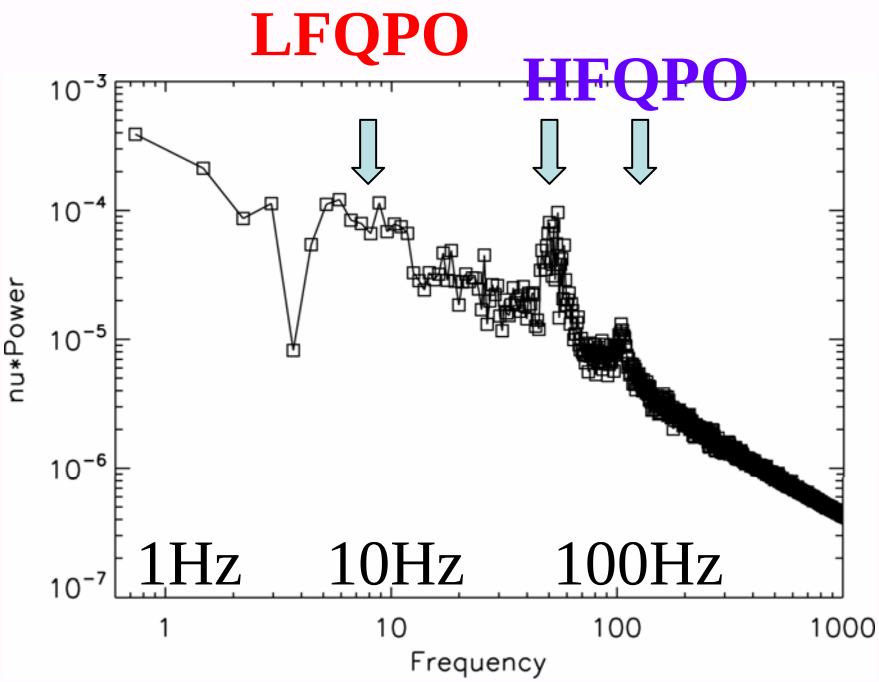


Power Spectrum of Luminosity Variations

Spatial distribution of the Power Spectrum



Power Spectral Density



Low Frequency Oscillation in the Inner Torus Excites High Frequency Disk Oscillations

SUMMARY

- We found that sawtooth-like oscillation takes place in the innermost region of radiatively inefficient accretion disks.
- The sawtooth oscillation is triggered by the growth of the non-axisymmetric m=1 mode in the inner torus, which amplify magnetic fields.
- The accumulated magnetic energy is suddenly released by magnetic reconnection. This may correspond to X-ray shots observed in Cyg X-1 and possibly explain flares observed in Sgr A*
- The X-ray flare forces the disk to oscillate with frequency comparable to the epicyclic frequency of the inner torus.
- Such oscillations may explain high frequency QPOs observed in black hole candidates.