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Nonlinear phenomena in magnetized accretion disks

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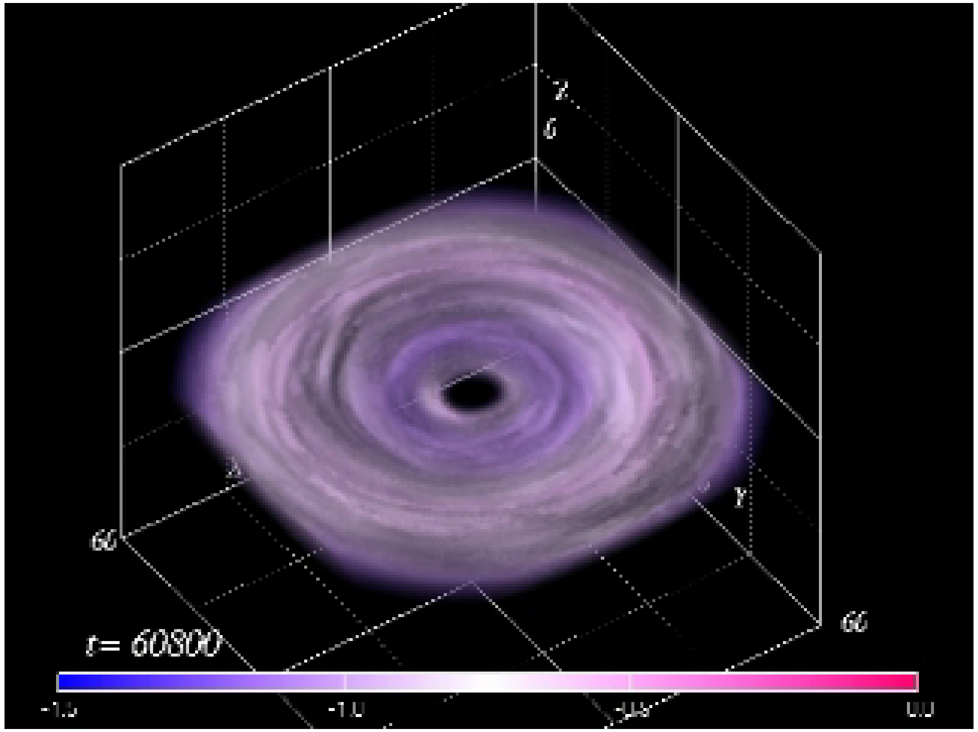
Nonlinear Phenomena in Magnetized Accretion Disks



Ryoji Matsumoto (Chiba University)

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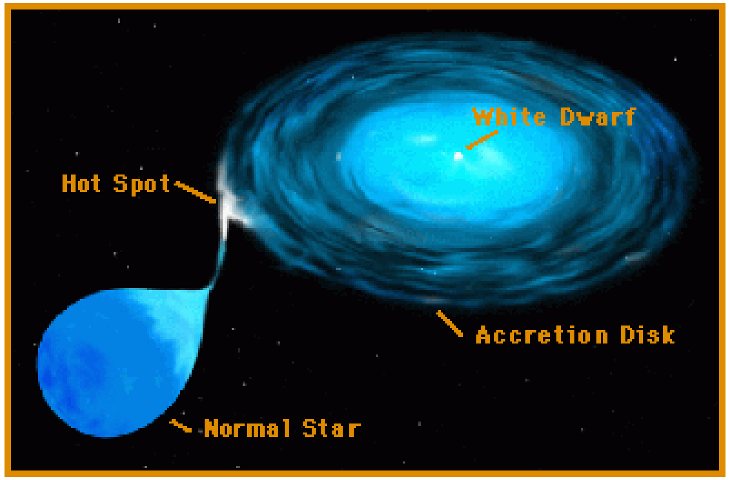
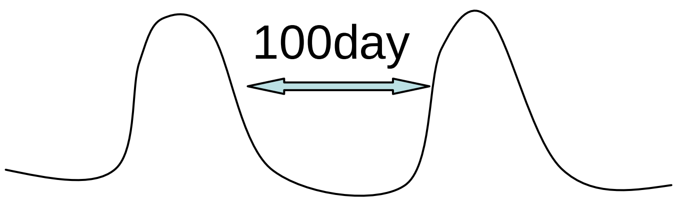
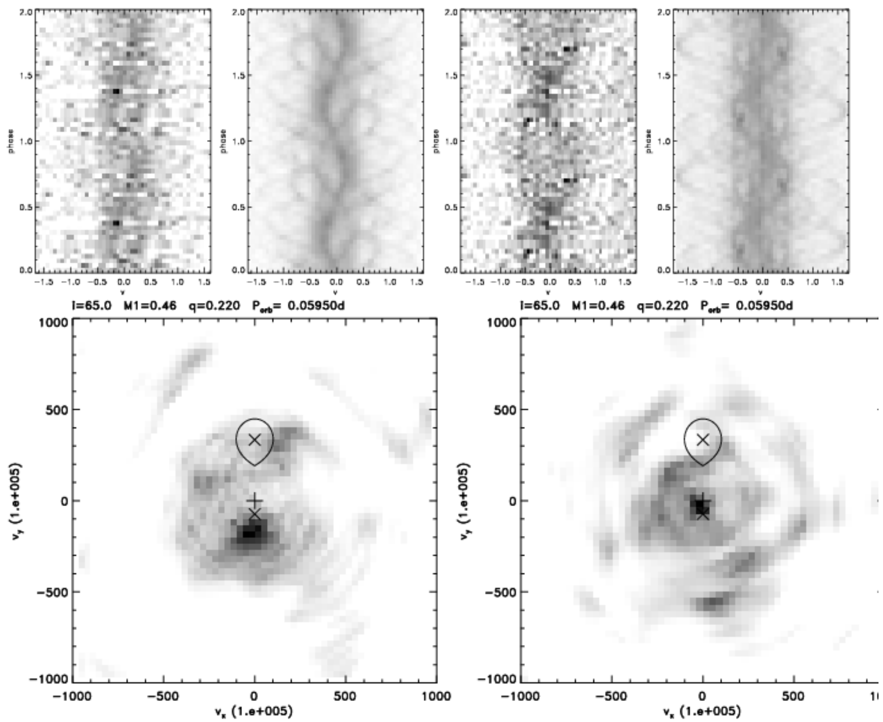
1. Introduction



A schematic picture of an accretion disk （NASA Web Page ）

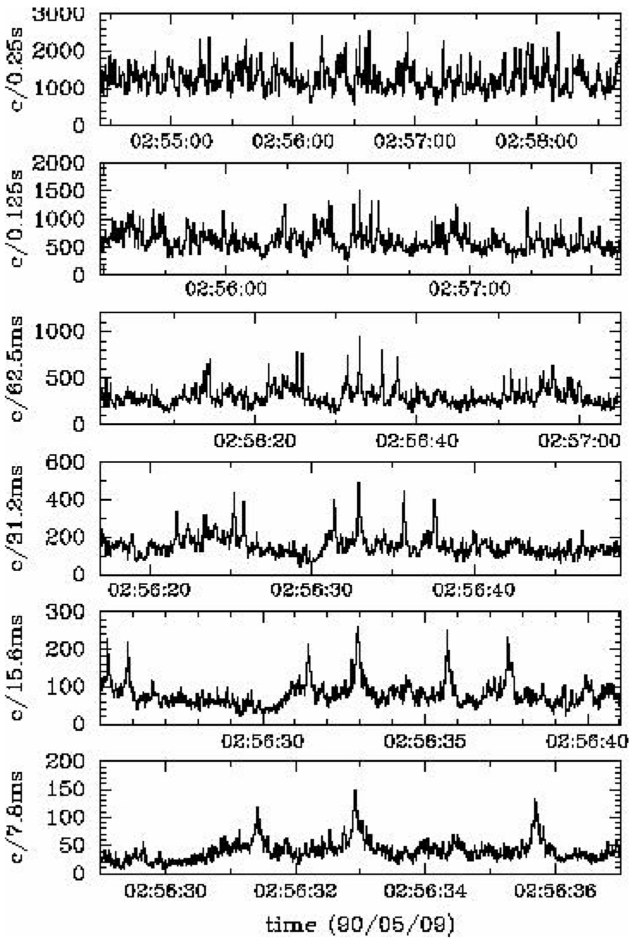


Light curve of a dwarf novae

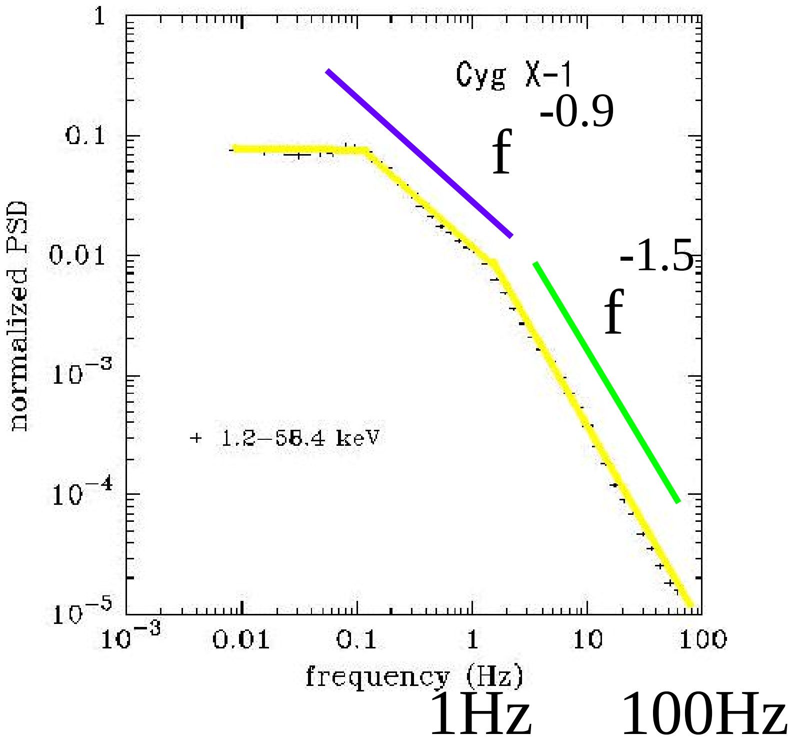


Doppler image of a dwarf novae FS Aurige (Neustroev 2002)

X-ray Light Curve of a Black Hole Candidate Cyg X-1

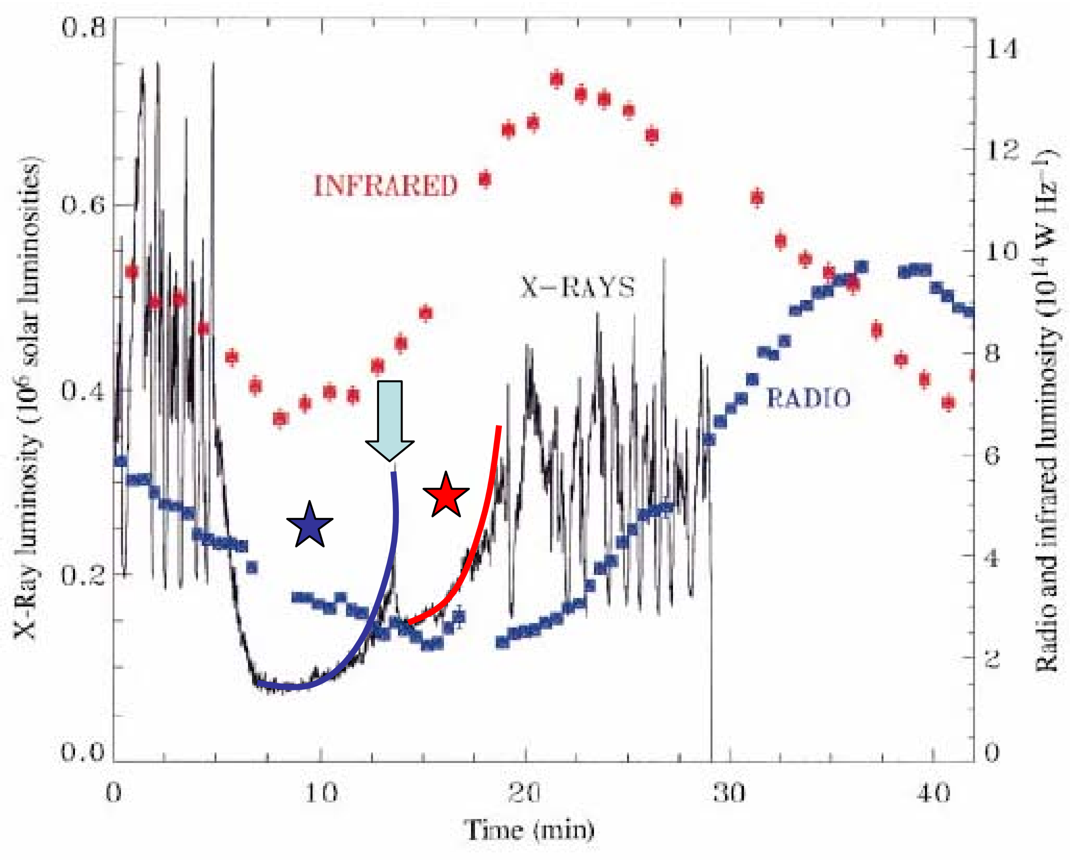


Negoro 1995

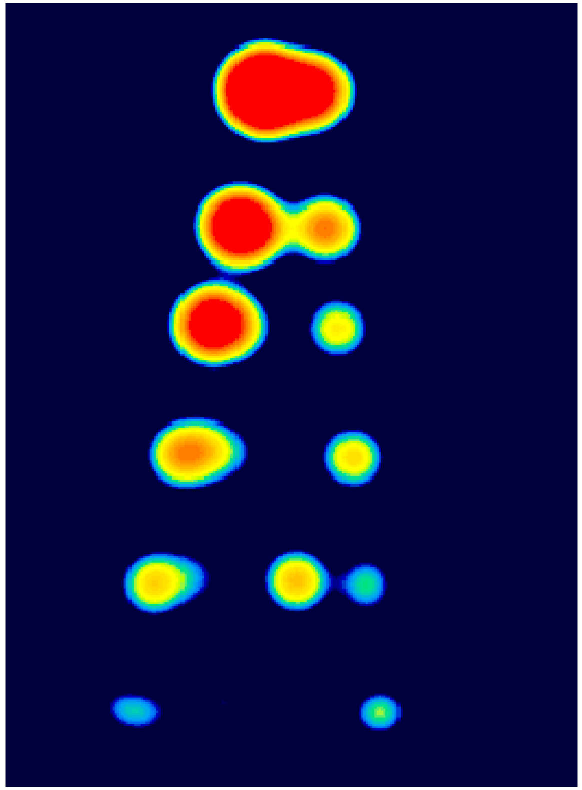


Power Spectrum of Time Variation in Cyg X-1

Violent Activity of Black Hole Candidates

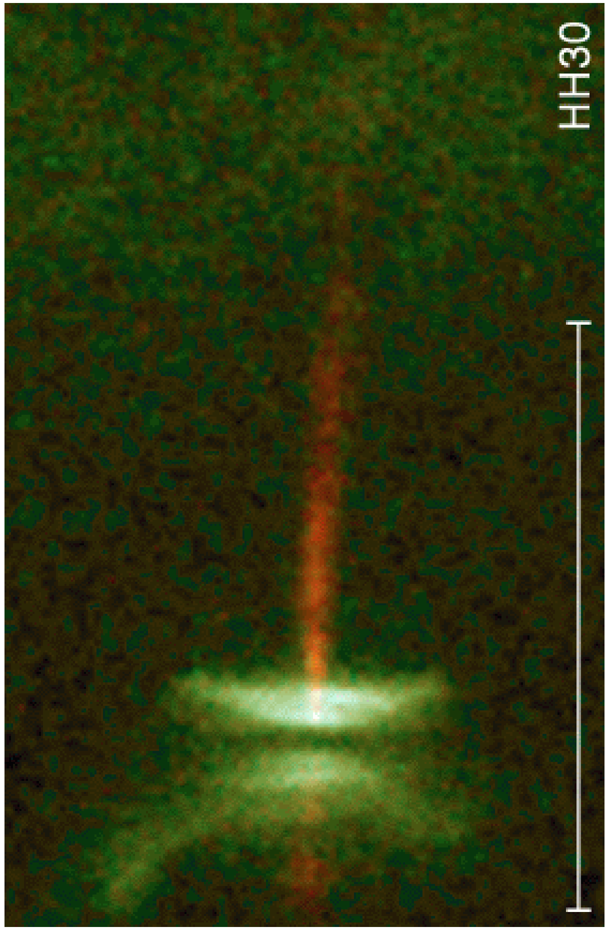


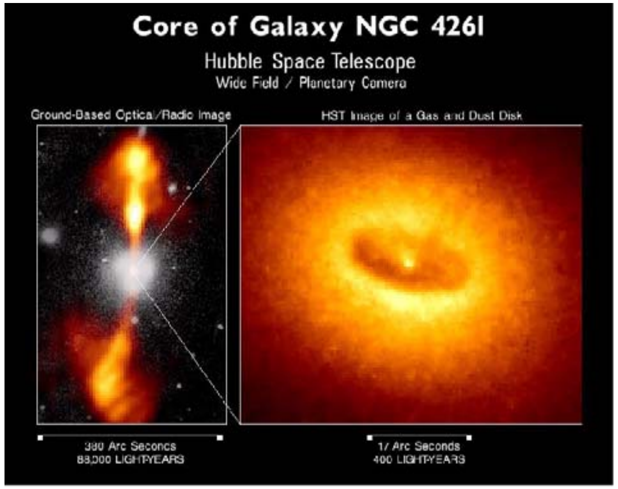
Light Curves of a Microquasar GRS1915+105
（ Mirabel and Rodriguez 1998)



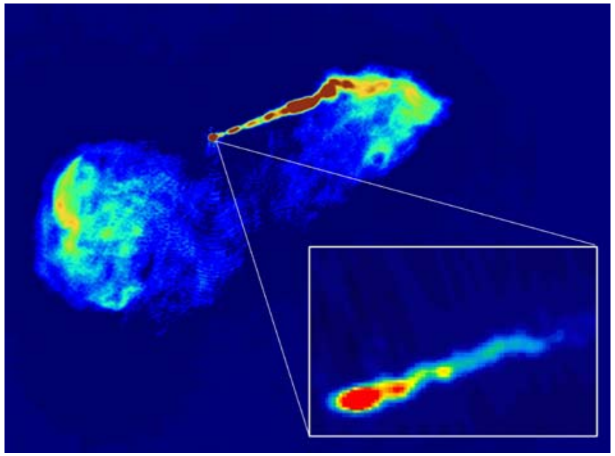
Superluminal Outflows
(Mirabel et al.1994)

Accretion Disks and Jets





NGC4261



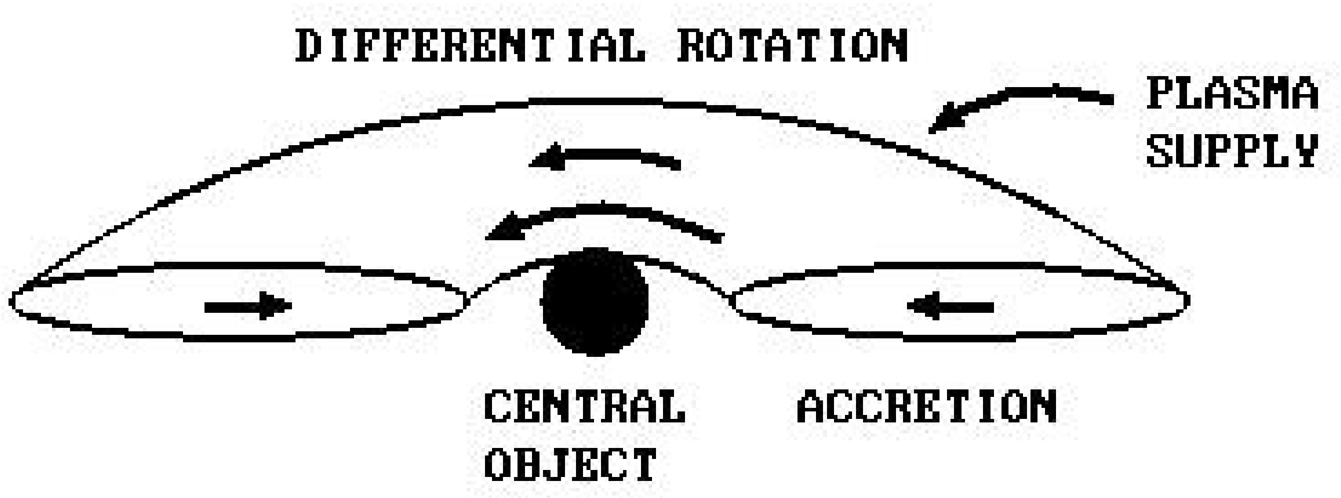
M87

VLA and Haruka

Protoplanetary Disk and Optical Jet

Jets in Active Galactic Nuclei

Angular Momentum Transport

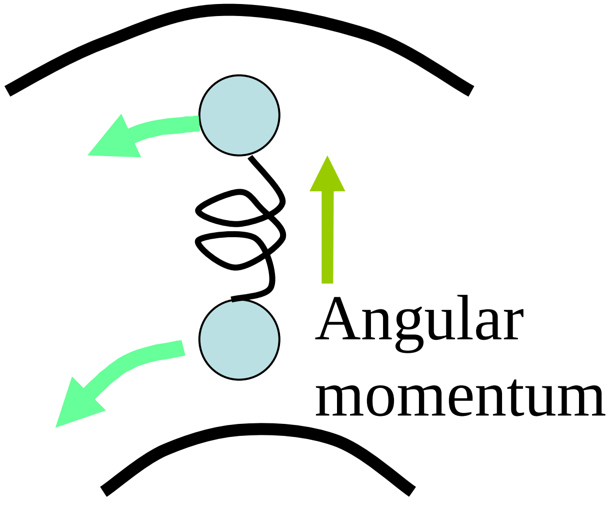


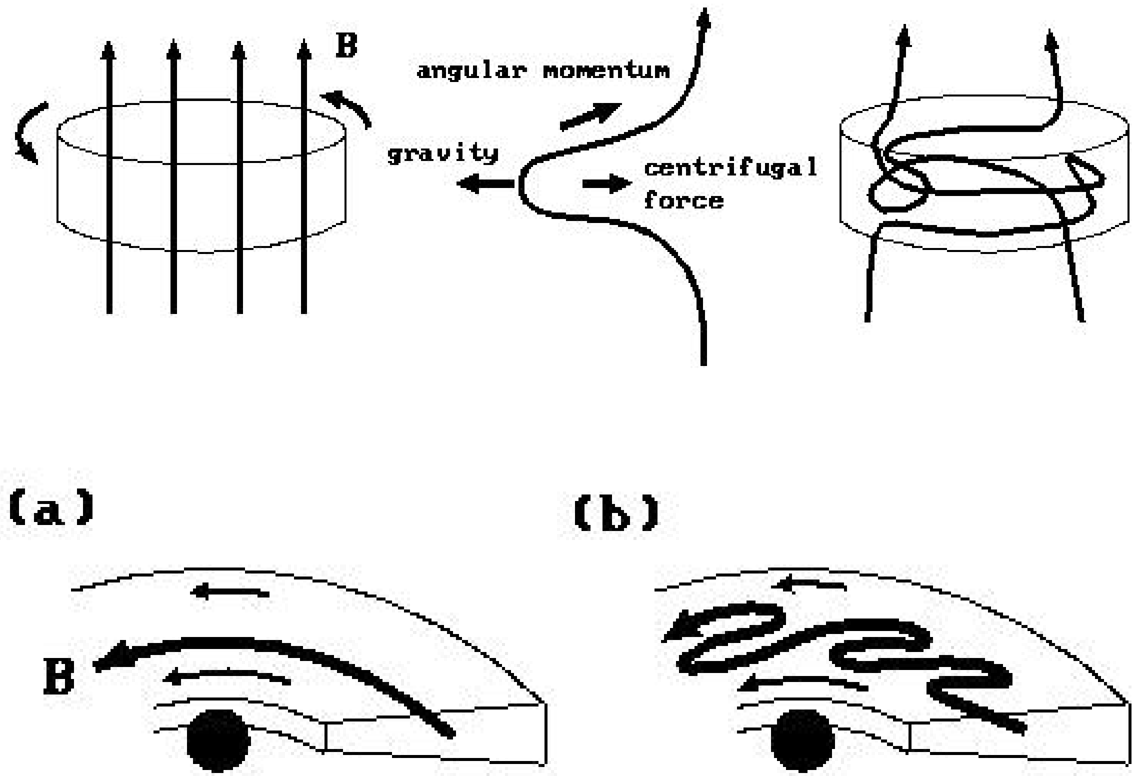
Rotating gas should lose angular momentum to accrete

Standard theory of accretion disk assume $T_{r\varphi} = \alpha P$

- Interval of dwarf nova outbursts indicate $\alpha = 0.01 \sim 0.1$
- In hydrodynamical disks $\alpha = O(0.001)$ too small !

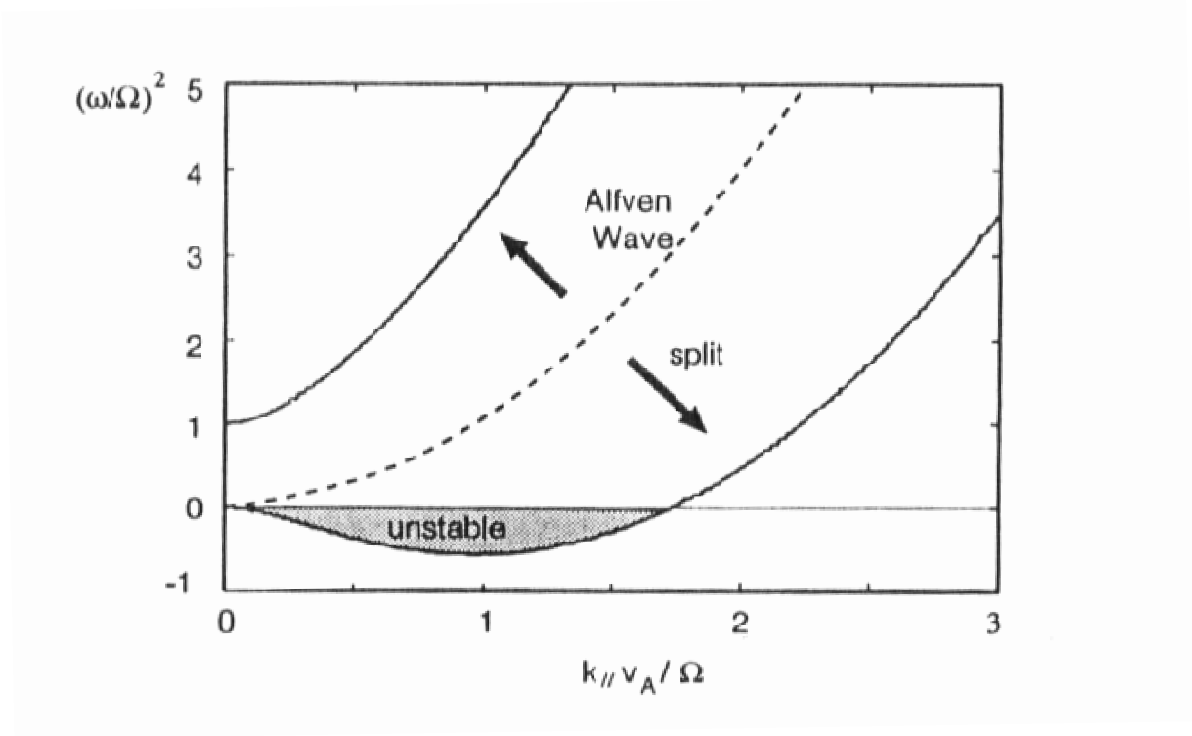
Magnetorotational Instability in Differentially Rotating Disks





Balbus and Hawley (1991)

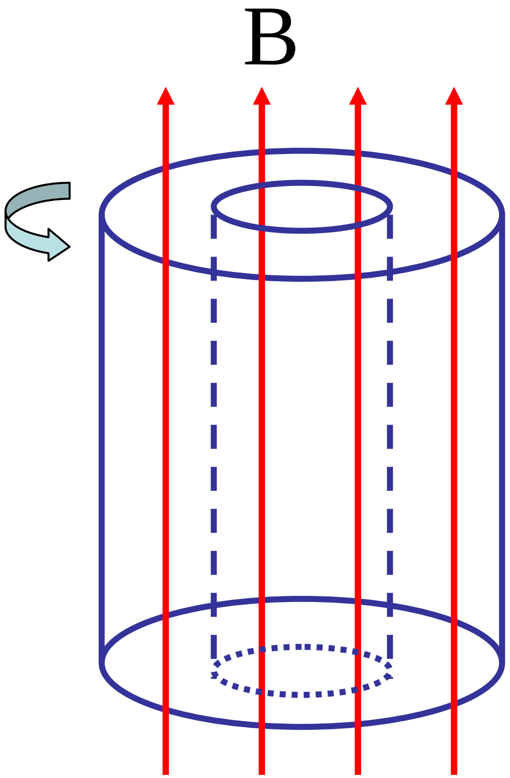
Growth Rate of MRI in Incompressible Plasma



Maximum growth rate is (3/4)Ω when $k_{//}v_A=(15/16)^{1/2}\Omega$

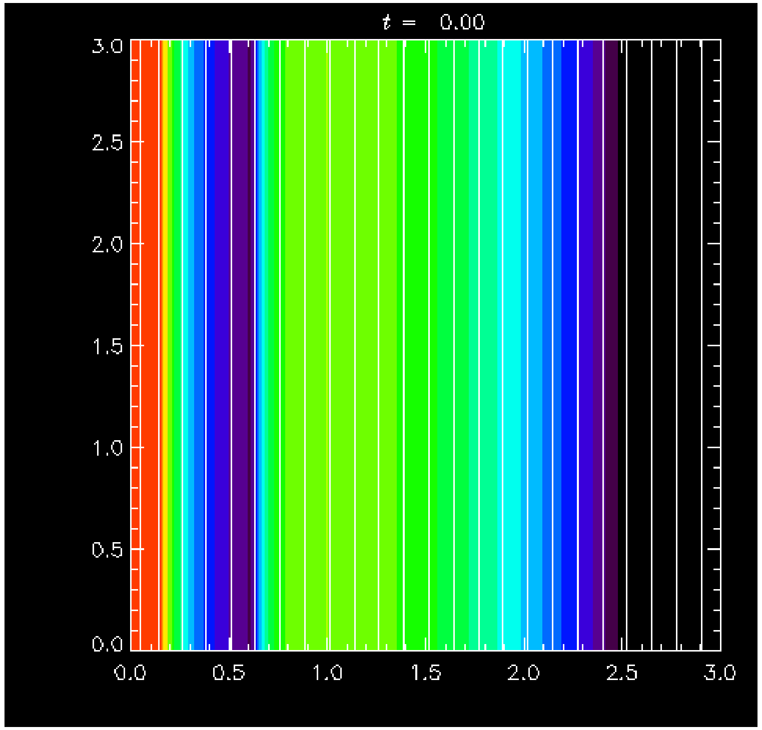
MRI grows in time scale of rotation

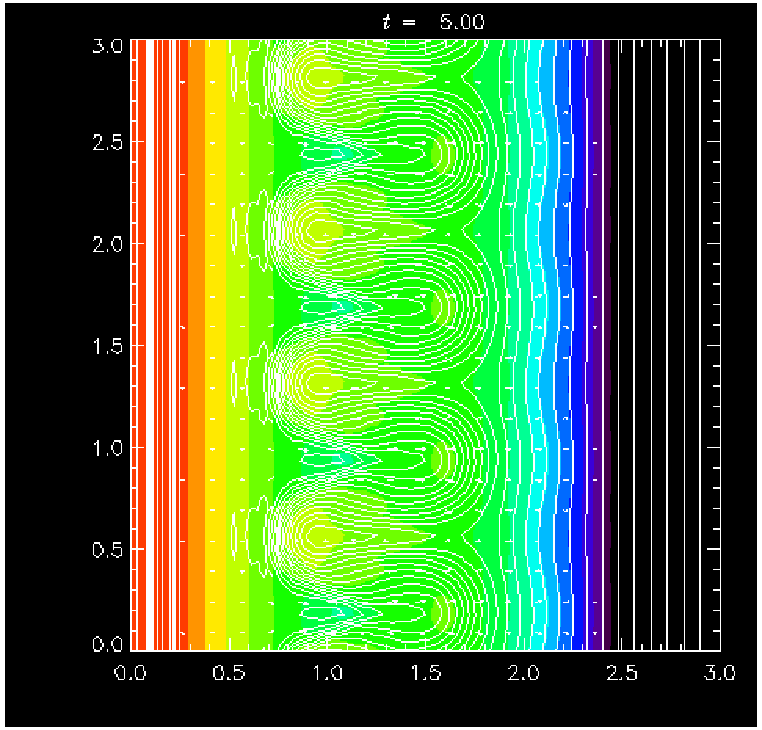
MHD Simulation of MRI



- Cylindrical Model
- Angular Momentum is a function of radius r
- Polytropic equation of state $P=K\rho^{1+1/n}$
- Assume isothermal gas outside the rotating cylinder

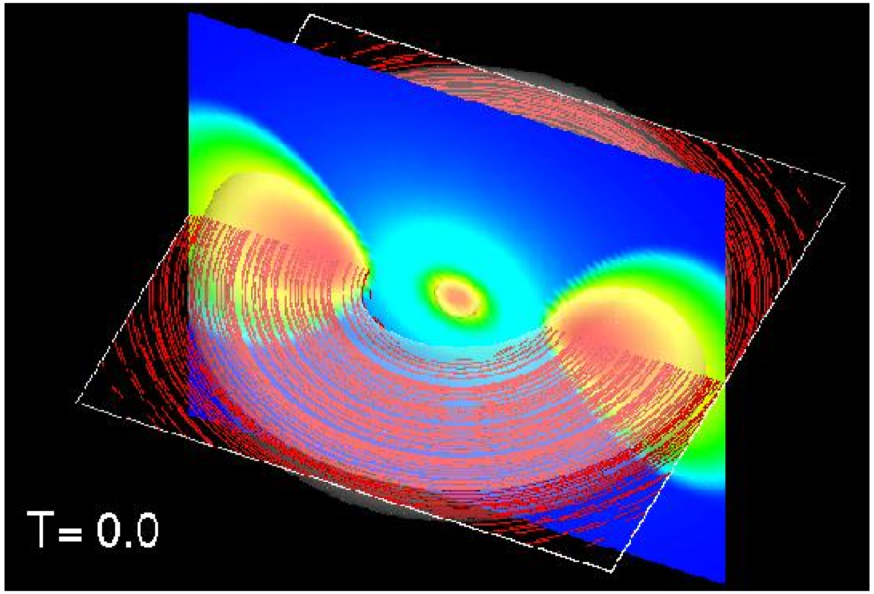
Numerical Results

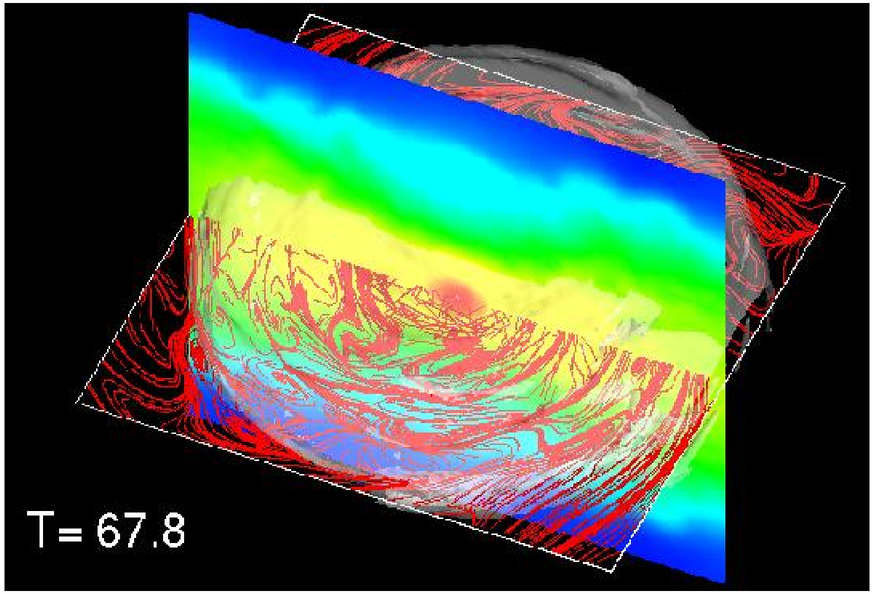




Growth of MRI in differentially rotating cylindrical plasma. Solid curves show magnetic field lines. Color shows density distribution.

Global 3D MHD Simulation of Differentially Rotating Torus





Initial Condition

$\beta = P_{gas}/P_{mag} = 100$

After 10 Rotation Period

200*64*240 grid points

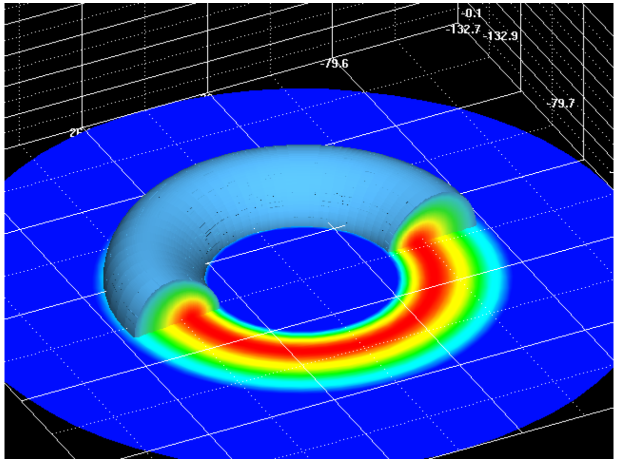
Matsumoto 1999

Global 3D MHD Simulations of Black Hole Accretion Disks (Machida et al. 2003)

Gravitational potential : $\phi = - GM/(r-rs)$

Initally weak toroidal magnetic field

β = Pgas/Pmag =100 at $r = r_0$



Anomalous Resistivity

$\eta = (1/Rm) \max [(J/\rho) / v_c - 1, 0.0]^2$

Unit

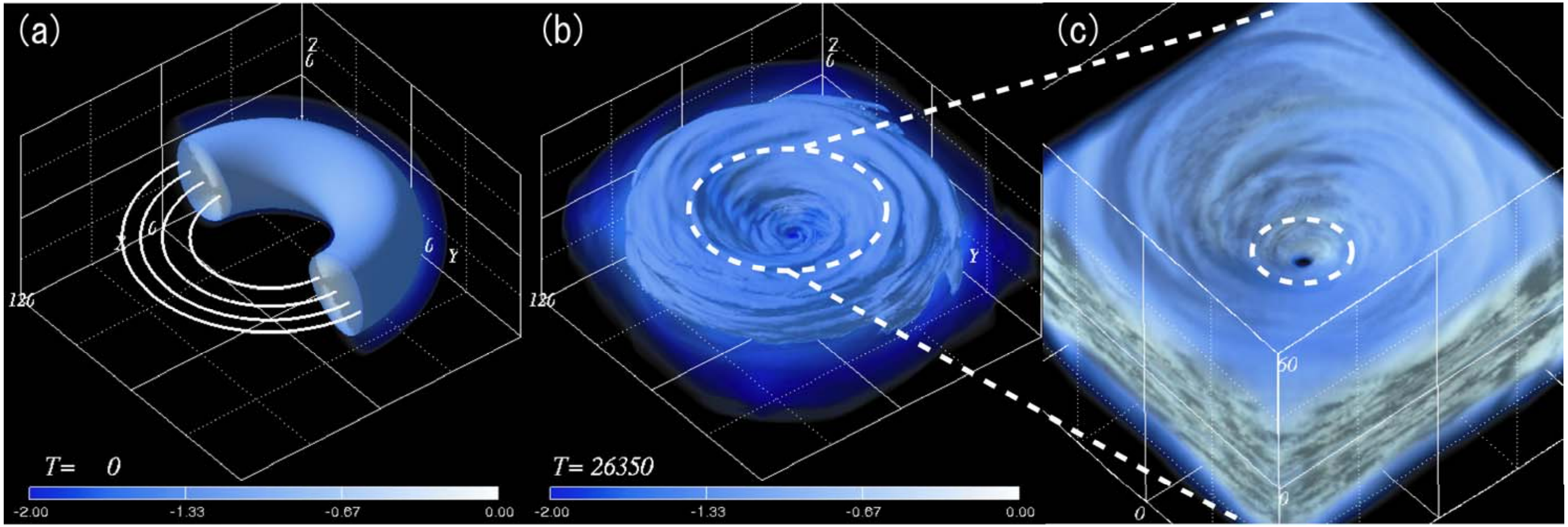
$r_s = 3.0 \times 10^6 (M/10M_{sun})$ cm

$t_0 = r_s/c = 10^{-4} (M/10M_{sun})$ sec

250*32*384mesh

250*64*384mesh

Formation of an Accretion Disk

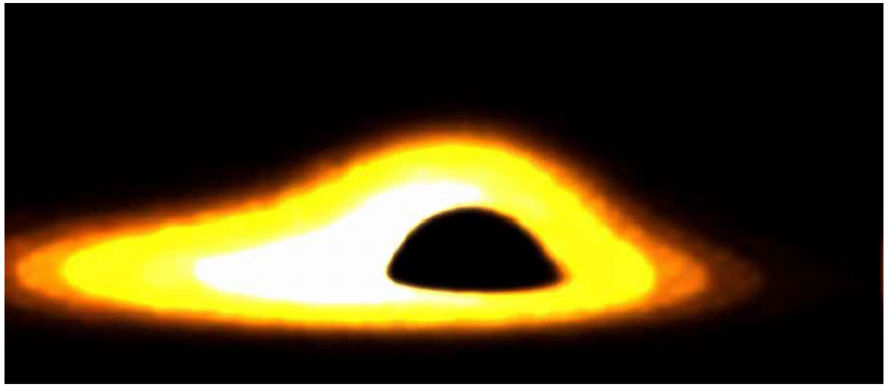


Initial state

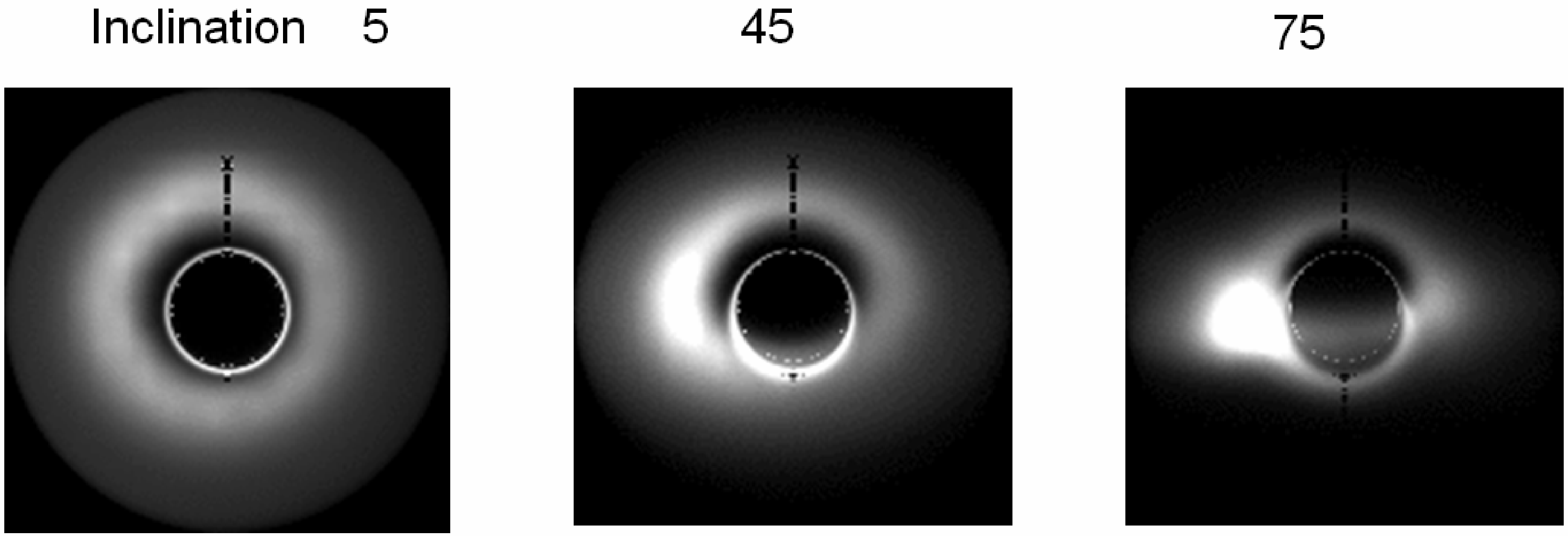
t=26350

unit time t_0=rg/c

How a Black Hole Looks Like



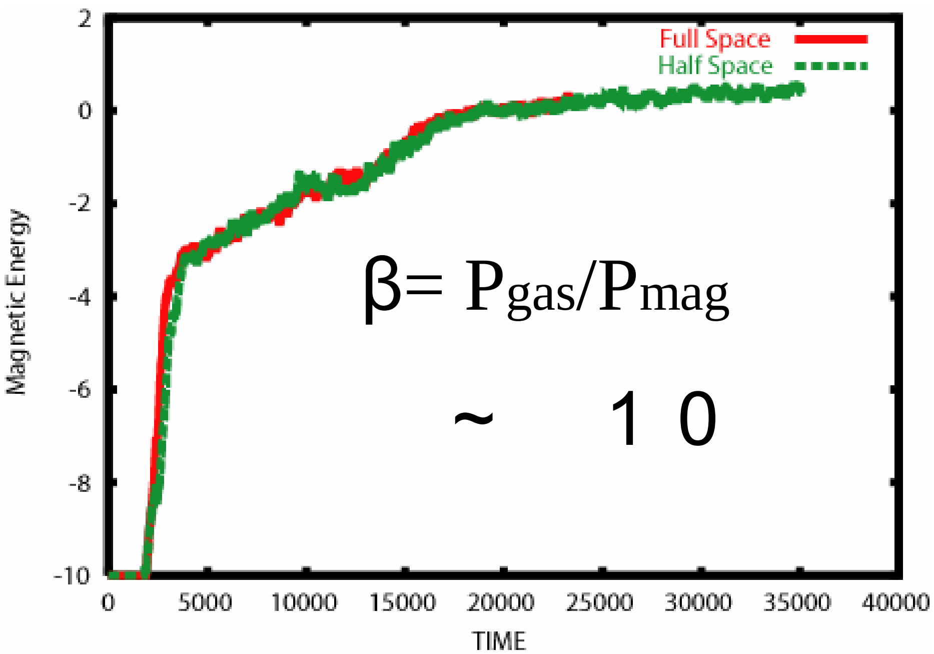
J. Fukue 1988



Calculated by M. Bursa

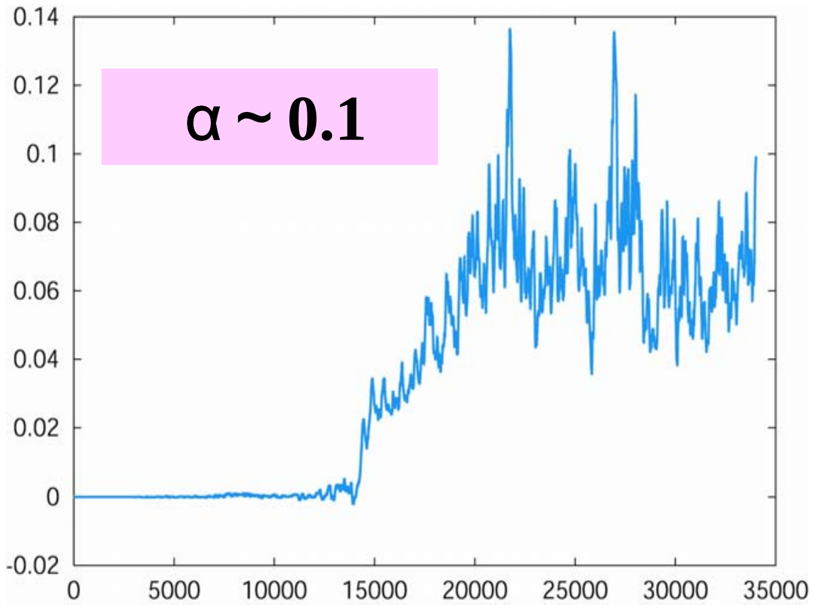
Time Evolution of Magnetic Energy and Maxwell Stress

Magnetic Energy



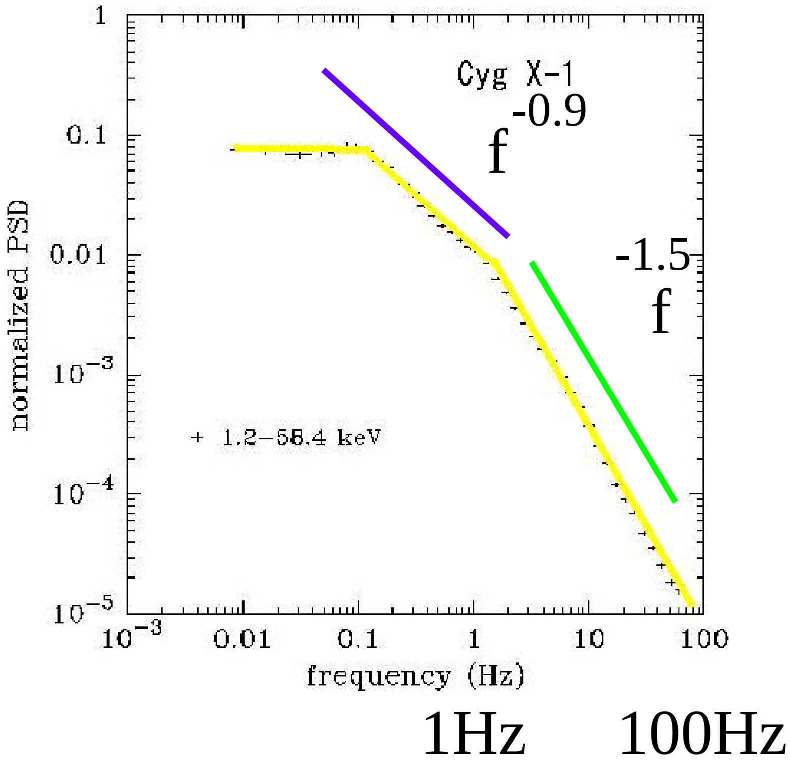
time

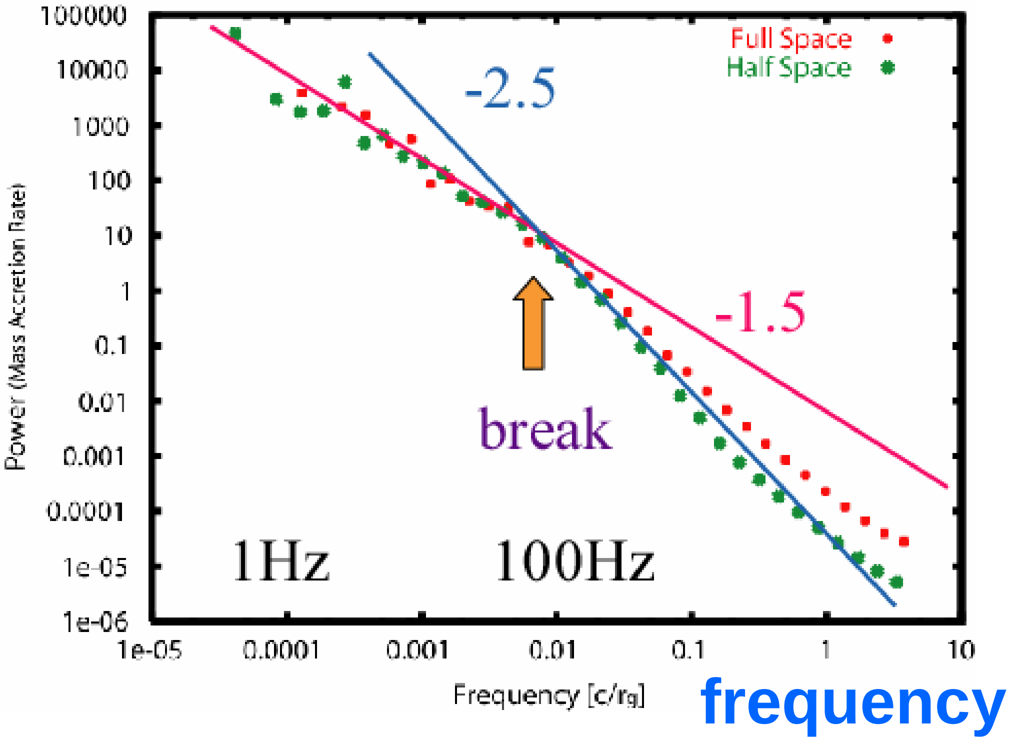
$\alpha = \langle B_r B_\varphi / 4\pi P_0 \rangle$



TIME

1/f-noise like time variabilities

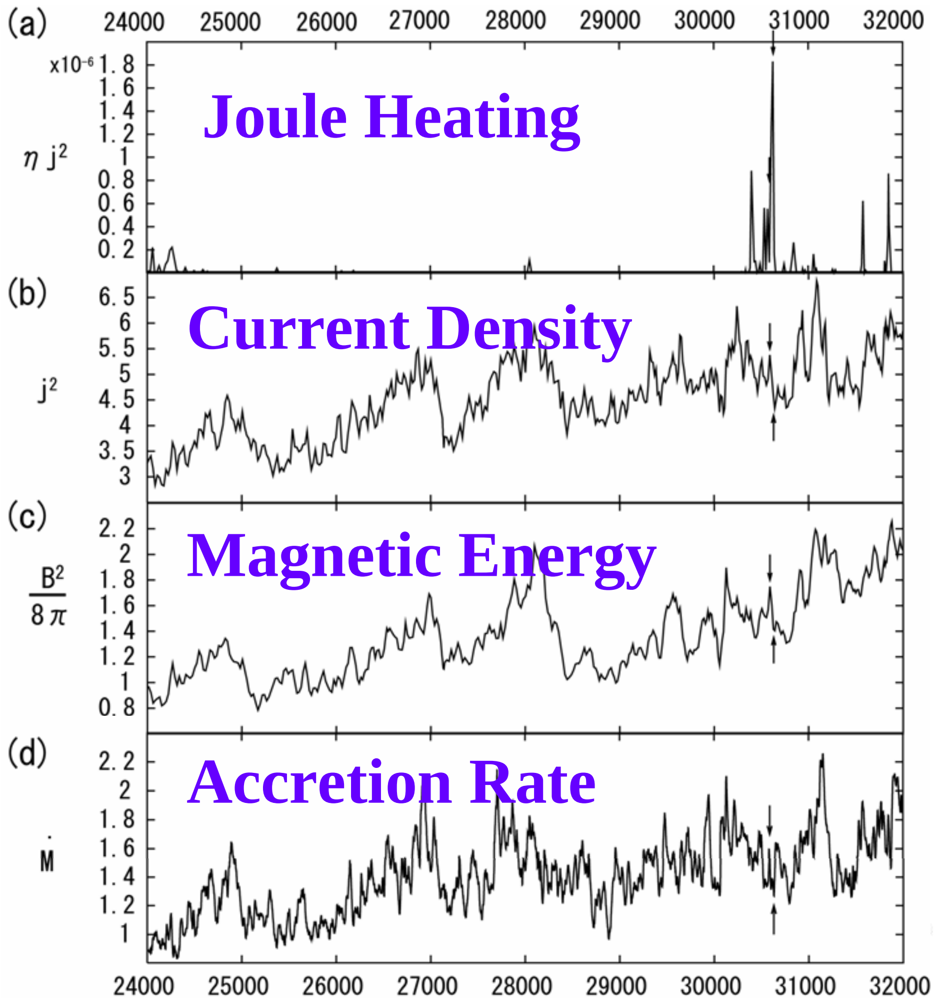




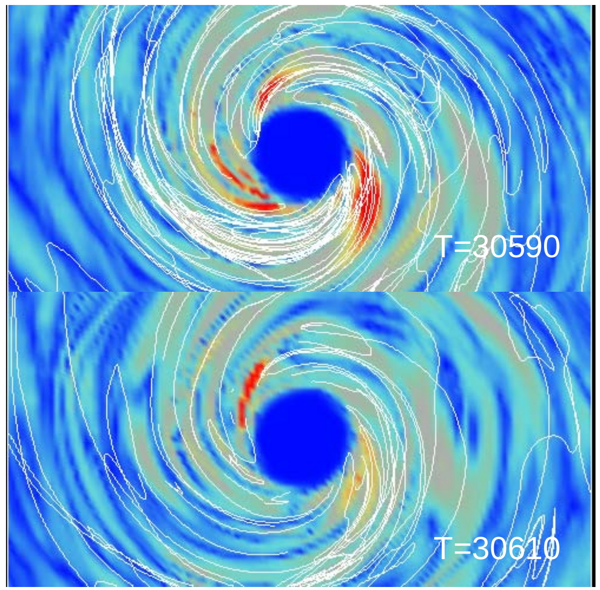
Power spectrum of time variabilities of Cyg X-1

Power spectrum of time variabilities obtained by numerical simulation

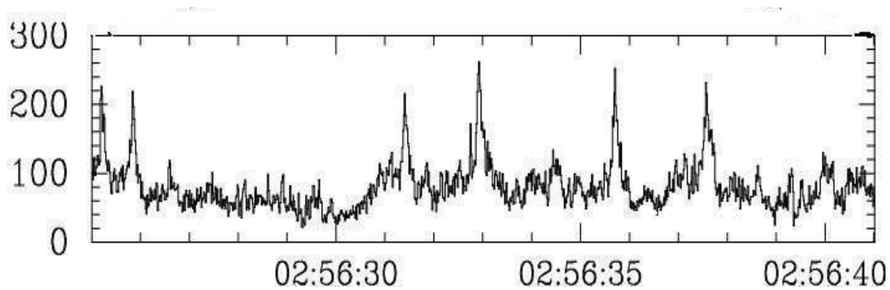
X-ray Shots in Black Hole Accretion Disks



time

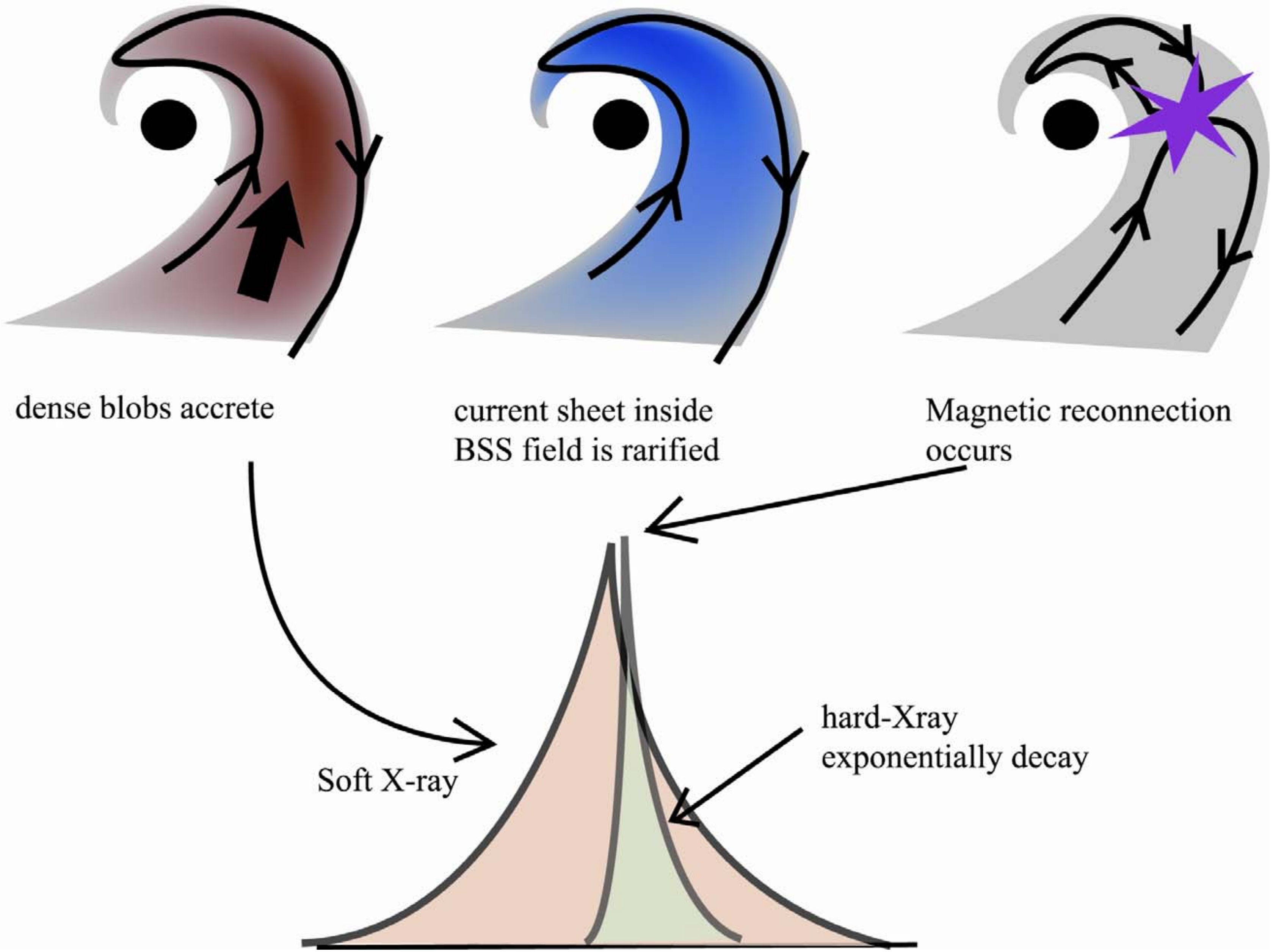


Current density(color)

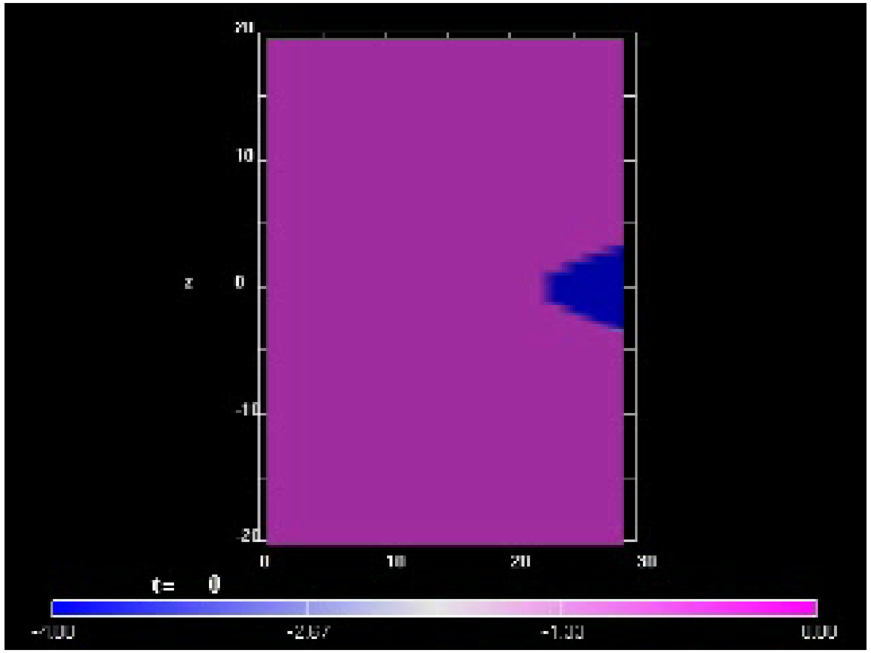


Time variabilities of Cyg X-1

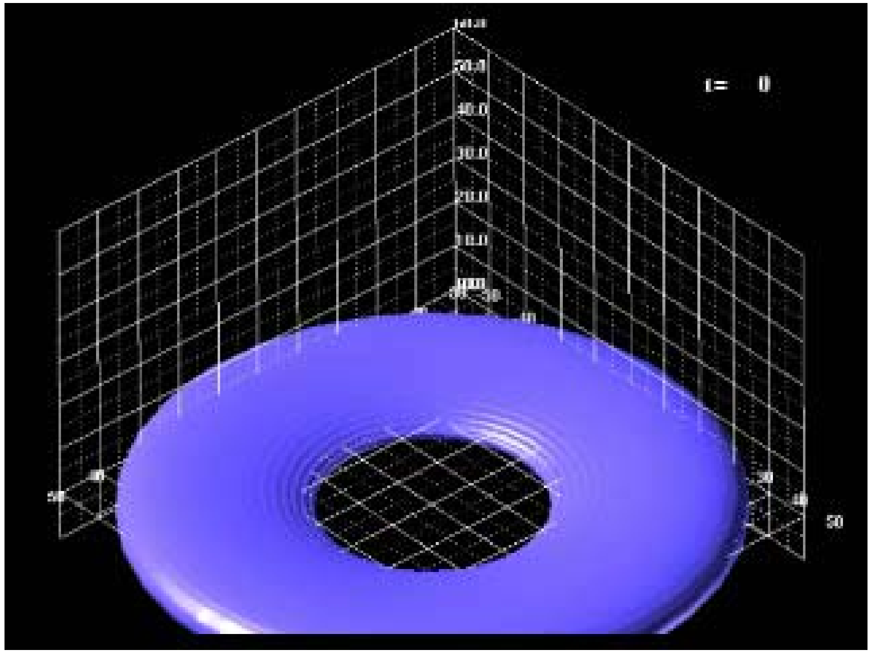
Schematic picture of X-ray shot based on MHD simulation



Formation of Outflows from Accretion Disks

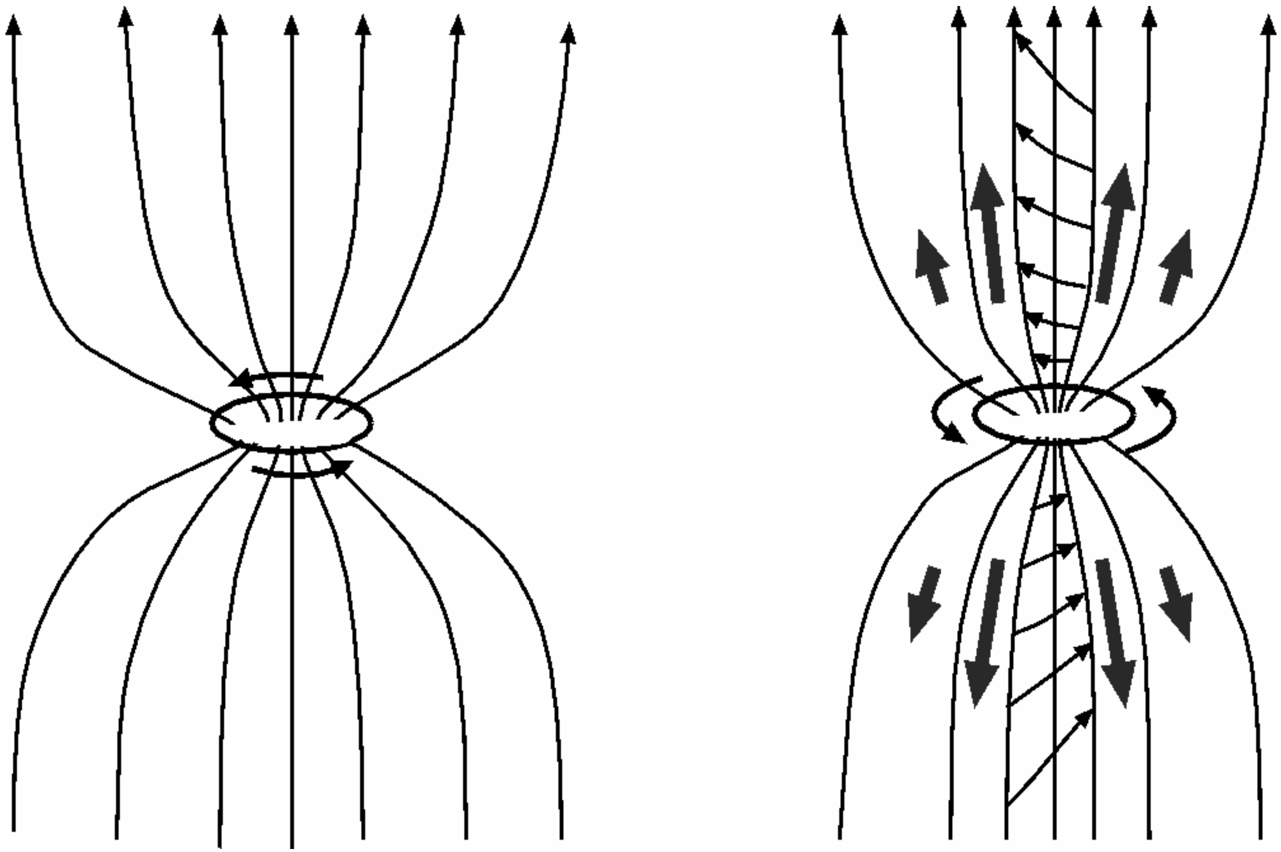


temperature



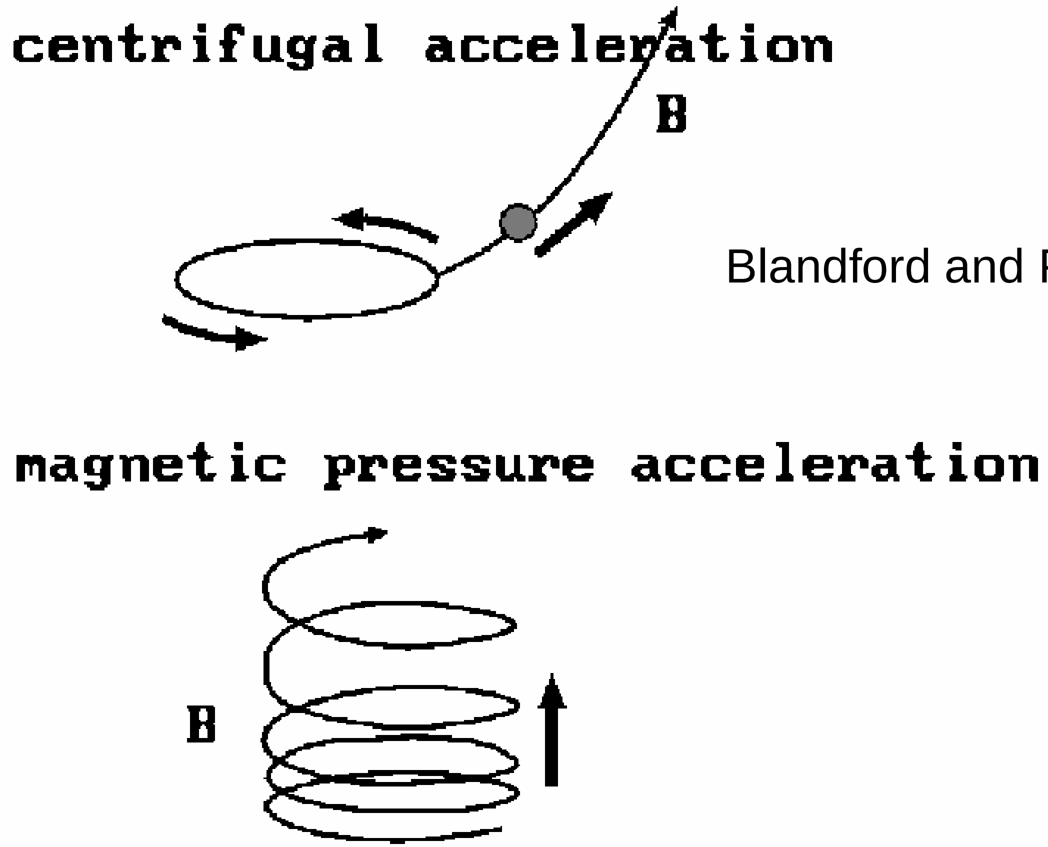
Isosurface of vertical velocity

Uchida-Shibata Model



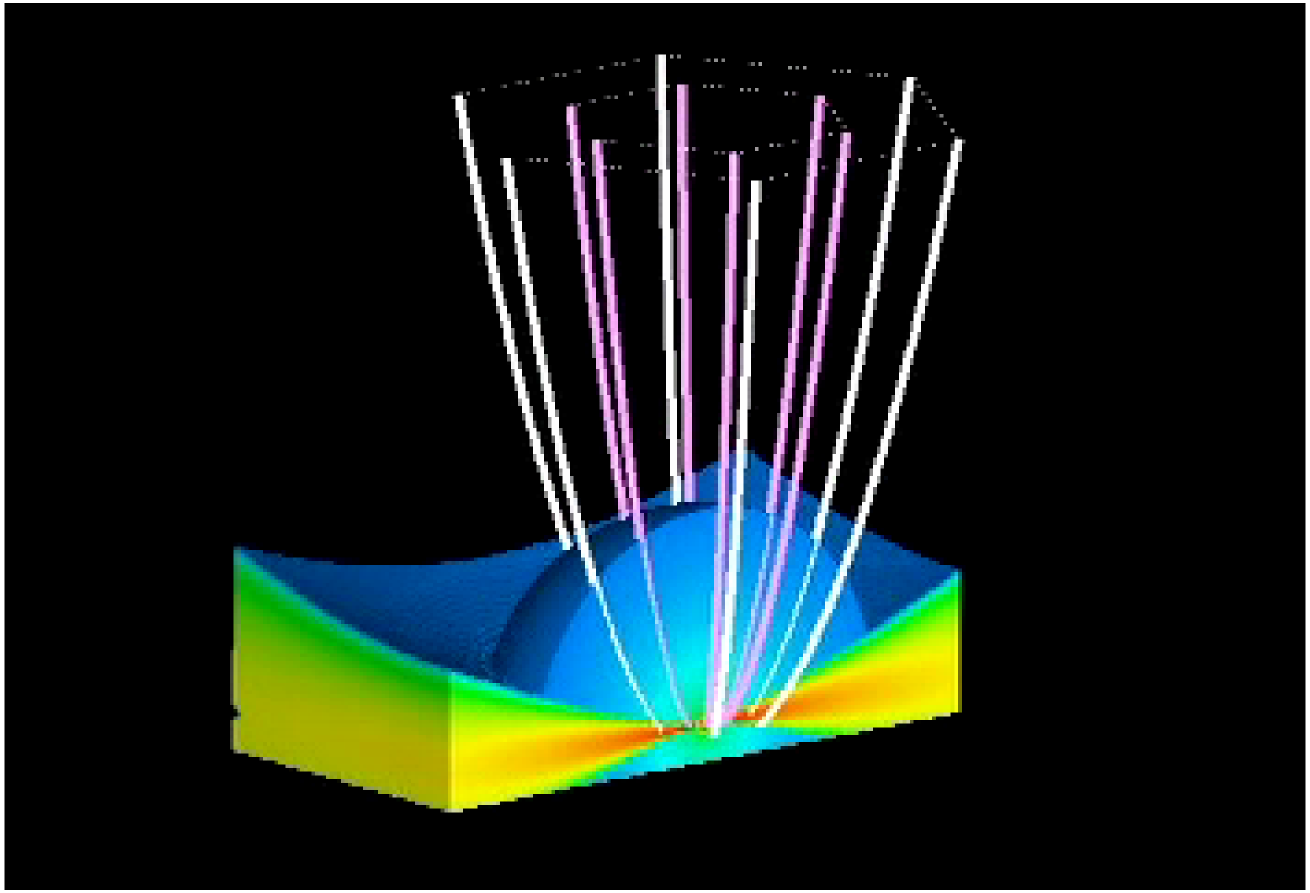
A schematic picture of Uchida-Shibata (1985) model. They carried out global 2D MHD simulation including accretion disk.

Two Mechanisms of Acceleration of MHD Jets and Outflows



Blandford and Payne 1982

MHD Simulation of Jet Formation



Kodoh et al. 2002

Questions for Nonsteady MHD Models of Jet Formation

- Are you simulating transient phenomena depending on the initial condition ?
- Does the system approach to a steady state ?

A: In ideal MHD simulations the jet formation is time dependent and intermittent but we can understand the acceleration mechanism of nonsteady jets by applying steady theory of magnetically driven jets

Steady Model of Axisymmetric Jets (Kudoh and Shibata 1997)

$$P = K\rho^{\gamma} ,$$

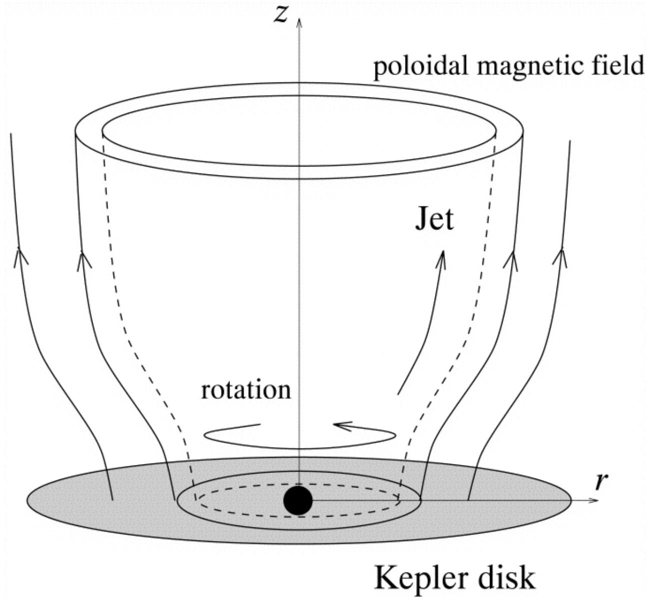
$$\rho v_p = \lambda B_p ,$$

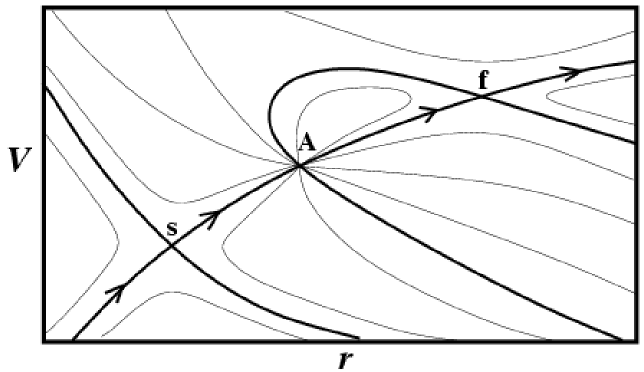
$$(v_\phi - \Omega r)B_p = v_p B_\phi ,$$

$$r\left(v_\phi - \frac{B_\phi}{4\pi\lambda}\right) = L ,$$

$$\frac{1}{2} v_p^2 + \frac{1}{2} v_\phi^2 + \frac{\gamma}{\gamma - 1}\frac{P}{\rho} + \Psi_g - \frac{r\Omega B_\phi}{4\pi\lambda} = E$$

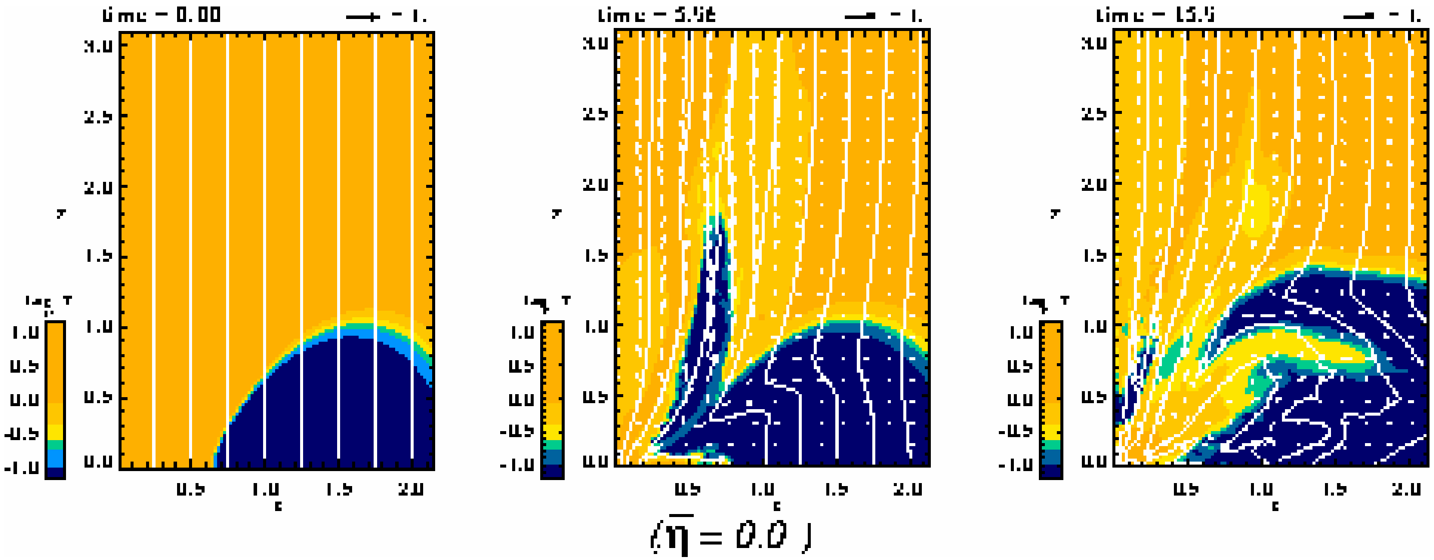
Along a Magnetic Field Line





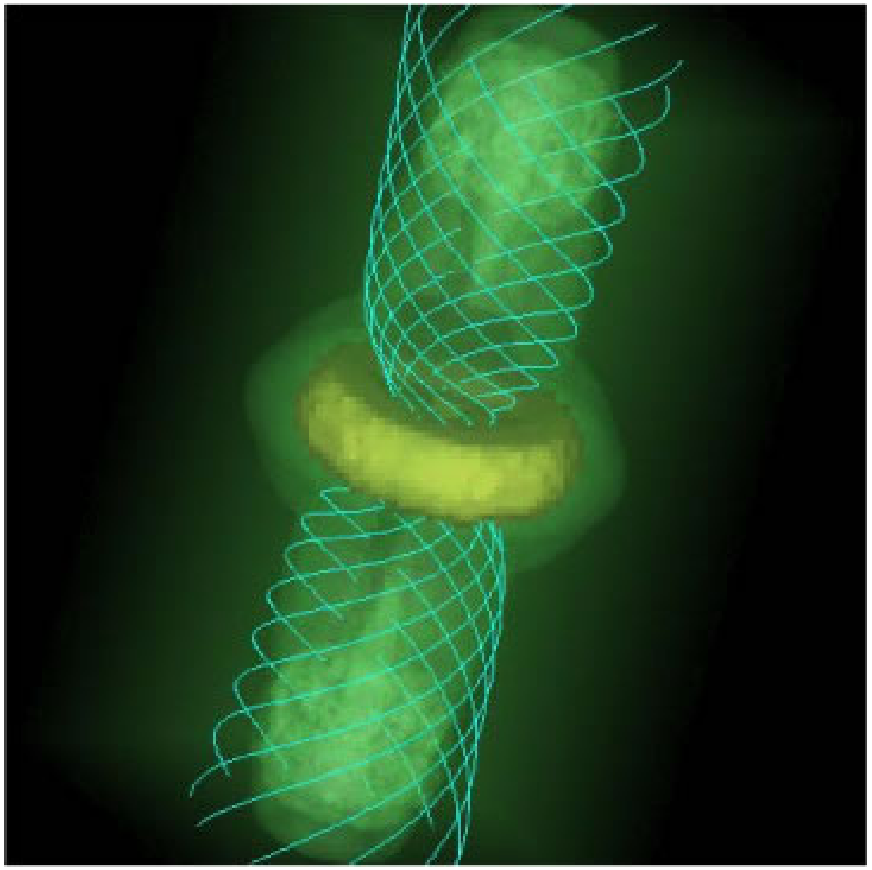
Ideal MHD Simulations often Show Intermittent Ejections

T



Result of ideal MHD simulation of jet formation by Kuwabara et al. 2000 (PASJ 52, 1109). Jet ejection takes place intermittently due to the growth of MRI in the disk

MHD Simulation including Resistivity



$$E_{th} = \frac{V_{S0}^2}{\gamma V_{K0}^2} = 5\times 10^{-2}$$

$$E_{mg} = \frac{V_{A0}^2}{V_{K0}^2} = 5\times 10^{-4}$$

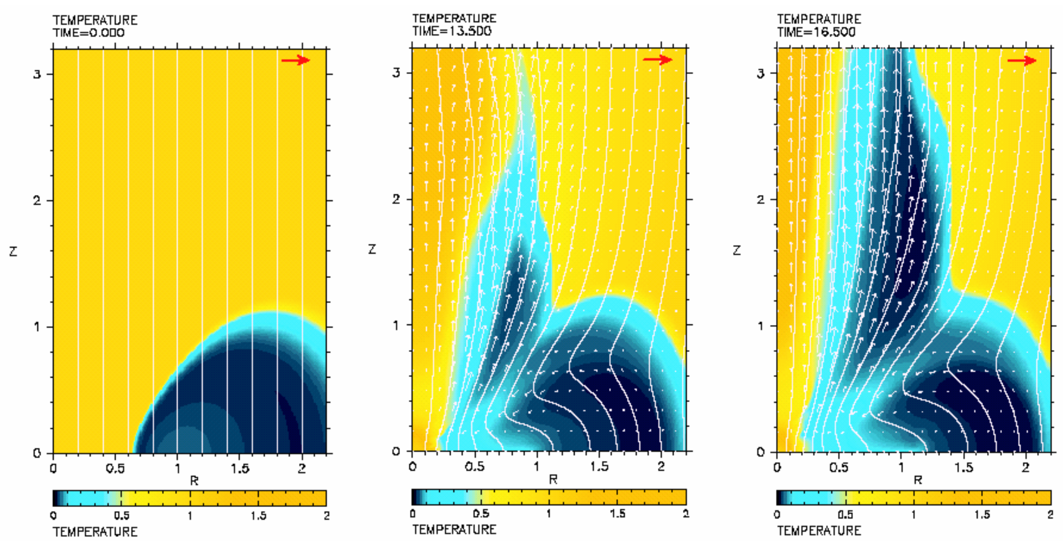
η = 0.0125 r_0 V_k0

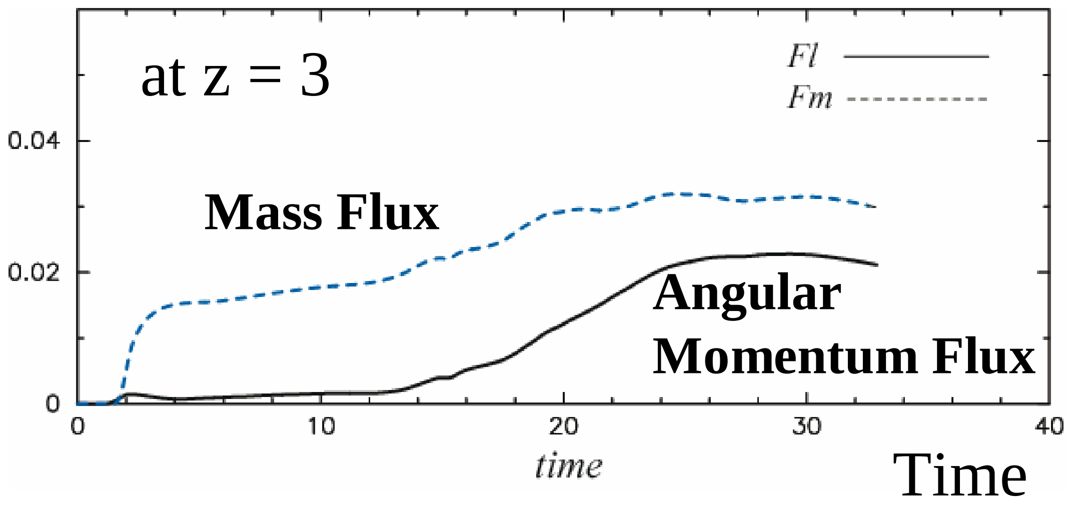
(Rm = 80)

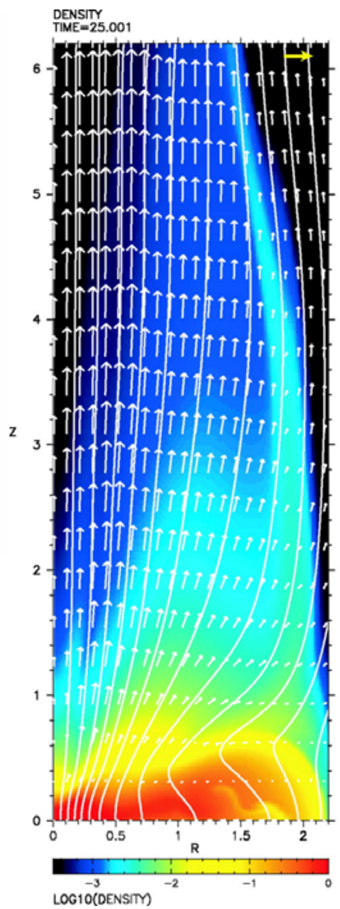
Kuwabara et al. 2000
PASJ 52, 1109

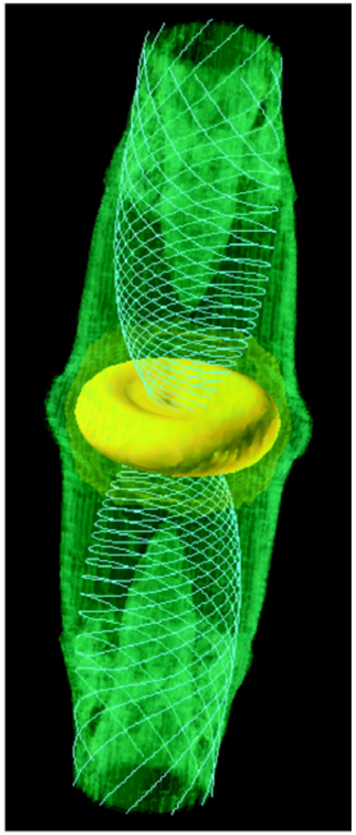
Similar simulations have been carried out by Casse and Keppens (2002,2004)

Formation of a Quasi-Steady Jet





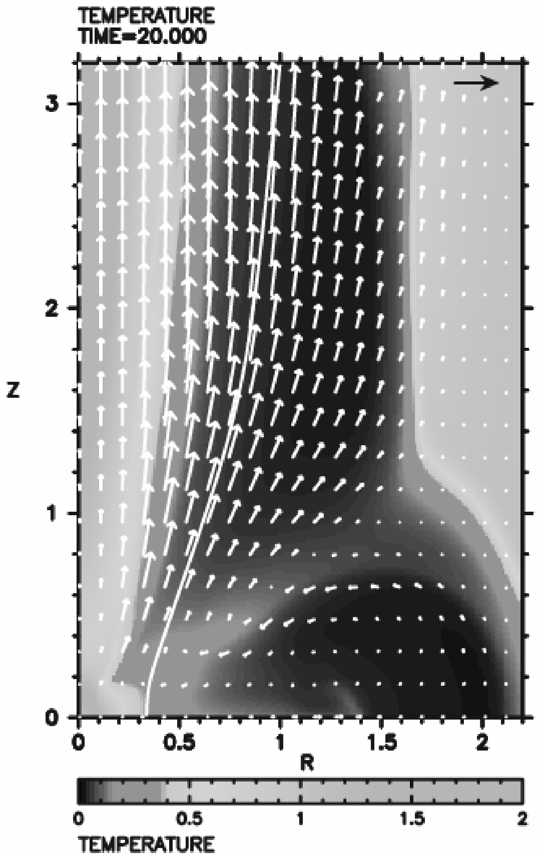


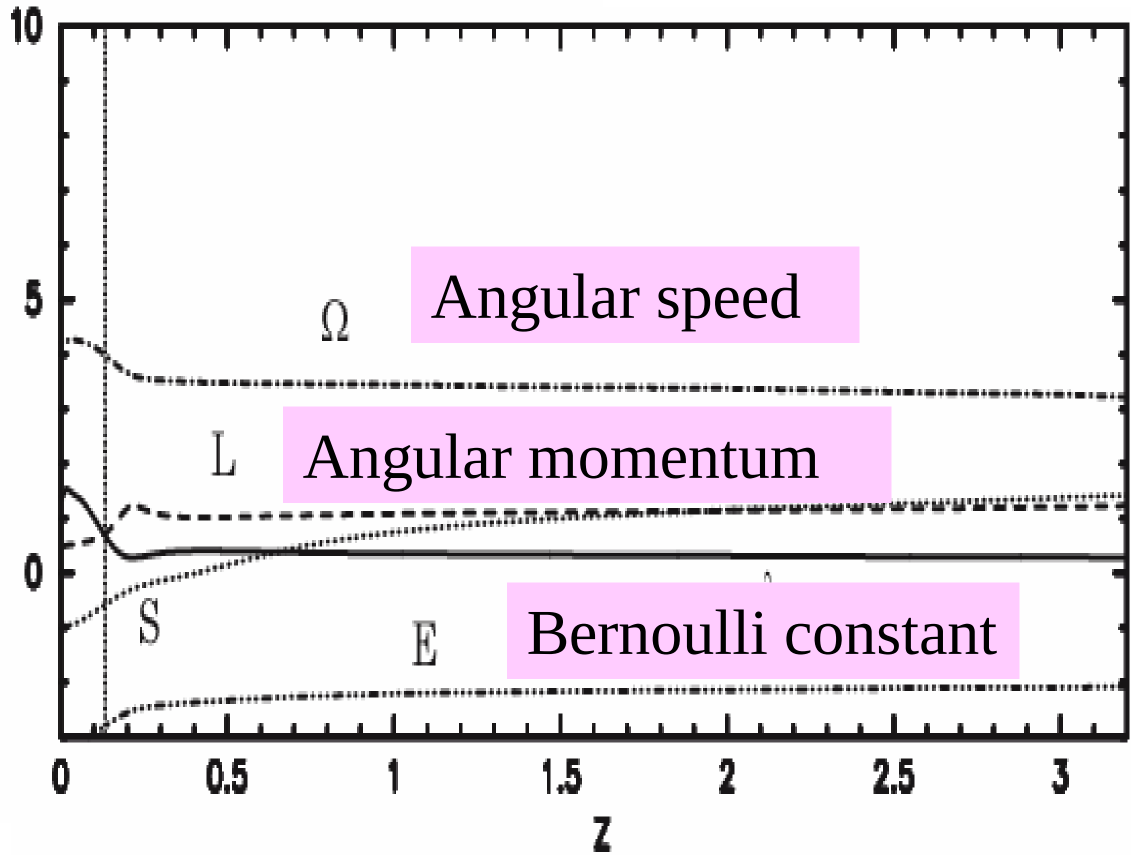


Density distribution at t = 25

Kuwabara et al. (2005)

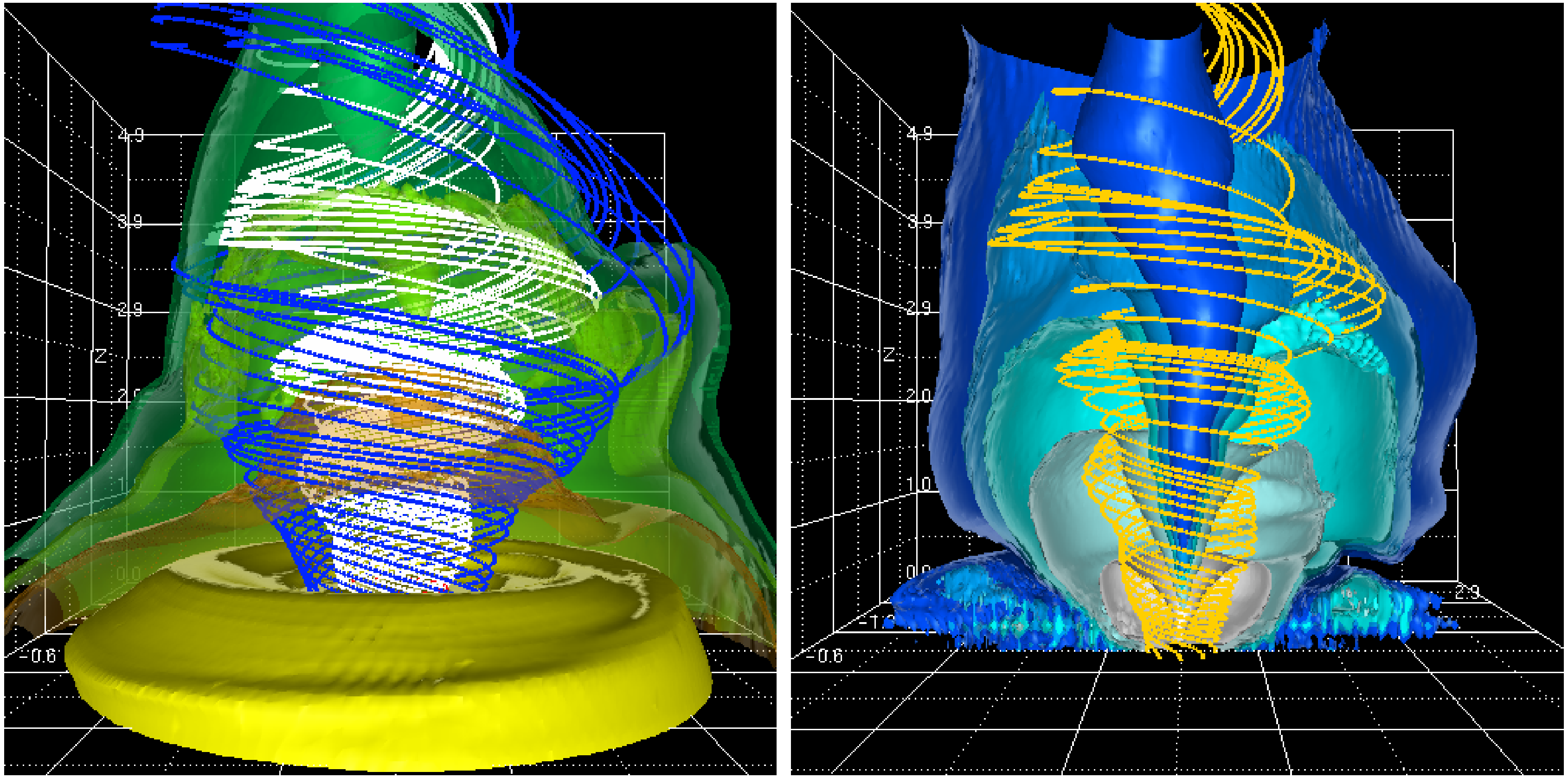
Constancy of Conserved Quantities along a Magnetic Field Line





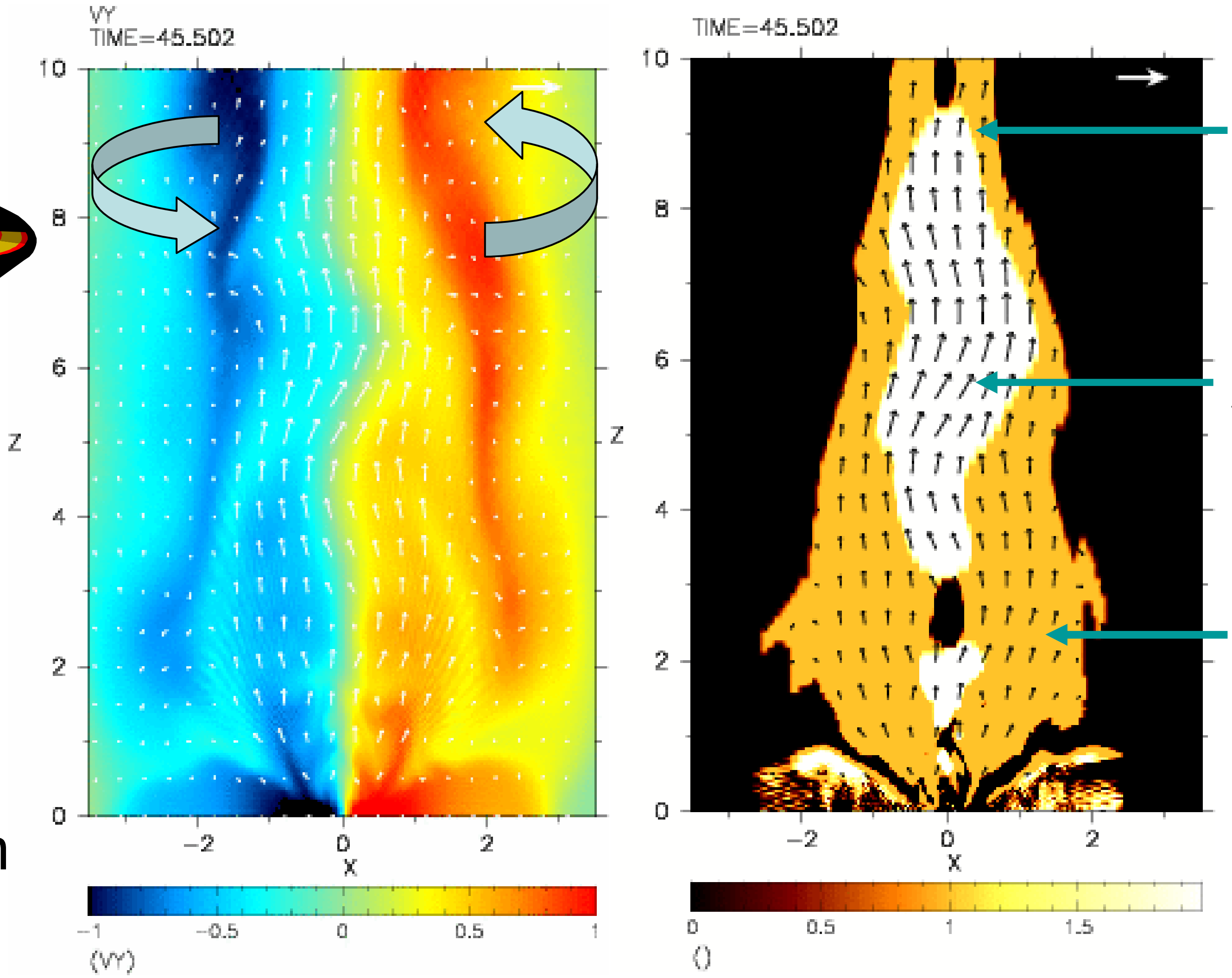
Kuwabara et al. 2005, ApJ 621, 921

Formation of Wiggle Structure



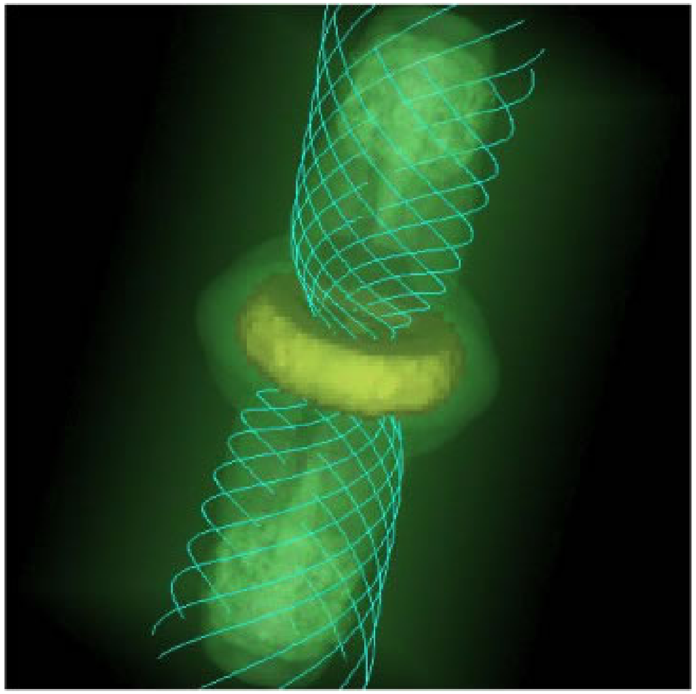
Numerical Result by using Cartesian 3D Code
(Kuwabara et al. 2006)

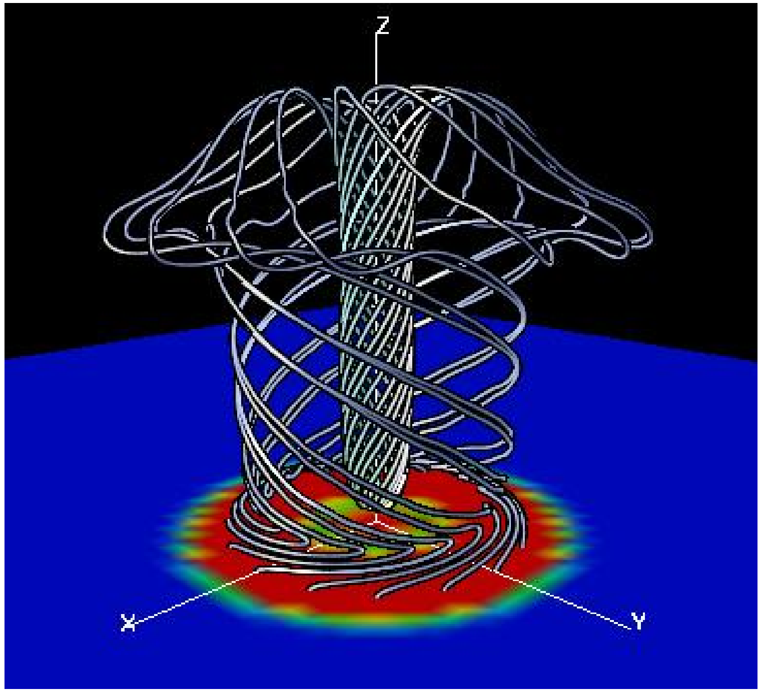
Stabilization by Rotation



Rotation
speed

Two Models of Magnetically Driven Jet





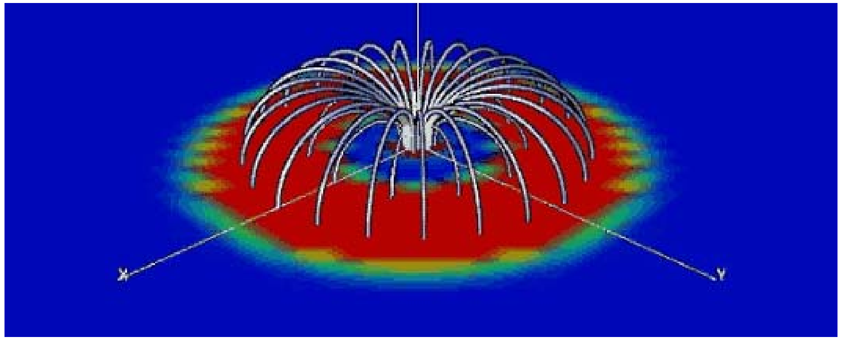
Magneto-centrifugally driven jet

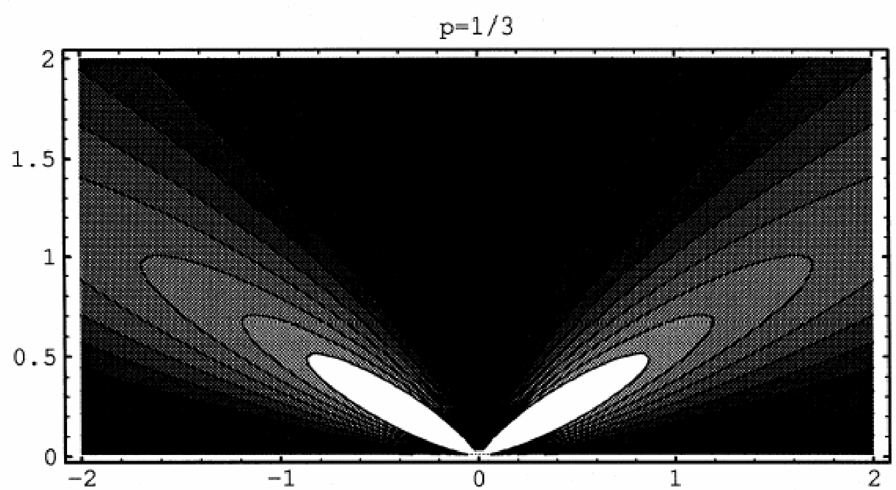
Magnetic tower jet

Blandford & Payne (1982)、Uchida and Shibata (1985)

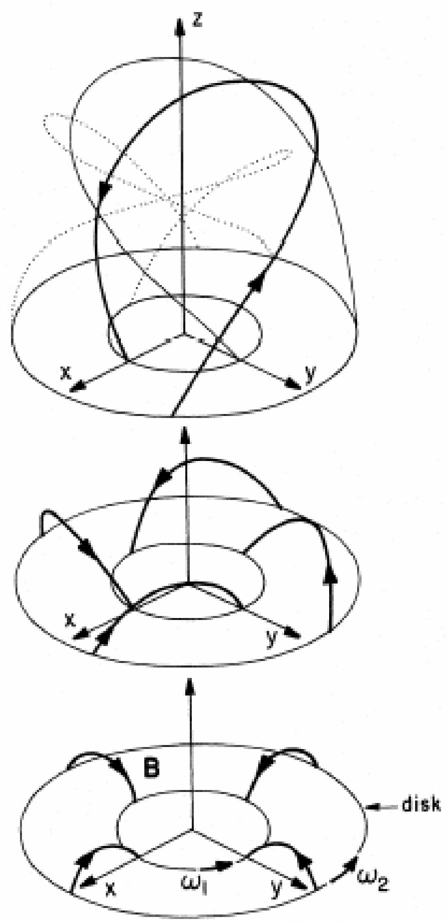
Lynden-Bell & Boily (1994)
Kato et al. (2004)

Inflation of Twisted Poloidal Magnetic Loops



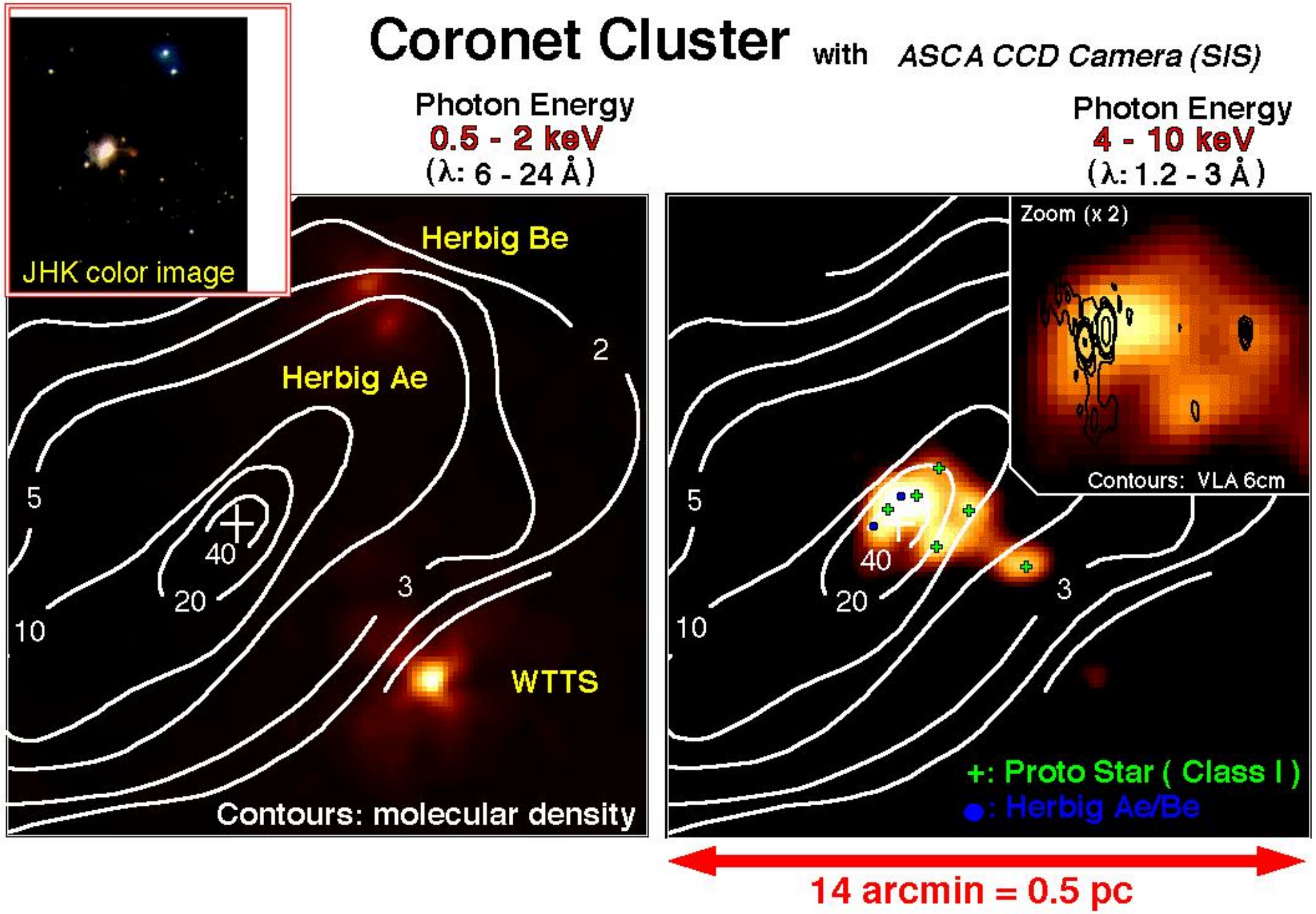


Lynden-Bell and Boily 1994

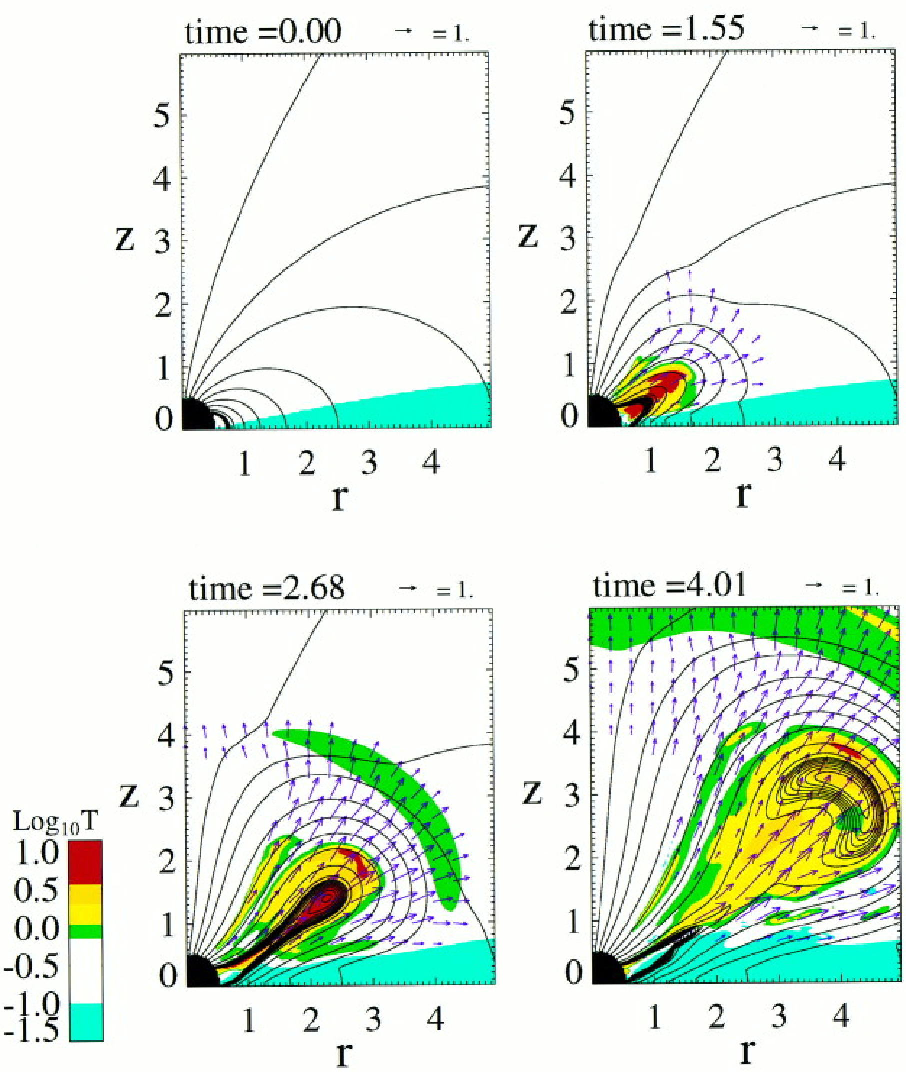


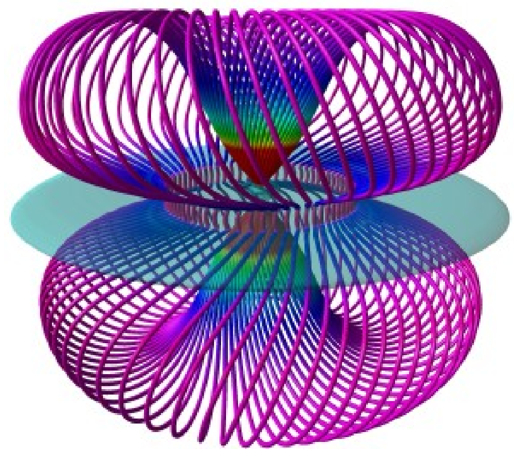
Lovelace et al. 1995

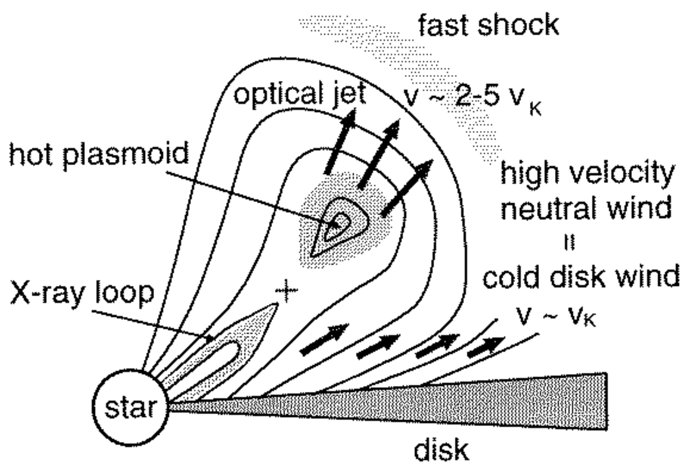
X-ray Flares in Protostars



MHD Simulation of Protostellar Flares

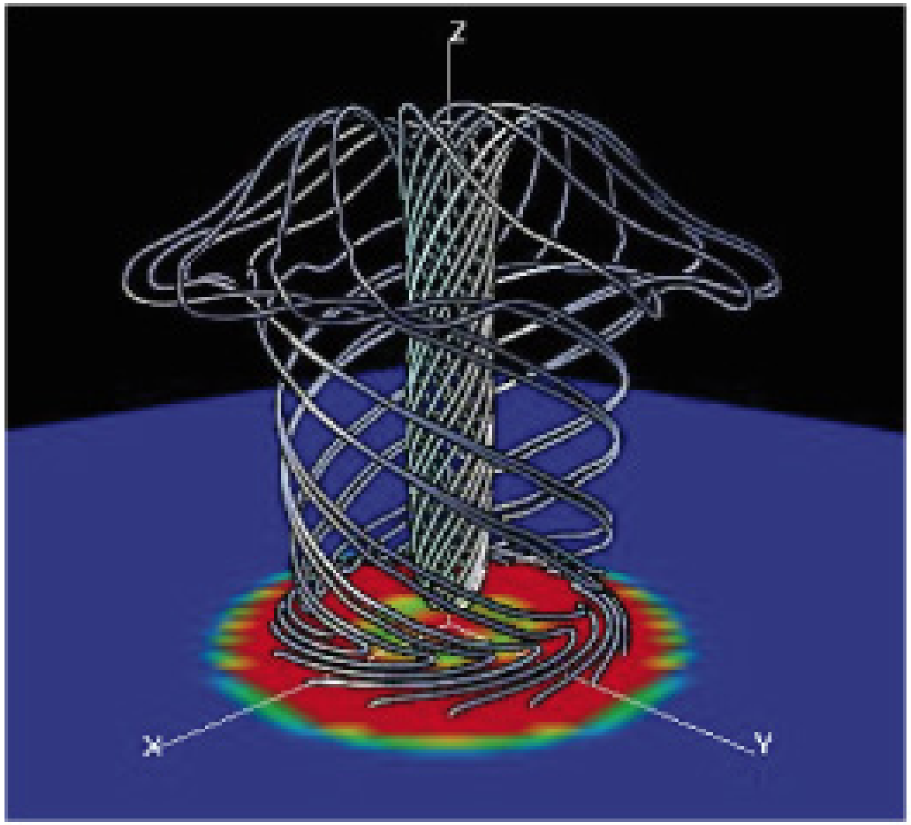


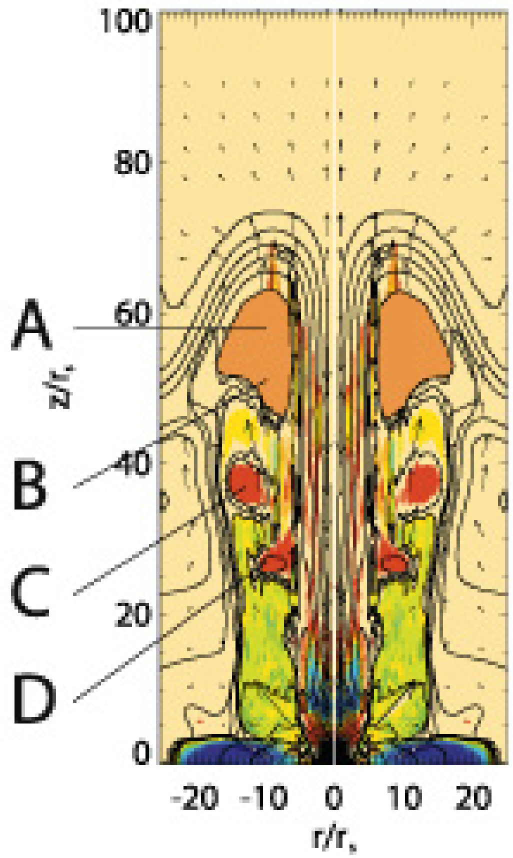




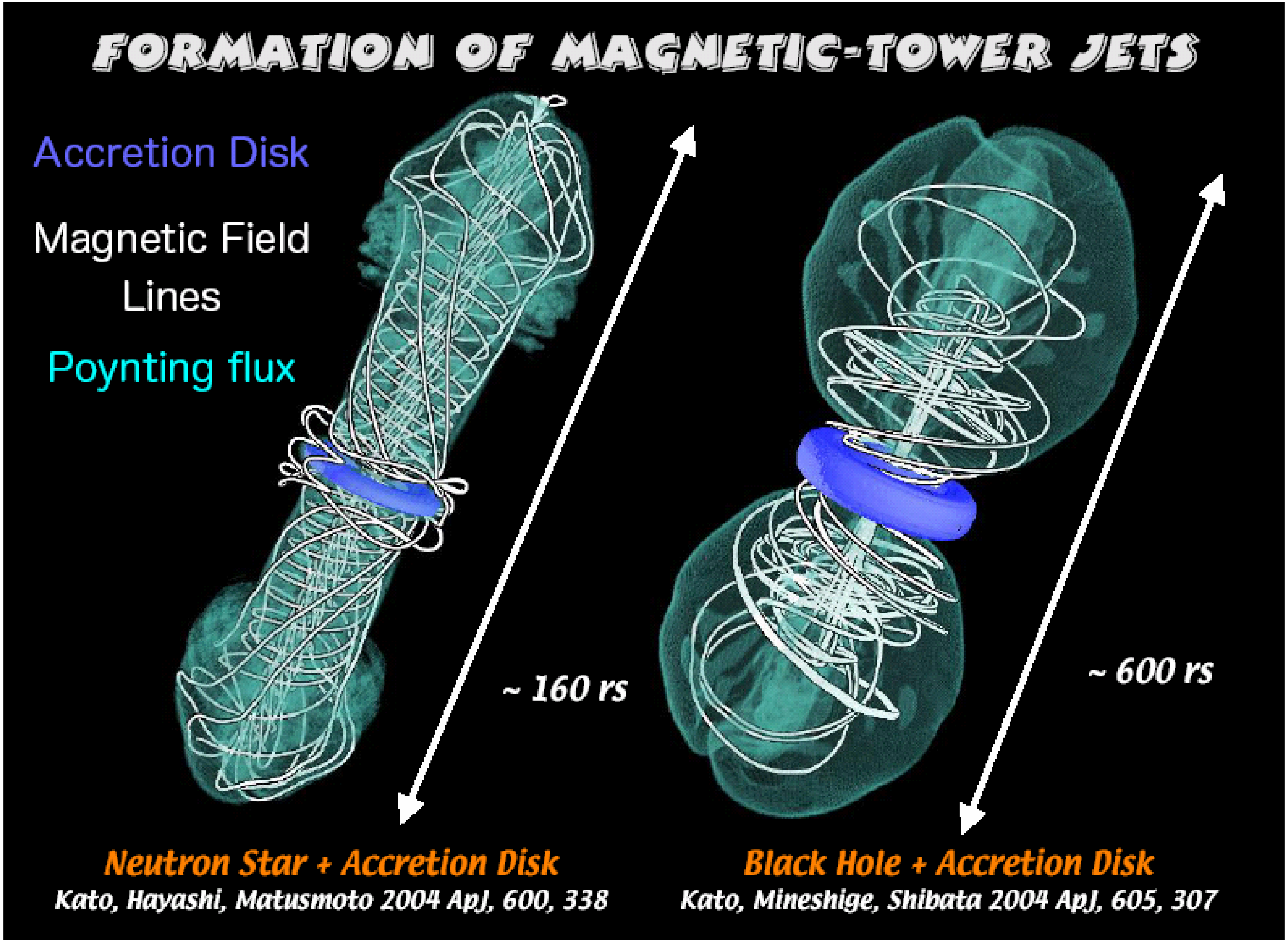
Hayashi, Shibata and Matsumoto 1996

Numerical Simulation of the Magnetic Tower Jet

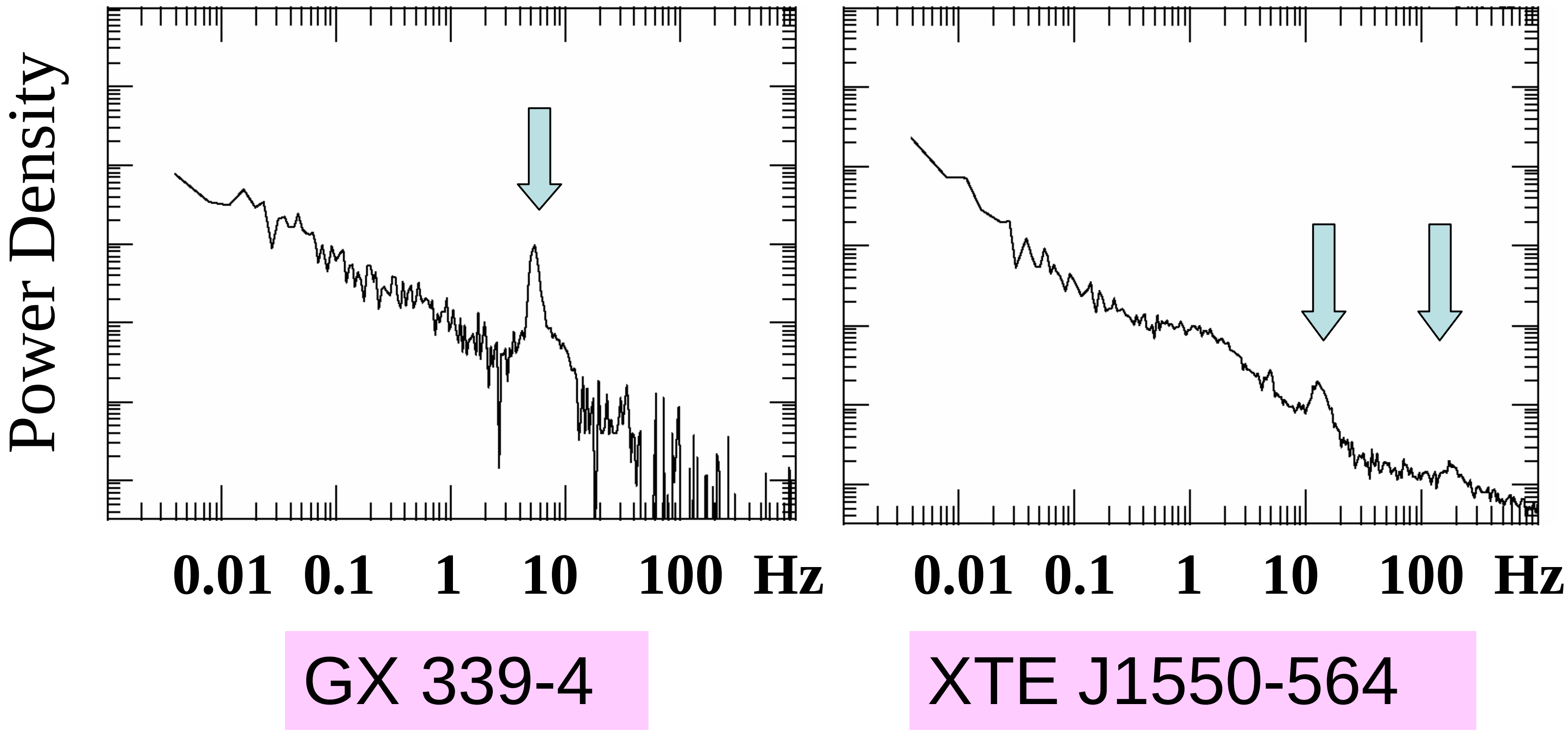




Kato, Hayashi, Matsumoto (2004)

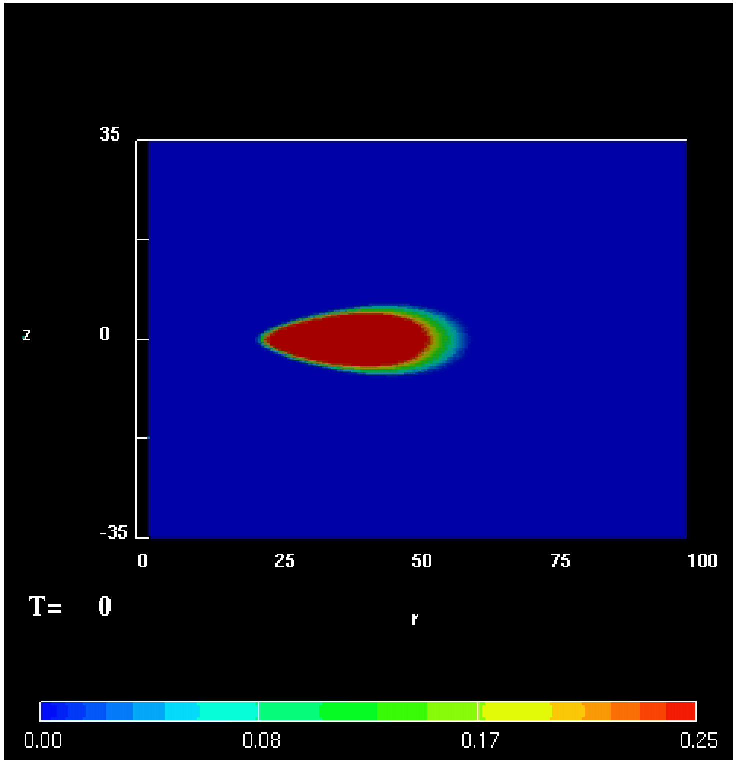

FORMATION OF MAGNETIC-TOWER JETS
Accretion Disk
Magnetic Field Lines
Poynting flux
~ 160 rs
~ 600 rs
Neutron Star + Accretion Disk
Kato, Hayashi, Matusmoto 2004 ApJ, 600, 338
Black Hole + Accretion Disk
Kato, Mineshige, Shibata 2004 ApJ, 605, 307

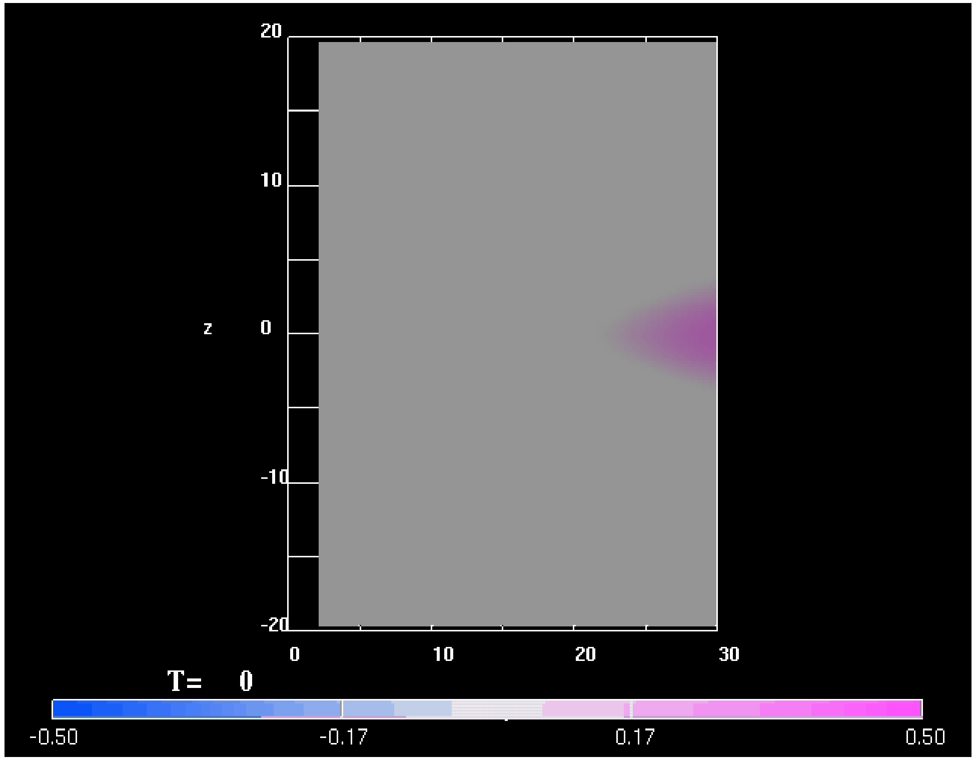
Quasi-Periodic Oscillations (QPOs) in Black Hole Candidates



McClintock and Remillard 2004

Time Evolution of Cool Disk

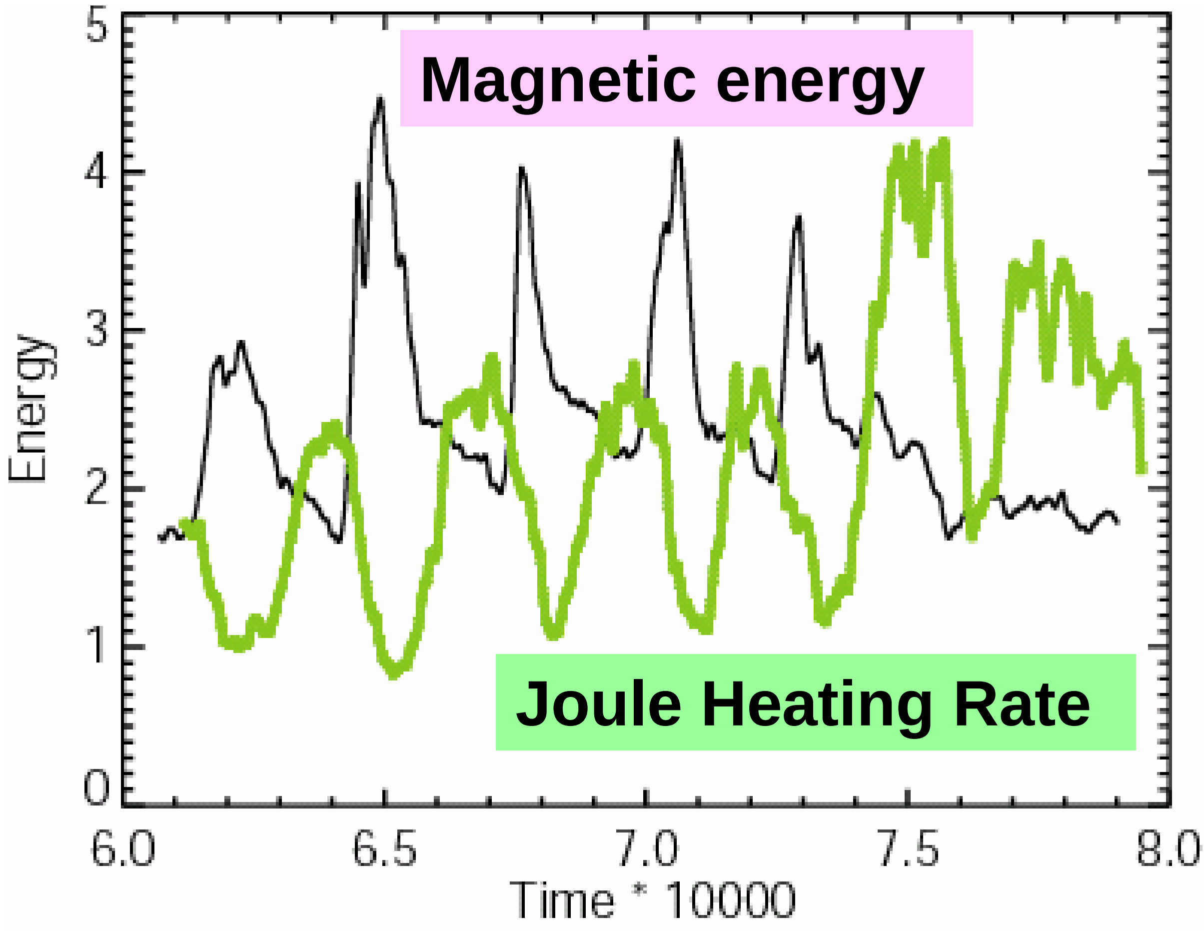




Density distribution

Toroidal magnetic field

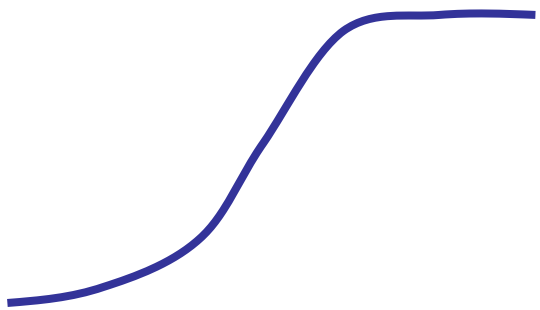
Sawtooth-like Oscillation



Sawtooth-like Oscillation in Nonlinear Systems

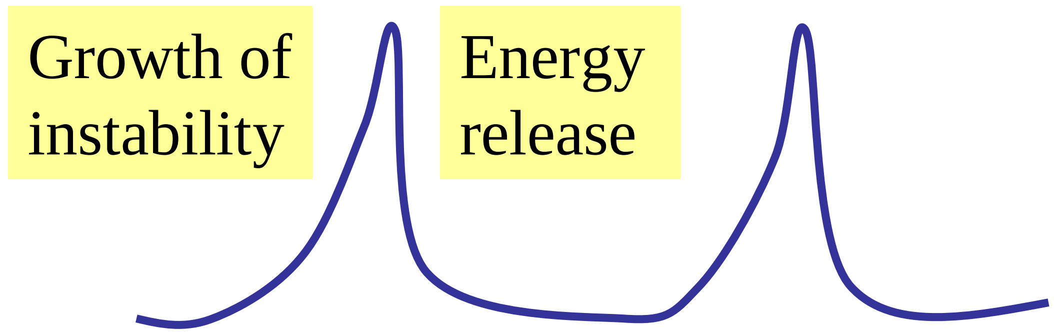
- Sawtooth oscillation takes place when instability and dissipation coexists

When dissipation is large



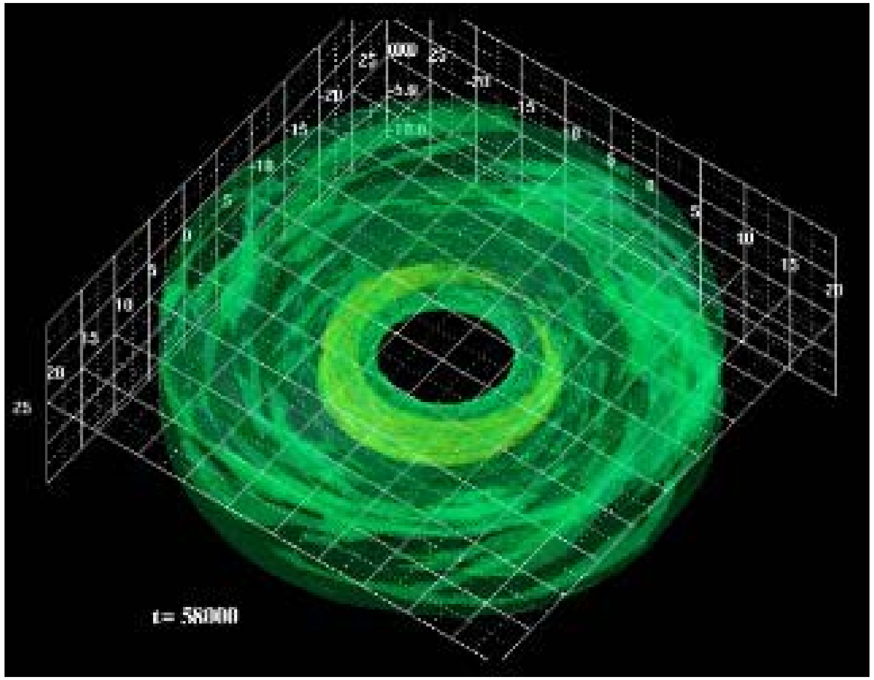
Approaches to a quasi-steady state

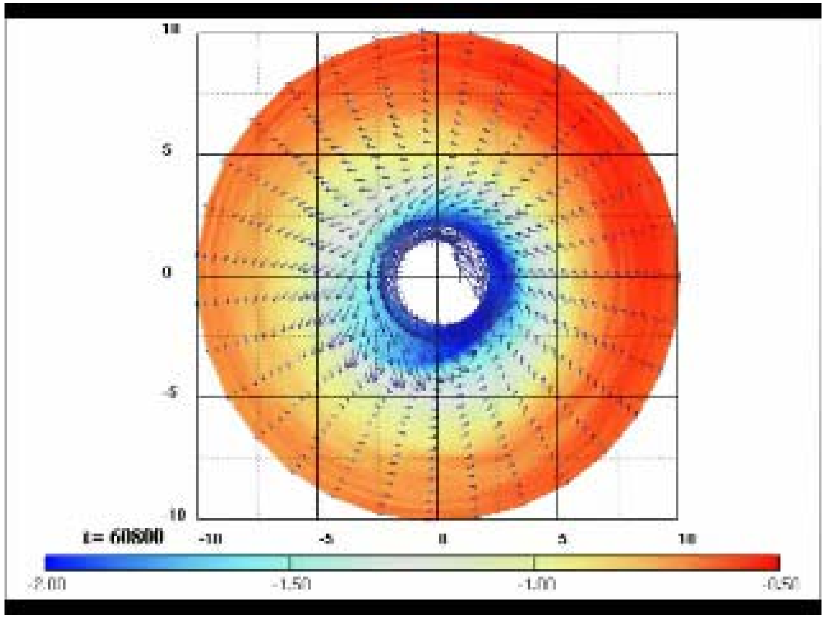
When dissipation is small



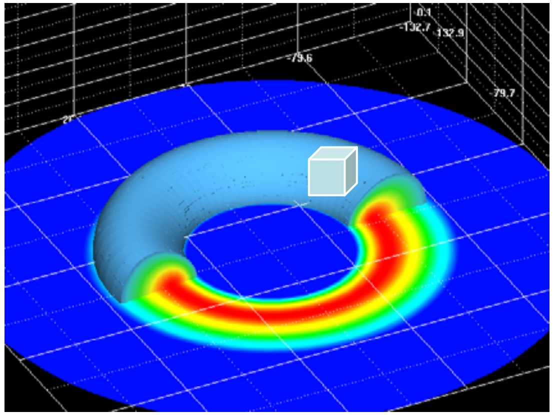
Sawtooth oscillation

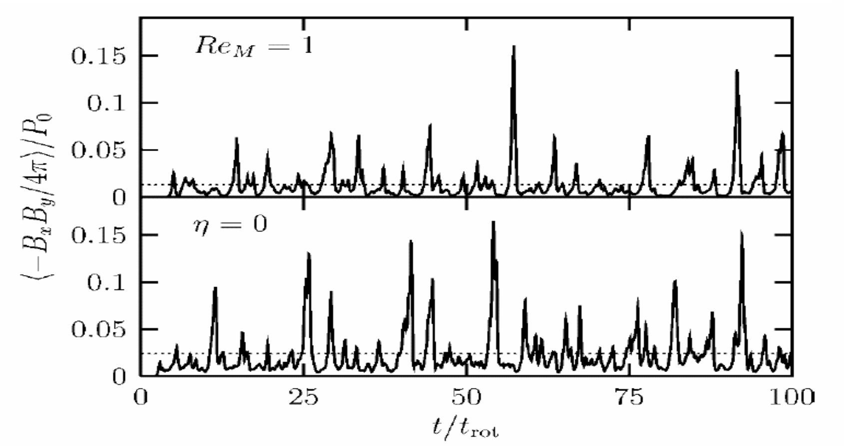
Growth and Disruption of m=1 Non-axisymmetric Mode

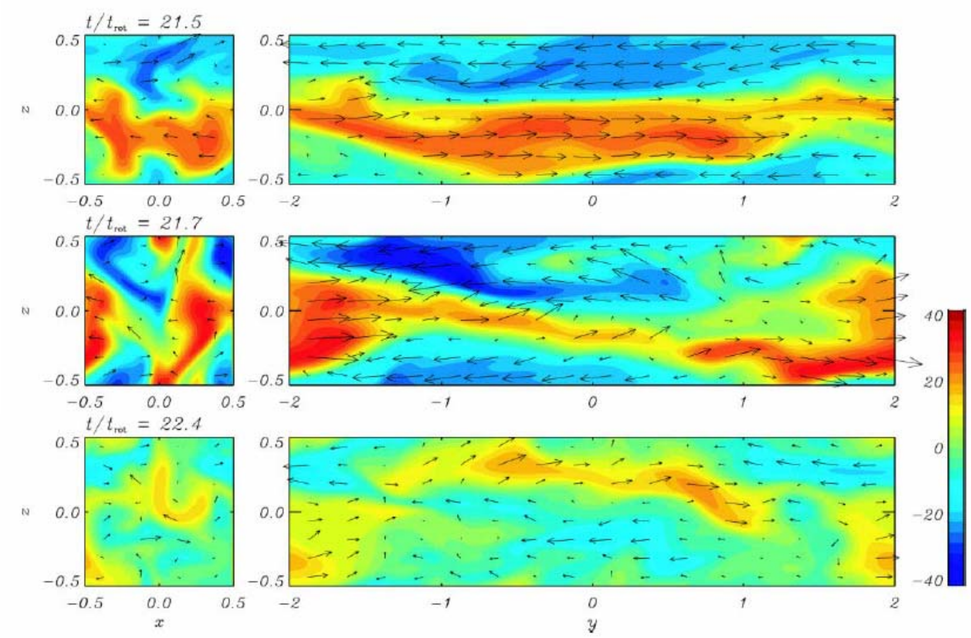




Similar Behaviors have been Observed in Resistive 3D Local MHD Simulations

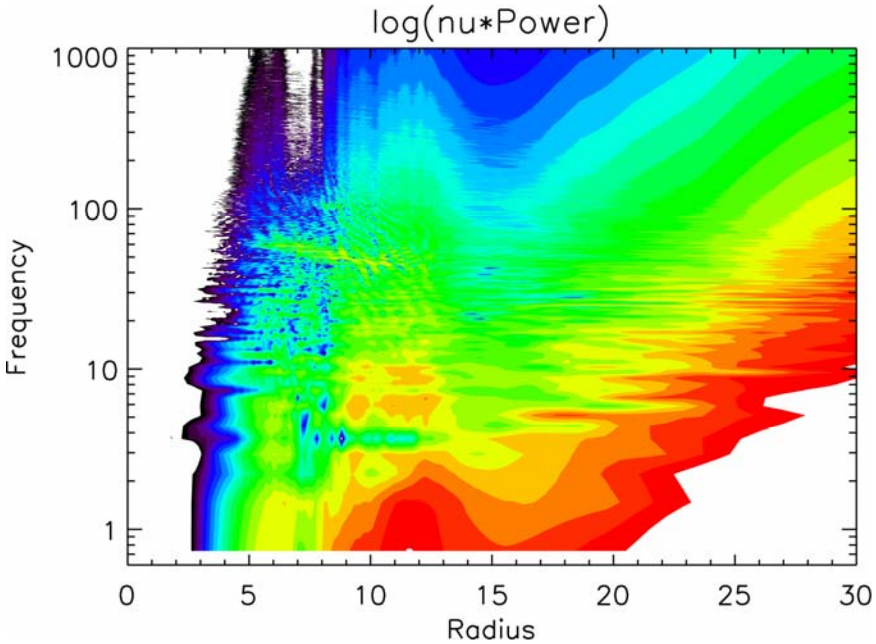




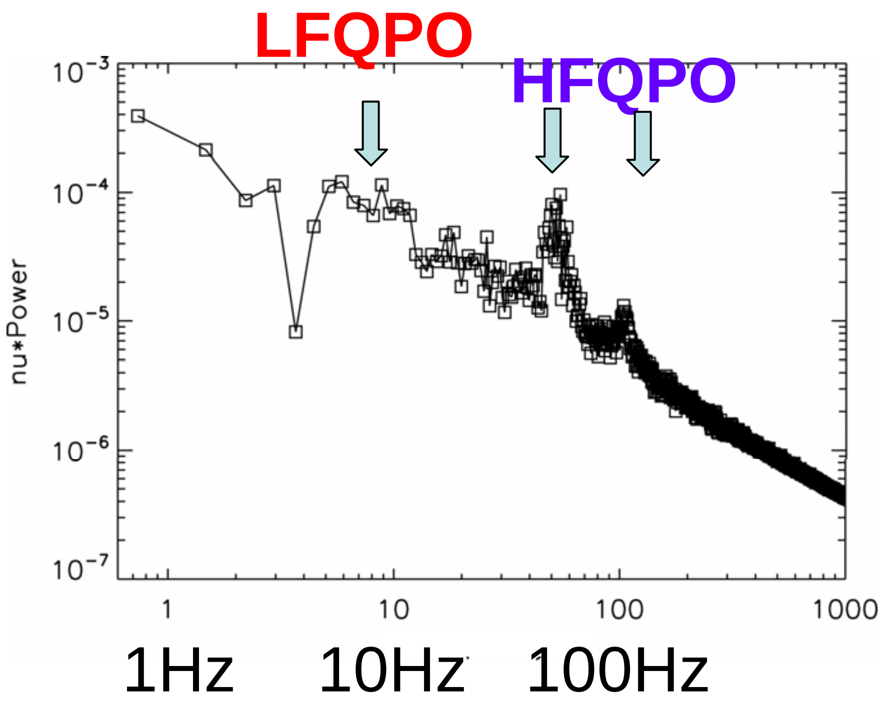


Sano and Inutsuka 2001

High Frequency QPOs are Excited during Sawtooth-like Oscillation

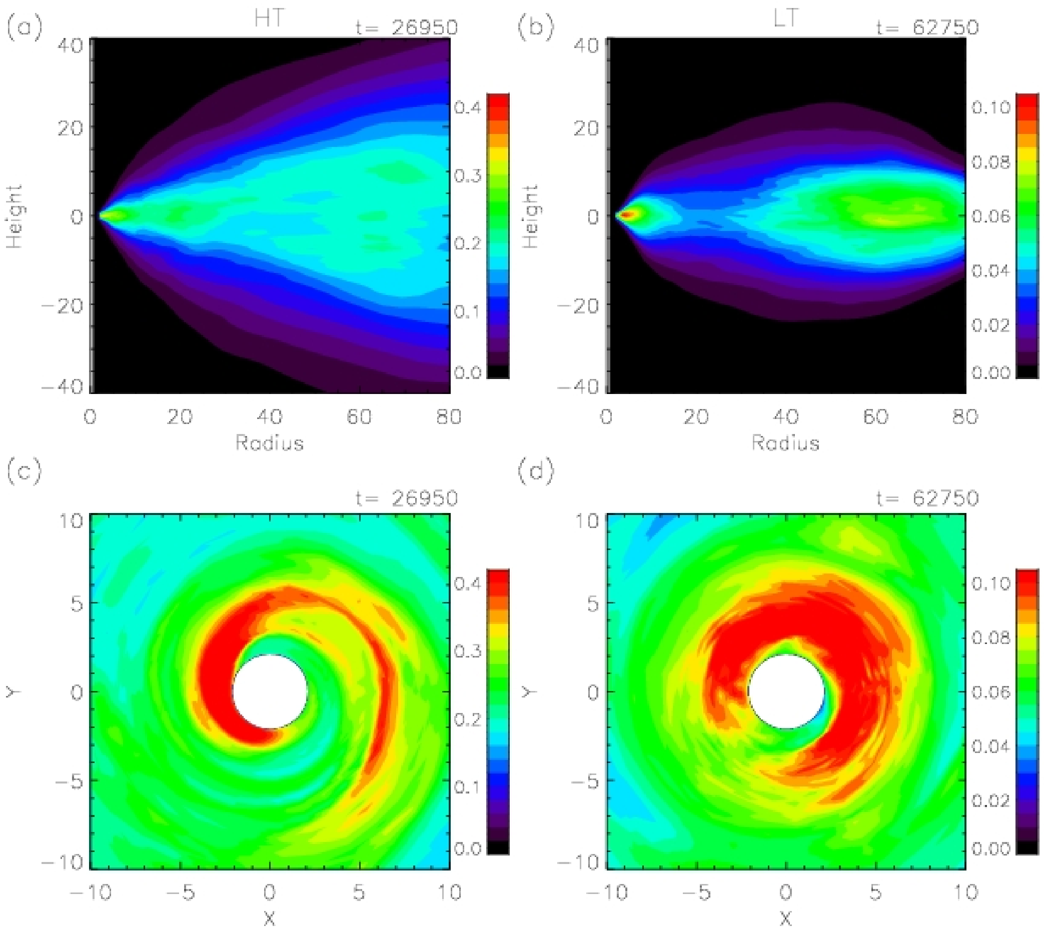


Distribution of power spectrum of oscillation



Power spectrum of luminosity variation

Why QPOs Appear in Low Temperature Disks ?

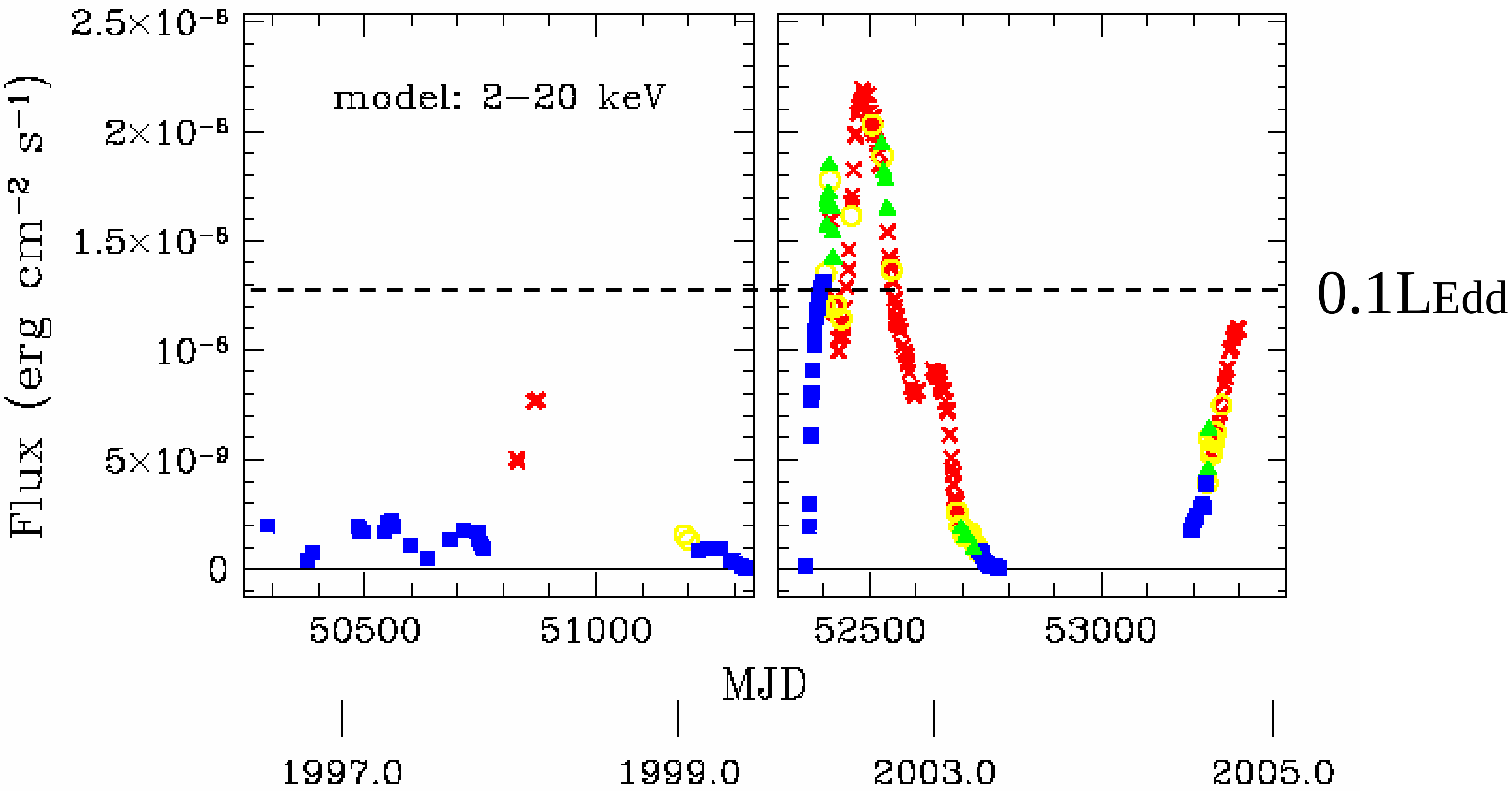


High temperature(HT) model

Low temperature (LT) model

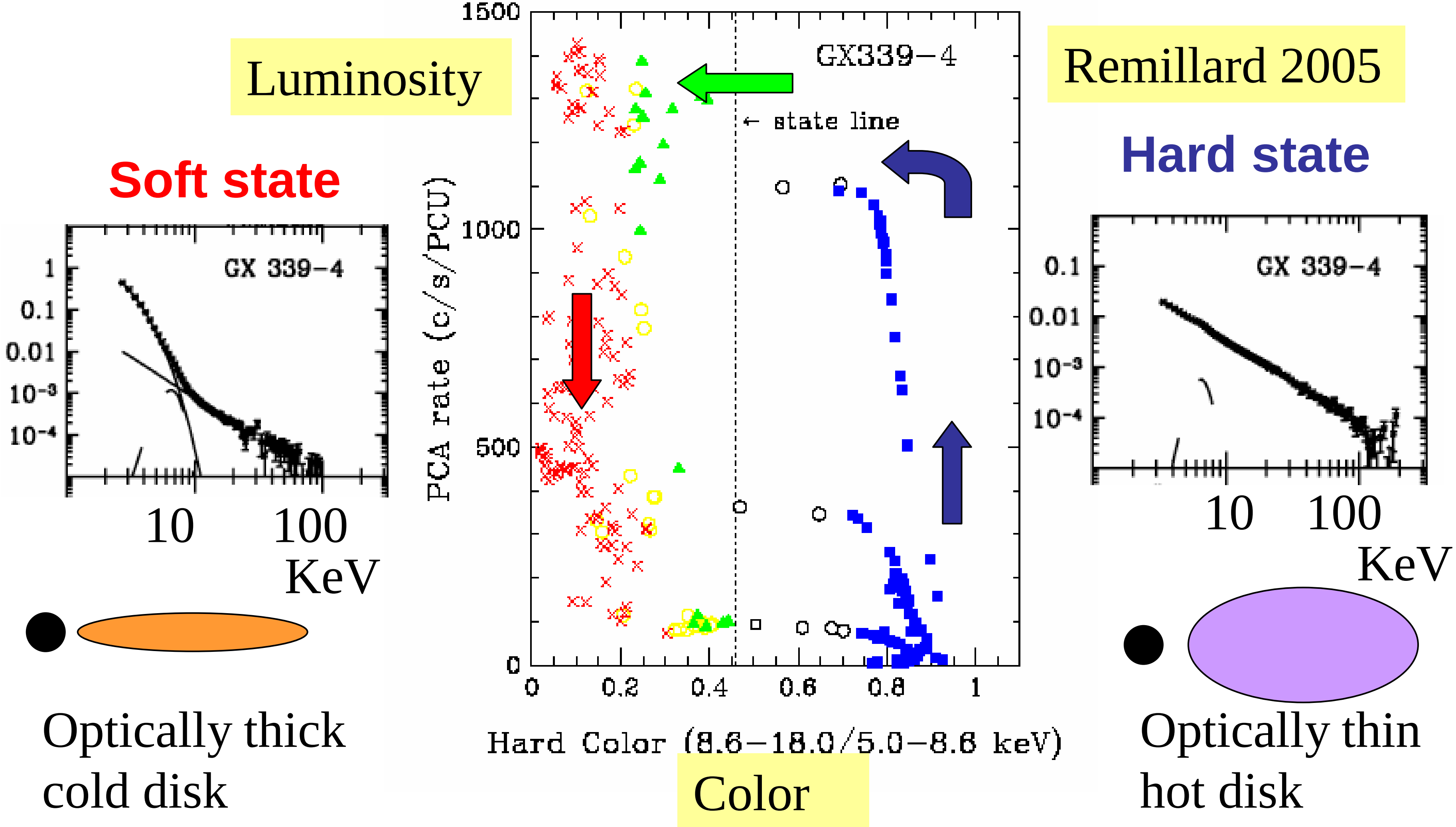
Formation ot the Inner Torus is Essential for QPOs

State Transitions of Black Hole Candidates



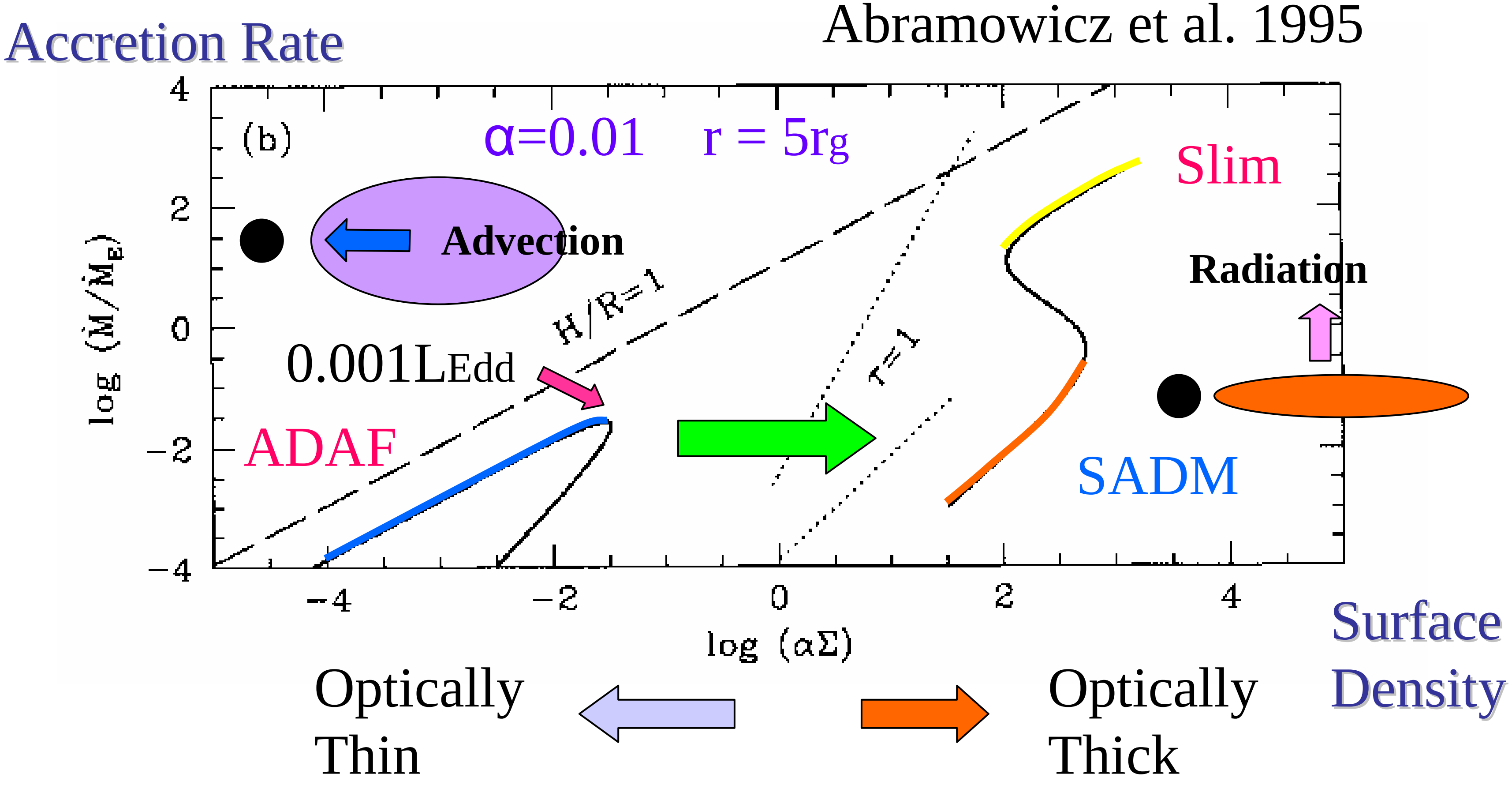
Light Curve of GX339-4 during outbursts (Remillard 2005)

Evolution in Color-Luminosity Diagram (HR Diagram)



Conventional Theory Failed to Explain Luminous Hard State Observed During the Hard-to-Soft Transition (Too Dark !)

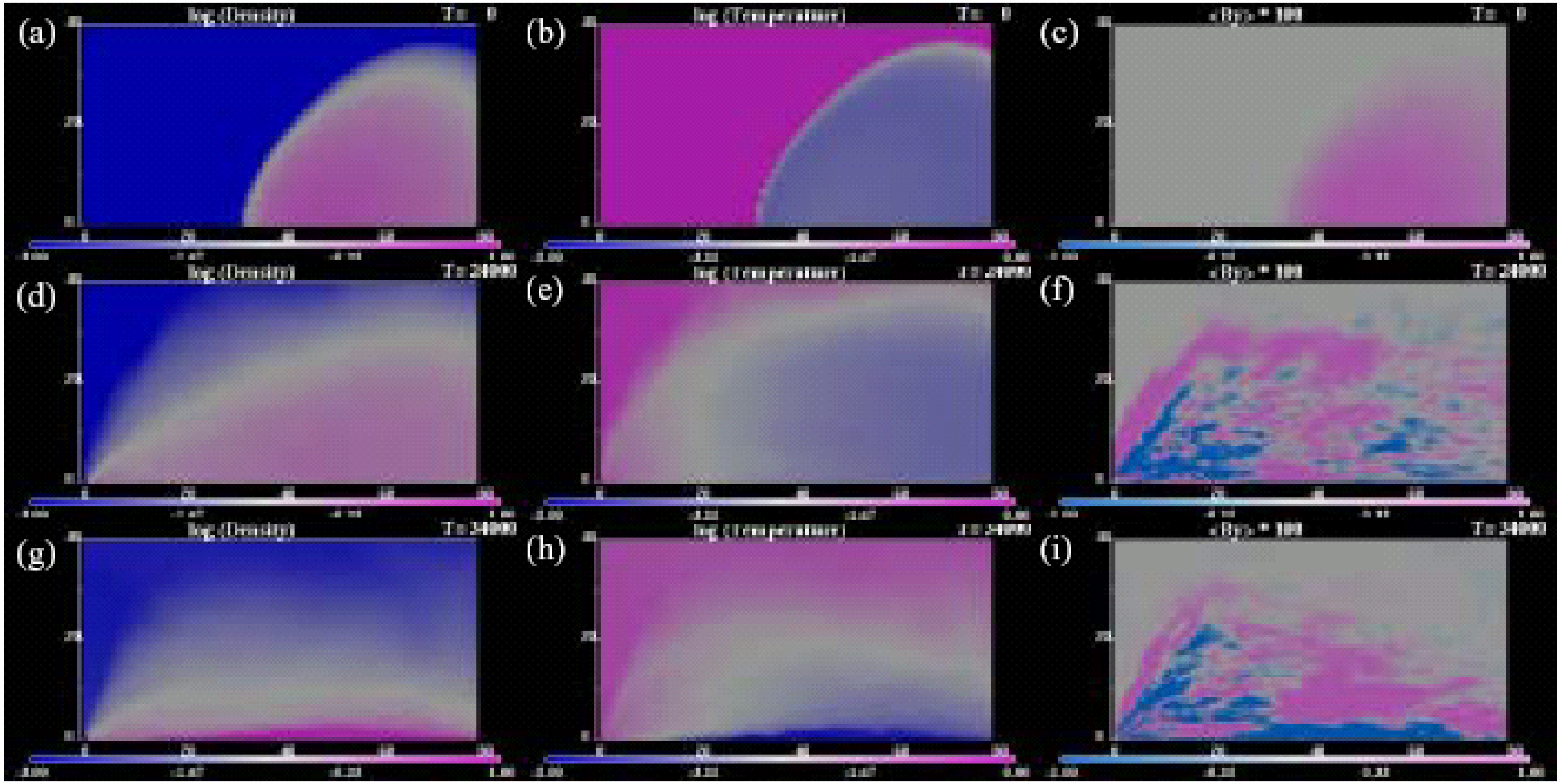
Abramowicz et al. 1995



3D MHD Simulation Including Optically Thin Radiative Cooling (Machida et al. 2006, PASJ 58, 193)

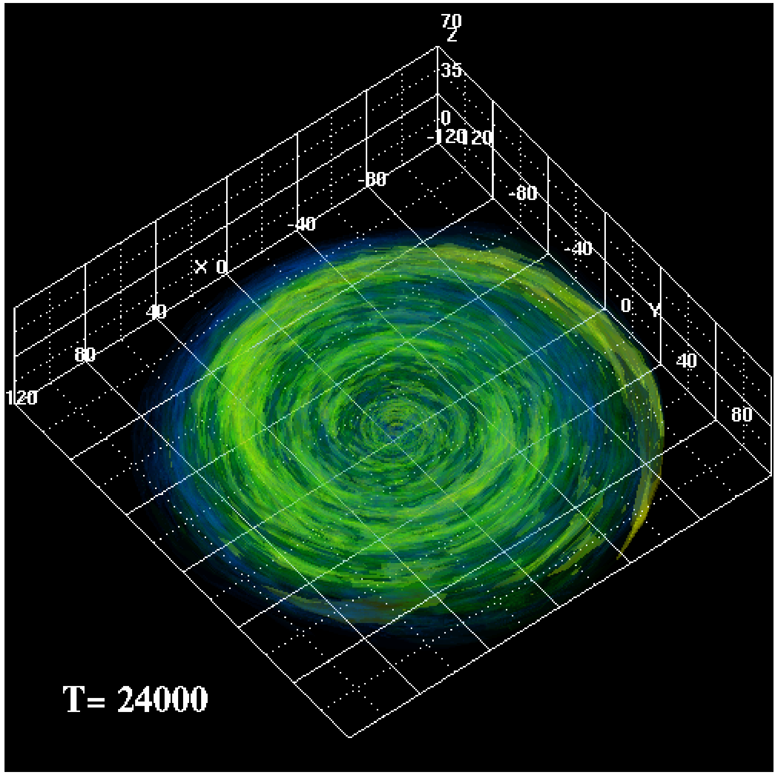
- Cooling term is switched on after the accretion flow becomes quasi-steady
- We assume bremsstrahlung cooling
  $Q_{rad} = Q_{\mathbf{b}} \rho^2 T^{1/2}$
- Cooling is not included in rarefied corona where $\rho < \rho_{crit}$

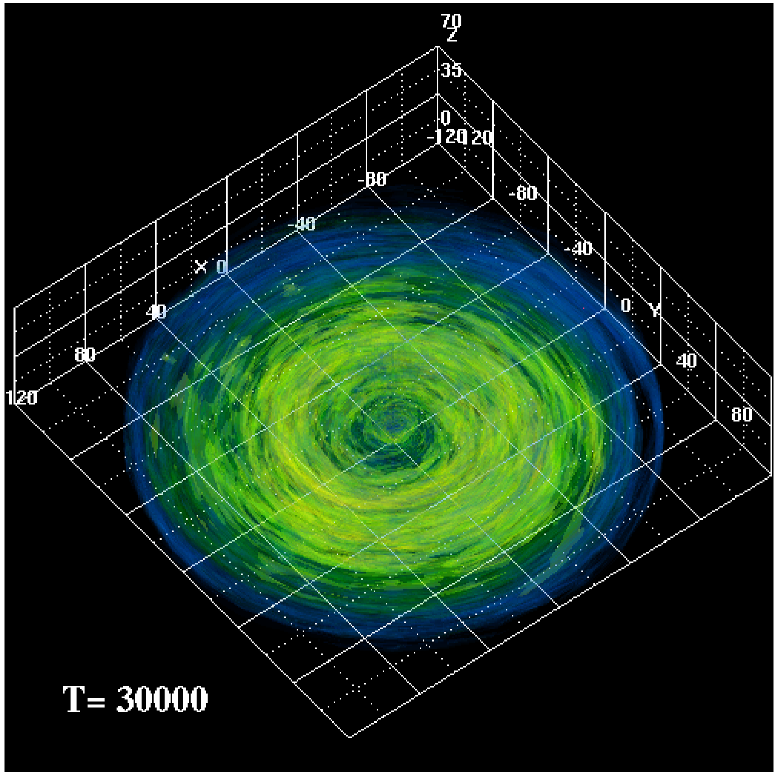
Transition to Cool Disk



density temperature Toroidal field

Formation of Low-beta Disk

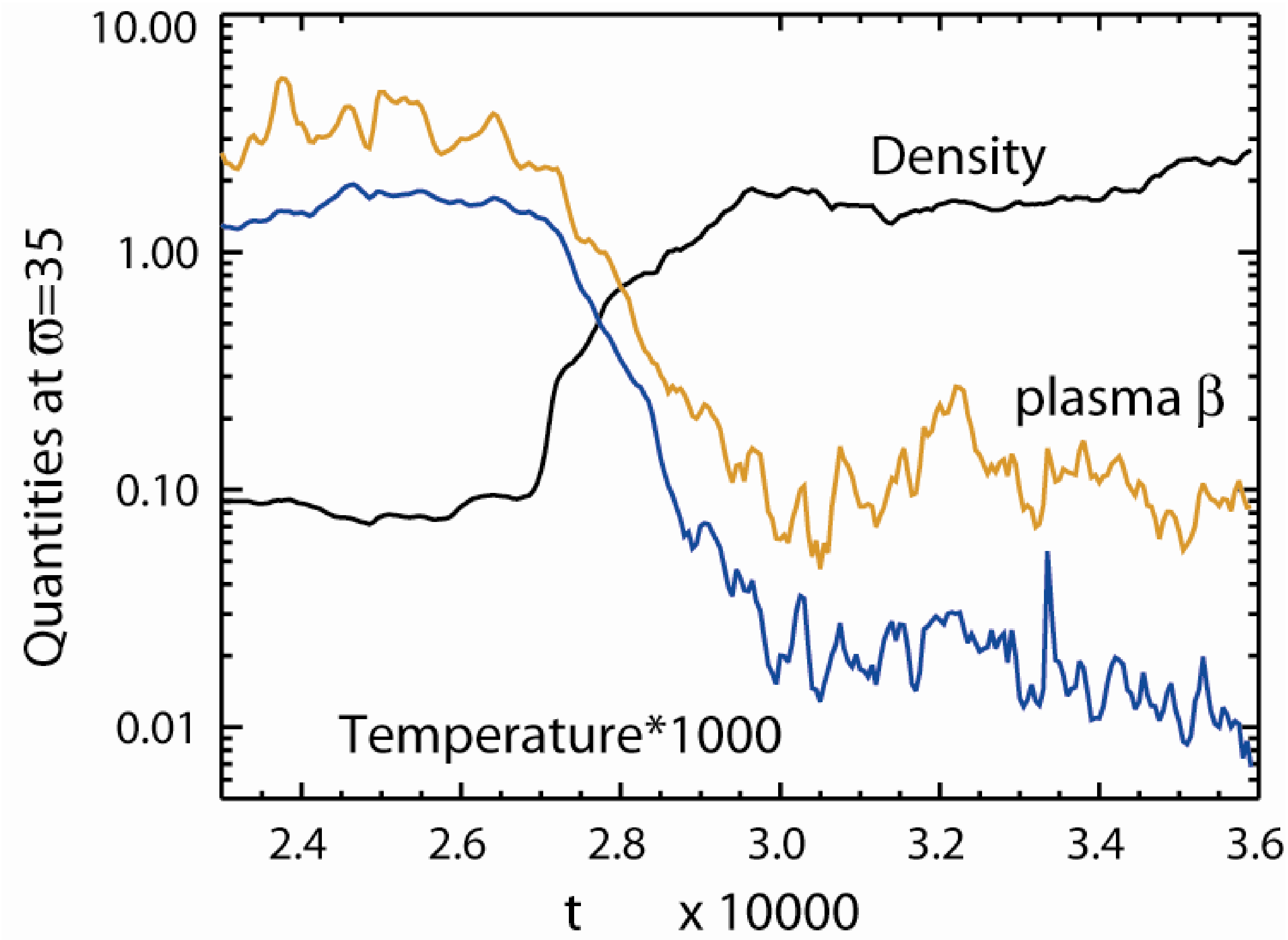




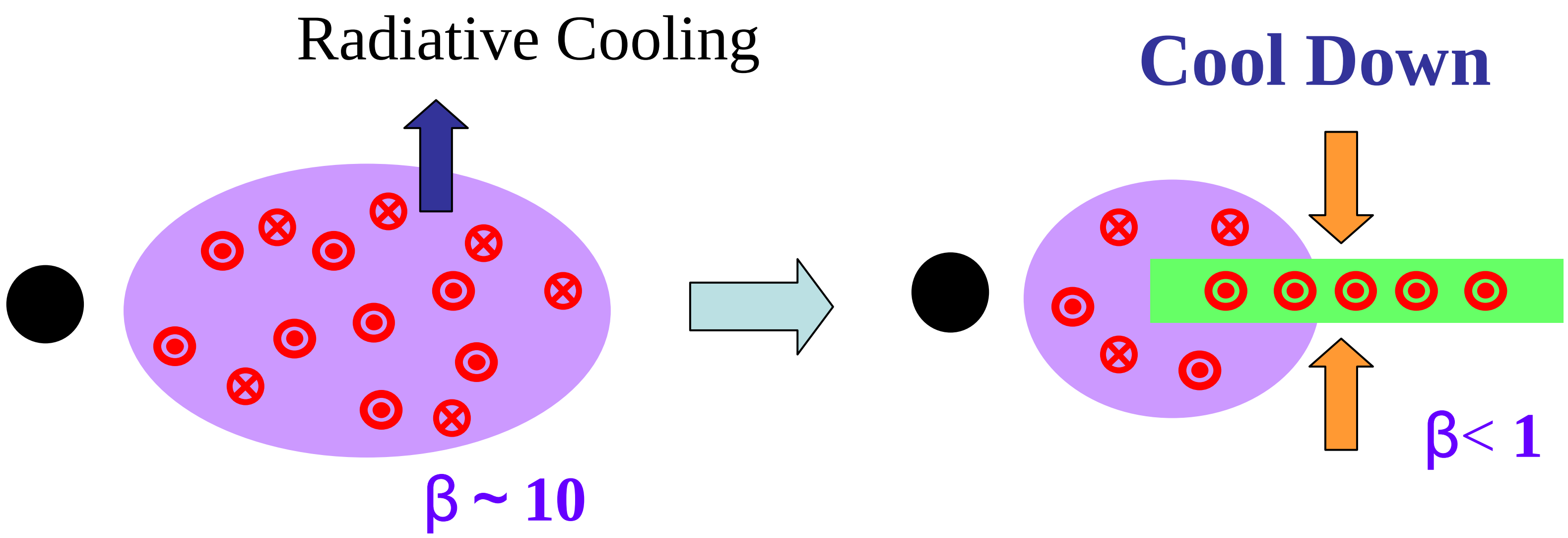
Before the transition

After the transition

Time Evolution



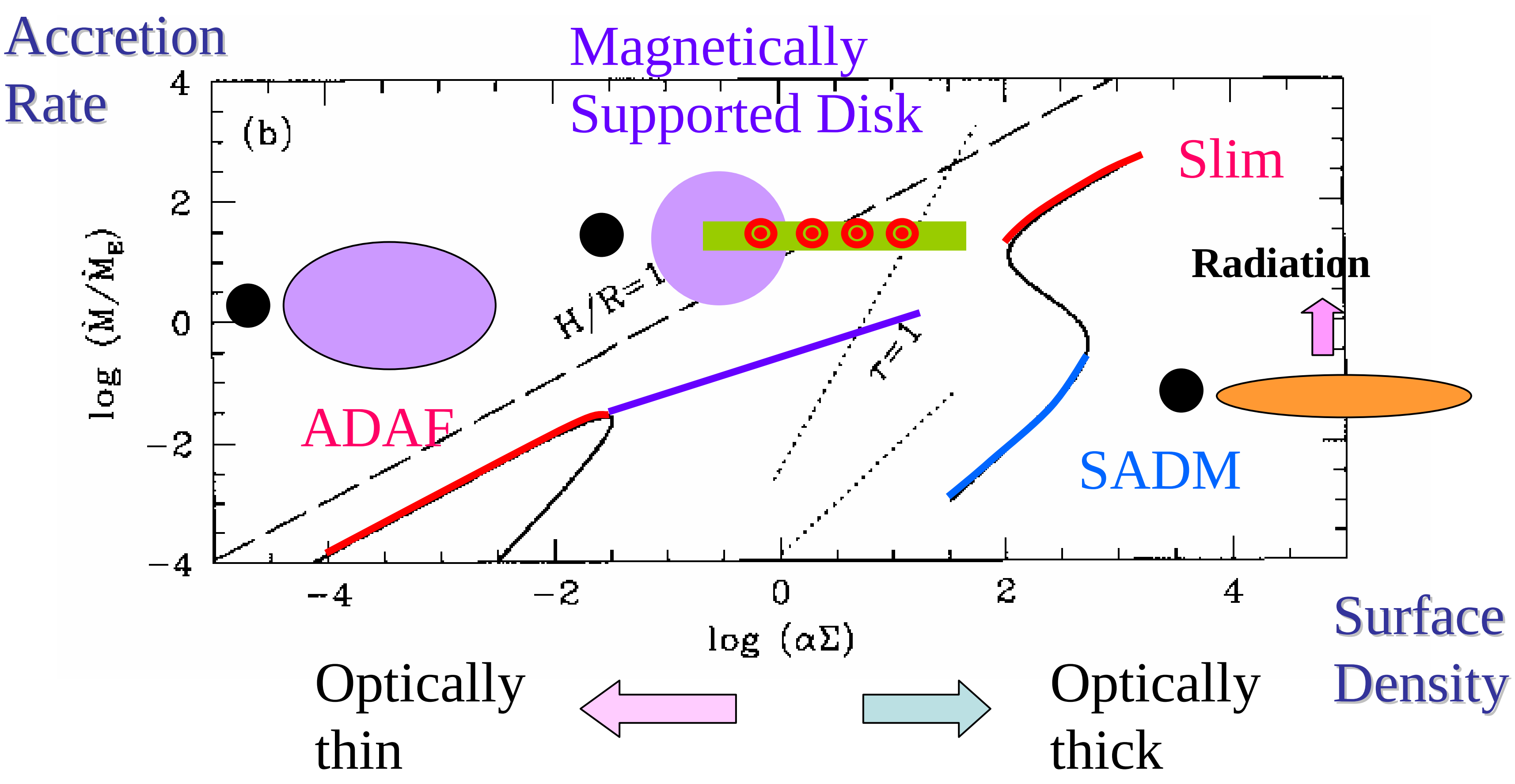
Formation of a Magnetically Supported Disk



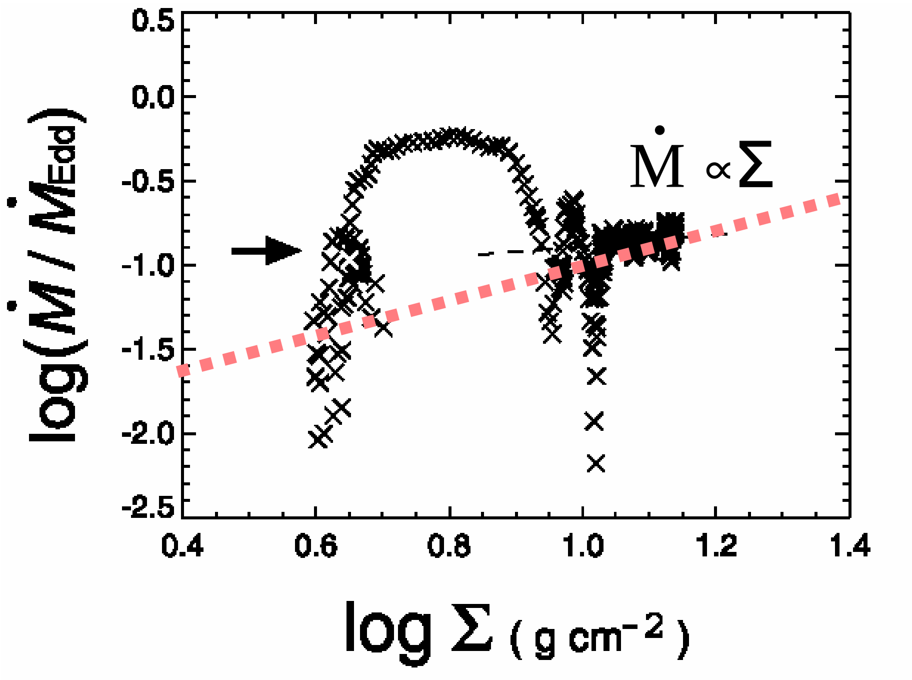
Optically Thin Hot Disk
Supported by Gas Pressure

Optically Thin Cool Disk
Supported by Magnetic Pressure

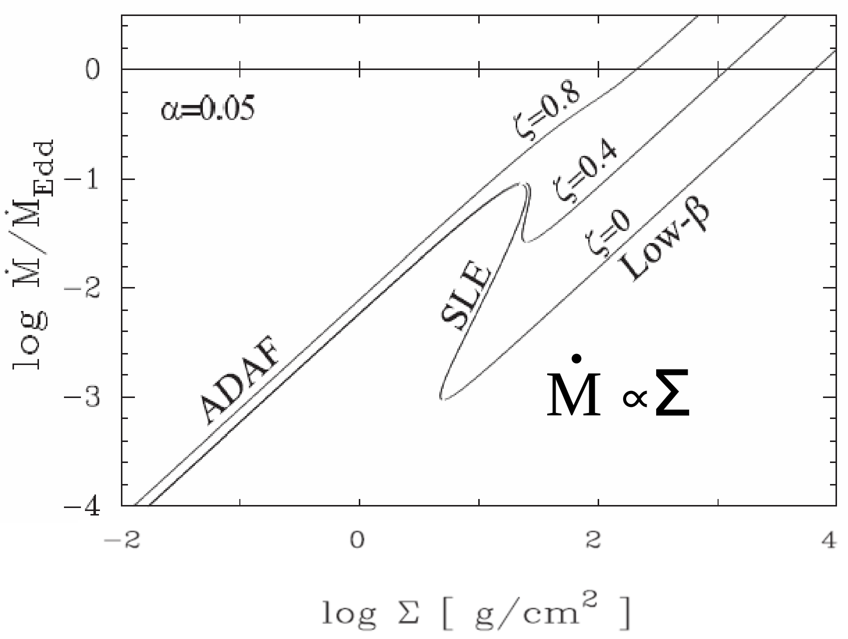
Thermal Equilibrium Curves of Accretion Disks Supported by Toroidal Magnetic Fields (Oda et al. 2006)



Comparison with Theoretical Model and Numerical Results

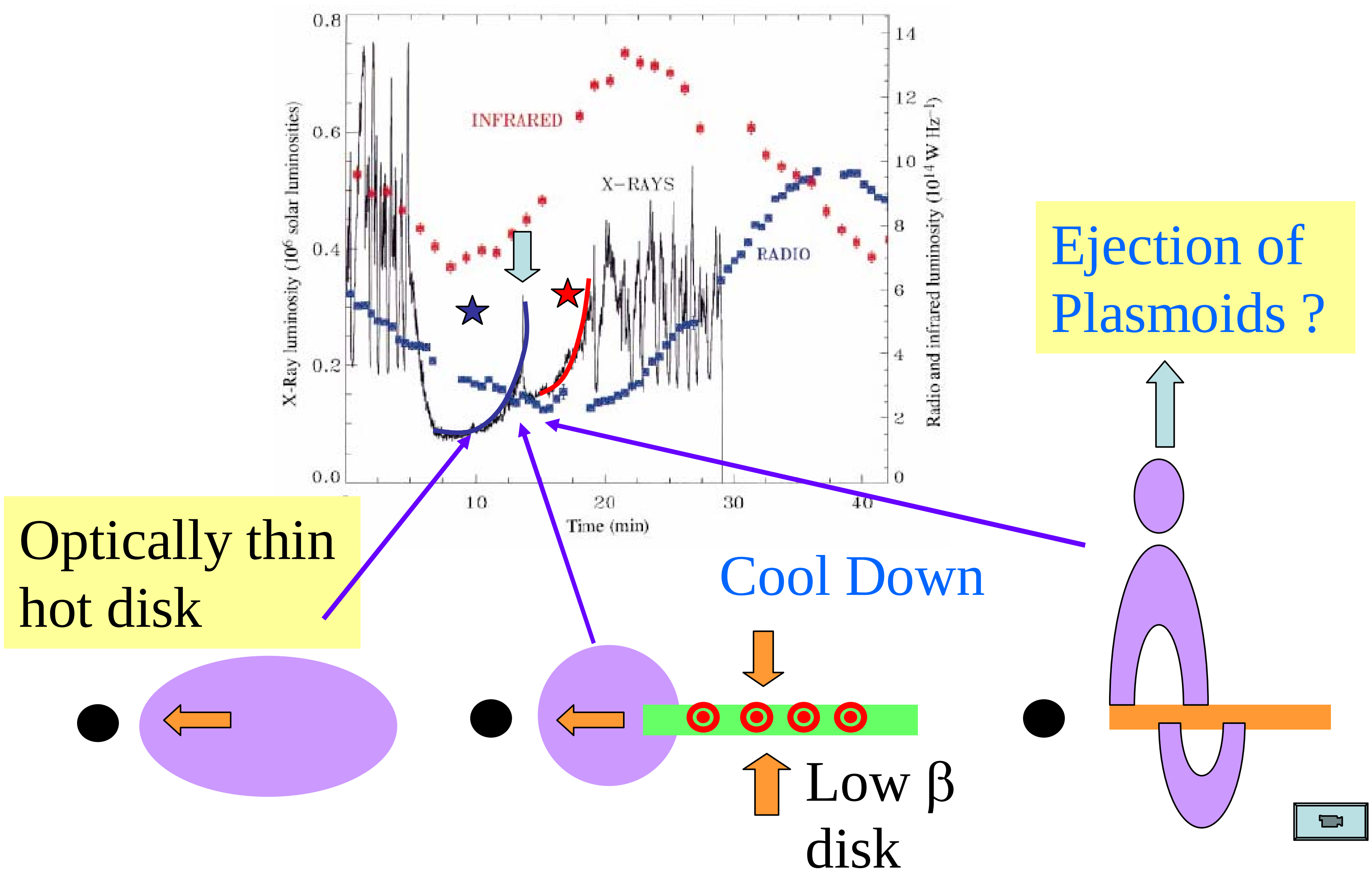


Numerical Result (Machida et al. 2006)

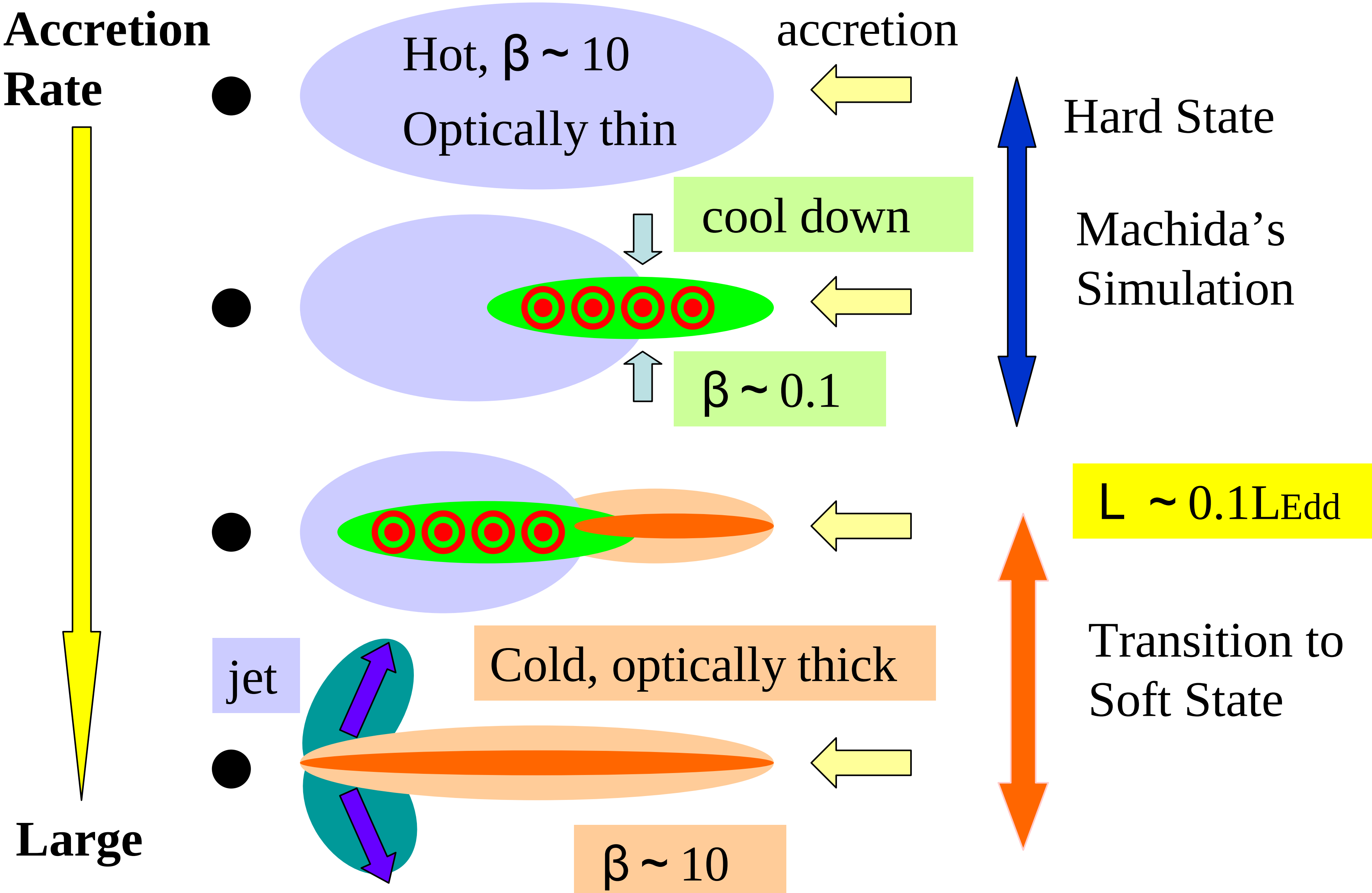


Theoretically Obtained Thermal Equilibrium Curve (Oda et al. 2006)

A Model of GRS1915+105



Evolution of an Accretion Disk During Outburst



Summary

- 3D global MHD simulations enable us to study the evolution of an accretion disk without introducing the phenomenological alpha-parameter of angular momentum transport
- Quasi-steady outflows appear from hot, geometrically thick accretion disks
- Global 3D resistive MHD simulations of cool disks indicate that they show sawtooth-like oscillations
- When sawtooth-like oscillation takes place, high frequency QPOs appear
- By carrying out global MHD simulations including radiative, cooling, we found that magnetically supported disk is created during the hard-to-soft transition.

End