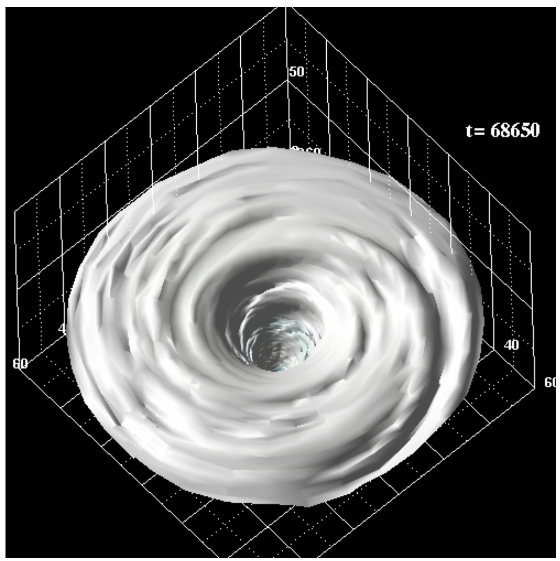
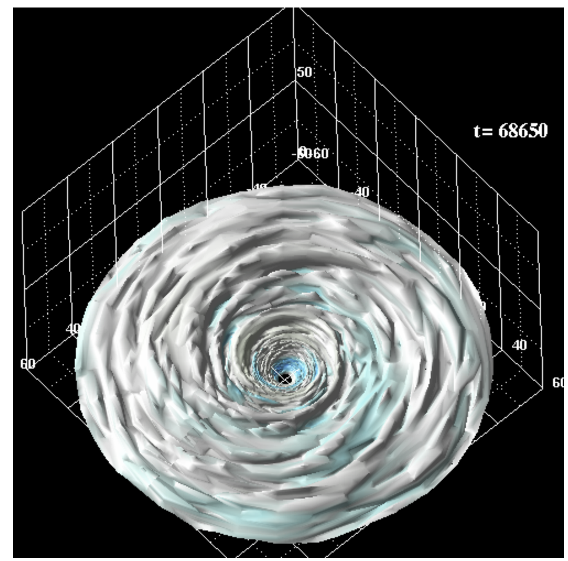
Global Simulations of Turbulence and Dynamos in Differentially Rotating Astrophysical Plasmas



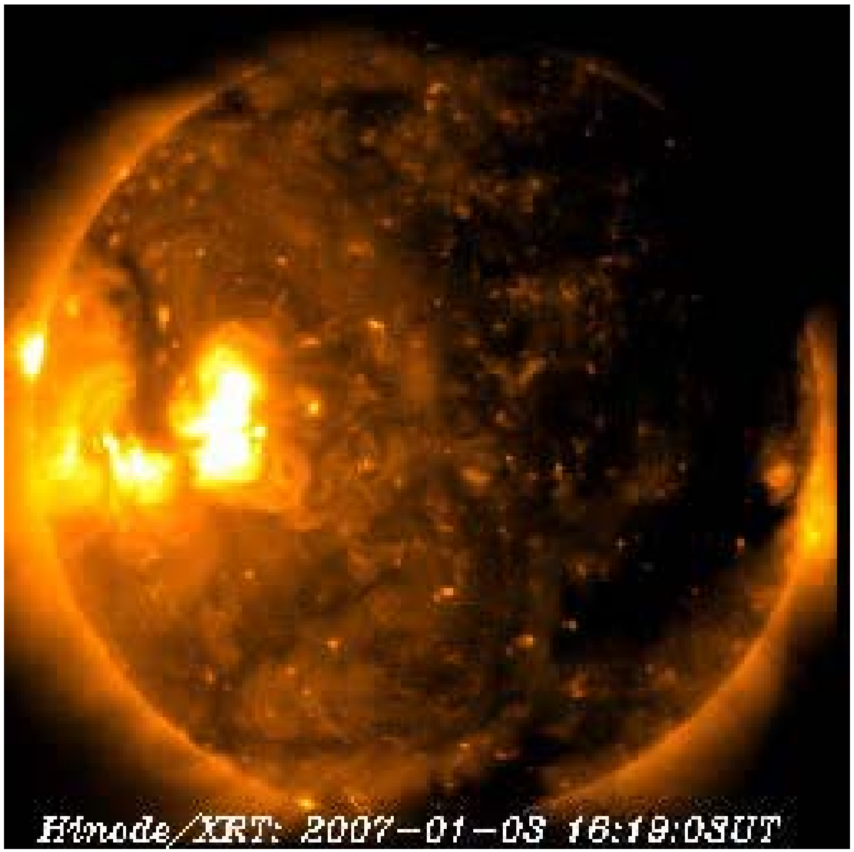


Ryoji Matsumoto (Chiba Univ.)

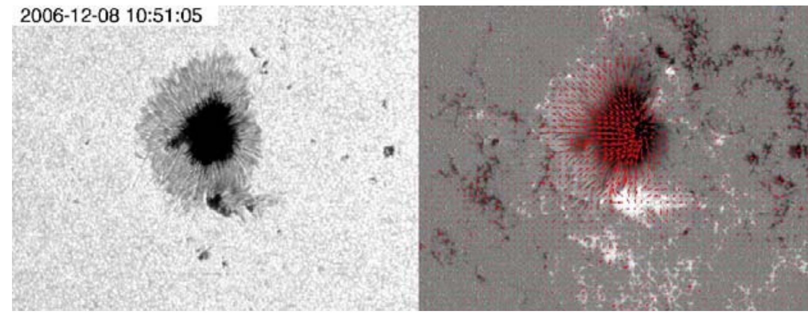
Collaborators: Minoru Tanaka (Chiba Univ.) and

Mami Machida (NAOJ)

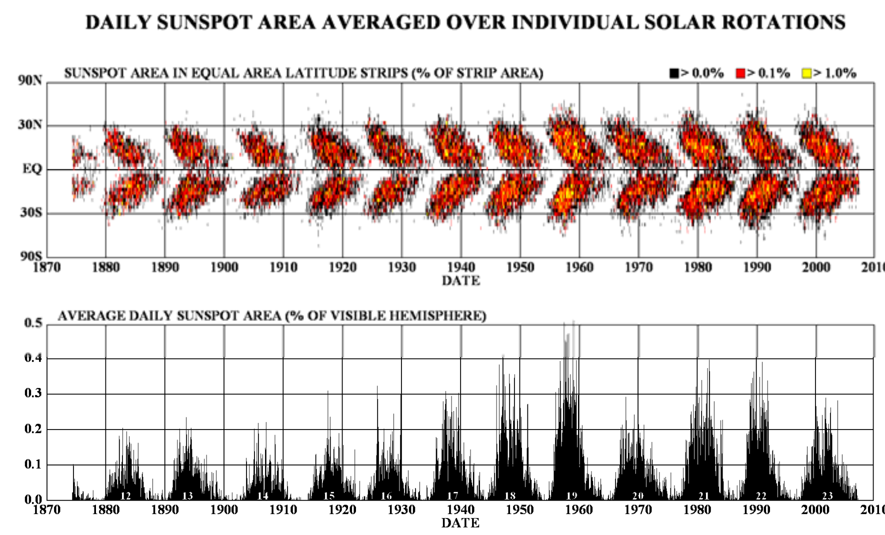
Magnetic Activities of Astrophysical Plasma



X-ray Image by HINODE Satellite

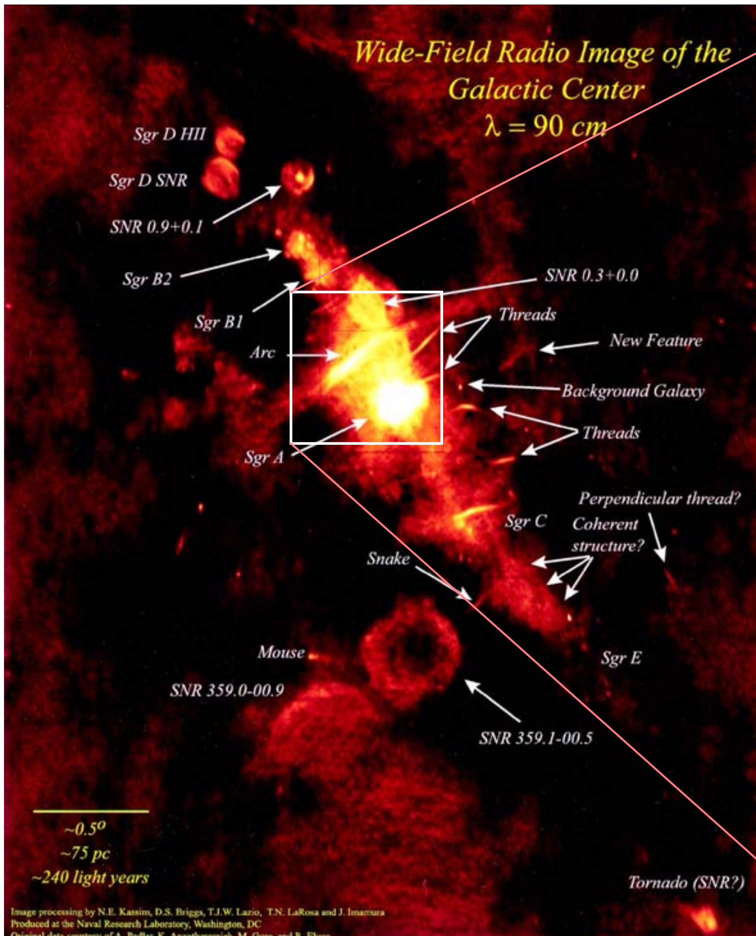


Optical image of sunspots by HINODE

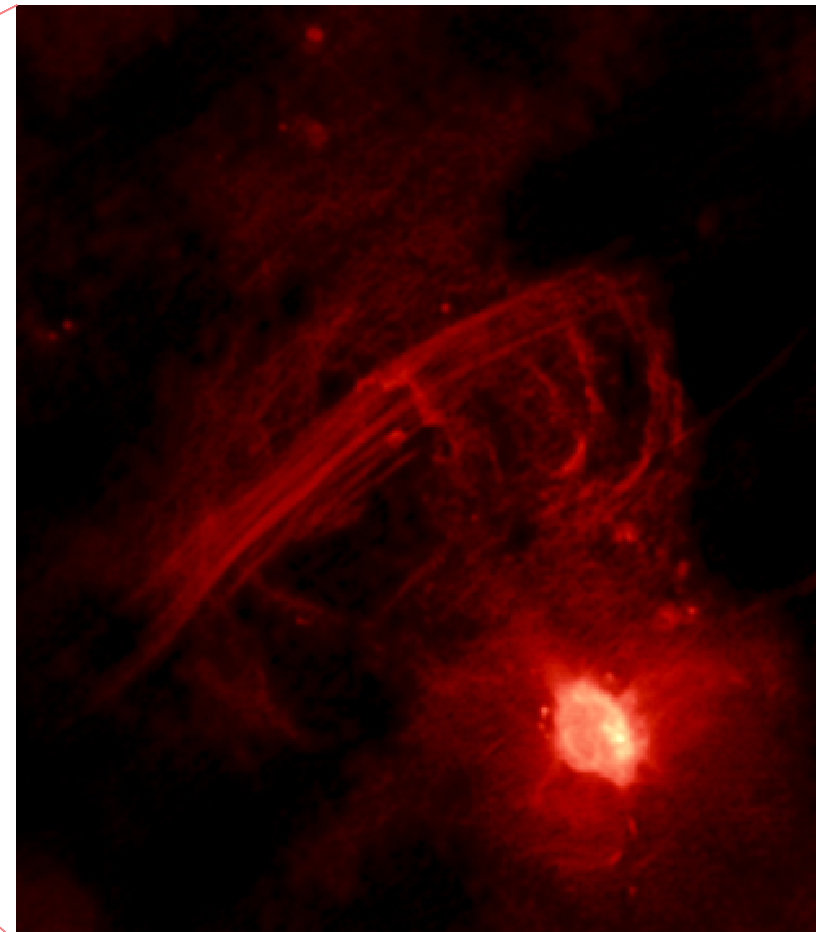


Butterfly Diagram of Sunspots (NASA)

Filamentary Structure and Radio Arc Near the Galactic Center

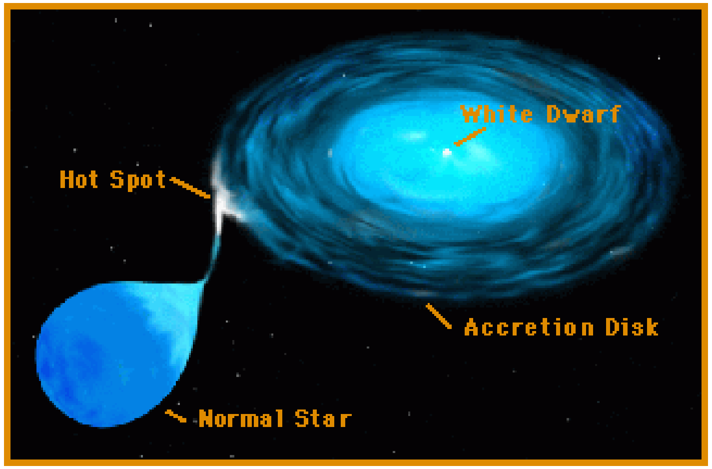


RaLosa et al (2000) VLA

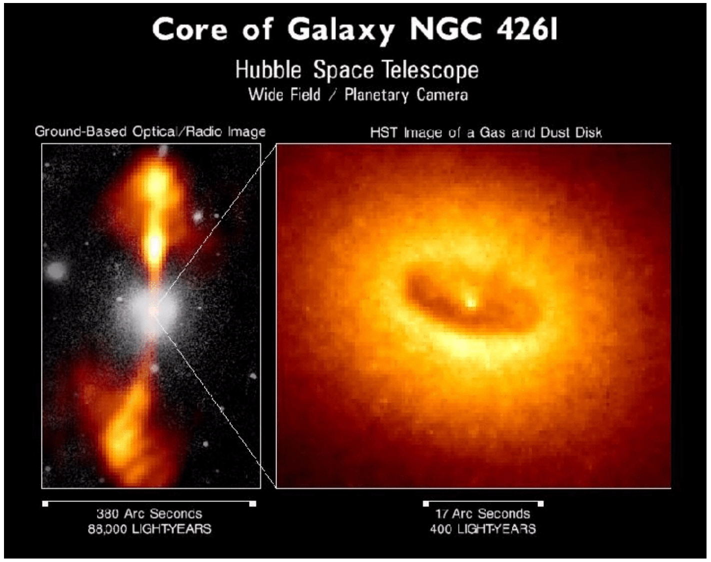


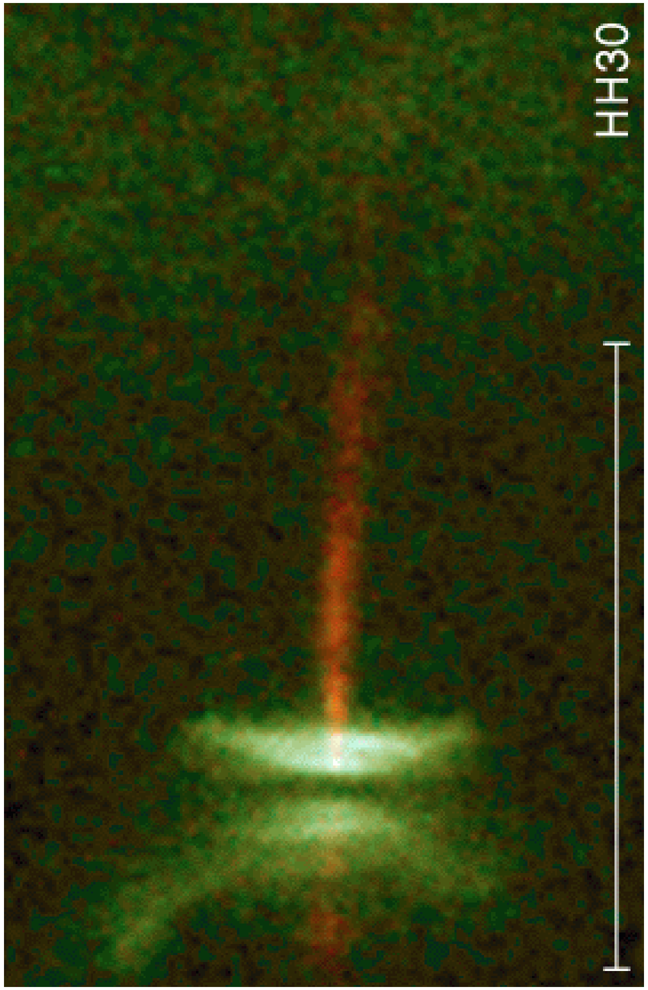
Yusef-Zadeh and Morris 1987

Accretion Disks and Jets



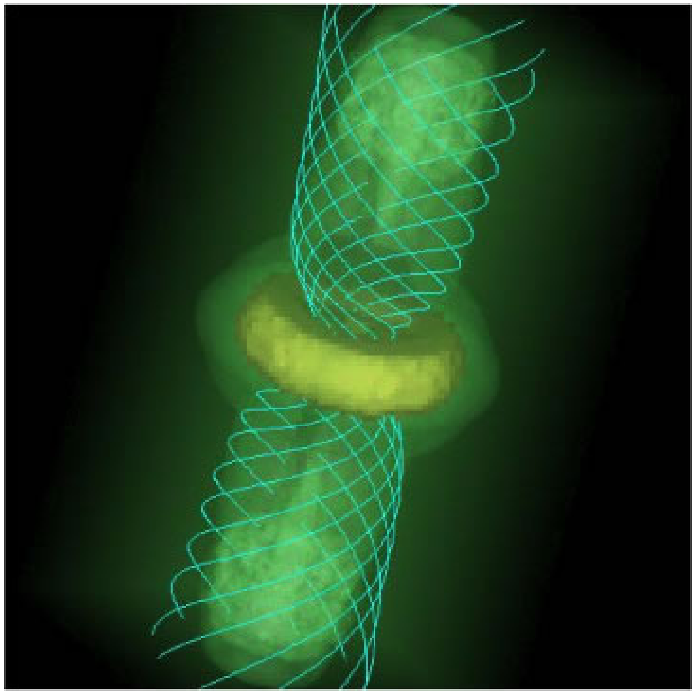
A Schematic Picture (NASA)





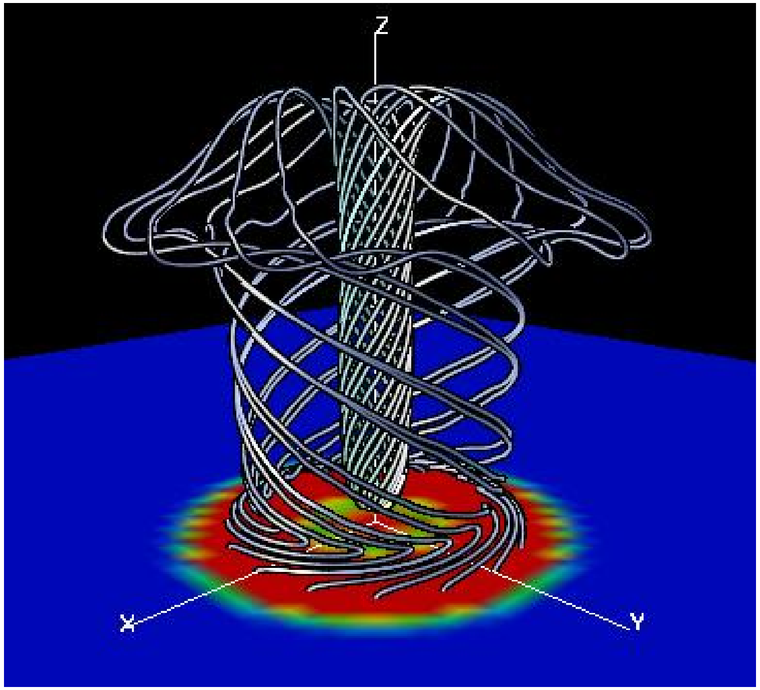
Protoplanetary Disk and Optical Jet (HST)

Two Models of Magnetically Driven Jet



Magneto-centrifugally driven jet

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



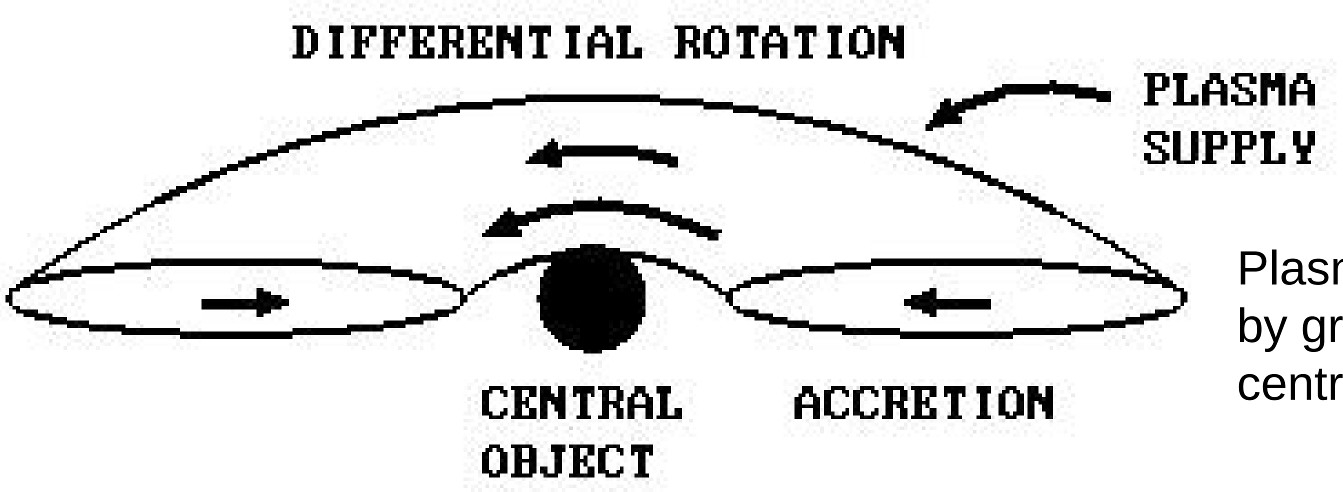
Magnetic tower jet

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

Outline of This Talk

- Flows, Turbulence and Magnetic Field Amplification in Astrophysical Rotating Disks
  - Angular momentum transport in differentially rotating disks
  - Global 3D MHD Simulations of Accretion Disks
  - Global 3D MHD Simulations of Galactic Gas Disks

Angular Momentum Transport in Accretion Disks



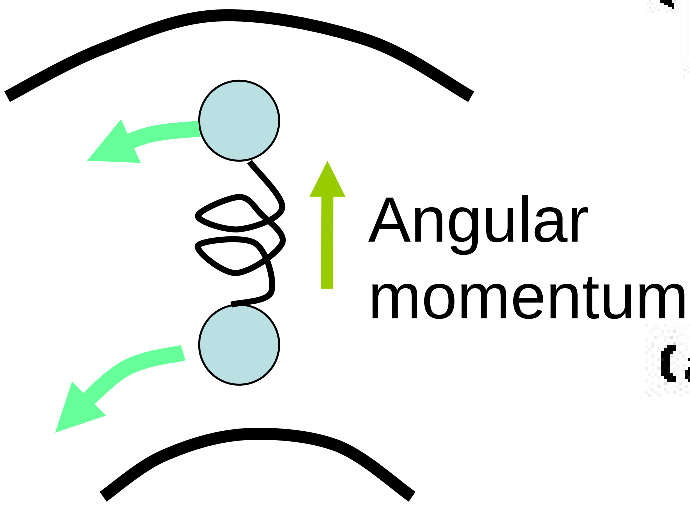
Plasma is confined by gravity and centrifugal force

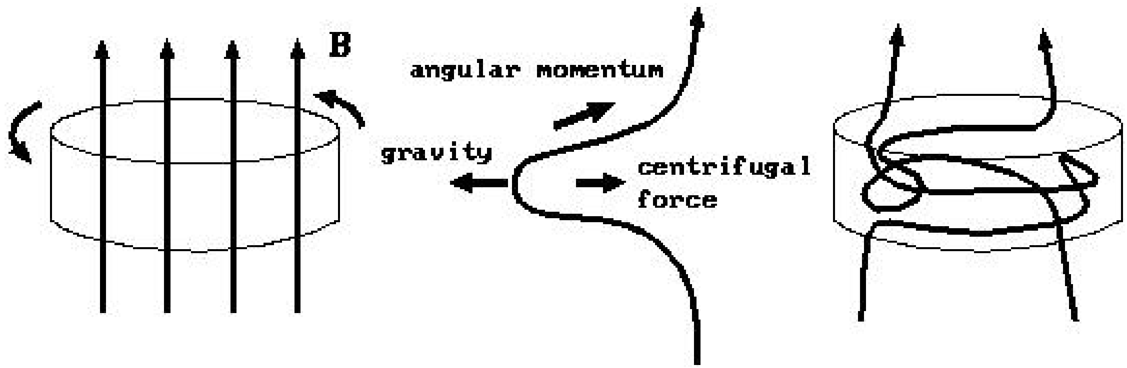
Rotating gas should lose angular momentum to accrete

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

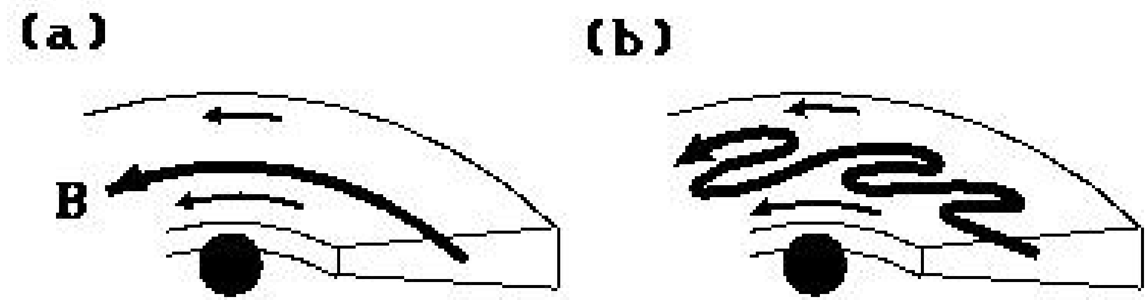
- Interval of dwarf nova outbursts indicate $\alpha = 0.01 - 0.1$
- In hydrodynamical disks $\alpha = O(0.001)$ too small !

Theoretical Breakthrough: Magnetorotational Instability





Plasma element perturbed inward loses angular momentum



MRI in differentially rotating disks (Balbus and Hawley 1991)

Global Three-dimensional Resistive MHD Simulations of Black Hole Accretion Flows

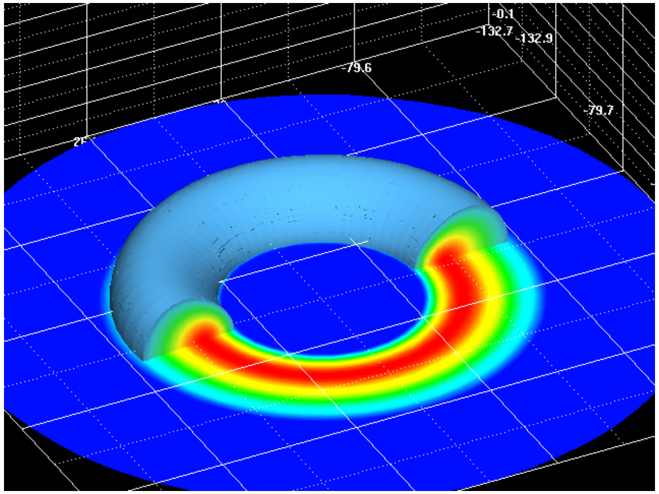
(Machida and Matsumoto 2003 ApJ)

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

Angular momentum : initially uniform

Magnetic Field : purely azimuthal

Pgas/Pmag = β = 100 at 50r_g

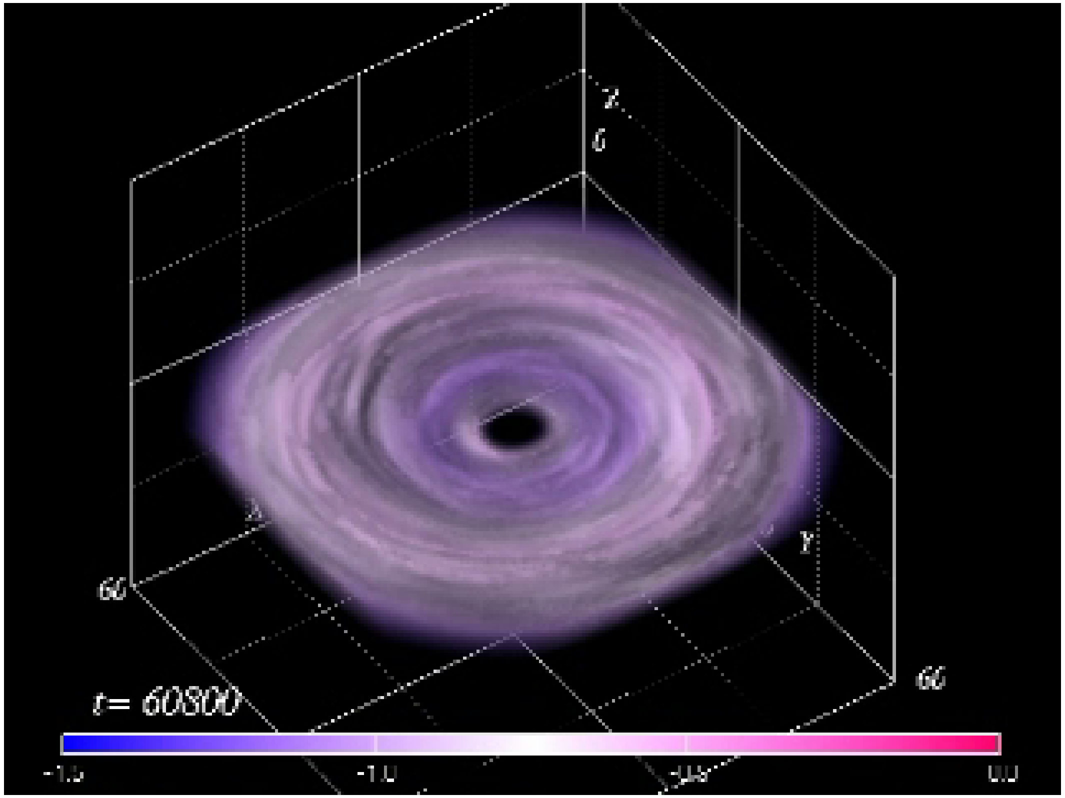


Anomalous Resistivity

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

250*64*192mesh

Formation of an Accretion Disk

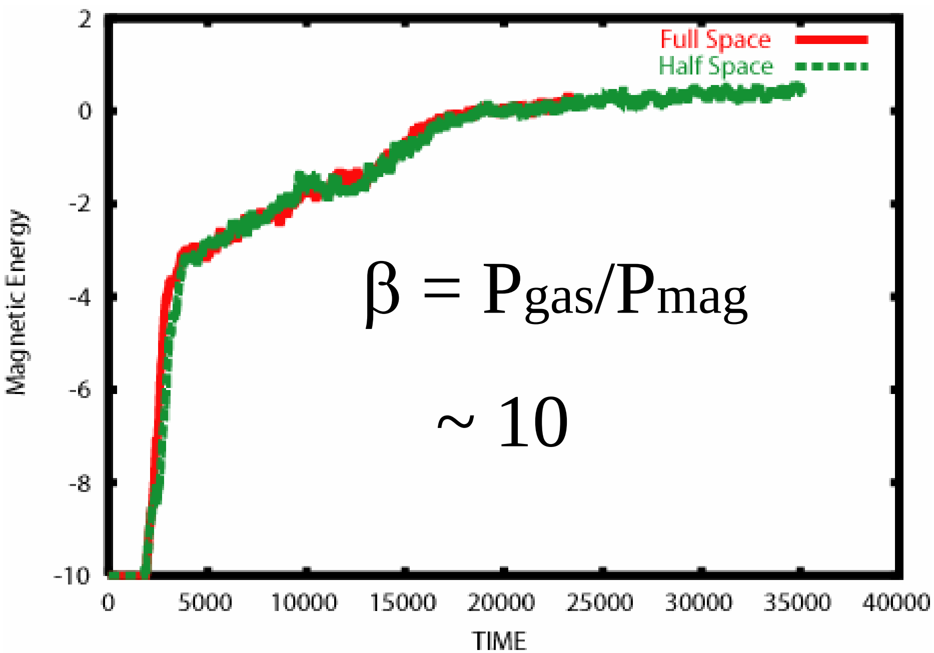


Machida (2005)

Volume rendered image of density distribution

Time Evolution of Magnetic Energy and Maxwell Stress

Magnetic Energy

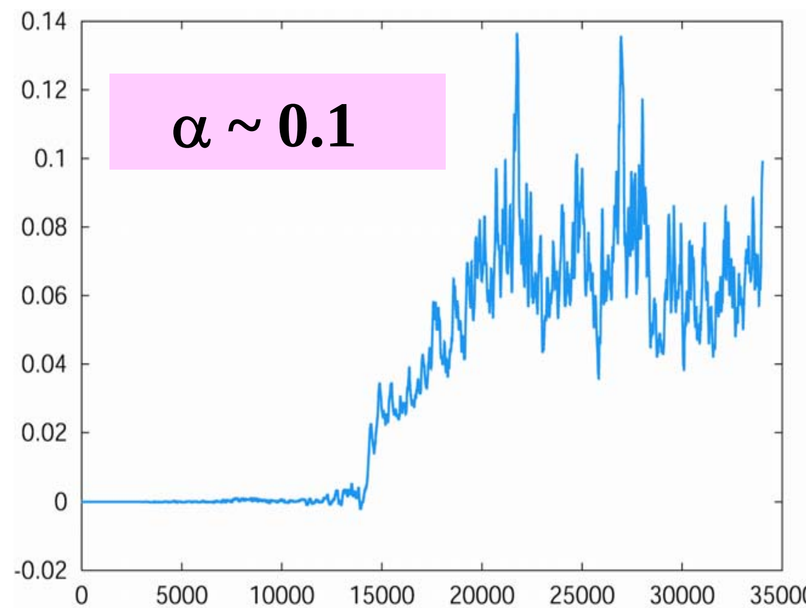


$\beta = P_{gas}/P_{mag}$

~ 10

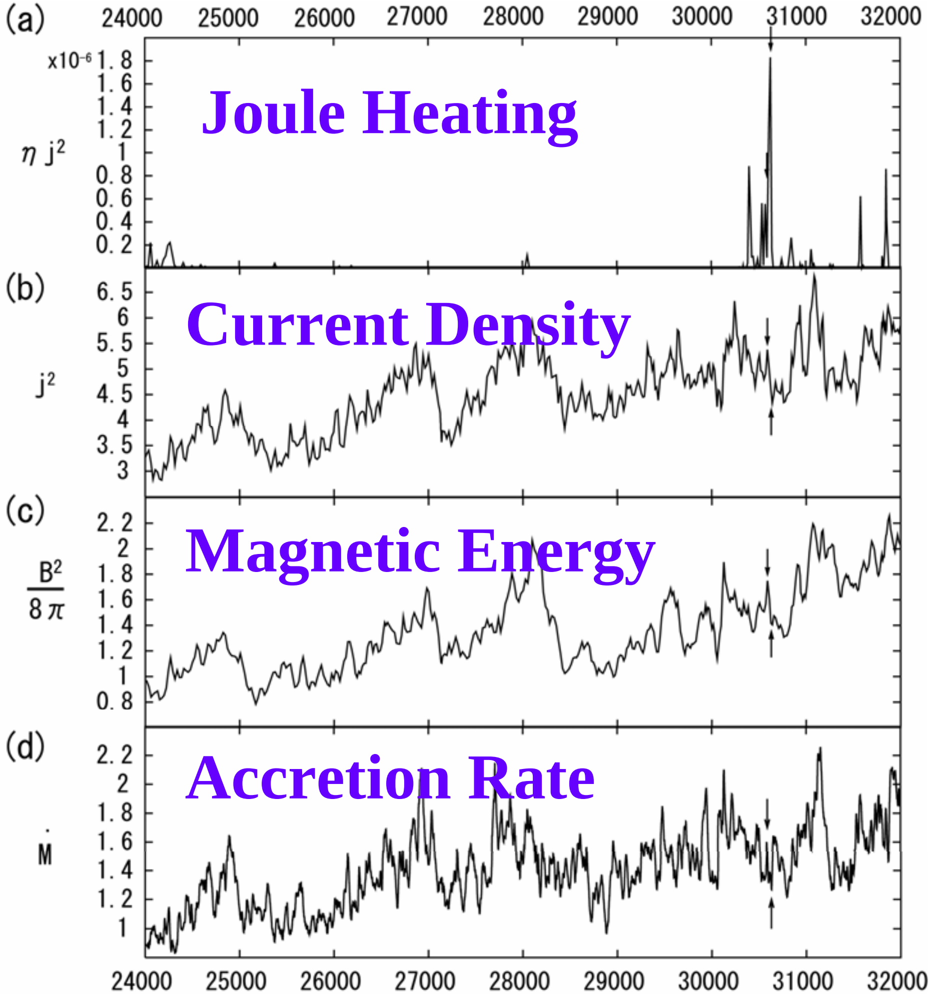
time

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

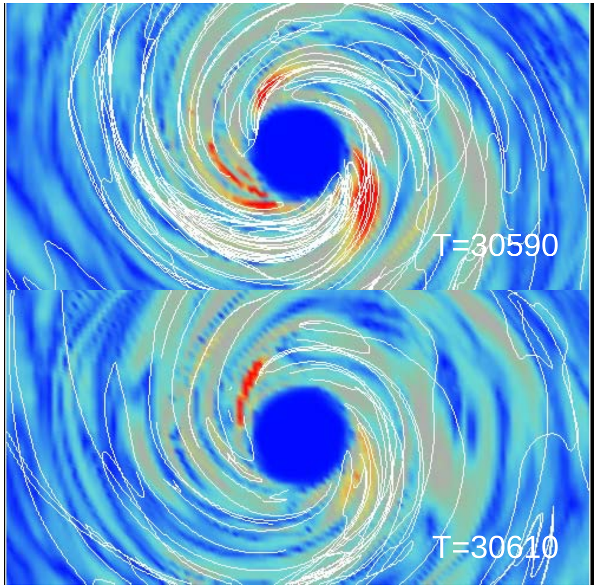


TIME

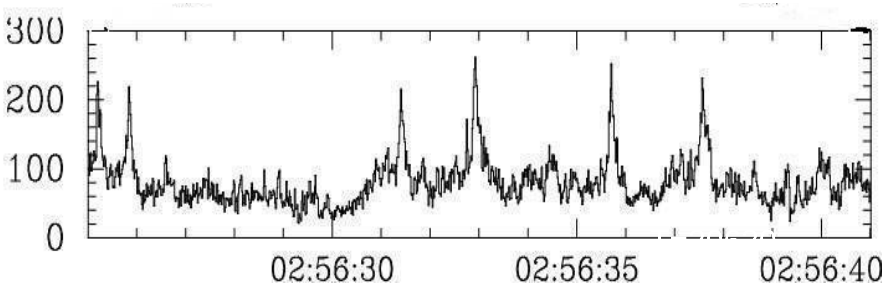
X-ray Shots in Black Hole Accretion Disks



time

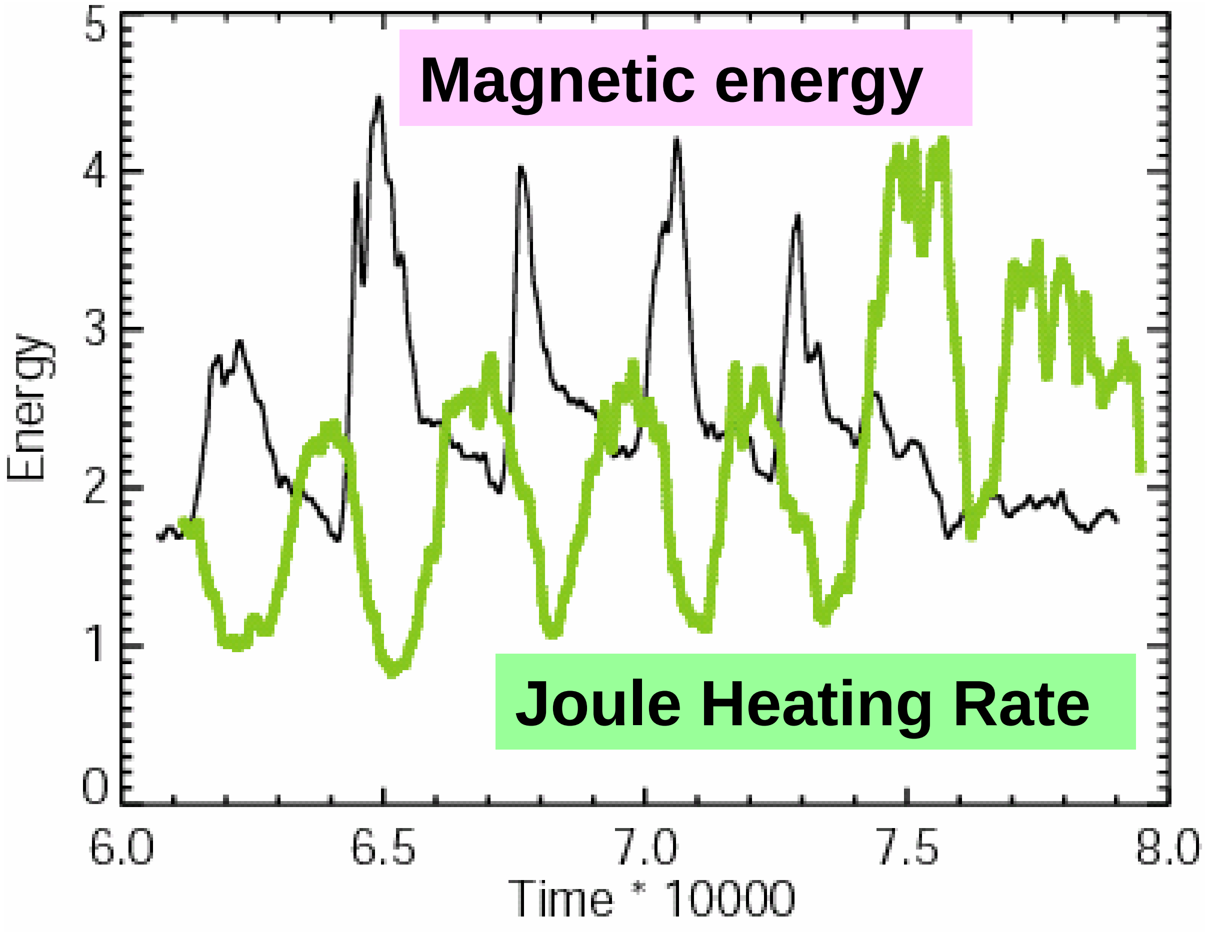


Current density(color)



Time variabilities of Cyg X-1
(Negoro 1995)

Sawtooth-like Oscillation

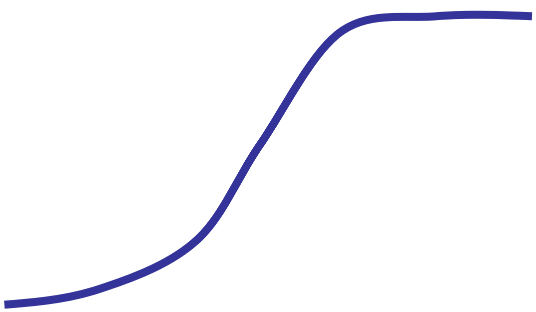


Sawtooth-like Oscillation in Nonlinear Systems

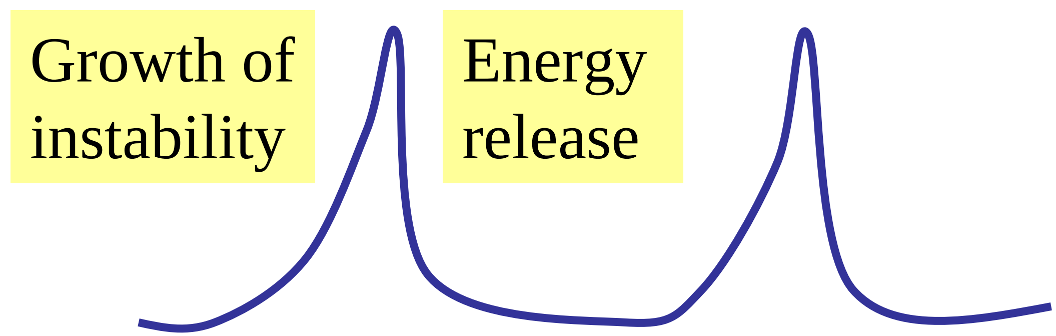
- Sawtooth oscillation takes place when instability and dissipation coexists

When dissipation is large

When dissipation is small

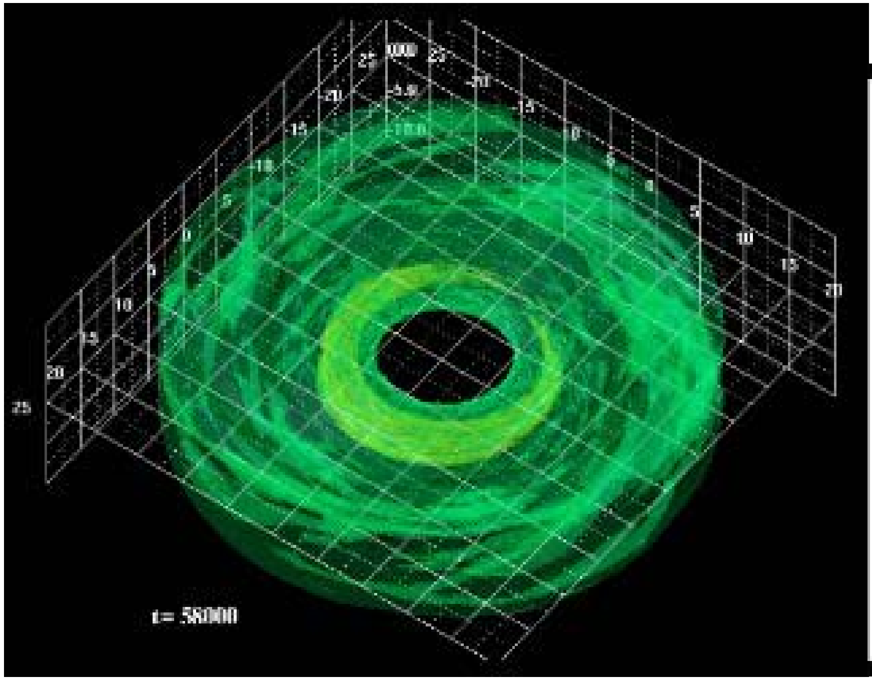


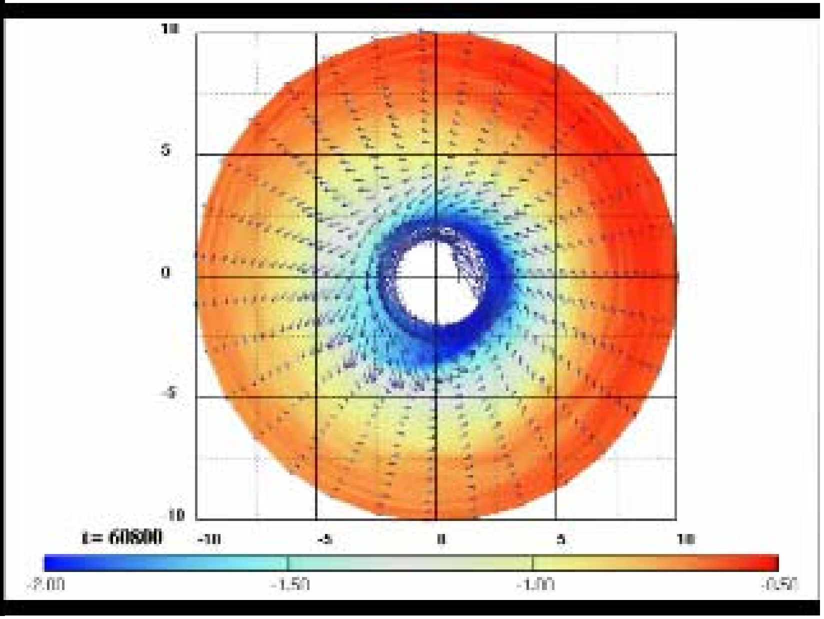
Approaches to a quasi-steady state



Sawtooth oscillation

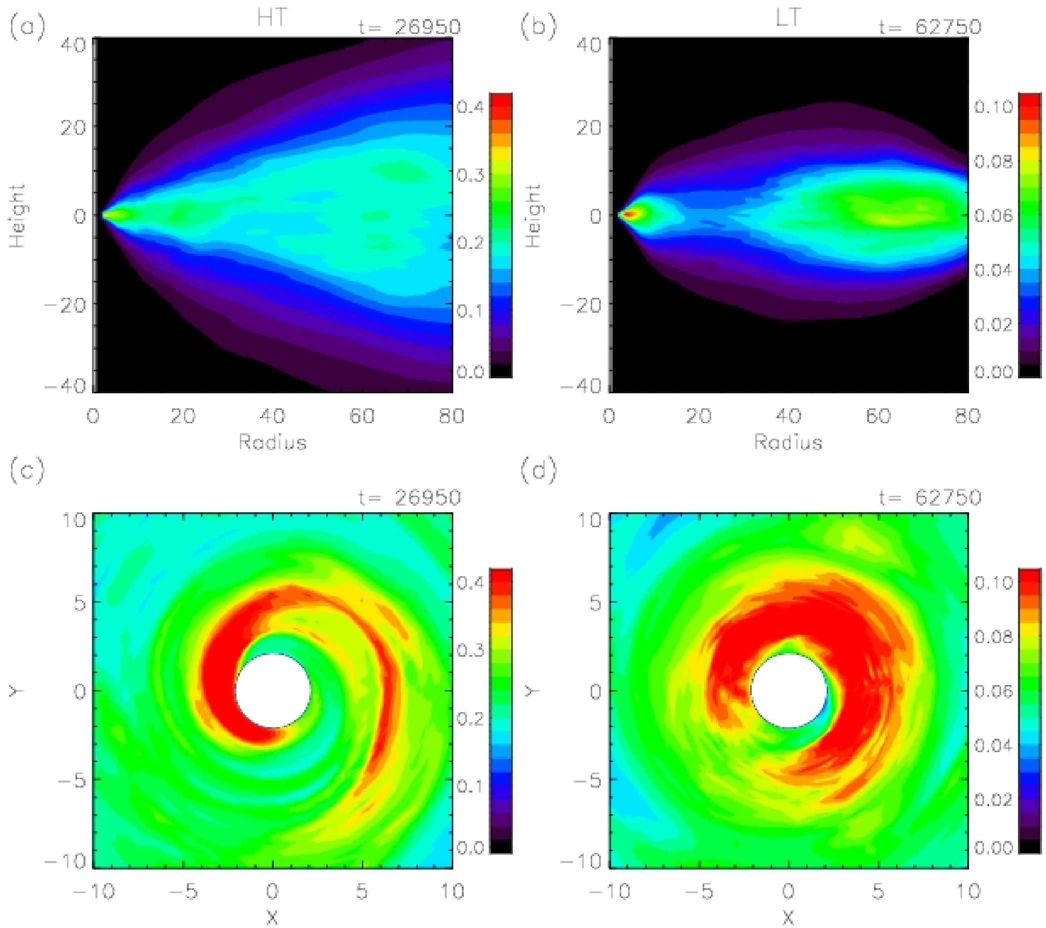
Growth and Disruption of m=1 Non-axisymmetric Mode





We found that during the amplification of magnetic energy, m=1 non-axisymmetric mode grows and deforms the disk to crescent shape.

Why Sawtooth-like Oscillations Appear in Low Temperature Disks ?



High temperature(HT) model

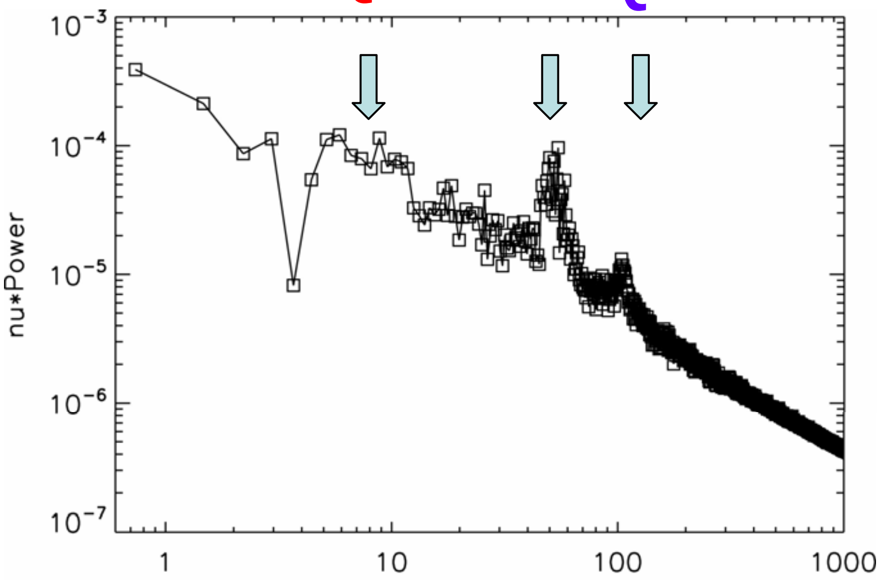
Low temperature (LT) model

Machida and Matsumoto 2007 submitted to PASJ

Formation ot the Inner Torus is Essential for sawtooth-like oscillations

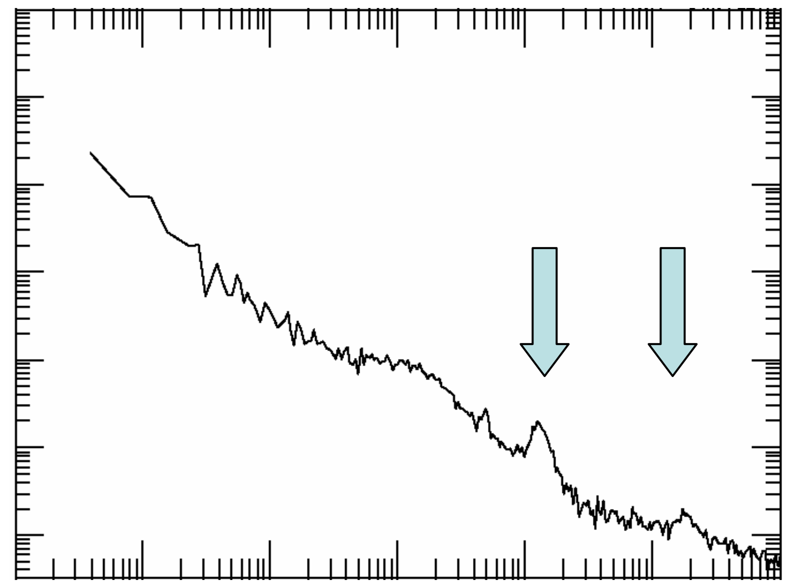
High Frequency Oscillations are Excited during Sawtooth-like Oscillation

LFQPO HFQPO



1Hz 10Hz 100Hz

Power spectrum of luminosity variation

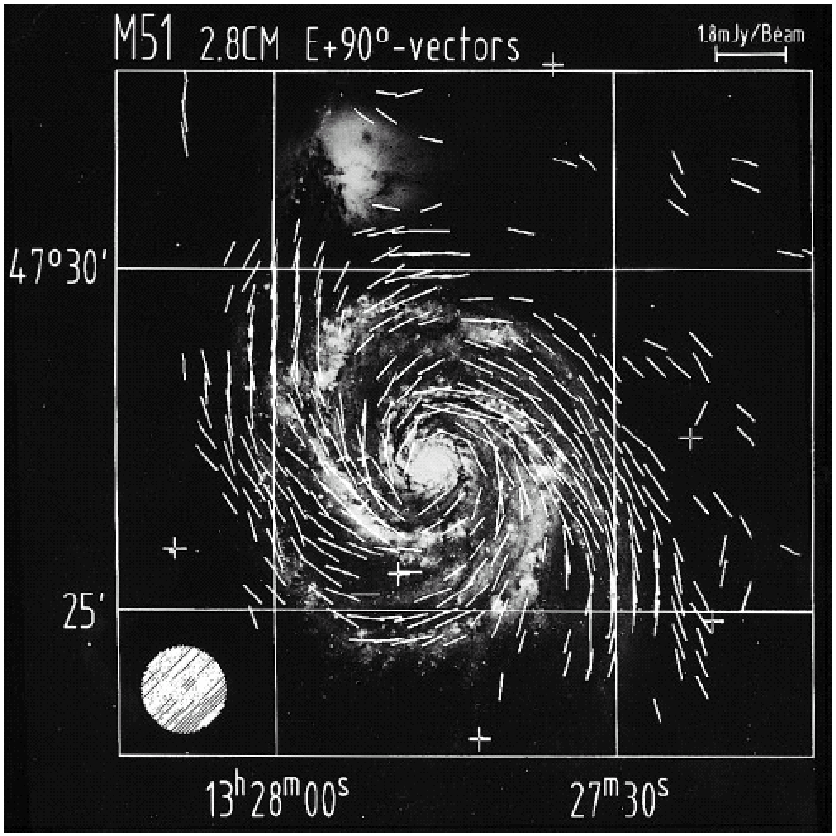


0.01 0.1 1 10 100 Hz

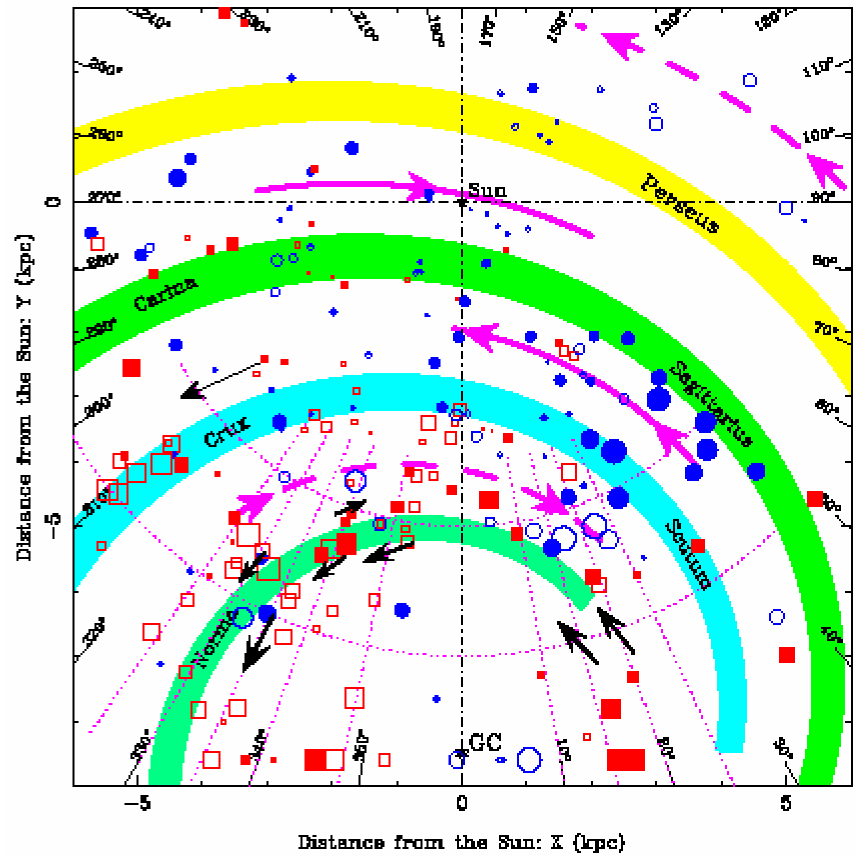
XTE J1550-564

McClintock and Remillard 2004

Magnetic Fields in Spiral Galaxies

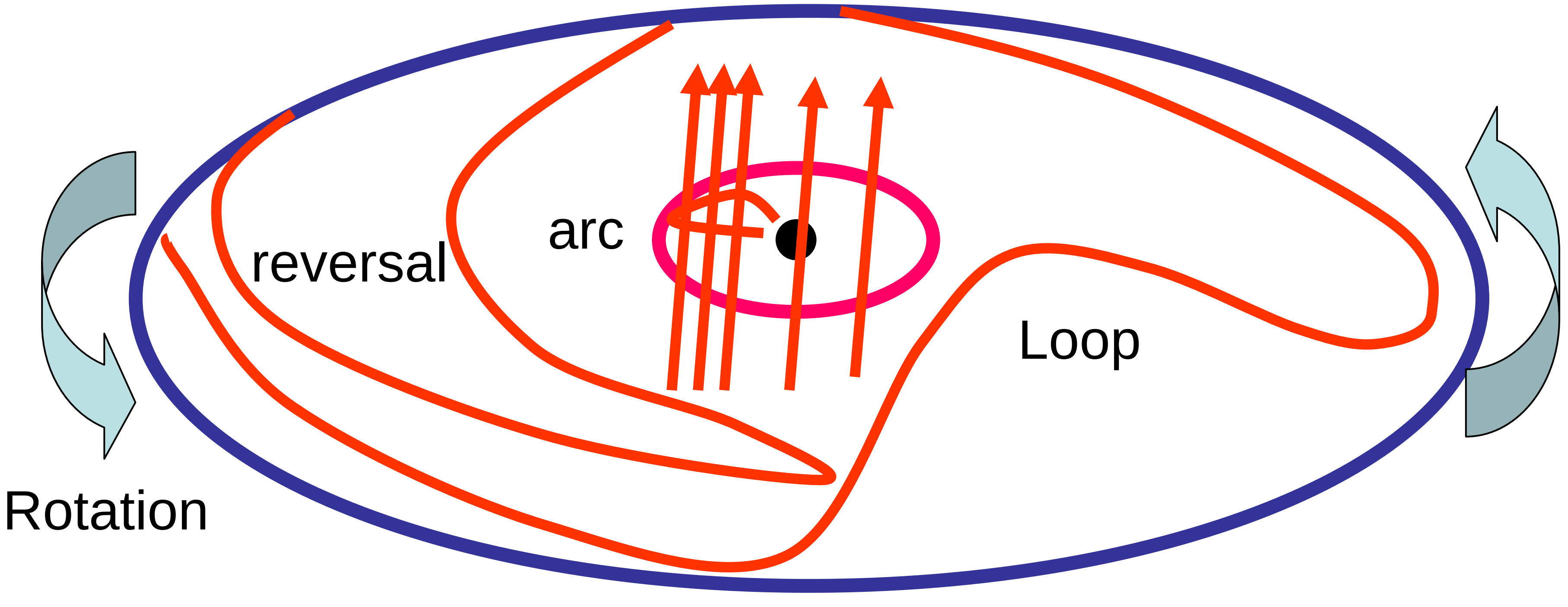


M51 (Berkhuijsen et al. 1997)



Our Galaxy (Han et al. 2002)

How Galactic Magnetic Fields are Amplified and Maintained ?



Magnetic Fields of Galactic Disk

Simulation Model for a Galaxy
≫Nishikori et al. 2006, ApJ 641,862)

- Axisymmetric Gravitational Potential

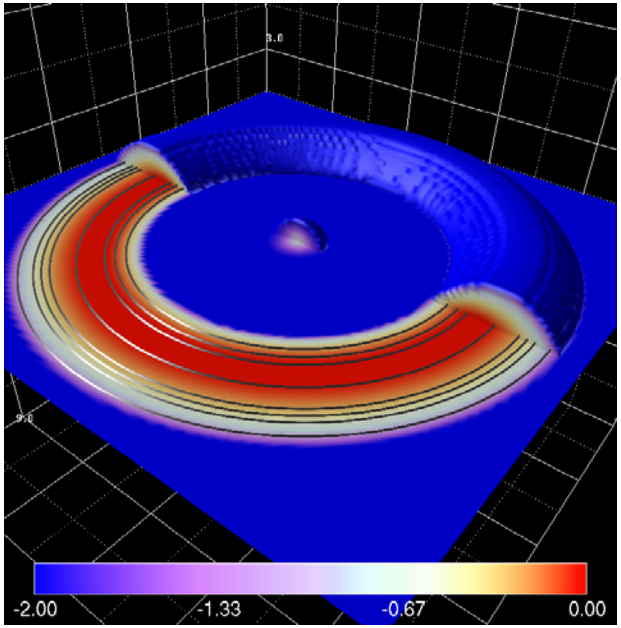
$$\phi(\varpi, z) = \sum_{i=1}^{3} \frac{GM_i}{[\varpi^2 + \{a_i + (z^2 + b_i^2)^{0.5}\}^2]^{0.5}},$$

Miyamoto et al. (1980)

- Cylindrical Coordinate System
- Simulation Region

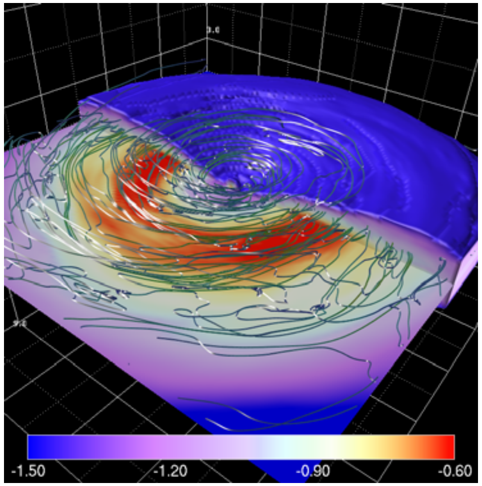
$$0 < \varpi < 56\text{kpc},\ 0 < z < 10\text{kpc}$$

- Absorbing boundary at r=0.8kpc
- Initally Weak Azimuthal Field
  - β = Pgas/Pmag = 100 –10000
- Mesh points : 250 x 64 x 319

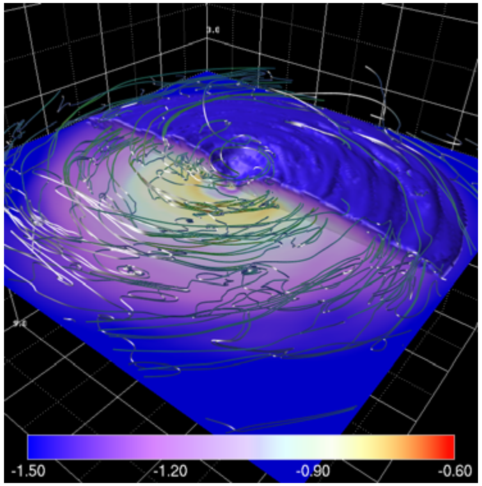


Numerical Results (β =100)

2Gyr



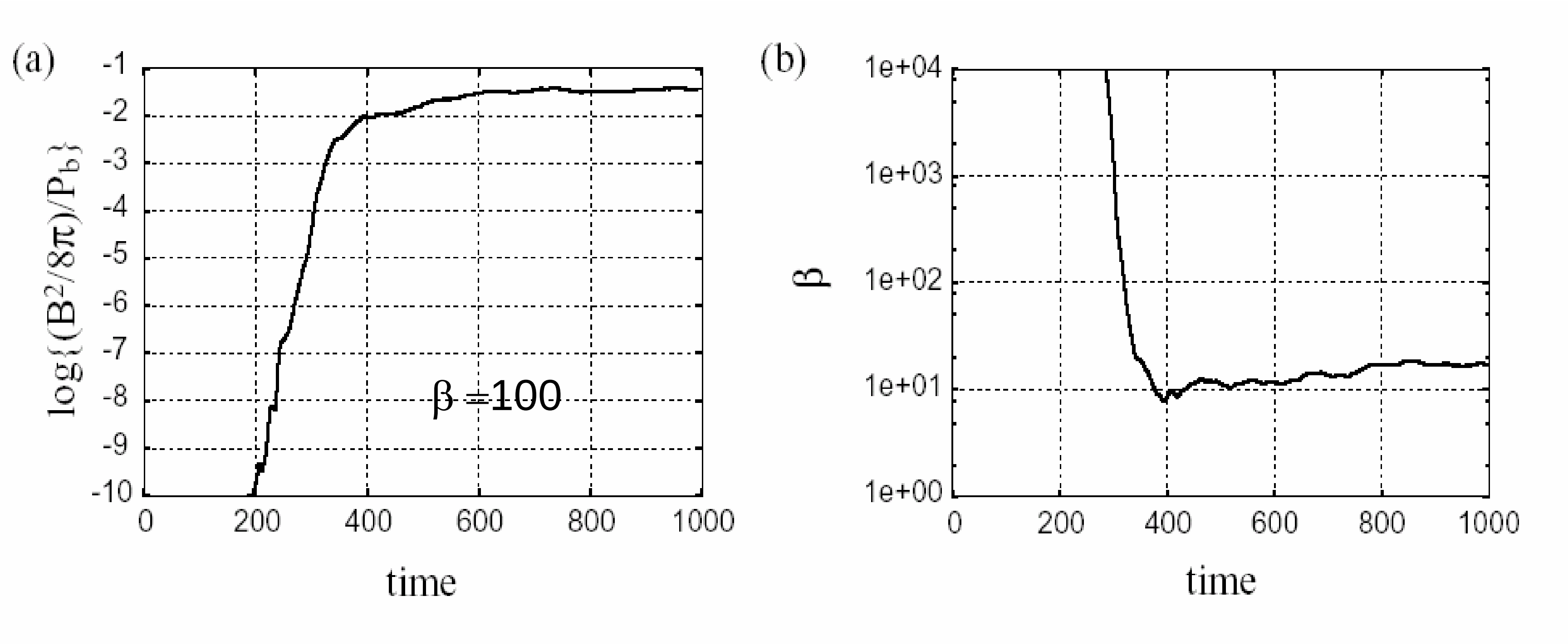
3.5Gyr



$\rho + \mathbf{B}$

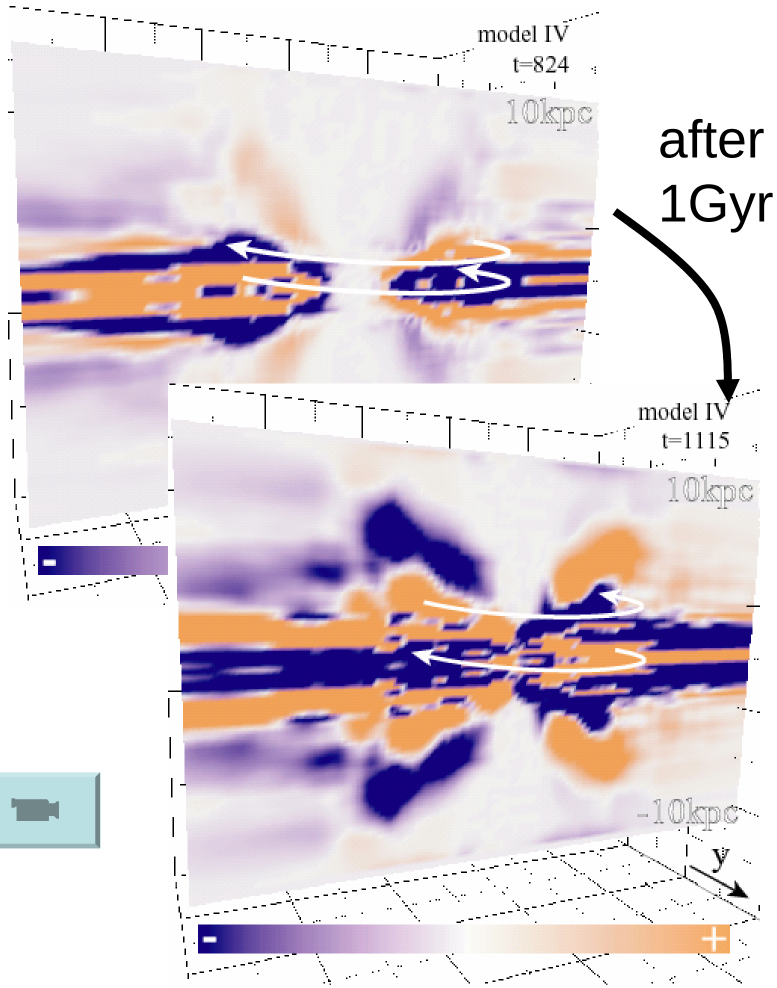
t = 3.8Gyr

Amplification and Saturation of Magnetic Fields

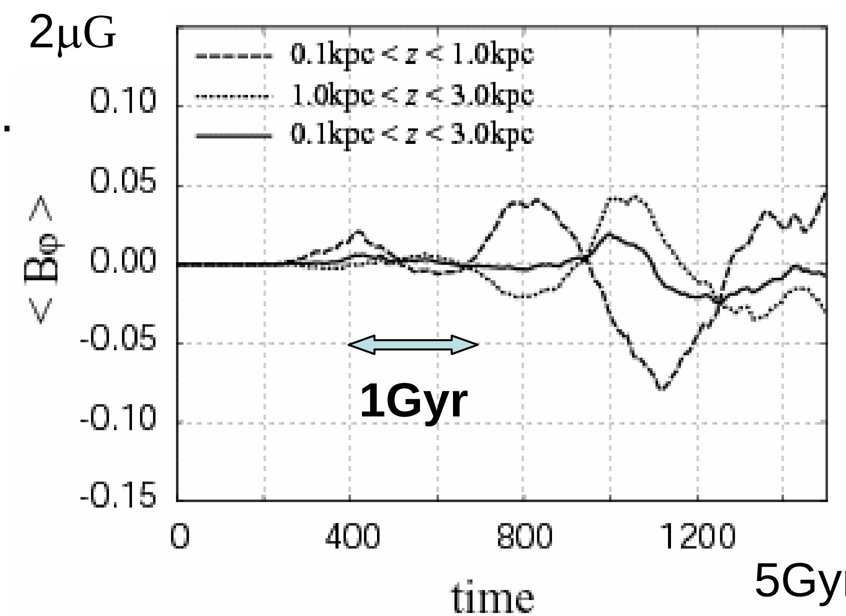


Average in 2kpc < r < 5kpc and 0 < z < 1kpc

Spacial and Temporal Reversal of Magnetic Fields (β =1000)



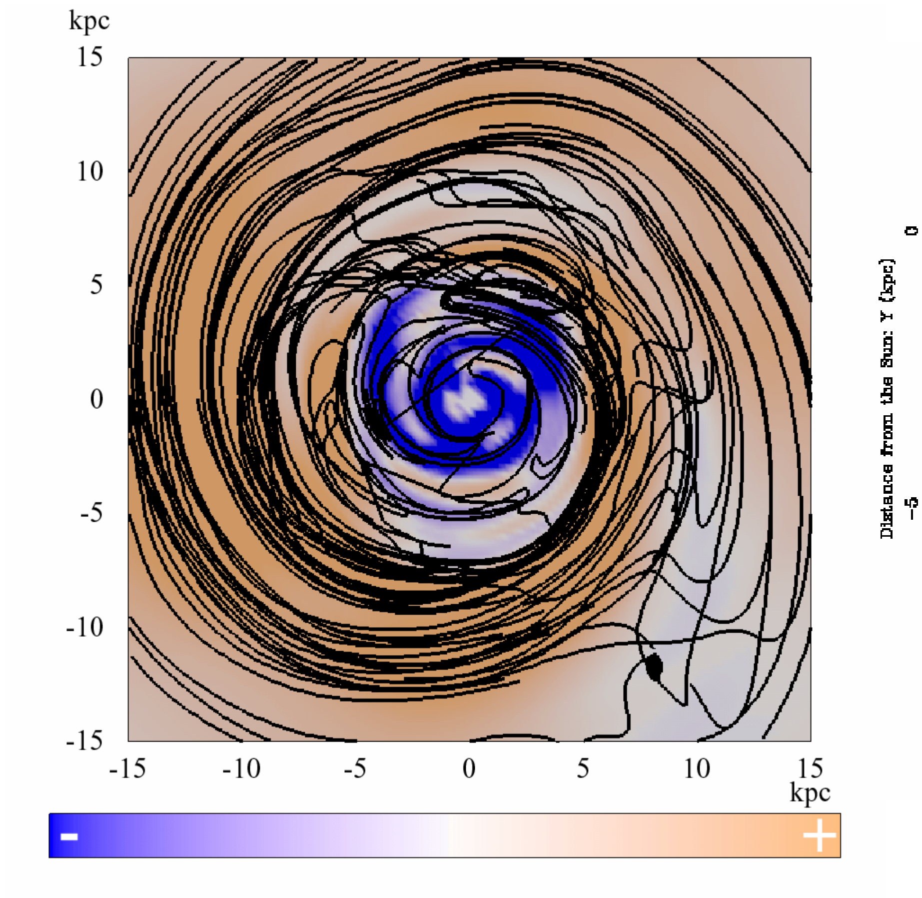
after 1Gyr…



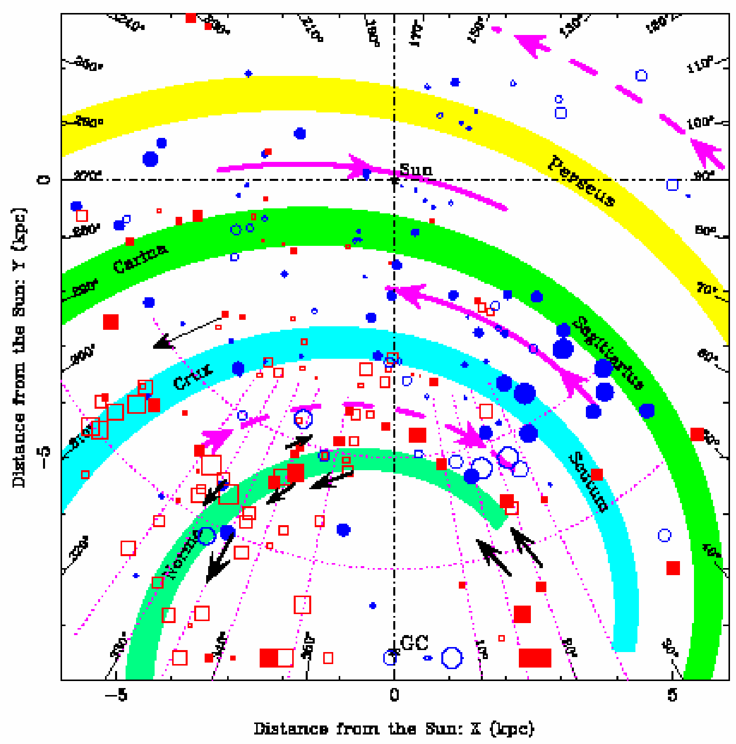
Time variation of mean azimuthal magnetic field

At 5kpc < r < 6kpc

Radial Reversal of Mean Magnetic Fields



Azimuthal field at t=3.8Gyr at z=0.25Kpc



Galactic magnetic field obtained by Rotation Measure

(Han et al. 2002)

Summary

- We carried out global 3D MHD simulations of differentially rotating astrophysical plasmas such as accretion disks and Galactic gas disks
- In cool gas is supplied, sawtooth-like oscillation is excited by the magnetic field amplification due to MRI and magnetic energy release due to magnetic reconnection
- In Galactic disks, mean magnetic fields are amplified up to 1-2 micro Gauss
- Azimuthal magnetic fields reverse their direction both in space and in time. The period of field reversal is about 1Gyr in our Galaxy.