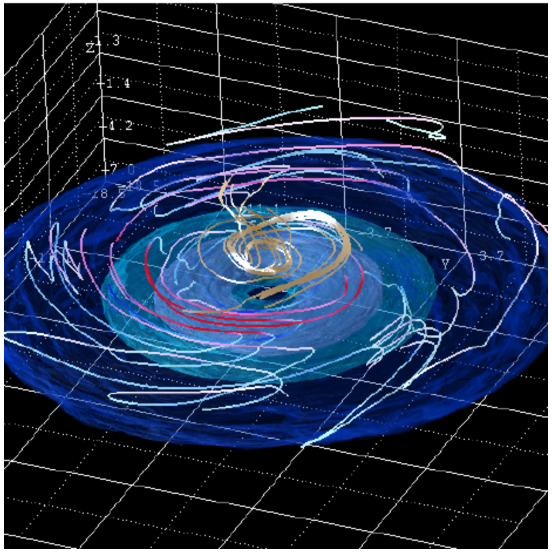
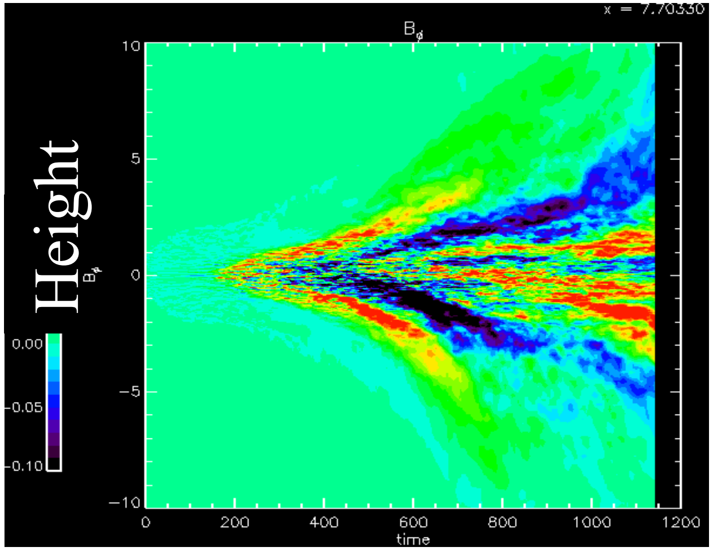
US-Japan Workshop on Magnetic Reconnection MR2012@Princeton

Three-dimensional Magnetohydrodynamic Simulations of Disk Dynamos

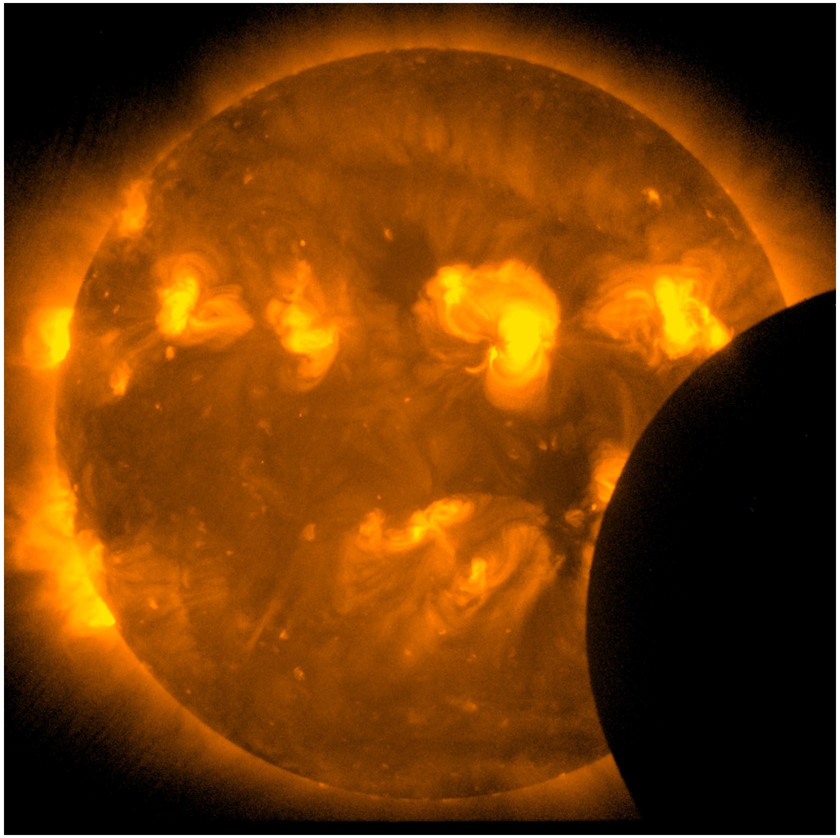




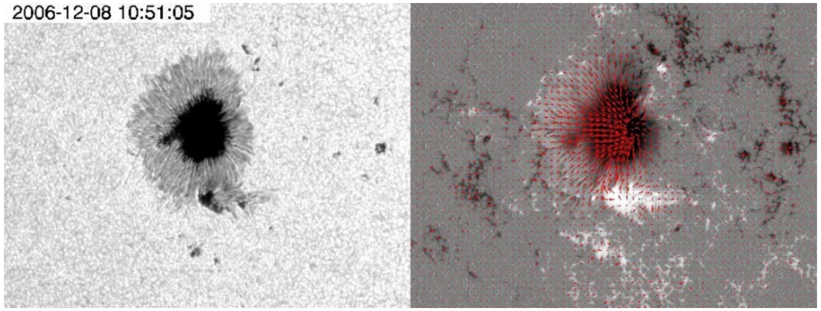
Ryoji Matsumoto (Chiba Univ.) and

Mami Machida (Kyushu University)

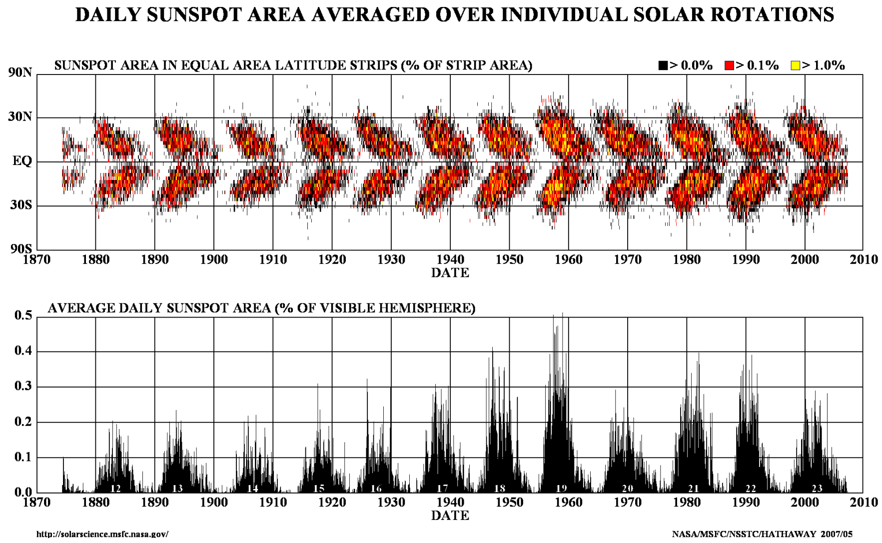
Solar Dynamo Cycle



X-ray Image by HINODE Satellite (May 20, 2012)

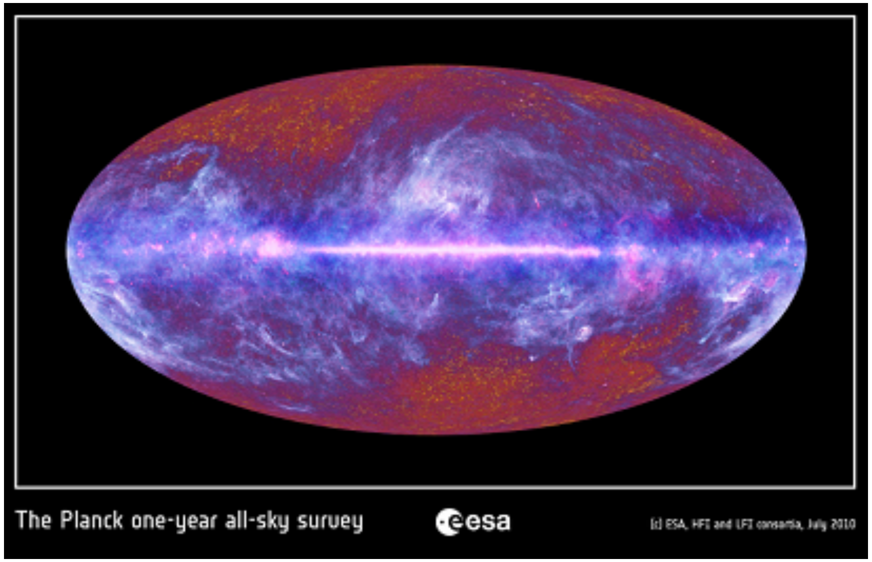


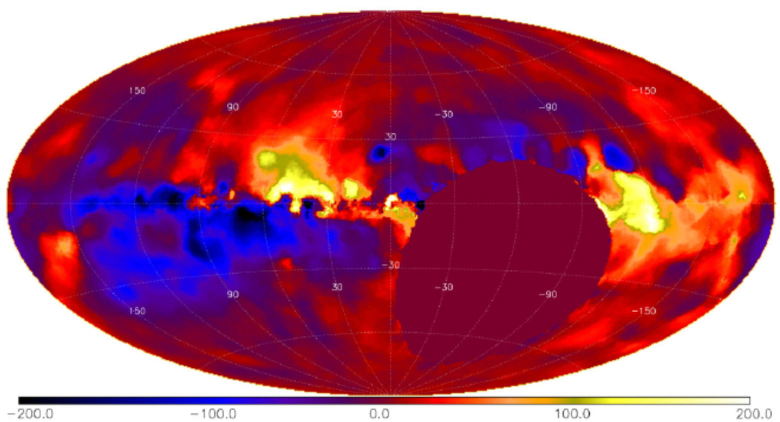
Optical image of sunspots by HINODE



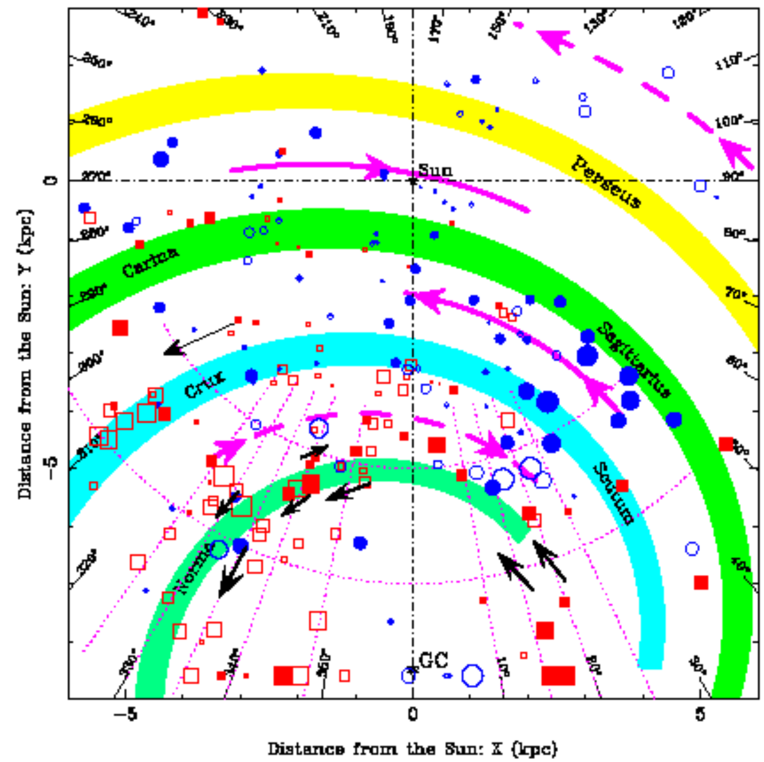
Butterfly Diagram of Sunspots (NASA)

Magnetic Fields in Our Galaxy



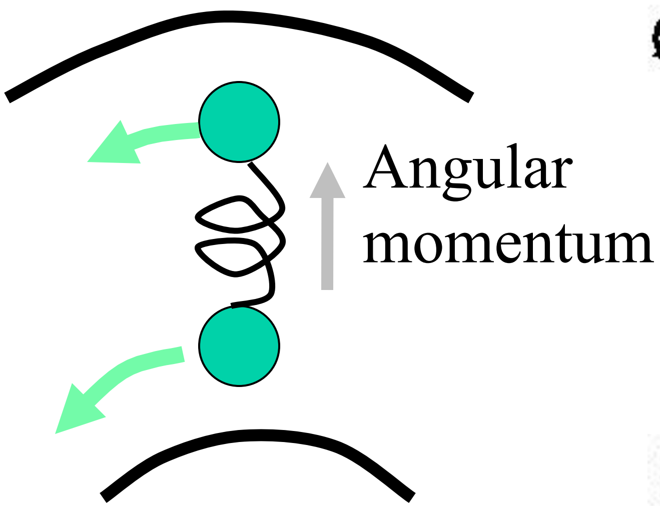


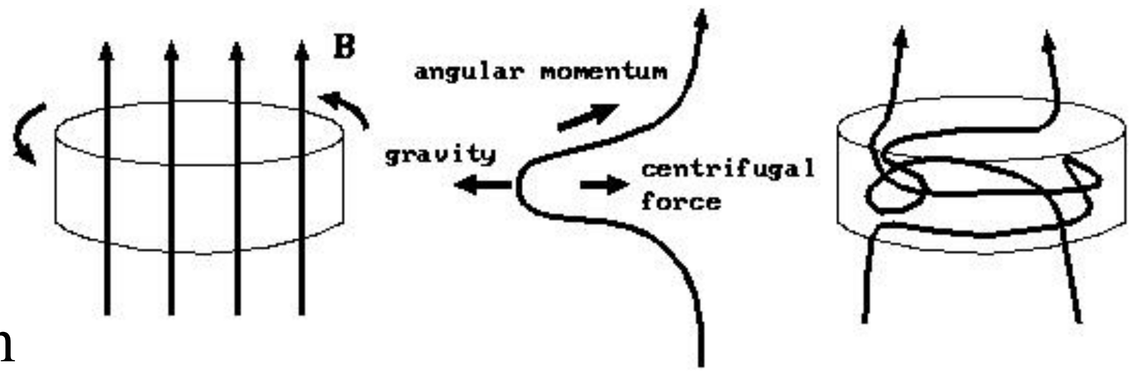
Rotation Measure (Taylor et al. 2009)



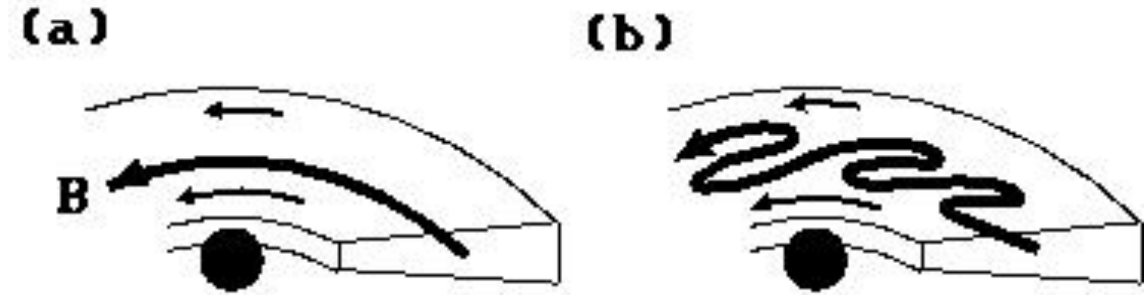
Galactic magnetic field measured by Faraday Rotation (Han et al. 2002)

Amplification of Magnetic Fields by Magneto-rotational Instability (MRI)





Balbus and Hawley (1991), Velikhov (1959)

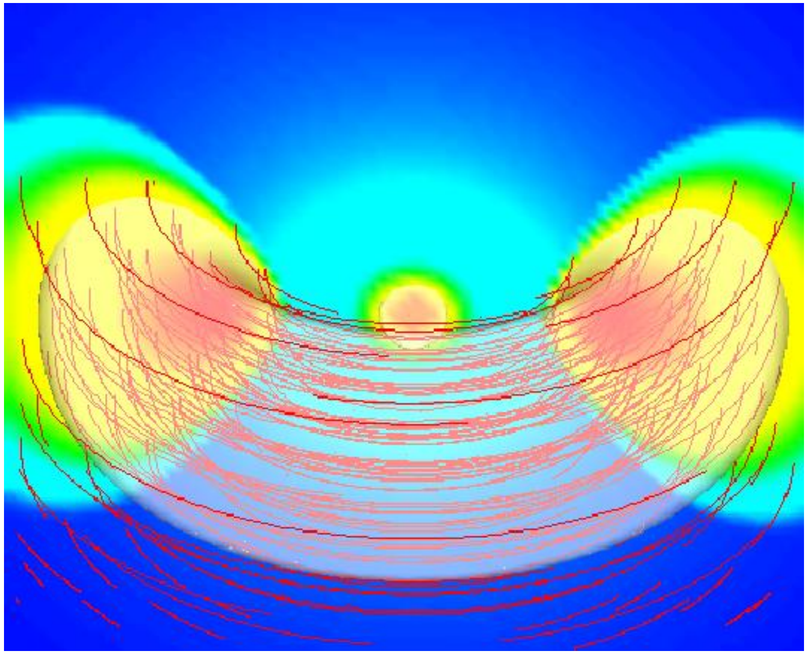


Can We understand Disk Dynamos by MRI ?

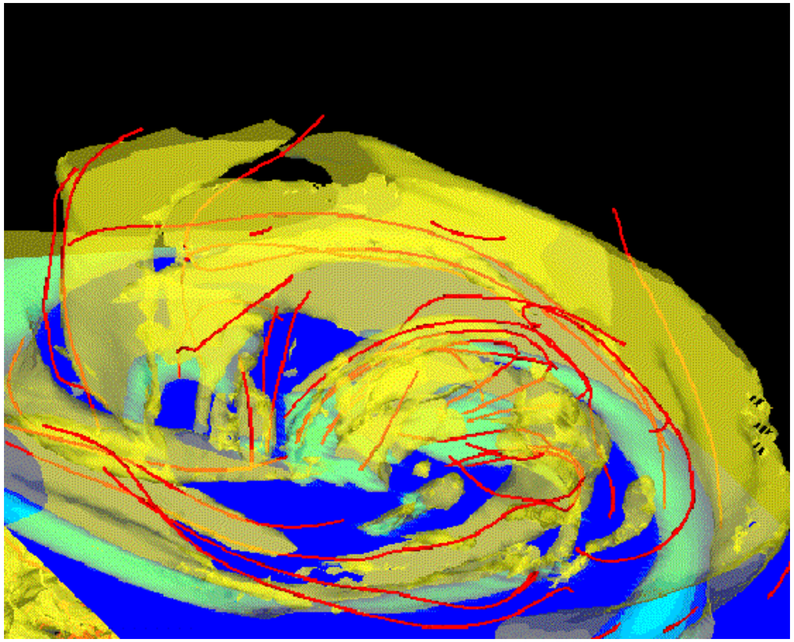
- MRI: $B\varphi \rightarrow Br$: α-effect $Br \rightarrow B\varphi$: ω-effect
- No flux amplification by MRI !

  $\langle B^2 \rangle$ increases but $\langle B\varphi \rangle$ is conserved
- No field reversal (no dynamo cycle)
- We should include vertical gravity to take into account the effects of magnetic buoyancy, which is essential in solar dynamo

Buoyant Rise of Magnetic Loops



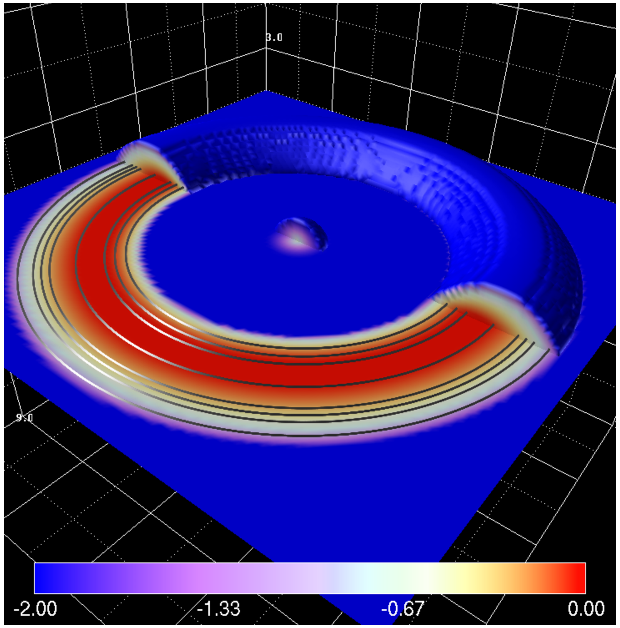
Initial condition



Machida et al. 2000

Global 3D MHD Simulation of Galactic Gas Disks

- Gravitational Potential
  - Axisymmetric potential by Miyamoto (1980)
- Initial Condition
  - Constant angular momentum torus
  - Weak Azimuthal field
- Absorbing boundary condition at r=0.8kpc

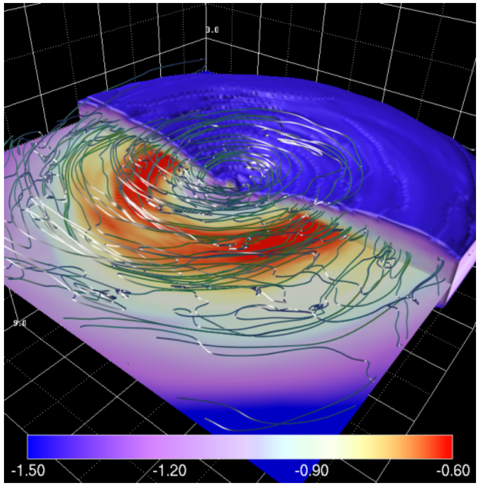


250*64*319 mesh

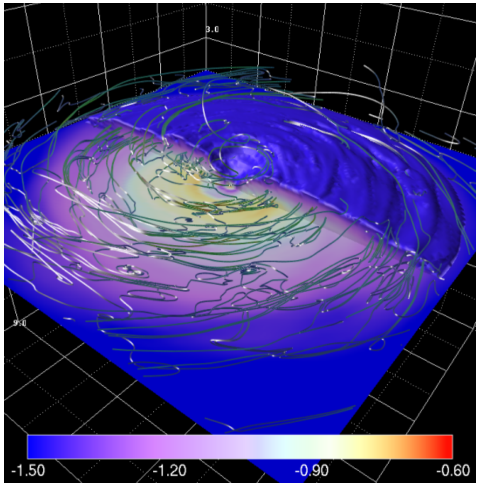
Nishikori et al. 2006

Result of Simulation

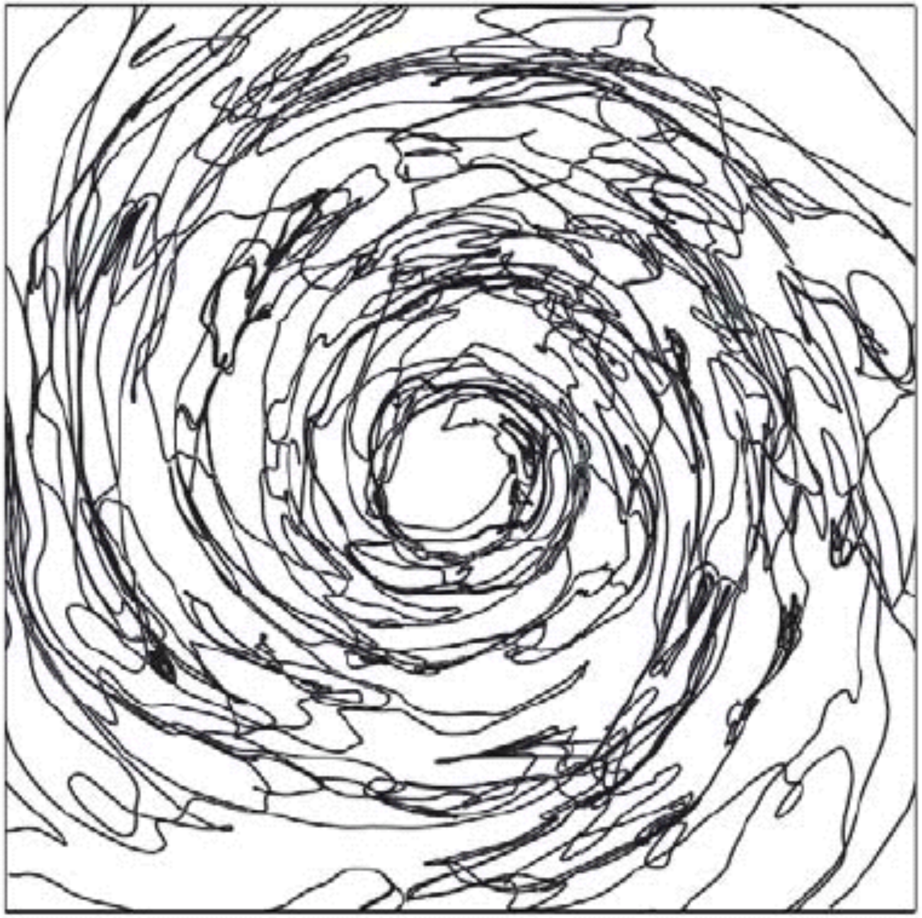
2Gyr



3.5Gyr

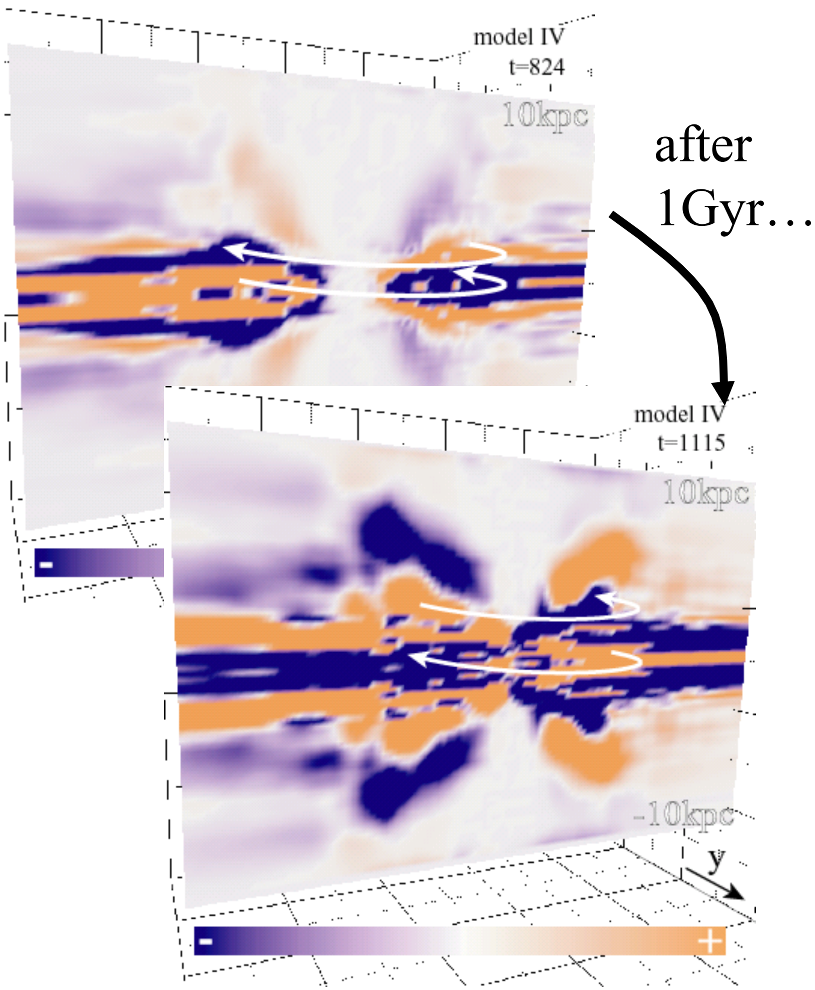


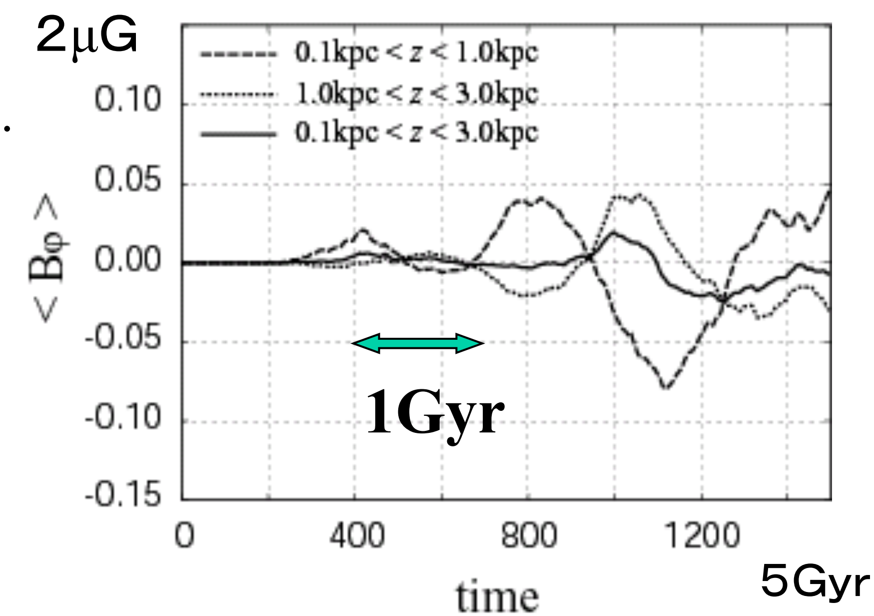
ρ+ B



t = 3.8Gyr

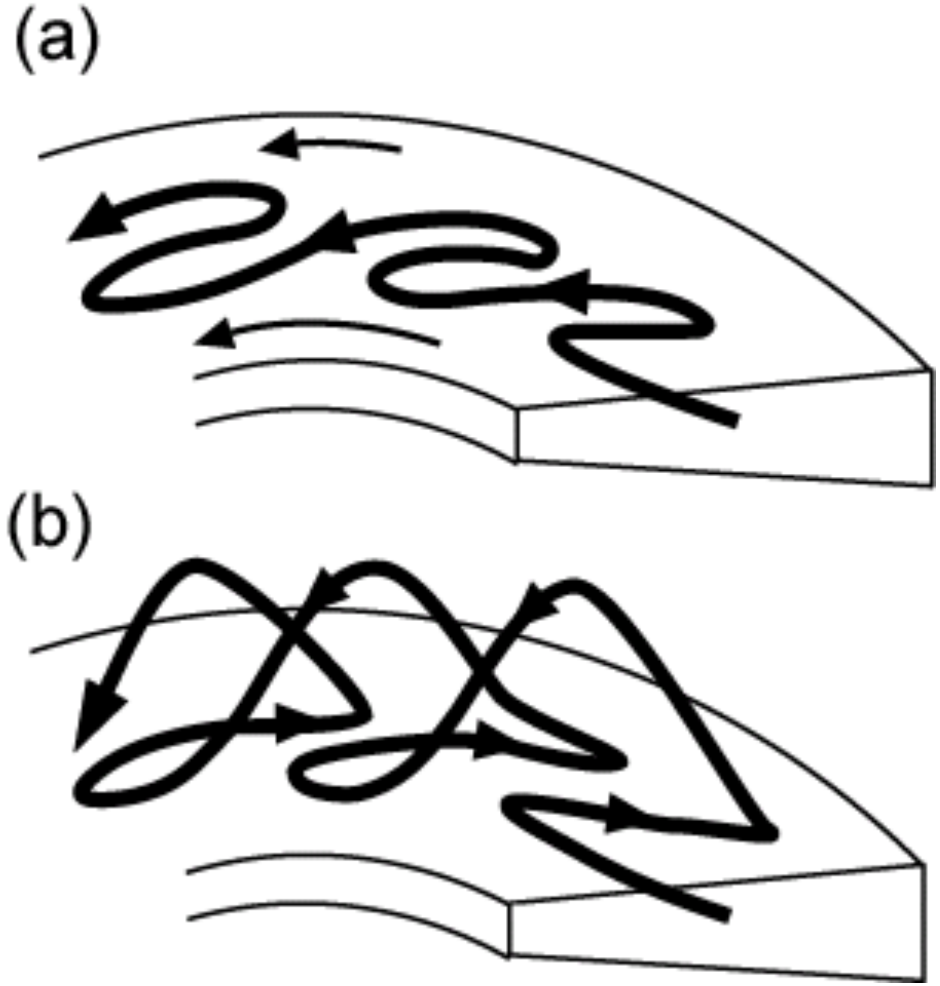
Reversal of Mean Azimuthal Magnetic Fields

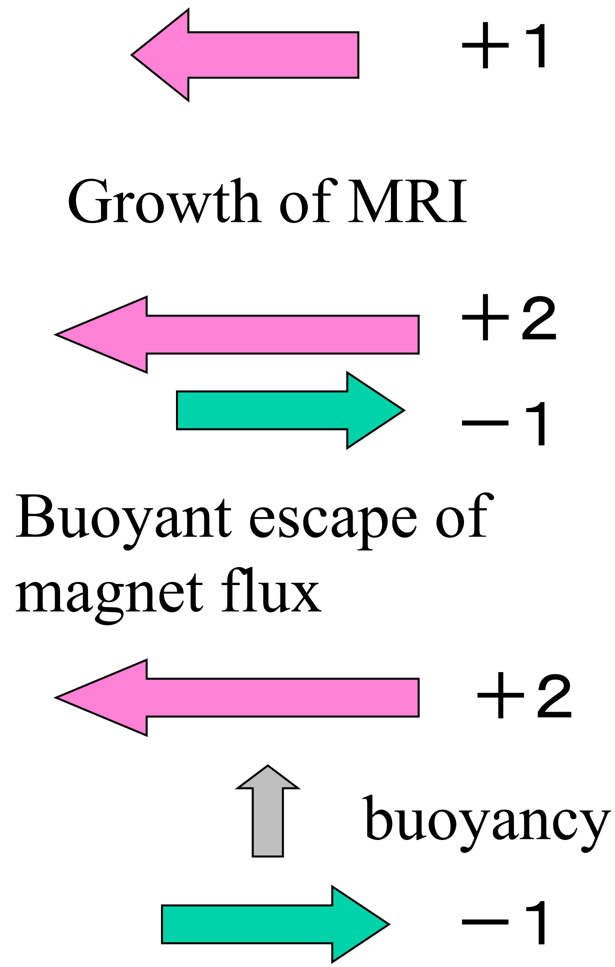




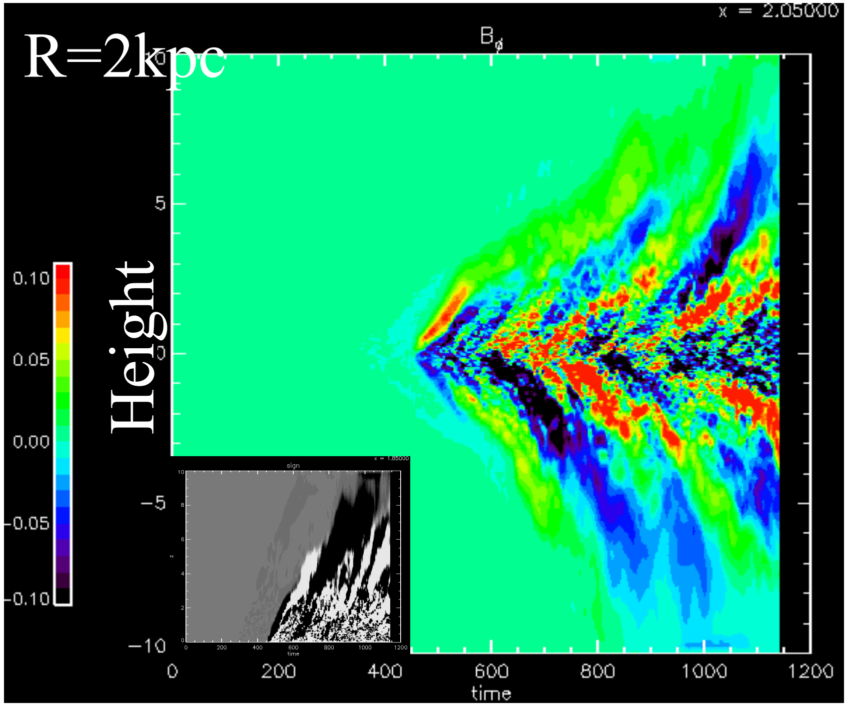
Time variation of mean azimuthal magnetic field at 5kpc < r < 6kpc

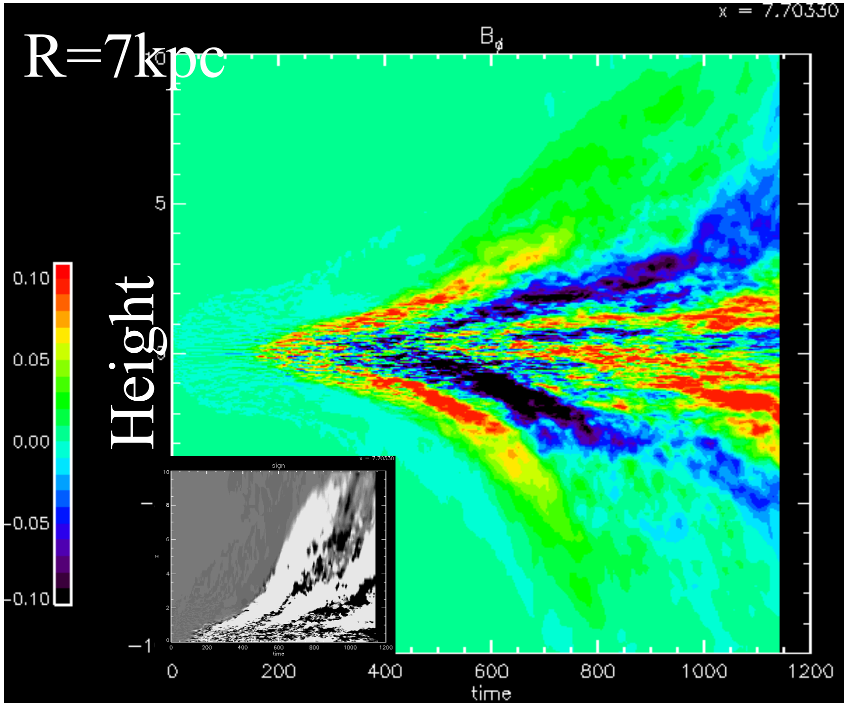
How are Azimuthal Magnetic Fields Reversed ?





Butterfly Diagram



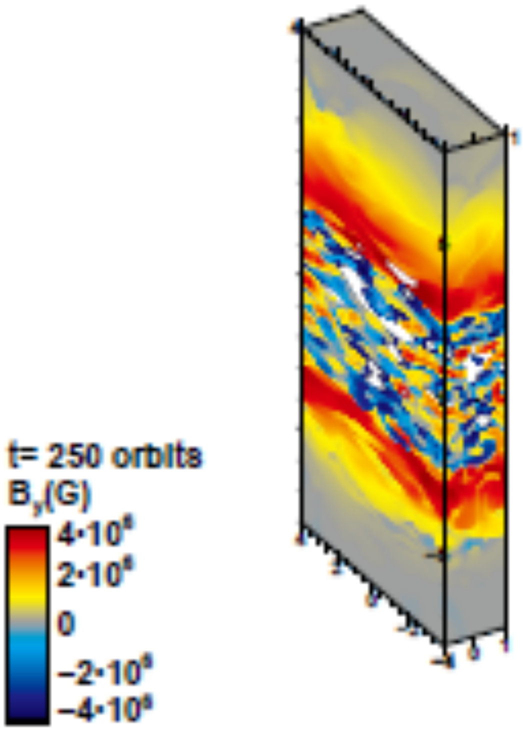


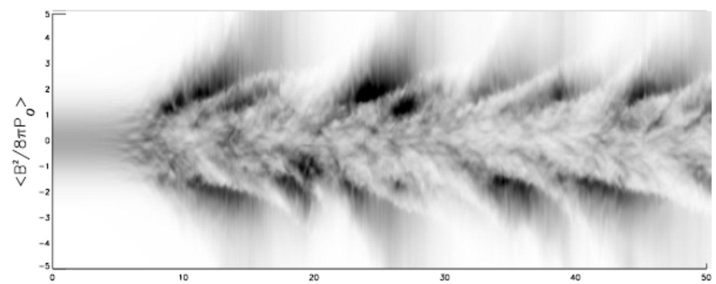
time time

Azimuthal Magnetic fields

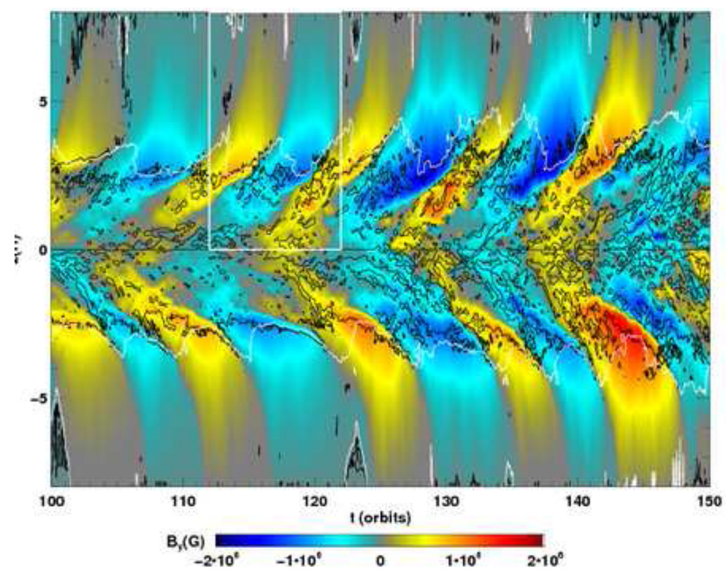
Machida et al. 2012

Dynamo Cycle obtained by Local 3D MHD Simulations





Miller and Stone 2000

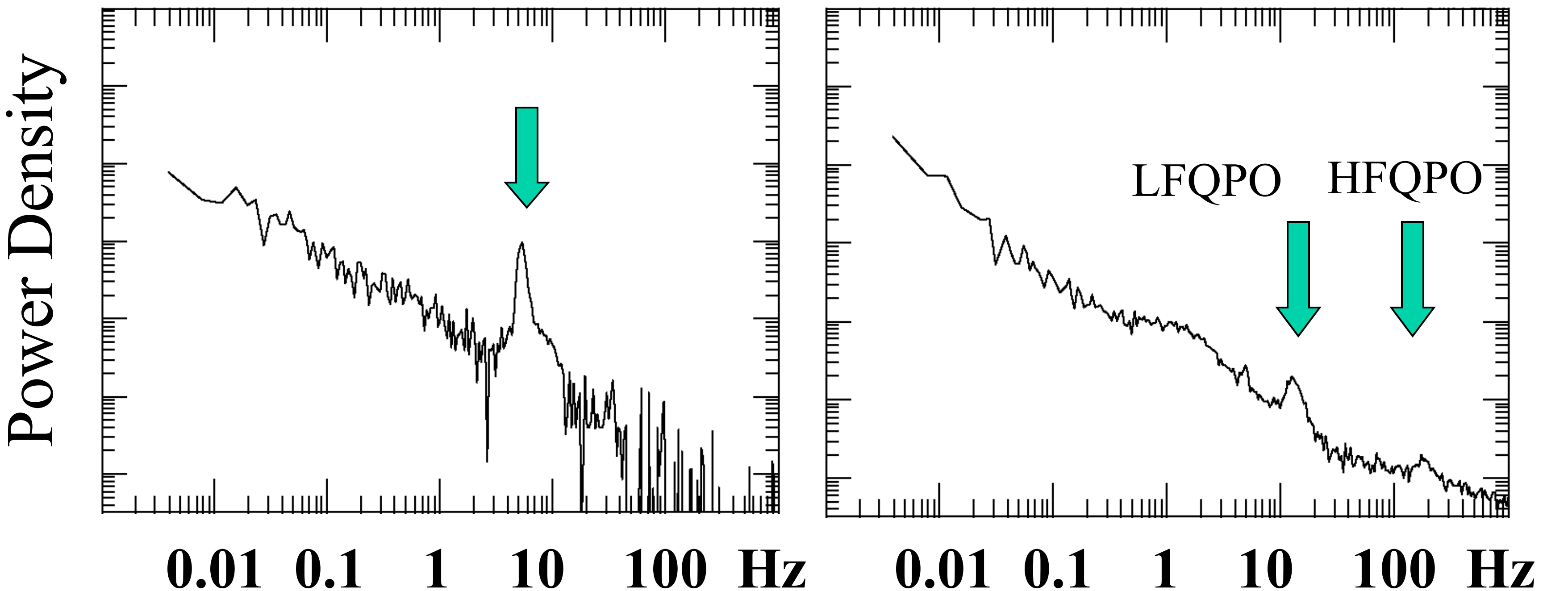


white : β = 1

Shi et al. 2010

Time Variabilities of Azimuthal Field

Quasi-Periodic Oscillations (QPOs) Observed in Black Hole Candidates

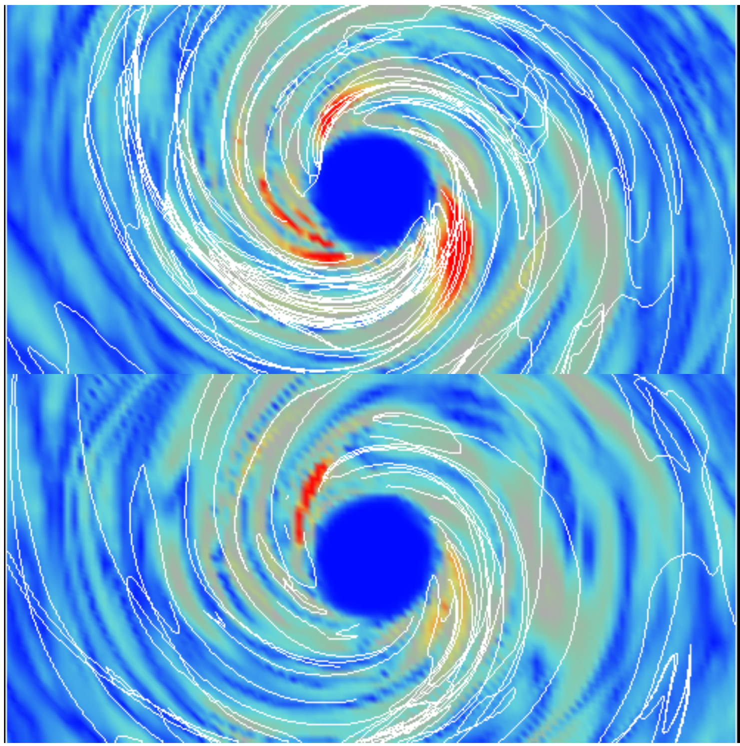


GX 339-4

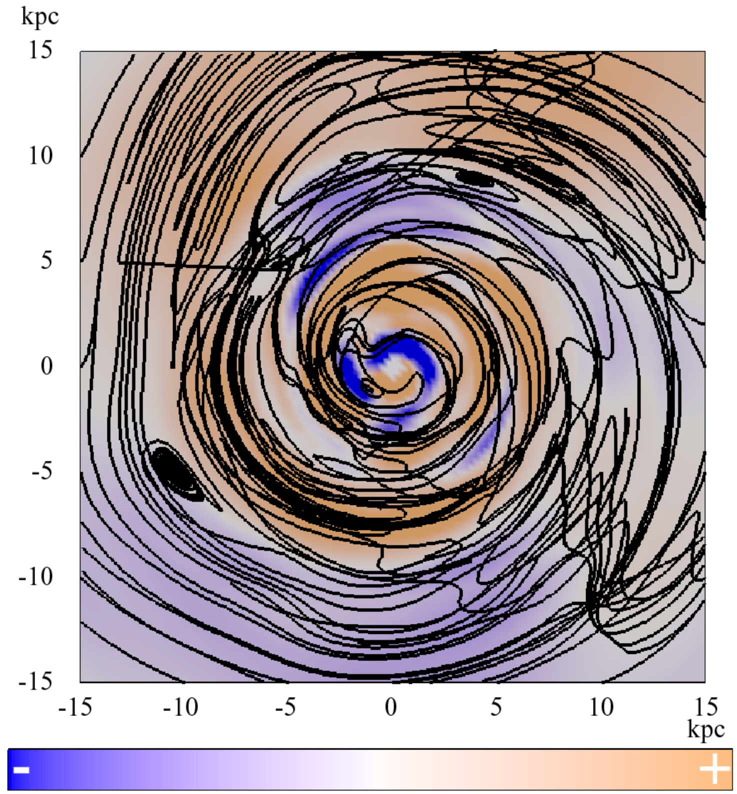
XTE J1550-564

McClintock and Remillard 2004

Magnetic Reconnection in Disks

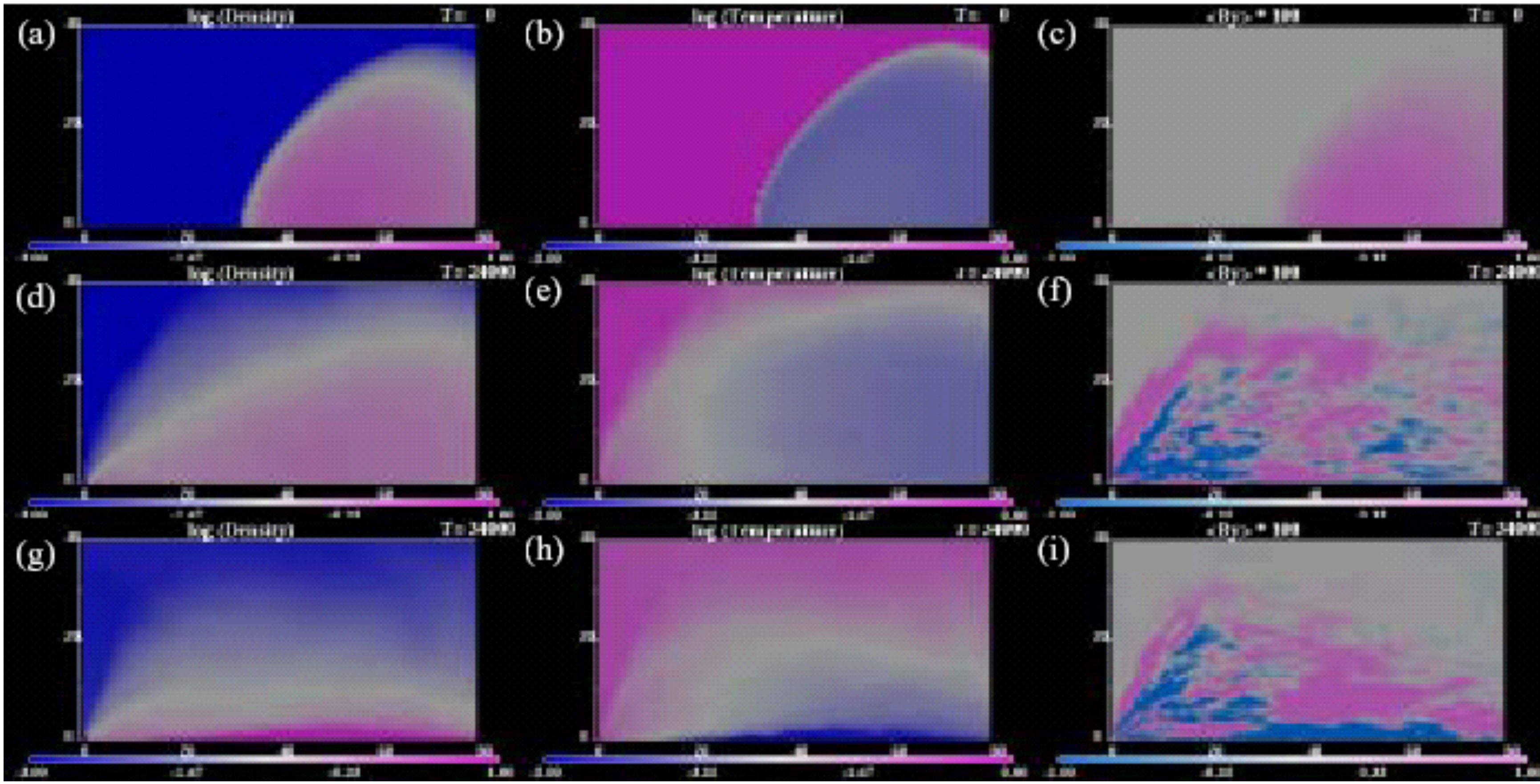


Current density (color) and magnetic field lines (Machida et al. 2003)



Magnetic fields are tightly wound and reconnect inside the disk when buoyant rise is suppressed

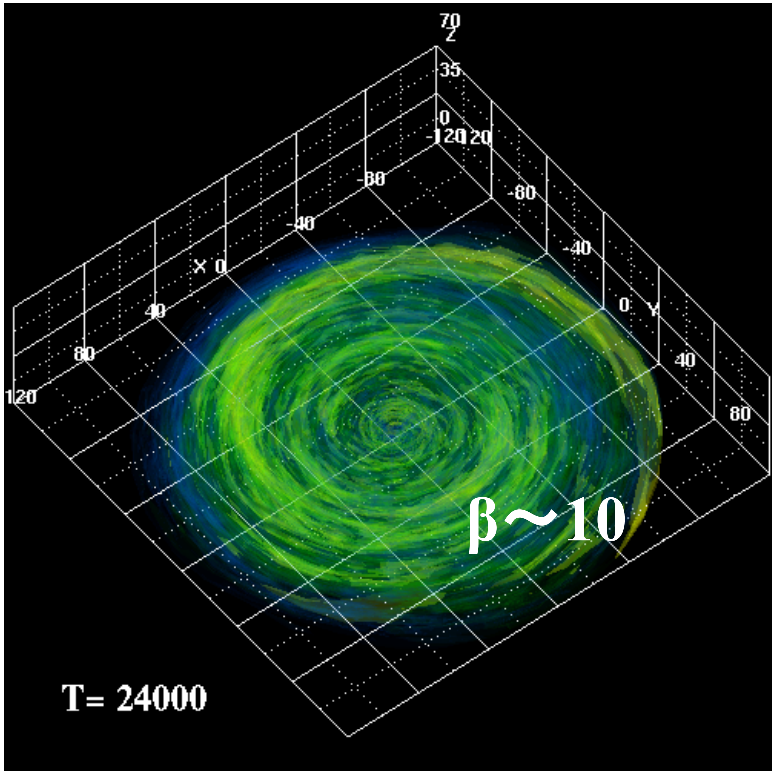
Growth of the Cooling Instability

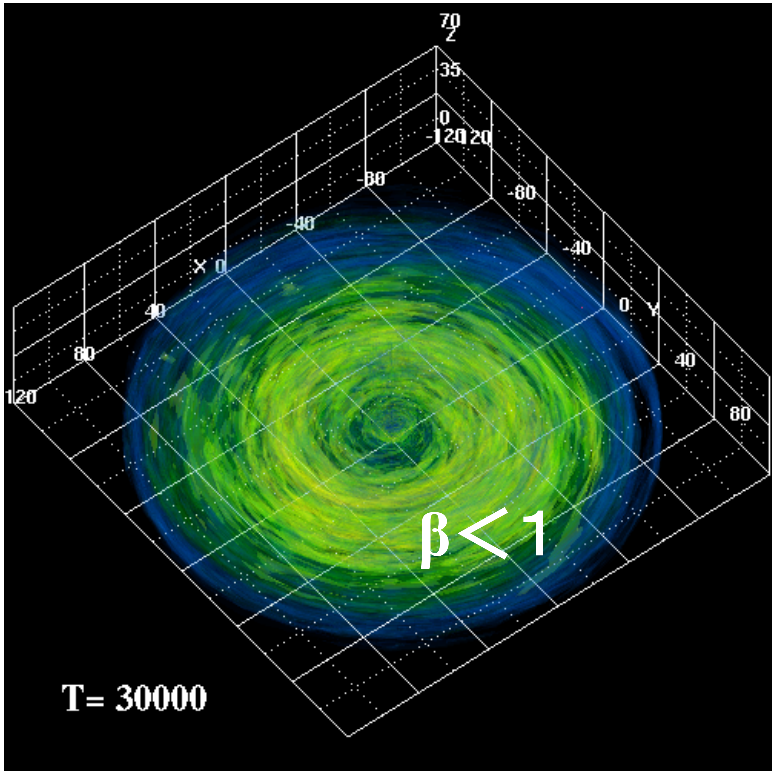


density temperature Toroidal field

Machida et al. 2006

Formation of a low-β Disk



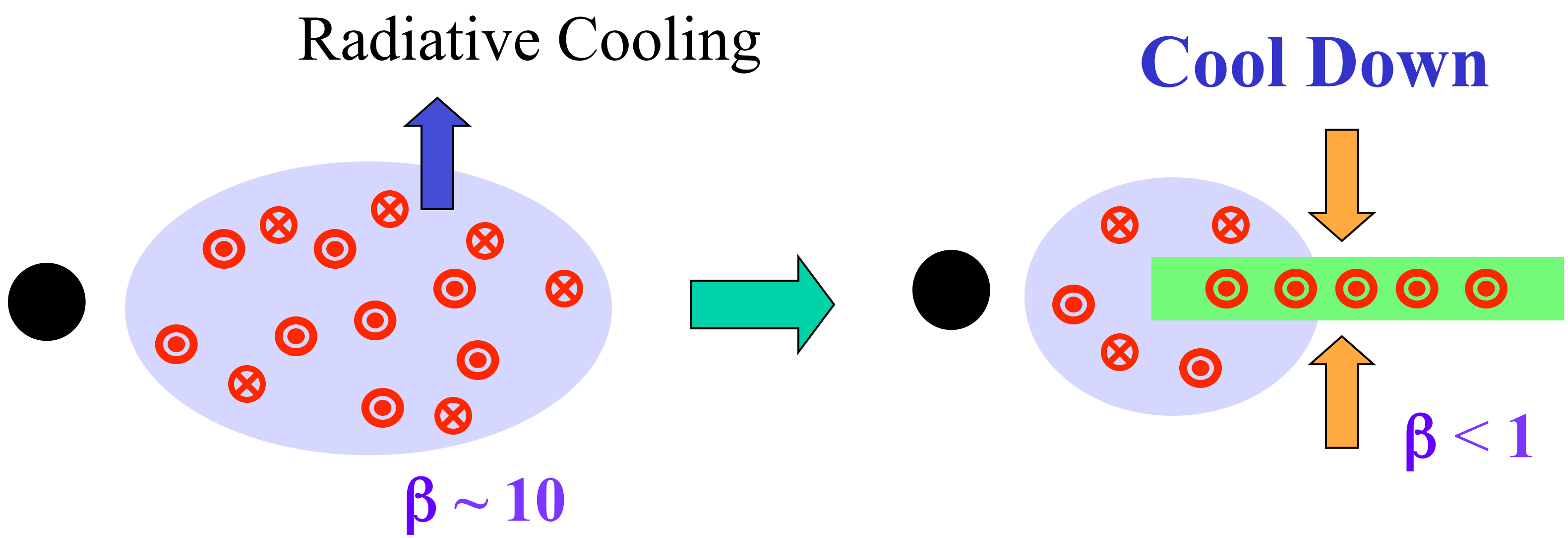


Before cooling

After cooling

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

Schematic Picture of the Formation of a Magnetically Supported Disk



Optically Thin Hot Disk
Supported by Gas Pressure

Optically Thin Cool Disk
Supported by Magnetic Pressure

Summary and Discussion

- Disk magnetic fields are amplified by the dynamo driven by MRI and buoyant rise of magnetic flux
- Mean azimuthal magnetic fields change their direction quasi-periodically with time scale of about 10 rotation period. This dynamo cycle can be the origin of low-frequency Quasi-Periodic Oscillations (QPOs) observed in black hole candidates
- Magnetic reconnection taking place inside the disk can limit the strength of disk magnetic fields and can be the origin of sporadic X-ray time variabilities observed in black hole candidates

END