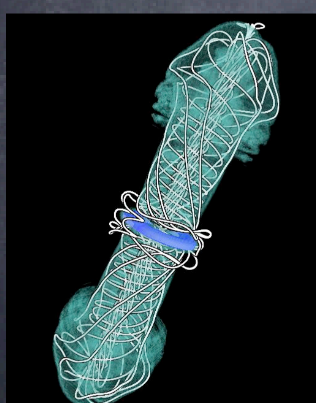
Magnetic-Tower Jet Solution for Astrophysical Jets



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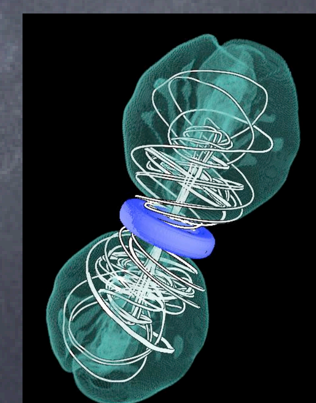
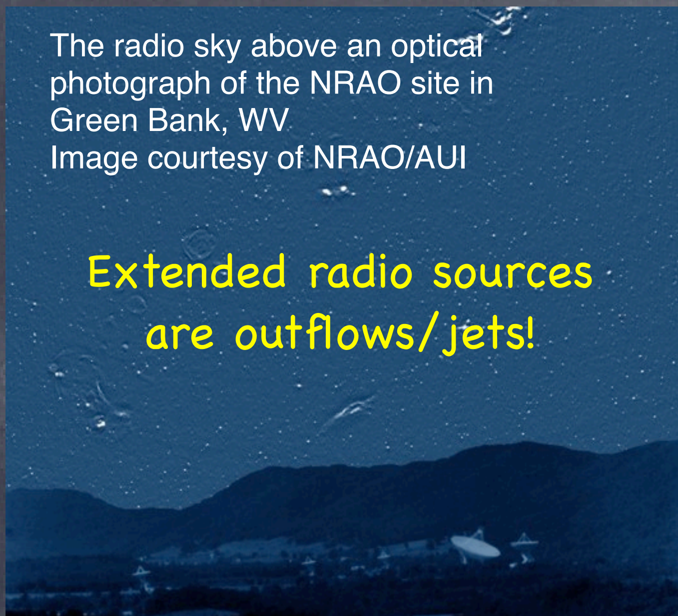


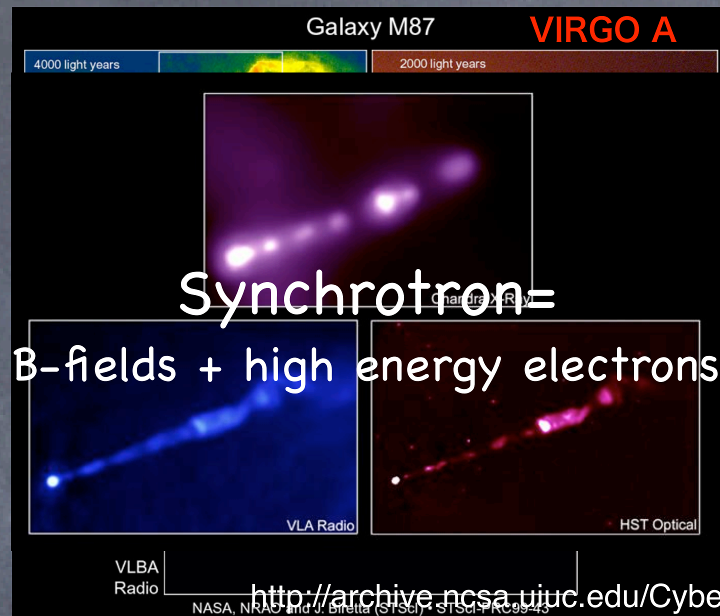
Workshop on MHD Processes in Galaxies, Accretion disks and in Star Forming Regions @ Chiba Univ. Nov. 17 - 18, 2005

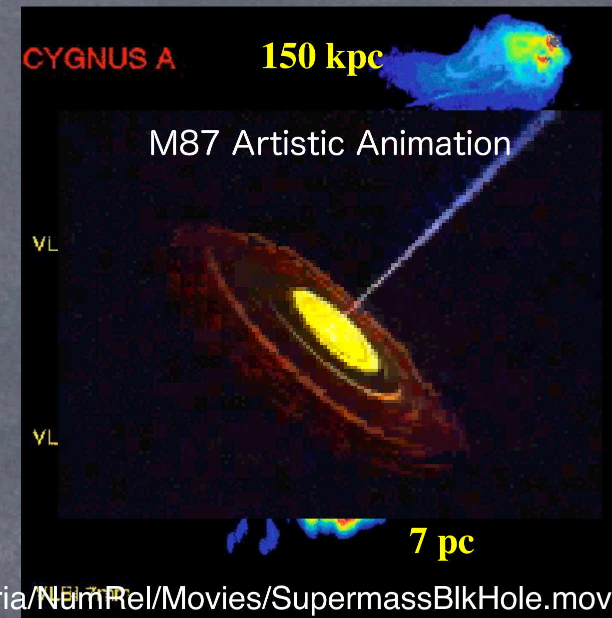
Outline of my talk

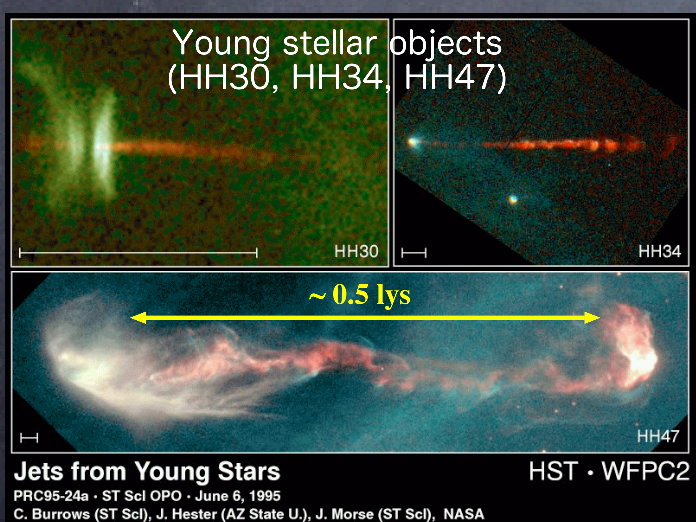
- Introduction
  - Why we study jets?
  - Connection between accretion disks and astrophysical jets
  - Previous studies of MHD jets and unresolved issues
- A new study of MHD jets "Magnetic-Tower Jet"
  - Formation of magnetic-tower jets in accretion disks around black holes
  - Formation of magnetic-tower jets in accretion disks around weakly magnetized neutron stars
- Summary

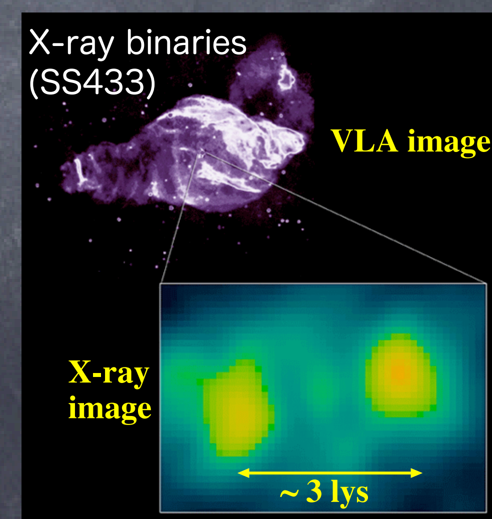
Why we study jets?







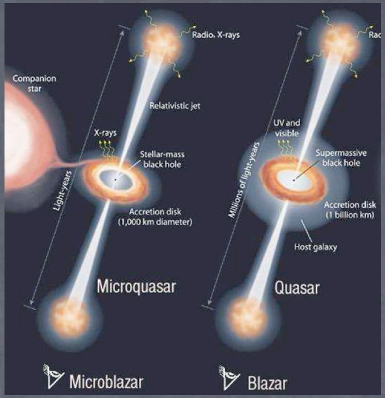




Keywords : Accretion Disks B-fields

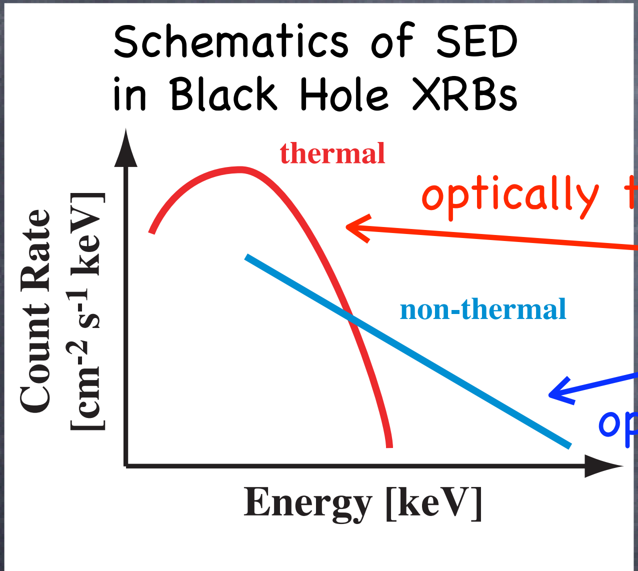
Accretion Disks & Astrophysical Jets

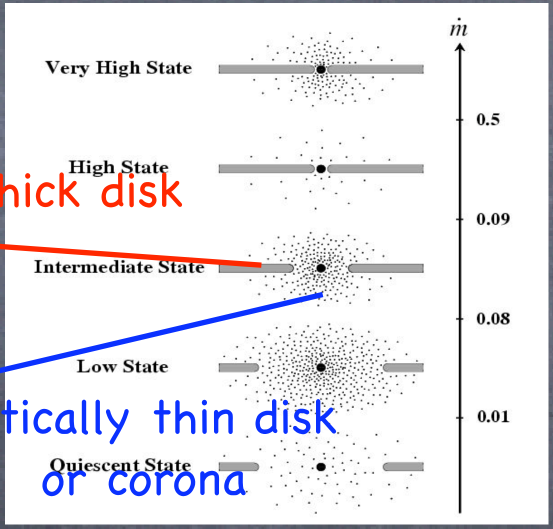
Microquasar : "small-Quasars/AGNs" X-ray Binaries



Mirabel 2004

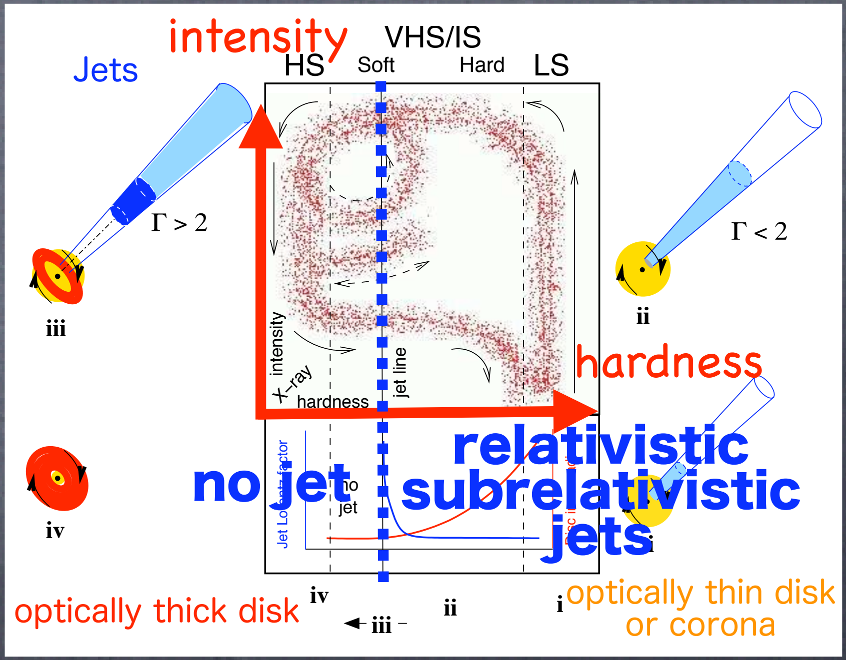
Spectral Type of X-ray Binaries (XRBs)





Tanaka & Lewin 1995

Microquasar GRS 1915+105



Fender et al. 2004

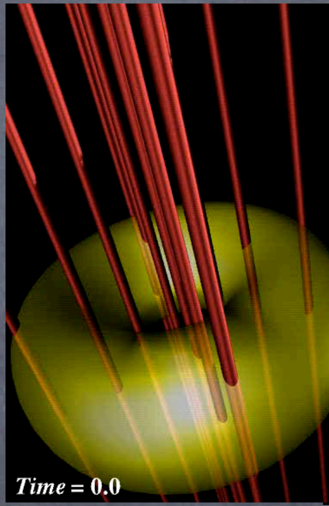
Accretion disks are launching pads for astrophysical jets

Previous Study of MHD Jets

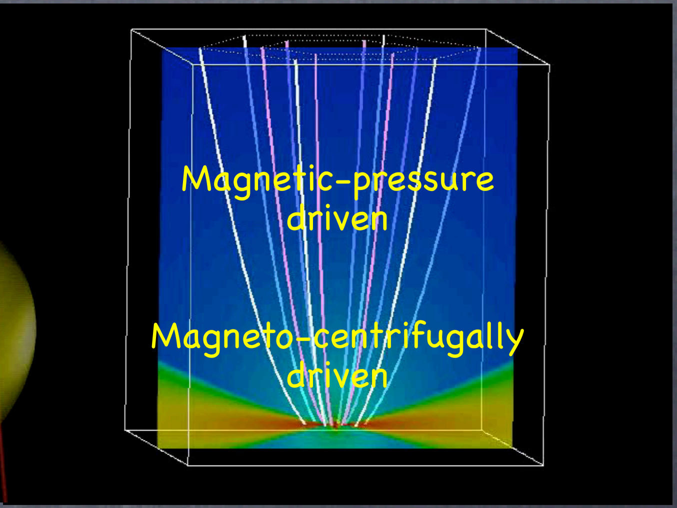
Large-scale ordered magnetic fields permeating the accretion disks

- Magneto-centrifugally driven outflows (Blandford & Payne 1982)
- Magnetic-pressure driven outflows (Uchida & Shibata 1984)
- Both accelerations may work simultaneously along the magnetic field lines (Kudoh & Shibata 1997)
- Although the origin of large-scale magnetic fields is not well understood,,,,

Uchida, Nakamura, Hirose



Kudoh, Shibata

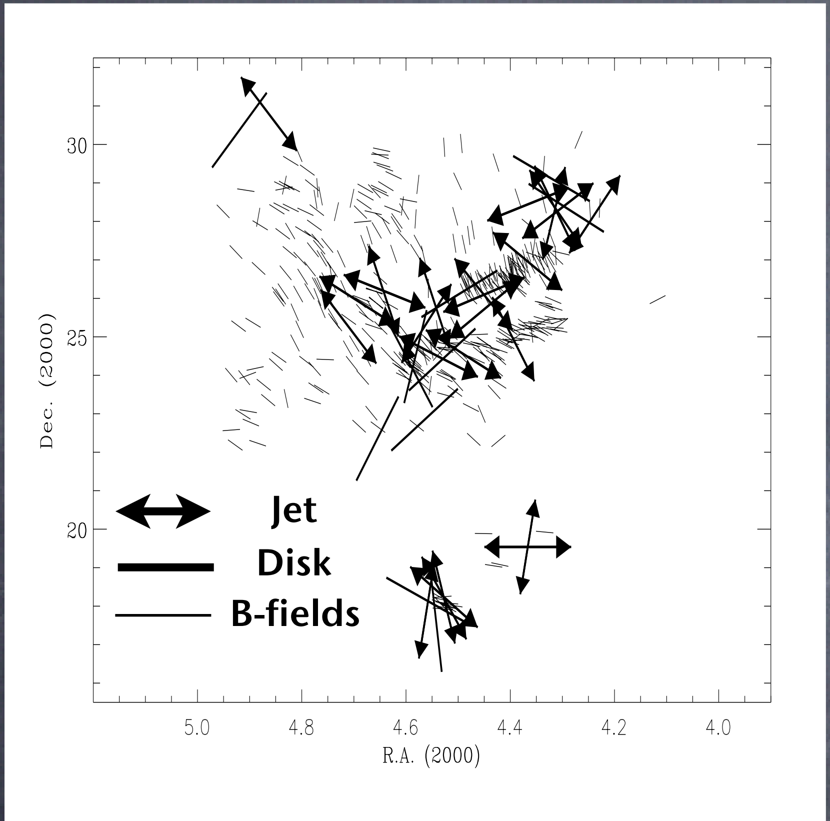


Colors = Density

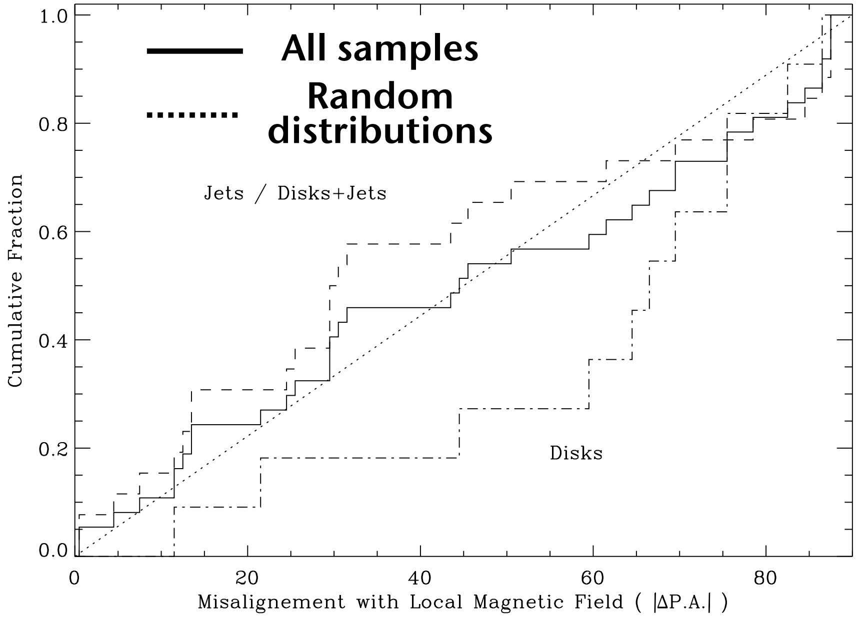
people frame the existence of large-scale magnetic fields within a paradigm of astrophysical jets

No-correlation between the direction of large-scale magnetic fields and that of the observed jets in YSOs

F. Ménard and G. Duchêne (2004)



Cumulative distribution function of the difference in polarization angles between the local B-fields and the CTTS symmetry axis.

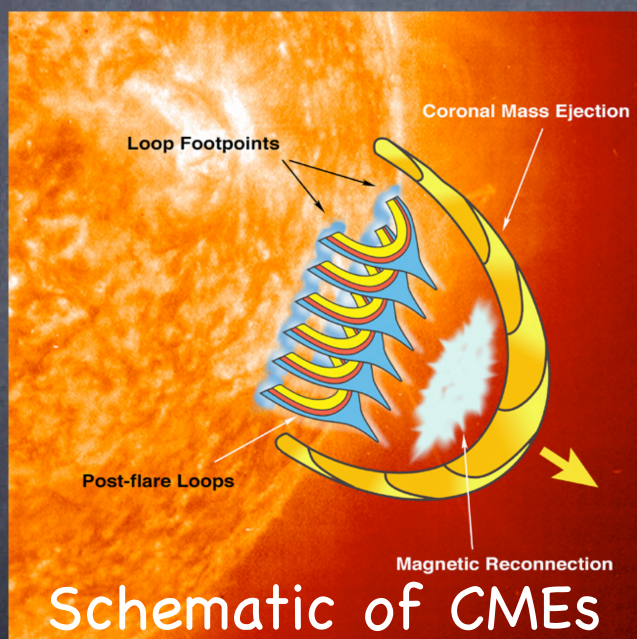


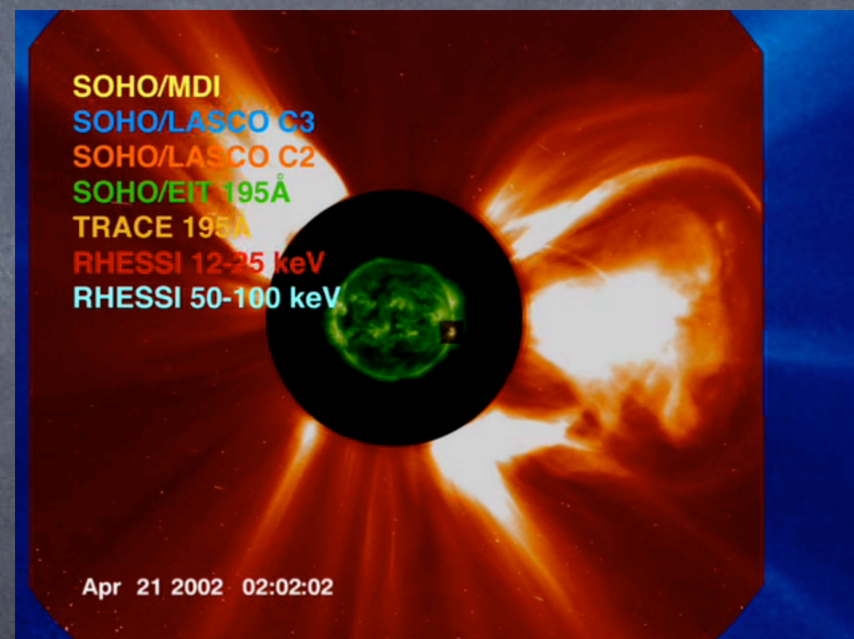
The existance of large-scale magnetic fields may not be a necessary condition for launching astrophysical jets

Look at the Sun!

Sun creates large-scale magnetic fields by its magnetic activities

Solar flare and Coronal Mass Ejections (CMEs)





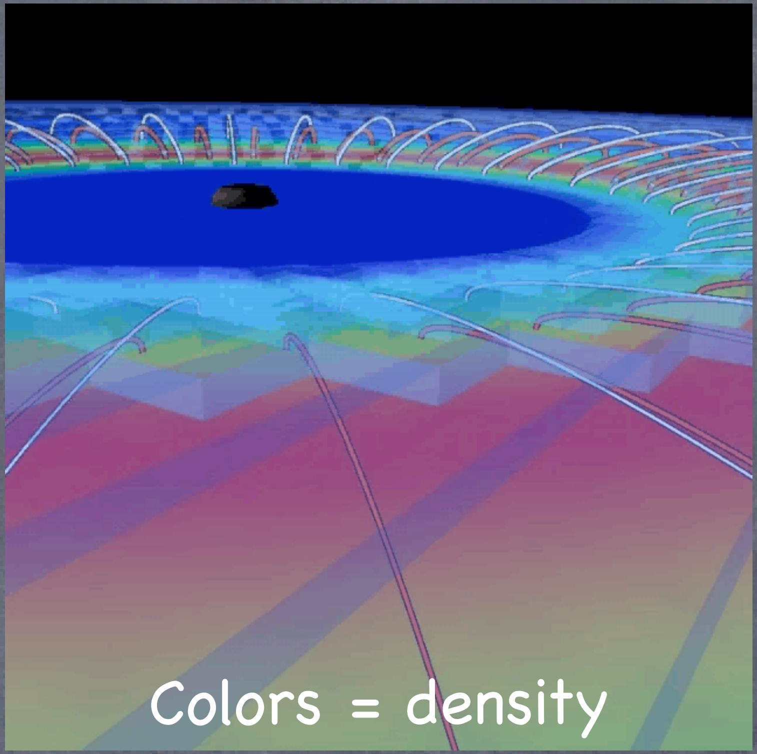
http://svs.gsfc.nasa.gov/vis/a000000/a002500/a002509/

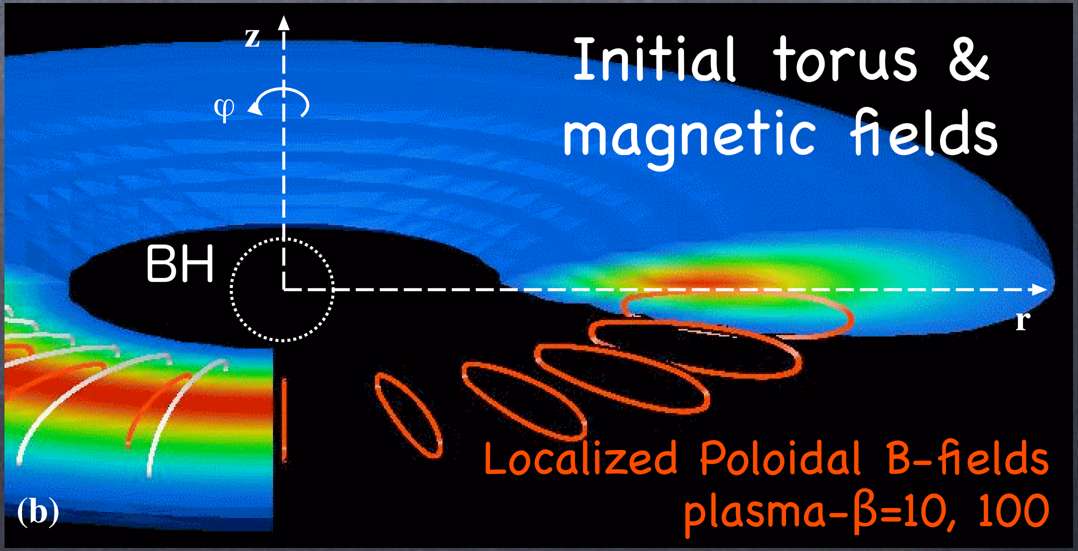
What about the accretion disks?

Initial Model

See Kato, Mineshige, Shibata 2004 for more detail

- A magnetized rotating torus is in equilibrium around a black hole:
$$\rho(r,z) = \rho(40r_s, 0) = \rho_0$$
- Isothermal, hot, low-density corona outside the torus:
$$\rho_{c,0} = 10^{-5}\rho_0 \qquad C_{s,corona} \approx 0.5 - 0.9c$$
- B-field is given by vector potential:
$$rA_\phi \propto \rho \quad \text{when } \rho > \rho_c$$
- Employ pseudo-Newtonian potential in order to take into account general relativistic gravity
$$\Psi = -\frac{GM}{r - r_s}$$
- Absorbing boundary at R=2rs sphere





Basic Equations

(Resistive MHD Equations)

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

$$\rho \frac{d\boldsymbol{v}}{dt} = -\rho \boldsymbol{\nabla} \psi - \boldsymbol{\nabla} p + \frac{\boldsymbol{J} \times \boldsymbol{B}}{c} \qquad \psi = -\frac{GM}{r - r_s}$$

$$\rho T \frac{ds}{dt} = \Gamma - \Lambda \quad \text{where } s = K \ln (p/\rho)$$

$$\Gamma = \eta |\boldsymbol{J}|^2 \;:\; \text{heating term} \qquad \Lambda = Q^{rad} \;:\; \text{cooling term}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c \boldsymbol{\nabla} \times \boldsymbol{E}$$

$$\boldsymbol{E} = -\left(\frac{\boldsymbol{v}}{c}\right) \times \boldsymbol{B} + \frac{4\pi\eta}{c^2} \boldsymbol{J}$$

$$\boldsymbol{J} = \frac{c}{4\pi} \boldsymbol{\nabla} \times \boldsymbol{B}$$

$$r_s = c = 1 \qquad \rho = \tilde{\rho}\rho_0 \qquad p = \tilde{p}(\rho_0 c^2) \qquad B = \tilde{B}(\rho_0 c^2)^{1/2}$$

Density is a free parameter

Assumptions:

Non-relativistic MHD approximation & Using pseudo-Newtonian potential.

Employ anomalous resistivity (Yokoyama & Shibata 1994):

$$\eta = \begin{cases} 0 & \text{for} \quad v_{\rm d} < v_{\rm crit} \\ \eta_{\rm max}[(v_{\rm d}/v_{\rm crit}) - 1]^2 & \text{for} \quad v_{\rm crit} < v_{\rm d} < 2v_{\rm crit} \\ \eta_{\rm max} & \text{for} \quad v_{\rm d} \geq 2v_{\rm crit} \end{cases}$$

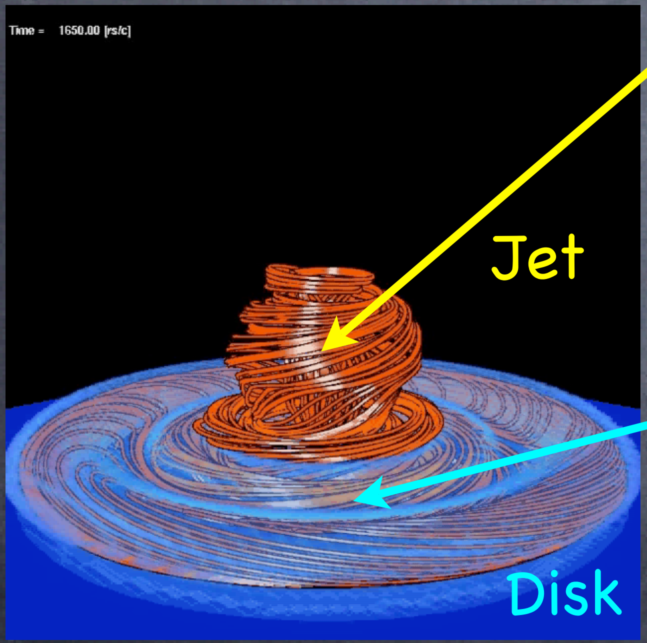
$$v_{\rm d} \equiv |\boldsymbol{J}|/\rho \qquad \eta_{max} = 10^{-3} c r_s \qquad v_{crit} = 10^{-2} c$$

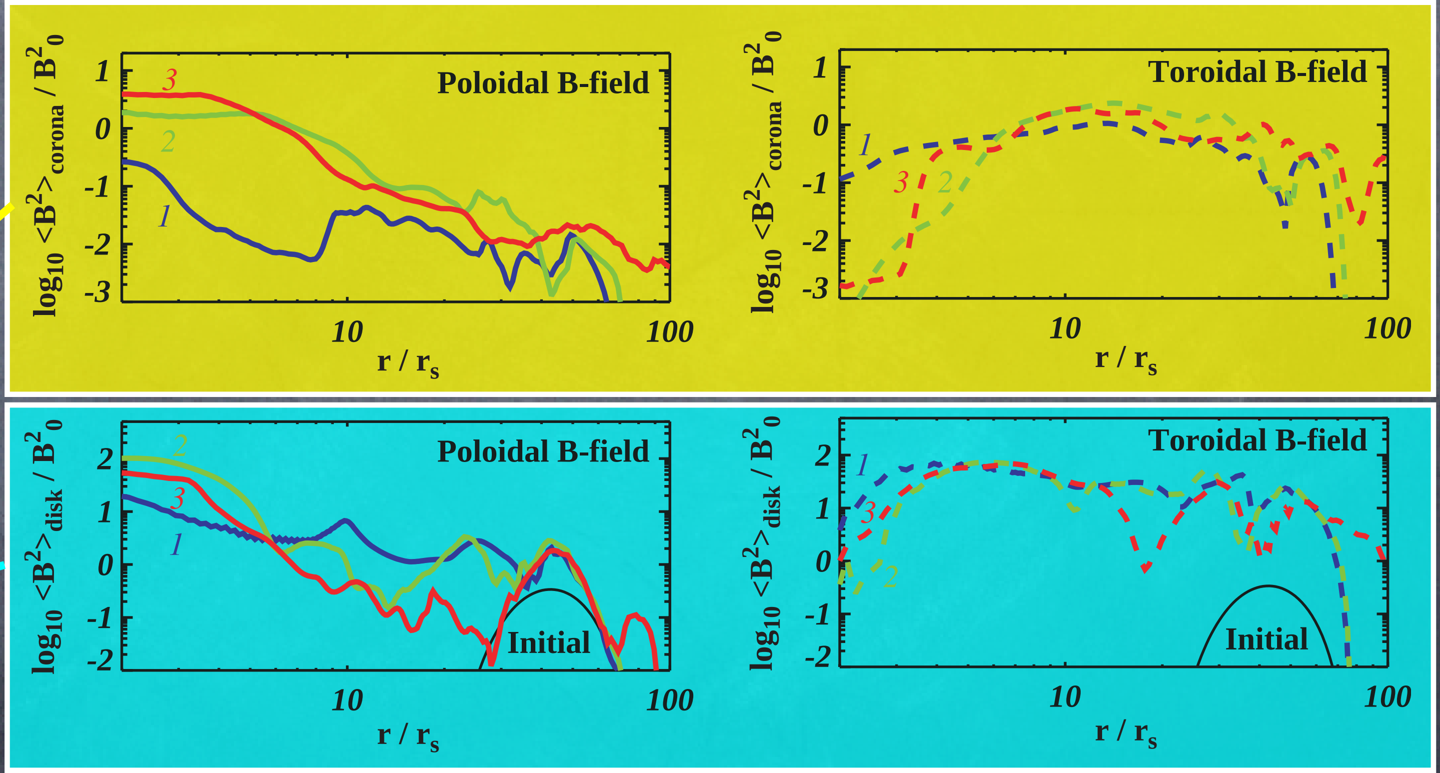
Neglect radiative cooling

Evolution of Magnetic Fields in the Disk and the Jet

(Magnetic Coupling between the Disk & the Jet)

1. Before the formation of jets
2. During the formation of jets
3. After the formation of jets



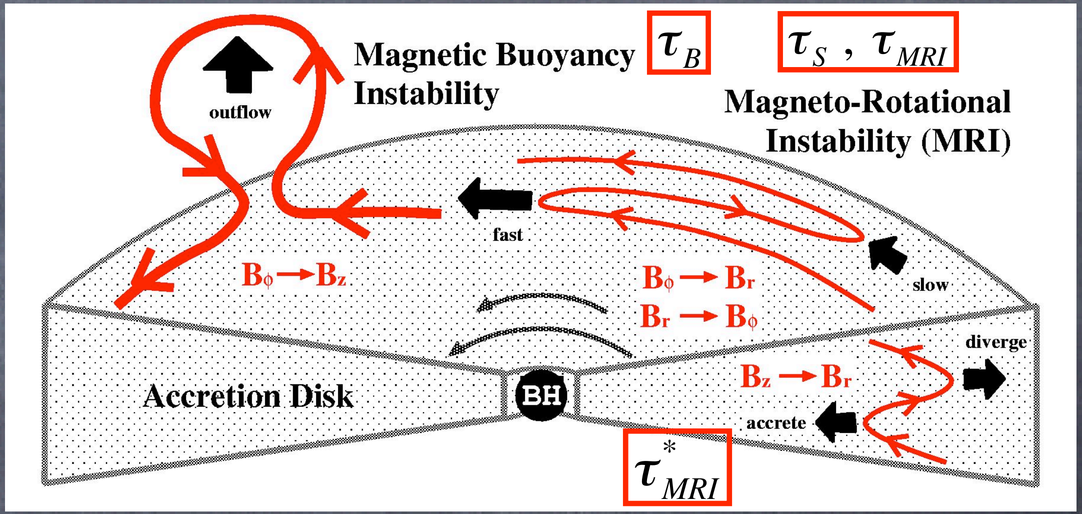


Initial weak poloidal fields are converted into toroidal fields, and the toroidal fields injected into the jet.

Magnetic Fields in the Accretion Disks and the Dynamo

- By transferring the angular momentum between the plasma connected via magnetic field lines, MRI (Balbus & Hawley 1991) creates the radial magnetic fields,
- Azimuthal magnetic fields are generated by winding up the radial magnetic fields as a result of the differential rotation,,,,
- MRI + differential rotation = Efficient Dynamo.

Schematic evolution of magnetic fields in the accretion disk



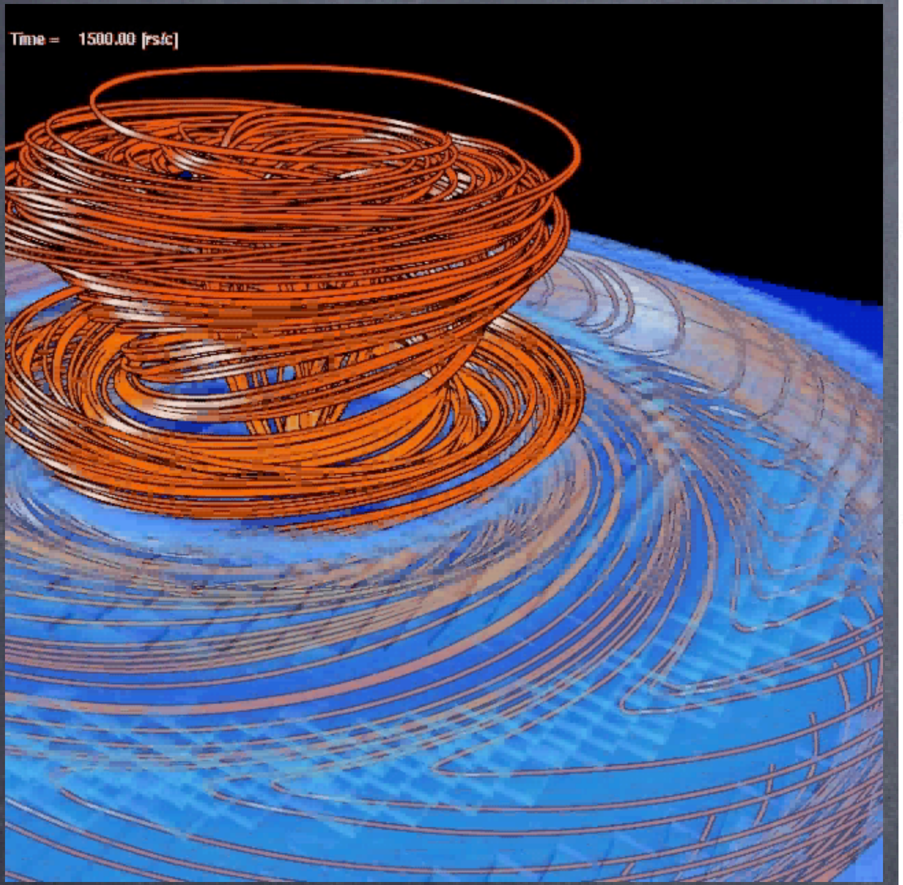
Time-scales:

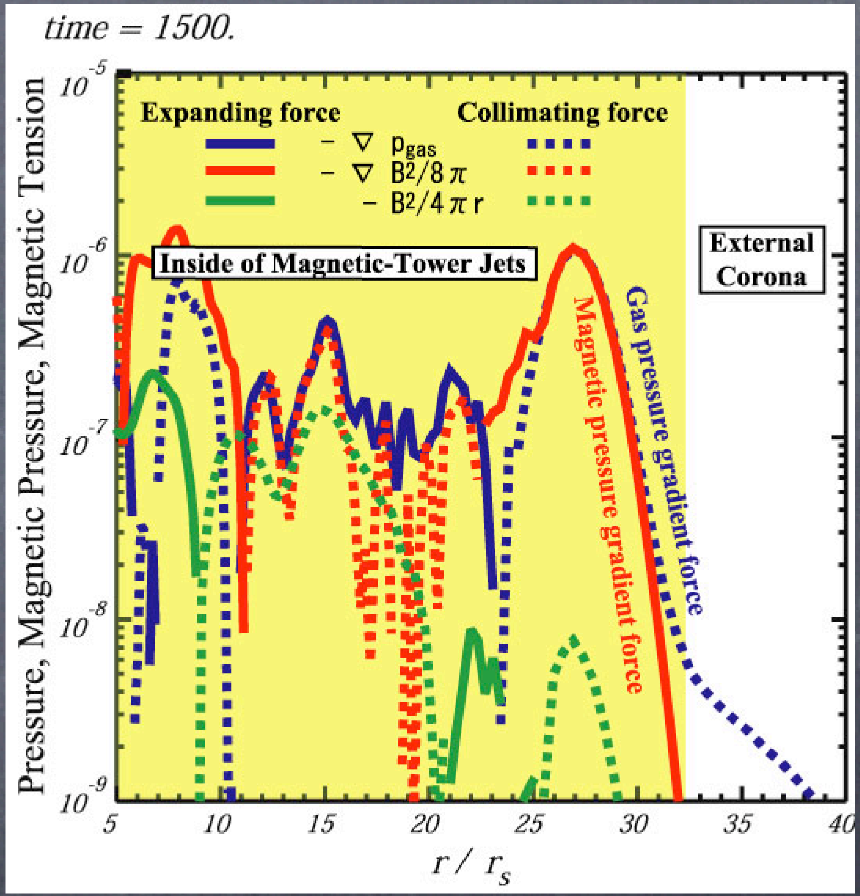
$$\tau_{MRI} \sim \tau^*_{MRI} \sim \tau_s = 1/\Omega \sim \tau_K$$

$$\tau_B \sim H/v_A = v_s/(v_A\Omega) \sim \beta\tau_K$$

Even if the initial magnetic field is weak, magnetic pressure can be comparable to gas pressure in a few dynamical time-scale.

Structure of Magnetic-Tower
(Collimation of Magnetic-Tower Jet)





Toroidal (poloidal) fields dominates poloidal (toroidal) field at the rim (core) of the tower.
Magnetic-tower is collimated by the external force = it is not collimated by itself!

Model dependencies

A. Strong B-fields, Hot Corona

Strong B_ϕ in the inner region of the disk

Transient jet / outflow

B. Weak B-fields, Hot Corona

Filamentary strong B_ϕ in the disk

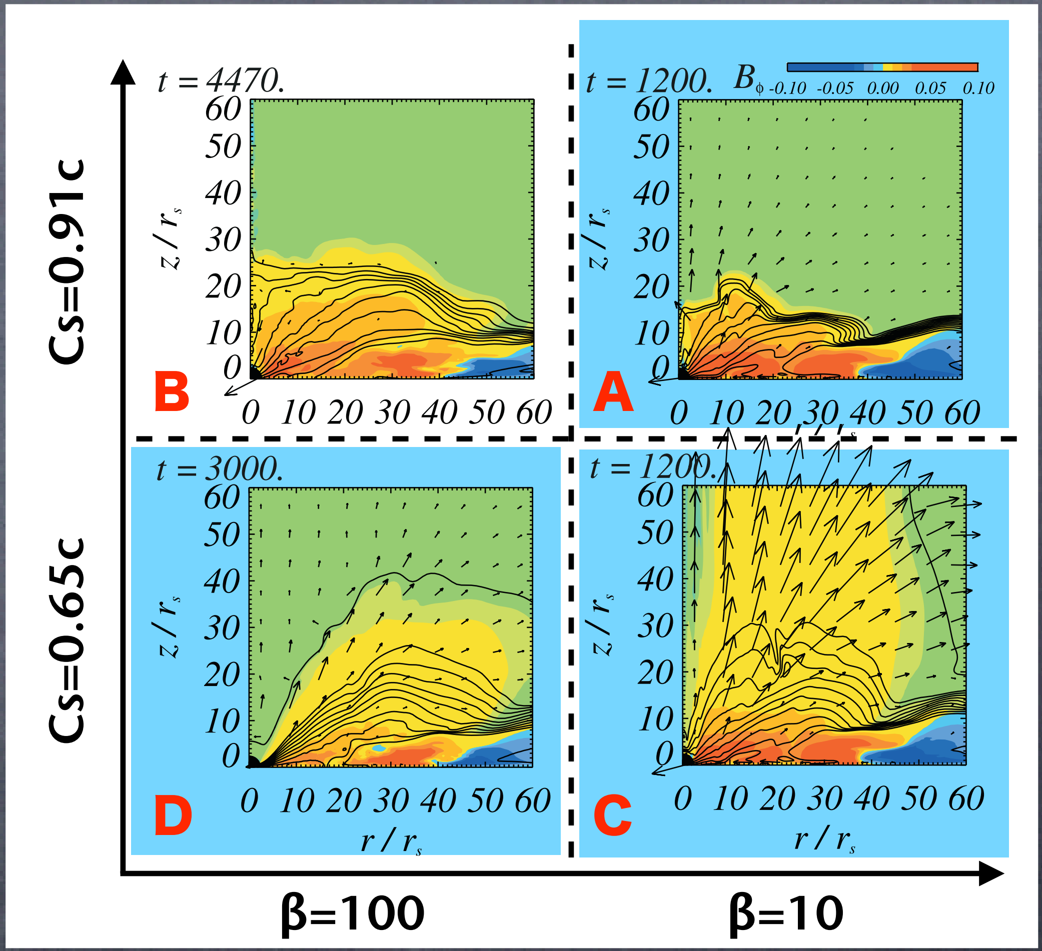
No jet / No outflow

C. Strong B-field, Cold Corona

Persistent strong jet / outflow ~ 0.5 c

D. Weak B-field, Cold Corona

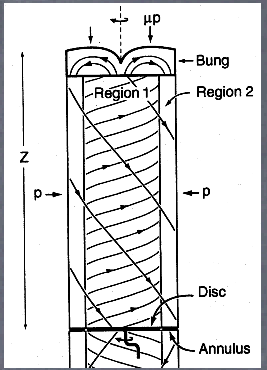
Persistent weak jet / outflow ~ 0.1 c

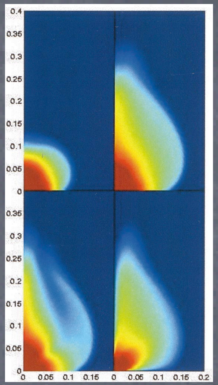


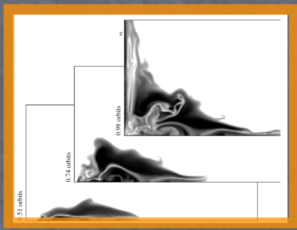
Formation, collimation, velocity of the jets depend on the corona

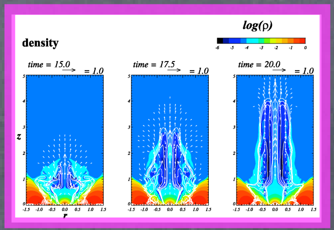
Related Works in Magnetic-Tower Jet Solutions

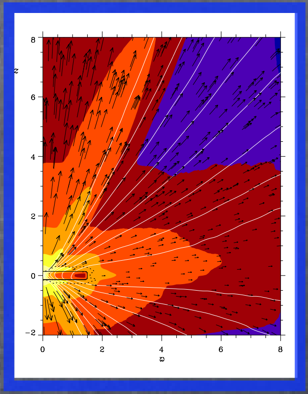
Lynden-Bell (1996)	Proposed a solution of a magnetic-tower			
Published Papers	**Dimension**	**Initial Disk**	**Initial B-fields**	**Notes**
Turner et al. (1999)	2-D Axisymmetric	Boundary Condition	Poloidal	Newtonian
Li et al. (2001)	2-D Axisymmetric	Boundary Condition	Dipole	Magneto-static solution
Kudoh et al. (2003)	2-D Axisymmetric	Thick Torus	Poloidal	Newtonian
von Rekowski et al. (2003)	2-D Axisymmetric	Thin Disk with Mass Supply	Poloidal	Newtonian α-ω Dynamo
Kato et al. (2004a)	2-D Axisymmetric	Thin Torus	Dipole	pseudo-Newtonian
Kato et al (2004b)	3-D	Thin Torus	Poloidal	pseudo-Newtonian
McKinney et al. (2004)	2-D Axisymmetric	Thick Torus	Poloidal	Full General Relativistic
Romanova et al. (2005)	2-D Axisymmetric	Thin Disk	Dipole	Newtonian

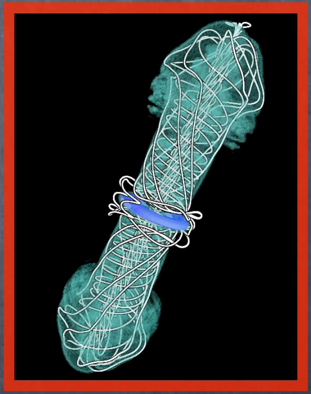


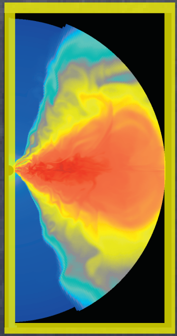


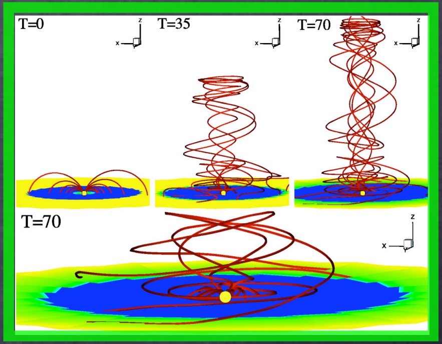






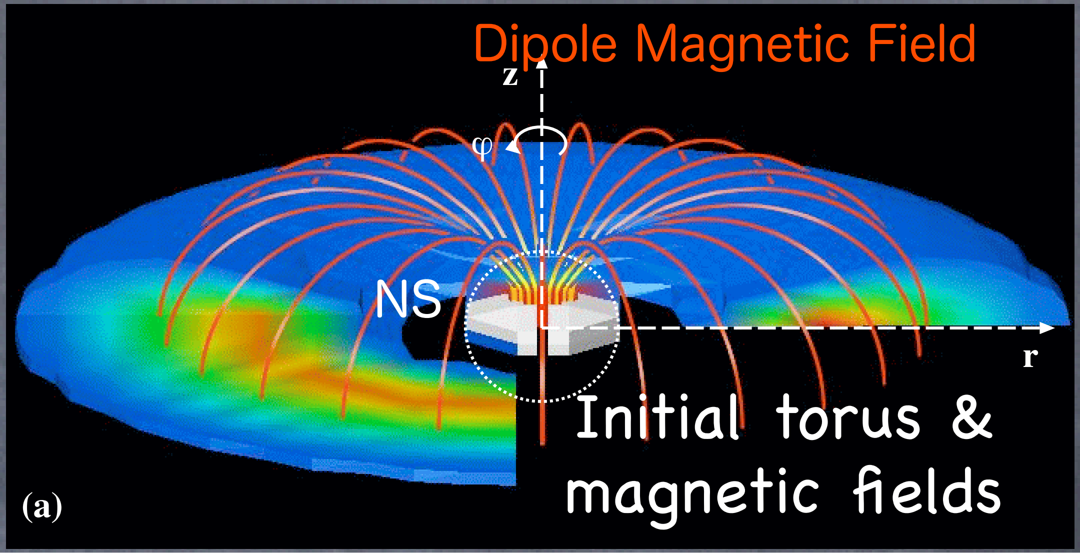






Initial Model for NS

See Kato, Hayashi, Matsumoto 2004
for more detail



- A magnetized rotating torus is in equilibrium around a black hole:

$$\rho(r,z) = \rho(13r_s, 0) = \rho_0$$

- Isothermal, hot, low-density corona outside the torus:

$$\rho_{c,0} = 10^{-5}\rho_0 \qquad C_{s,corona} \approx 10^{-2}c$$

- B-field is given by vector potential:

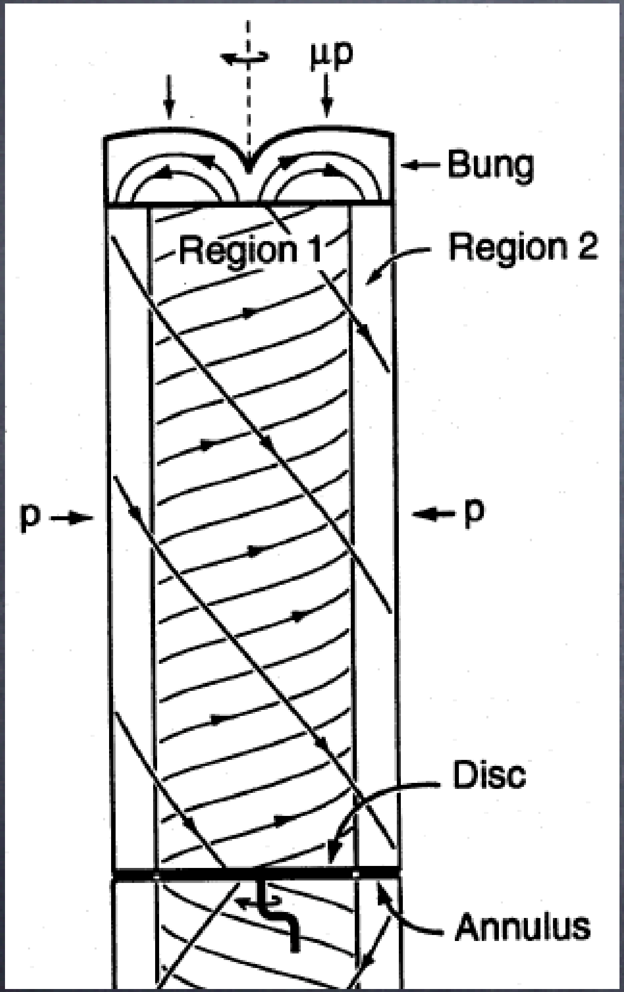
  Dipole Magnetic Fields

- Employ pseudo-Newtonian potential in order to take into account general relativistic gravity

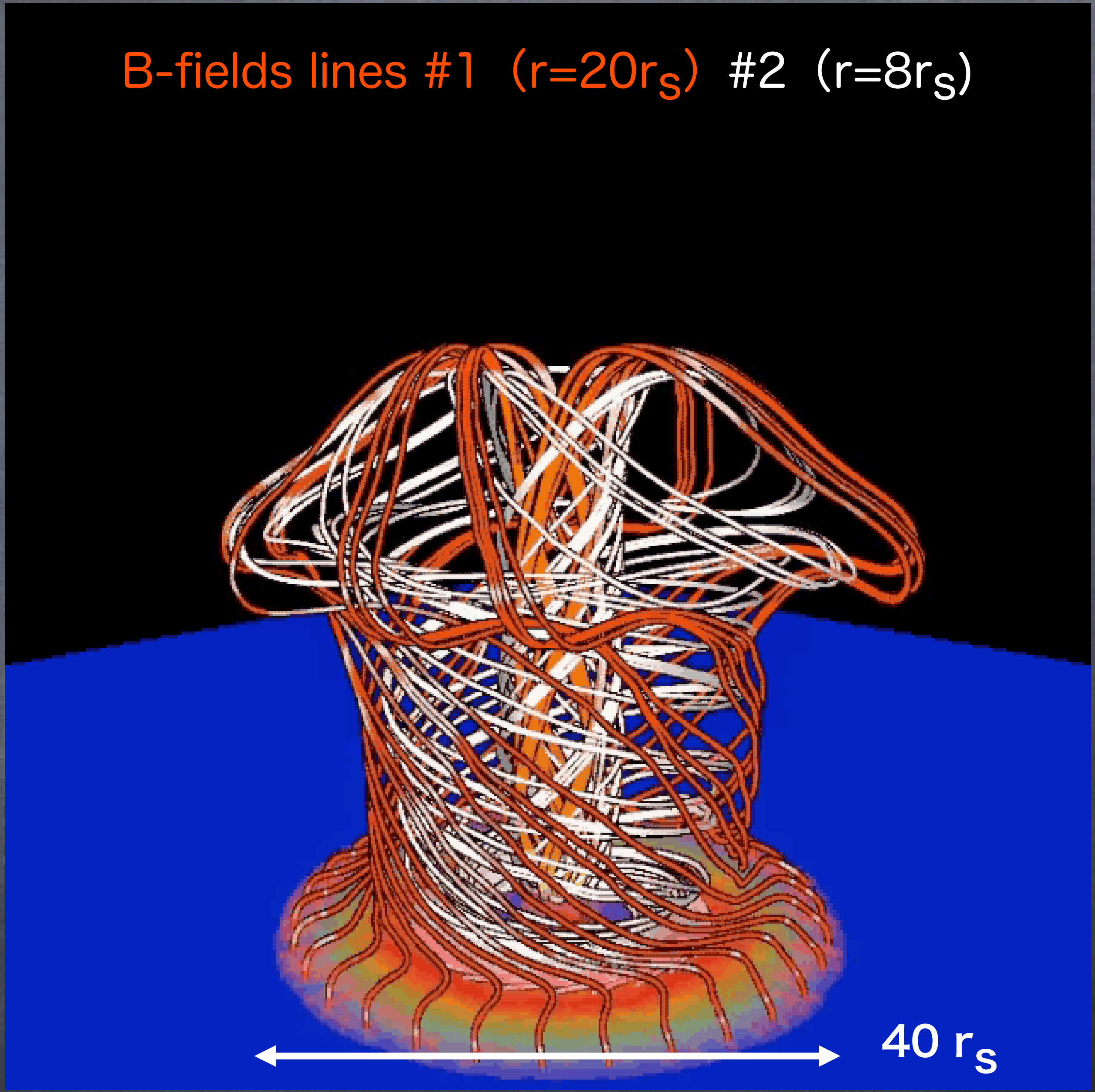
$$\Psi = -\frac{GM}{r - r_s}$$

- Fixed boundary at R=2rs sphere

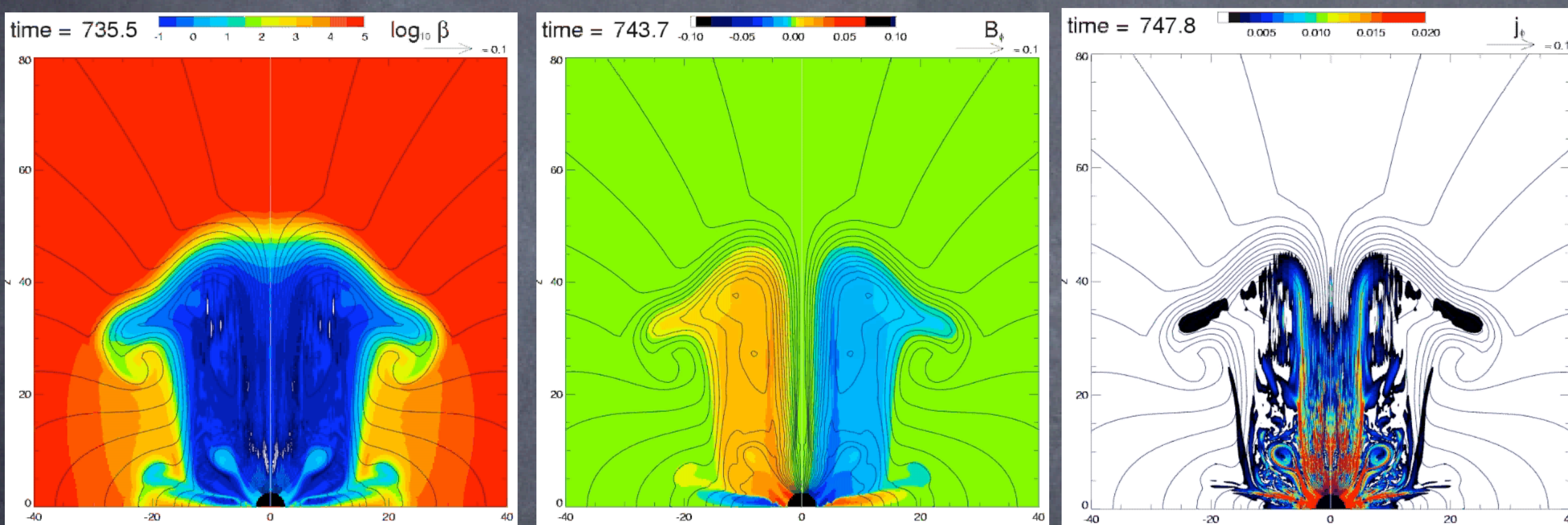
Magnetic-Tower Jets in NS-Disk System



Lynden-Bell 1996



Magnetic Flares & Magnetic-Tower Jets in NS-Disk System

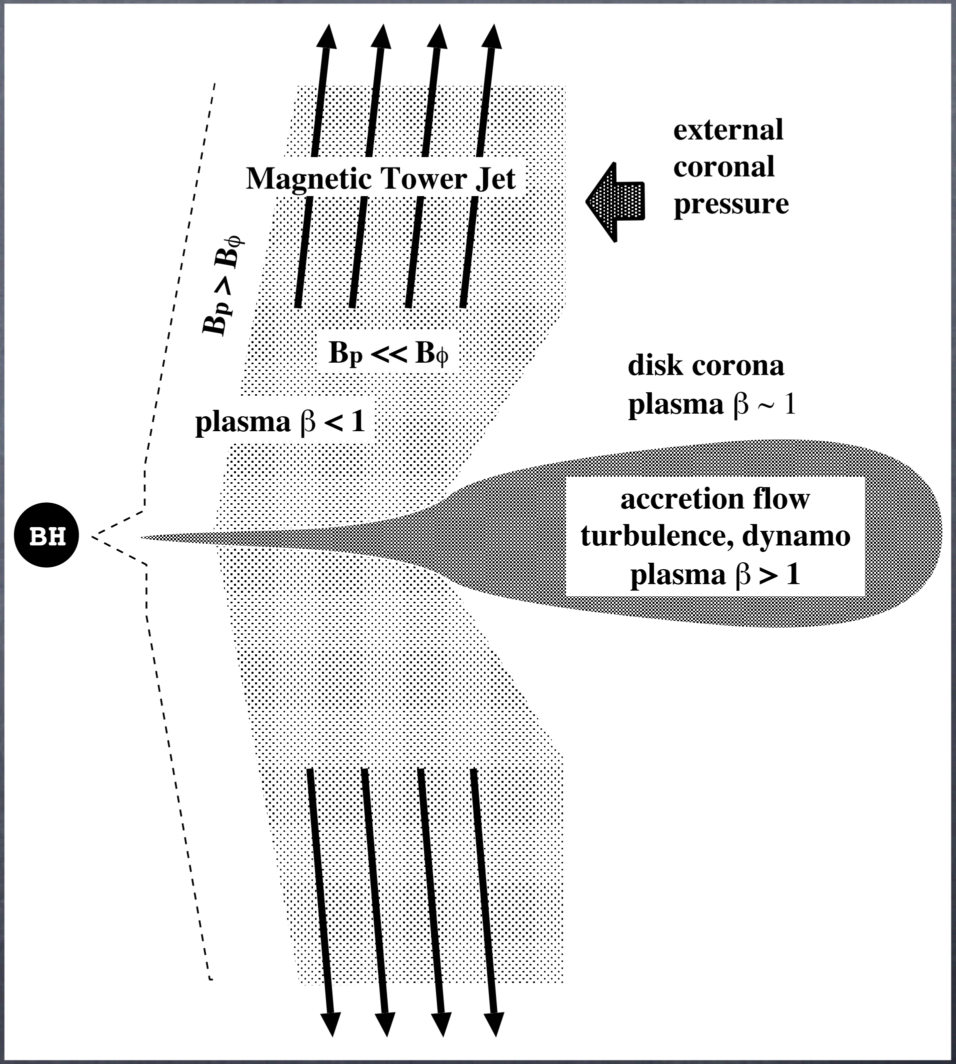


plasma-β　　Bϕ　　Jϕ

Hot plasmoids are injected into the magnetic-tower and propagate along it

Summary of magnetic-tower jets

- The magnetic-tower jets are universal mechanism which can produce jets in dynamo-active accretion disks even when strong structured magnetic fields do not exist in the system
- The magnetic-tower jet is a kind of process to generate large-scale structured magnetic fields



A New MHD Jet Solution

Magnetic-Tower Jets