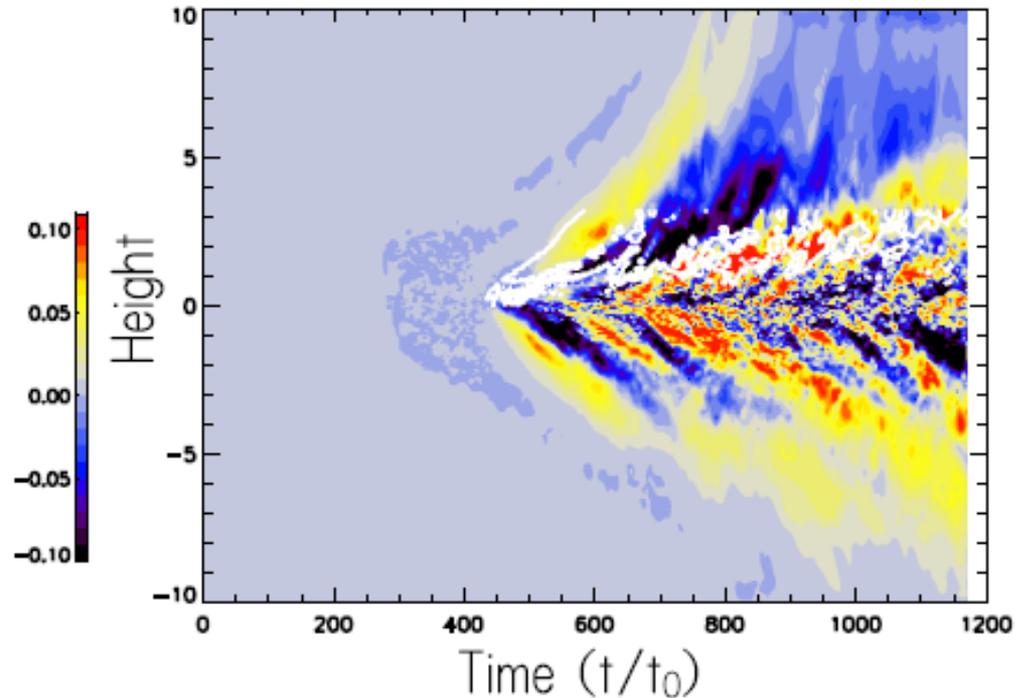
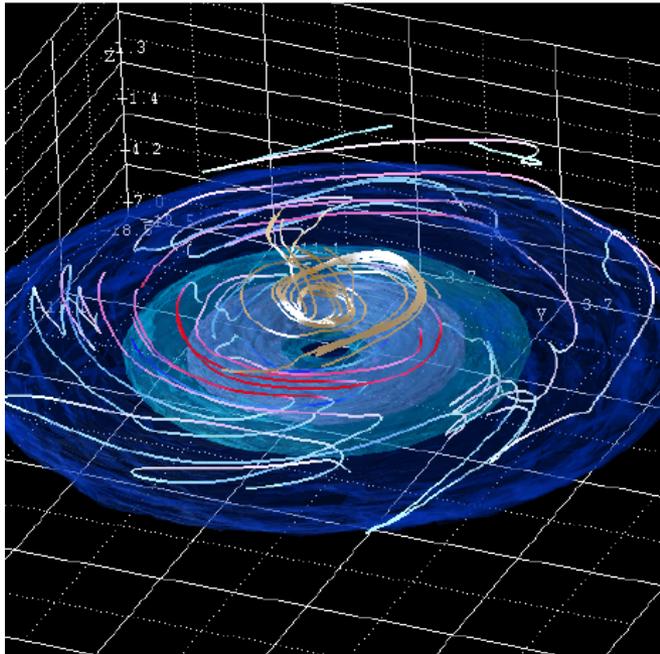


降着円盤の角運動量輸送問題

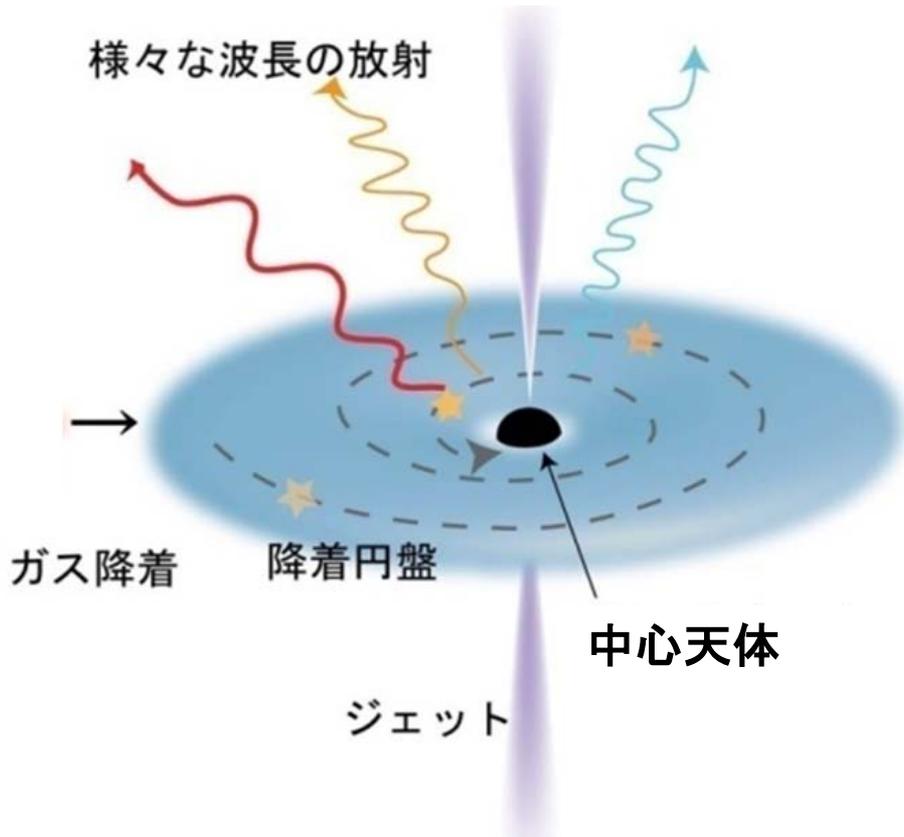


松元亮治 (千葉大学)

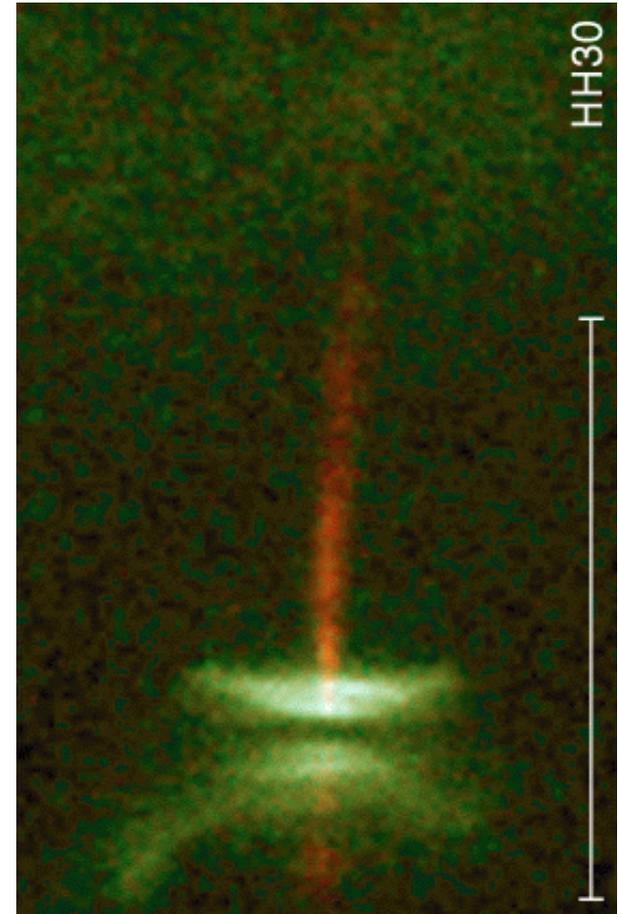
講演内容

- 降着円盤とは
- 降着円盤における流体不安定性
- 磁気回転不安定性
- 局所3次元磁気流体シミュレーション
- 大局的3次元磁気流体シミュレーション
- 円盤ダイナモ
- 降着円盤の状態遷移
- まとめ

降着円盤とは？

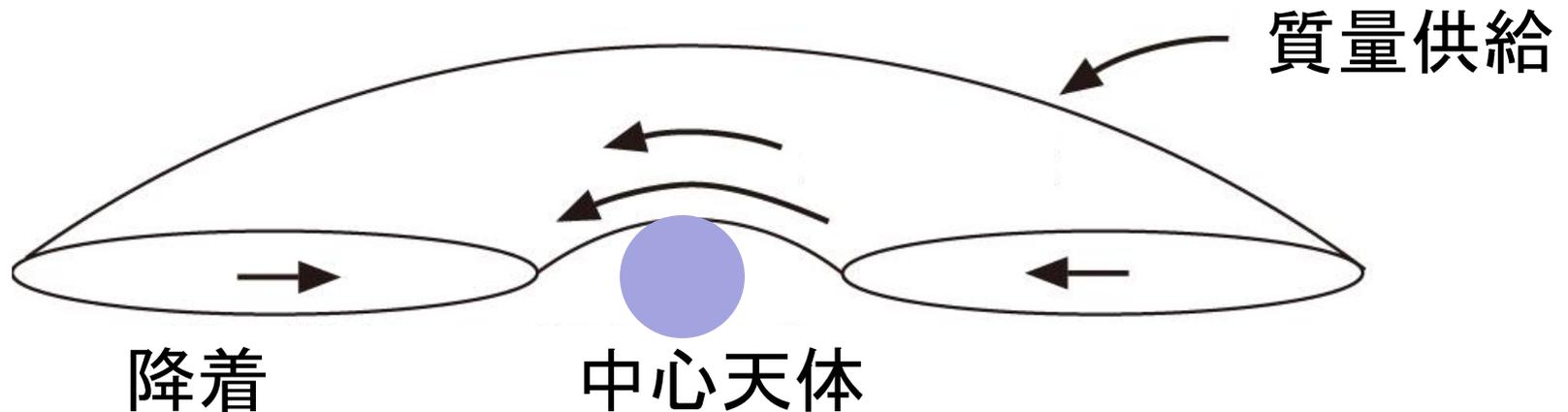


回転物質が天体に落下する際に形成される円盤。重力エネルギーを輻射やジェットのエネルギーに変換するエンジン。



原始星円盤とジェット
(Burrows 1995)

Angular Momentum Transport in Accretion Disks



回転物質が落下するためには角運動量を失う必要がある

標準降着円盤理論では $T_{r\phi} = \alpha P$

- 理論と観測の比較から $\alpha = 0.01 \sim 0.1$ と見積もられている

Local Analysis of the Hydrodynamic Instability

運動方程式

$$\rho \left(\frac{Du_R}{Dt} - 2\Omega u_\phi \right) = -\frac{\partial P}{\partial R} + \eta_V \nabla^2 u_R,$$

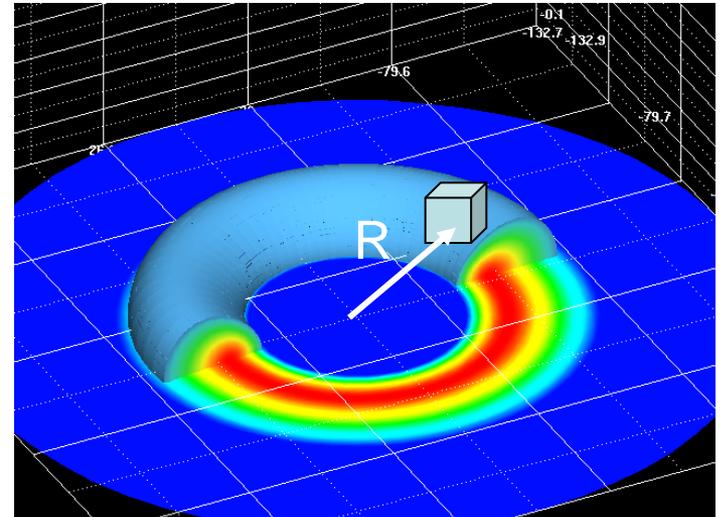
$$\rho \frac{Du_z}{Dt} = -\frac{\partial P}{\partial z} - \rho \frac{\partial \Phi}{\partial z} + \eta_V \nabla^2 u_z,$$

$$\rho \left(\frac{Du_\phi}{Dt} + \frac{\kappa^2}{2\Omega} u_R \right) = -\frac{1}{R} \frac{\partial P}{\partial \phi} + \eta_V \nabla^2 u_\phi,$$

where $u_\phi = v_\phi - R\Omega$

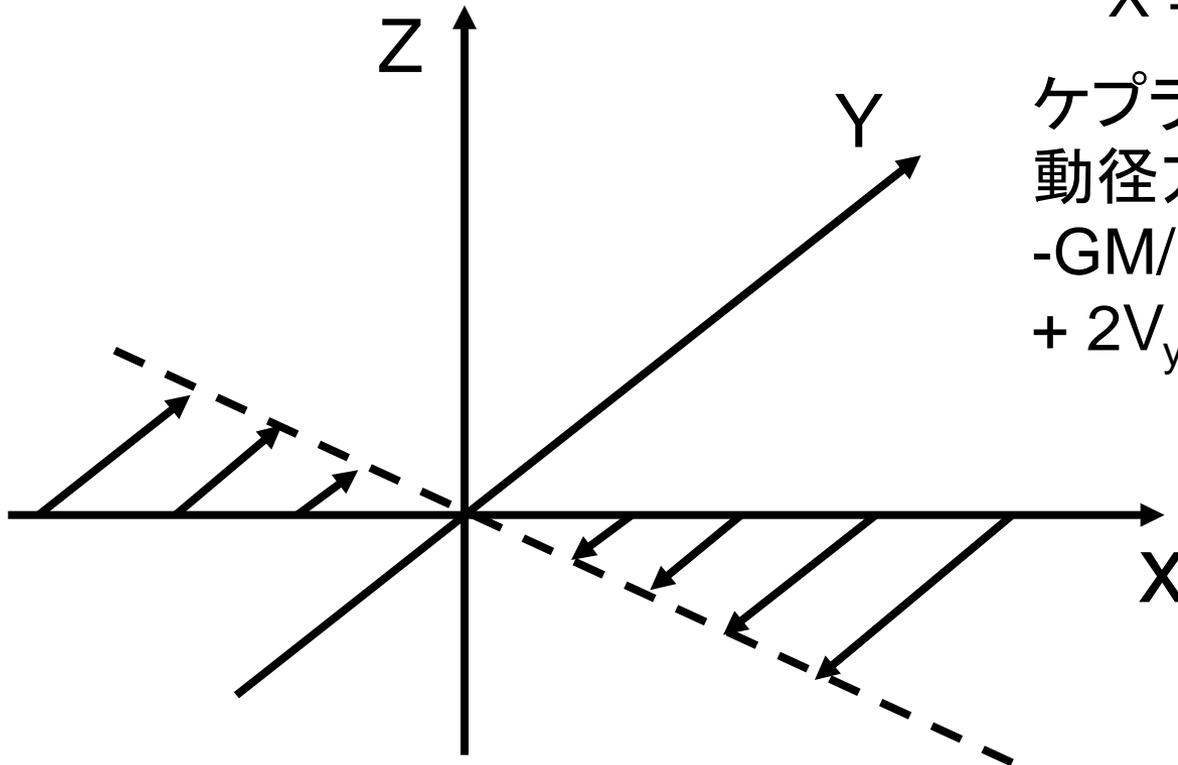
$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla + \Omega \frac{\partial}{\partial \phi}$$

and $\kappa^2 \equiv \frac{1}{R^3} \frac{d(R^4 \Omega^2)}{dR}$ Epicyclic frequency



Local Cartesian Frame
rotating with angular
speed Ω

Equilibrium Shear Flow



$$X = R - R_0 \ll R_0$$

ケプラー回転円盤における
動径方向の力のつりあい
 $-GM/(R_0+x)^2 + (R_0+x) \Omega^2$
 $+ 2V_y \Omega = 0$

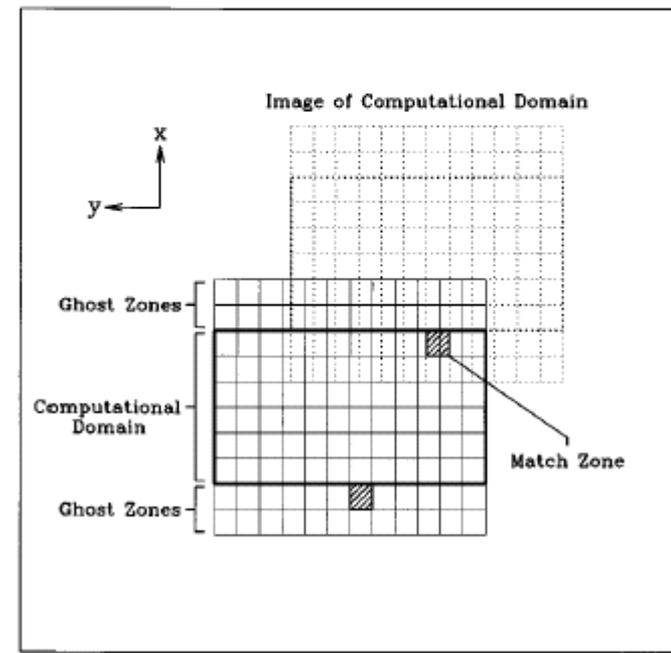
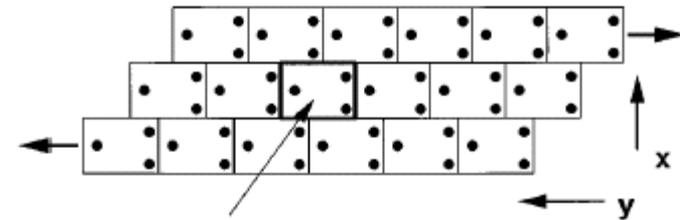
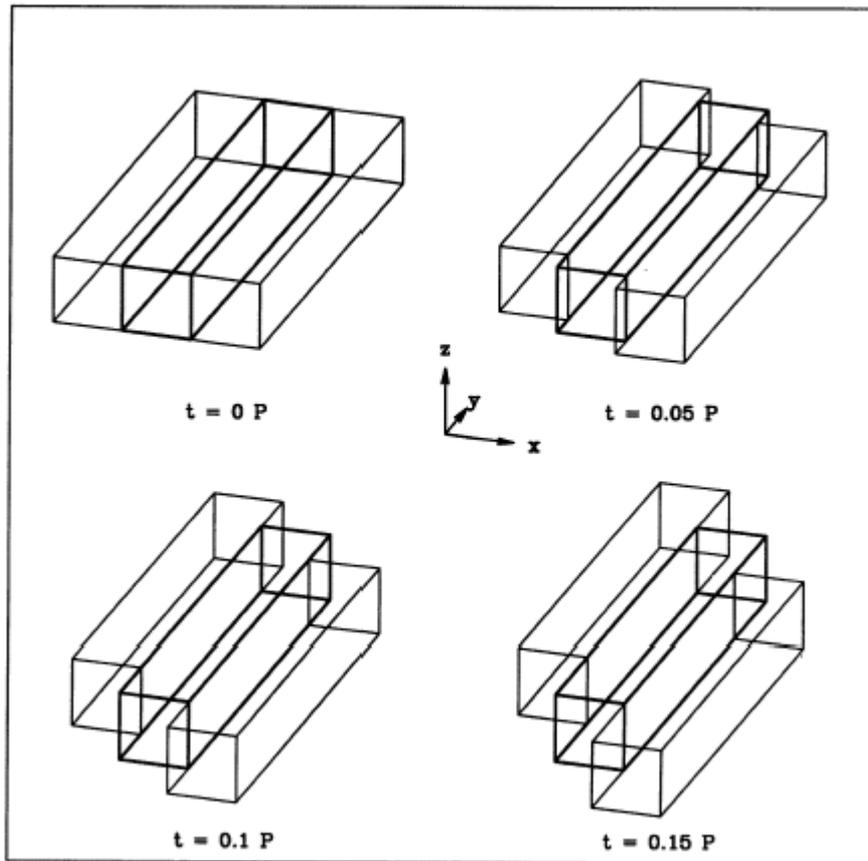


$$V_y = -1.5\Omega x$$

一般には $v_y = 2Ax$
 $A = (R/2) (d\Omega/dR)_{R_0}$

このシア流は安定か？

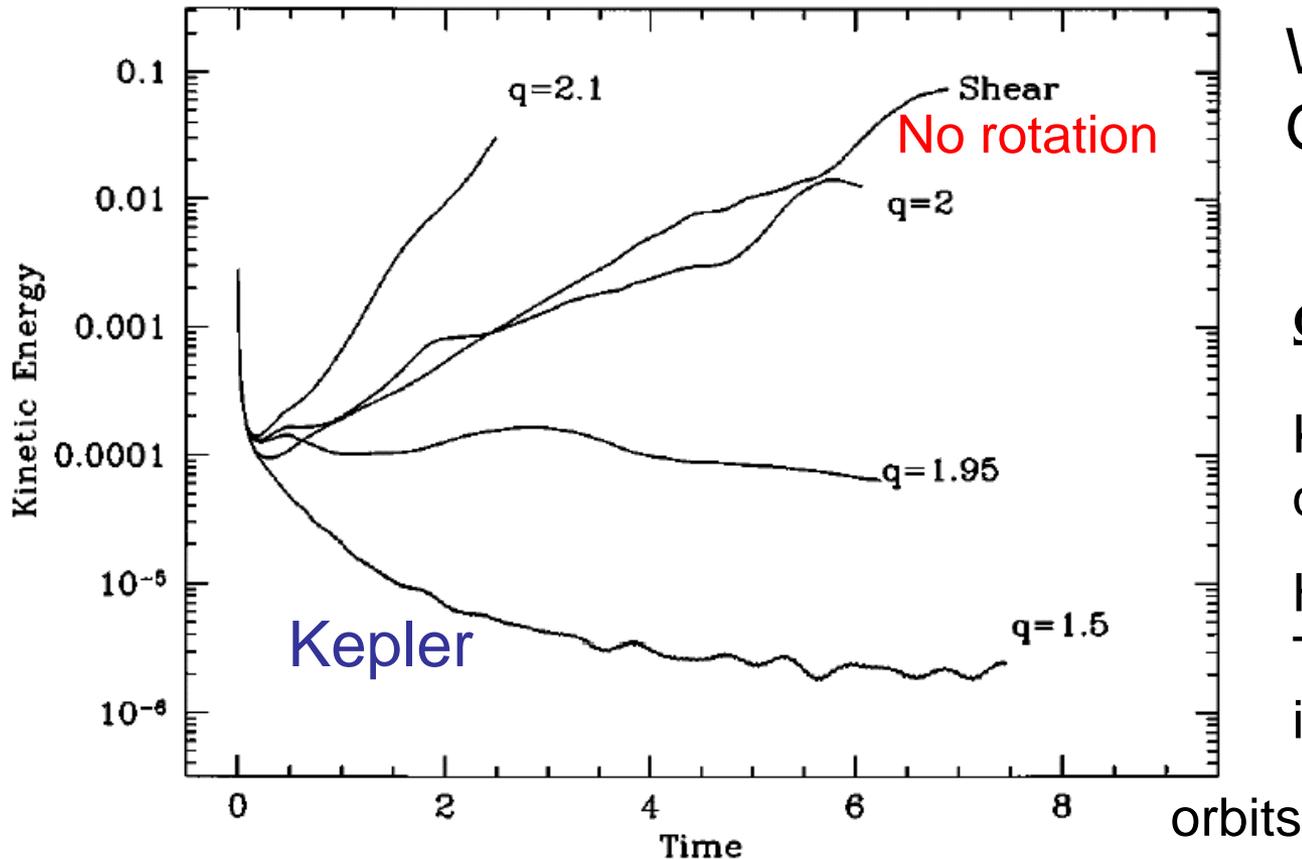
3D Simulation Model



Hawley et al. 1995, ApJ 440, 742

Shearing Box Boundary Condition

Results of 3D Hydrodynamic Simulation



Without Vertical Gravity

$$\Omega(R) \propto R^{-q}$$

Keplerian Disk :
 $q=1.5$

Hydrodynamical
Turbulence Decays
in Keplerian Disks

Result of 3D hydrodynamical simulation using shearing box
(Balbus and Hawley 1998, Rev. Mod. Physics)

Effects of Vertical Gravity

- Entropy $dS/dz < 0 \rightarrow$ Convectively Unstable
- Linear Analysis (Ryu and Goodman 1992)
Angular Momentum is Transported **Inward**
- 3D Hydro-Simulation (Lesur and Ogilvie 2010)

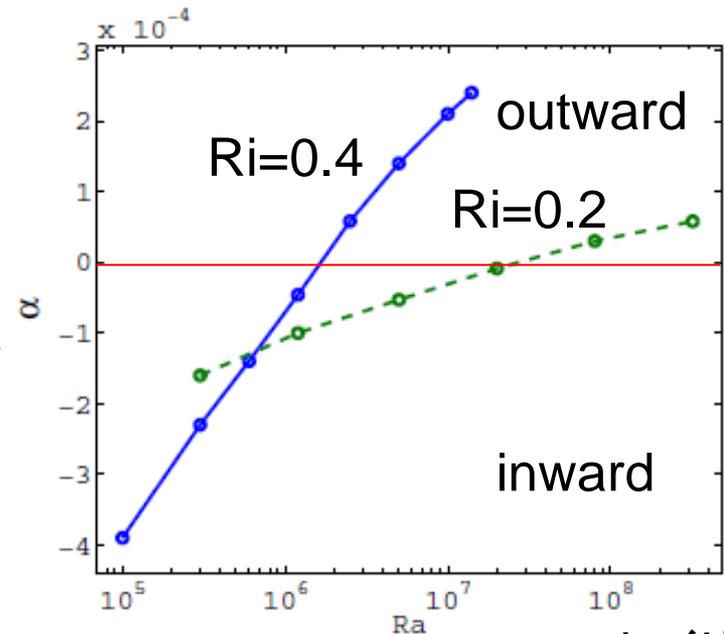
Outward Transport is Possible $\alpha \sim O(10^{-4})$

$$Ra = -N^2 L^4 / \chi \nu$$

$$Ri = -N^2 / S^2$$

N: Brunt-Vaisala Frequency

- Linear Analysis including Radial Entropy Gradient (Volponi 2010)



Lesur and Ogilvie 2010

レイリー数

Global 3D Hydrodynamic Simulations of Differentially Rotating Torus

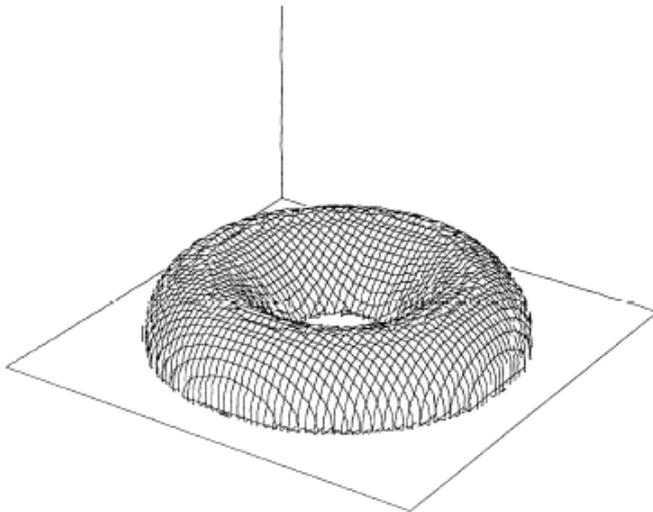


FIG. 4a

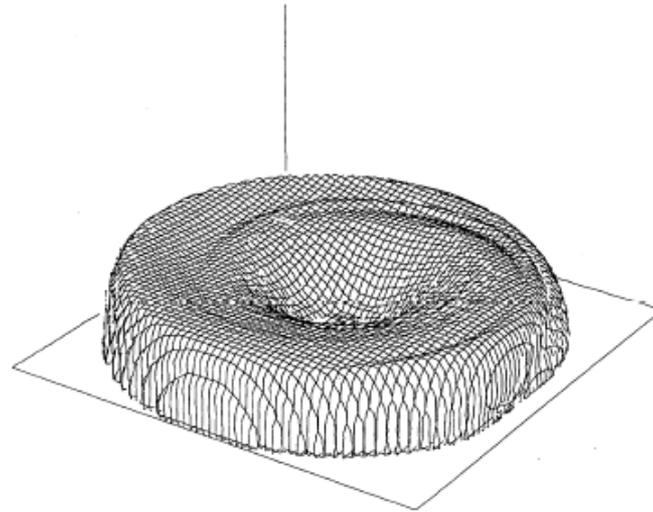


FIG. 4b

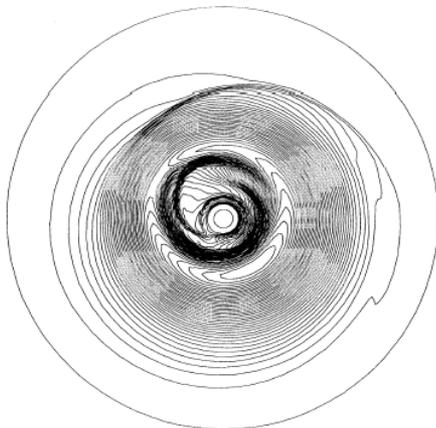
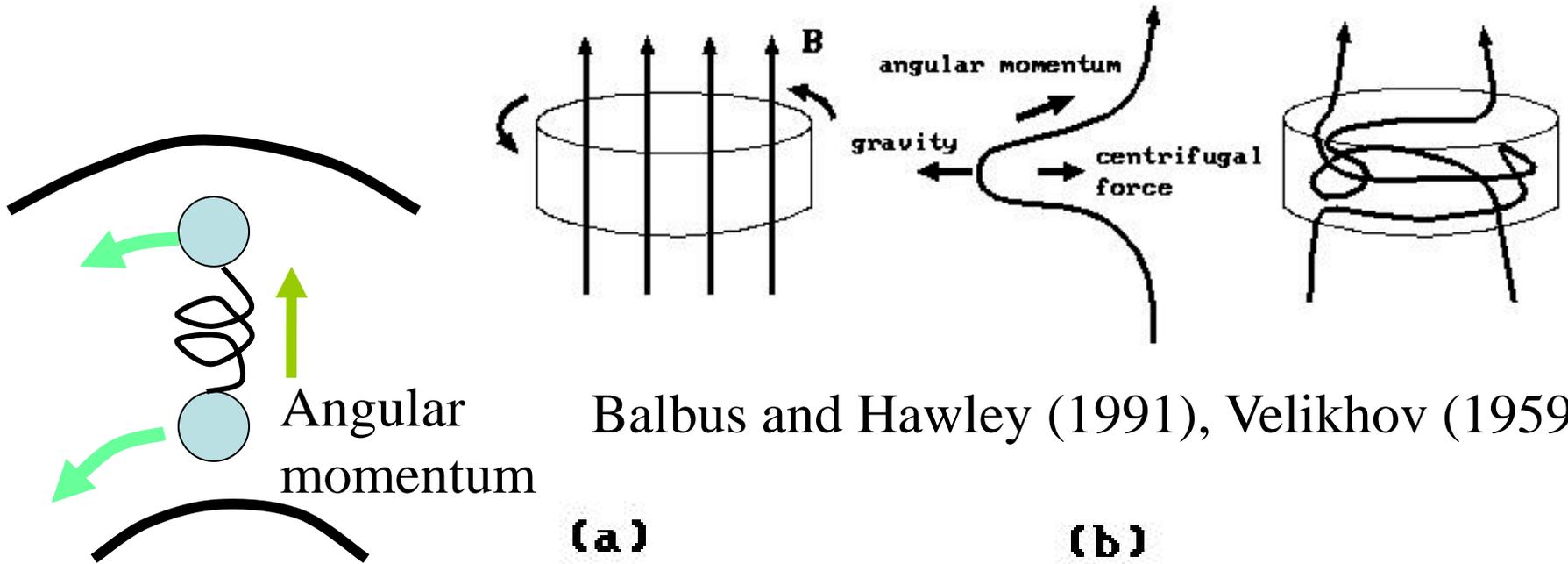


FIG. 4c

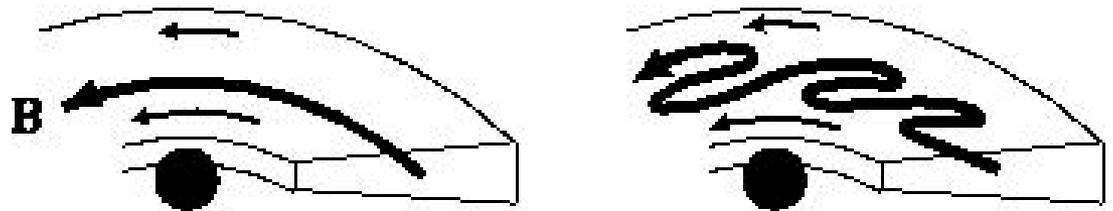
Hawley 1991, ApJ 381, 496

Non-axisymmetric ($m=1$) mode known as Papaloizou-Pringle instability grows but does not develop into turbulence

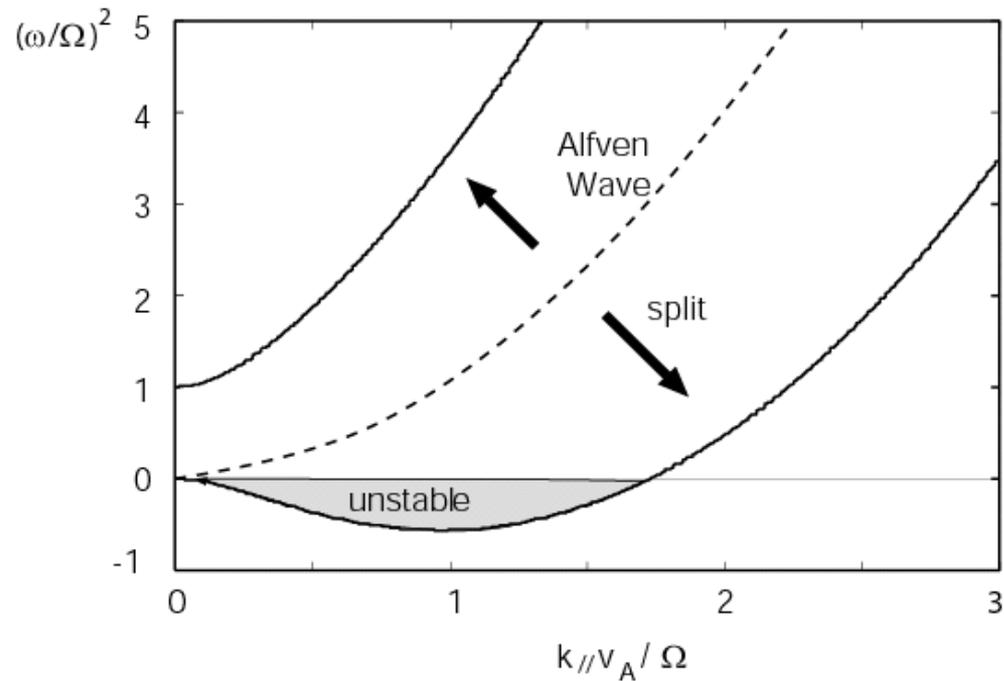
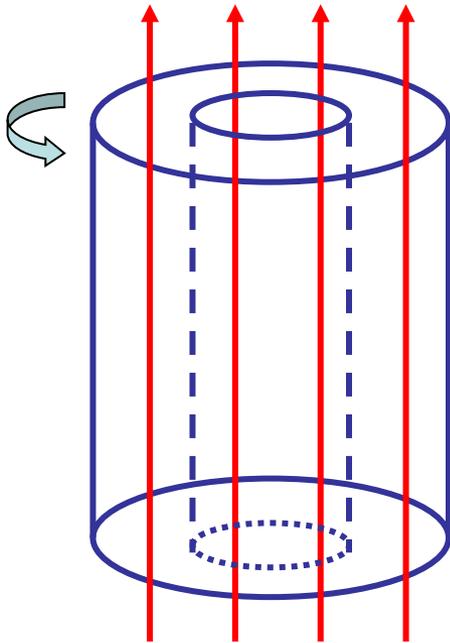
Magneto-Rotational Instability (磁気回転不安定性)



Balbus and Hawley (1991), Velikhov (1959)



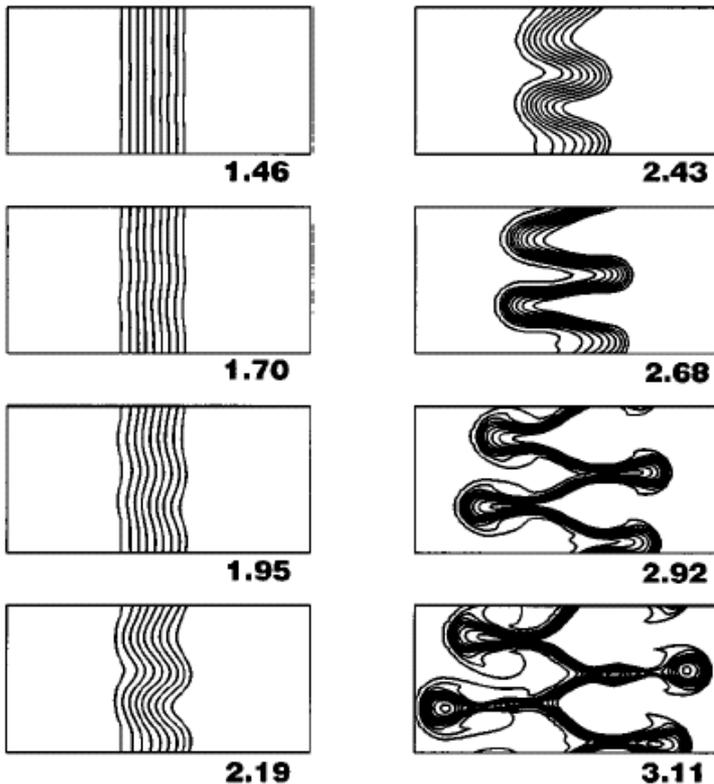
Linear Growth Rate of MRI



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

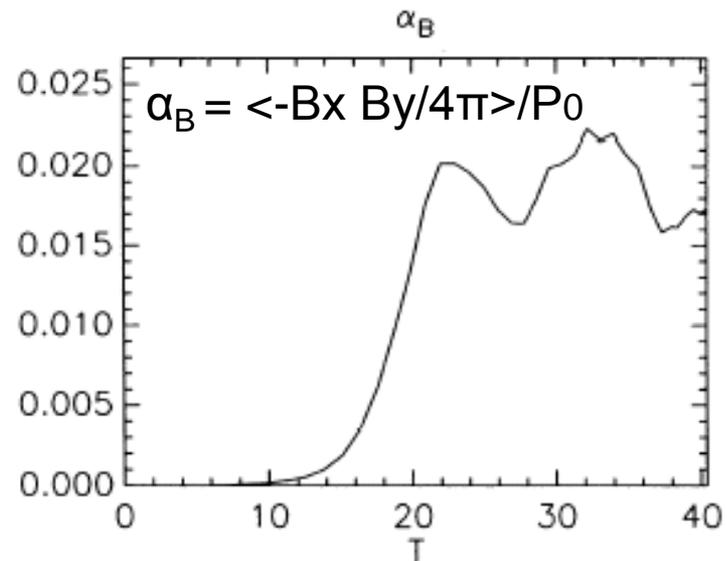
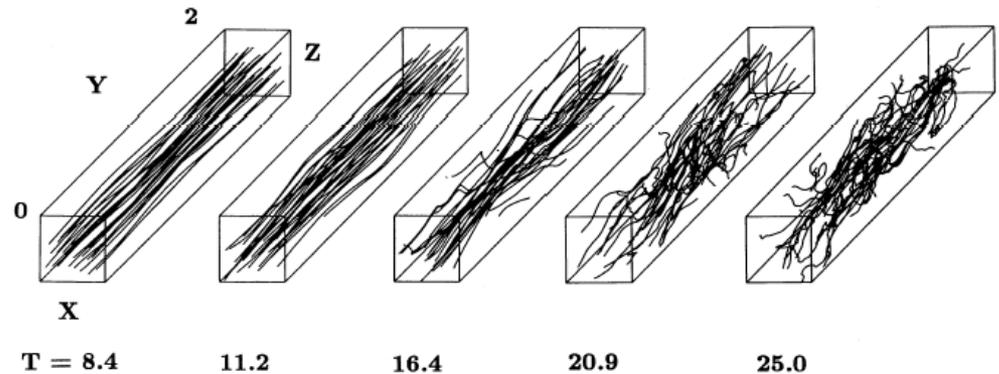
MRI grows in time scale of rotation

3D MHD Simulation of MRI



Magnetic field lines

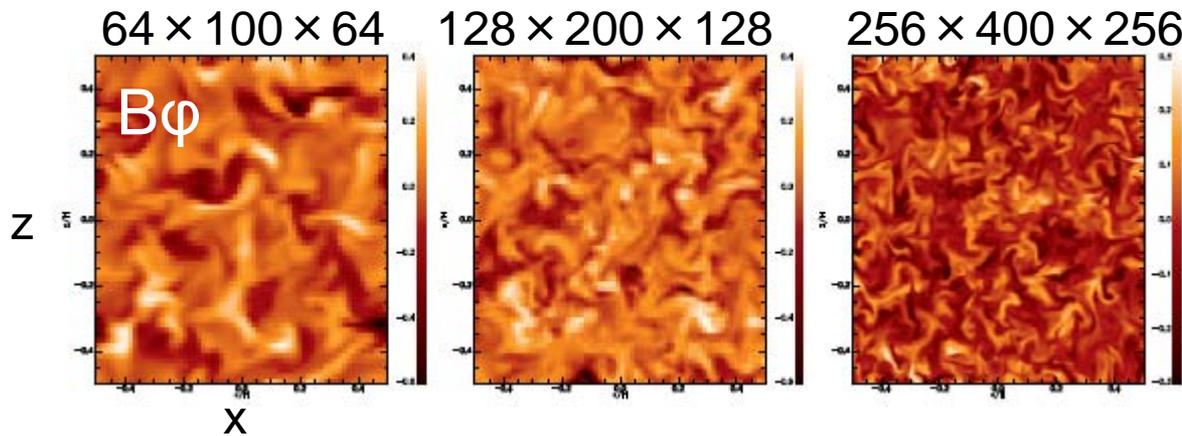
Hawley and Bulbus 1991, 1998



Matsumoto and Tajima 1995

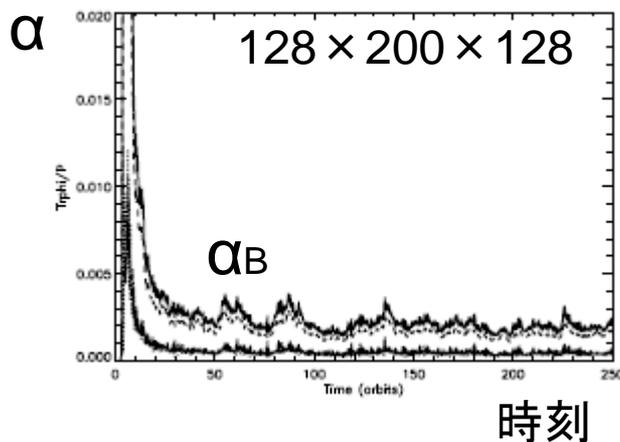
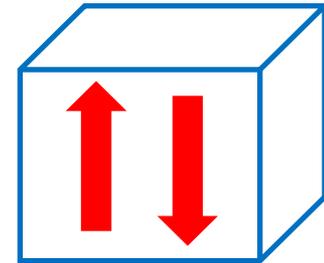
Convergence Problem

- Net Flux = 0、周期境界条件のもとでは解像度を高めると角運動量輸送率が小さくなる

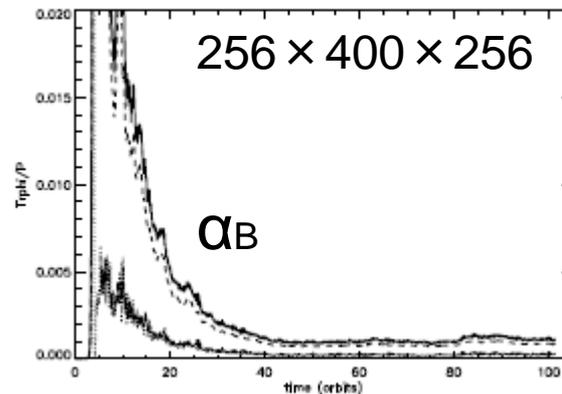


初期条件 (net zero)

$$B_z = B_0 \sin(2\pi x/H)$$



時刻

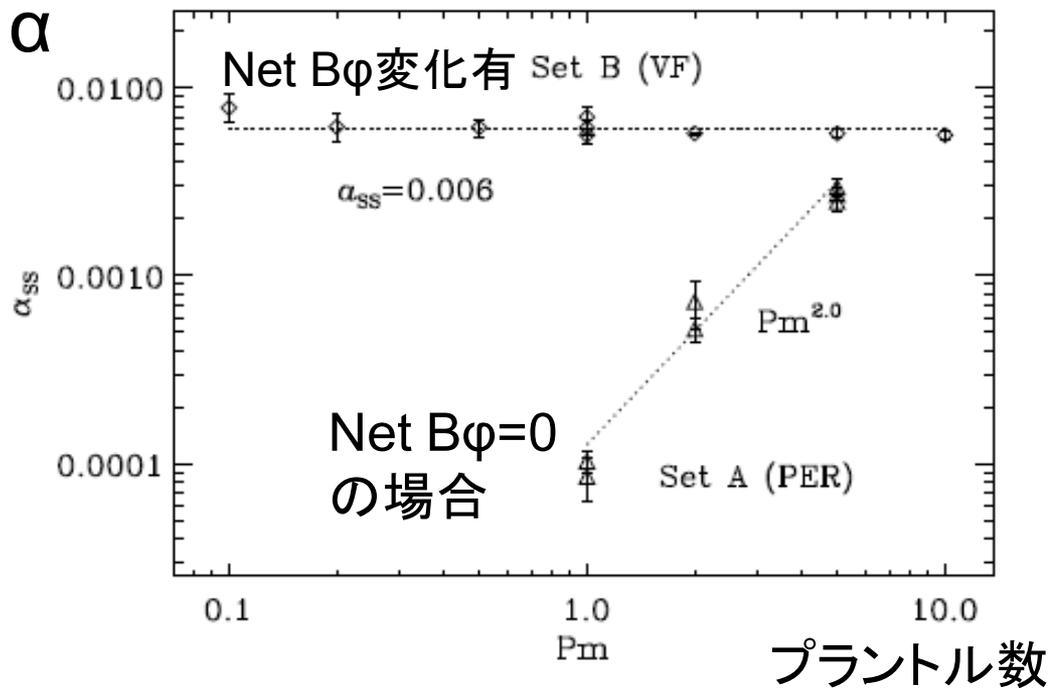


時刻

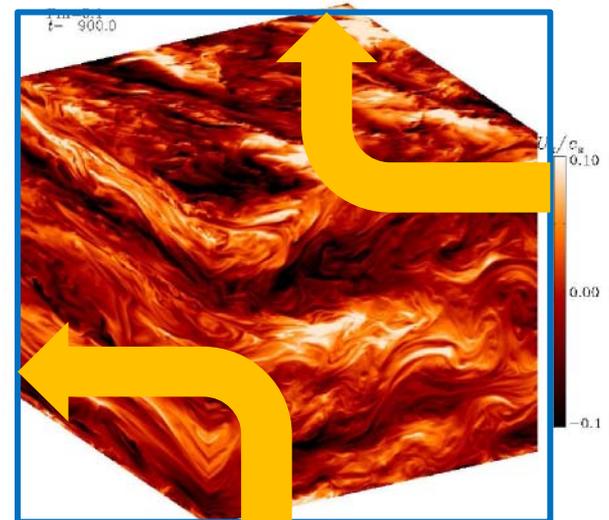
Fromang and
Papaloizou
2007

磁気プラントル数 ($Pm = \nu / \eta$) 依存性

- Net $B\phi = 0$ だと Pm を小さくすると角運動量輸送率が小さくなる。Net $B\phi$ の変化を許すと α の値は一定になり、解像度依存性も小さくなる。

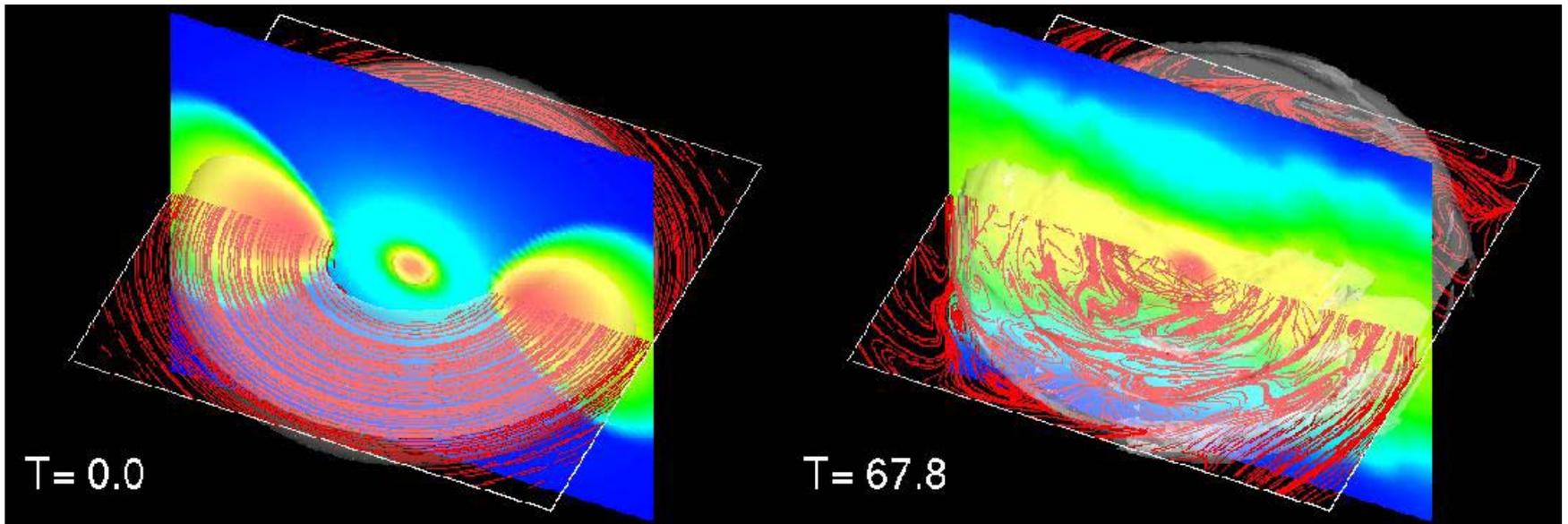


Kapyla and Korpi 2011



Z方向の境界で $B_x = B_y = 0$
 $\partial B_z / \partial z = 0$ の境界条件で計算した場合の V_x の分布

Global 3D MHD Simulation of Differentially Rotating Torus



Initial Condition

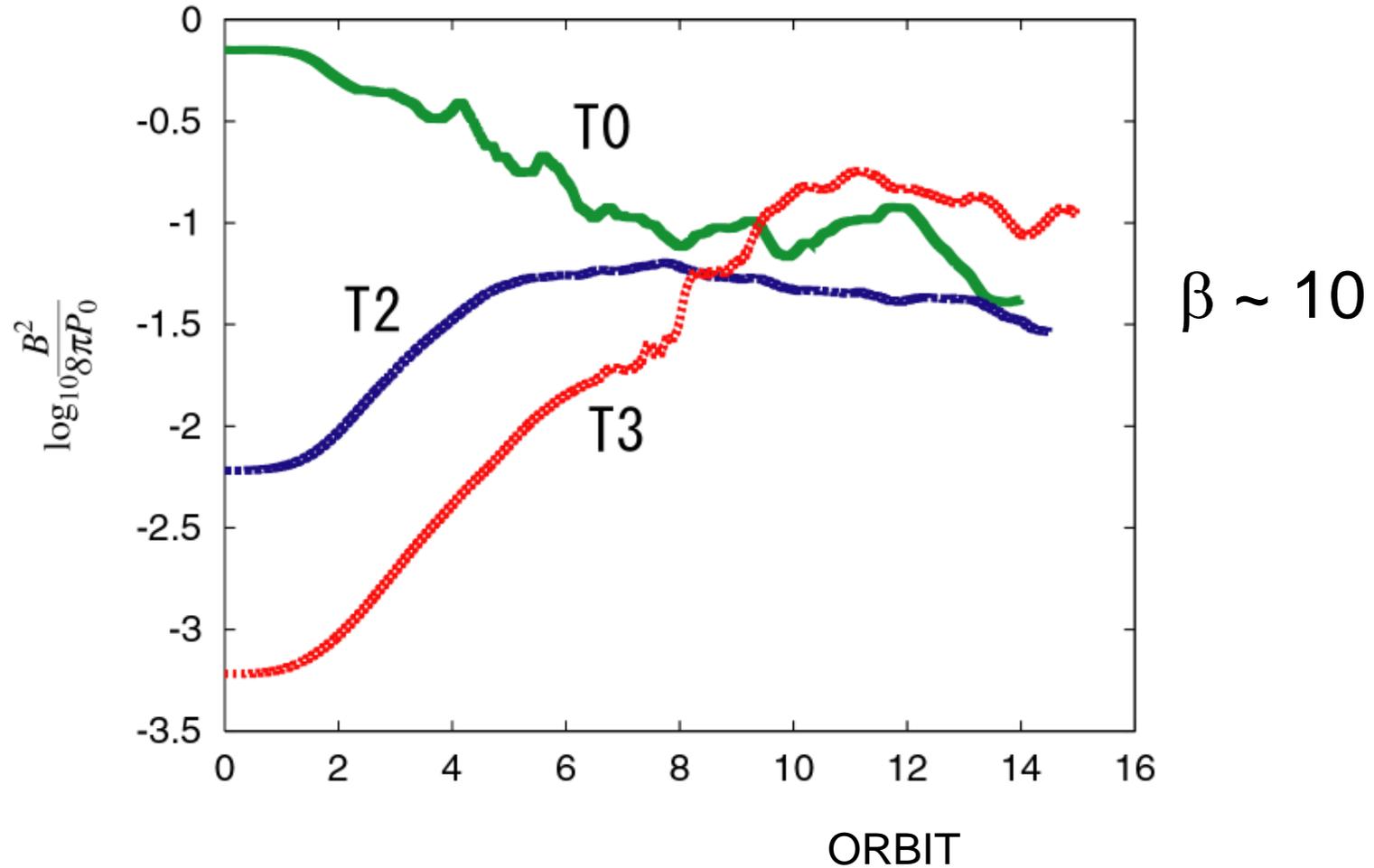
$$\beta = P_{\text{gas}}/P_{\text{mag}}=100$$

After 10rotation

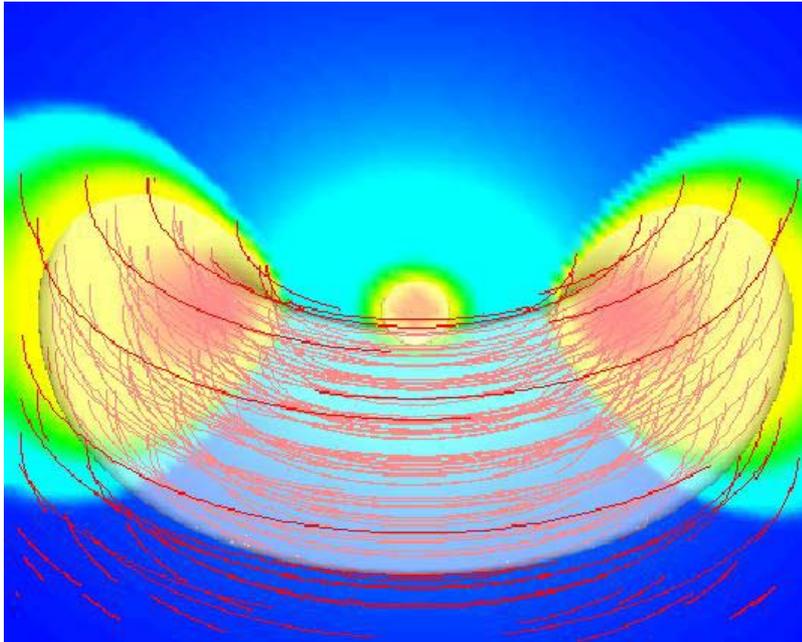
200*64*240 grid points

Matsumoto 1999

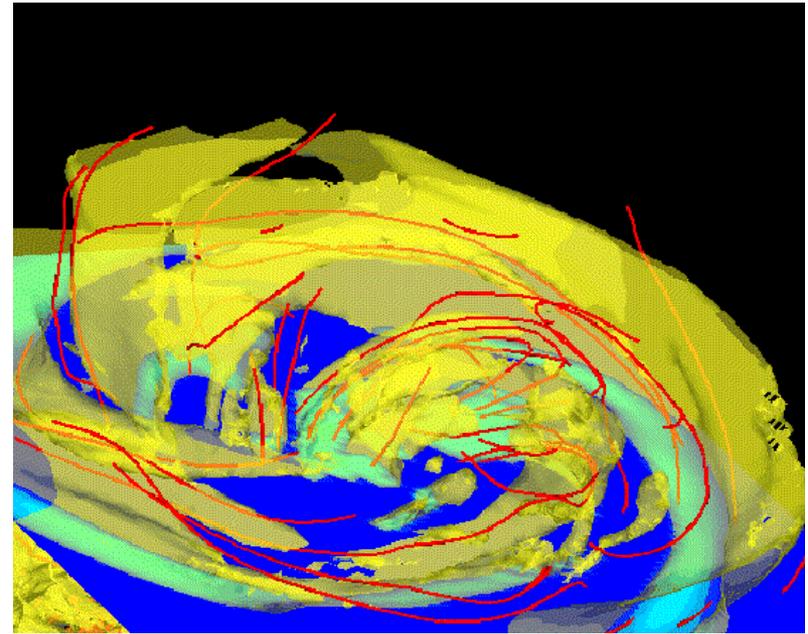
Dependence on the Initial Magnetic Field Strength



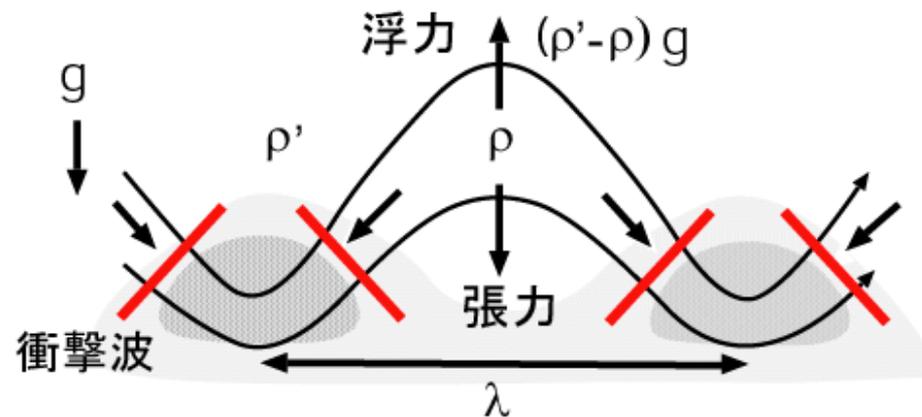
Formation of Buoyantly Rising Loops



初期条件

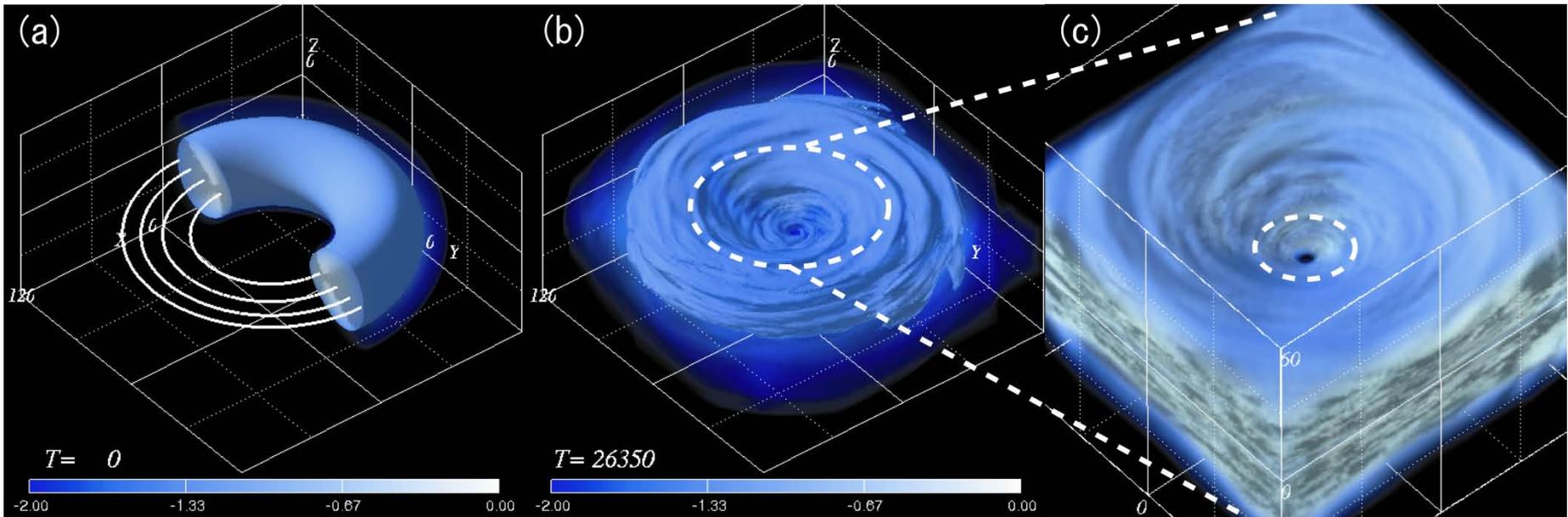


Machida et al. 2000



Parker
Instability

Global 3D MHD Simulations of Black Hole Accretion Flows

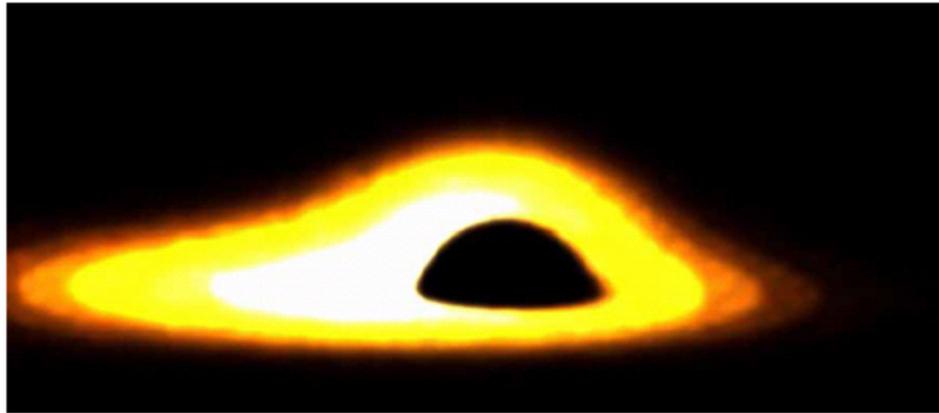


Initial state

$t=26350$

Machida et al. 2003

How a Black Hole Looks Like ?

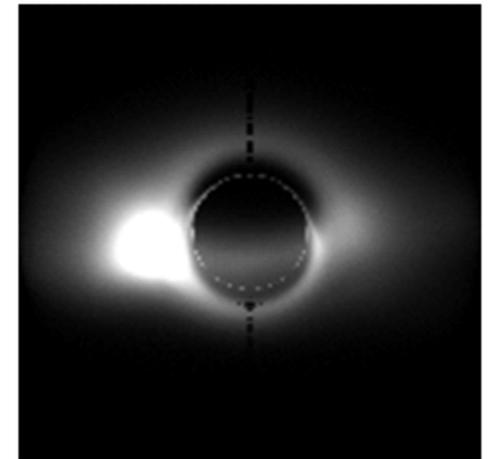
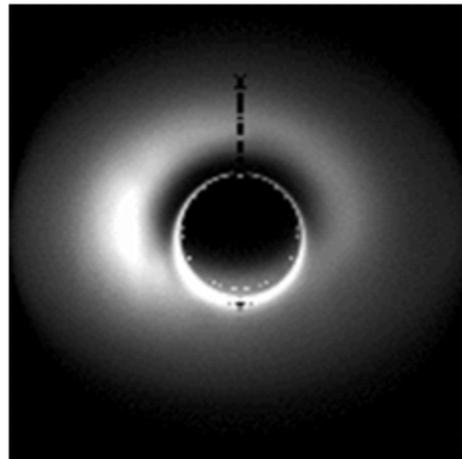
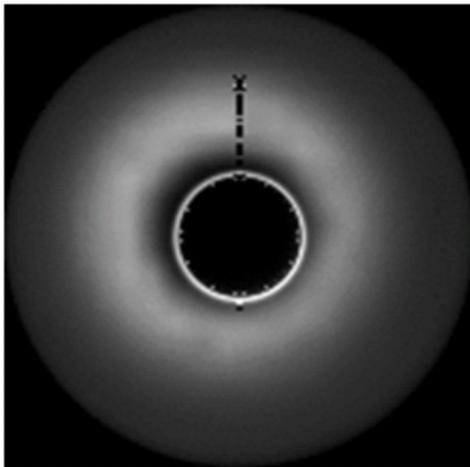


J. Fukue 1988

Inclination 5

45

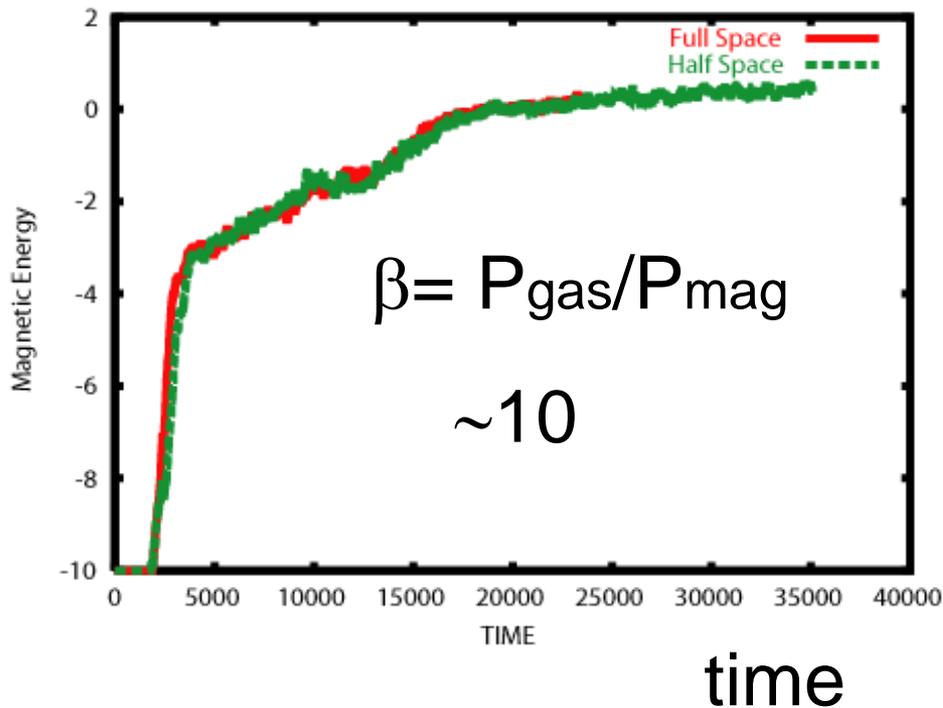
75



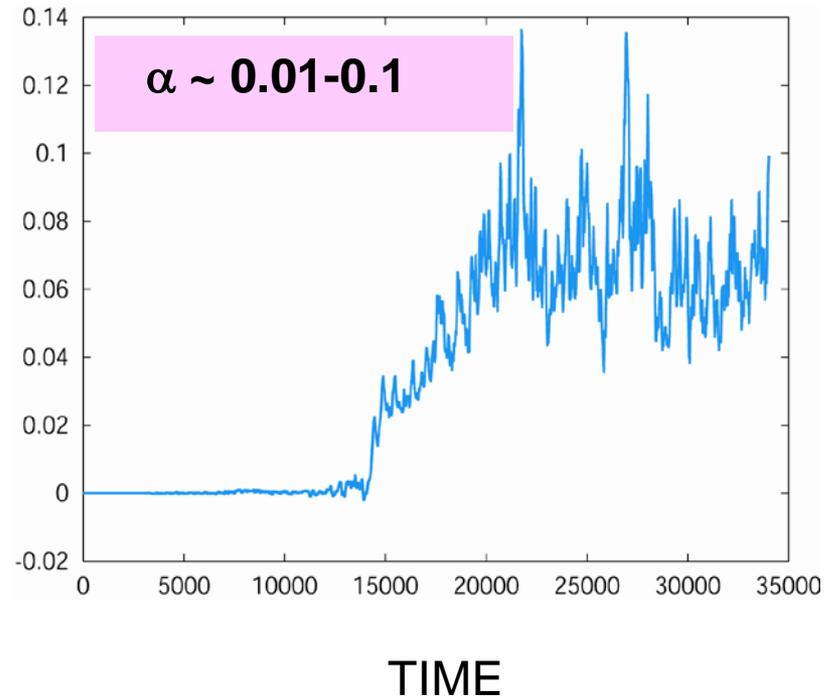
Calculated by M. Bursa²⁰

Amplification of Magnetic Energy and Angular Momentum Transport

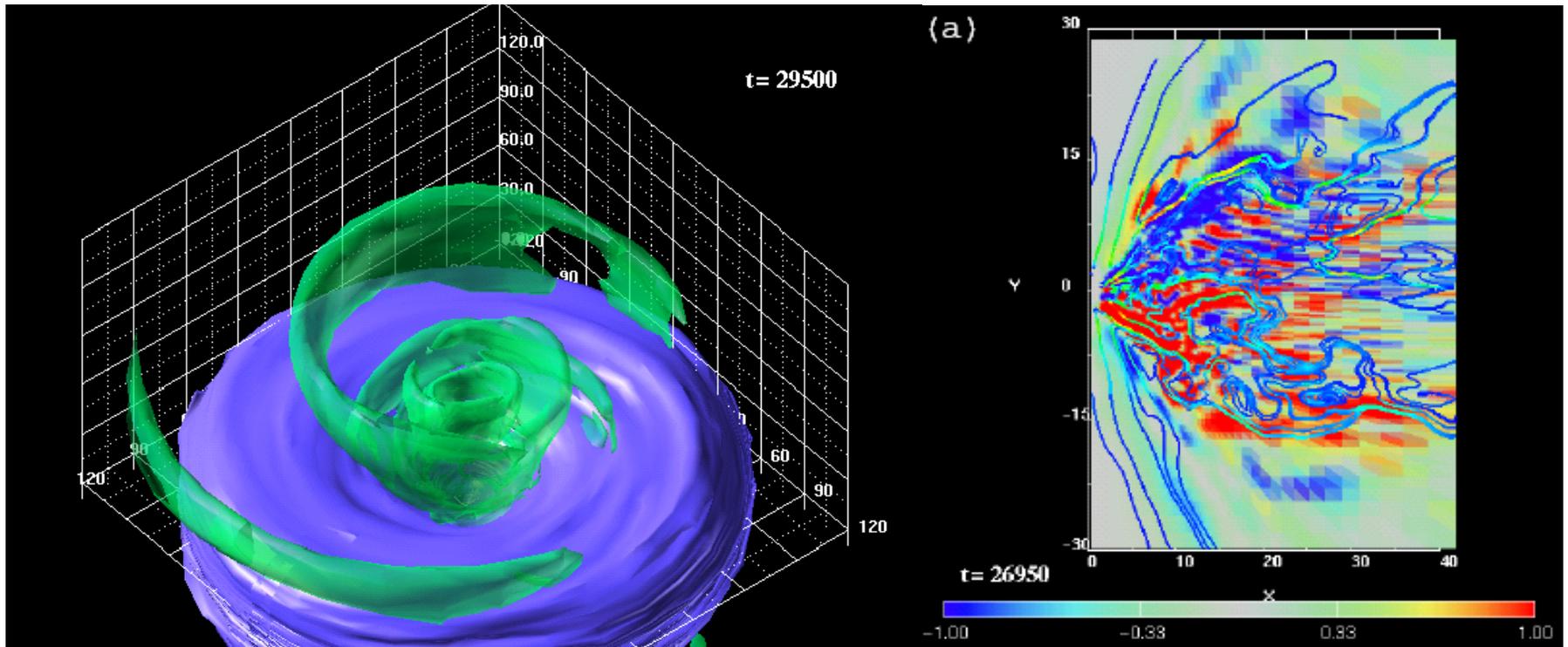
Magnetic Energy



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



Formation of Outflows



Isosurface of $v_z=0.05c$

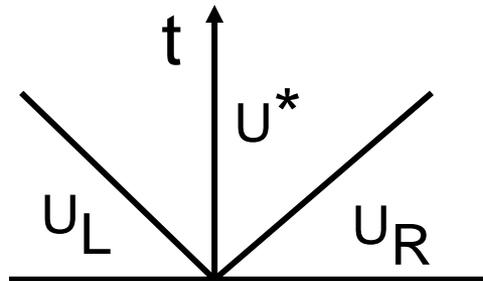
Magnetic field lines and
azimuthal magnetic field

Machida et al. 2008

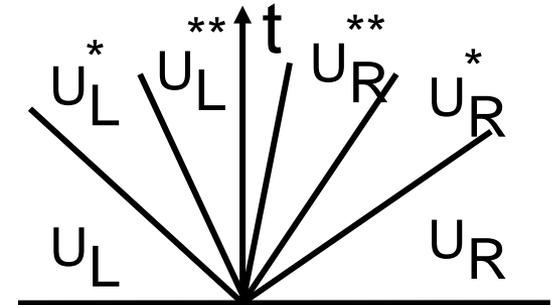
磁気流体シミュレーションエンジン改訂

- HLLD Scheme (Miyoshi and Kusano 2005)

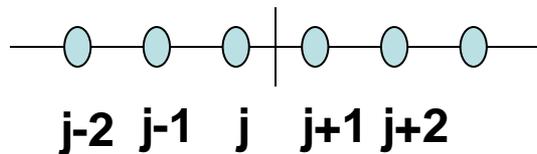
HLL
Scheme



HLLD
Scheme



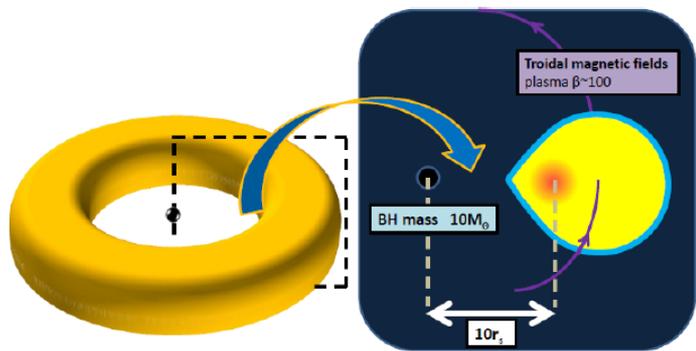
- MP5 Scheme (Suresh and Huynh 1997)



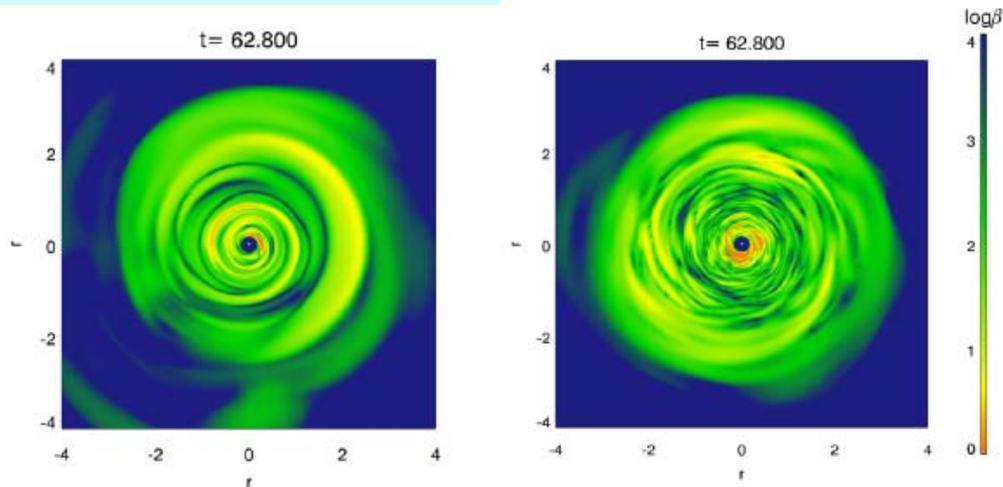
数値拡散を抑制するため、セル境界値を空間5次精度で求め、数値振動抑制のためのリミターの許容範囲を広げて極大、極小がならされてしまわないようにする

- $\text{div } \mathbf{B} = 0$ からのずれを移流拡散
(GLM法: Dedner et al. 2002)

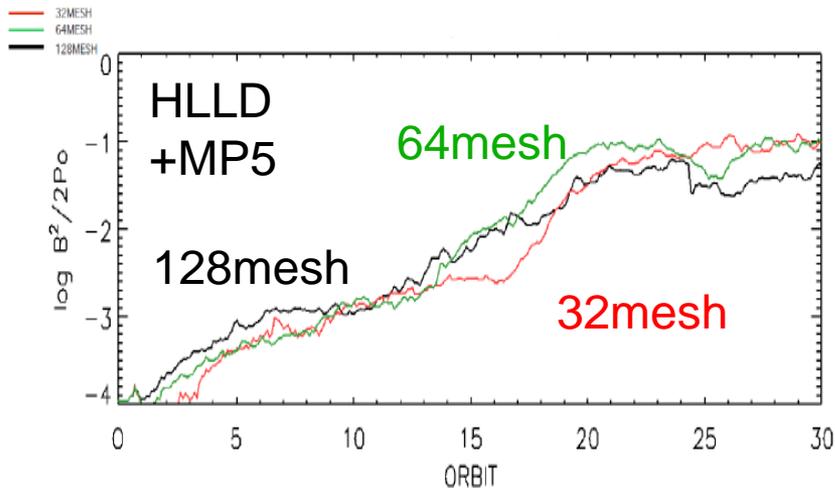
円盤ダイナモシミュレーション



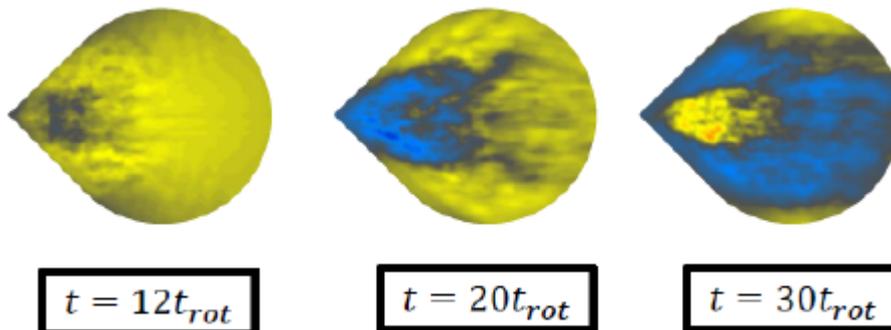
初期条件



方位角方向64メッシュ計算の $\beta = P_{\text{gas}}/P_{\text{mag}}$ 分布
左:空間2次精度、右:空間5次精度(MP5)

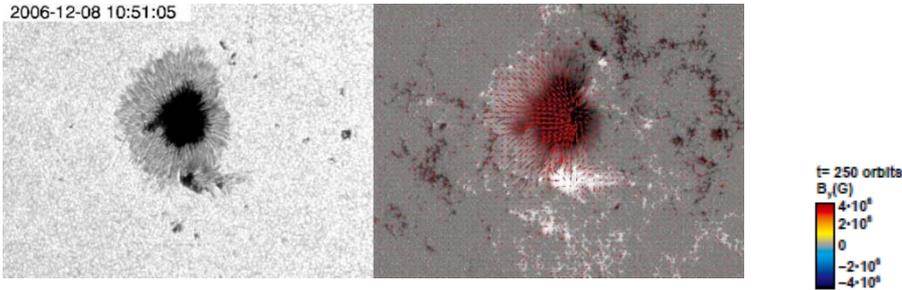


磁気エネルギー変化の解像度依存性

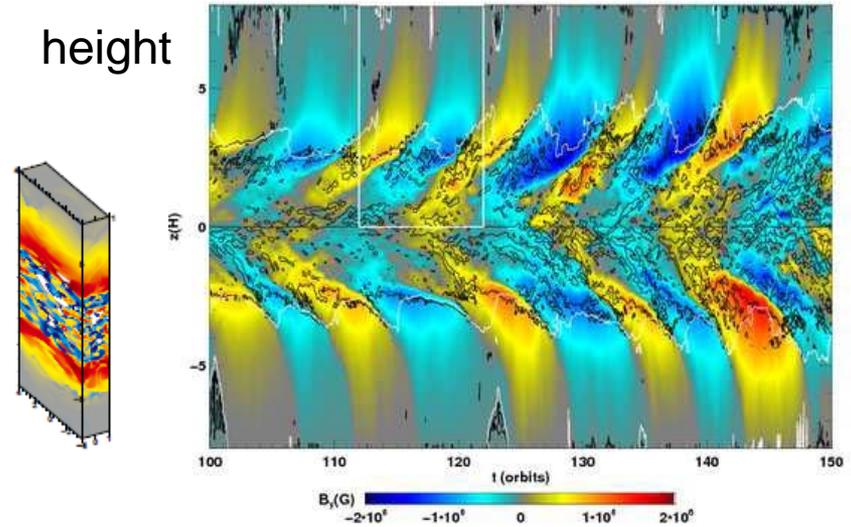


方位角磁場分布: 黄色+, 青-
10回転時間程度毎に磁場方向が反転 24

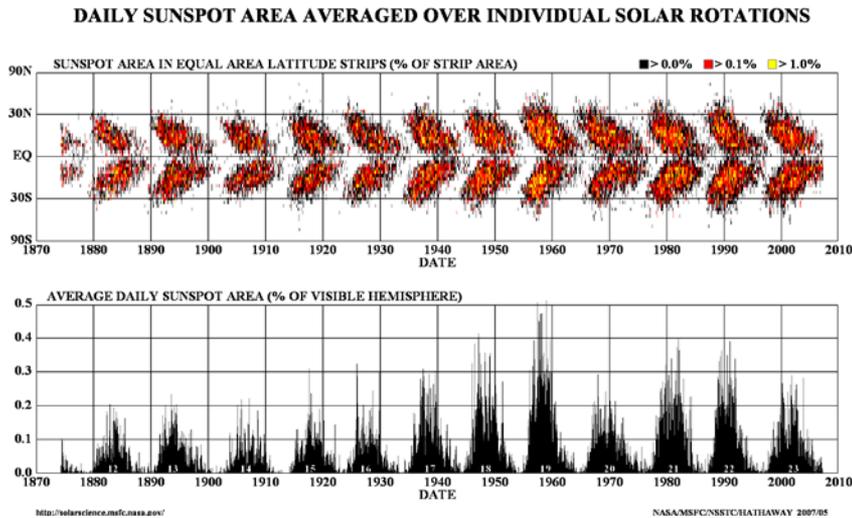
Butterfly Diagram



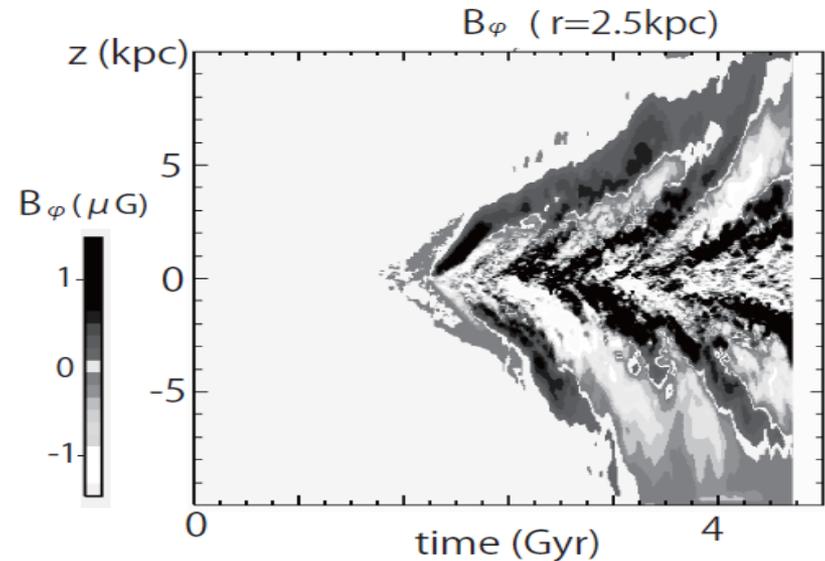
Optical image of sunspots



Shi et al. (2010) local simulation



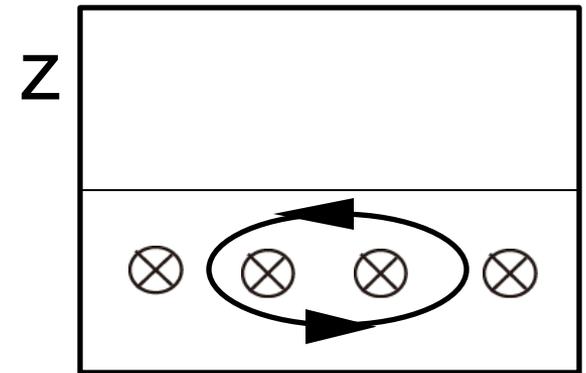
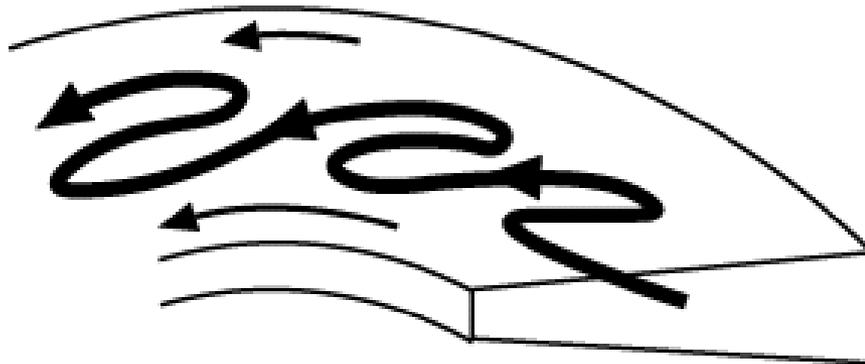
Butterfly Diagram of Sunspots (NASA)



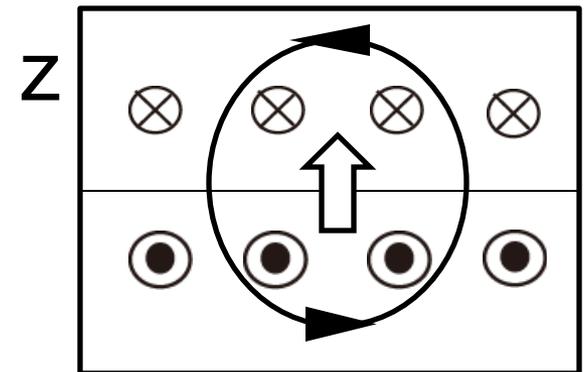
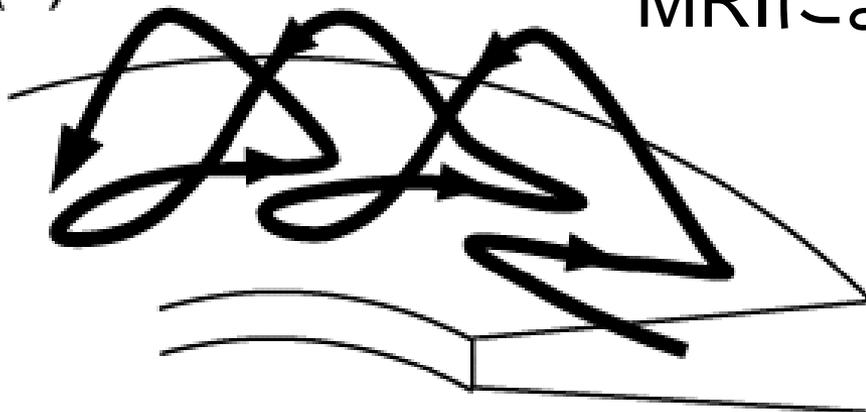
Machida et al. (2013)
Global simulation

方位角磁場の反転メカニズム

(a)



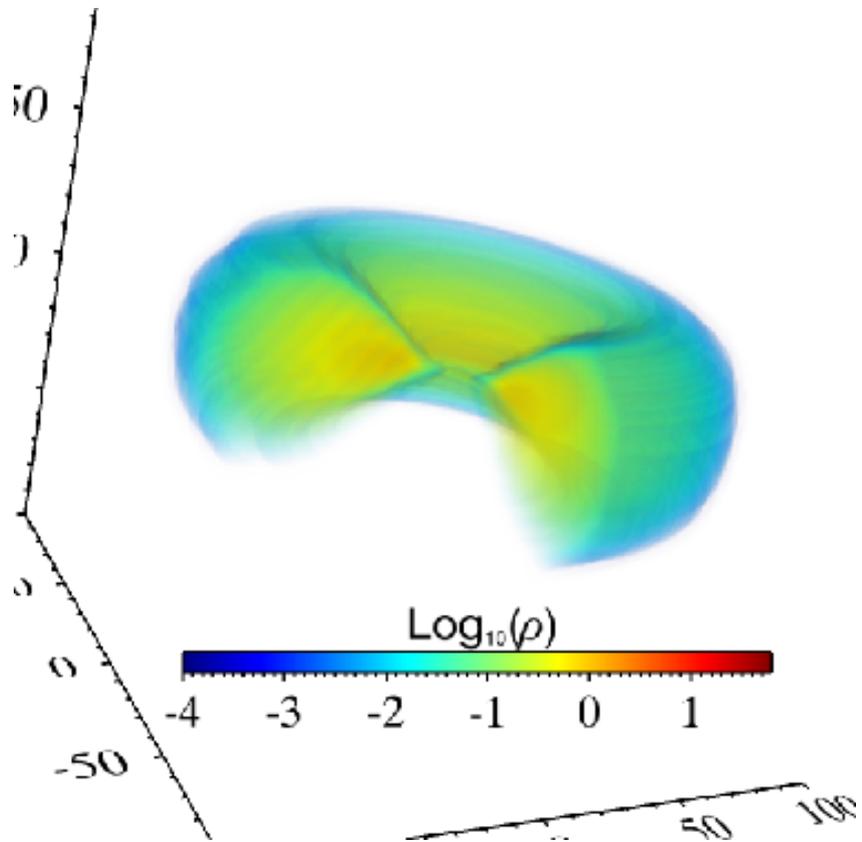
(b)



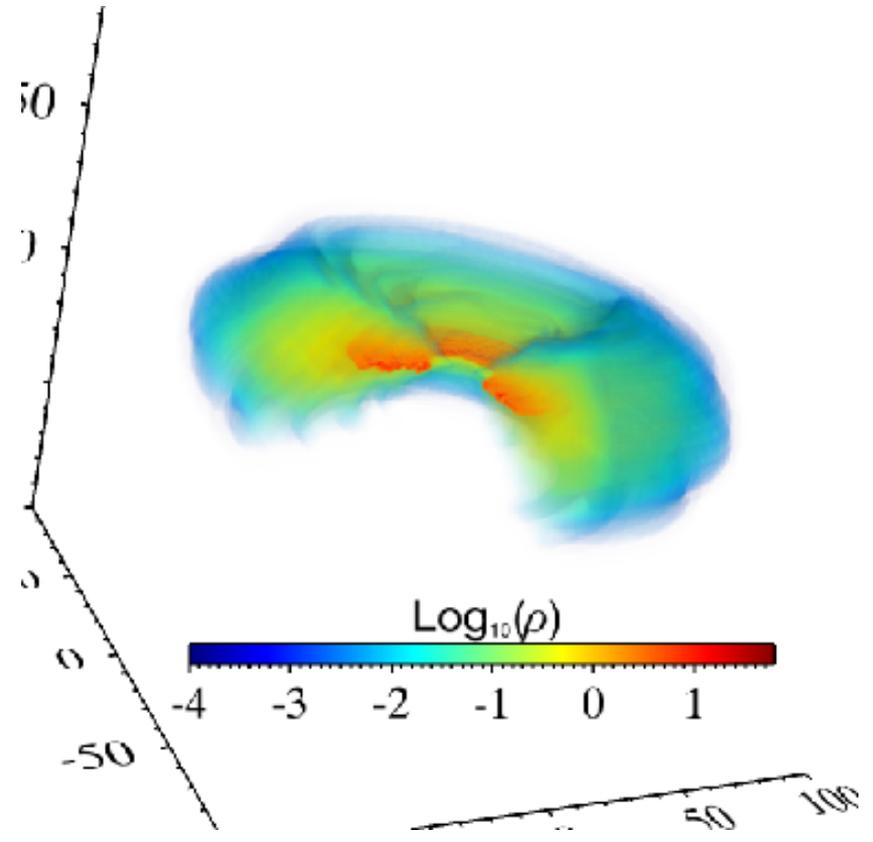
MRIによる磁場増幅

パーカー不安定性による磁束浮上

State Transition by Cooling



(256,64,256)メッシュ計算で
準定常降着流が形成された後、
輻射冷却項を加える



冷却不安定性の成長による
低温高密度領域の形成

Summary

- 様々な降着天体の観測から示唆されている $\alpha = 0.01-0.1$ の効率良い角運動量輸送は磁気回転不安定性によって励起される磁気乱流のマクスウェルストレスによって説明できる。
- 磁気回転不安定性による磁場増幅と鉛直方向への磁束流出により、方位角磁場方向が10回転毎に反転する円盤ダイナモが発生する。
- 原始惑星系円盤の一部など磁気回転不安定性に対して安定な領域における角運動量輸送についてはさらに研究が必要。

END