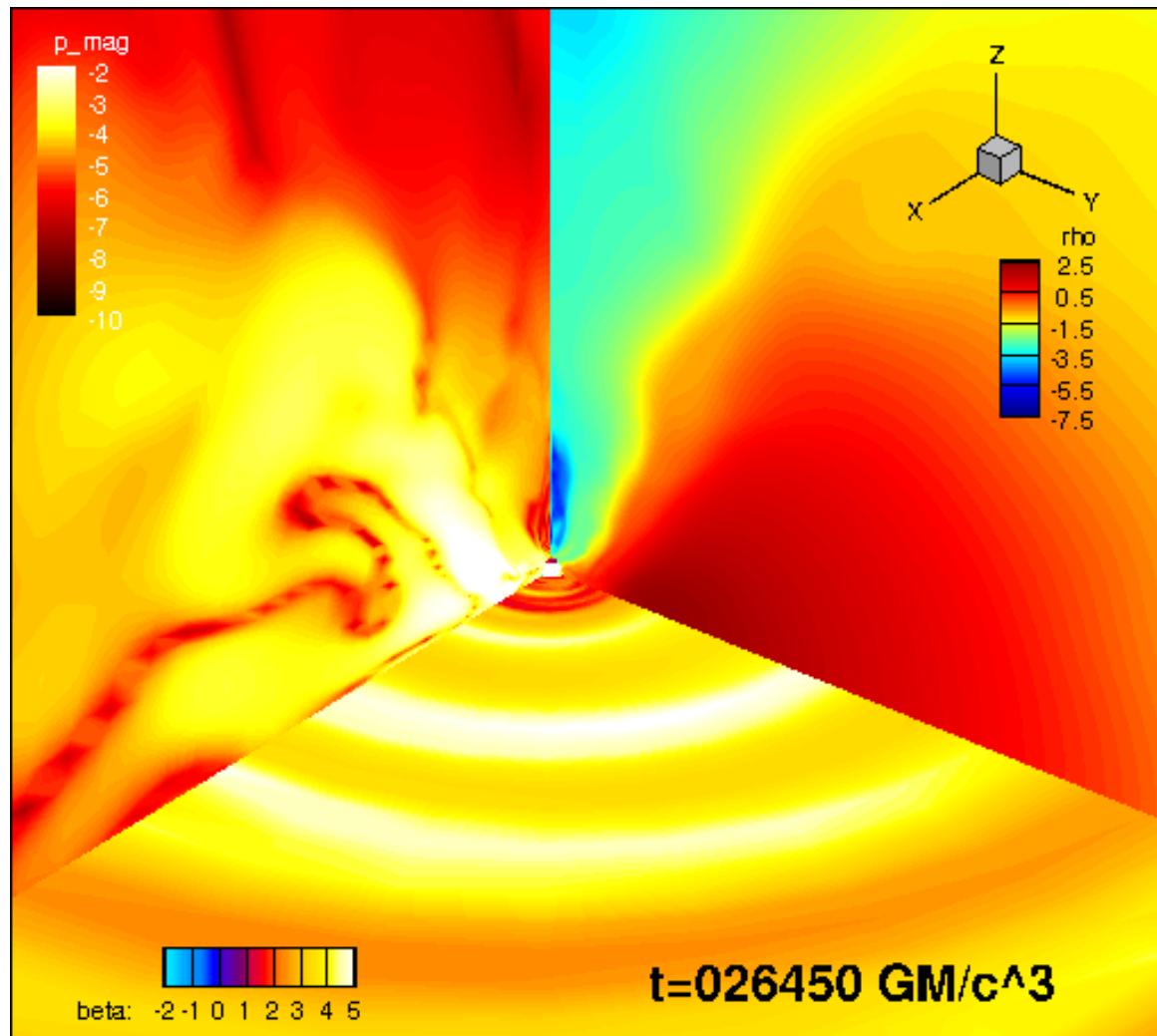


# 3D GRMHD simulation of accretion flows onto BH and relativistic jet formation



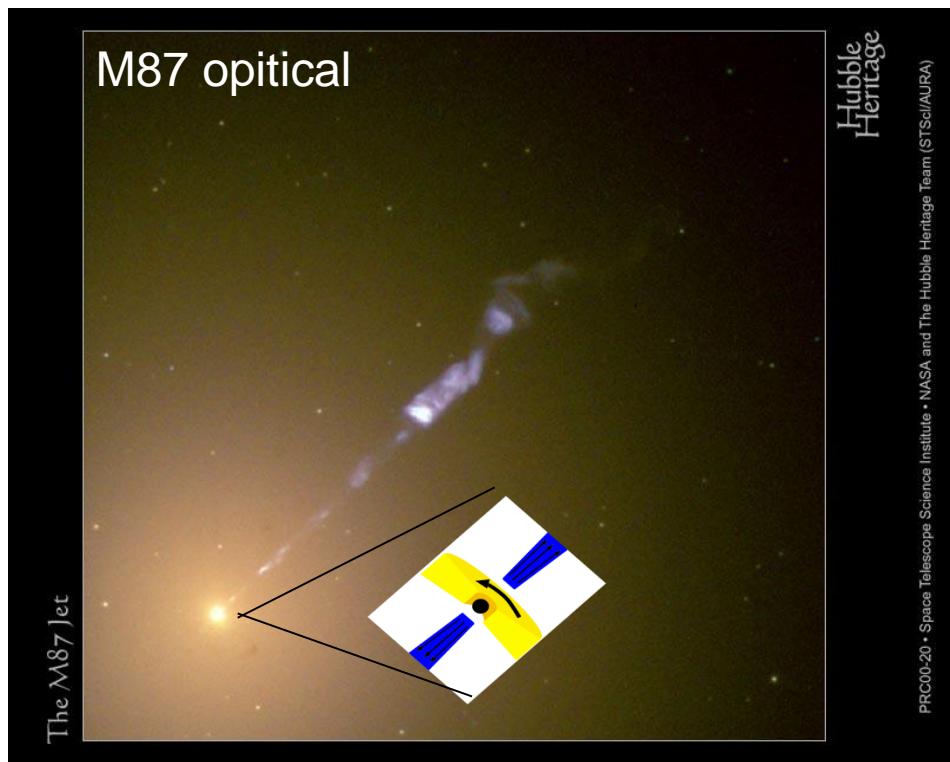
Akira Mizuta(RIKEN)

Toshikazu Ebisuzaki  
(RIKEN)

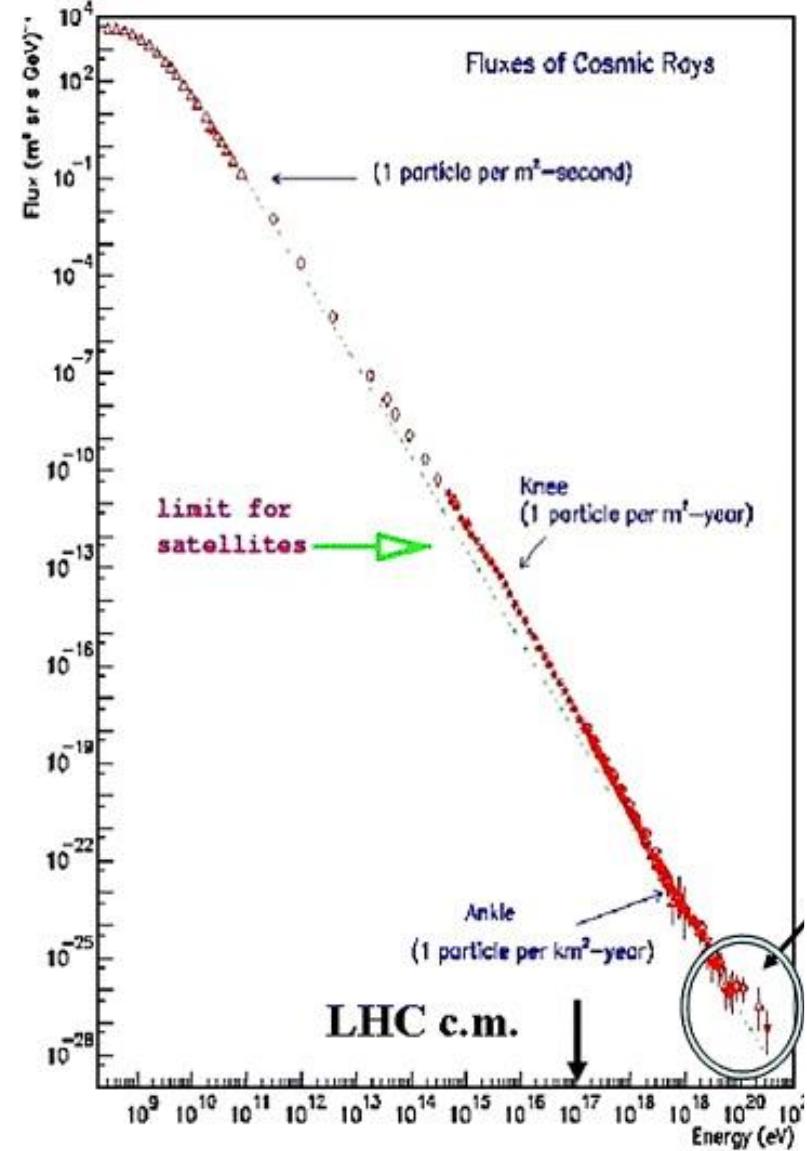
Toshiki Tajima  
(UCI)

Shigehiro Nagataki  
(RIKEN)

# AGN : UHECR accelerator ? (1)



M87 optital



銀河中心超巨大ブラックホールを取り囲む降着流の一部はほぼ光速の相対論的ジェットを生成する

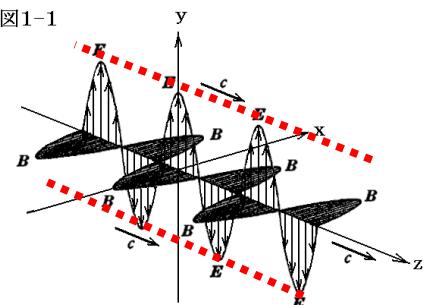
● 宇宙線の加速源は？

SNRs, neutron stars, GRBs, AGNs

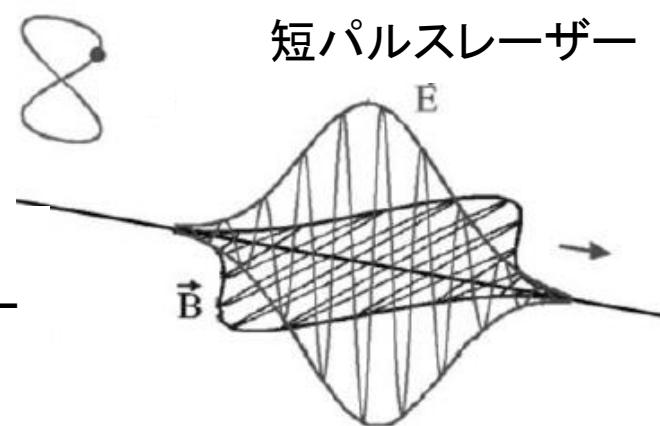
● 加速原理は？ Fermi 加速, reconnection 加速 or others ?

# Wakefield acceleration (Tajima & Dawson PRL 1979)

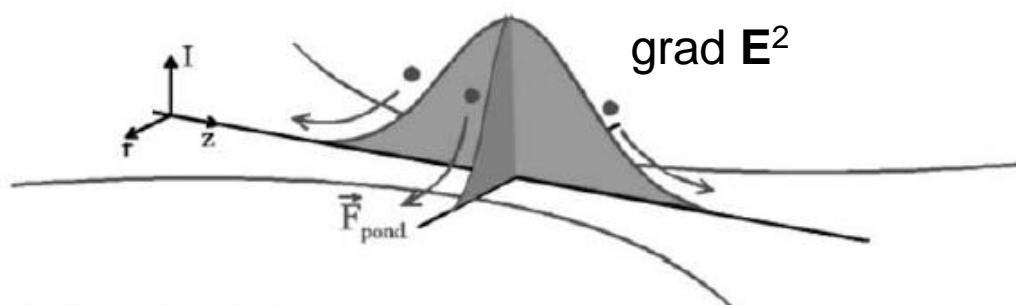
波と物質の相互作用による加速機構



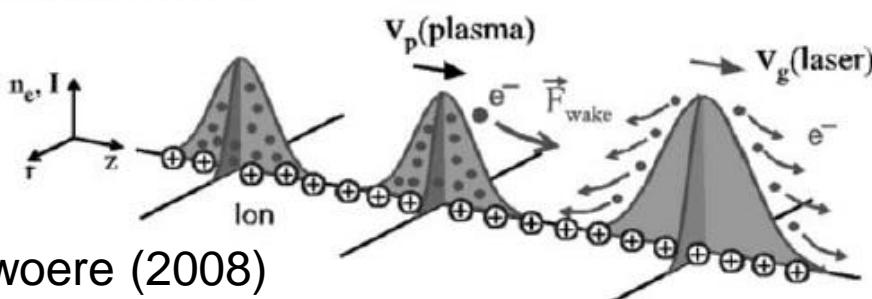
プラズマ中に等振幅レーザー



b) Ponderomotive force



c) Wake field acceleration



Schwoere (2008)

$$\mathbf{F} = q \left( \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right)$$

電場の振動による運動で  $\mathbf{v}$  が生じ、 $\mathbf{v} \times \mathbf{B}$  によって進行方向にも振動する  $|\mathbf{v}| \sim c$  となると  $\mathbf{v} \times \mathbf{B}$  による振動も大きくなる。

外場である電場( $\mathbf{E}^2$ )に勾配があると電子は電場の弱い方向に集まる  
(ポンデラモーティブポテンシャル)

レーザープラズマでは超高強度 ( $I \sim 10^{18} \text{ W/cm}^2$ ) で相対論的  
レーザーパルスの後に生じる航跡場  
(wakefield) 中で電子が加速される

- 通常の加速器に比べ高効率  $10 \text{ GeV/m}$   
(通常の加速器の100-1000倍),

Electrons: ~GeV  
Ions : ~数十MeV

相対論的なAlfven wave によっても Wakefield acceleration が可能  
Takahashi+2000, Chen+2002 (NS-NS merger でのSGRB に応用)  
Lyubarsky 2006, Hoshino 2008 でも

# AGN : UHECR accelerator ? (2)

Wakefield acceleration model (excited by Alfvén wave) (Ebisuzaki & Tajima 2014)

Intense laser pulse => strong Alfvén wave ( $v_A \sim c$ , 橫波)

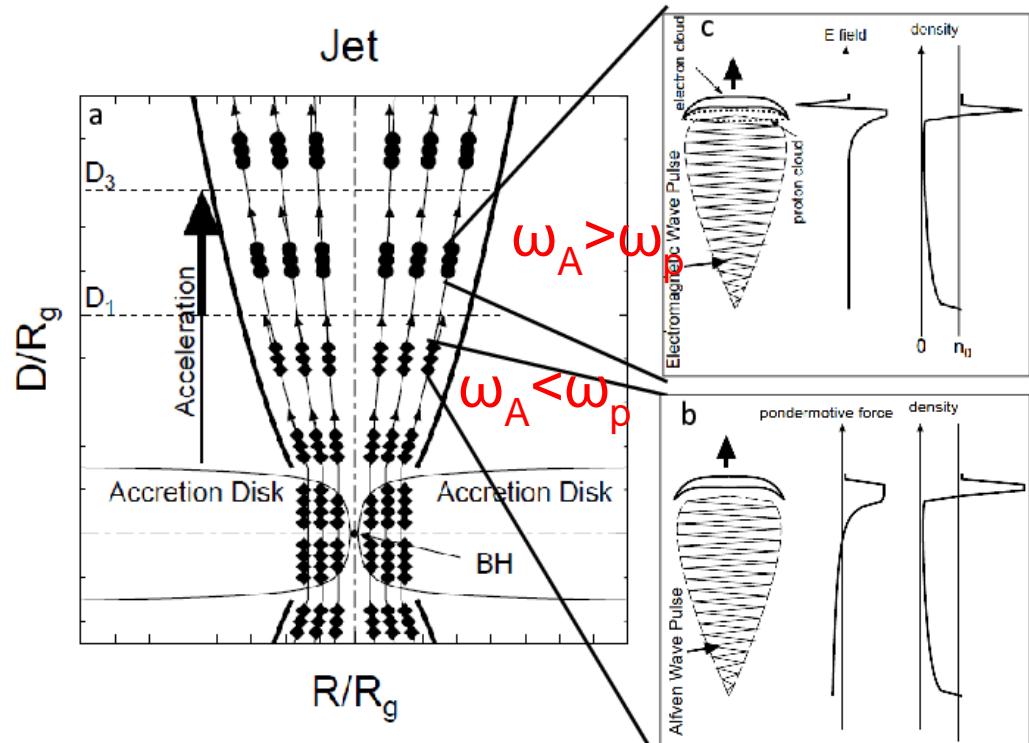
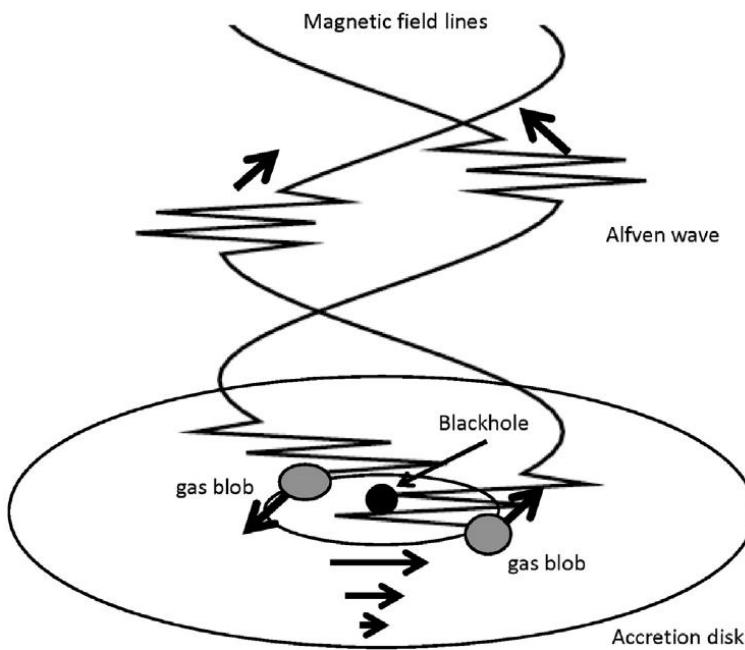
降着円盤内部で励起されたアルフヴェン波がアウトフロー中に伝搬

磁場が十分強ければ光速に近い位相速度となり、プラズマ中を伝搬すれば

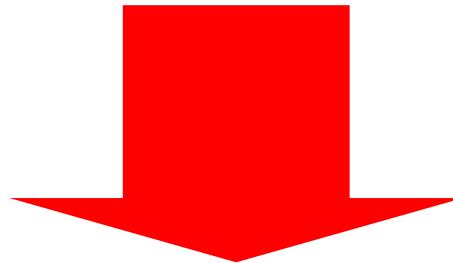
Ponderomotive 力での  
「加速」

$$a = \frac{eE}{m_e \omega_{AC} c} = 2.3 \times 10^{10} \left( \frac{\dot{M}}{0.1 \dot{M}_c} \right) \left( \frac{M_{\text{BH}}}{10^8 M_{\odot}} \right) \gg 1$$

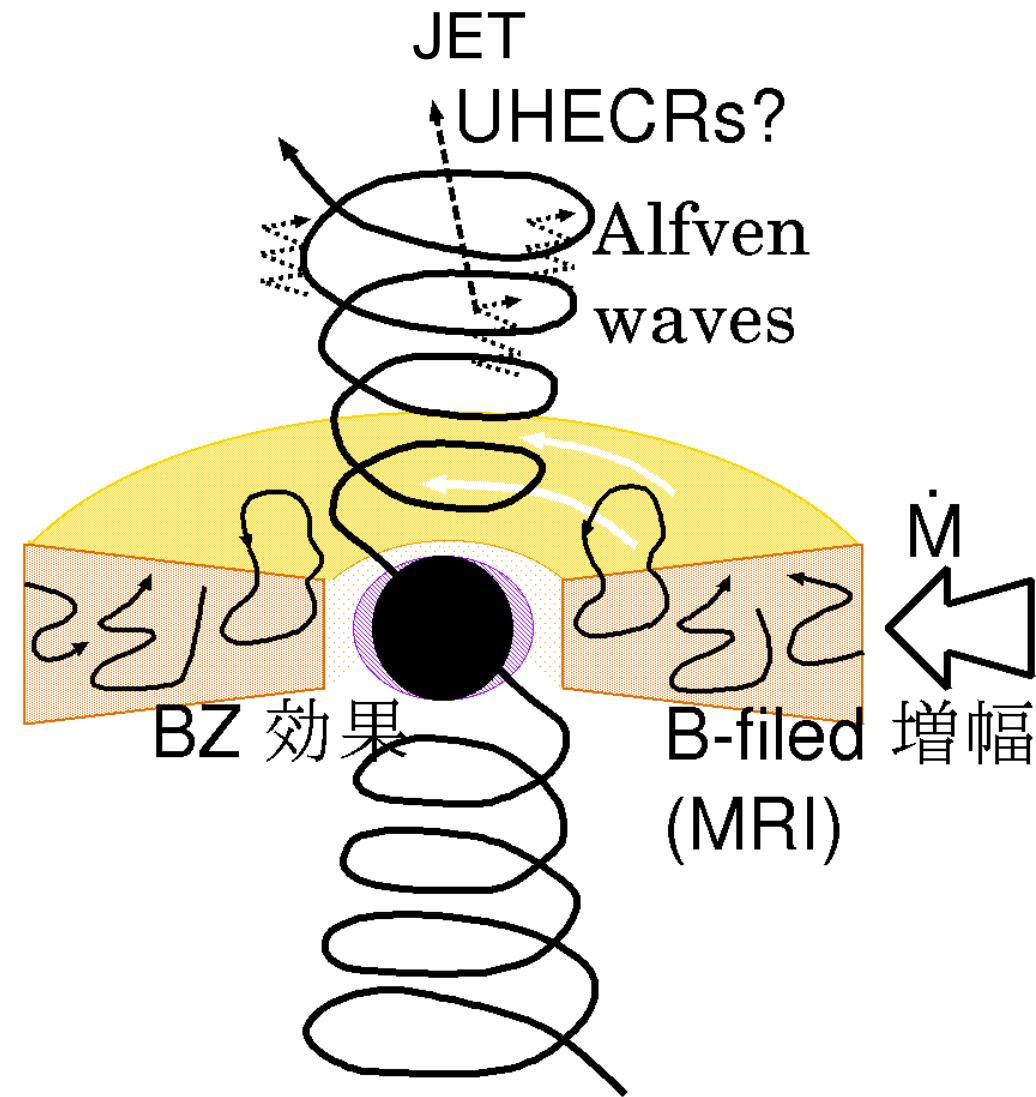
nonlinear & relativistic Alfvén mode Standard-disk  
(Shakra & Sunyaev (1973) を仮定)



降着円盤内部でMRIによって増幅した磁場に起因する  
アルフヴェン波のモードがジェット中に伝わるか？



GRMHD numerical  
simulations of accretion  
disks and jet formation



# Basic Equations : GRMHD Eqs (GM=c=1, a: Kerr spin parameter)

$$\frac{1}{\sqrt{-g}} \partial_\mu (\sqrt{-g} \rho u^\mu) = 0 \quad \text{Mass conservation Eq.}$$

$$\partial_\mu (\sqrt{-g} T_\nu^\mu) = \sqrt{-g} T_\lambda^\kappa \Gamma^\lambda_{\nu\kappa} \quad \text{Energy-momentum conservation Eq.}$$

$$\partial_t (\sqrt{-g} B^i) + \partial_j (\sqrt{-g} (b^i u^j - b^j u^i)) = 0 \quad \text{Induction Eq.}$$

$$p = (\gamma - 1) \rho \epsilon \quad \text{EOS } (\gamma=4/3)$$


---

$$\frac{1}{\sqrt{-g}} \partial_i (\sqrt{-g} B^i) = 0 \quad \text{No-monopoles constraint} \quad u_\mu b^\mu = 0 \quad \text{Ideal MHD condition}$$

$$u_\mu u^\mu = -1 \quad \text{Normalization of 4-velocity}$$

Energy-momentum tensor

$$T^{\mu\nu} = (\rho h + b^2) u^\mu u^\nu + (p_g + p_{\text{mag}}) g^{\mu\nu} - b^\mu b^\nu$$

$$p_{\text{mag}} = b^\mu b_\mu / 2 = b^2 / 2$$

$$b^\mu \equiv \epsilon^{\mu\nu\kappa\lambda} u_\nu F_{\lambda\kappa} / 2 \quad B^i = F^{*it}$$

Kerr-Schild metric (no singular at event horizon)

$$ds^2 = g_{tt} dt^2 + 2g_{tr} dt dr + 2g_{t\phi} dt d\phi + g_{rr} dr^2 + 2g_{r\phi} dr d\phi + g_{\theta\theta} d\theta^2 + g_{\phi\phi} d\phi^2$$

$$g_{tt} = \frac{2r}{\Sigma} - 1 \quad g_{rr} = 1 + \frac{2r}{\Sigma} \quad g_{\phi\phi} = \sin^2 \theta \left( \Sigma + a^2 \sin^2 \theta \left( 1 + \frac{2r}{\Sigma} \right) \right)$$

$$g_{tr} = \frac{2r}{\Sigma} \quad g_{t\phi} = \frac{-2ar \sin^2 \theta}{\Sigma} \quad g_{r\phi} = -a \sin^2 \theta \left( 1 + \frac{2r}{\Sigma} \right)$$

$$g_{\theta\theta} = \Sigma \quad \Sigma = r^2 + a^2 \cos \theta \quad g = \det(g_{\mu\nu}) = -\Sigma^2 \sin^2 \theta$$

## Computational domain, grids

Spherical coordinate ( $r, \theta, \phi$ )  $R[1.4:3e4]$   $\theta[0:\pi]$   $\phi[0:2\pi]$

[Nr=124, Nθ=124, Nφ=28]

$r=\exp(n_r)$ ,  $d\theta \sim 1.5^\circ$ ,  $d\phi \sim 13^\circ$ : uniform

– not enough high resolution to resolve MRI growth

**Units**  $L : Rg=GM/c^2 (=Rs/2)$ ,  $T : Rg/c=GM/c^3$ , mass : scale free

$\sim 1.5 \times 10^{13} \text{ cm} (M_{\text{BH}}/10^8 M_{\text{sun}})$   $\sim 0.5 \text{ day} (M_{\text{BH}}/10^8 M_{\text{sun}})$

## Initial condition

Fisbone-Moncrief (1976) solution – hydrostatic solution of disk around BH ( $a=0.9$ ,  $rH \sim 1.44$ ),  $l_* \equiv -u^t u_\phi = \text{const} = 4.45$ ,  $r_{\text{in}}=6$ .

- equilibrium state : gravitational potential, pressure gradient, and centrifugal force
- geometrical thick disk
- impose weak poloidal B-field

$$A_\phi \propto \max [\rho/\rho_{\text{max}} - 0.2, 0]$$

## GRMHD code (Nagataki 2009,2011)

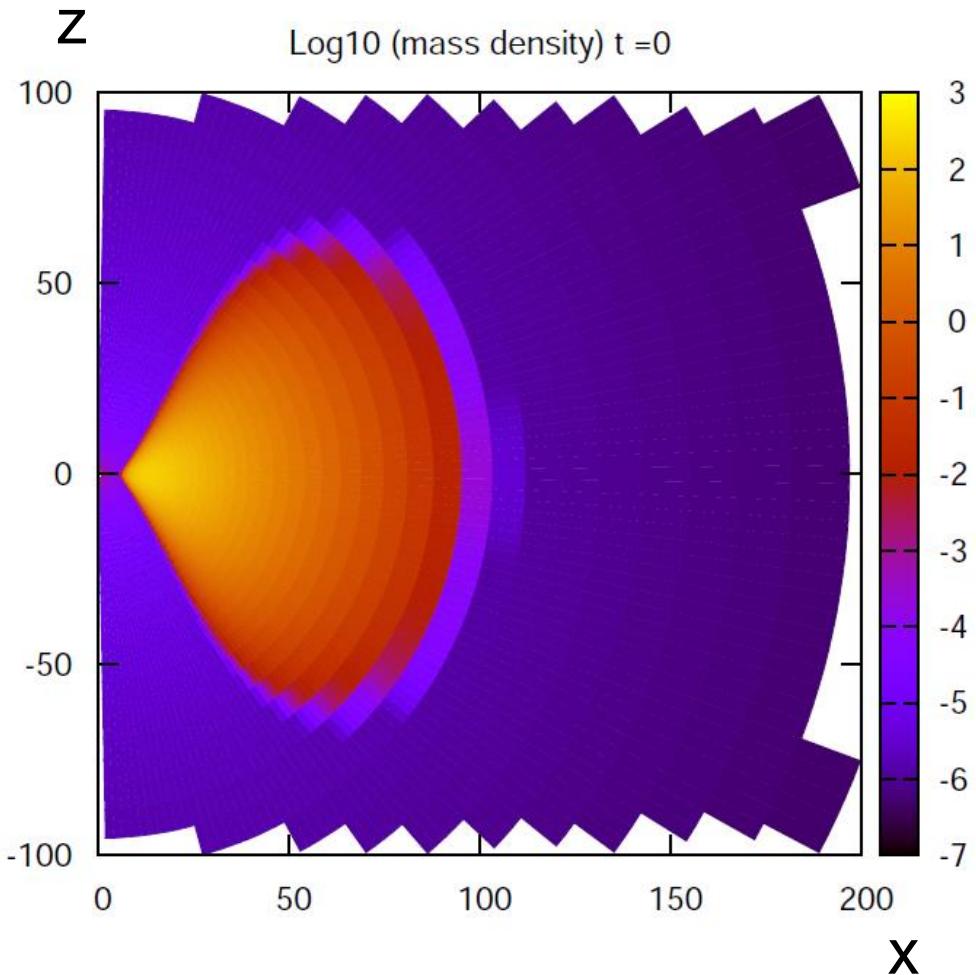
HLL flux, 2<sup>nd</sup> order in space (van Leer), 2<sup>nd</sup> or 3<sup>rd</sup> order in time

See also, Gammie +03, Noble + 2006

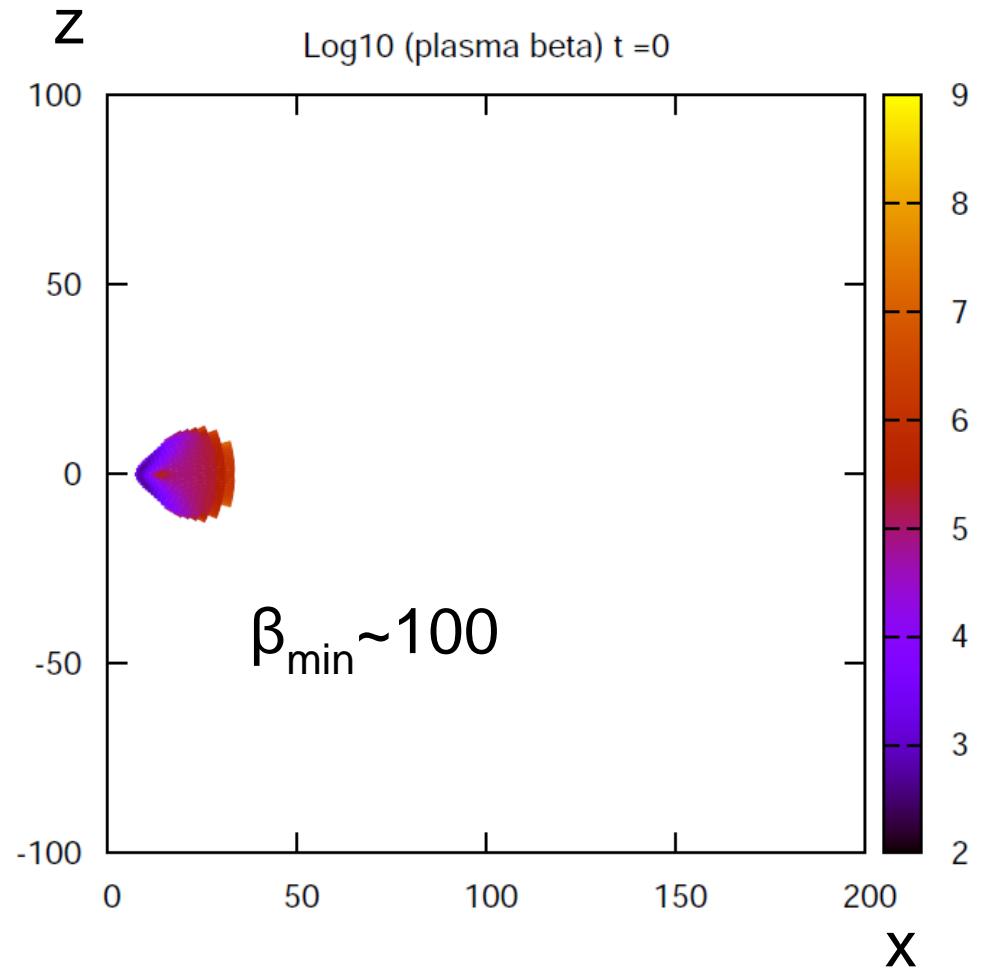
Flux-interpolated CT method for divergence free

# Initial Condition

Log10 (Mass density)



Log10( Pgas/Pmag)

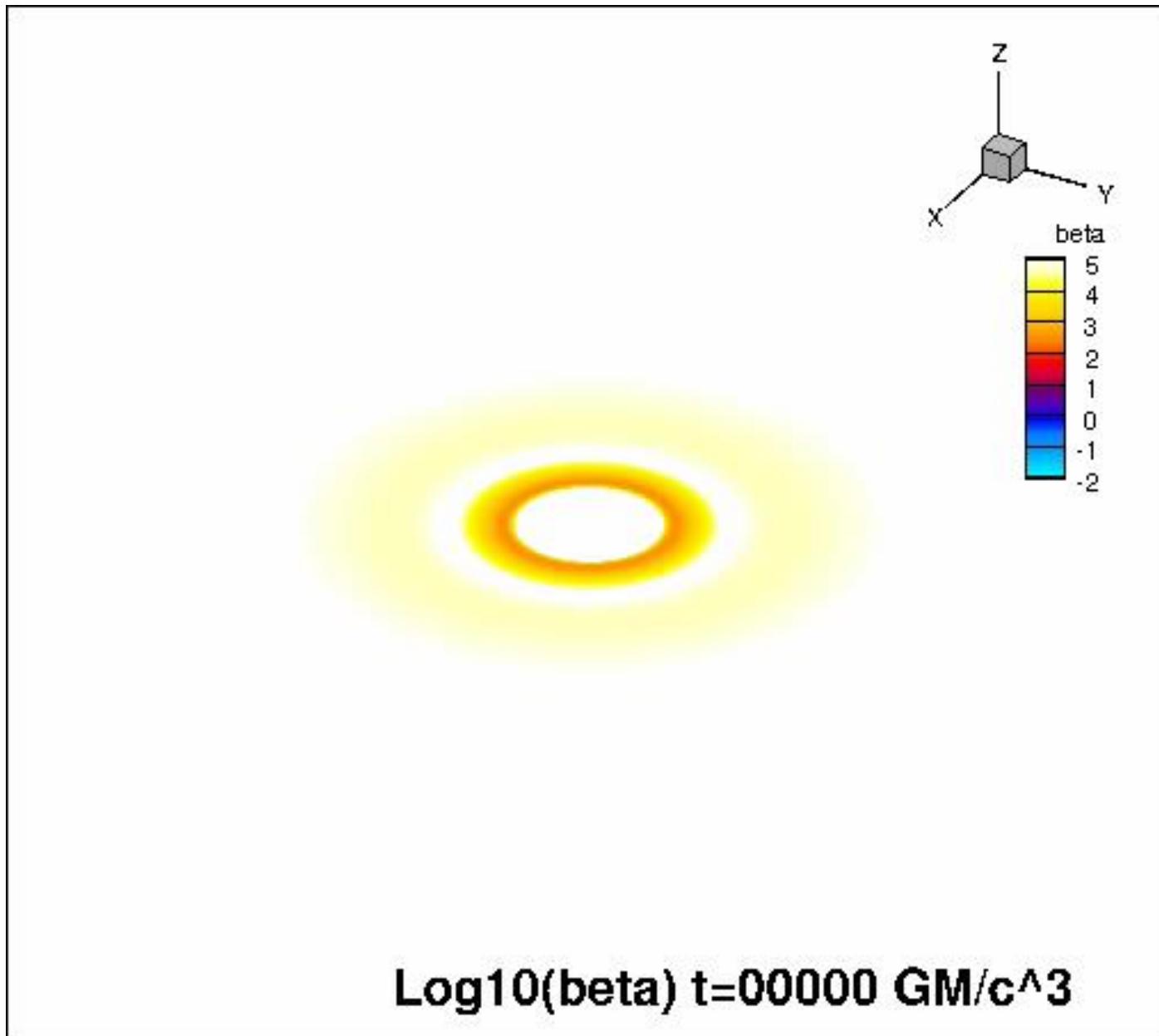


$$A_\phi \propto \max [\rho/\rho_{\max} - 0.2, 0]$$

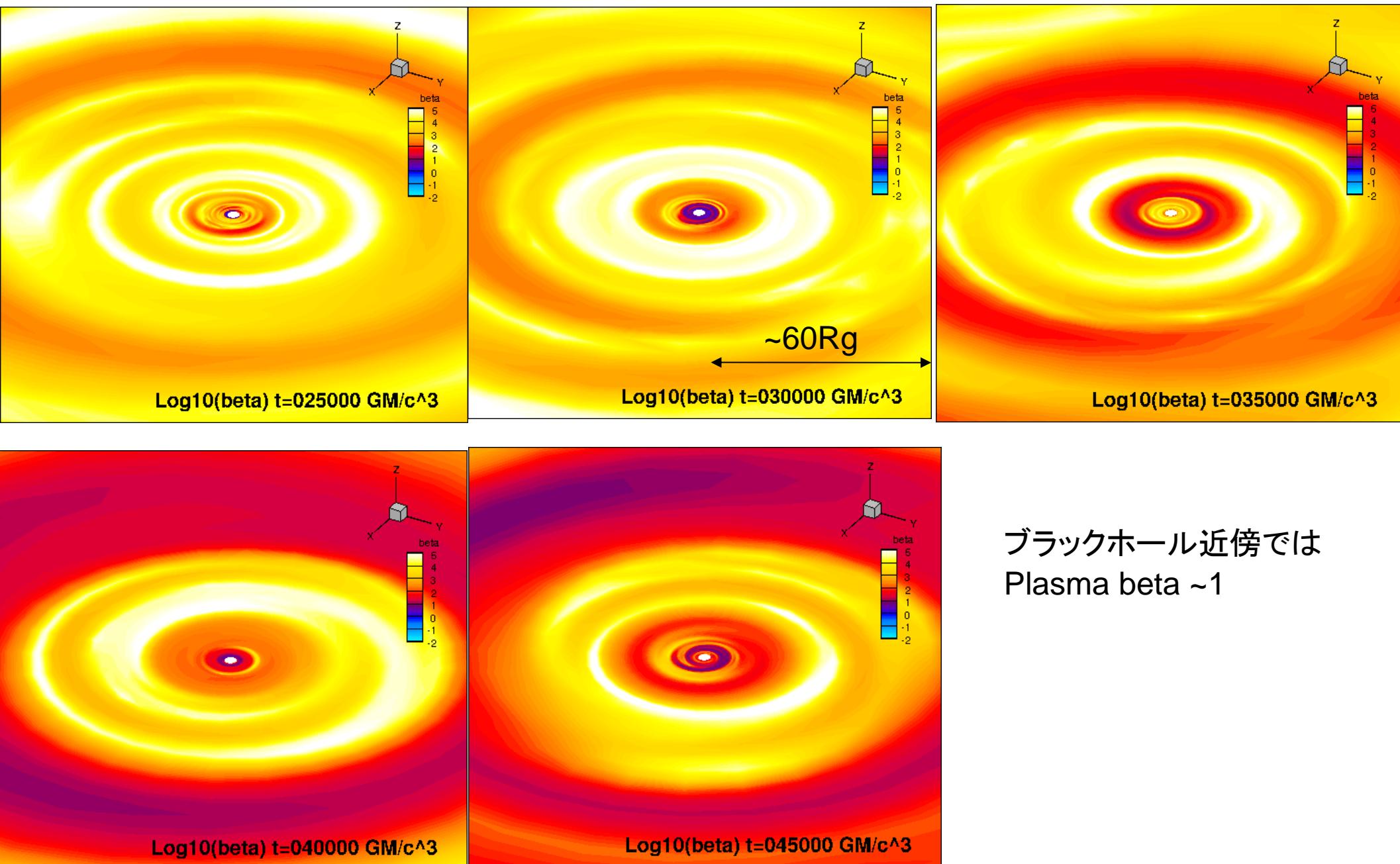
Fisbone-Moncrief (1976) solution :  $a=0.9$ ,

$$l_* \equiv -u^t u_\phi = \text{const} = 4.45, r_{\text{in}} = 6.$$

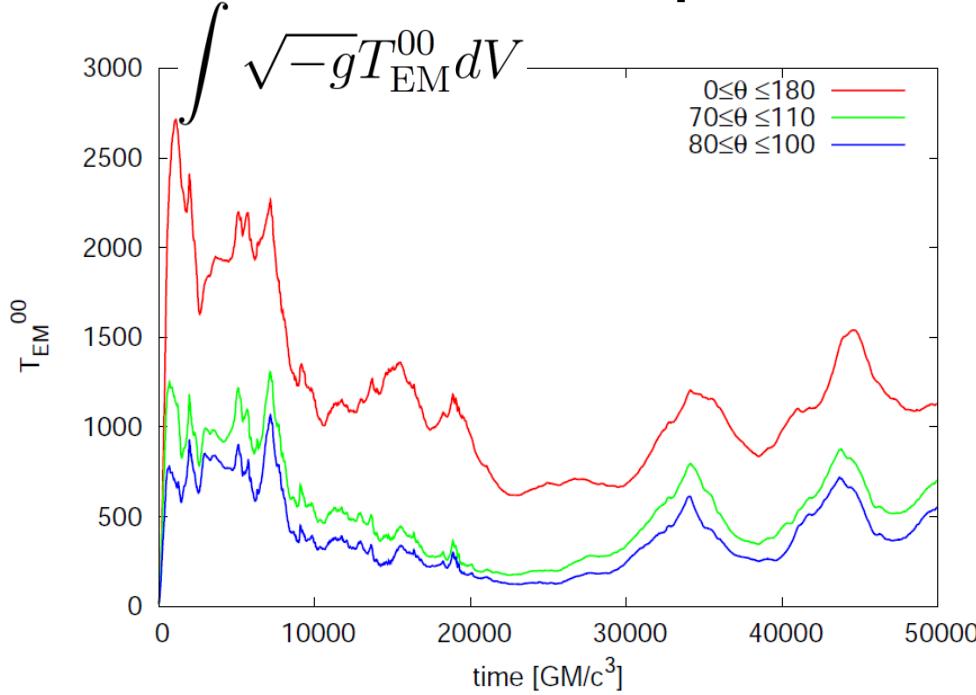
# Plasma beta ( $P_{\text{Gas}}/P_{\text{Mag}}$ )@p equator



# Time evolution log10(plasma beta= $P_{\text{Gas}}/P_{\text{Mag}}$ ) @ equatorial plane



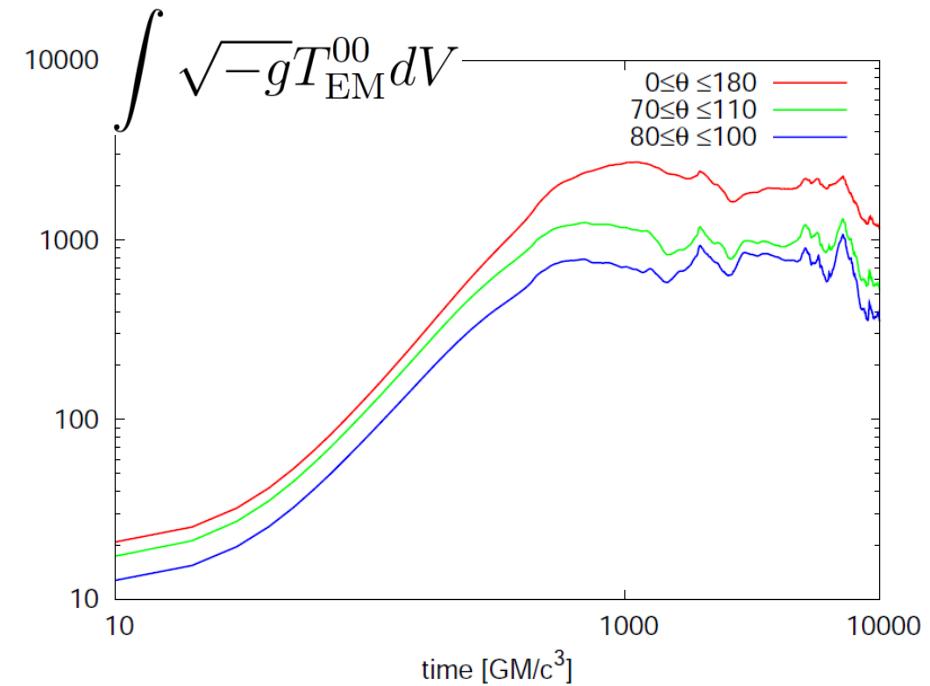
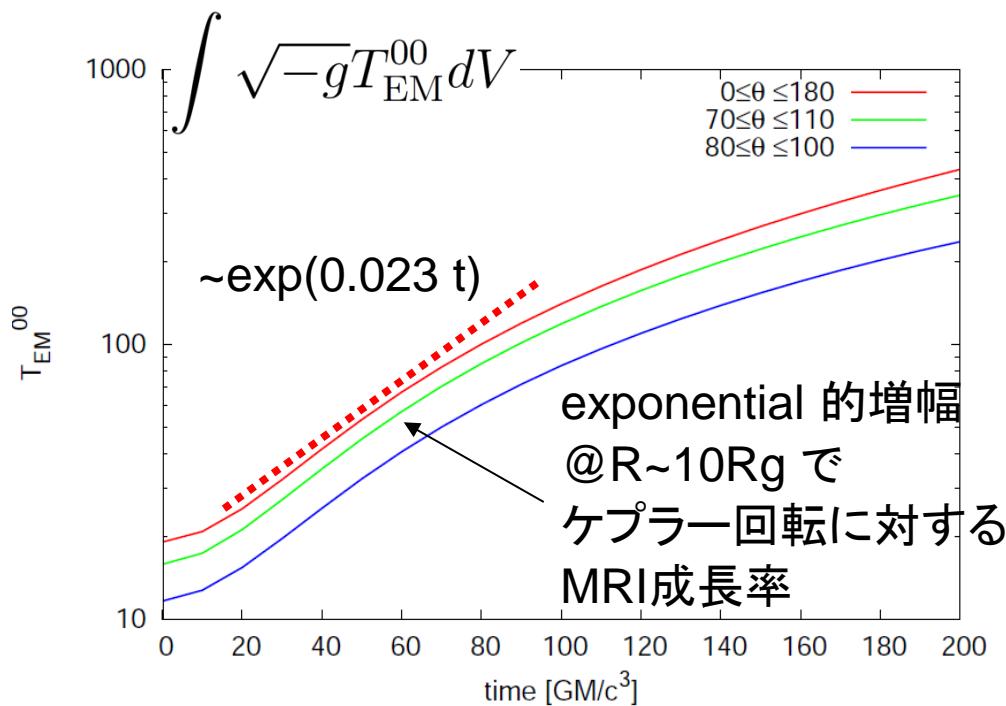
# B-field amplification and saturation



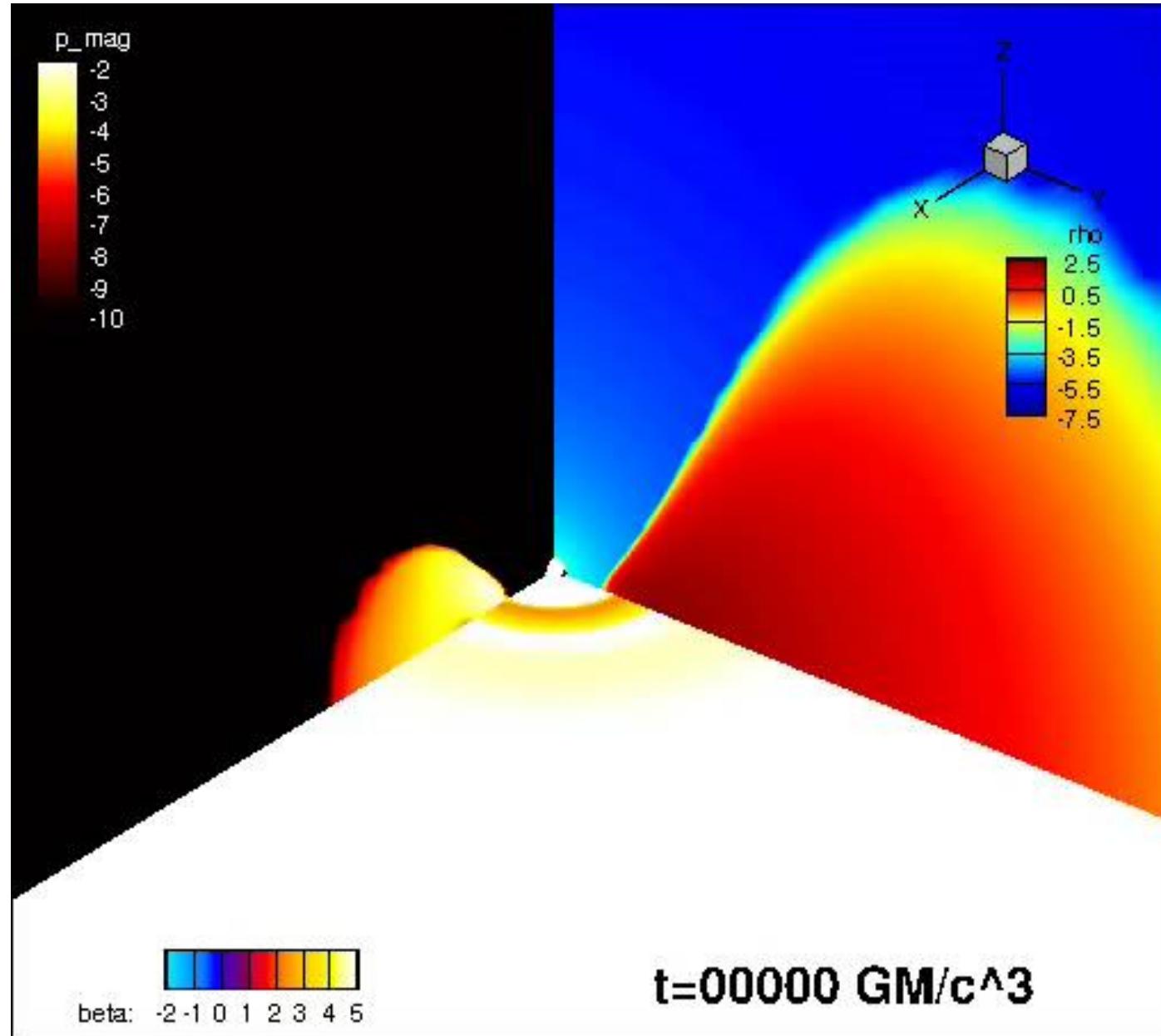
磁場は初期に増幅され  
 $t > 10000 \text{GM}/c^3$  では準定常的になり、長い時間スケールで振動する。

極初期は exponential に近い増幅  
(MRI? 要解像度テスト)

その後  $t \sim 1000$  でべき的増幅

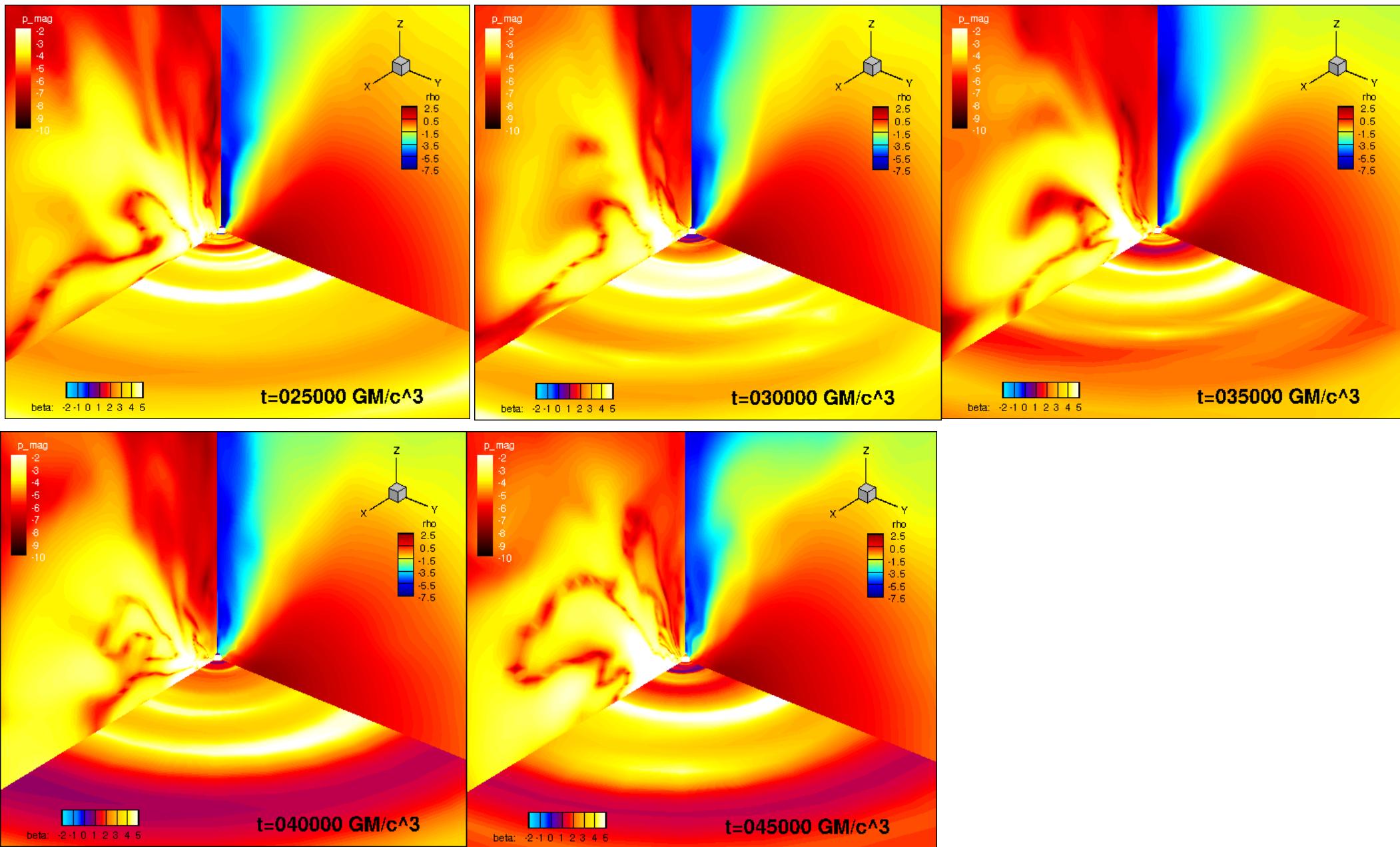


# Magnetized jet launch

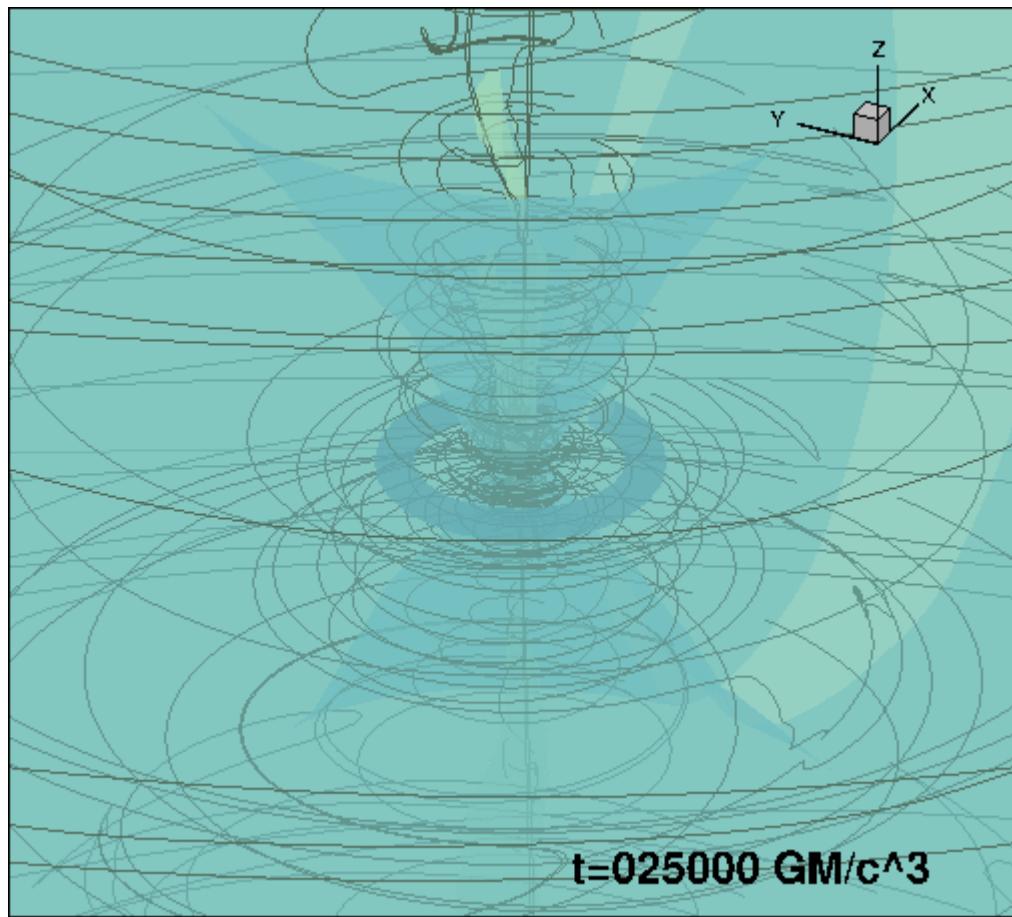


数十-数百時間単位でフレア的磁場優勢ジェットが生じる

# Magnetized jet launch



# Magnetic field

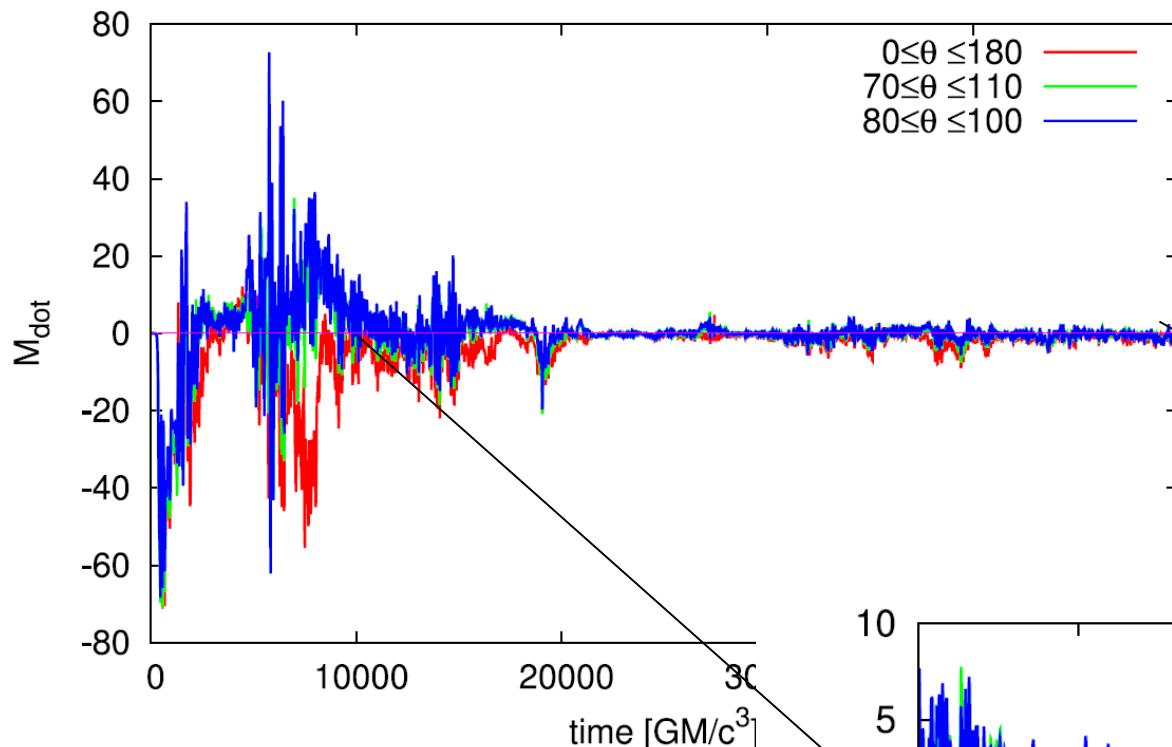


極方向にtoroidal 磁場を伴うア  
ウトフロー

isosurface  
 $\log_{10}(\rho) = -5.3, -0.7, 2.2$

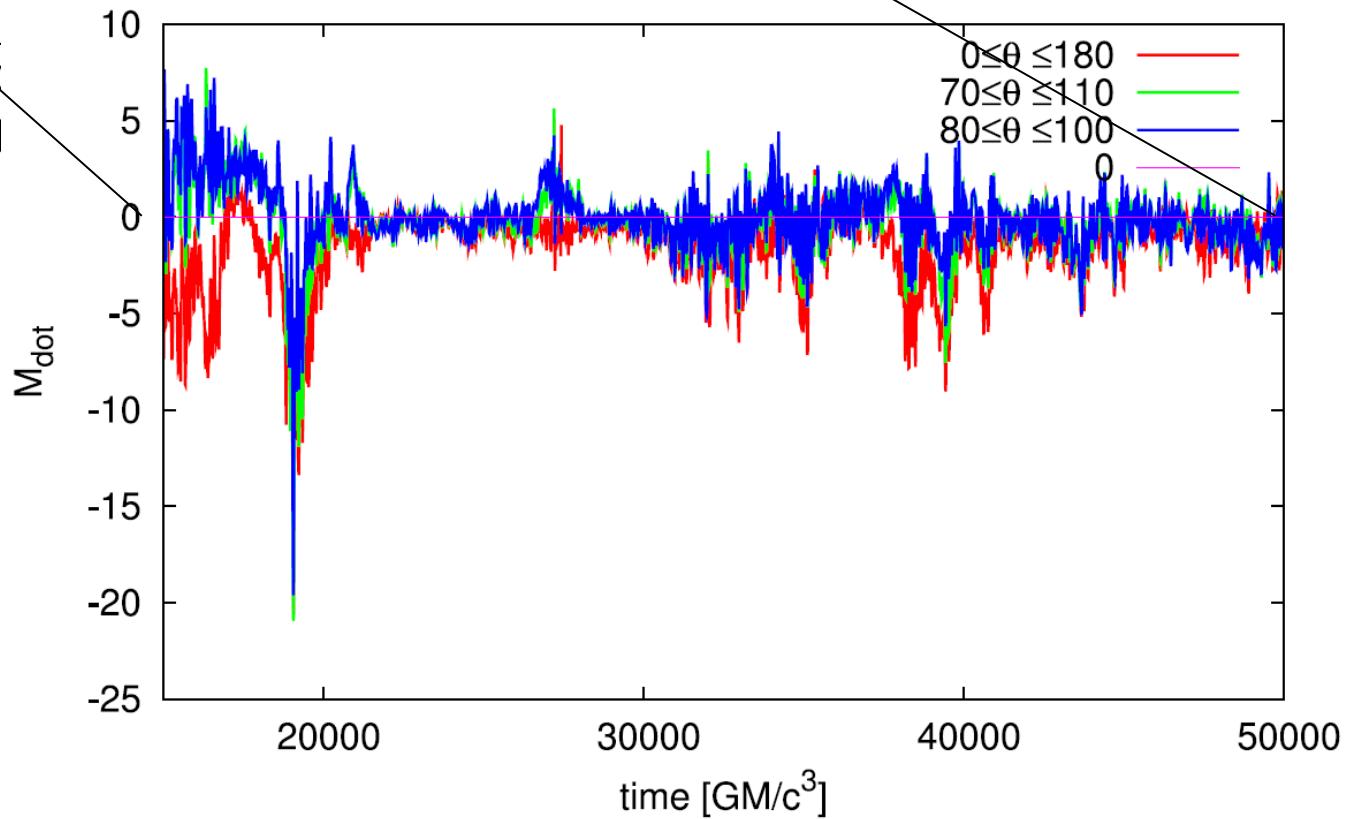
# History of accretion rate (1) r=5rg

r=5Rg

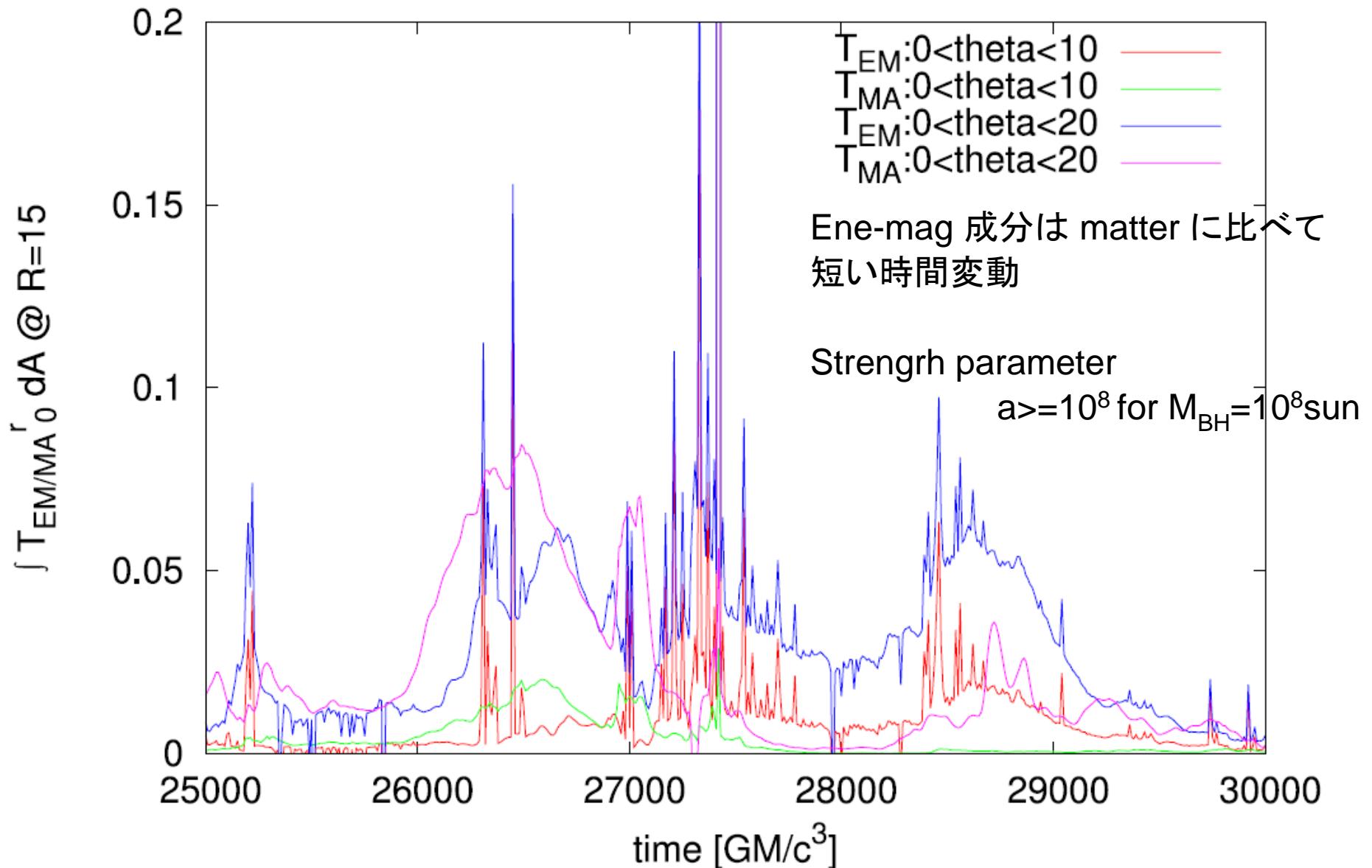


$$M_{\dot{M}} = \int_{\theta=\theta_0}^{\theta=\theta^1} \int_{\phi=0}^{\phi=2\pi} \sqrt{-g} \rho u^1 dA$$

r=5Rg

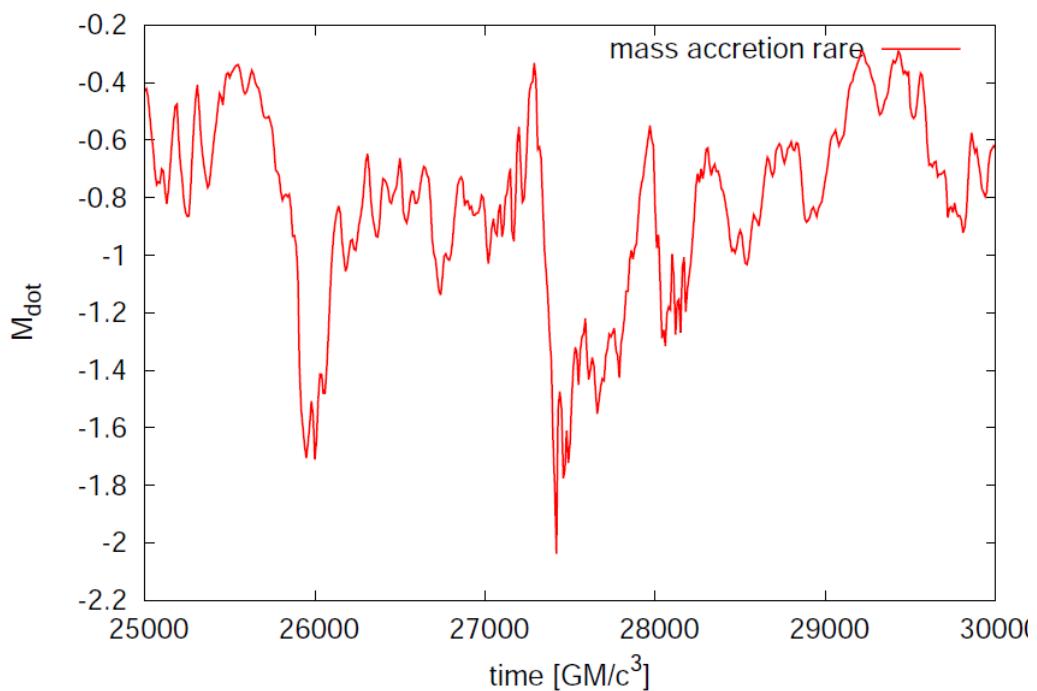


# Matter & ene-mag in Jet

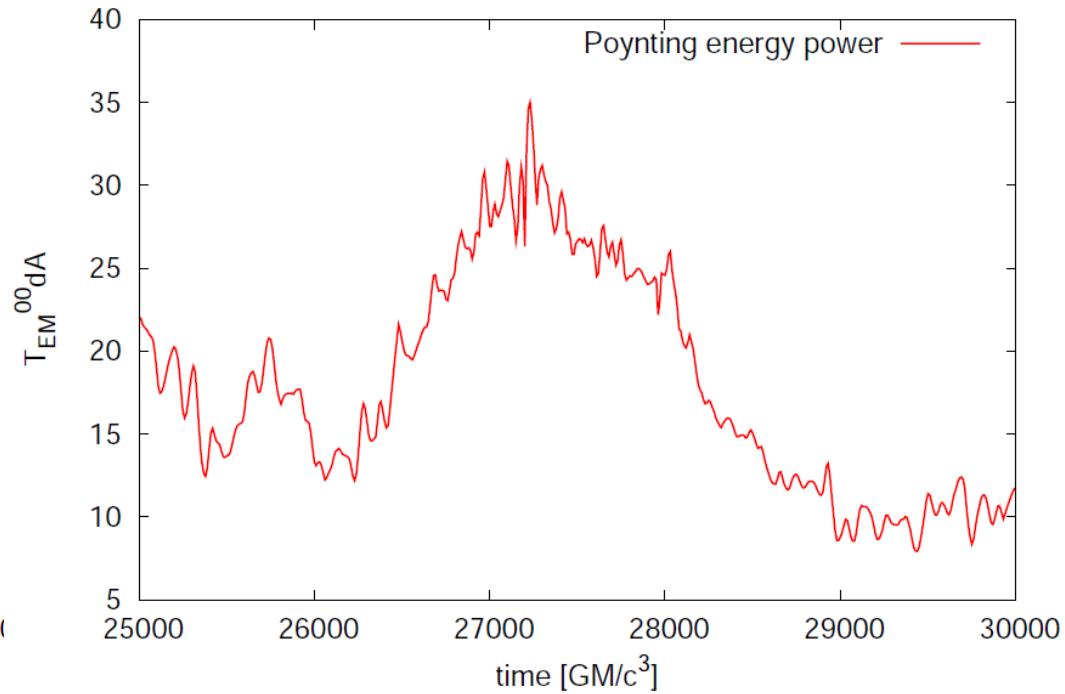


# Mass accretion rate & EM power @ horizon

質量降着率



EM power



Horizon での質量降着率、EM power は  
フレアジェットとの相関は見られない

# Summary

ブラックホール周りの降着円盤の3DGRMHD シミュレーション

– Fishbone-Moncrief 解 + Poloidal B-filed

– 初期にMRI的磁場增幅、その後べき的増幅

$T \sim > 10000 Rg/c^3$  で準平衡状態

– 極方向に強いジェット成分

– 電磁場 成分に matter 成分よりも短い時間変動

– 今度解像度依存性