ブラックホール磁気圏と相対論的ジェット

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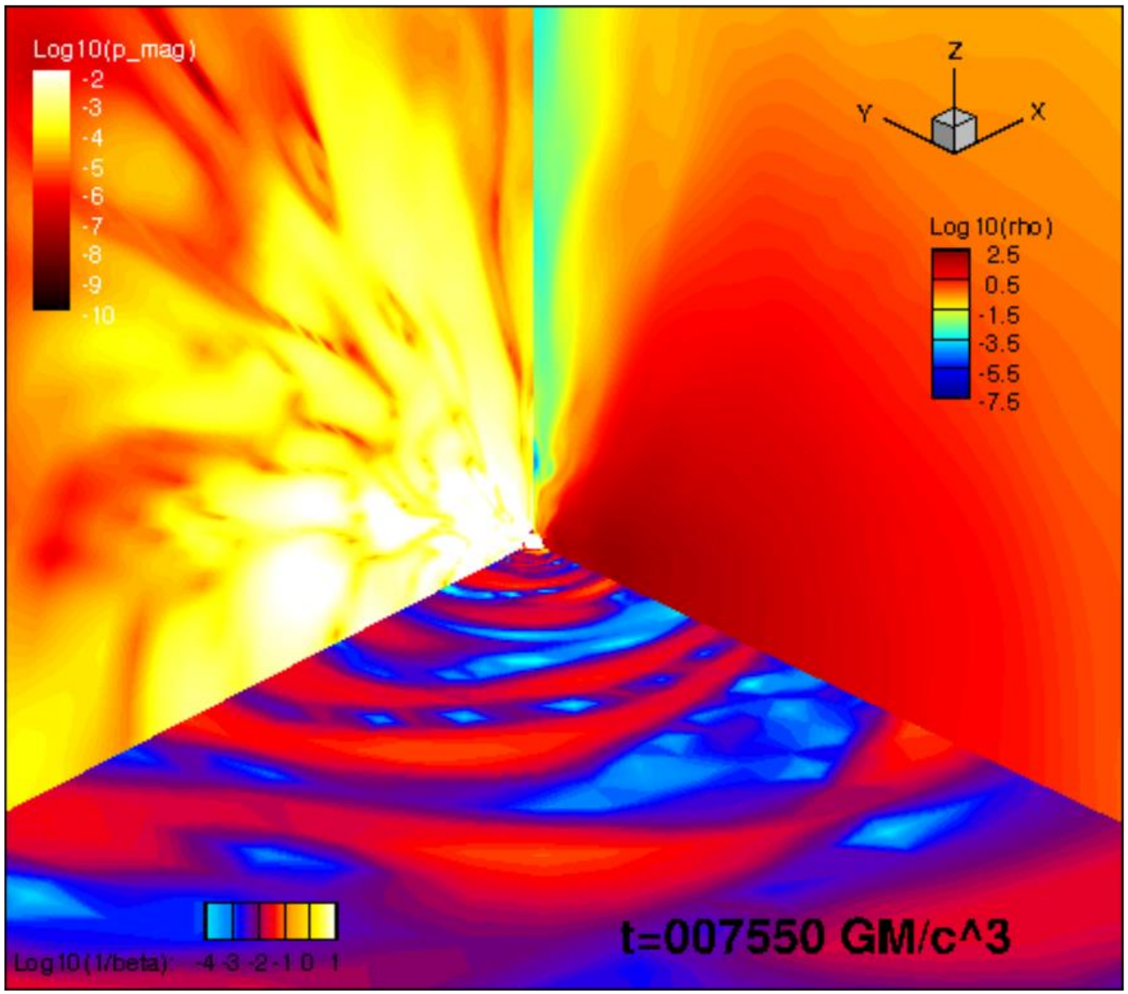

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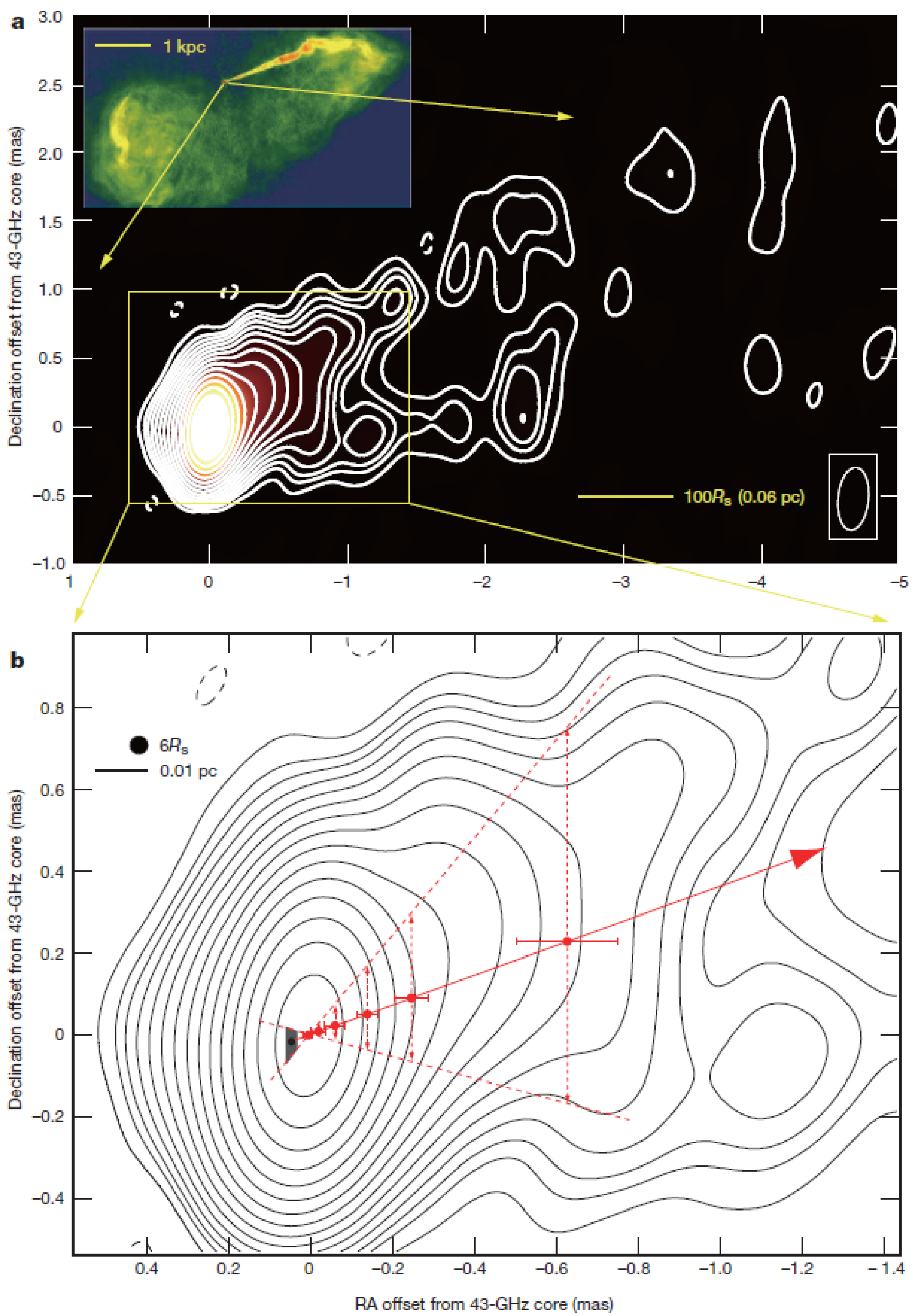
OUTLINE

- Introduction
- 3D GRMHD simulations of black hole and accretion disks
- Blandford -Znajek process
- Summary

Motivation : radio observations around jet base



M87 radio observation   Hada +(2011)

- Detailed and high quality radio observation near central BH and jets.

- Results by Event horizon telescope will come soon.

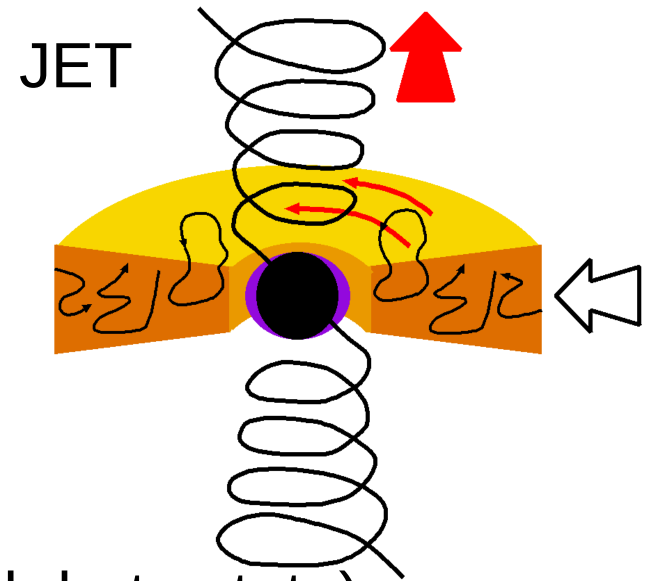
AGN jets are laboratory

- Jet formation
  - – GR effect,
  - – accretion disk physics
  - – MHD turbulence
  - – relativistic jets

    radio to high energy gamma-rays morhology, timevariability etc.

- strong candidate of ultra high energy cosmic ray
  - – acceleration physics

Relativistic jets from BH+accretion disk



CENTRAL ENGINE (Black Hole(BH)＋ disk)
-Time variability (Shibata +1990,
Balbus & Hawley1991)
-- MRI growth (B ↗ => low beta state)

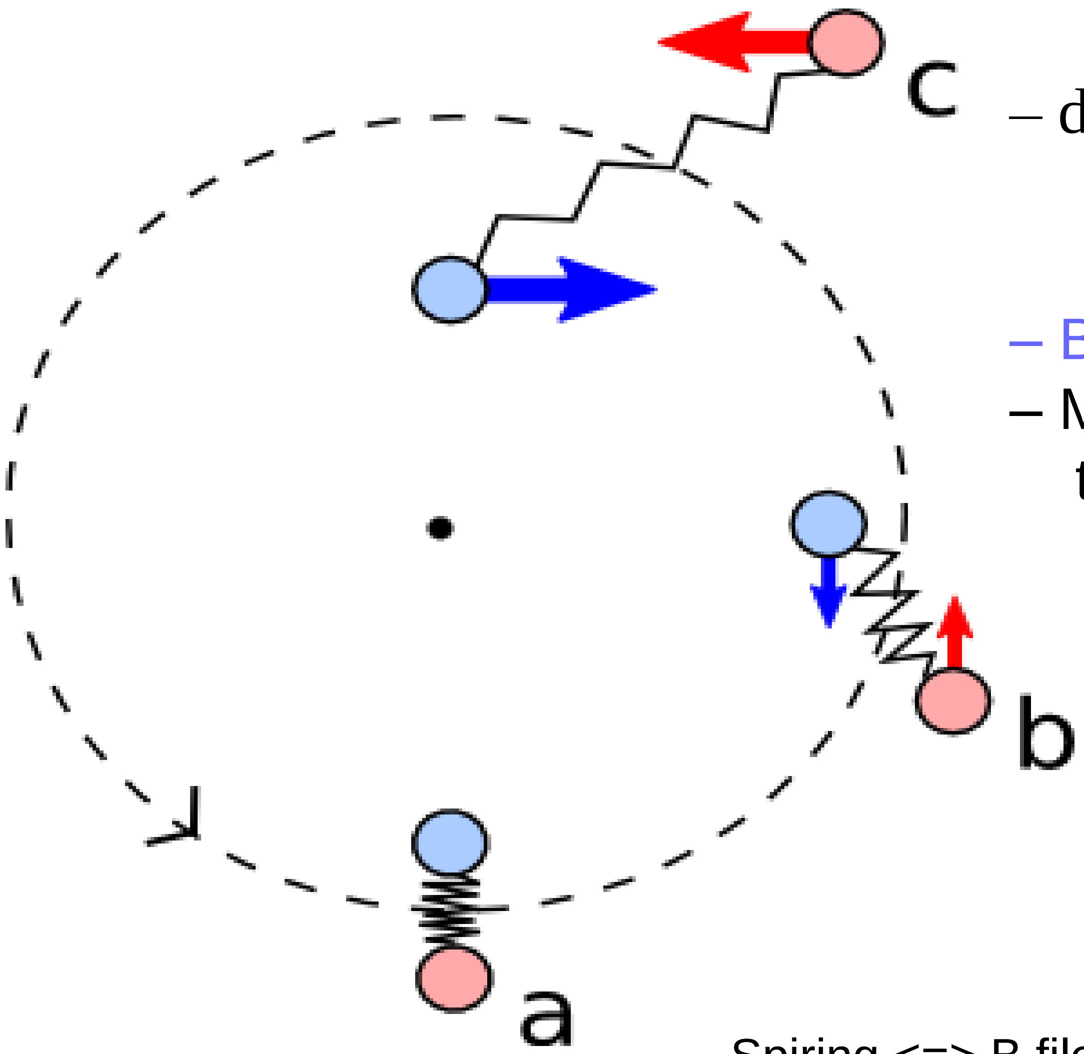
-- dissipation of magnetic energy (B ↘=> high beta state)
- Strong Alfven burst (low β => high β)

➡ Poynting flux dominated jet
with relativistic Aflven waves (Ebisuzaki & Tajima 2014)

➡ Particle acceleration (protons and electrons)
via Ponderamotive force by relativistic EM waves
(Ebisuzaki & Tajima 2014)

Time variability in the disk ➡ Time variability in the jet with strong Alfven wave ➡ Particle acceleration

B-filed amplification inside the disk (1)



Magnetorotational instability (MRI)

– differentially rotating disk :

$d\Omega_{disk} /dr < 0$

$\Omega_{disk} \propto r^{-1.5}$:Kepler rotation

– $B \propto \exp(i\omega t)$

– MRI enhances angular momentum transfer

Spiring <=> B filed

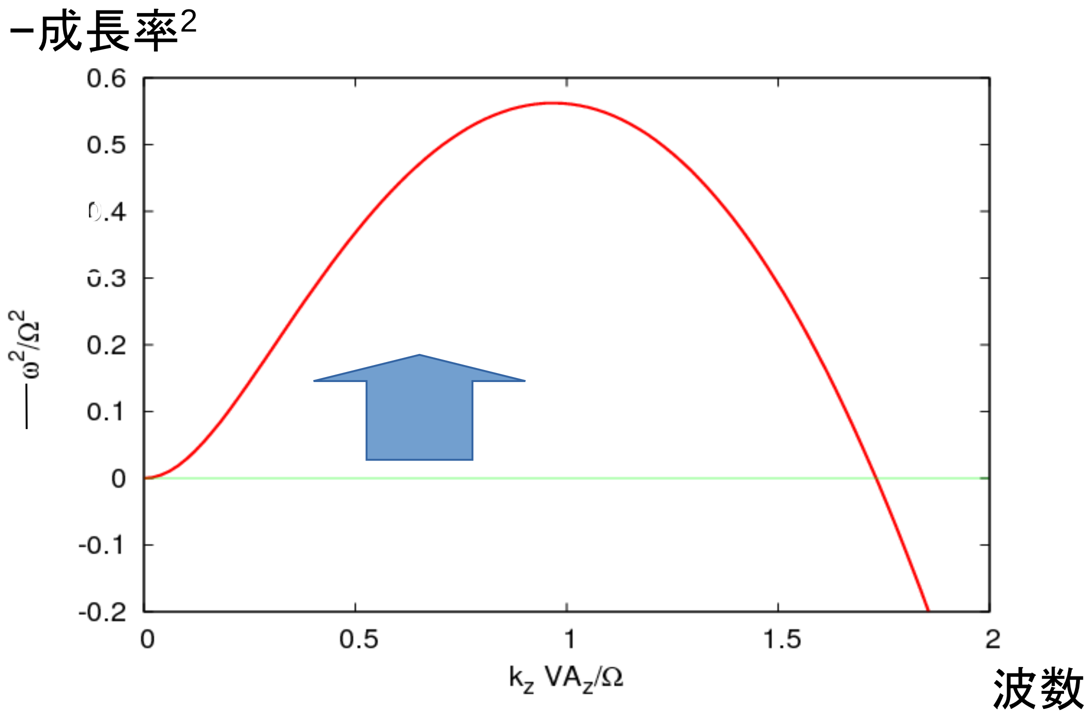
Velikhov (1959) Chandrasekhal (1960)
Balbus &Hawley (1991)

B-filed amplification inside the disk (2)

MRI growth rate depends on the wavelength.
For Kepler rotation, i.e., $\Omega_K \propto R^{-3/2}$,

$B \propto \exp(-i\omega t)$

$$\omega^2 - k_z^2 V_{Az}^2 = \pm\sqrt{\Omega^2\omega^2 + 3\Omega^2 k_z^2 V_{Az}^2}$$



Unstable @ $0 < kV_a < 1.73\ \Omega_K$
Most unstable @ $kV_a \sim \Omega_K$
$\omega \sim 0.75\Omega_K$

Balbus &Hawley (1991)

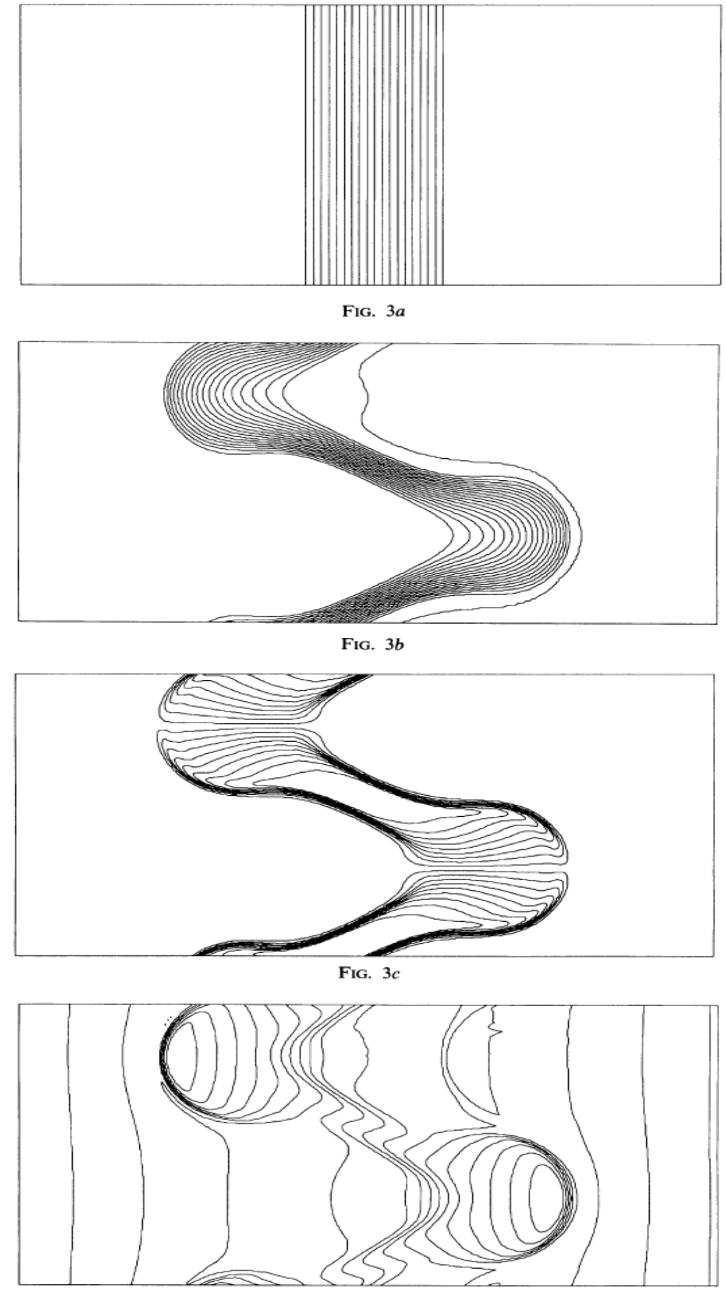
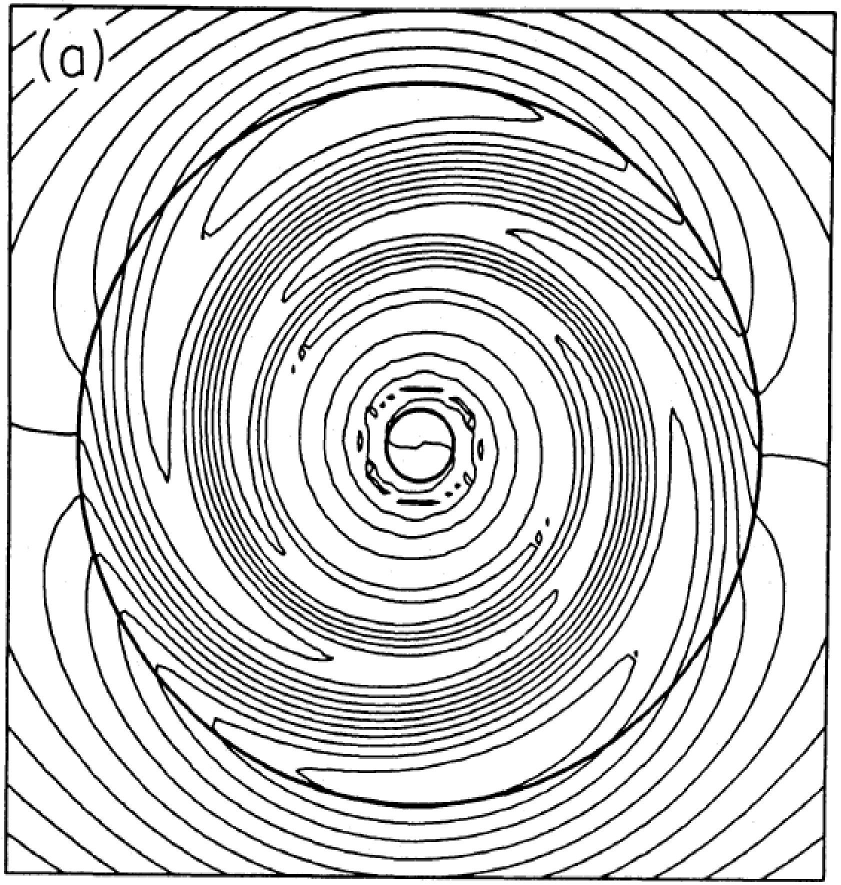
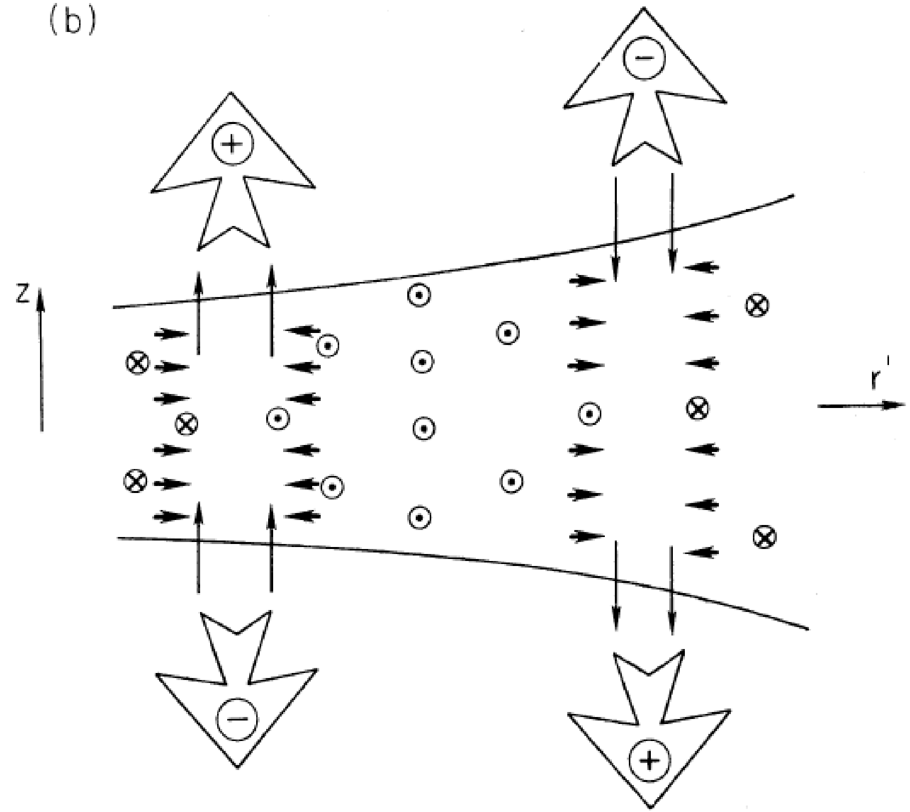


FIG. 3a
FIG. 3b
FIG. 3c
FIG. 3d

Disk state transition



B-field lines of accretion flow onto dwarf nova disk (Tajima &Gilden (1987))



Haswell, Tajima, & Sakai (1992)

B-field is stretched, then released generating Alfven bursts.

Disk state transition between high β state to low β state repeats (Shibata Mastumoto & Tajima (1990))

Basic Equations : GRMHD Eqs.

GM=c=1, a: dimensionless Kerr spin parameter

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

$$\partial_\mu(\sqrt{-g}T^\mu_\nu) = \sqrt{-g}T^\kappa_\lambda \Gamma^\lambda{}_{\nu\kappa}$$ Energy-momentum conservation Eq.

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

$$p = (\gamma - 1)\rho\epsilon$$ EOS (γ=4/3)

Constraint equations.

$$\frac{1}{\sqrt{-g}}\partial_i(\sqrt{-g}B^i) = 0$$ No-monopoles constraint

$$u_\mu b^\mu = 0$$ Ideal MHD condition

$$u_\mu u^\mu = -1$$ Normalization of 4-velocity

Energy-momentum tensor

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

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

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

GRMHD code (Nagataki 2009,2011)

Kerr-Schild metric (no singular at event horizon)

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

See also, Gammie +03, Noble + 2006

Flux-interpolated CT method for divergence free

Grids to capture MRI fastest growing mode

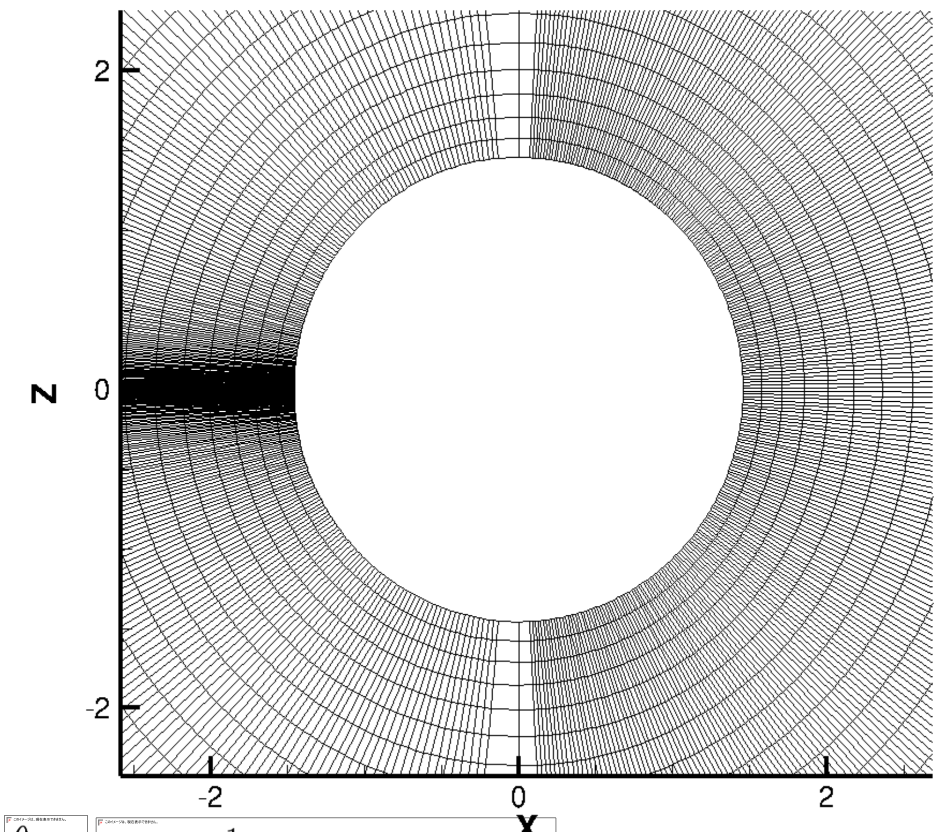
Wavelength of fastest growing mode in the disk

$\lambda_{MRI} = 2\pi \langle C_{Az} \rangle / \Omega_K (R) \sim 0.022 (R/R_{ISCO})^{1.5}$

$\langle C_{Az} \rangle \sim 10^{-3}$ c

R_{ISCO} (a=0.9)=2.32

$N_\theta = 252$



$$\theta = \pi x_2 + \frac{1}{2}(1-h)\sin(2\pi x_2)$$

x_2 = [0:1] Δx_2=cost

h=0.2

$\Delta\theta$=cost

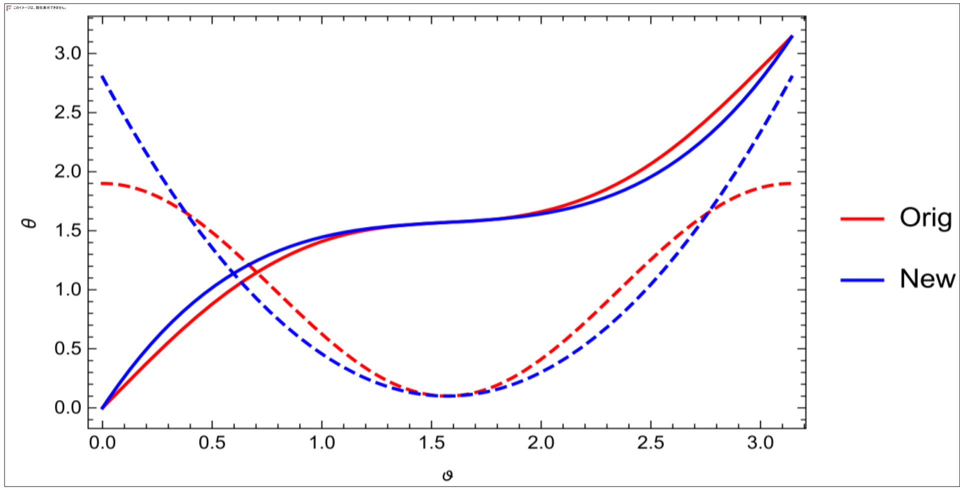
h=1

McKinney and Gammie

□□□□

Any coordinates described by analytic function can be applied (generalized curvilinear coordinates)

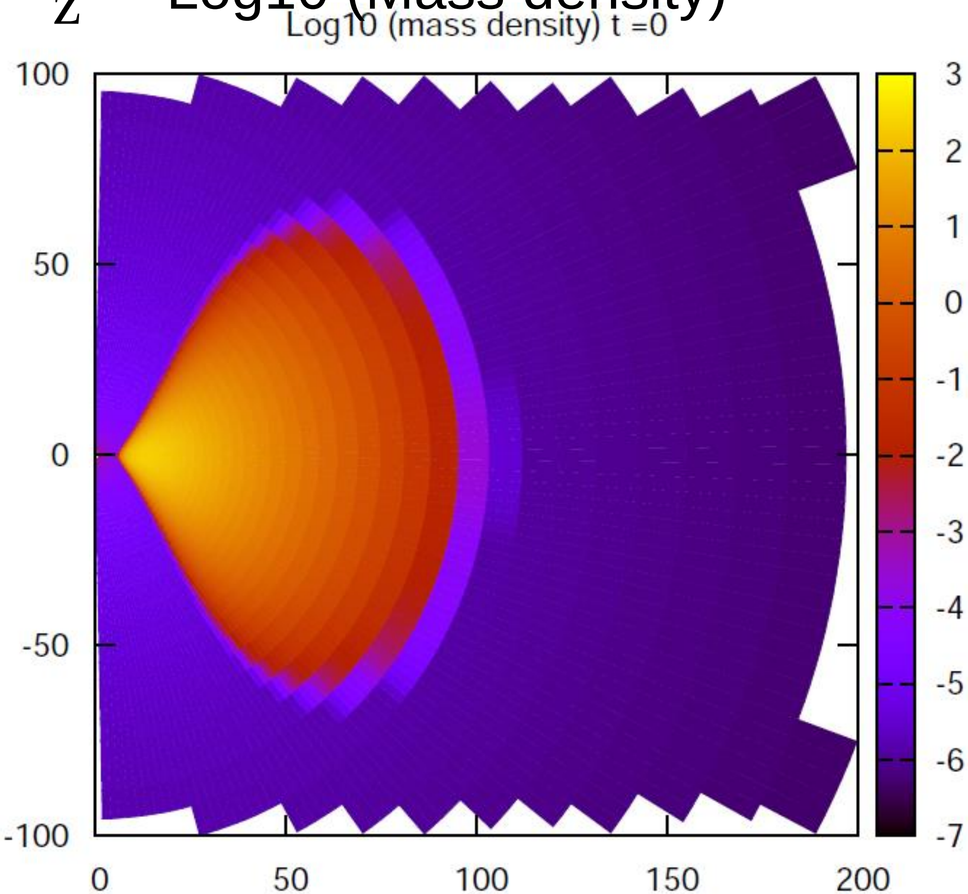
$$\theta_{KS}(\vartheta) = \vartheta + \frac{2h\vartheta}{\pi^2}(\pi - 2\vartheta)(\pi - \vartheta).$$



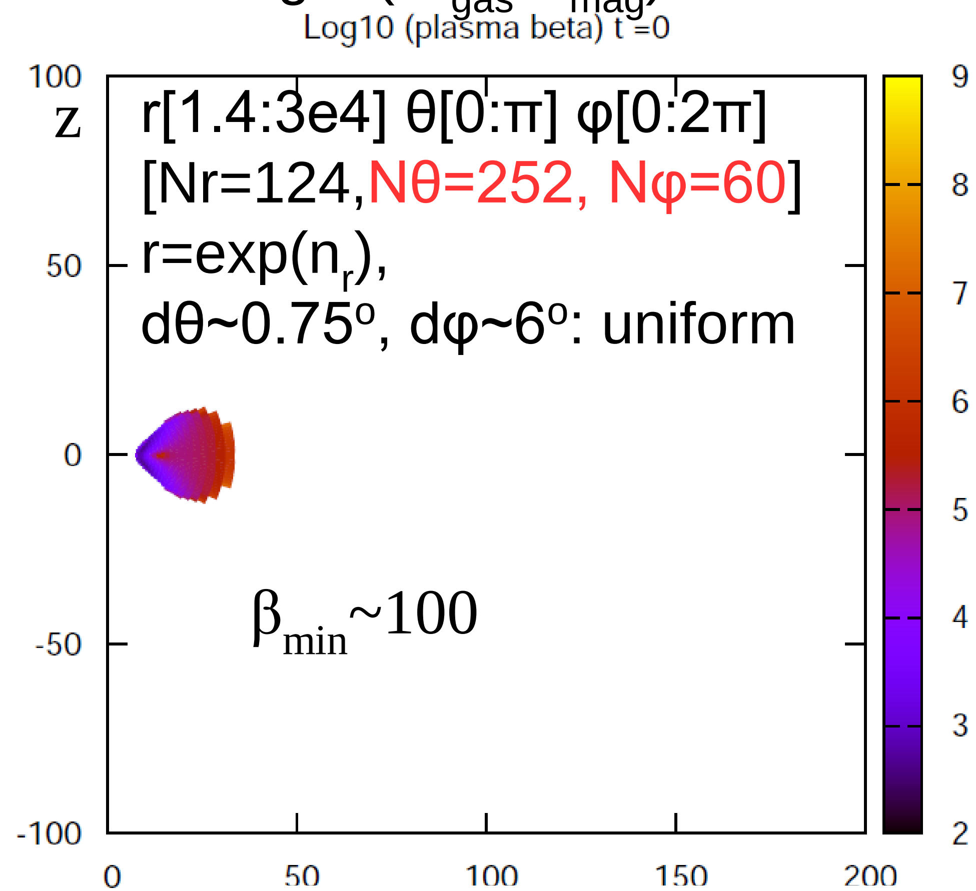
Porth + 2017

Initial Condition

z Log10 (Mass density)



Log10(P_{gas}/P_{mag})



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

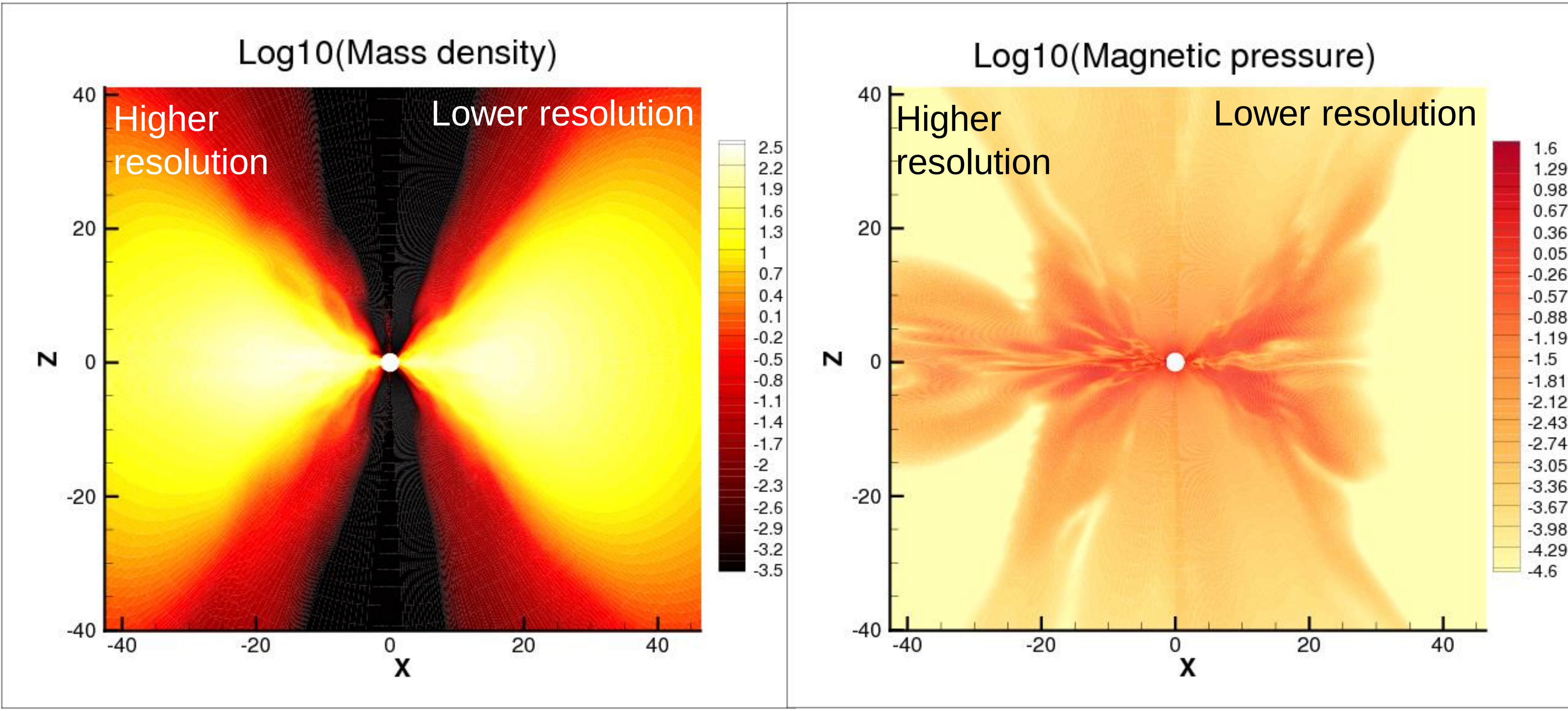
Fisbone-Moncrief (1976) solution – hydrostatic solution of tori around rotating BH (**a=0.9**, rH~1.44), $l_* \equiv -u^t u_\phi$ =const =4.45, r_{in}=6. > r_{ISCO}

With maximum 5% random perturbation in thermal pressure.

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

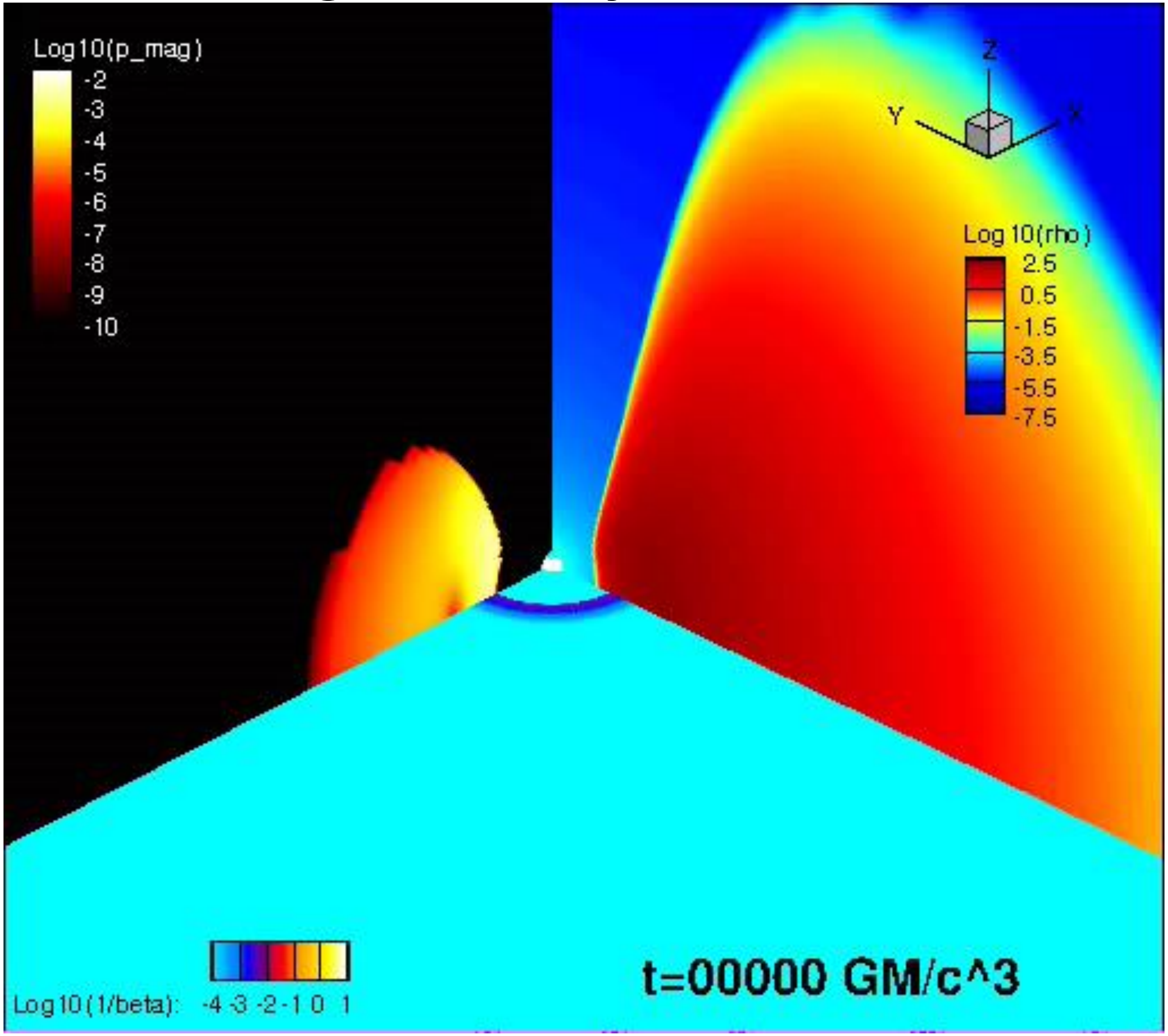
~1.5x10^{13}cm($M_{BH}/10^8 M_{sun}$) ~500s ($M_{BH}/10^8 M_{sun}$)

Higher resolution calculation (θ) around equator



Right : about 5 times higher resolution in theta @ equator

Magnetized jet launch



Disk : Fishbone Moncrief solution, spin parameter **a=0.9**

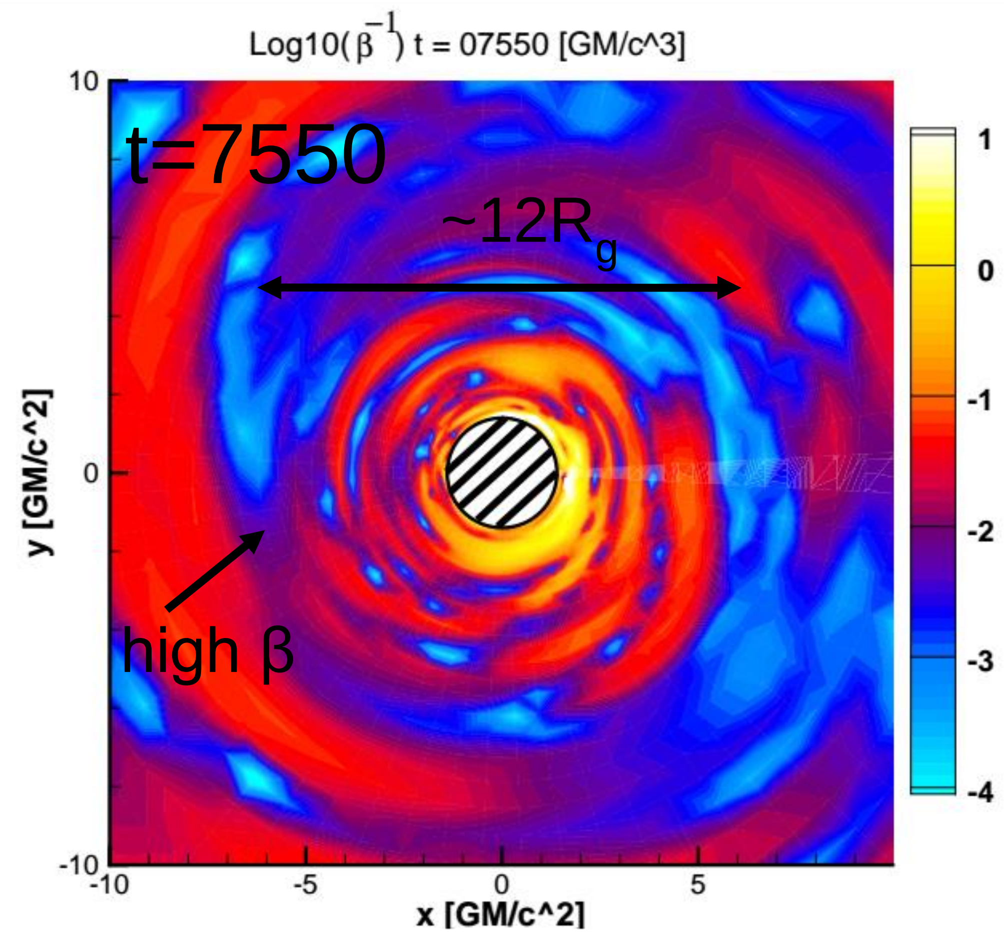
spherical coordinate R[1.4:3e4] θ[0:π] φ[0:2π]

[NR=124,**Nθ=252, Nφ=60**] r=exp(n_r), θ :**non-niform (concentrate @ equator)**

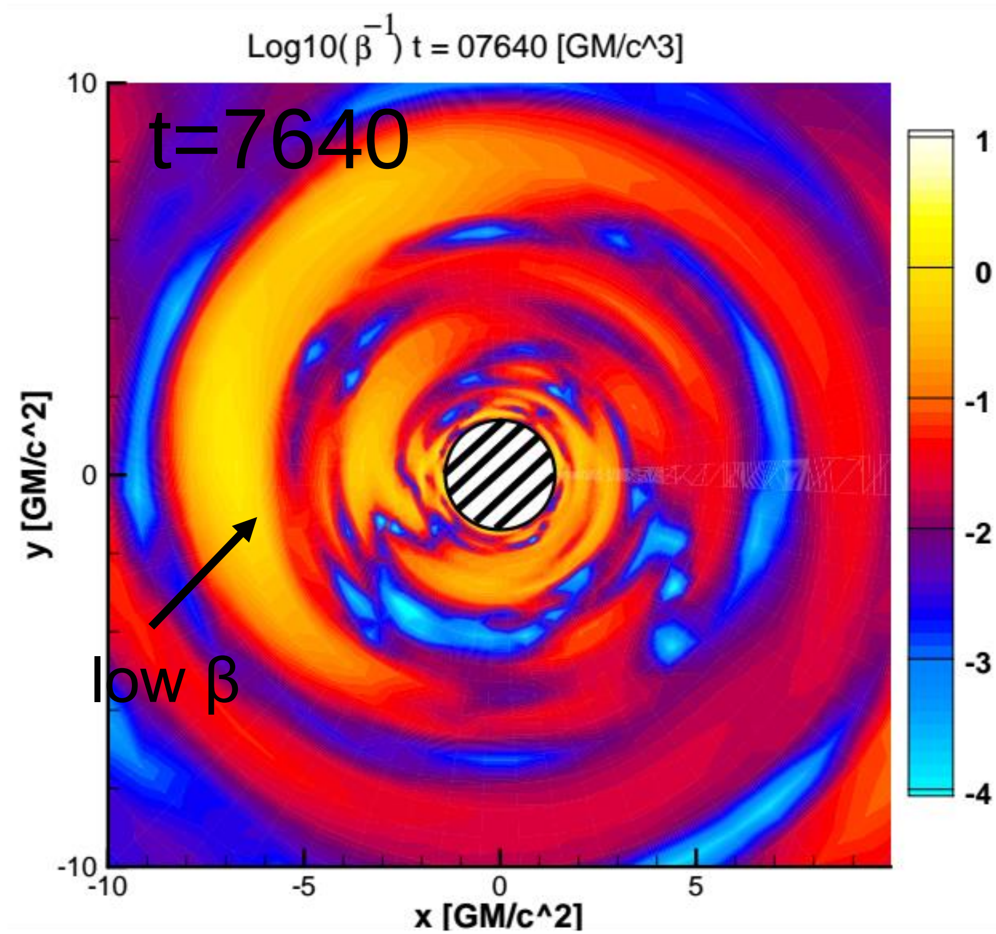
dφ~6^o: uniform Poloidal B filed, β_min=100

Plasma β (P_{th} /P_{mag})

high β state | low β state



Log(1/ β) @ equator

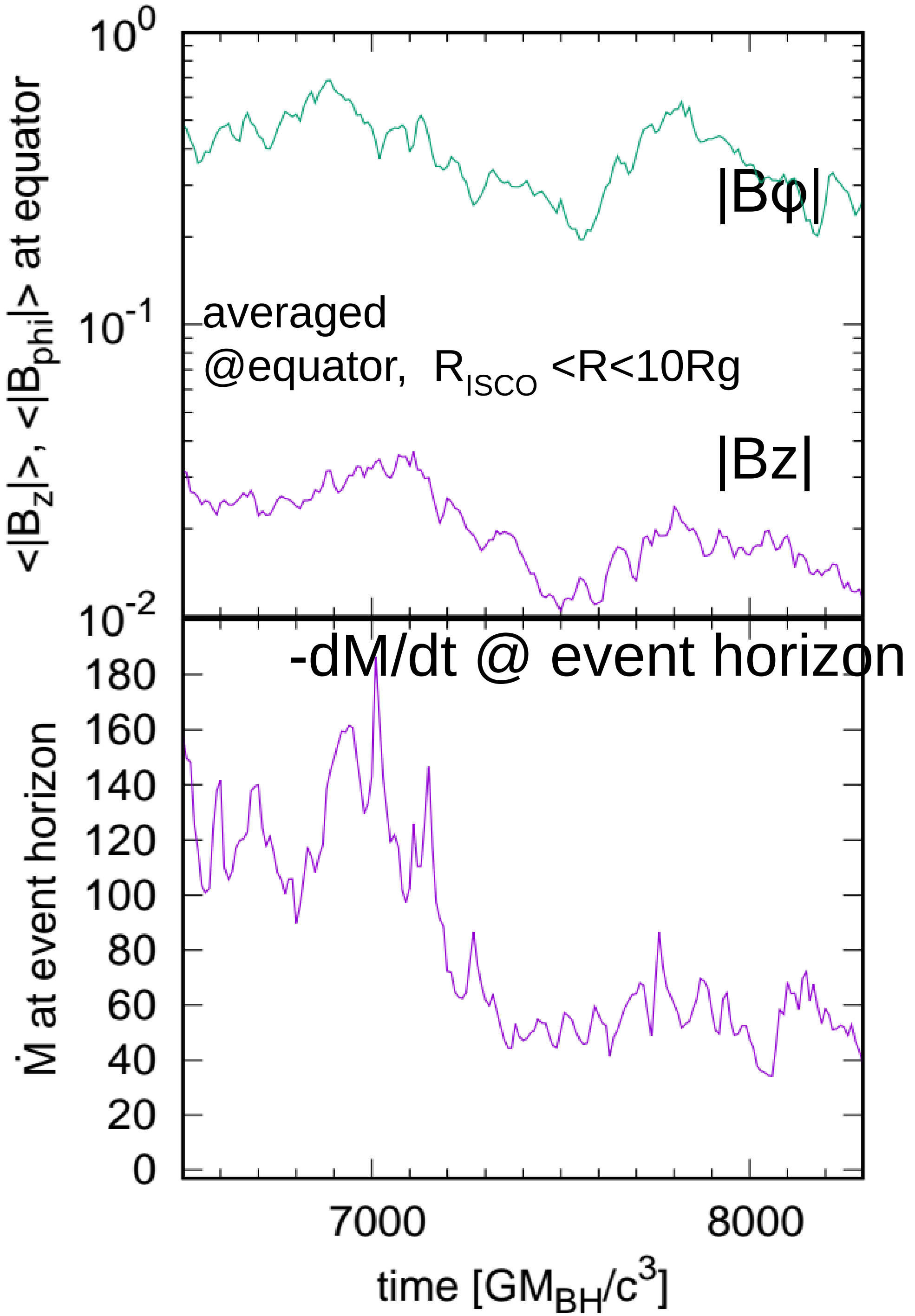


Log(1/ β) @ equator

– transitions between high β starte and low β state
Shibata, Mastumoto, & Tajima (1990) and other MHD simulations).

– Highly non-axis symmetric

B-filed amplification & mass accretion

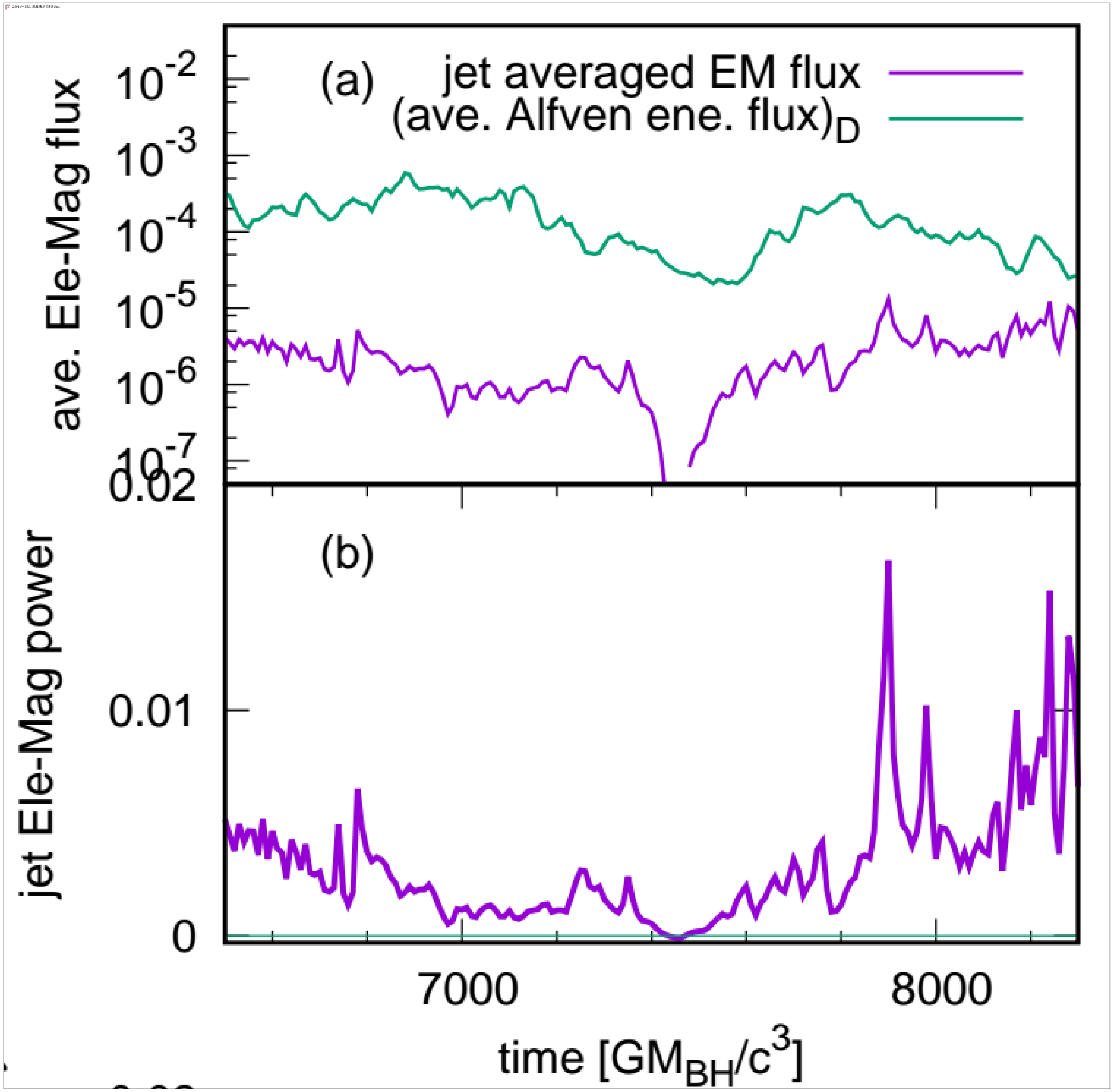


– B- filed amplification works as a viscosity
➔alpha viscosity in Shakura & Sunyaev 1973)

– B-field amplification via MRI (Balbus & Hawley 1991)
λ~0.1Rg ~8 grids size
~filamentaly structure
growth timescale ~ 30 GM/c^3
➔t_{MRI} @ r_{ISCO} +α

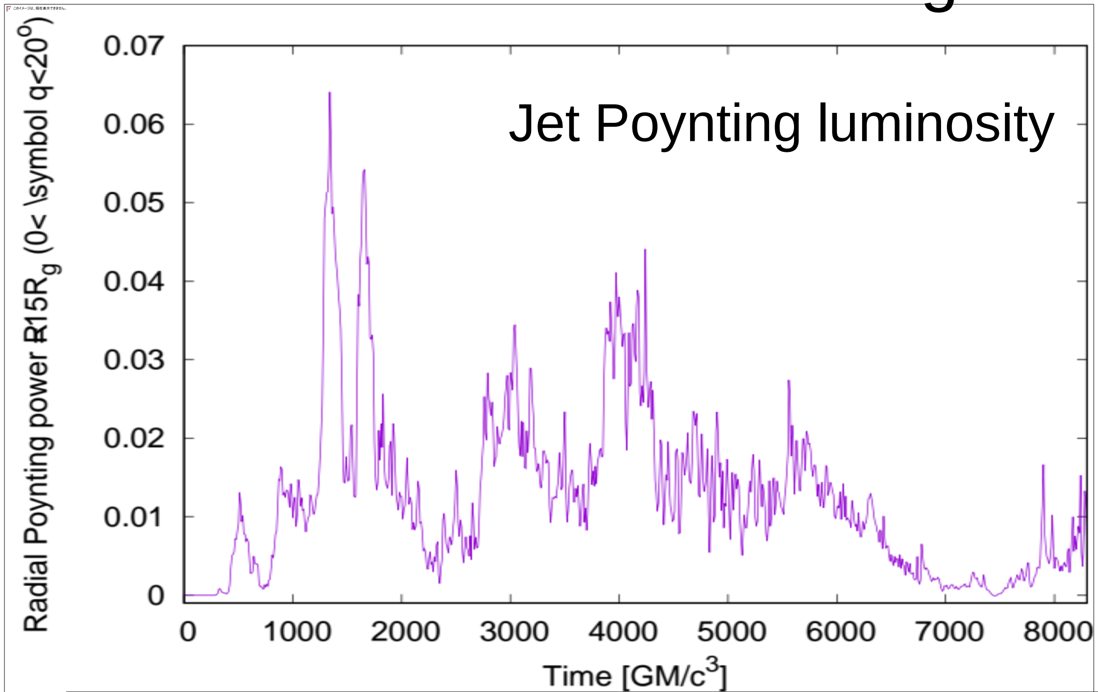
– Repeat cycle
~200 hundreds GM/c^3
~10 times orbital period
(Stone et al. 1996, Suzuki & Inutsuka 2009, O'Neill et al. 2011)

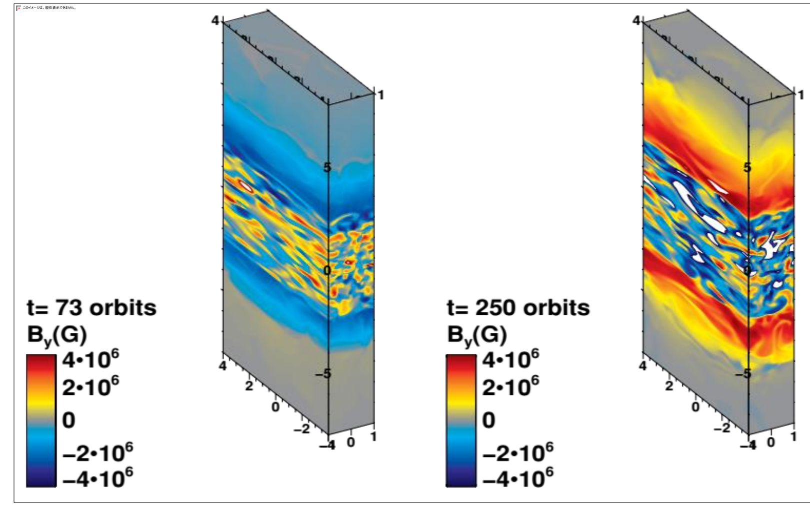
Large Alfven flares in the jet

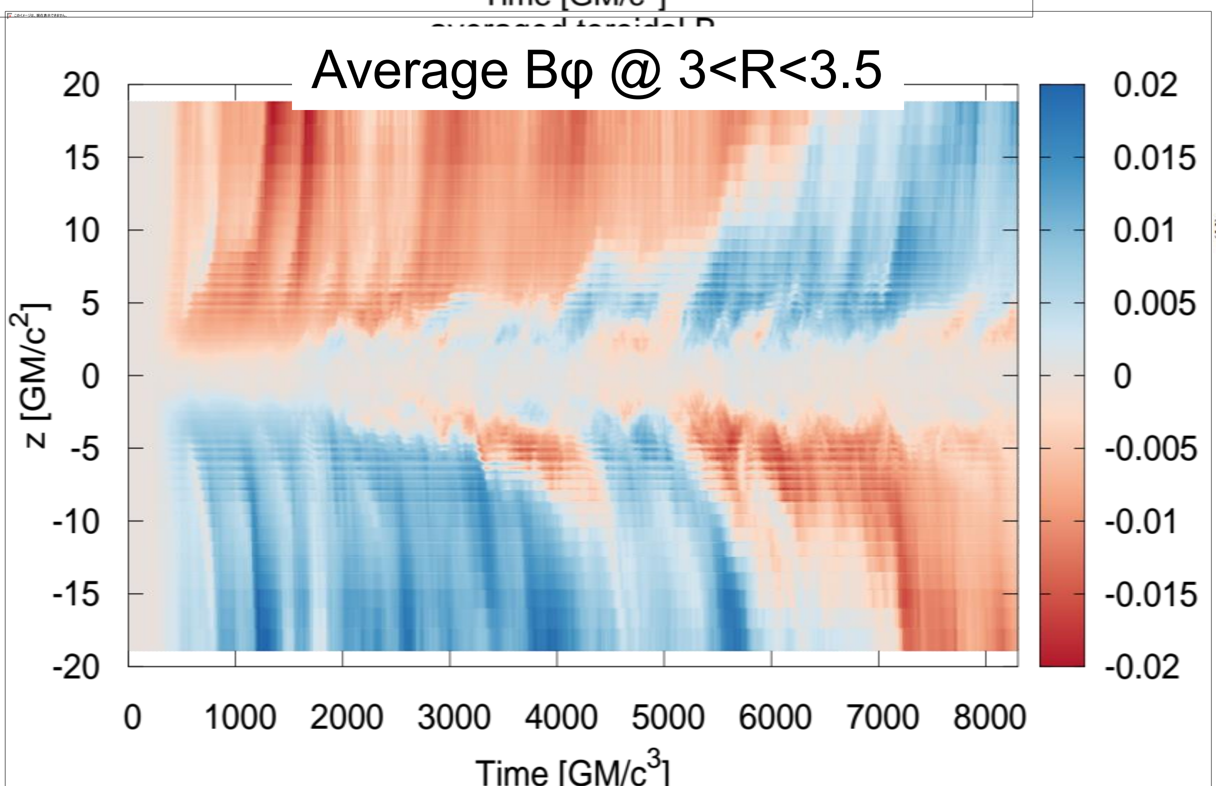


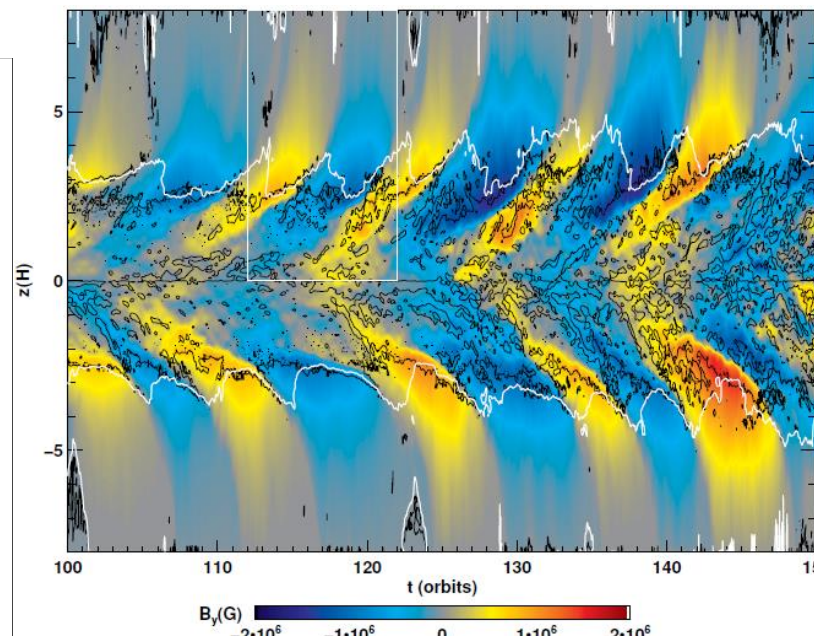
- Same time variability seen at disks.
- Flare activity
- Ele-Mag flux in the jet reaches to Aflven flux in the disk when Ele-Mag jet is active.

Torodial magnetic fields rise up





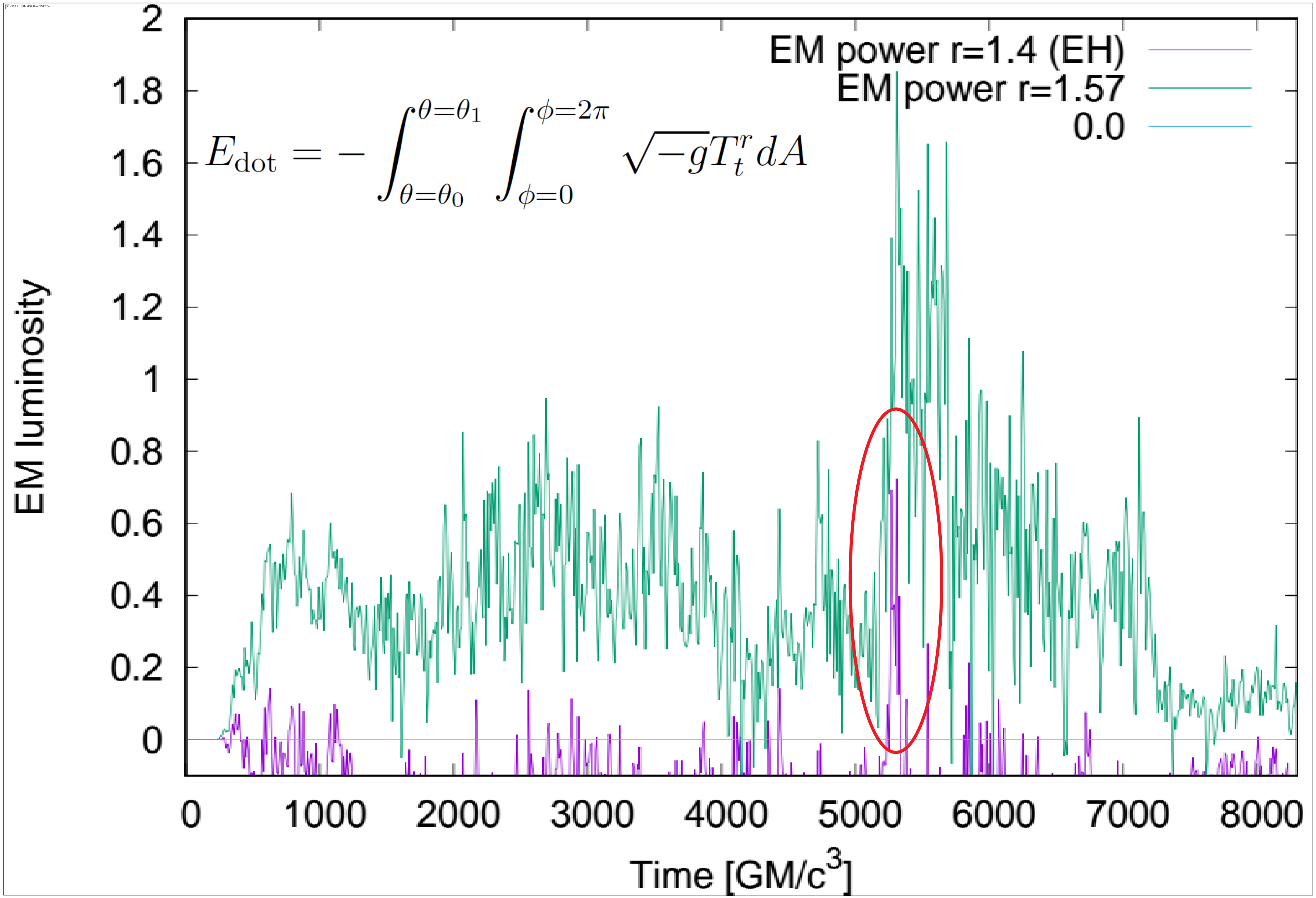




Periodic feature
T~10 orbiral period.
Local box simulation Shi + 2010

Blandford-Znajek process ?

Electric-magnetic power near horizon



Inefficient – 1/10-1/100 of mass accretion rate x c^2

BZ flux v.s. EM flux @ horizon (1)

BZ1977, McKinney & Gammie2004

Radial electric-magnetic flux is described as

$$F_{\rm E}^{\rm EM}(r,\theta) = -2(B^r)^2\omega r\left(\omega - \frac{a}{2r}\right)\sin^2\theta - B^r B^\phi \omega (r^2 - 2r + a^2)\sin^2\theta$$

@ event horizon

$$r = r_{\rm H} = 1 + \sqrt{1-a^2}$$

$$F_{\rm E}^{\rm EM}(r = r_{\rm H},\theta) = 2(B^r)^2\omega r_H(\Omega_{\rm H} - \omega)\sin^2\theta$$

$$\Omega_{\rm H} = \frac{a}{2r_{\rm H}}$$

Rotation frequency of BH

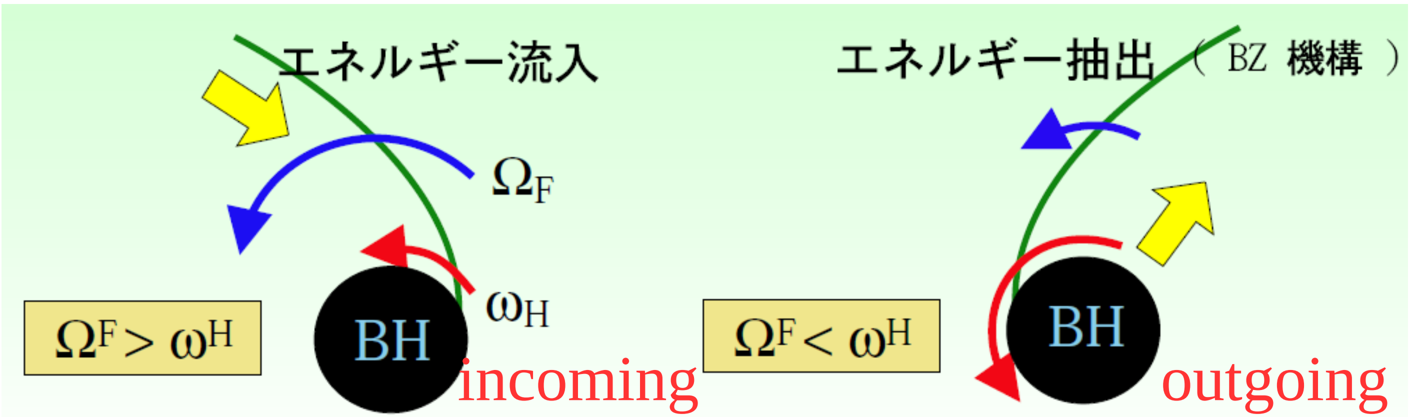
$$\omega = -\frac{F_{tr}}{F_{\phi r}} = -\frac{F_{t\theta}}{F_{\phi\theta}}$$

Rotation frequency of EM field

$$\omega = -\frac{F_{tr}}{F_{\phi r}} = -\frac{b^\theta u^\phi - b^\phi u^\theta}{b^t u^\theta - b^\theta u^t}$$

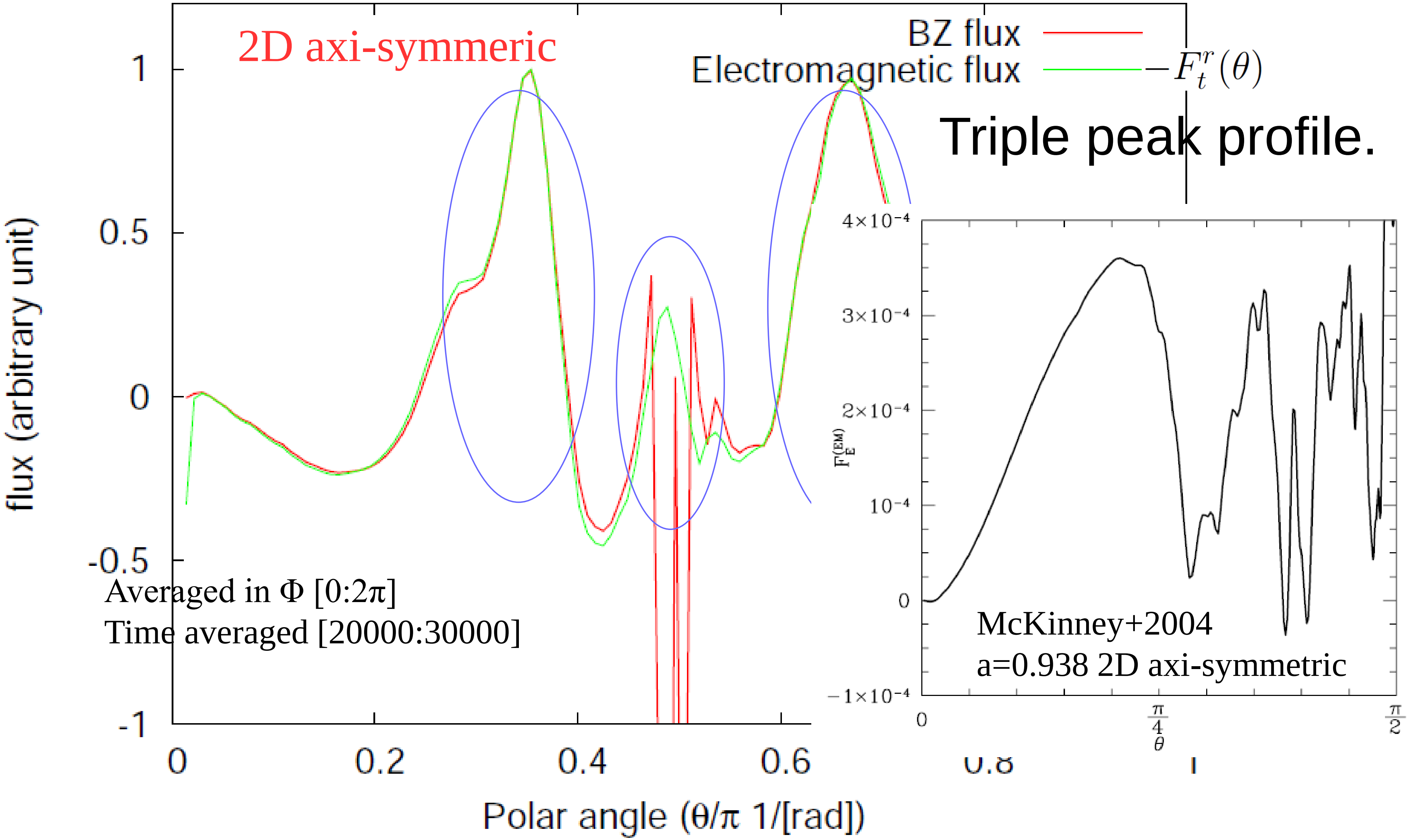
$$\omega = -\frac{F_{t\theta}}{F_{\phi\theta}} = -\frac{b^r u^\phi - b^\phi u^r}{b^t u^r - b^r u^t}$$

$0<\omega<\Omega_{\rm H} \Rightarrow$ outgoing flux



From Takahashi's (AUE) slide

BZ flux v.s. EM flux @ horizon (2)

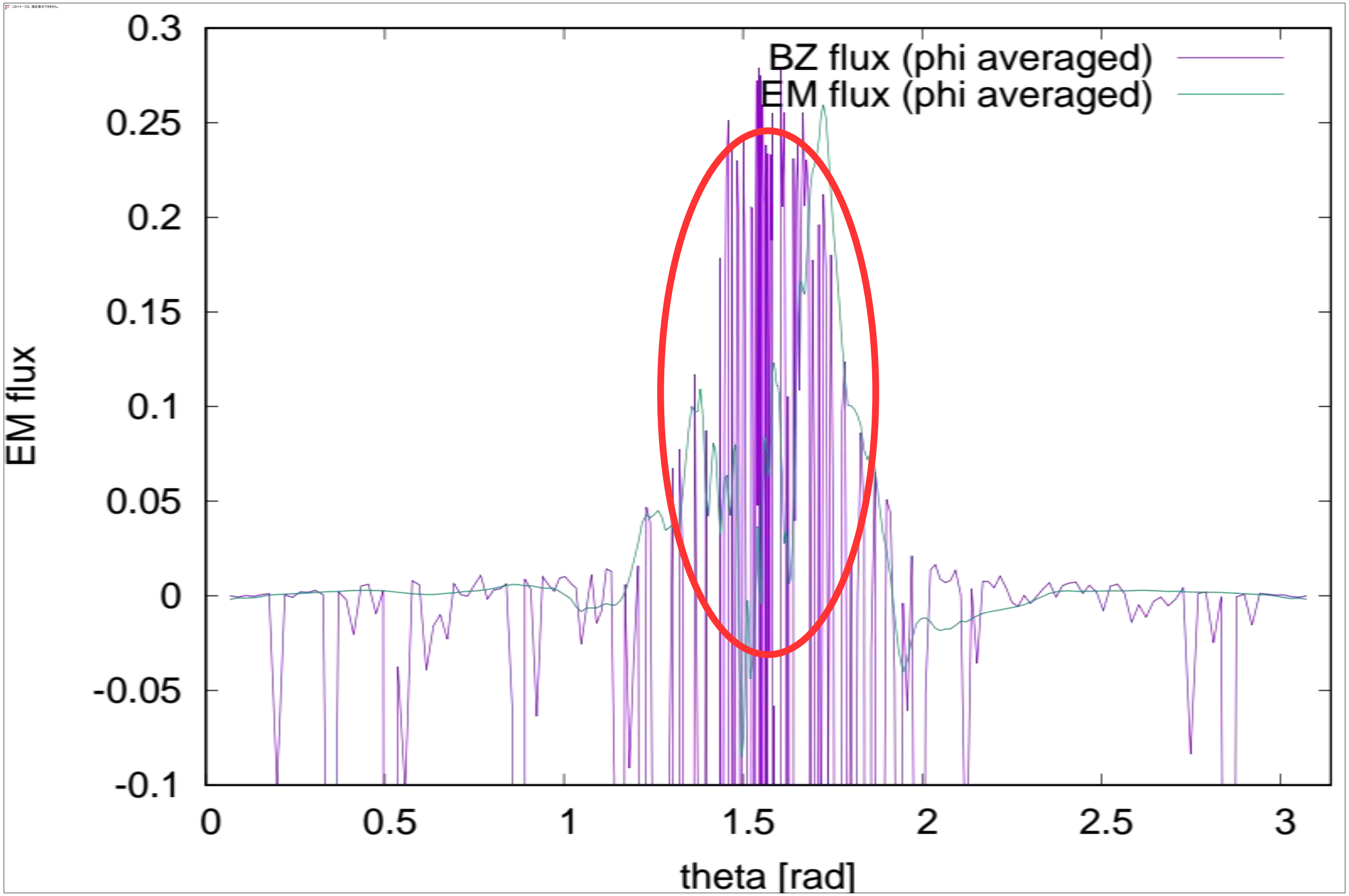


For 2D axi-symmetric case, time-averaged BZ flux is good agreement with electromagnetic flux at horizon.

BZ power is very efficient ~ 100 tiems mass accretion power.

BZ flux v.s. EM flux @ horizon (3)

3D case



Electromagnetic flux is roughly good agreement with BZ flux.
Outgoing flux is concentrated around equator.

Conclusion

3D GRMHD simulations of rotating BH+accretion disk

– B filefd amplification via MRI
– low beta disk ⇔ high beta disk transition
  short time variability
– toroidal magnetic field rise up from the equator
– BZ power is not so high as comparared with mass accretion power

Future works

– Long term calculations w/ wide range Kerr parameters, different initial conditions are necessary.
– code improvement is under development