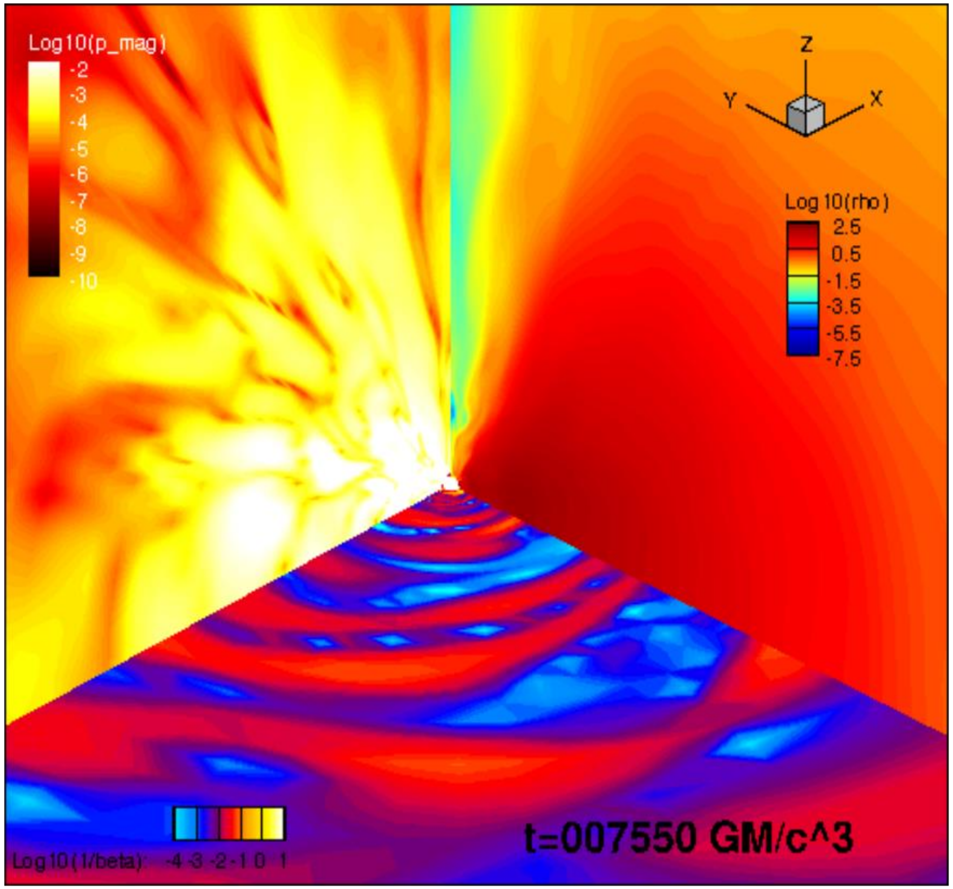
3D GRMHD simulation of black hole accretion flows and jets

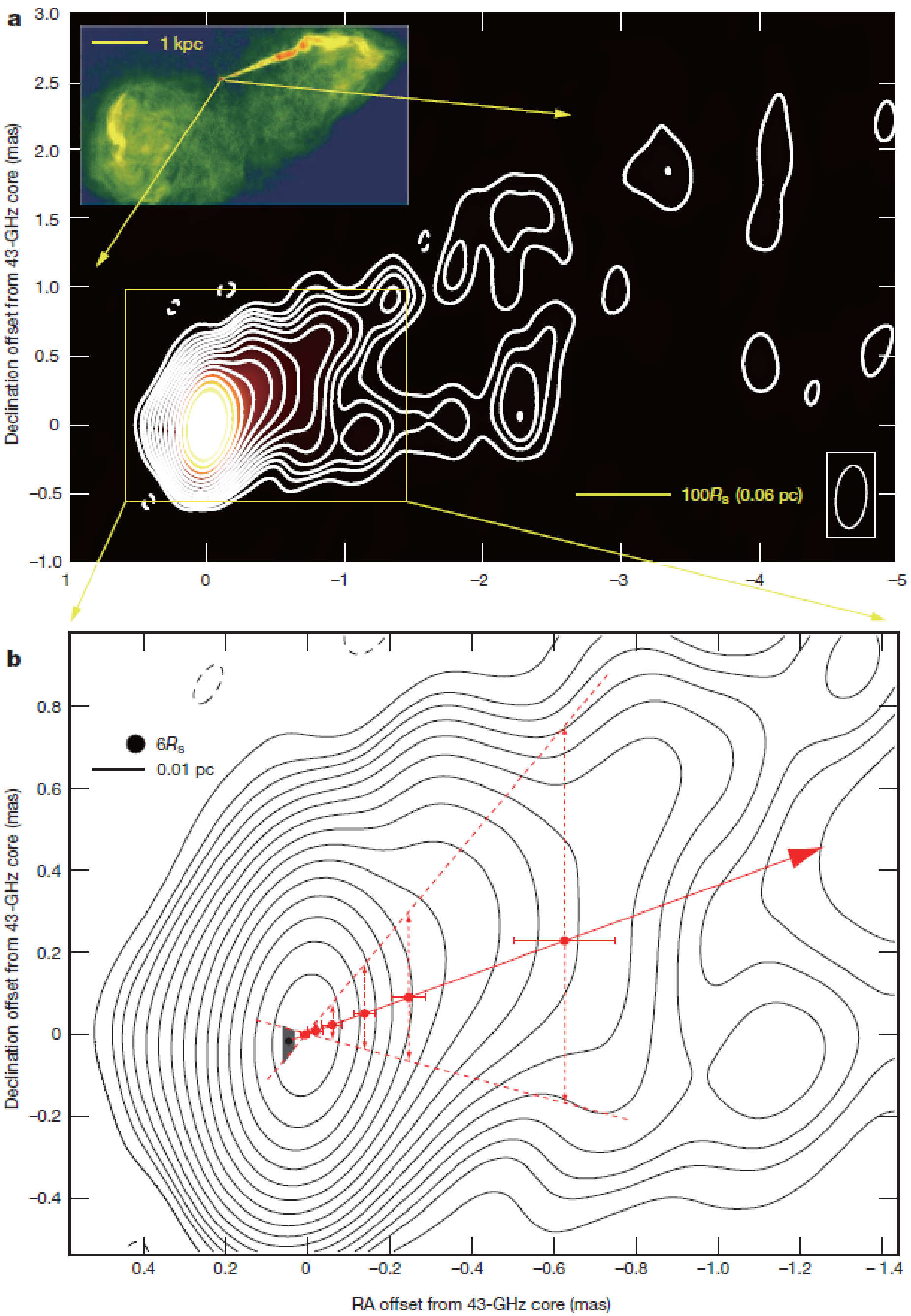


Akira MIZUTA (RIKEN)

References
AM, Ebisuzaki, Tajima, Nagataki, MNRAS 479 2534(2018)
the case of BH spin a=0.9
AM+ in prep.
parameter study in BH spin (a)

RIKEN-RESCEU Joint Seminar
@Univrsity of Tokyo
2019.03.19

Active Galactic Nuclei Jet



M87 radio observation Hada +(2011)

Hilghlly collimated outflows from center of galaxy

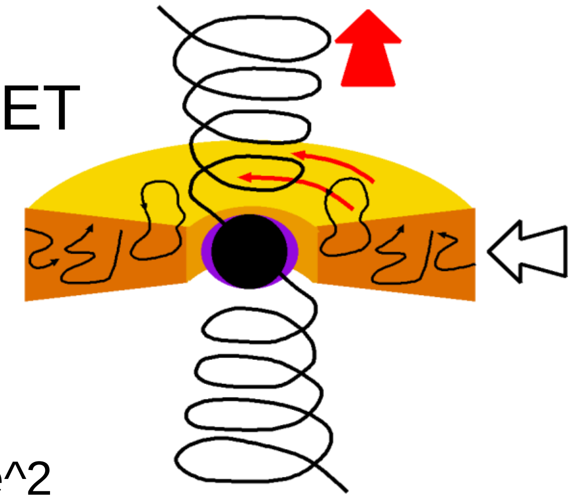
- central engine
  supermassive black hole
  +
  accretion disk
- relativistic outflows
  Bulk Lorentz factor : Γ ~ 10
- multiwavelength emission
  radio to high energy γ-rays
- strong candidate of
  ultra high energy cosmic ray accelerator
  via Fermi acc. ? (1954)
  wake field acc.
  (Ebisuzaki & Tajima 2014)

Black hole accretion flows and jets

Central engine (Black Hole(BH)＋ disk)

-Timevariability (Shibata +1990,

Balbus & Hawley1991)



-- MRI growth (B ↗ => Low beta state)

Magnetorotational instability

– differential roration : $d\Omega_{disk}/dr < 0$

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

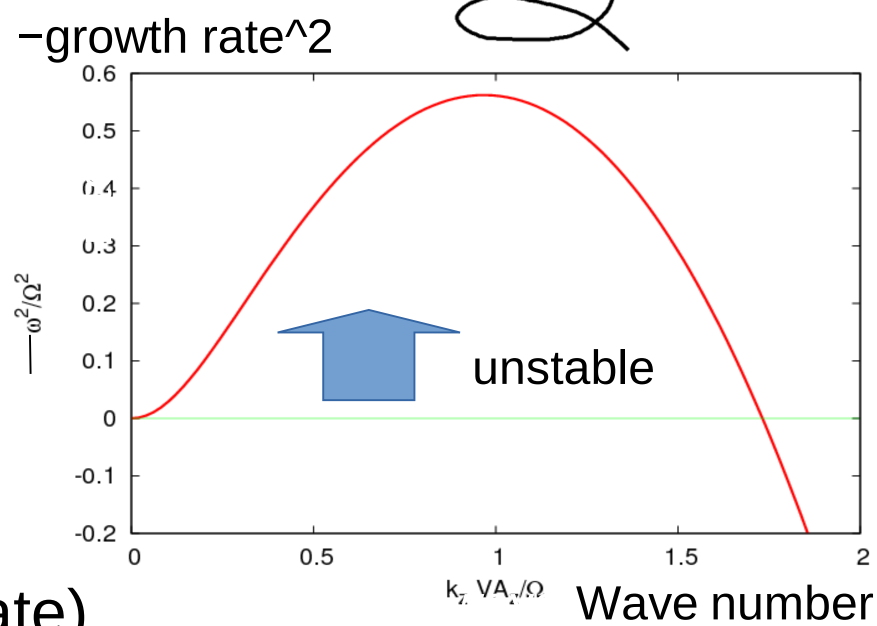
– $B \propto \exp(i\omega t)$

Unstable @ $0 < kV_a < 1.73\ \Omega_K$

Most unstable @ $kV_a \sim \Omega_K$ $\omega \sim 0.75\Omega_K$

– angular momentum transfer

$10T_K$



-- dissipation of B (B ↘=> High beta state)

-- Strong Alfven burst @ transition from low β state to high β state.

Efficient charged particle acceleration via ponderomotive force

short time variablities in blazar γ-ray flare (Ebisuzaki+14, A.M+18)

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)

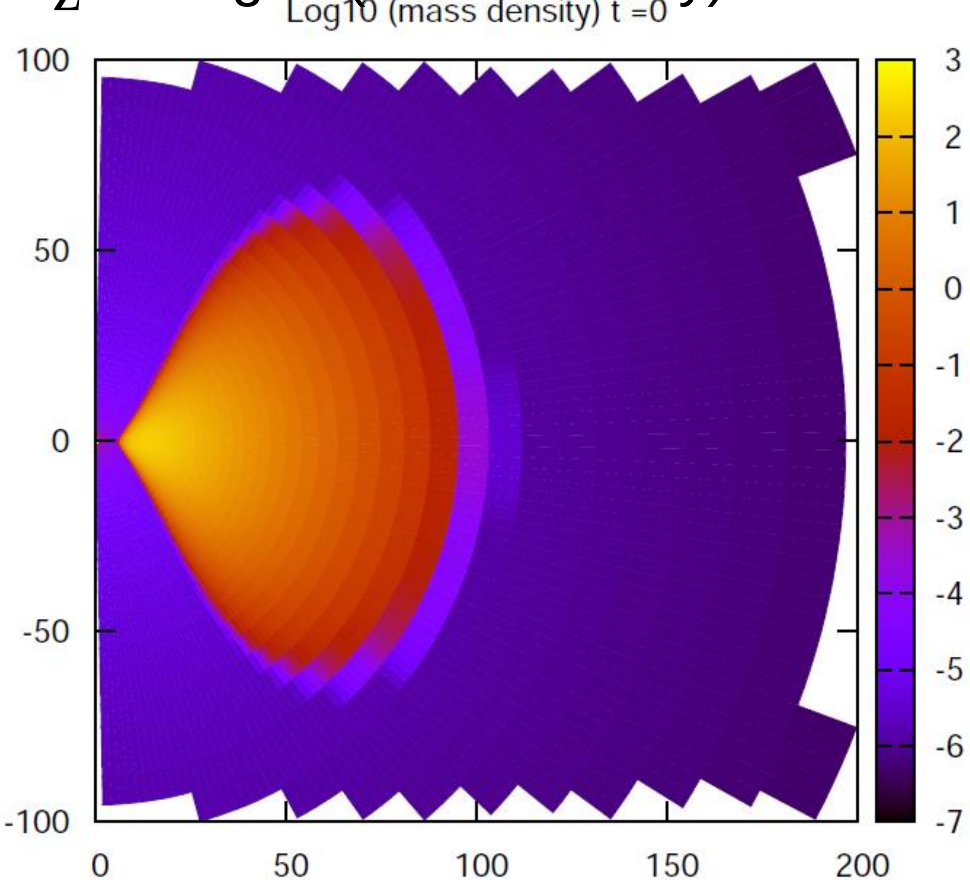
HLL flux, 2nd order in space (van Leer), 2nd or 3rd order in time

See also, Gammie +03, Noble + 2006

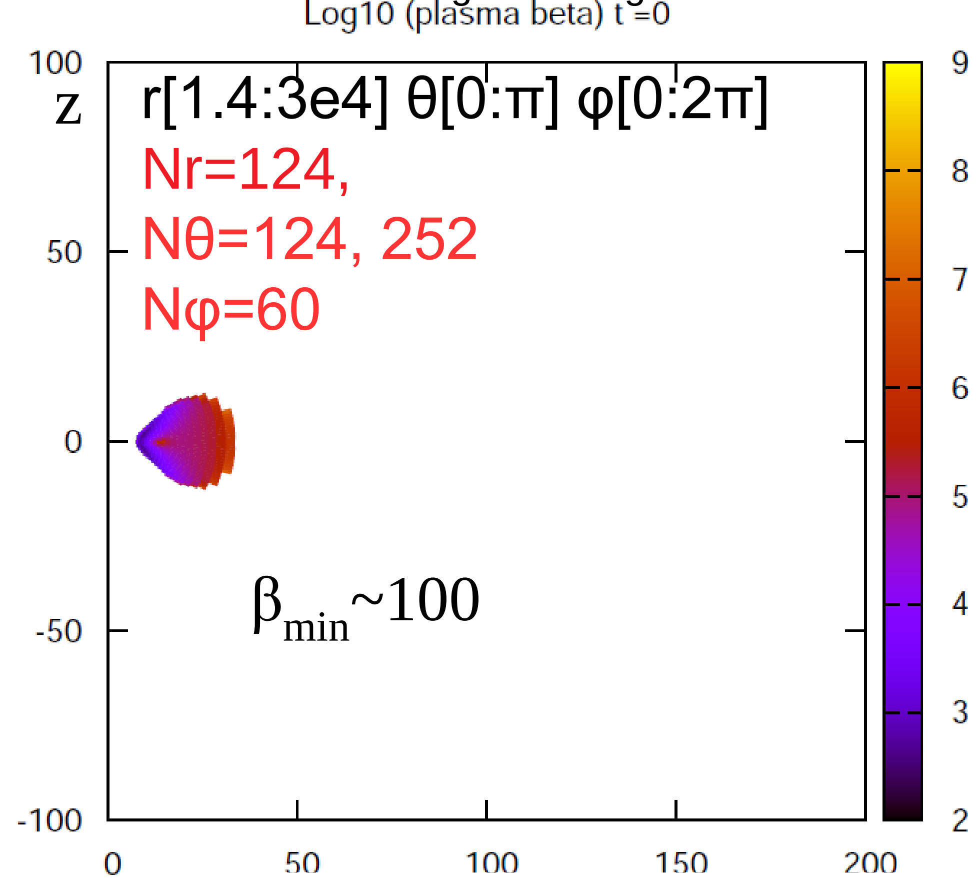
Flux-interpolated CT method for divergence free

Initial Condition

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

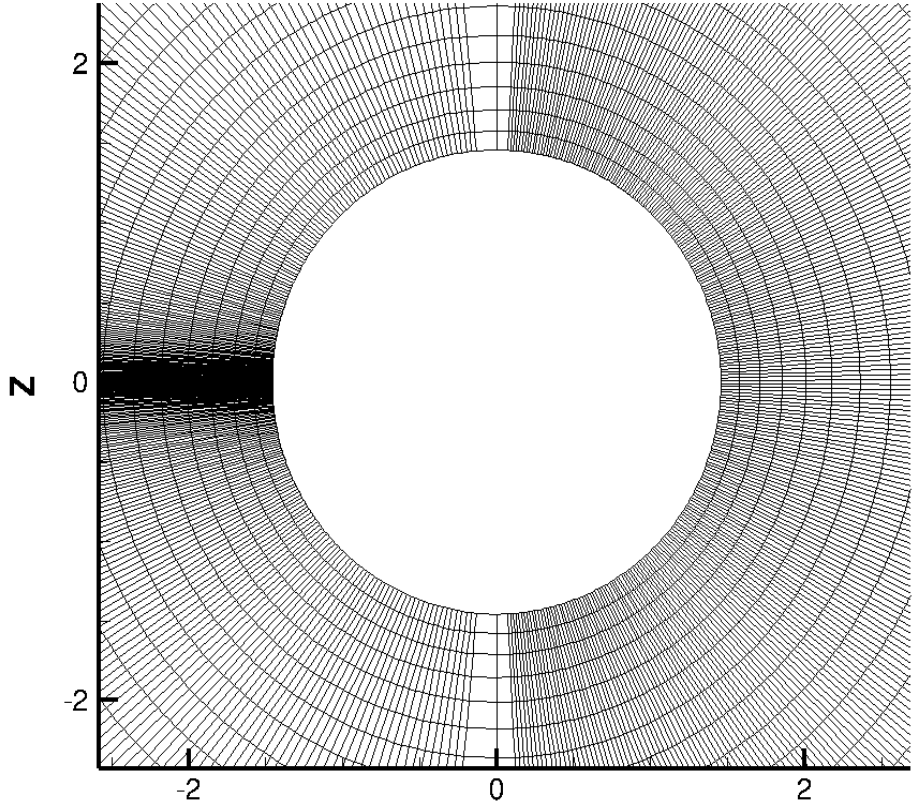
Grids to capture MRI fastest growing mode

Wavelength of fastest growing mode in the disk

$\lambda_{MRI} = 2\pi <C_{az}> / \Omega_K (R) \sim 0.022 (R/R_{ISCO})^{1.5}$

$<C_s> \sim <C_{A\,z}> \sim 10^{-3}$ c
R_{ISCO} (a=0.9)=2.32

$N_\theta = 252$



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

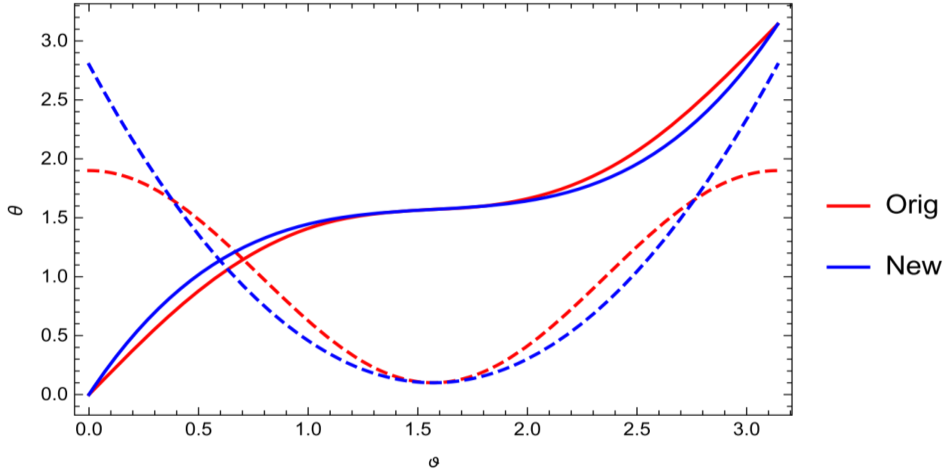
x_2 = [0:1] Δx_2=cost
h=0.2

Δθ=cost
h=1

McKinney and Gammie ････

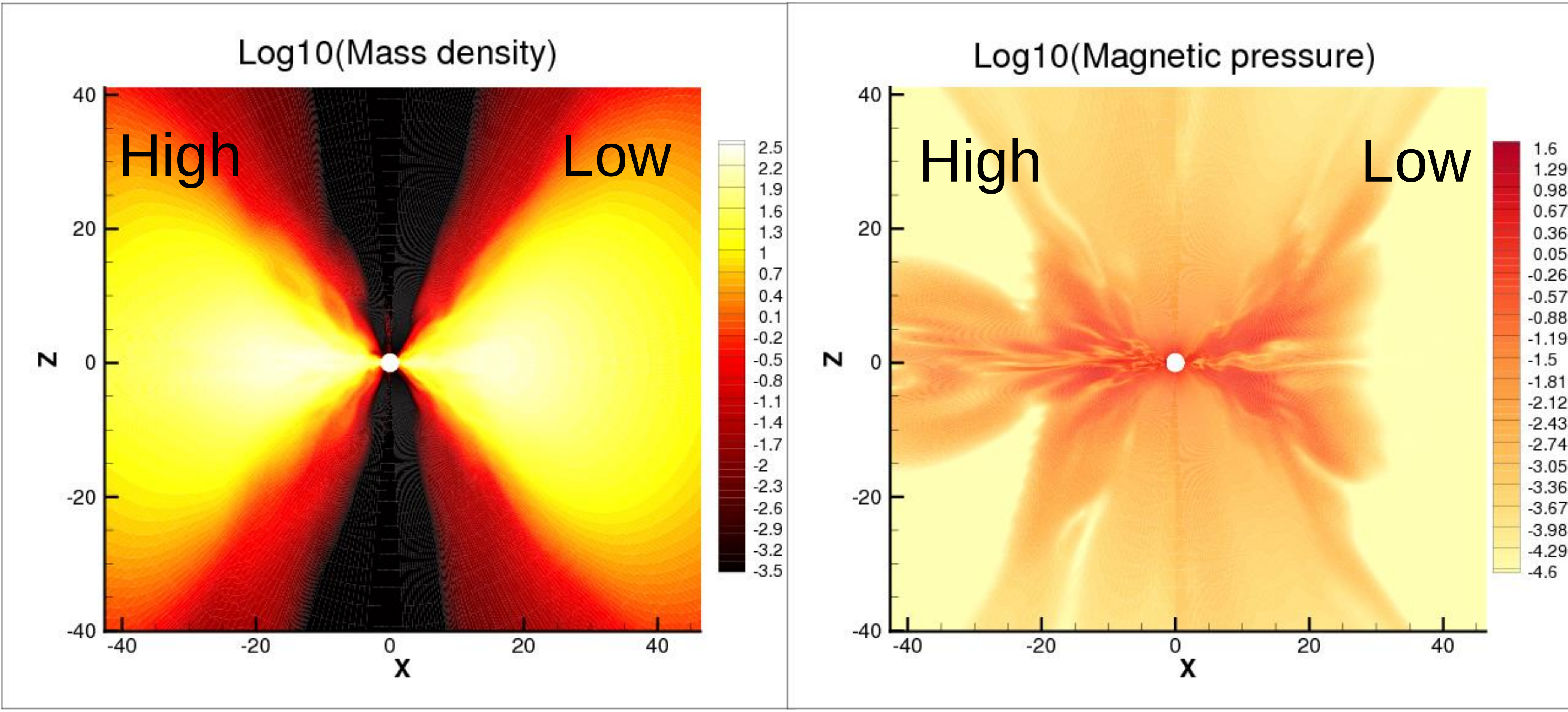
Any coordinates described by analytic function can be applied (generalized curvilinear coordinates)

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

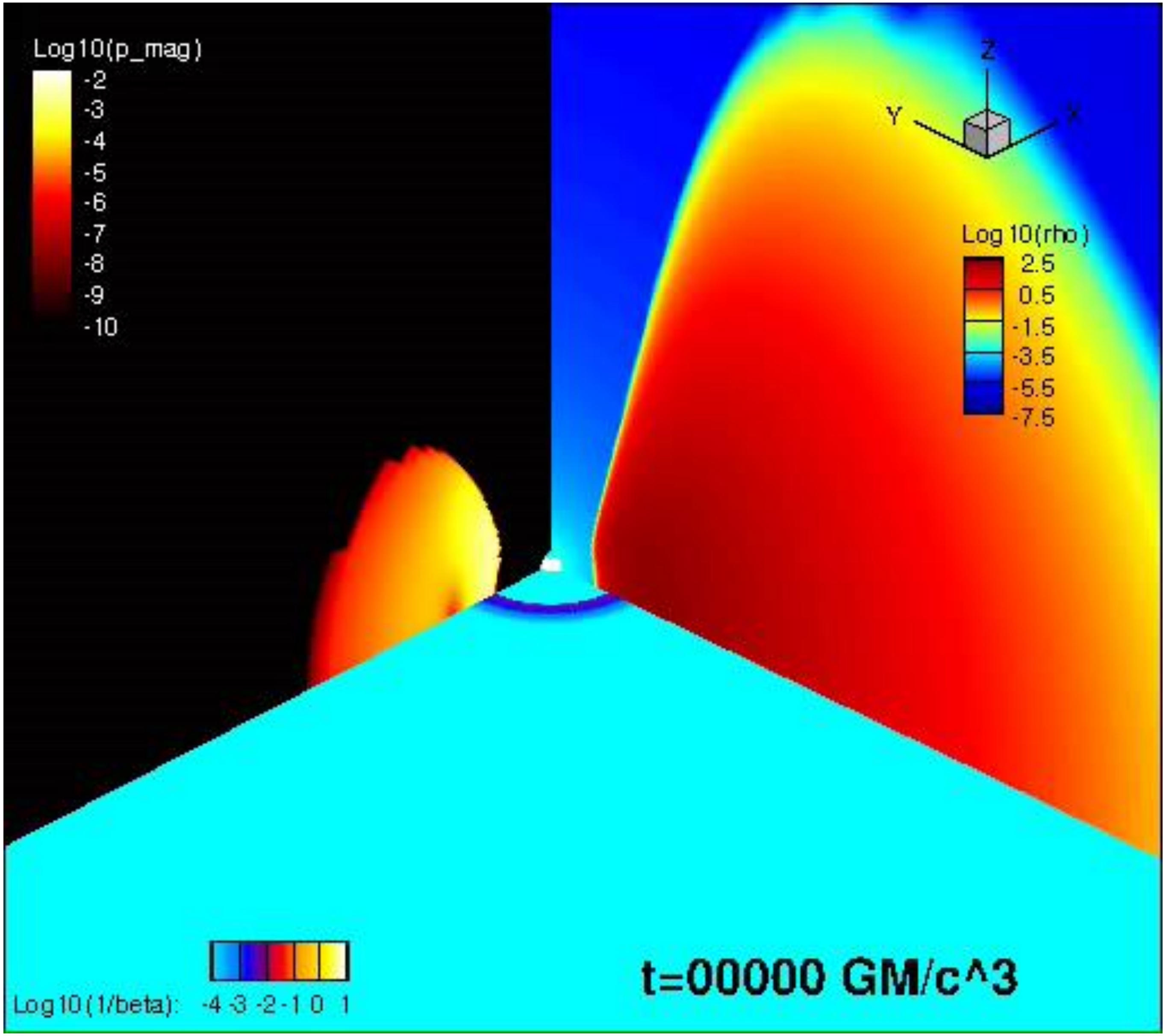


Porth + 2017

Higher resolution calculation in θ around equator



Right : about 8 times higher resolution in theta @ equator



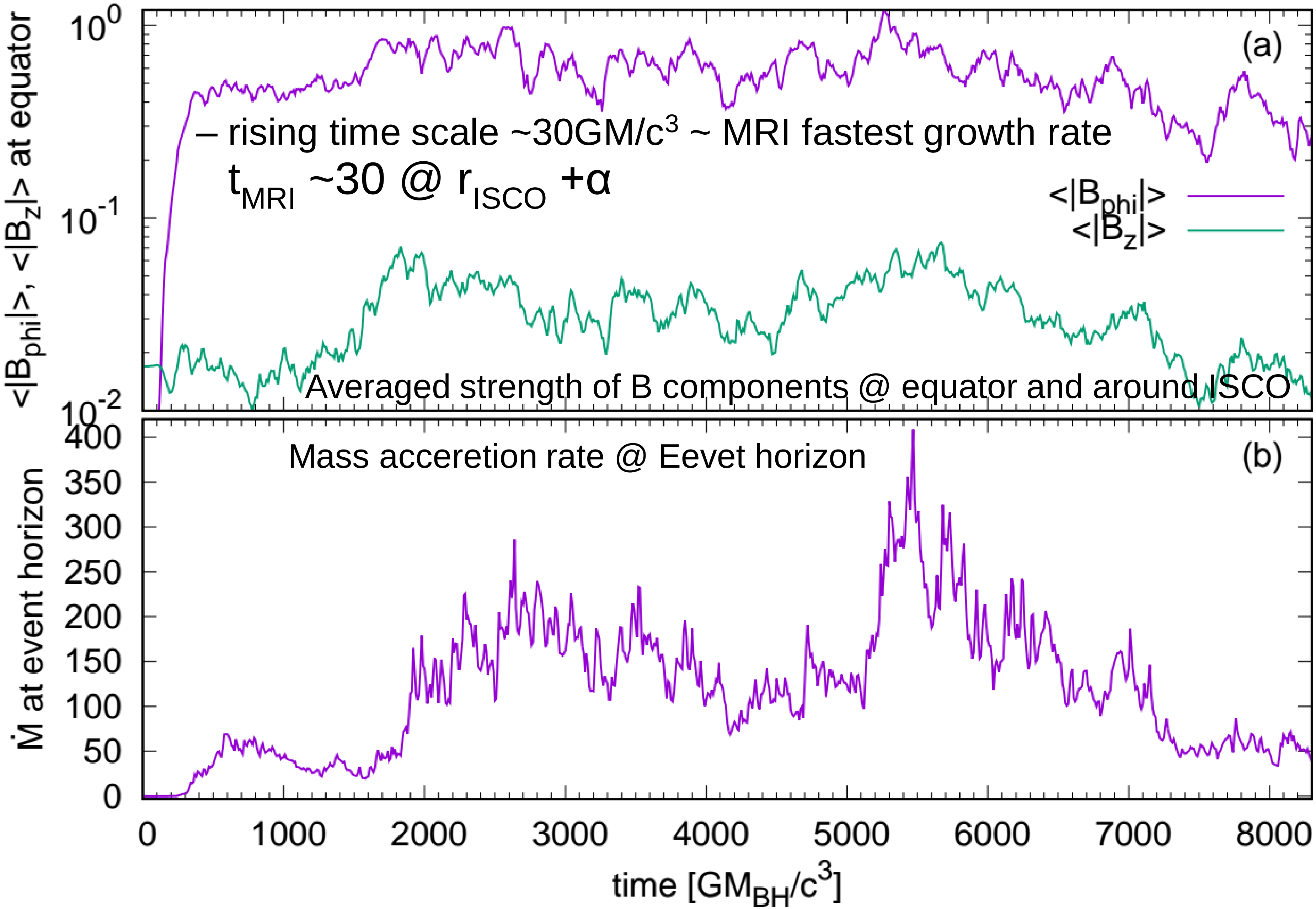
Disk : Fishbone Moncrief solution, spin parameter **a=0.9 (0.7, 0.5, 0.3, 0.1)**

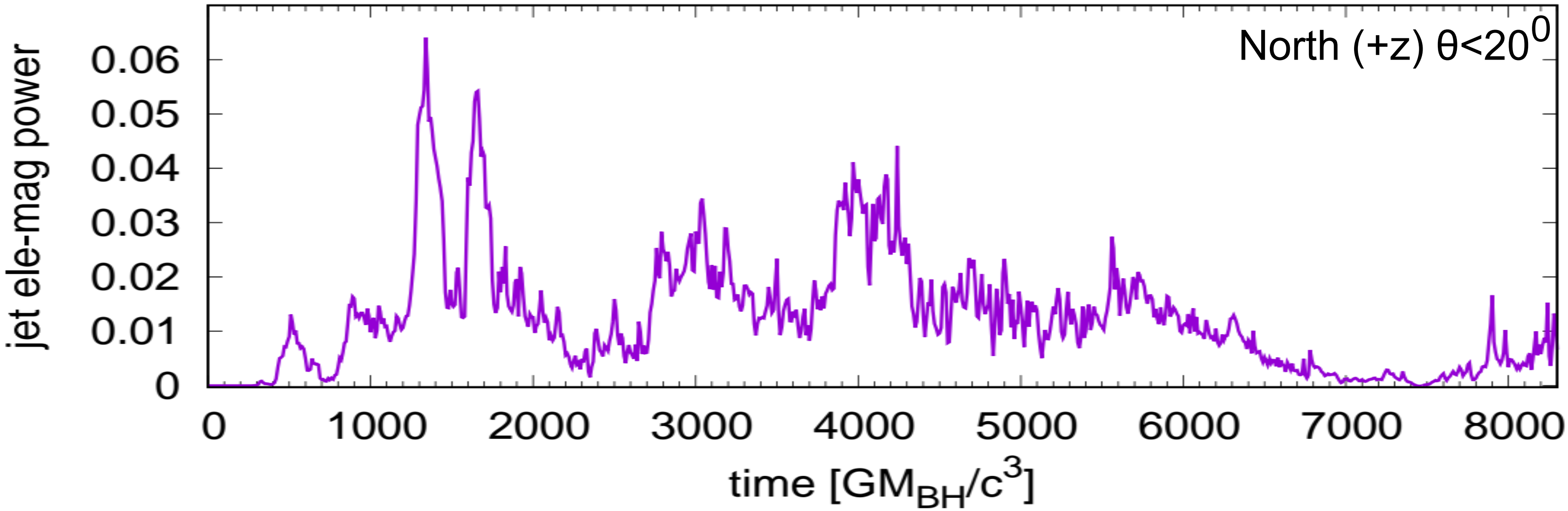
spherical coordinate R[0.98 r_H (a):3e4] θ[0:π] φ[0:2π]

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

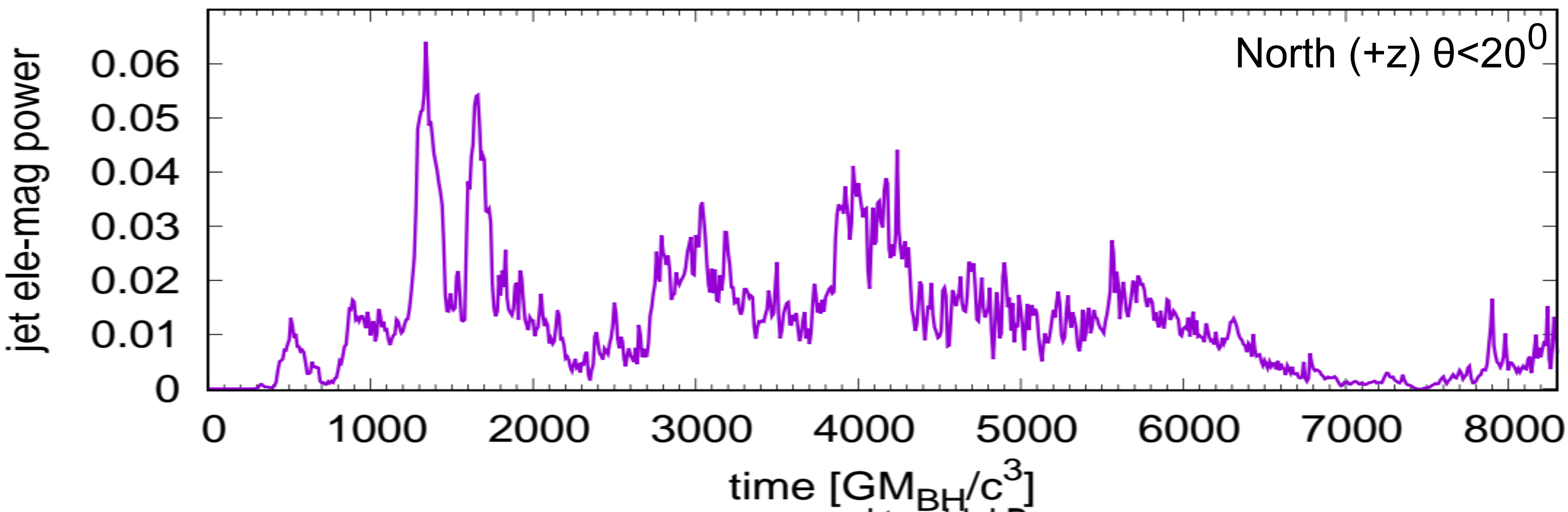
dφ~6^o: uniform Poloidal B filed, β_min=100

B-filed amplification & mass accretion

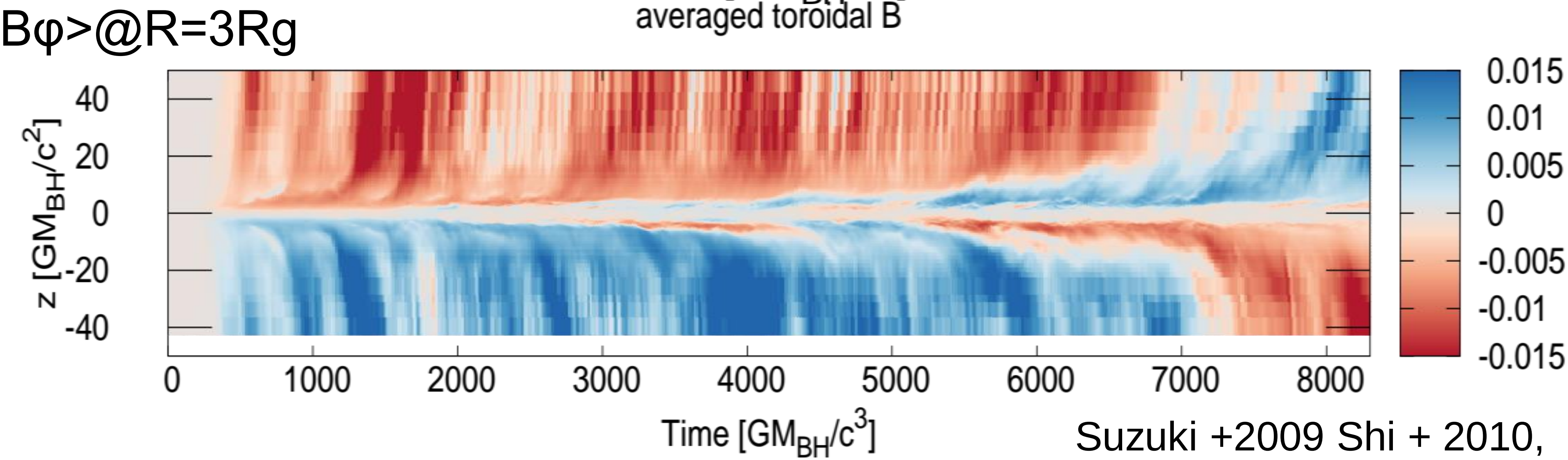




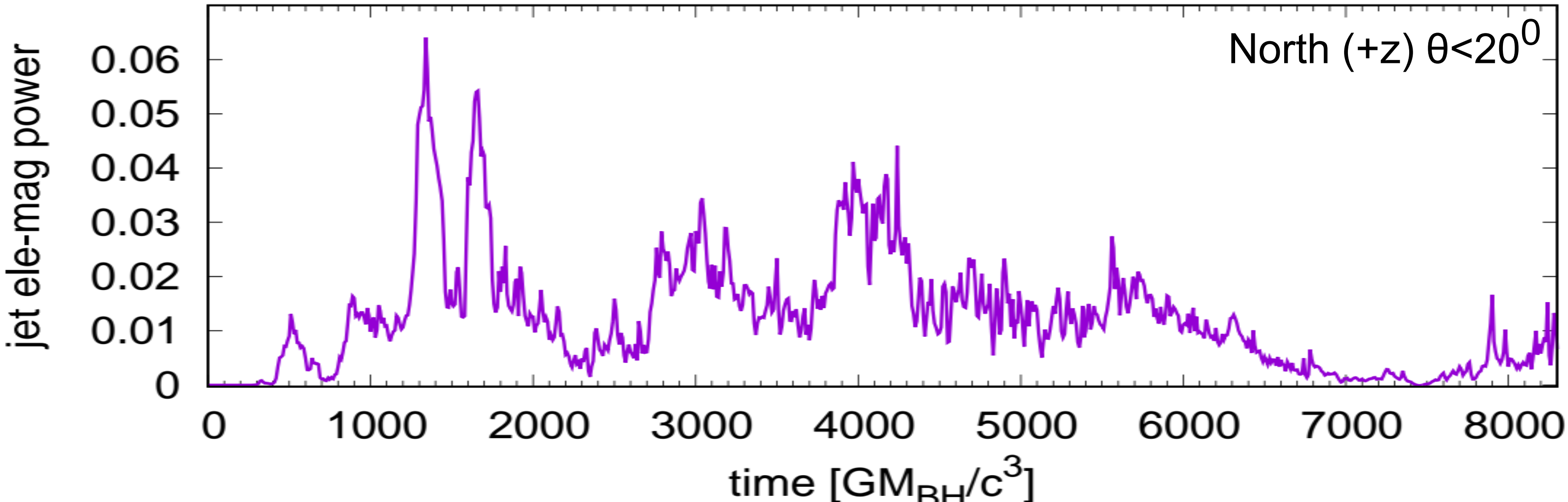
North (+z) θ<20^0
jet ele-mag power
0.06
0.05
0.04
0.03
0.02
0.01
0
0
1000
2000
3000
4000
5000
6000
7000
8000
time [GM_{BH}/c^3]



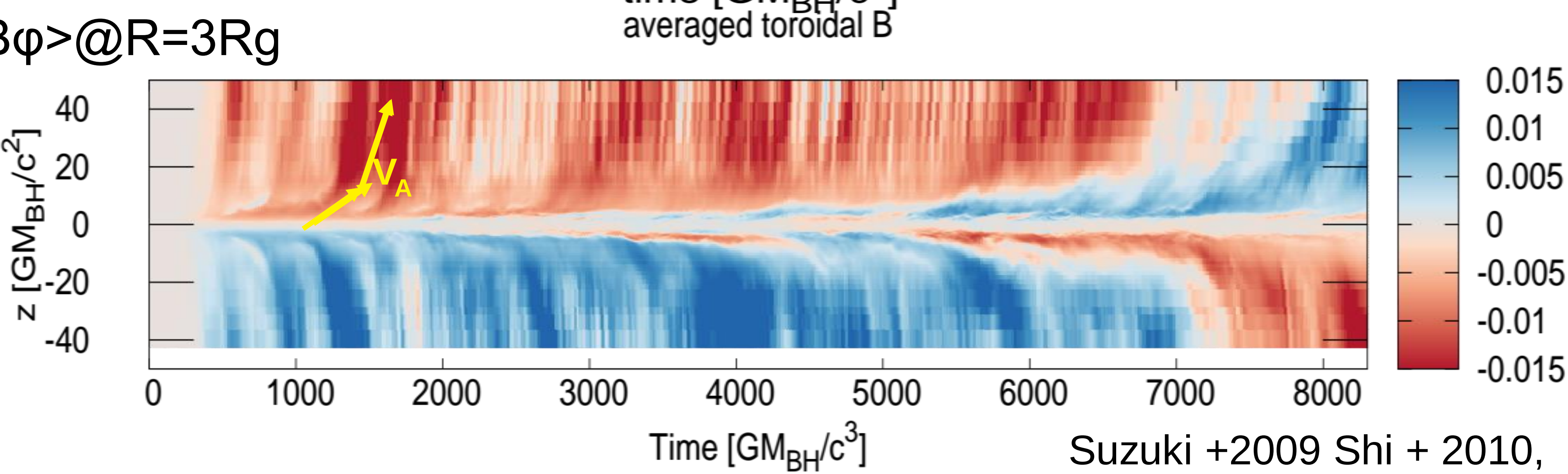
<Bφ>@R=3Rg



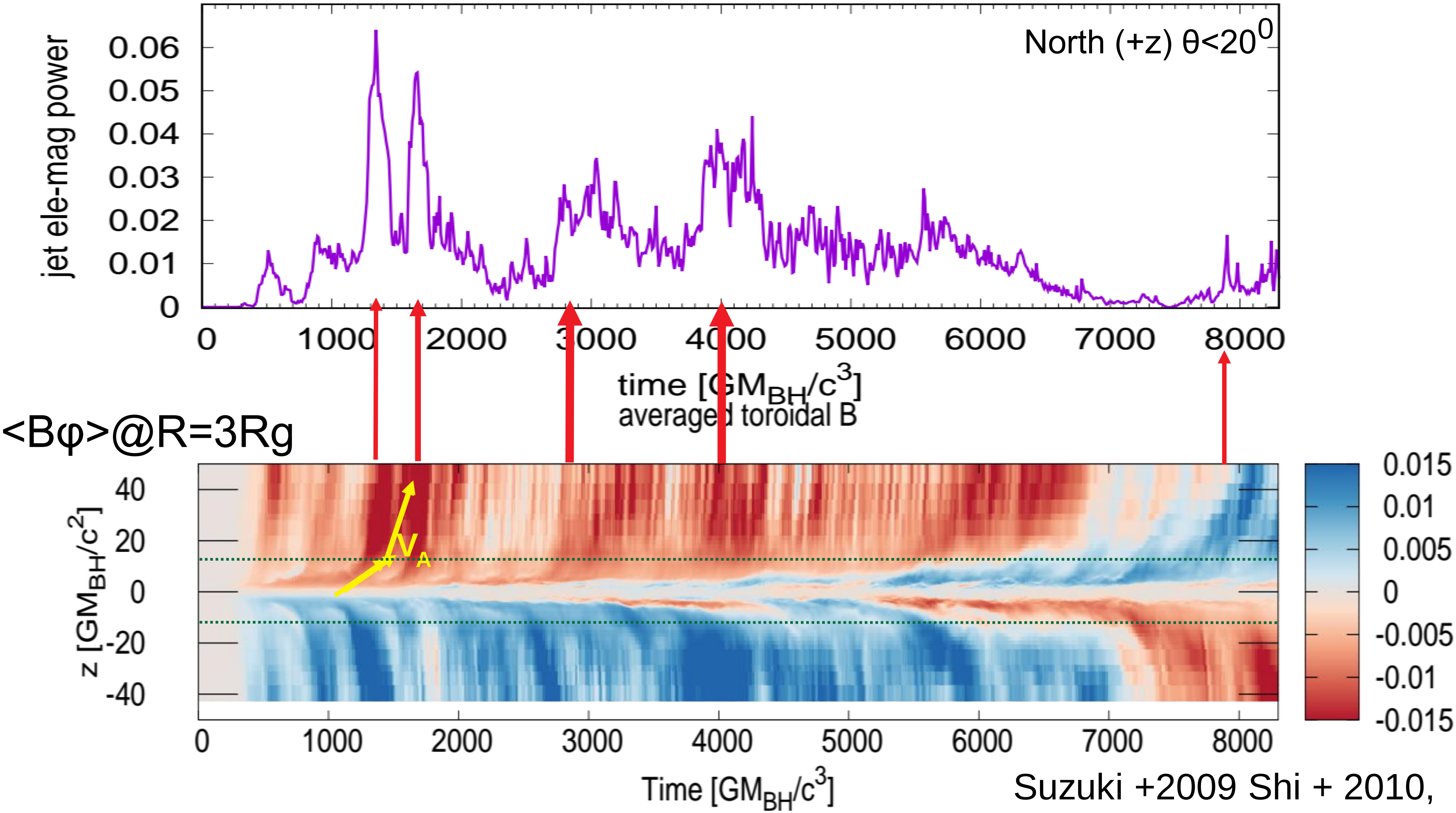
Suzuki +2009 Shi + 2010,
Machida +2013



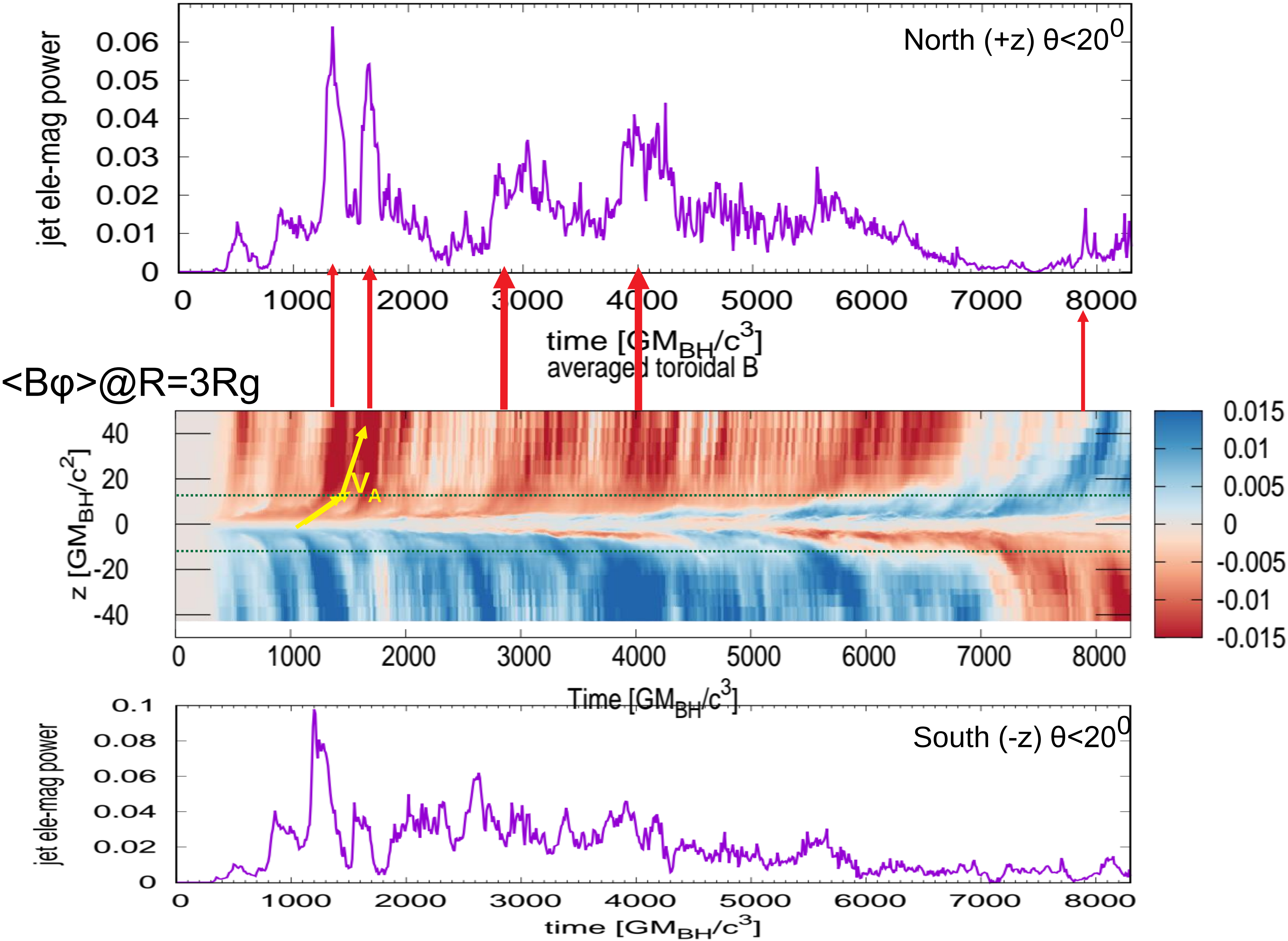
<Bφ>@R=3Rg



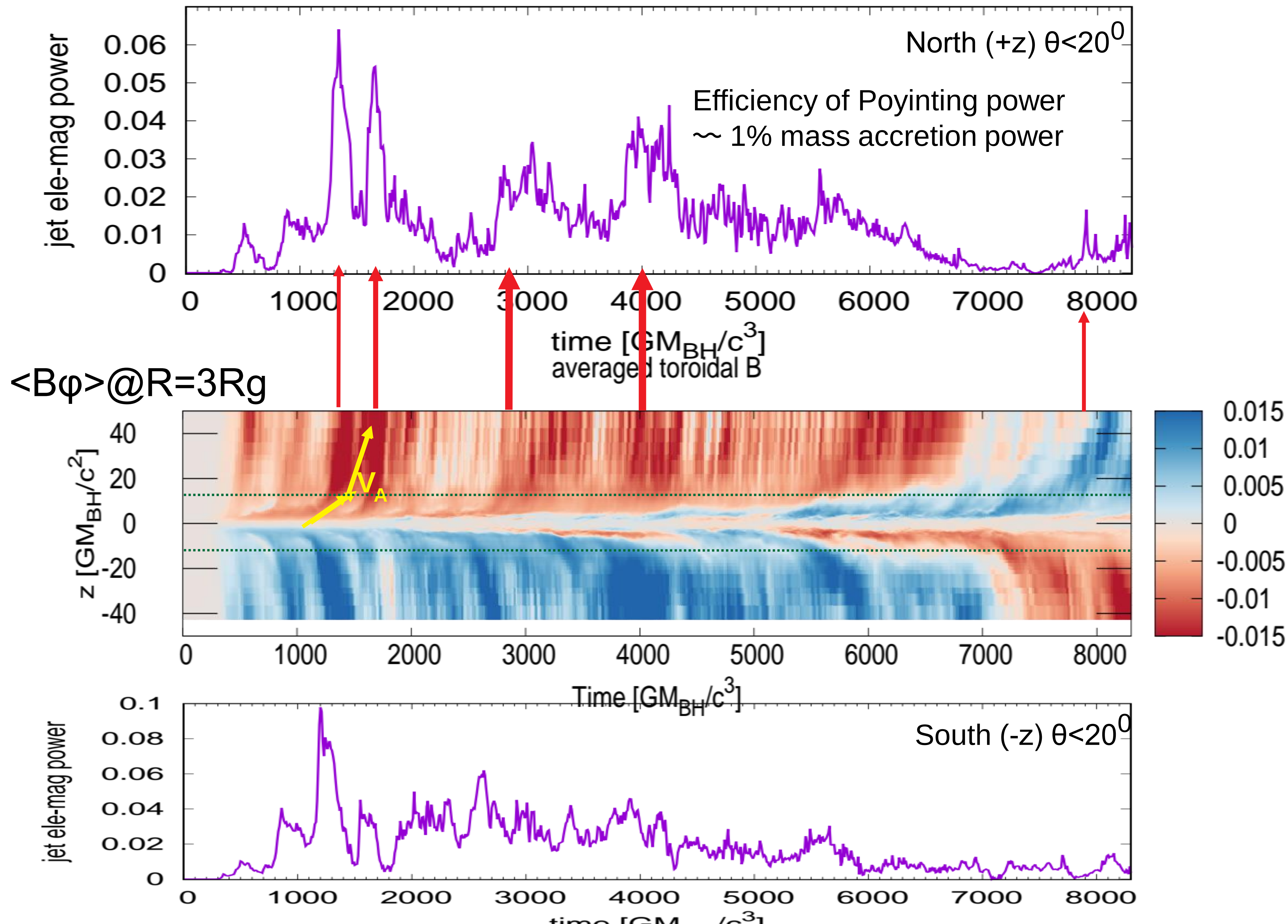
Suzuki +2009 Shi + 2010, Machida +2013



Suzuki +2009 Shi + 2010,
Machida +2013
Takasao+2018

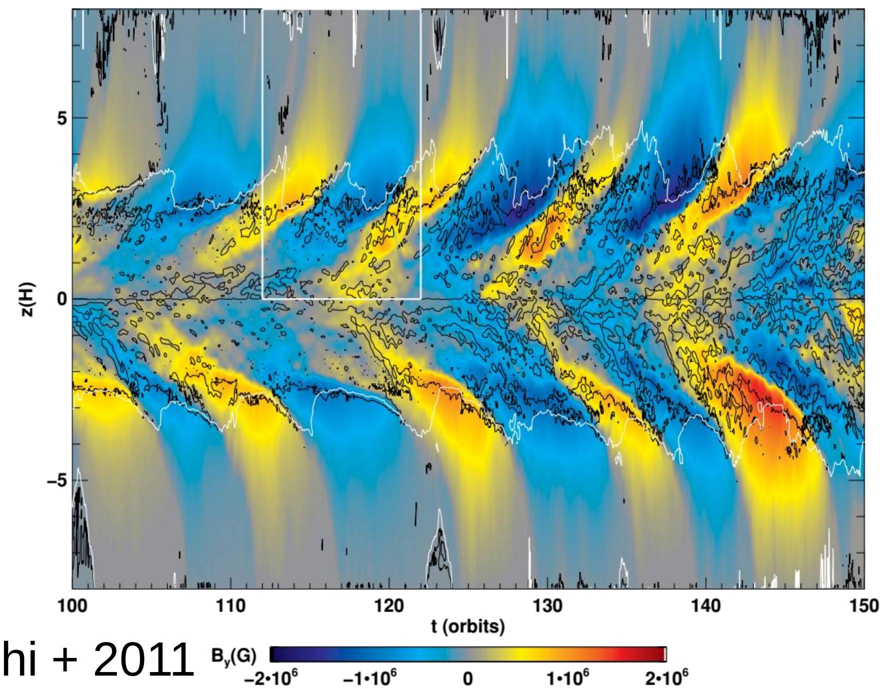


North (+z) θ<20⁰
jet ele-mag power
time [GM_BH/c³]
averaged toroidal B
<Bφ>@R=3Rg
z [GM_BH/c²]
V_A
Time [GM_BH/c³]
South (-z) θ<20⁰
jet ele-mag power
time [GM_BH/c³]



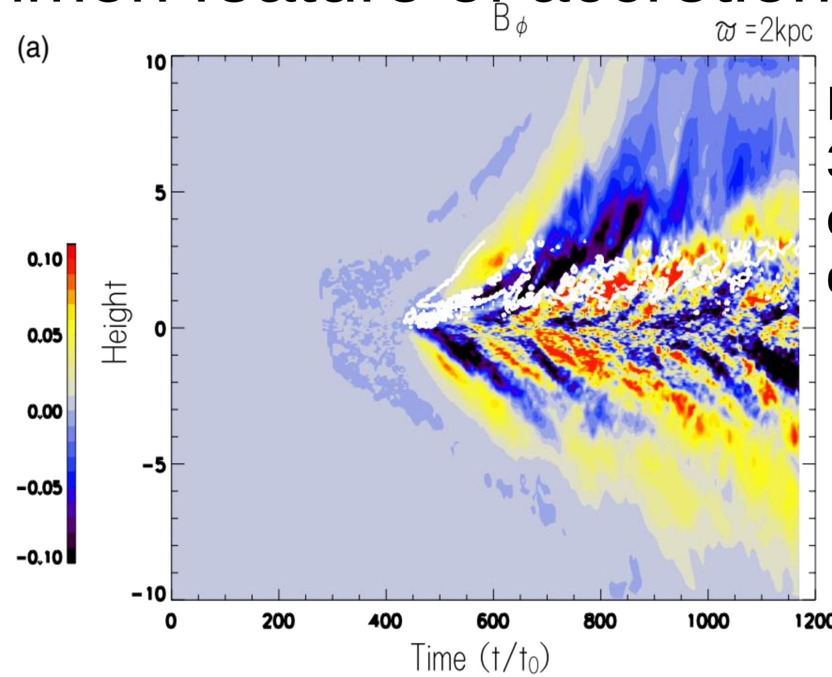
North (+z) θ<20^0
Efficiency of Poyinting power
~~ 1% mass accretion power
jet ele-mag power
time [GM_BH/c^3]
averaged toroidal B
<Bφ>@R=3Rg
V_A
z [GM_BH/c^2]
Time [GM_BH/c^3]
South (-z) θ<20^0
jet ele-mag power
time [GM_BH/c^3]

Butterfly diagram is common feature of accretion disk

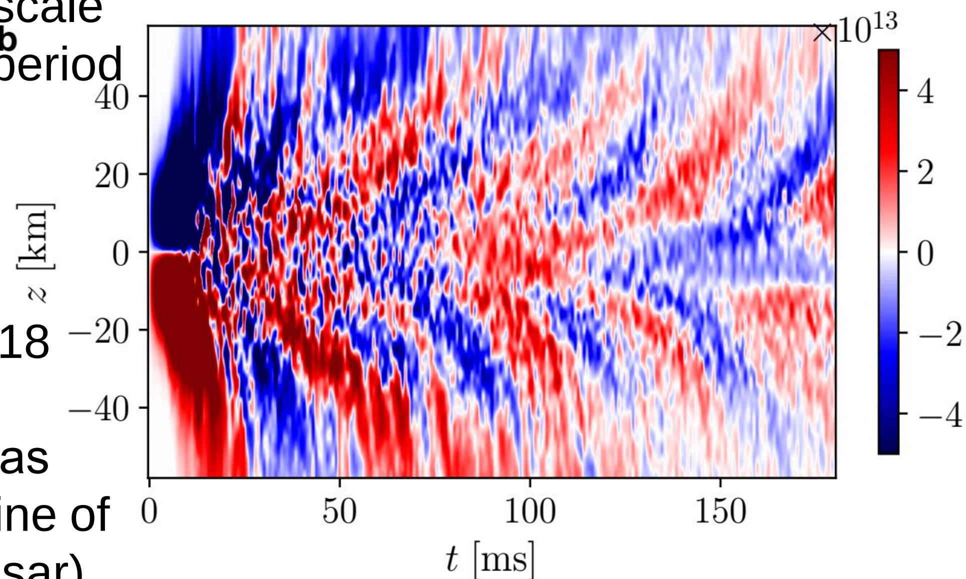


Shi + 2011
Local box sim.
Protosteller disk

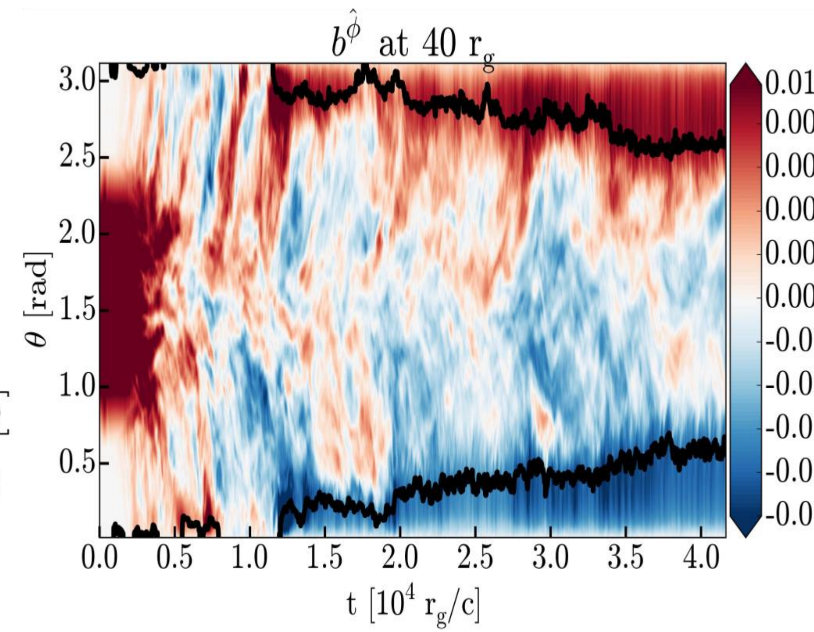
Repeat timescale
∼10 orbital period



Machida + 2013
3D MHD sim
of galactic
dynamo

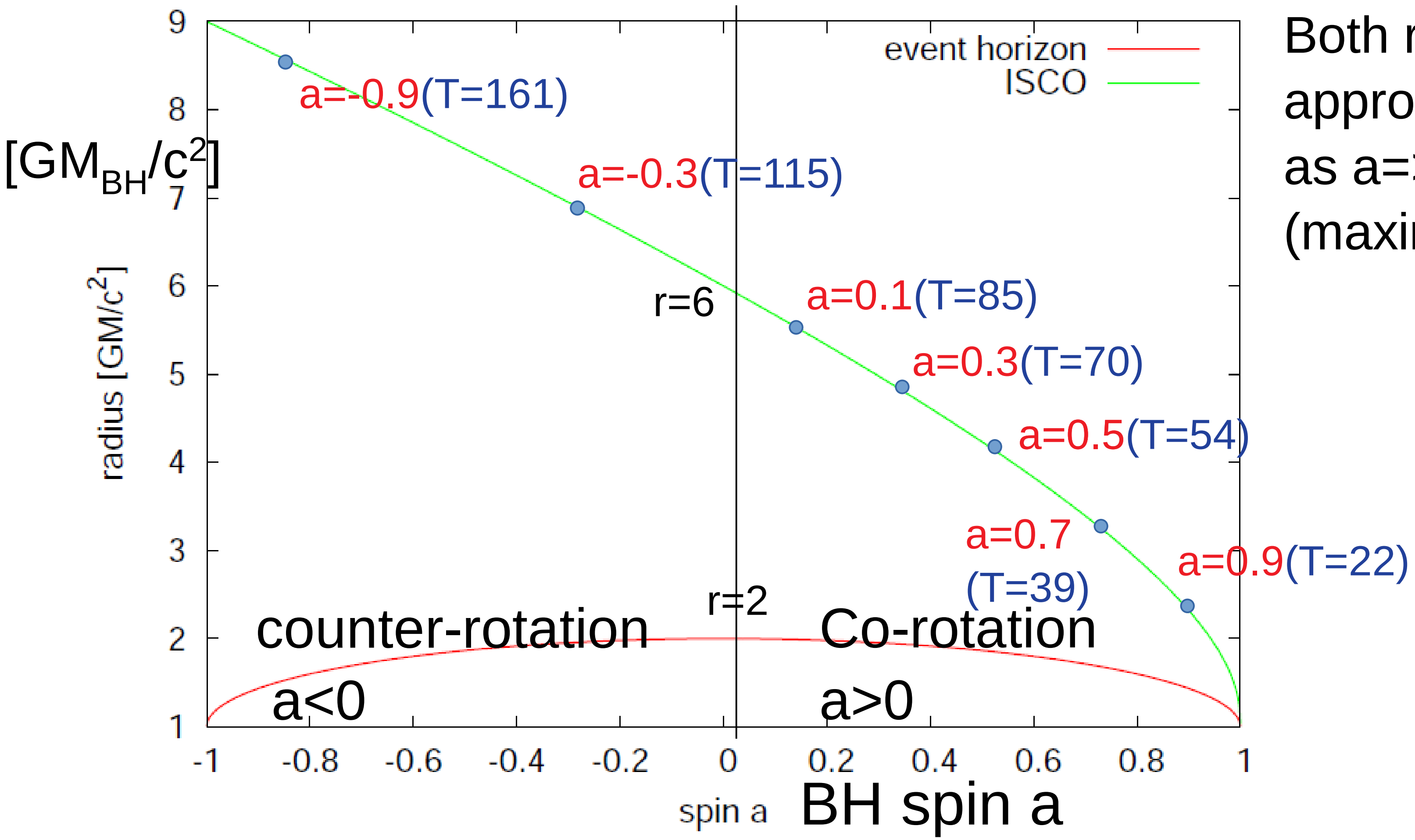


Siegel + 2018
GRMHD
+ ν cooling as
central engine of
GRB(collapsar)



Liska + 2018
GRMHD+AMR

Event horizon / ISO(innermost stable circular orbit)



Both r_H and r_{ISCO} approaches r=1 as a=> 1 (maximum spin)

$$r_{\rm H} = 1 + \sqrt{1-a^2}$$ (g_{rr} =0 @ Boyer-Lindquist)

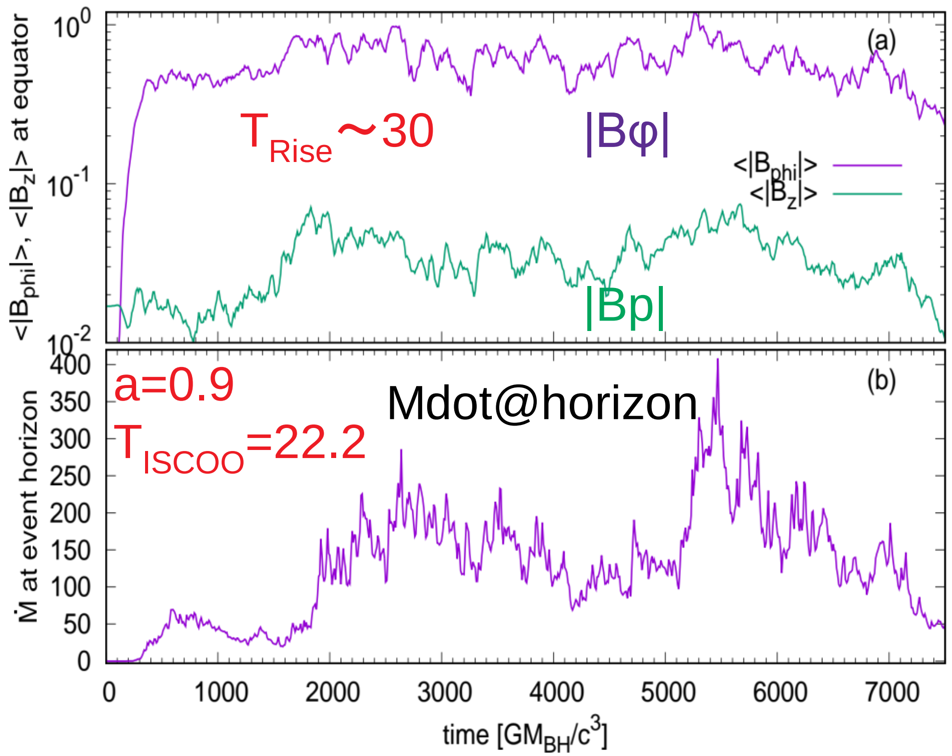
$$r_{\rm ISCO} = 3 + g(a) \mp \sqrt{[3-f(a)][3+f(a)+2g(a)]}$$

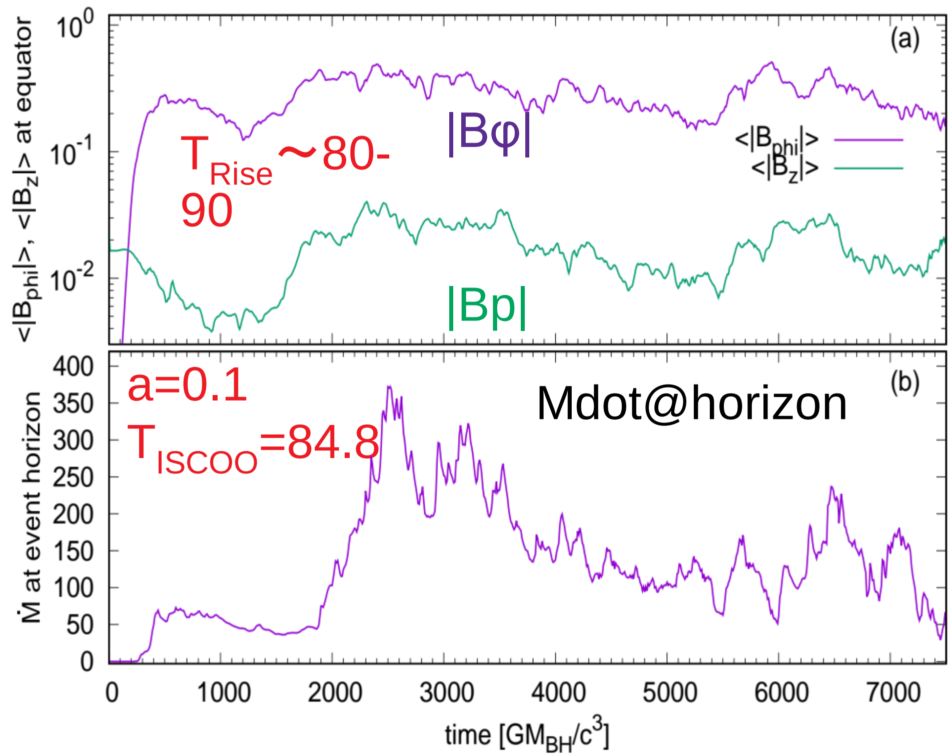
where $$f(a) \equiv 1 + (1-a^2)^{1/3}[(1+a)^{1/3} + (1-a)^{1/3}]$$

$$g(a) \equiv \sqrt{(3a^2 + f(a)^2)}$$

Bardeen +1972

Kerr Spin parameter (a) dependence

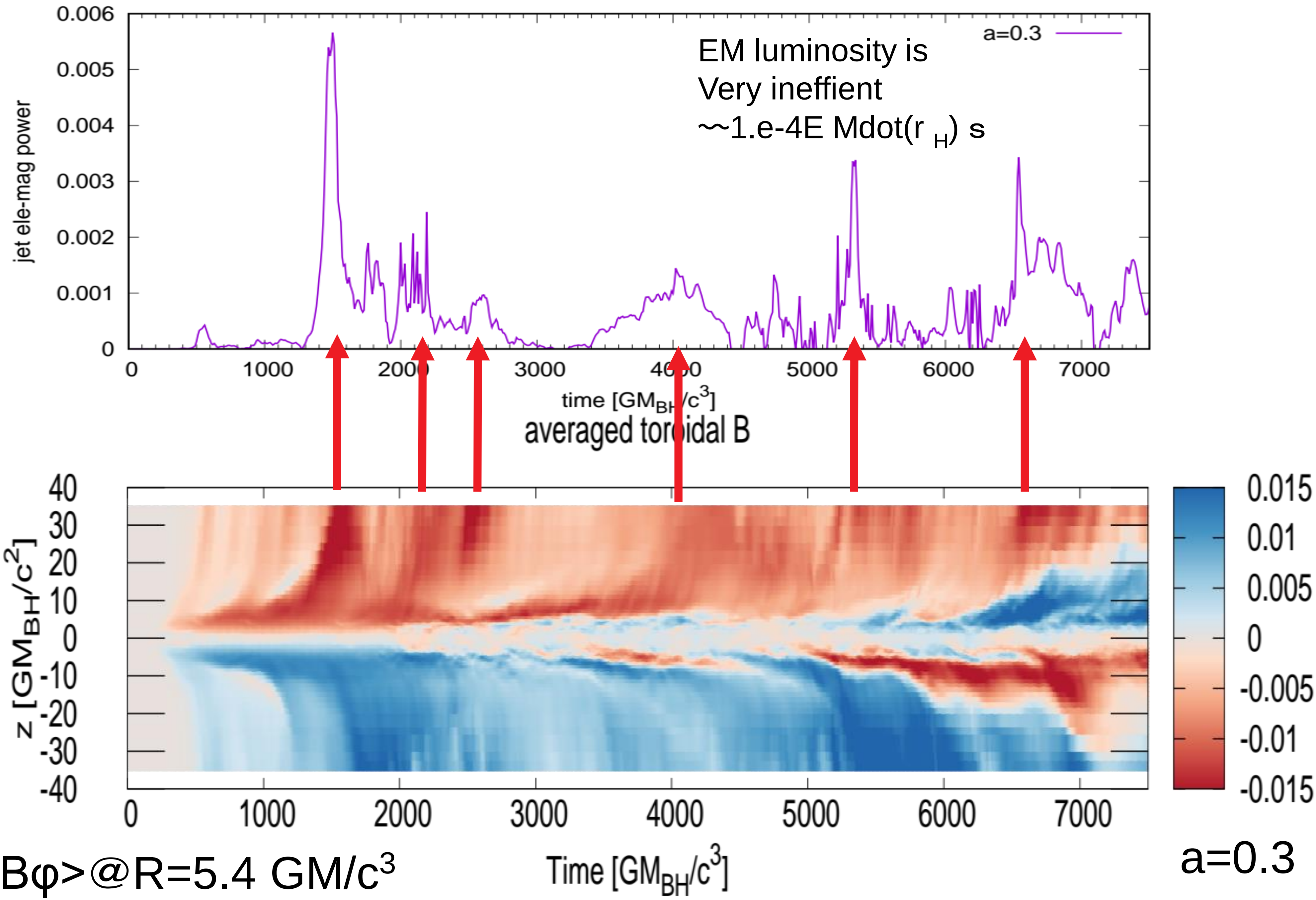




— Longer timescales for B-filed amplification and mass accretion rate for low “a”.

—The timescales are consistent with orbital pereod @ radius = r_{ISCO} + α.

Butterfly diagram & EM jet power



<Bφ>@R=5.4 GM/c^3

a=0.3

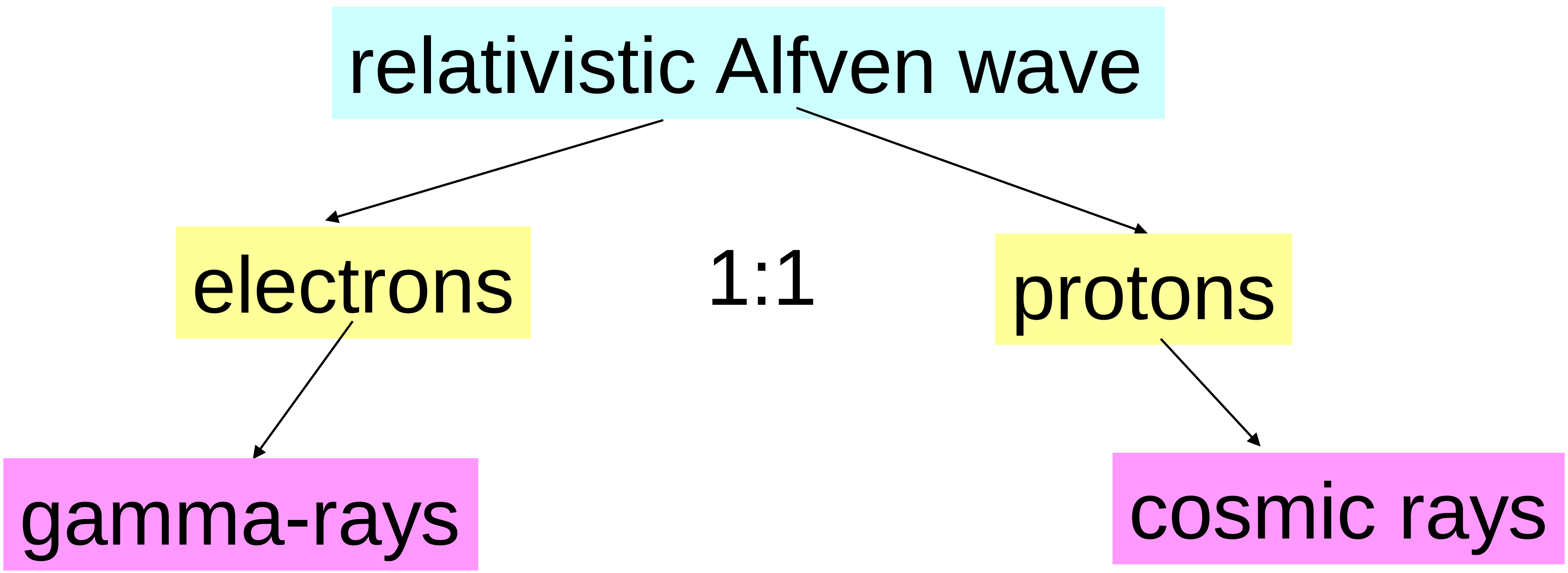
Particle Acceleration via Ponderomotive Force

– strength parameter a_0 at maximum peak in Alfven flare highly exceeds unity as estimated in Ebisuzaki & Tajima (2014);

$$a_0 = \frac{eE}{m_e \omega c} = 1.4 \times 10^{11} \left(\frac{M_{\rm BH}}{10^8 M_\odot} \right)^{1/2} \left(\frac{\dot{M}_{\rm av} c^2}{0.1 L_{\rm Ed}} \right)^{1/2}$$

– Alfven wave=>EM wave due to decrease of density

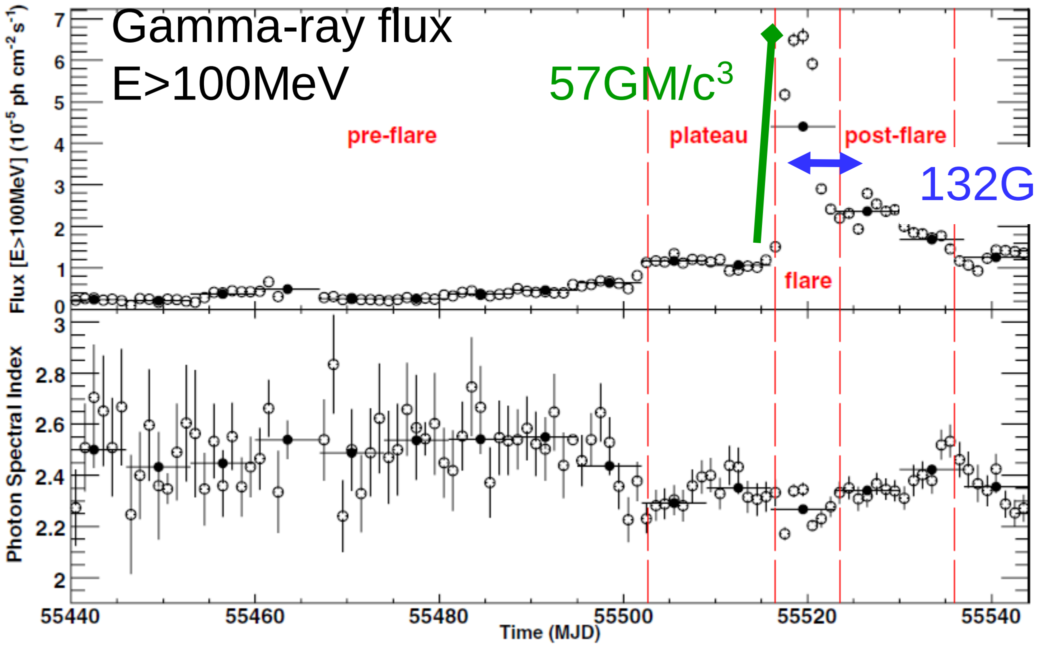
– particle acceleration via Ponderomotive



– blazars

Ebisuzaki & Tajima 2014

Gamma-ray flare of blazars by Fermi



Fermi observation Abdo + ApJ 2010

– rekativistic Alfven wave emission($a_0 \gg 1$)
– => EM mode

– particle acceleratio power law distribution of protons and electrons (Mima+ 1990)

– +B synchrotron emission IC emission (gamma-rays)

	our results	3C454.3	AO0235+164
rising timescale of flares ($\bar{\tau}_1$)	30	57[a]	325[b]
repeat cycle of flares ($\bar{\tau}_2$)	100	132[a]	433[b]

3C454.3 (M_{BH} ~$5\times10^8 M_{sun}$ Bonnoli et al. 2011)

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 emerge around the equator
  to outside the disk
  – jet large Poynting flare for high spin case

Future works

– Long term calculations w/ wide range Kerr parameters, different initial conditions are necessary.s