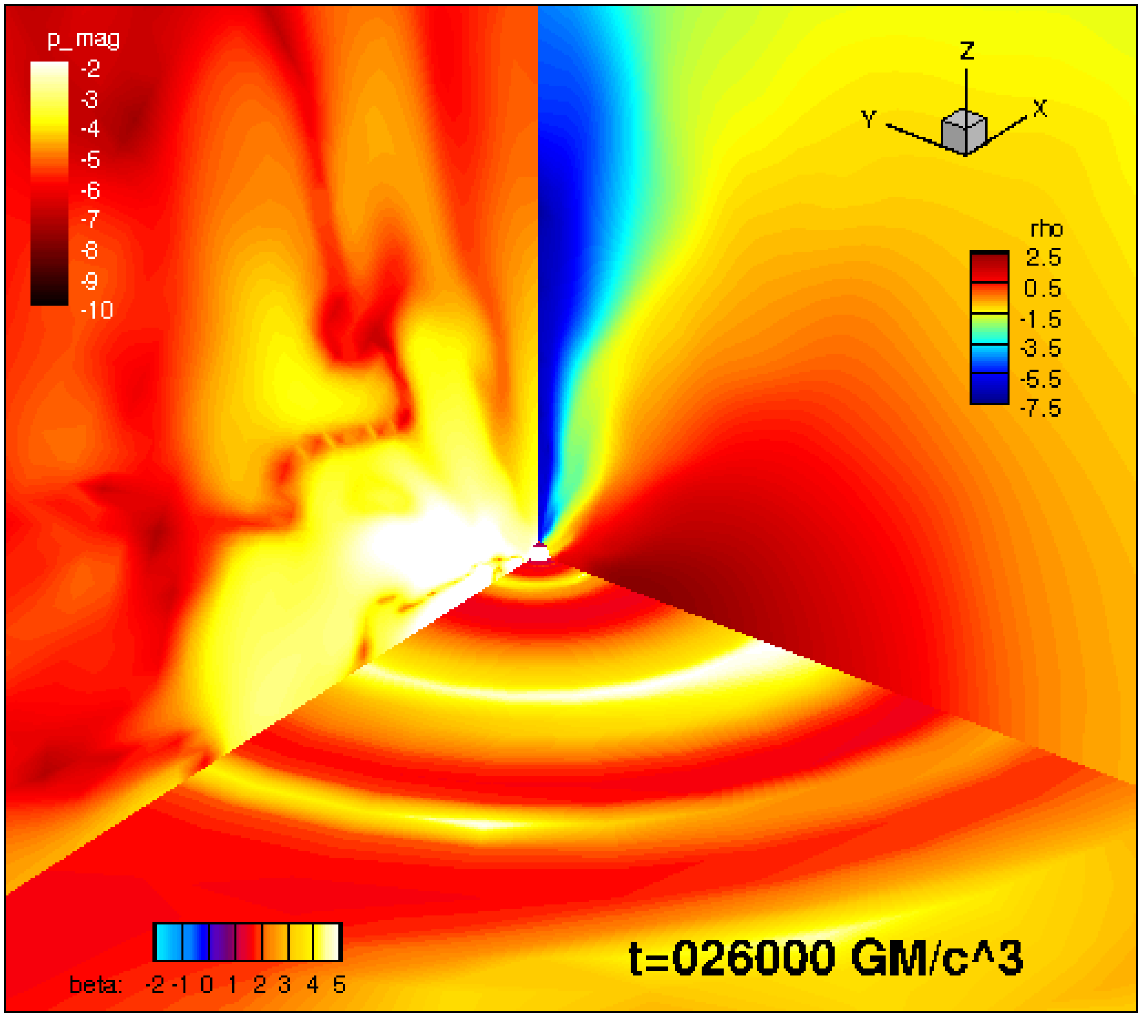
GRMHD simulations of black hole and accretion disk



Akira MIZUTA(RIKEN)

Toshikazu Ebisuzaki (RIKEN)
Toshiki Tajima (UCI)
Shigehiro Nagataki (RIKEN)

The extreme Universe viewed in very-high-energy gamma-rays 2015
@ICRR, U. Tokyo 16.01.14

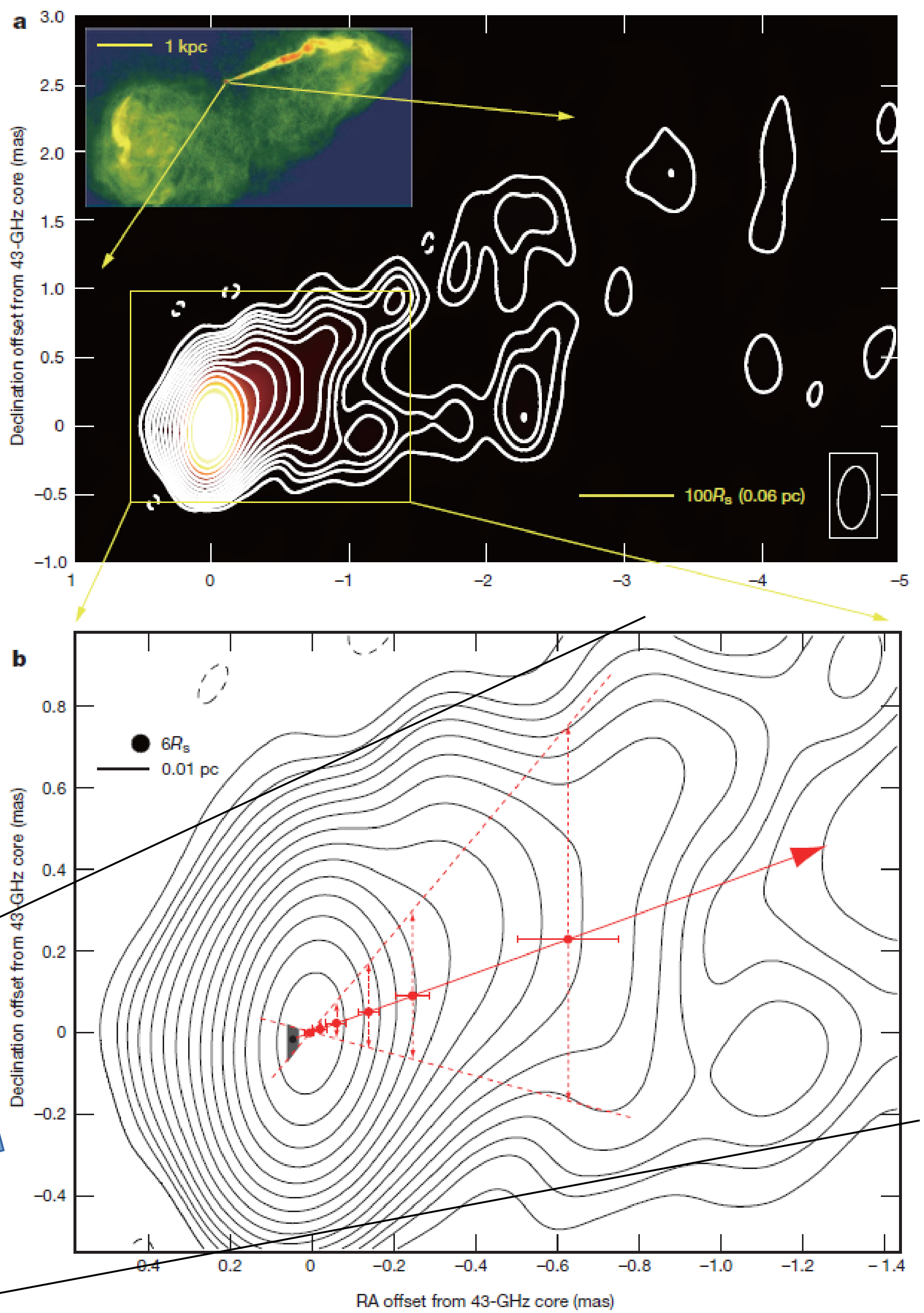
OUTLINE

- Introduction: observations of AGN jets
- GRMHD simulations of black hole and accretion disks
  - Blandford-Znajek process
  - bulk acceleration outflows
- Particle acceleration by wakefield acceleration
- Summary

Introduction

observations of AGN jets

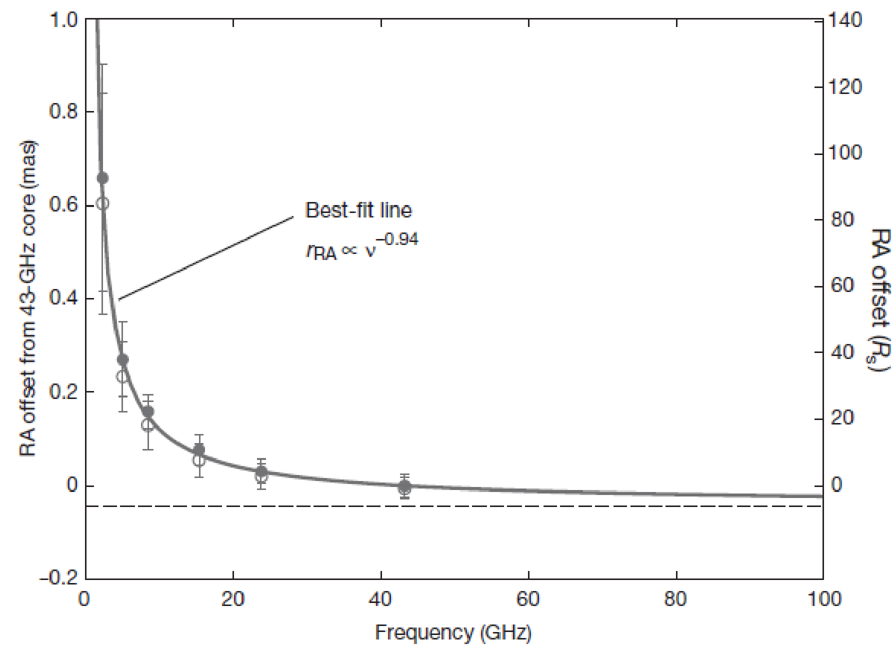
M87 radio observations



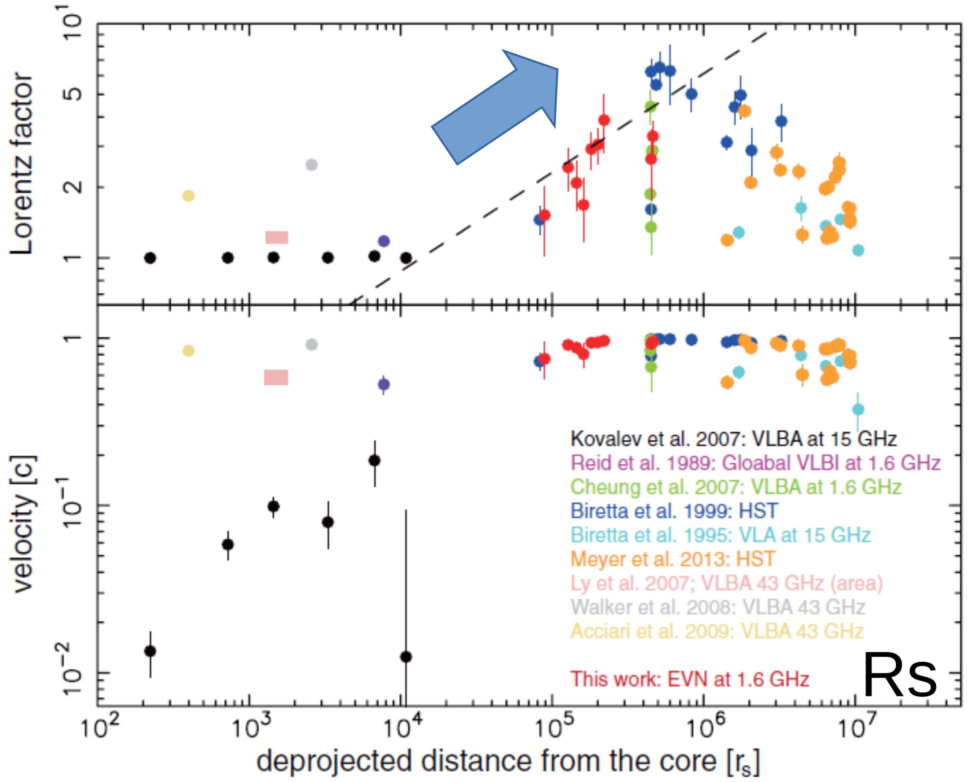
BH ?
No !

M87 radio observation Hada +(2011)

- M87 D=16.7Mpc
- M_{BH}~3.2-6.6x 10^9M_sun
- Location of the central BH is near the radio core by analysis of several bands of radio observations.
- The shape of the jet near the core is not conical but paraboric.
- Rim brightening @ 100Rs

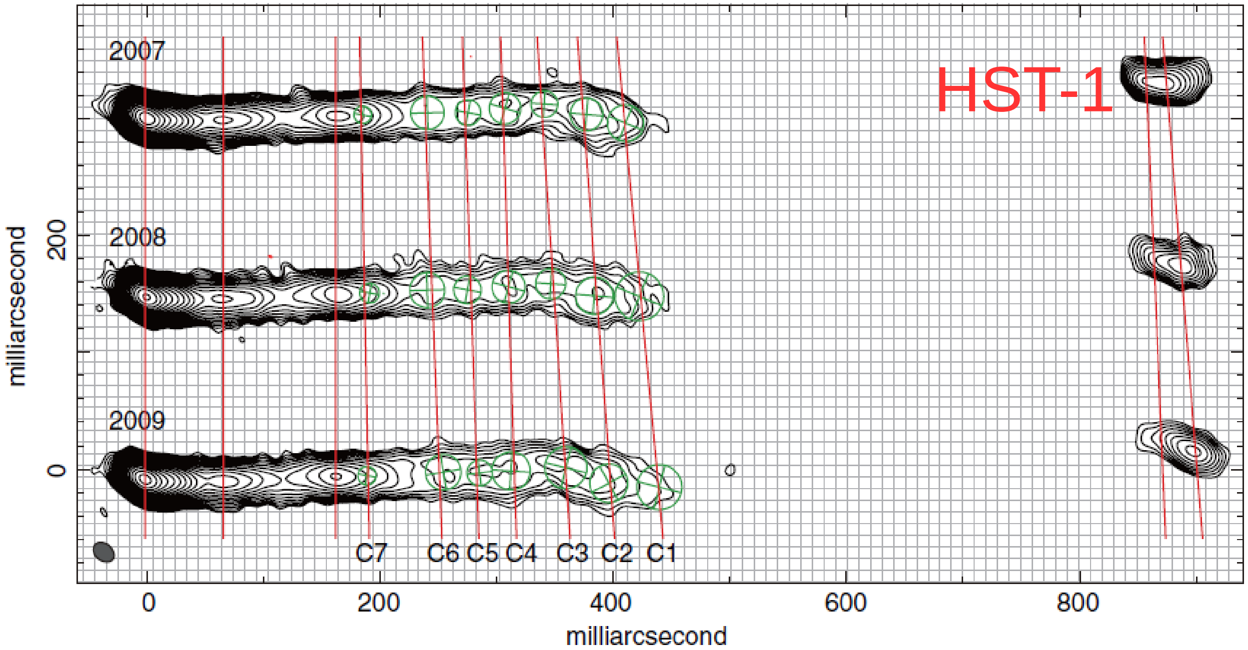


Where is acceleration site ?



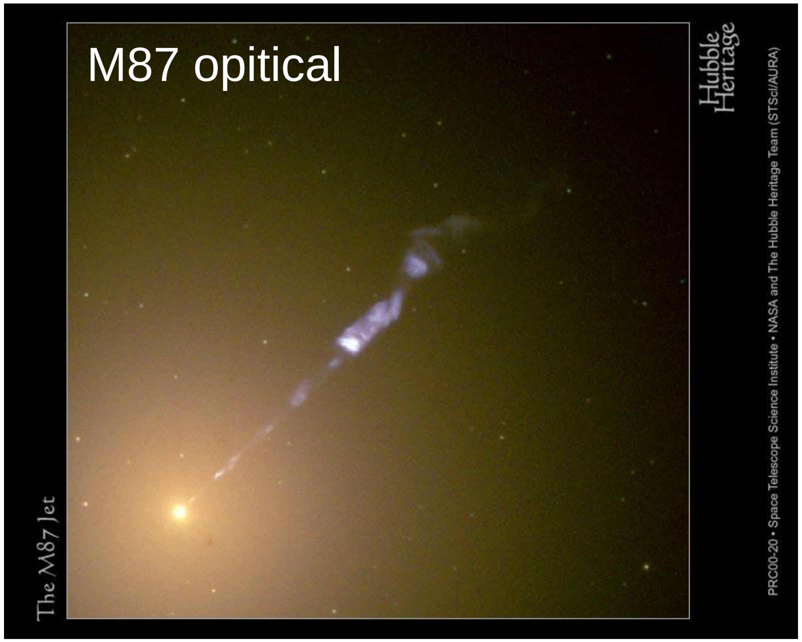
- Bulk velocities are measured by using a series of radio observations of M87 up to $10^{5\text{-}6}$ Rs.
- Acceleration to relativistic velocities occurs at $\sim 10^4$Rs.

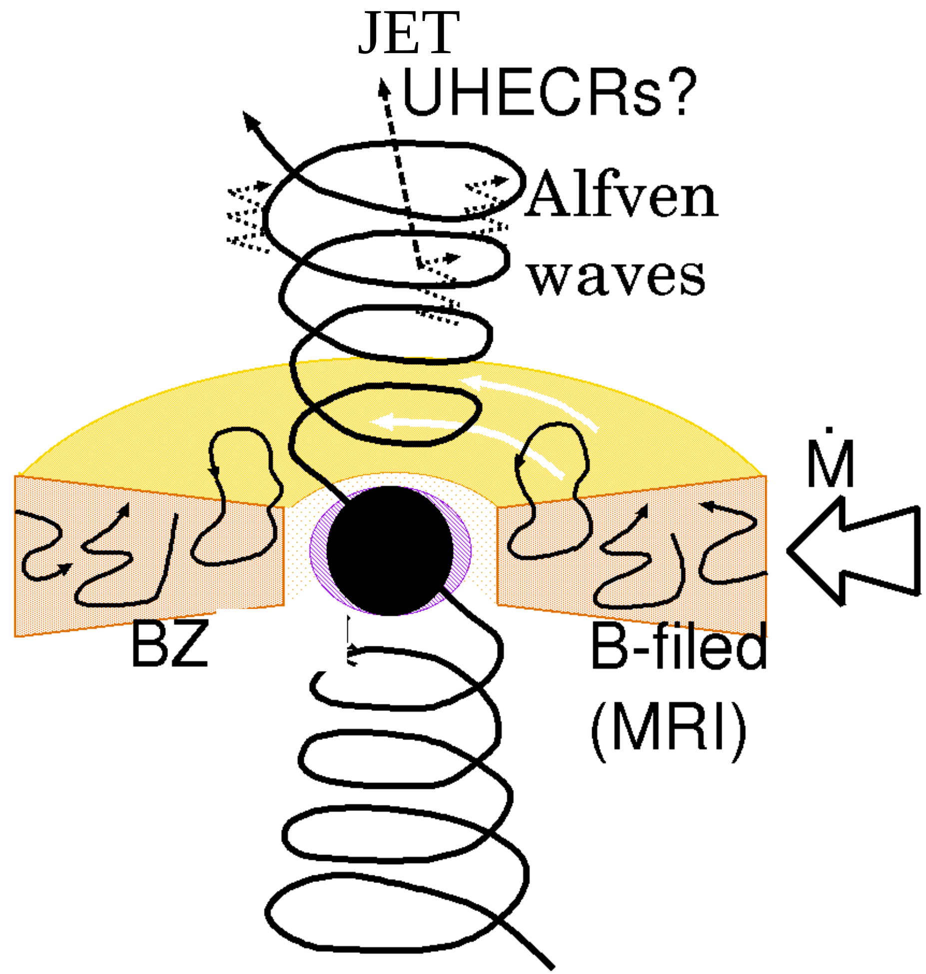
- Similar results for Cygnus A jets. (Boccardi + A&A (2016))



Asada +2014

Relativistic jet launched from BH+accretion disk





- Central Engine
  - -Black Hole(BH)＋accretion disk
  - -B filed amplification
- relativistic jet (Γ~10 for AGN jet)
  - -How to launch the jet is also a big problem for astrophyics.

    Blandford-Payne (magnetic centrifugal force)

    Blandford-Znajek (general relativistic + B filed effect)

    or others ?

B filed plays an important role !

GRMHD simulations of Black hole and accretion disks

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

Computational domain, grids

Spherical coordinate (r, θ, φ) R[1.4:3e4] θ[0:π] φ[0:2π]

[Nr=124,Nθ=124, Nφ=28]

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

– not enough high resolution to resolve fastest MRI growth mode

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

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

Initial condition

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

– equilibrium state : gravitational potential, pressure gradient, and centrifugal force, geometrical thick disk

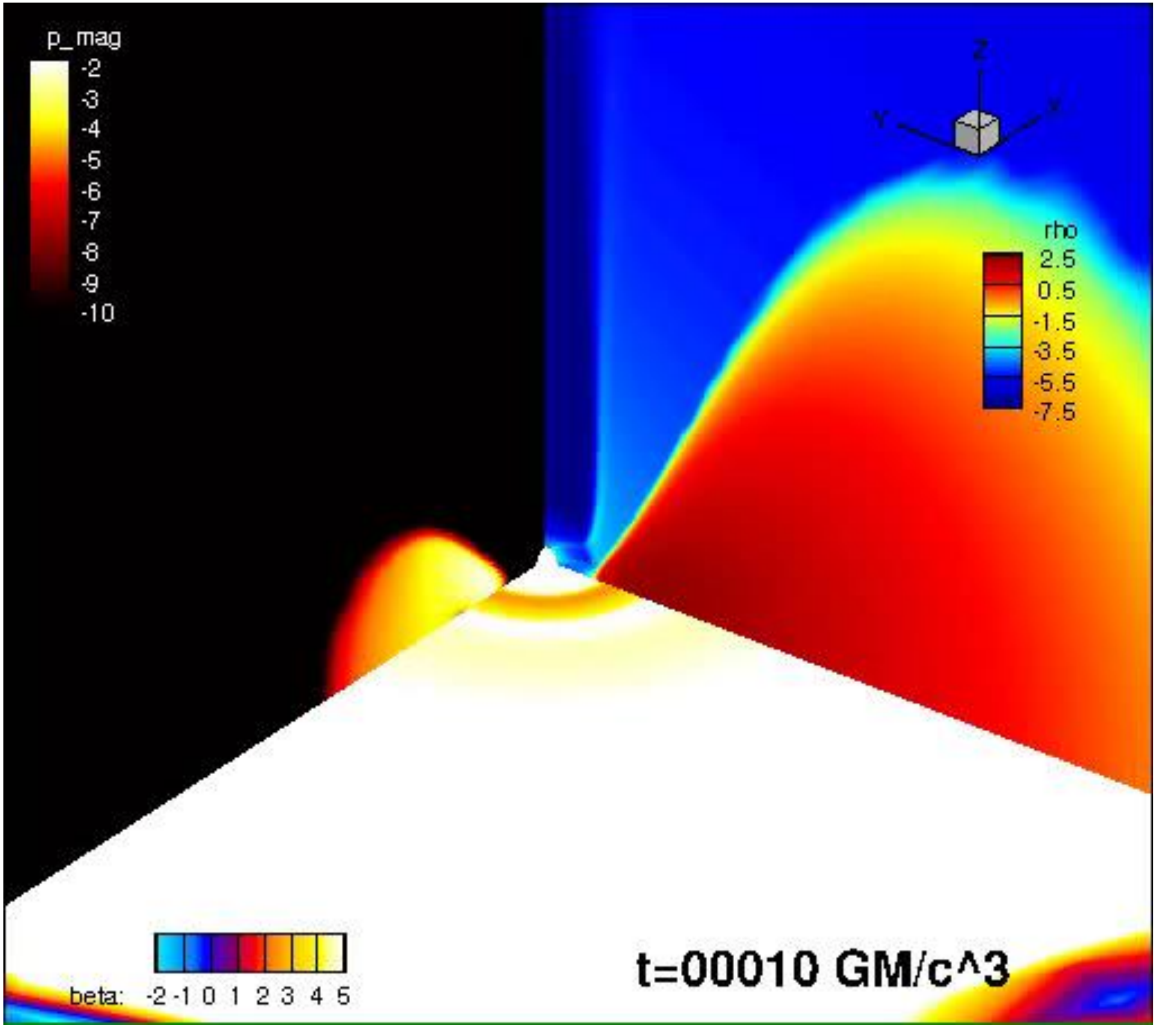
– impose weak poloidal B-field (Minimum plasma beta =100)

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

case1. maximum 5% random perturbation in thermal pressure (3D)

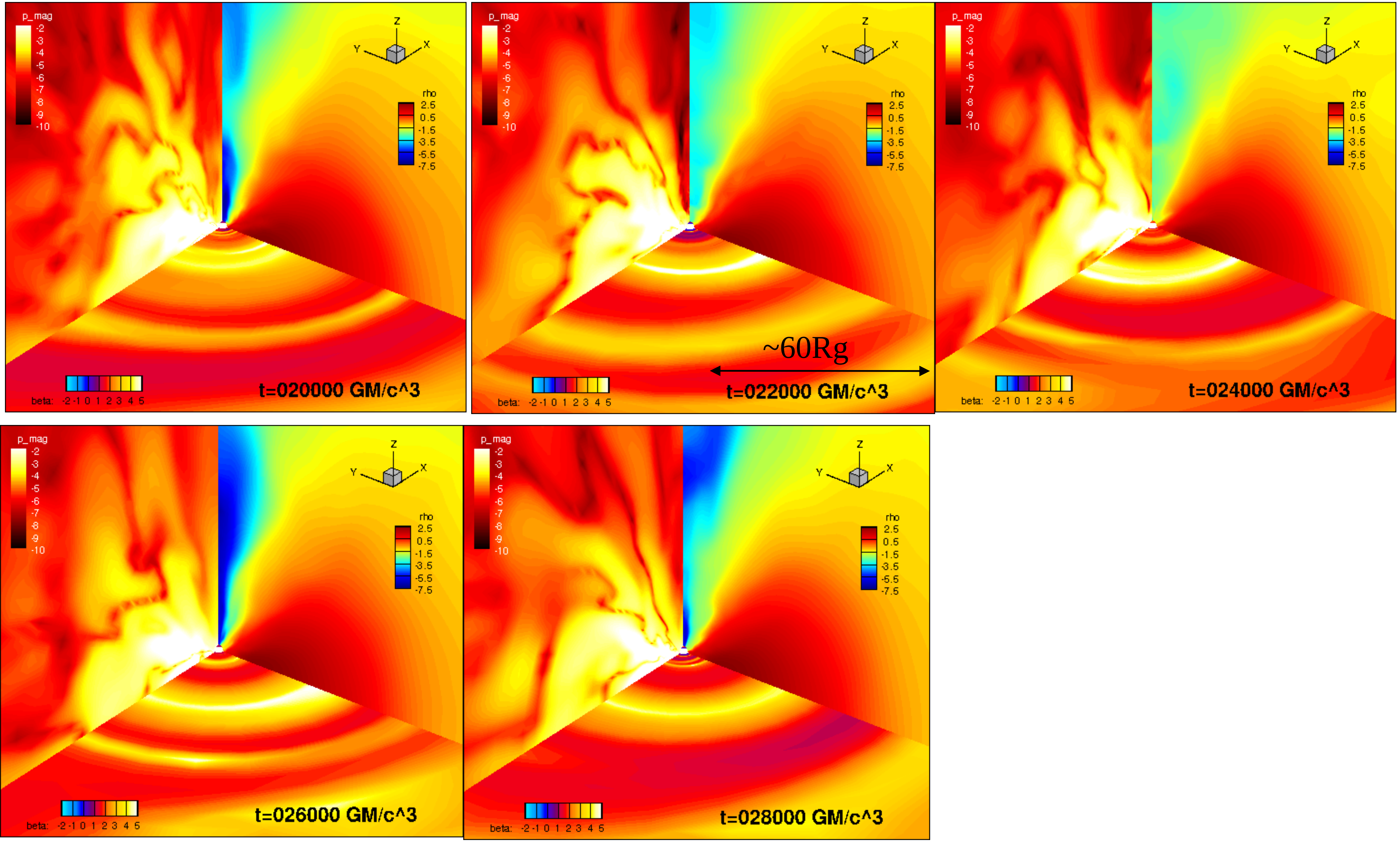
case2. w/o perturbation in thermal pressure (2D)

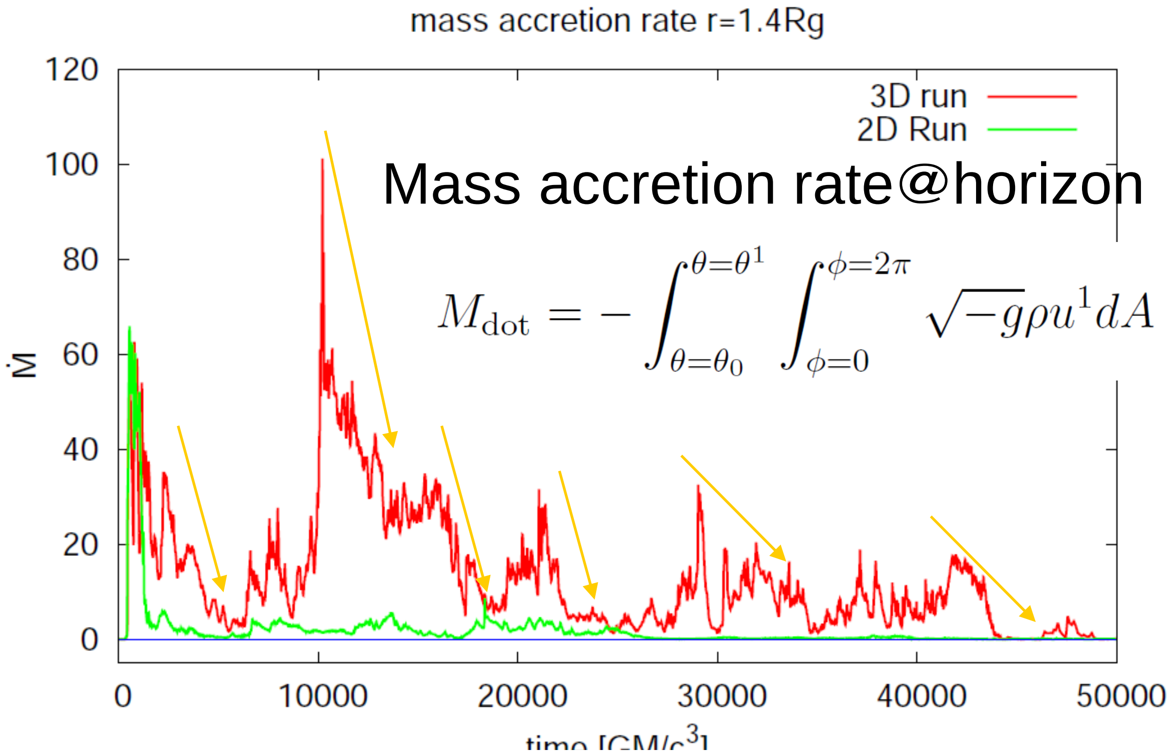
Magnetized jet launch

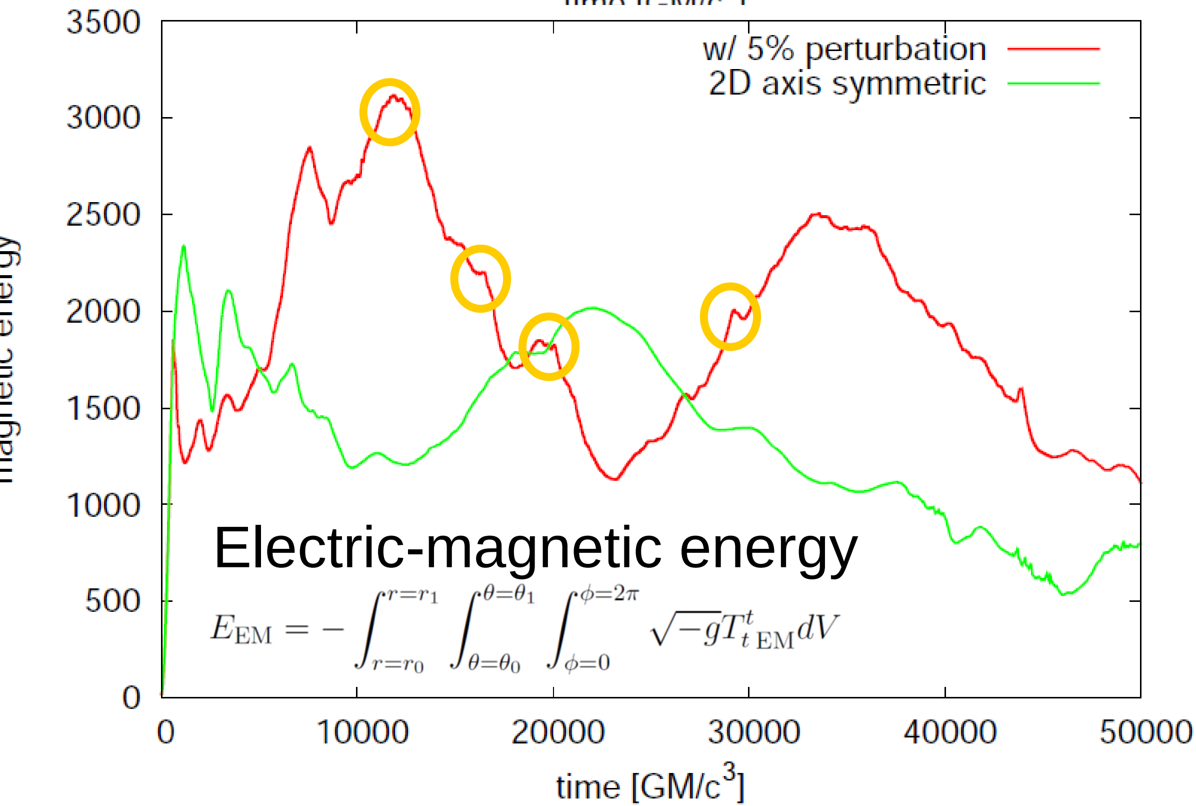


Low mass density and electromagnetic flux along the polar axis. Intermittent

Magnetized jet launch





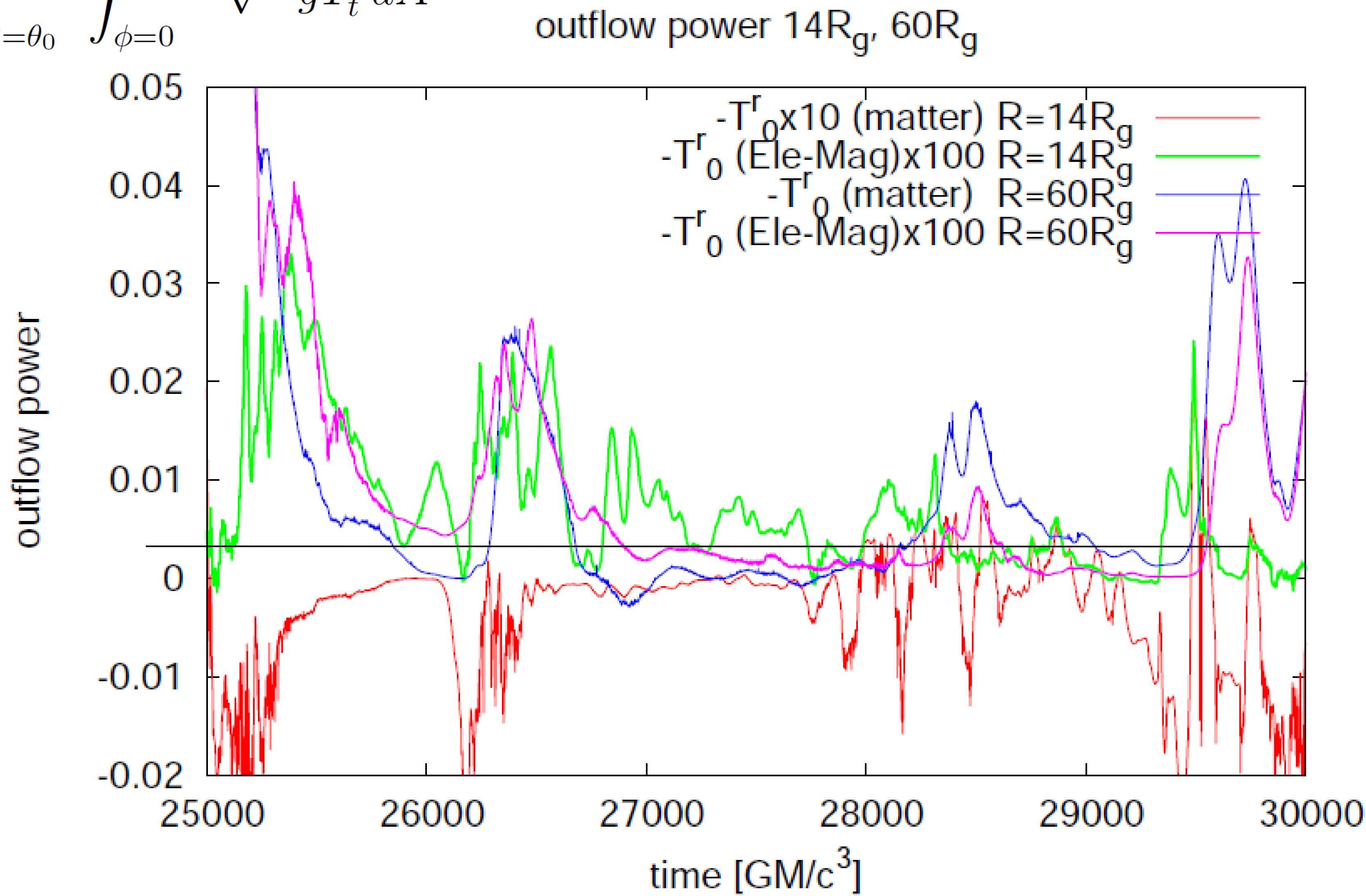


- In transition phase (t<18000 for 3D) accretion late is relatively high.
- After that a new phase starts.
- Short time availability (Δt ~a few tens to a few hundreds.)
- Accretion rate for 2D is 1/10-1/100 lower than that of 3D.

Outflow luminosity for 3Dcase (0<θ<10°)

$$E_{\rm dot} = -\int_{\theta=\theta_0}^{\theta=\theta_1}\int_{\phi=0}^{\phi=2\pi}\sqrt{-g}T^r_t\,dA$$

$\theta_0=0$
$\theta_1=10$



Short time variavilitry (Δt~a few tensGM/c^3) in electromagnetic components (green and pink) :
=> possible origine for flares in blazars (on axis observer),

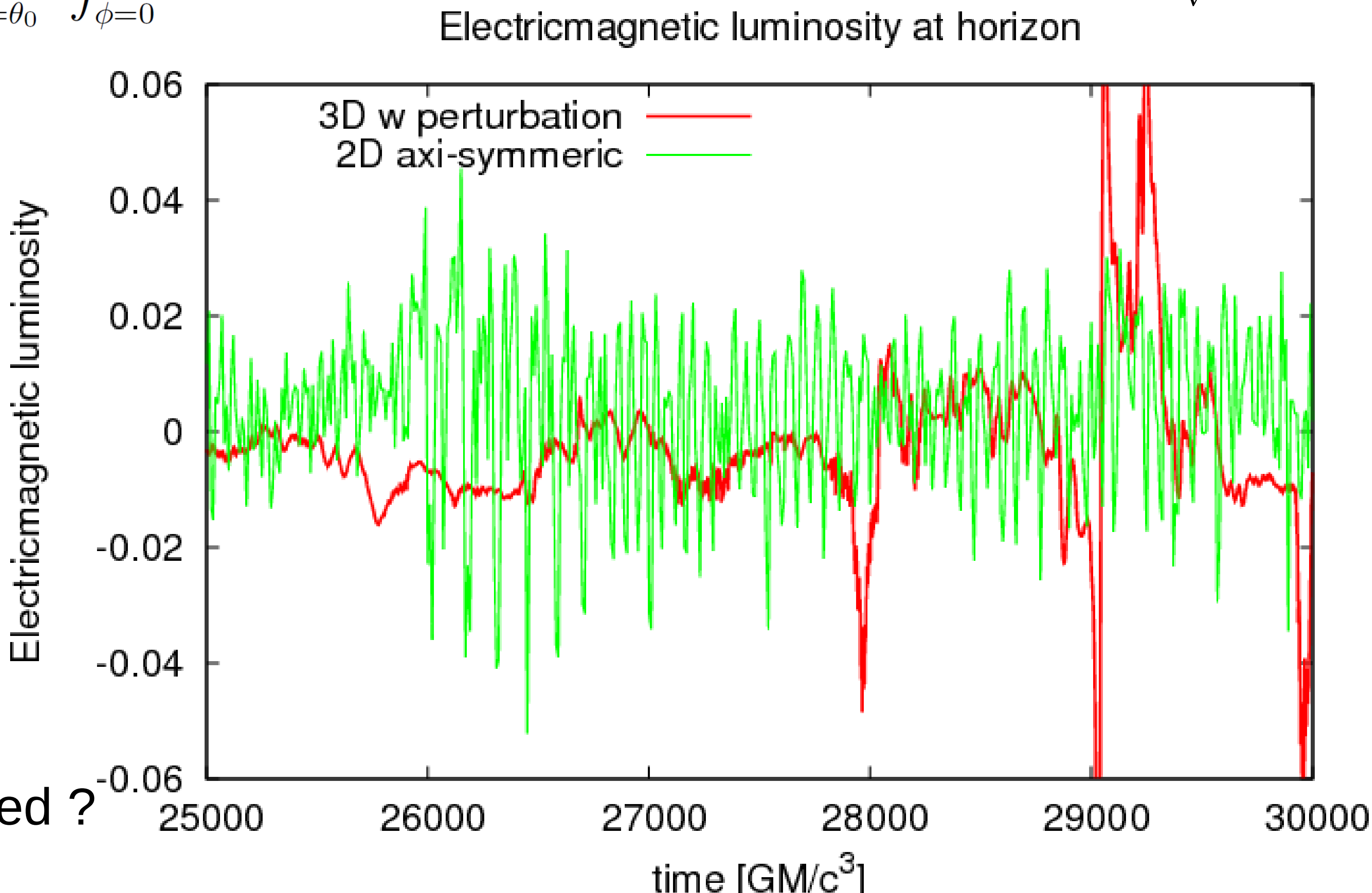
Blandford-Znajek process

Electricmagnetic power at the horizon

$$E_{\mathrm{dot}} = -\int_{\theta=\theta_0}^{\theta=\theta_1} \int_{\phi=0}^{\phi=2\pi} \sqrt{-g}\, T^r_t \, dA$$

Electromagnetic components in $T^{\mu}{}_{\nu}$

$\theta 0=0, \theta 1=\pi$



BZ powered ?

Efficiency (Ele-mag power/M_dot) is good for 2D case.

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

BZ1977, McKinney & Gammie2004

Radial electric-magnetic flux is described as

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

@ event horizon

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

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

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

Rotation frequency of BH

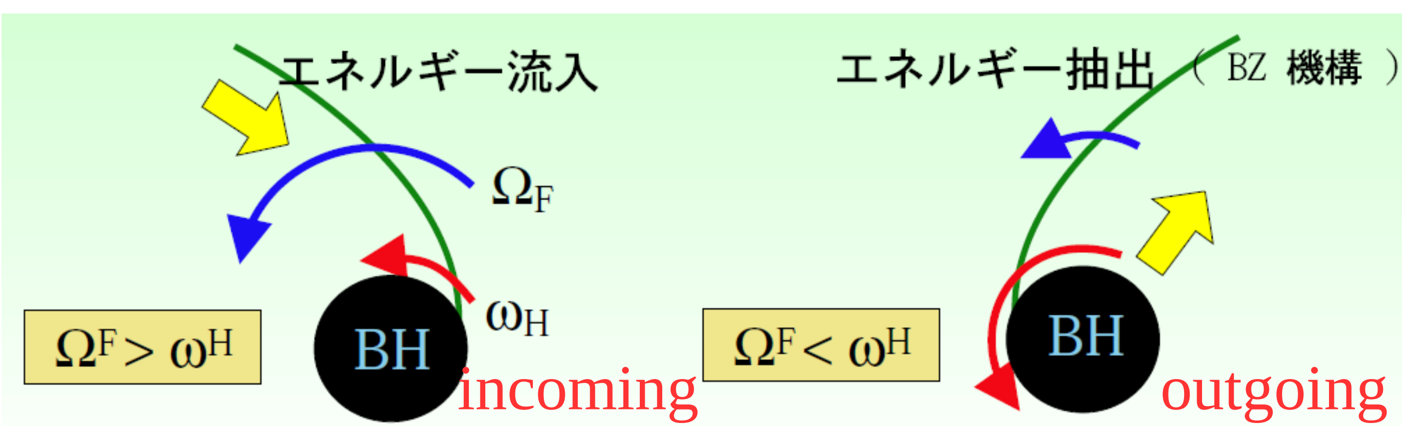
$$\omega = -\frac{F_{tr}}{F_{\phi r}} = -\frac{F_{t\theta}}{F_{\phi\theta}}$$

Rotation frequency of EM field

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

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

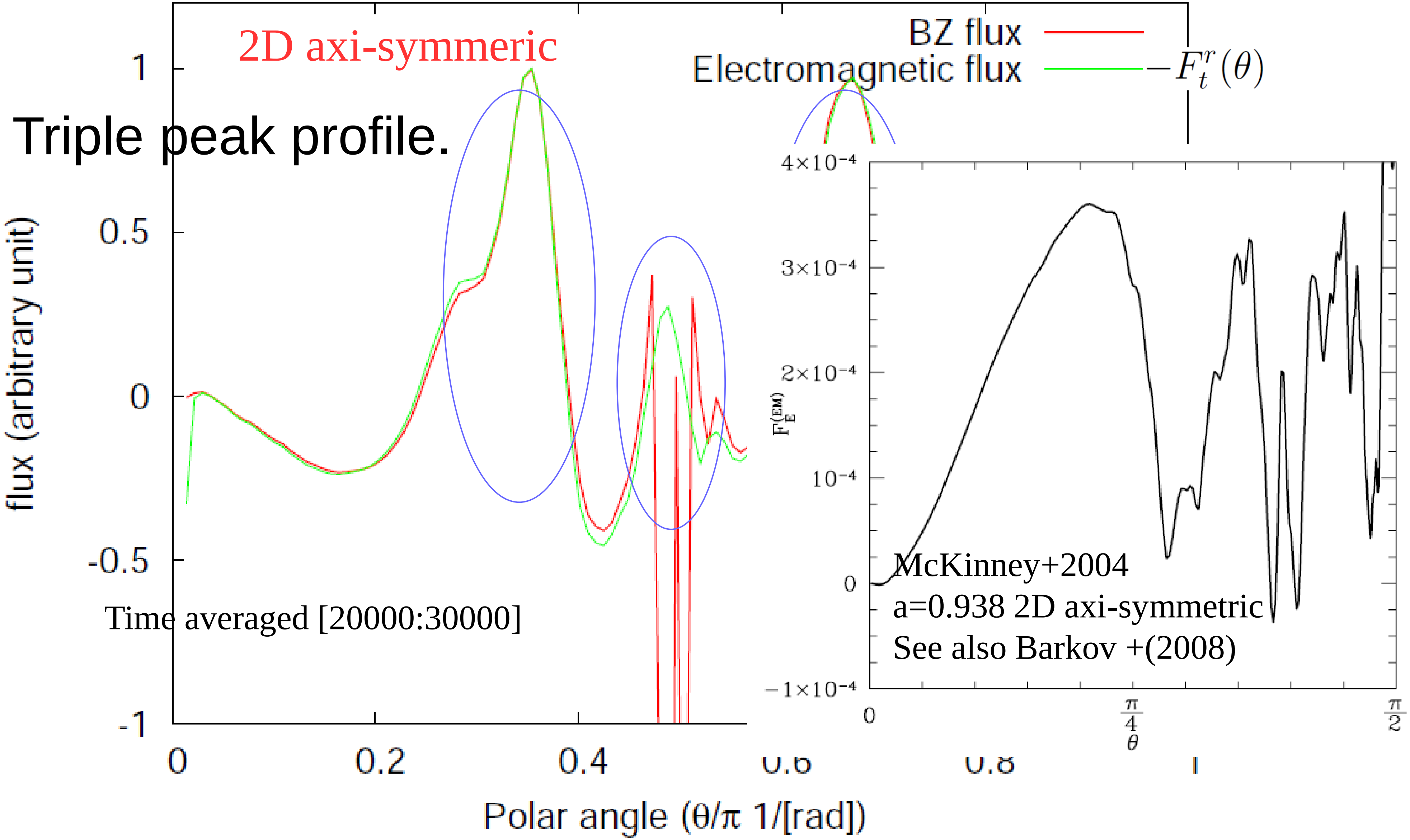
$0<\omega<\Omega_{\mathrm{H}} \Rightarrow$ outgoing flux



From Takahashi's (AUE) slide

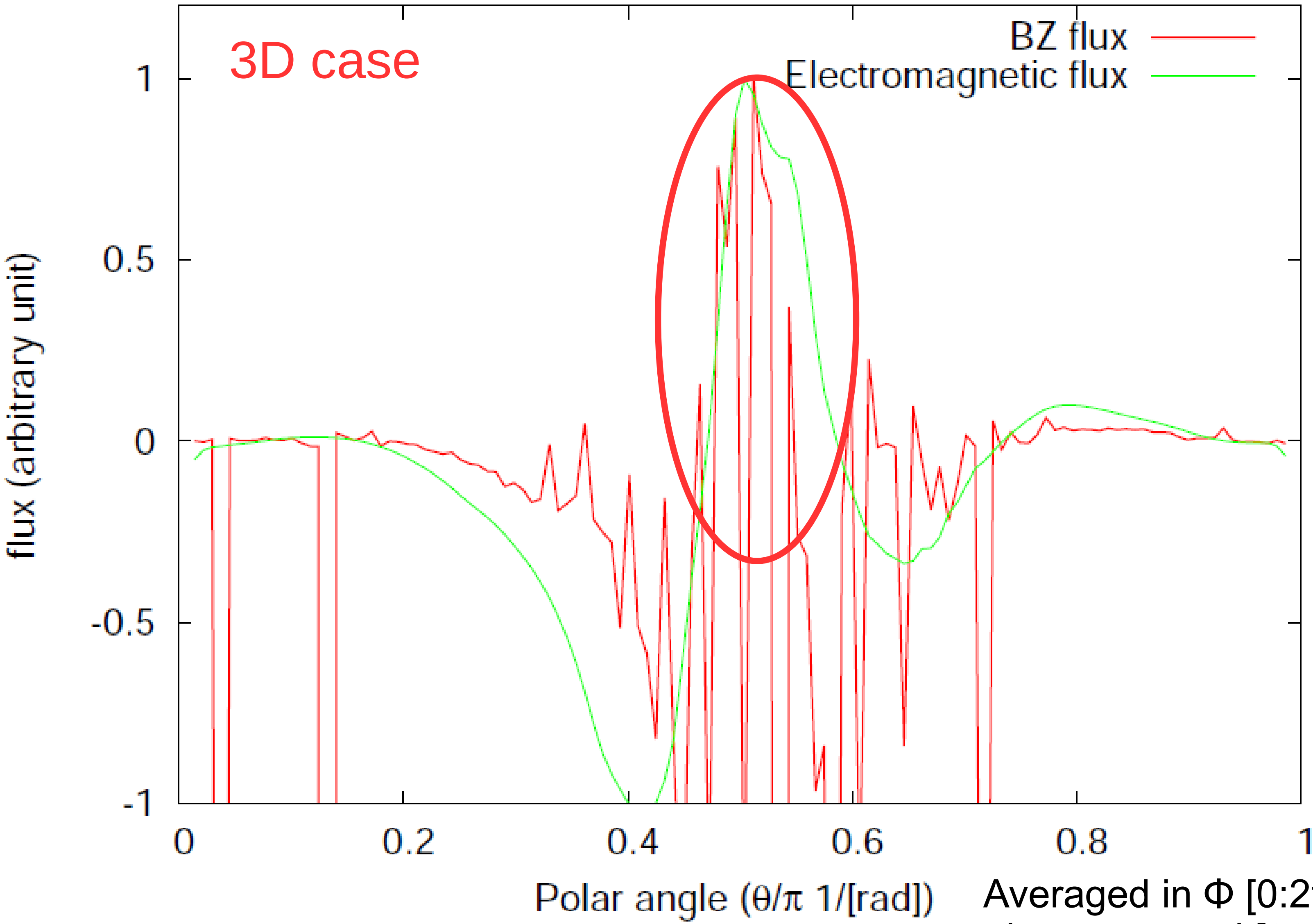
BZ flux v.s. EM flux @ horizon (2)

Triple peak profile.



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

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



Averaged in Φ [0:2π]
Time averaged [20000:30000]

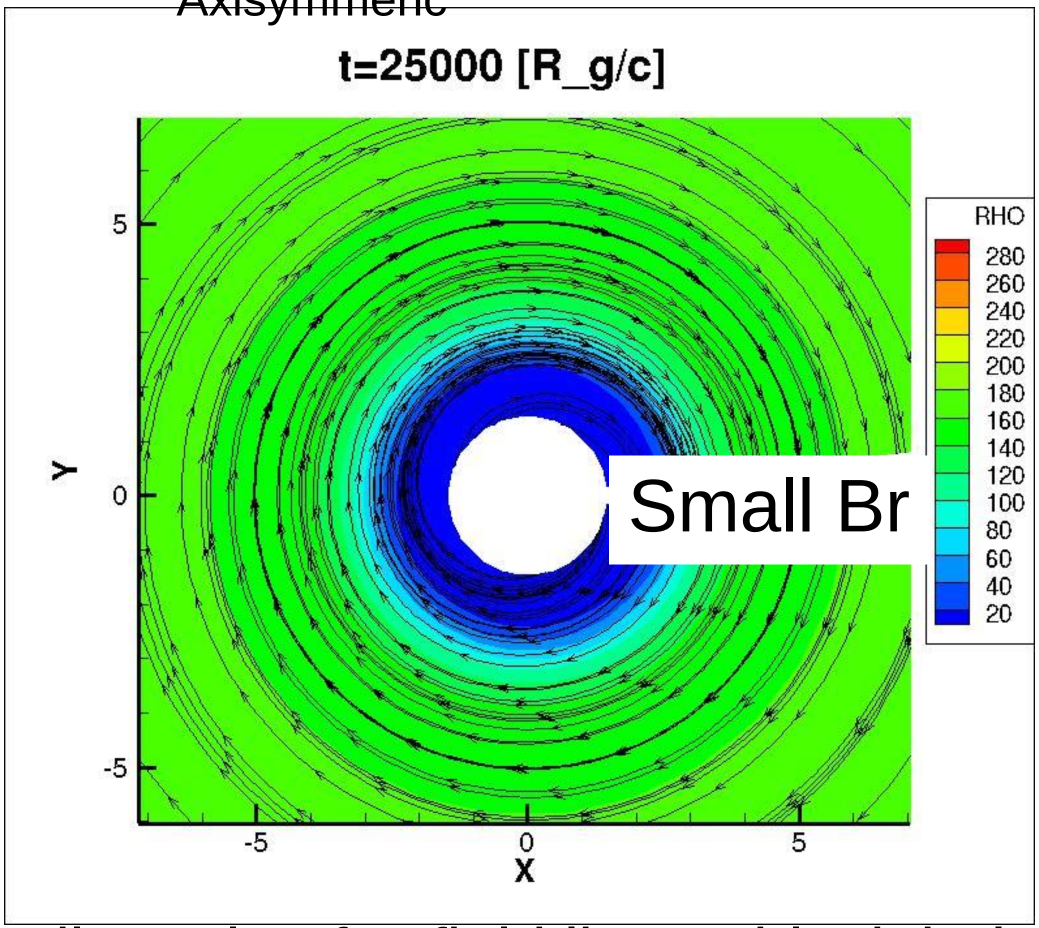
Electromagnetic flux is roughly good agreement with BZ flux.
Outgoing flux is concentrated around equator.

B-Filed line @equator

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

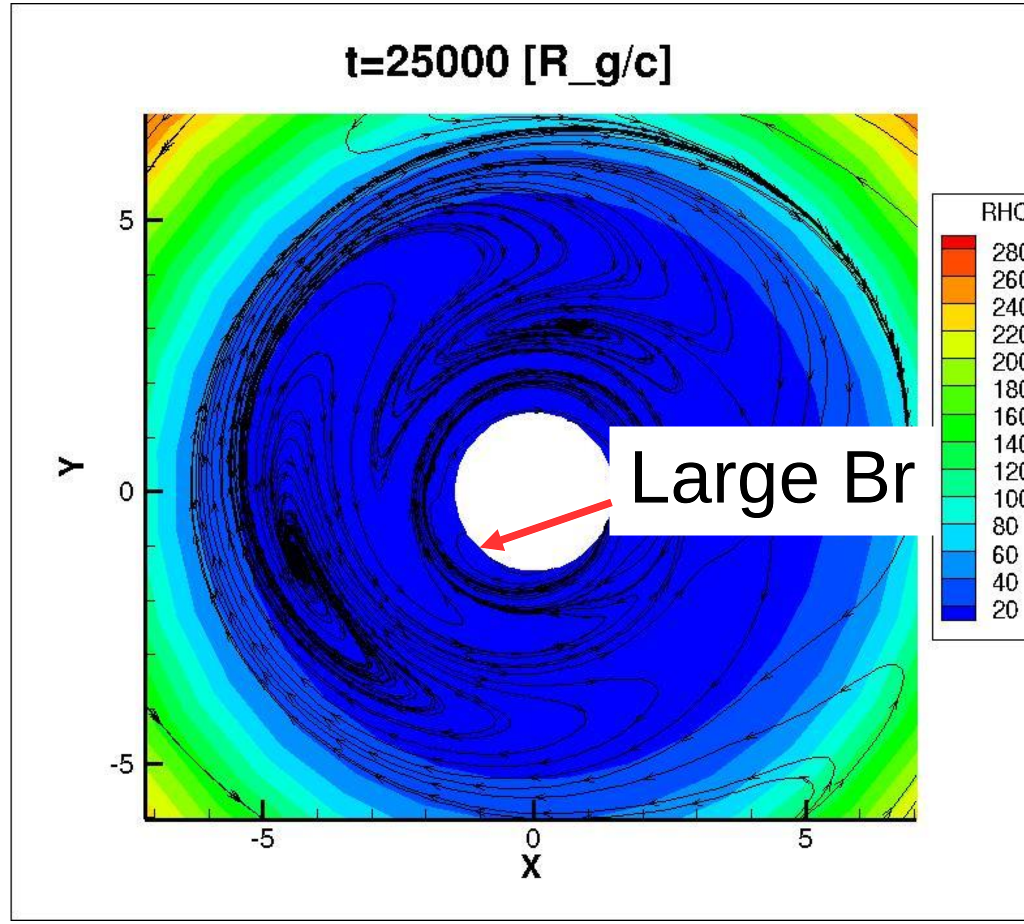
2D Axis-symmetric case

Axisymmeric



Tilt angle of B-field line to black hole surface normal is large.
Small Br

3D case

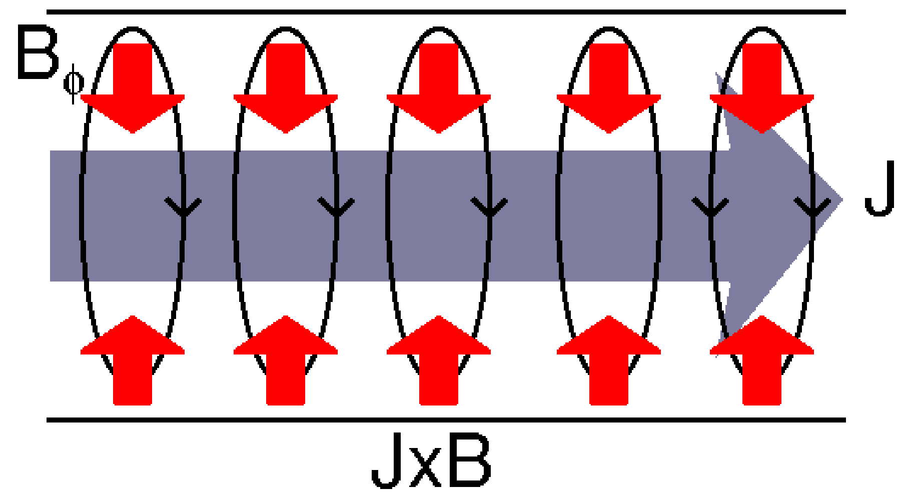


Tilt angle of B-filed line to black hole surface normal is large.
Br large in Local

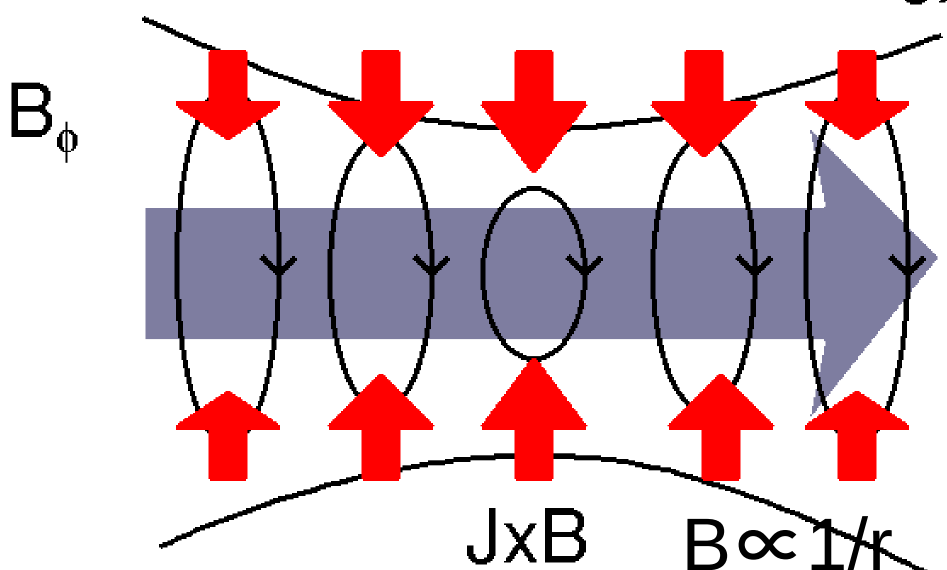
Bulk Acceleration

How to convert magnetic energy
to kinetic energy ?

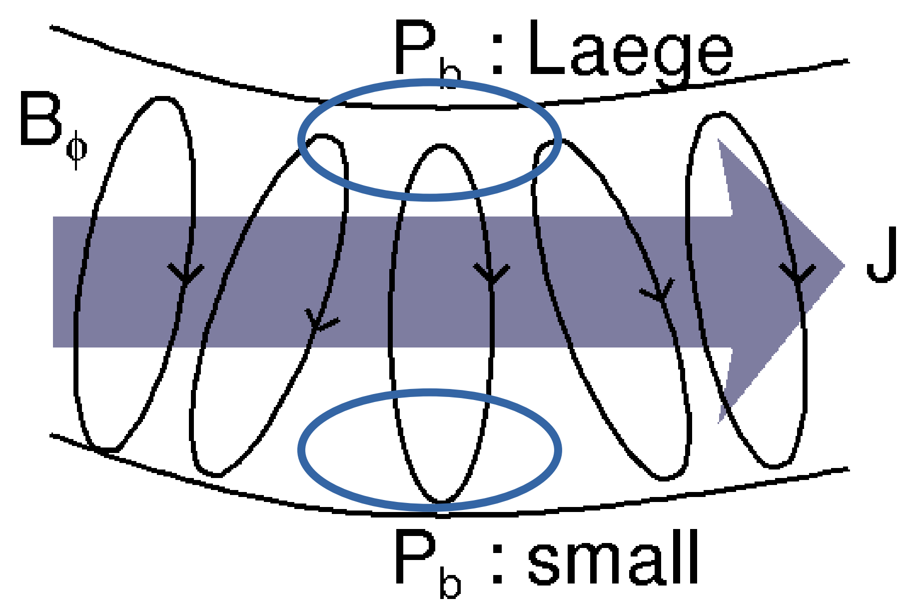
MHD instability
(current driven instability)



Z-pinch

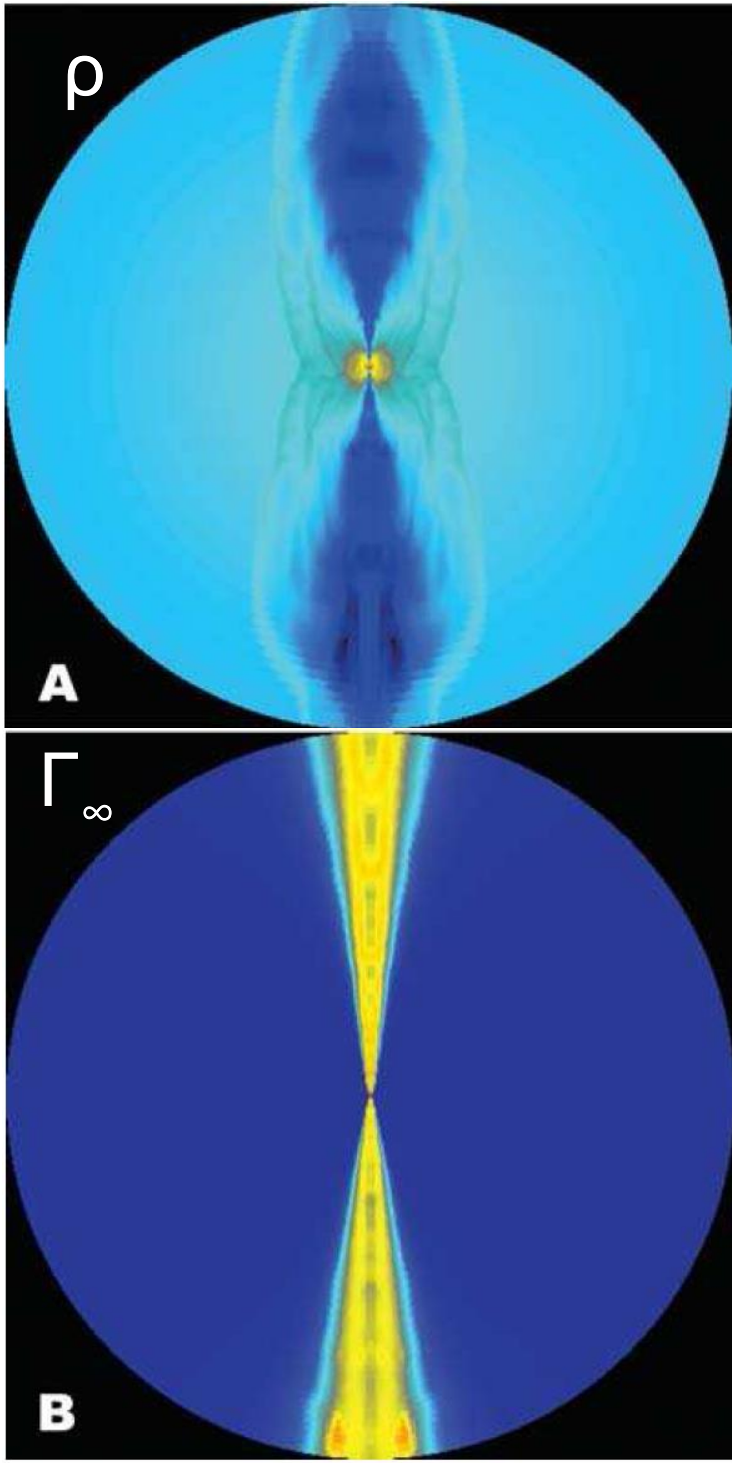


Sausage instability
m=0 mode



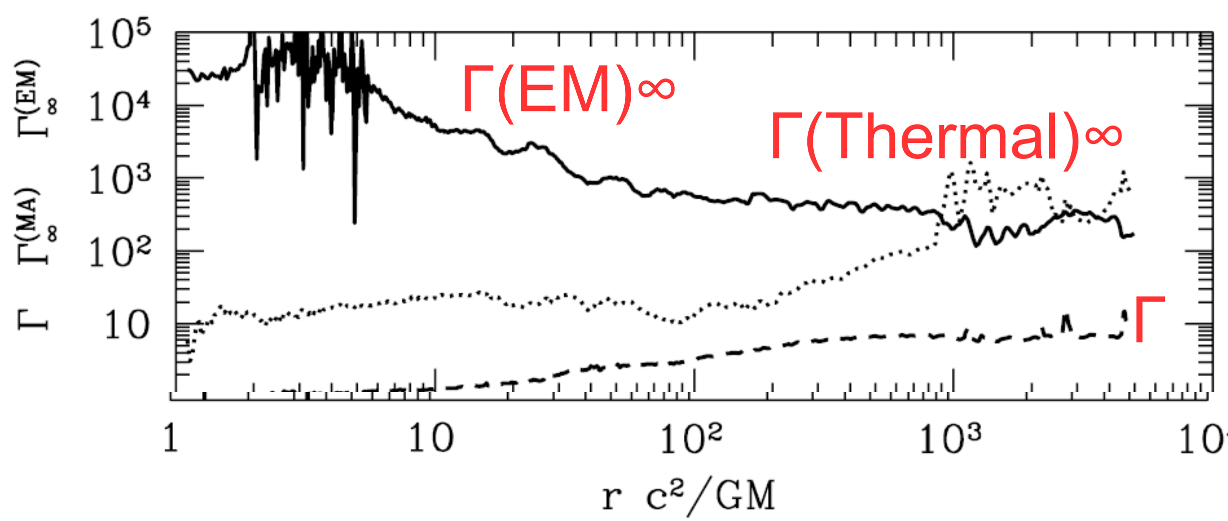
Kink instability
m=1 mode

Sausage instability (m=0 mode)



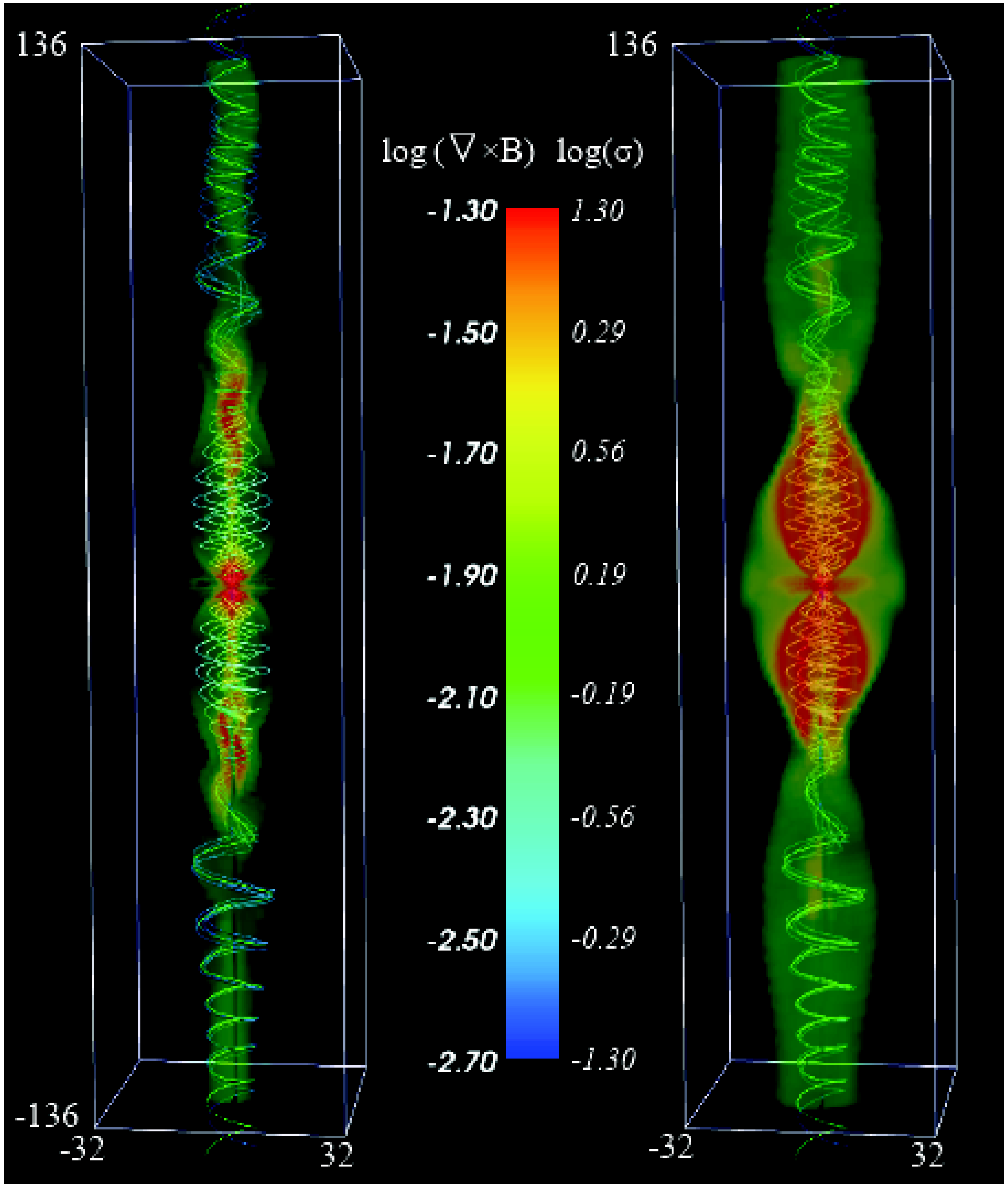
10^4Rg

- 2D GRMHD simulation
- Sausage (pinch) instability grows up.
- It enhances oscillation and generates waves, converting magnetic energy into lateral kinetic energy
- Finally shock dissipation



McKinney 2006 MNRAS 368 (2006)

Kink instability (m=1 mode)



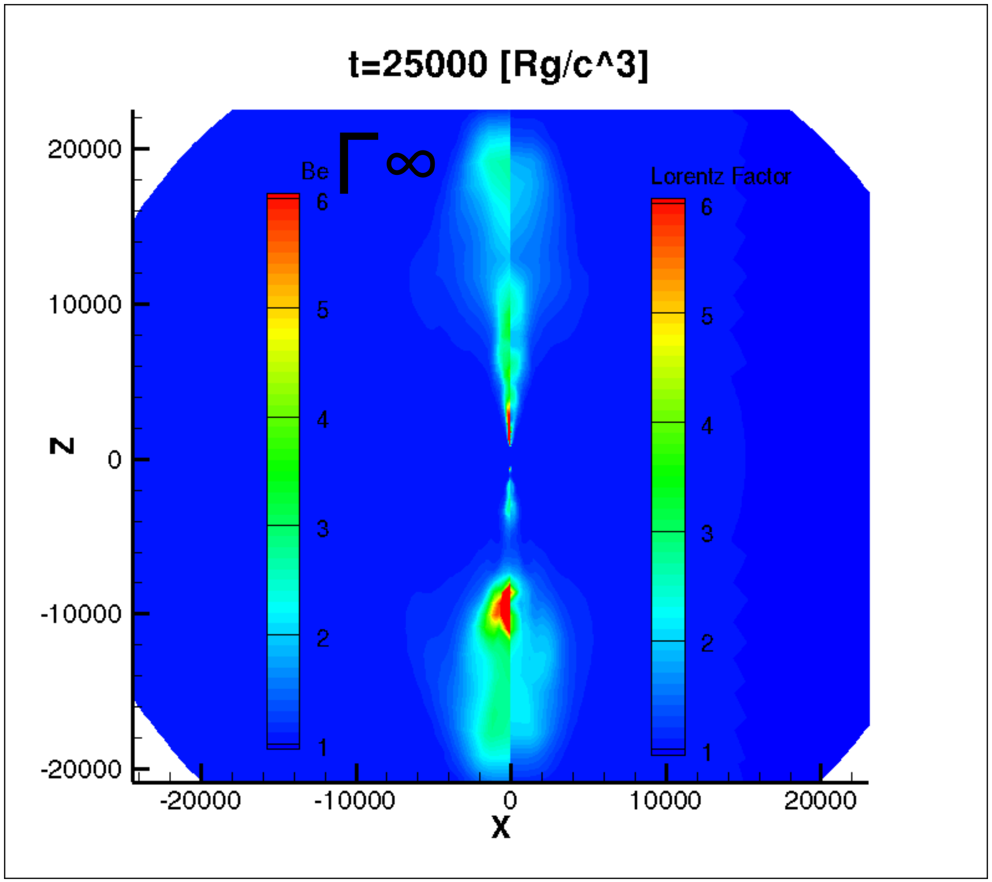
- Magnetized jet propagation in large scale.
- Kink instability (m=1 mode) grows up.
- Dissipation (recconection) happens. Then magnetic energy is converted to thermal and kinetic energy.

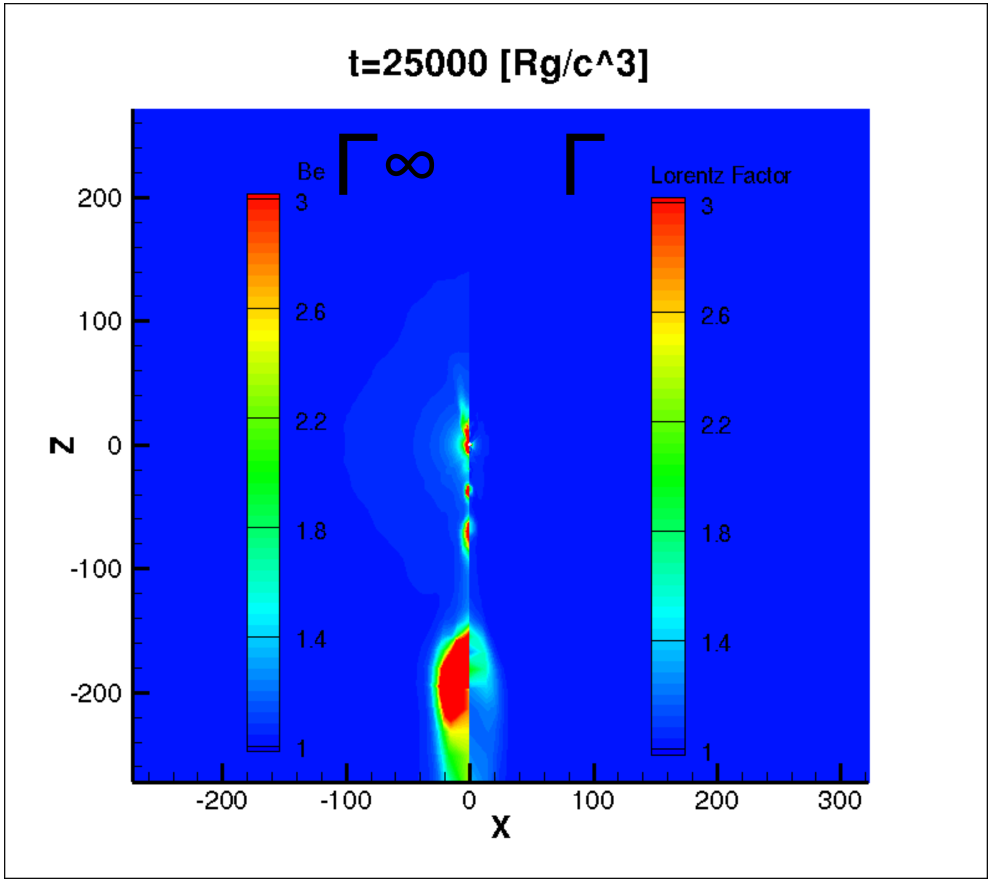
Kink instability riggers small angle recconection (Drenkhahn 2002, Drenkhahn & Spruit 2002)

3D RMHD simulation
of magnetized jets propagation
in massive star.
(Bromberg & Tchekhovskoy 2015)

Left: log10 [rot(∇xB)] (conduction current)
Right: log10 [σ]

Bulk acceleration Γ~2





Structures are resolved by only 1-2 grids.
Higher resolution calculation necessary to see MHD instability and bulk acceleration.

Mizuta+ in prep.

AGN : UHECR accelarator ?

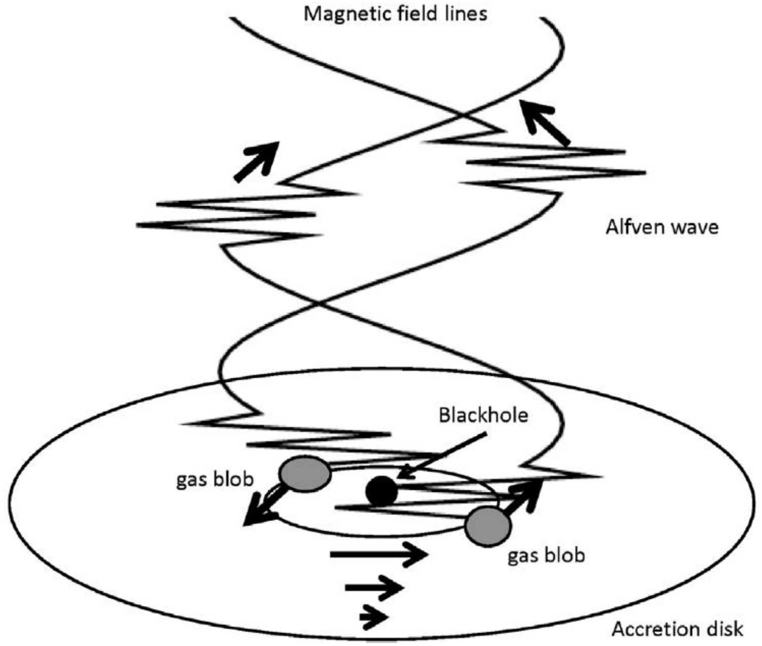
Wakefield acceleration model (excited by Alfven wave)

Intense laser pulse => strong Alfven wave ($v_A \sim c$, transverse wave)

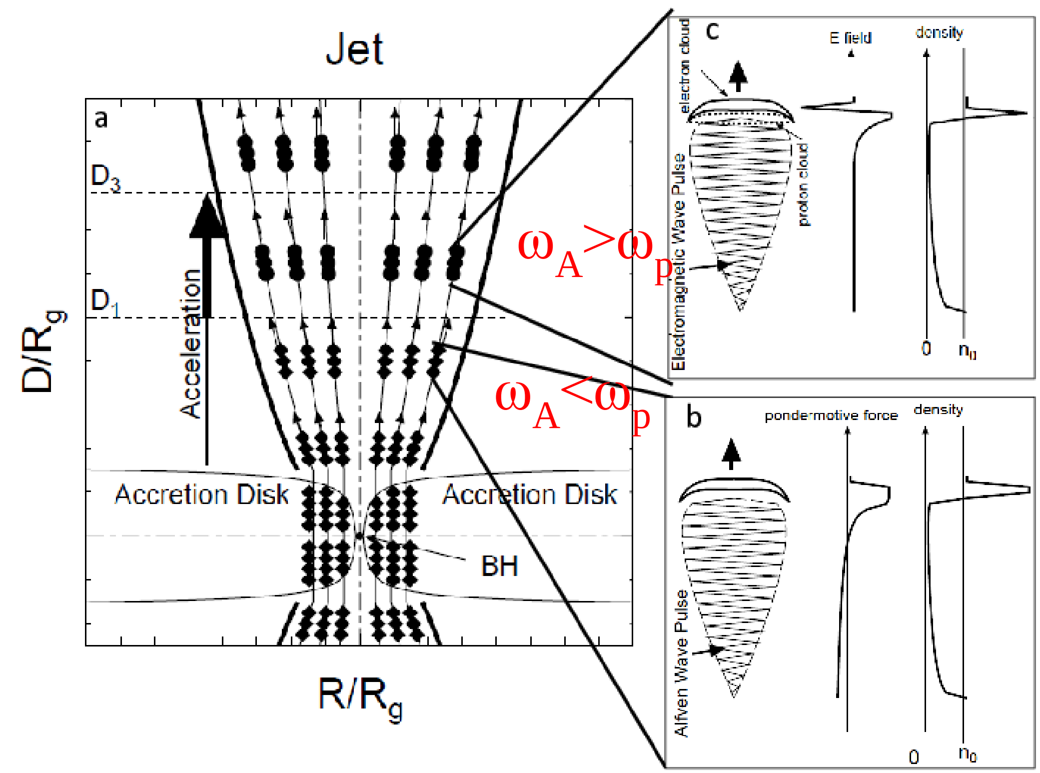
Alfven waves excited in the accretion disk propagates into the outflows.If magnetic field is enough high, relativistic Alfven waves is possible.

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

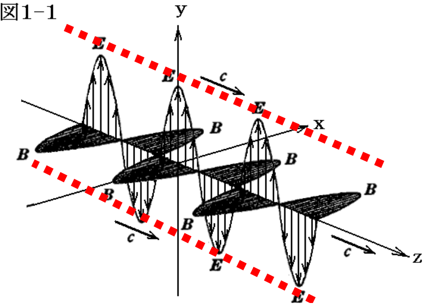
nonlinear & relativistic Alfven mode Standard-disk (Shakra & Sunyaev (1973) is assumed)



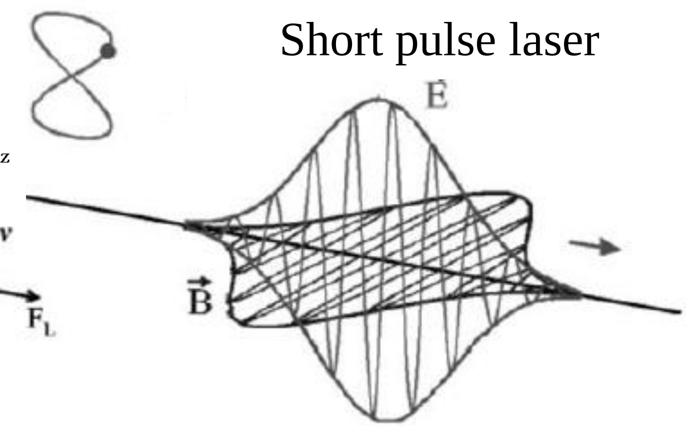
Ebisuzaki & Tajima 2014



Wakefield acceleration (Tajima & Dawson PRL 1979)



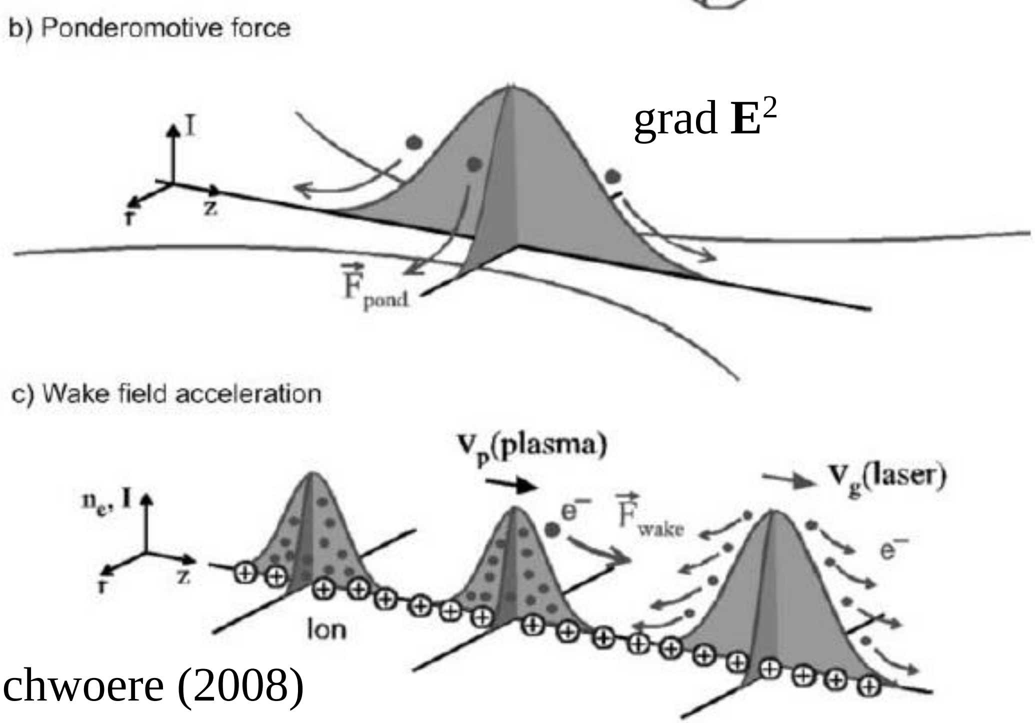
Acceleration mechnism by interaction between wave and plasma.



Laser plasma Interaction
⇒ 8 shape motion.

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

Osillation of Electrifield ⇒ **v (ossilation up, down)**
vxB force ⇒ ossilation forward and backward.
|v| ~ c => large amplification motion by **vxB. (8 shape motion).**



Schwoere (2008)

If there is gradient in $\mathbf{E}^2$, charged particles feel the force towars lees $\mathbf{E}^2$ side. = Ponderamotive force

Effective acceleration for I~10^{18}W/cm^2 (relativistic intensity).
– acceleration efficiency 10GeV/m
(100-1000 higher than normal accelarators.,
Electrons: ~GeV, Ions : a few tens MeV

Relativistic Alfven wave can be applied to Wakefield acceleration.
Takahashi+2000, Chen+2002 (for short GRBs : NS-NS merger)
Lyubarusky 2006, Hoshino 2008 (wakefield acc. @ relativistic shock)

Summary

2D & 3D GRMHD simulations of rotating BH+accretion disk

– B filefd amplification, saturation, dissipation
– Higher mass accretion rate for 3D than that in 2D case
– Electromagnetic flux @ horizon is consistent with BZ flux
– Higher resolution calculations are necessry to discuss bulk acceleration