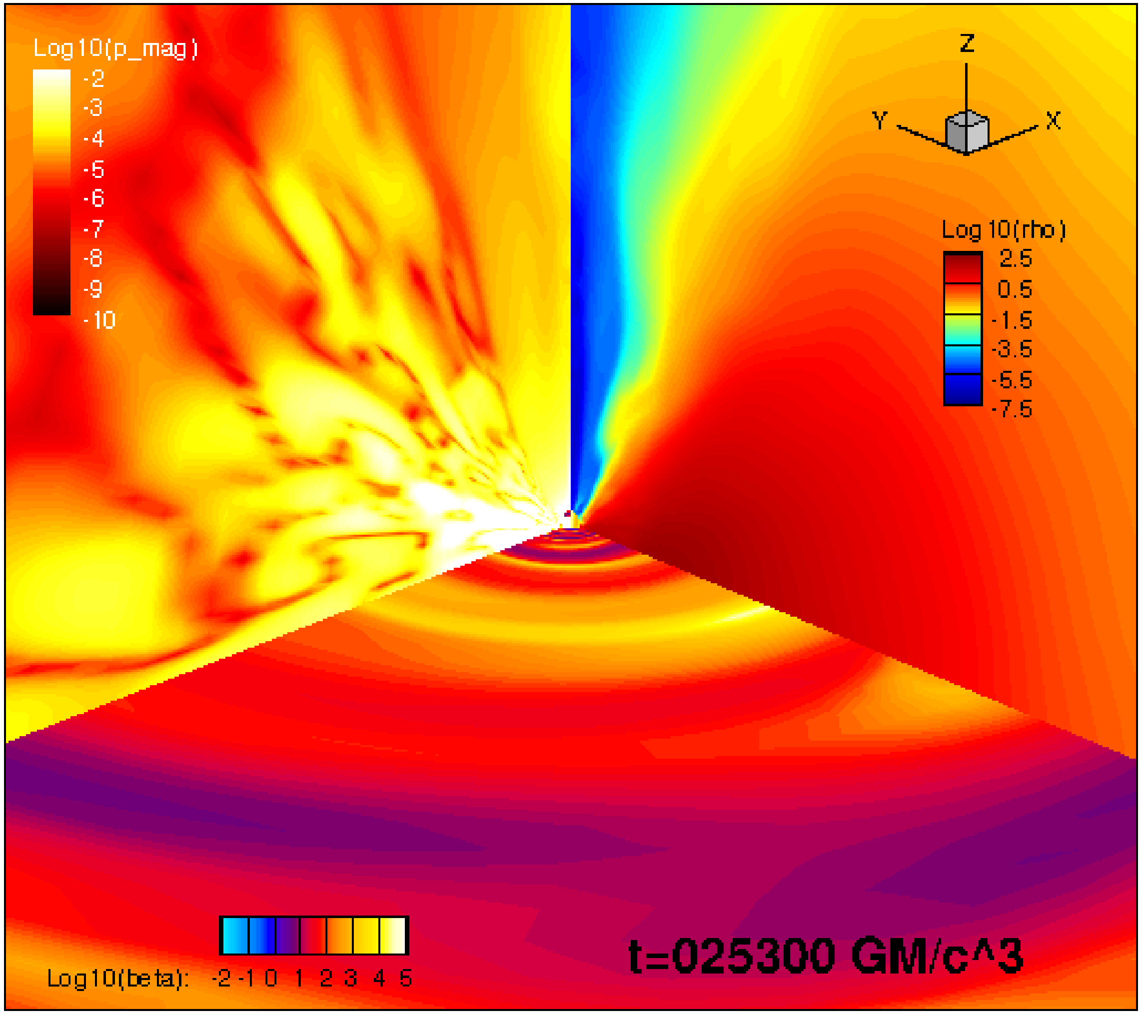
ブラックホール降着円盤の時間変動と相対論的ジェットの活動性



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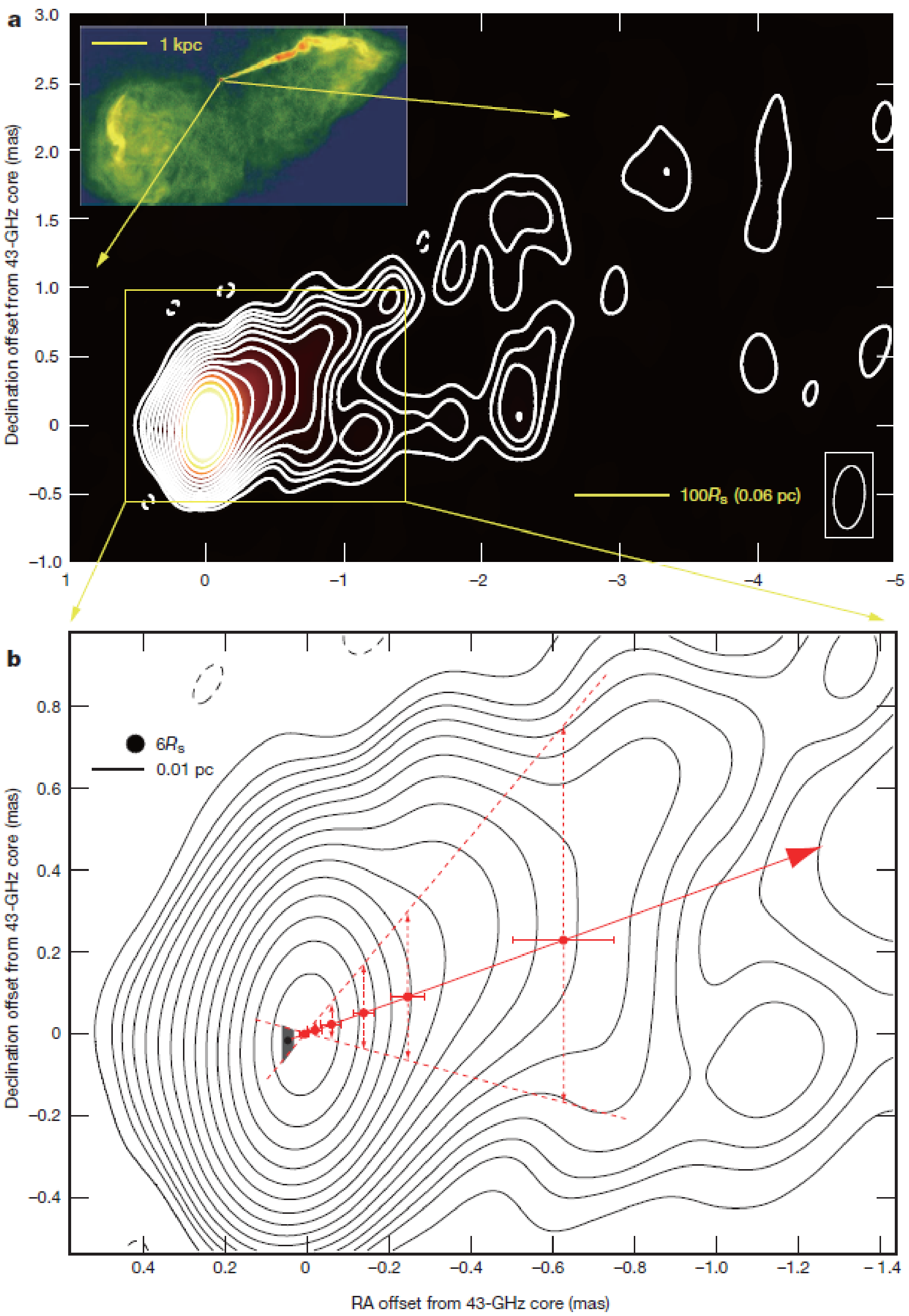
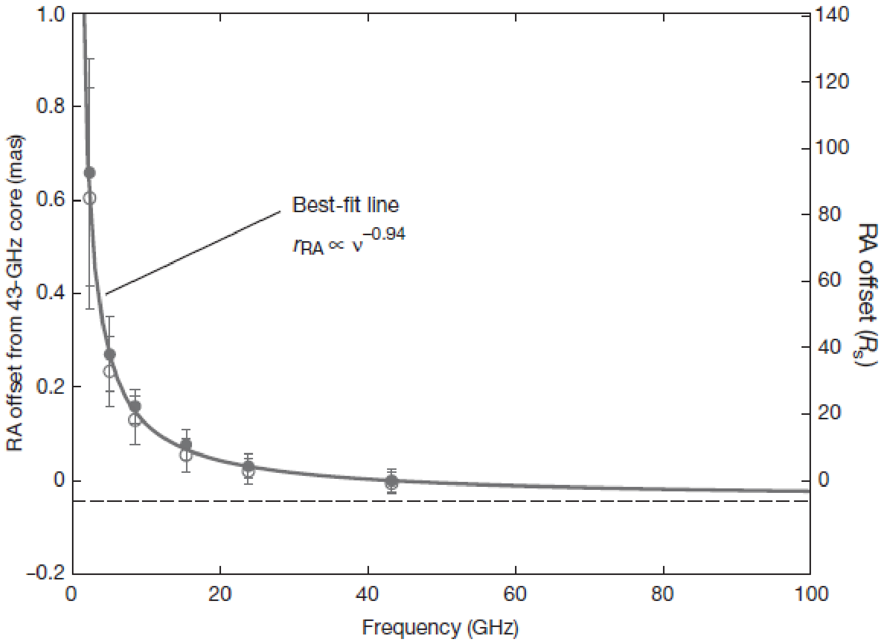
高エネルギー宇宙物理研究会 @
YITP, Kyoto U. 2017.9.5
AM +2017(arXiv1707.08799)

AGN jet radio observations

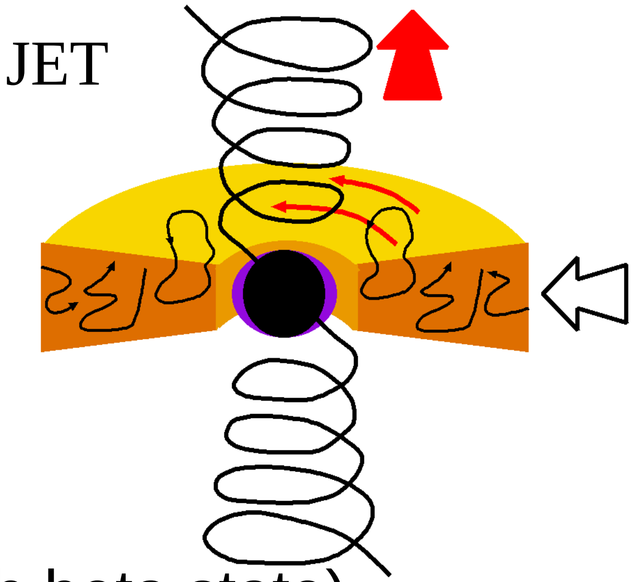
- M87 D=16.7Mpc
- M_{BH}~3.2-6.6x 10^9M_sun
- Location of the central BH is near the radio core by analysis of several bands of radio observations.
- It is consistent that the shape of the jet near the core is not conical but parabola.
- Rim brightening @ 100Rs



M87 radio observation   Hada +(2011)



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

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

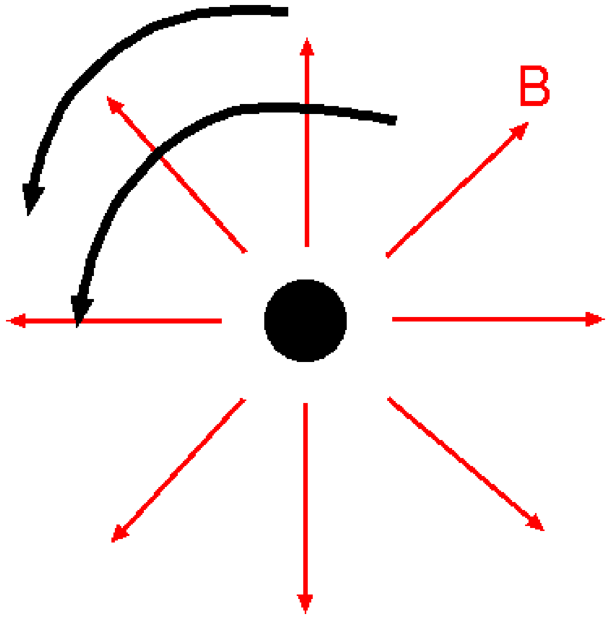
Time variability in the disk ➡ Time variability in the jet with strong Alfven wave ➡ Particle acceleration

B-filed amplification inside the disk (1)

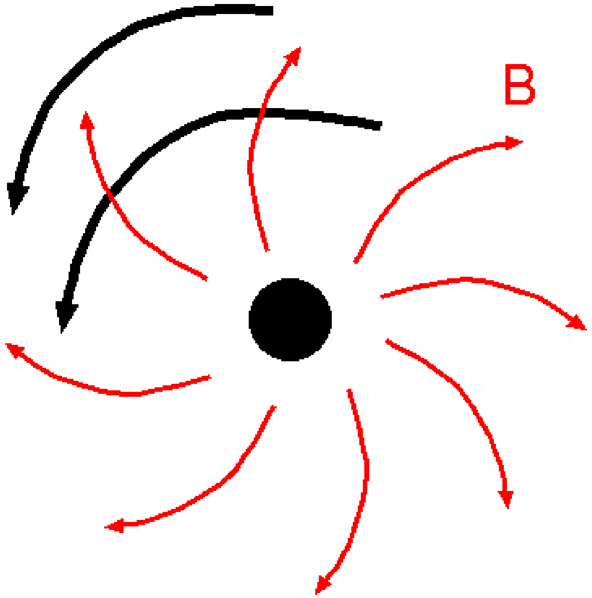
– differentially rotating disk : $d\Omega_{disk} /dr \neq 0$, ($<0$ for MRI)

Winding effect

$B \propto \Omega_{disk}\, t$



EkΦ=> BΦ

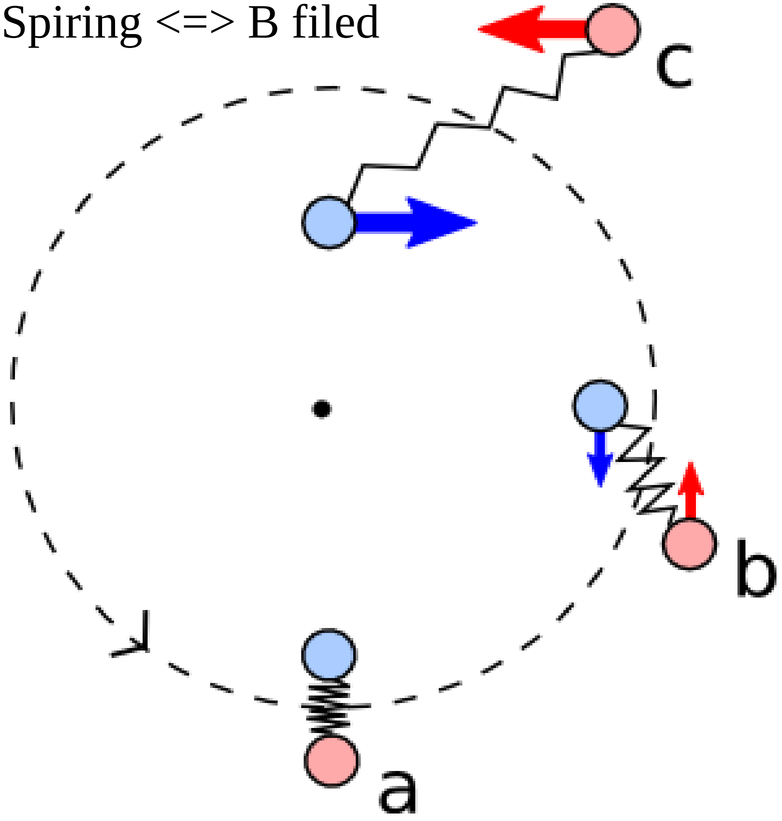


Magnetorotational instability (MRI)

MRI enhances angular momentum transfer

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

Spiring <=> B filed



Velikhov (1959) Chandrasekhal (1960)

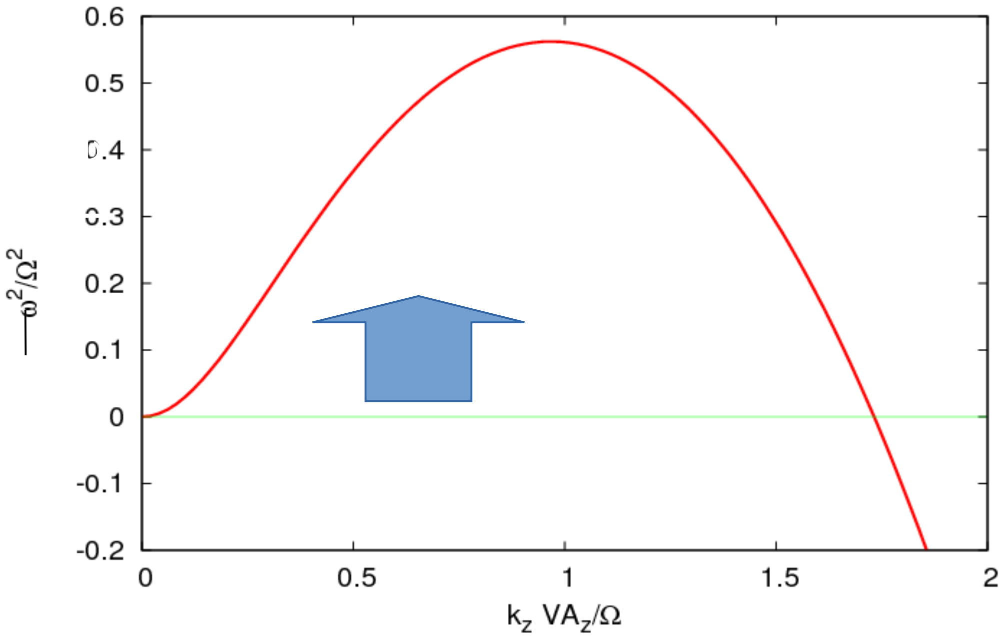
Balbus &Hawley (1991)

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)

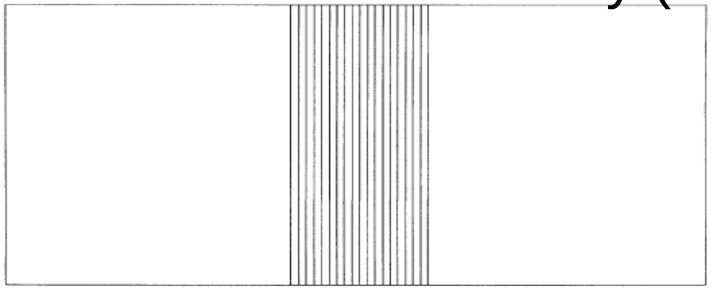


FIG. 3*a*

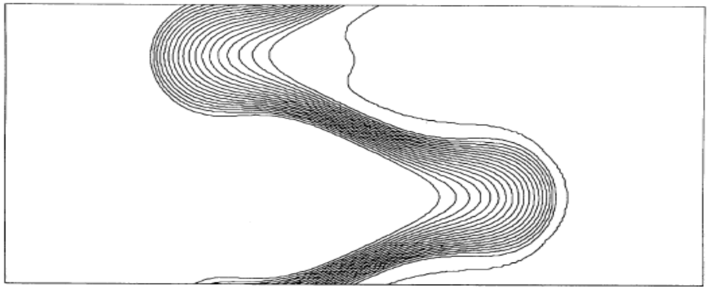


FIG. 3*b*

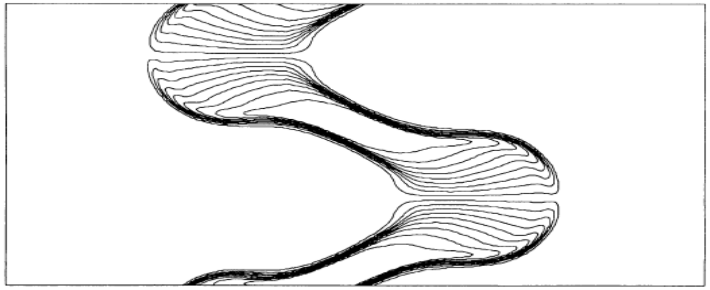


FIG. 3*c*

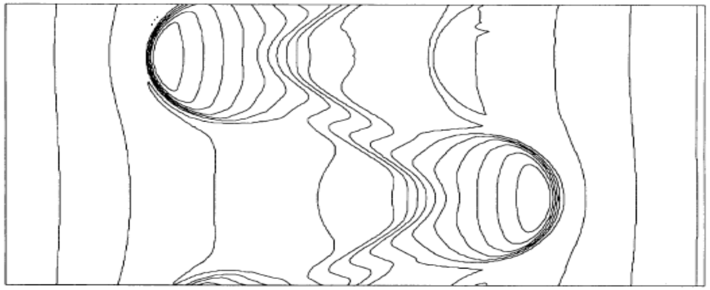
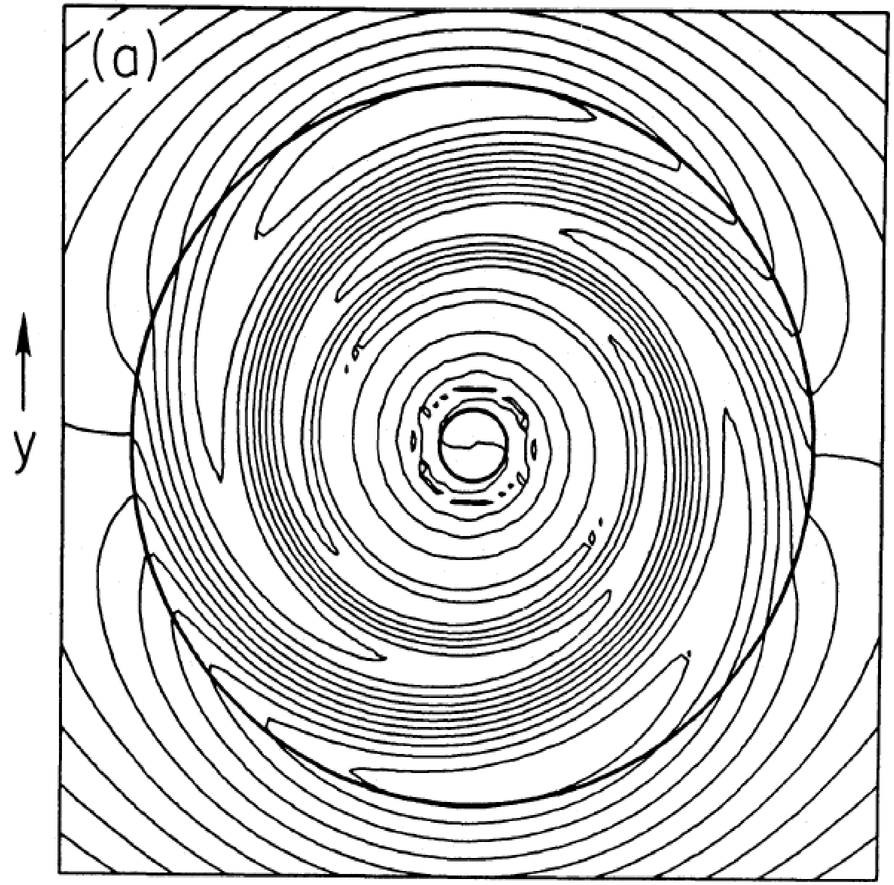
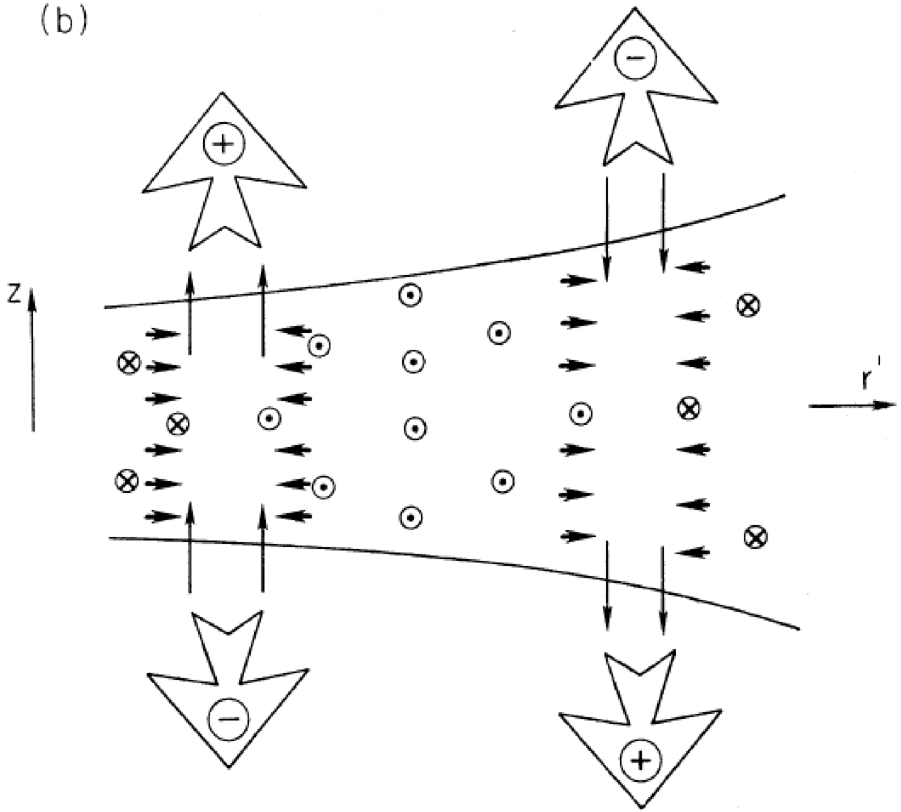


FIG. 3*d*

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)

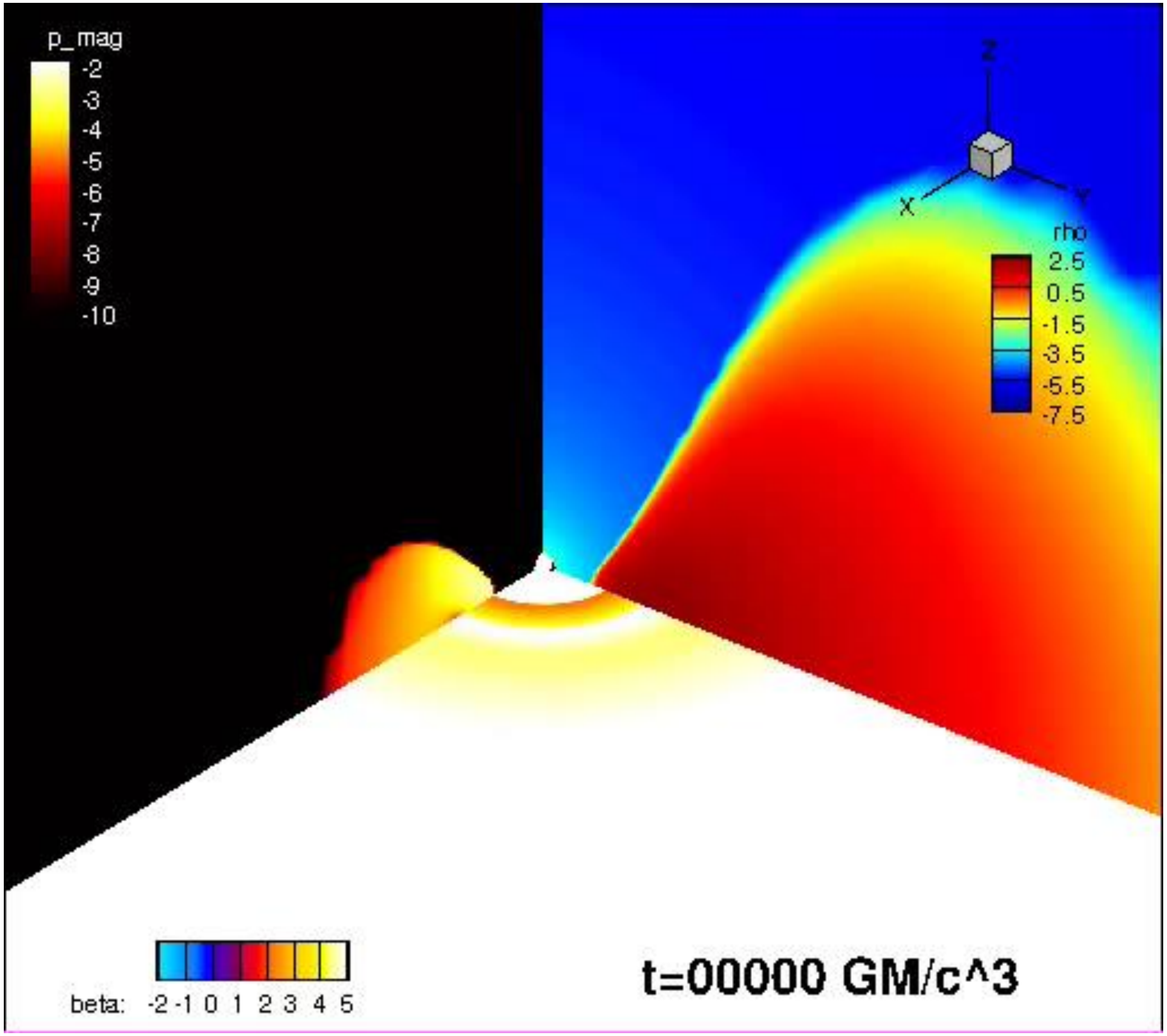
Kerr-Schild metric (no singular at event horizon)

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

Magnetized jet launch



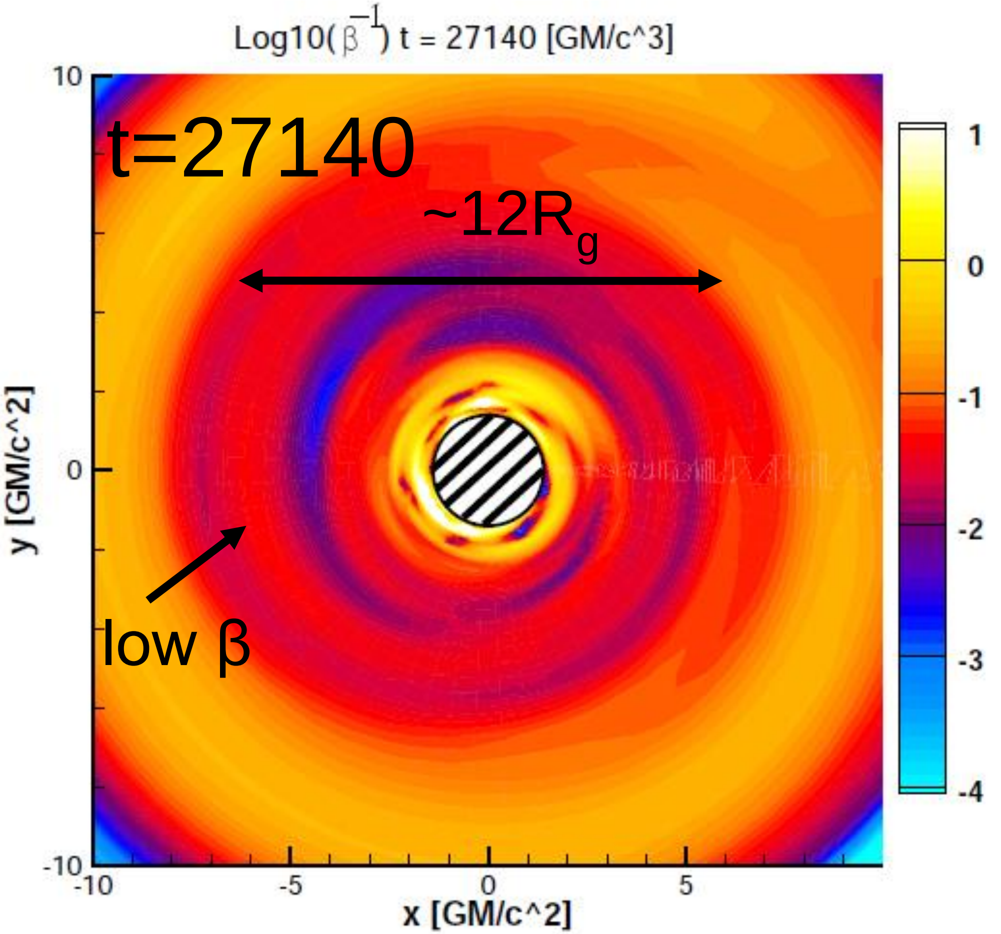
Disk : Fishbone Moncrief solution, spin parameter **a=0.9**

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

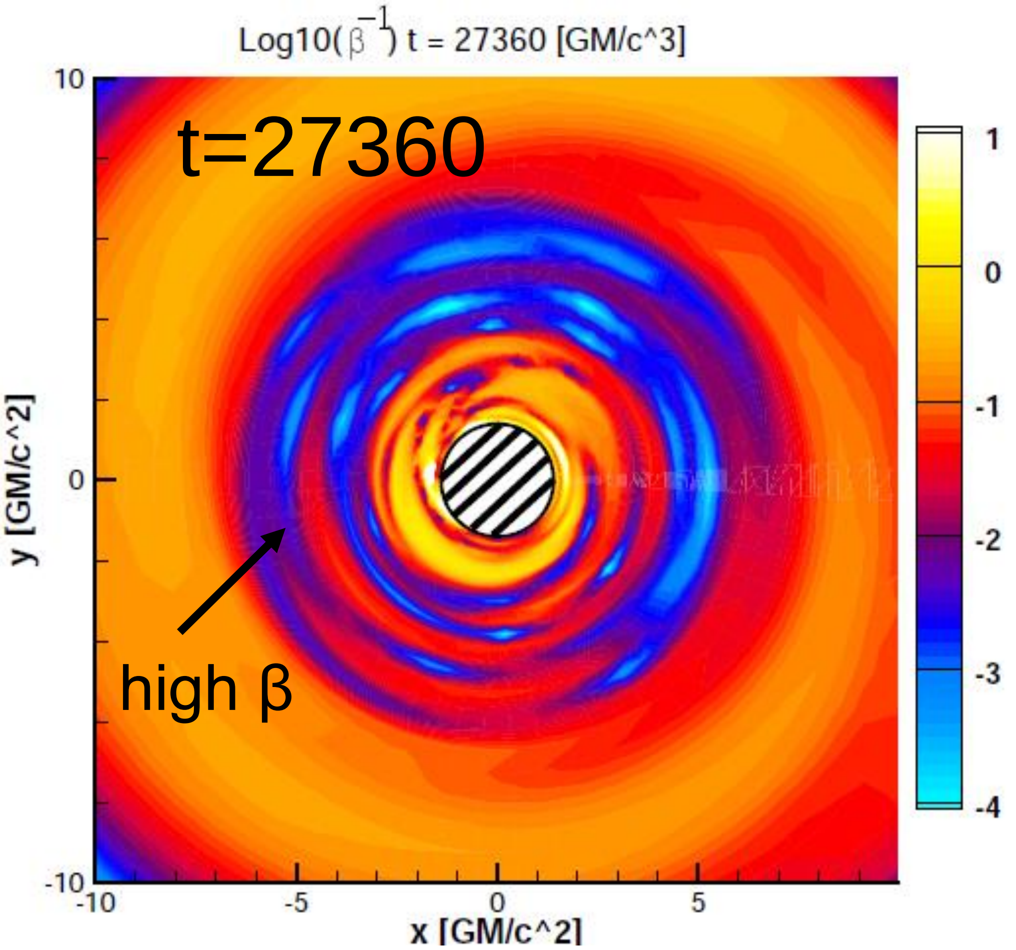
[NR=124,**Nθ=252, Nφ=60**] r=exp(n_r), dθ~0.75°, dφ~6°: uniform

Poloidal B filed, β_min=100

Plasma β (P_{th} /P_{mag})



Log(1/ β) @ equator

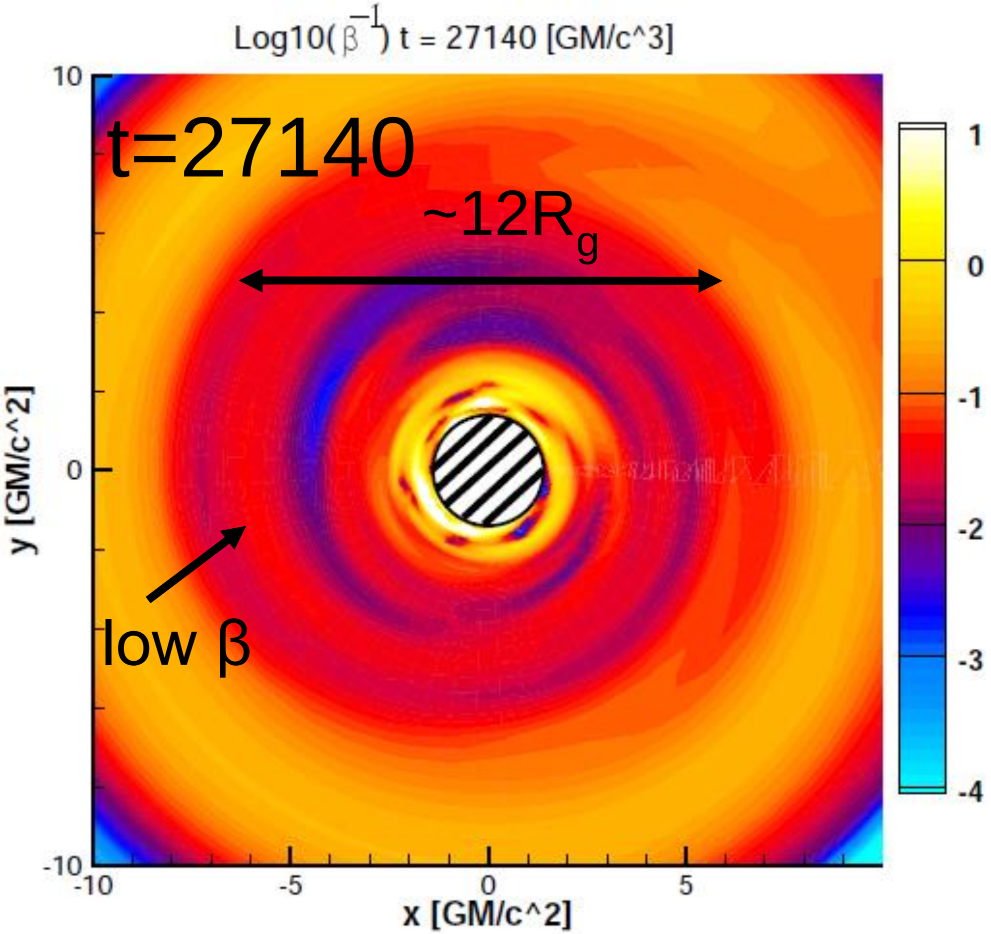


Log(1/ β) @ equator

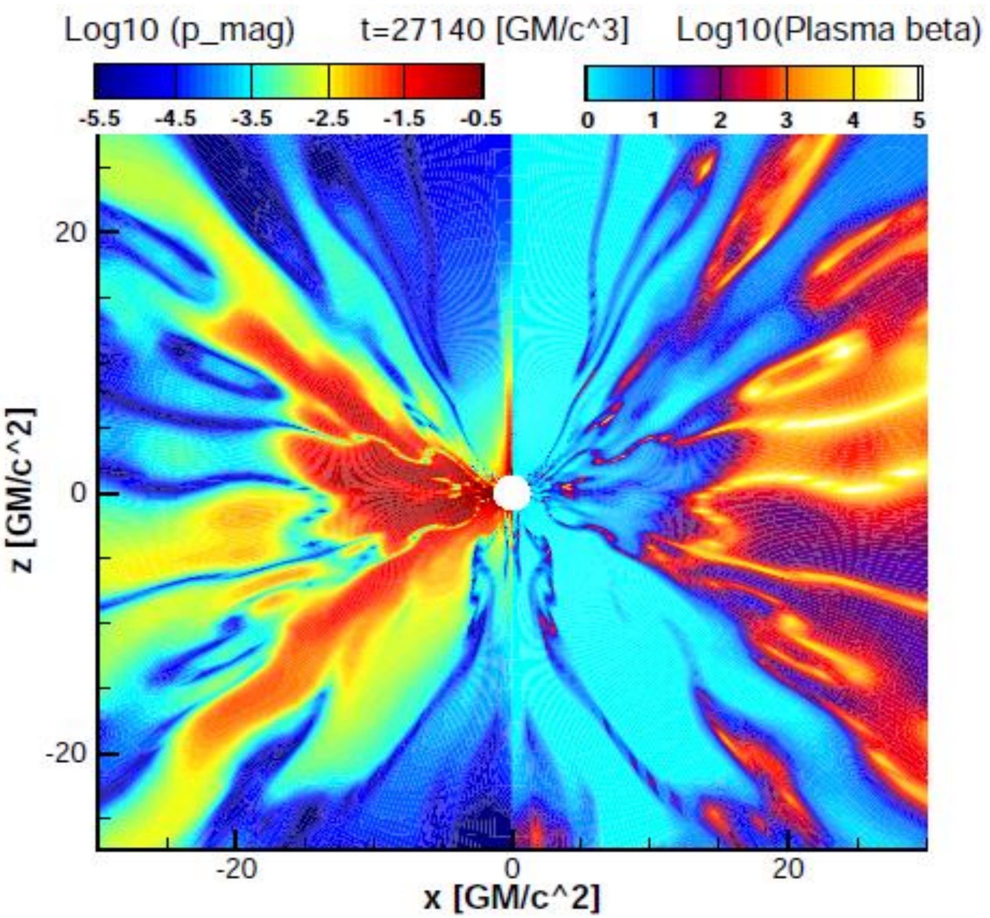
– transitions between low β starte and high β state
Shibata, Mastumoto, & Tajima (1990) and other MHD simulations).

– Highly non-axis symmetric

Plasma β (P_{th} /P_{mag})



Log(1/ β) @ equator

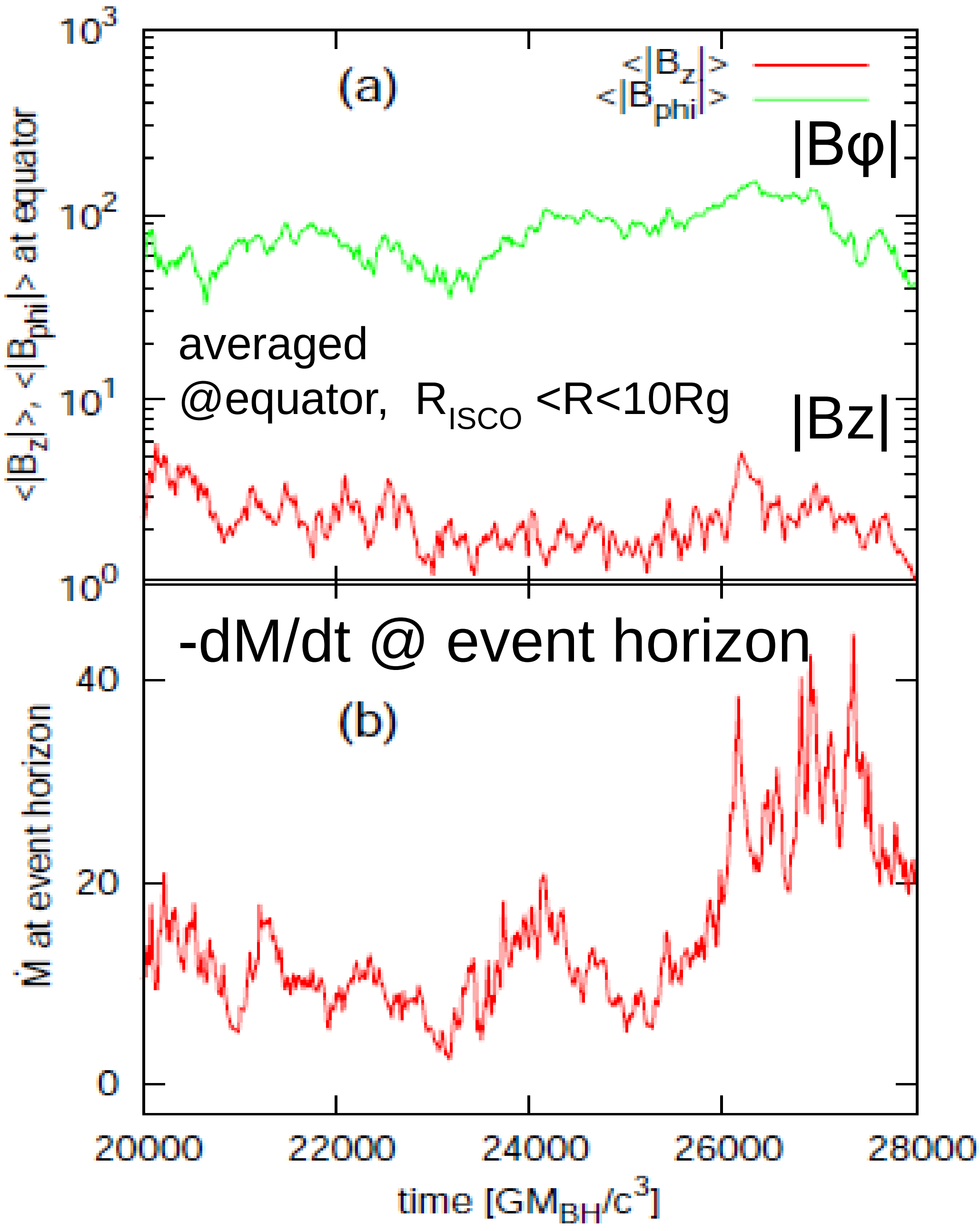


Log(P_{mag}) & Log(Plasma β)

- – transitions between low β starte and high β state Shibata, Mastumoto, & Tajima (1990) and other MHD simulations).
- – Highly non-axis symmetric
- – Filamentaly structure ; thickness ~0.5 Rg

Mizuta + in prep.

B-filed amplification & mass accretion

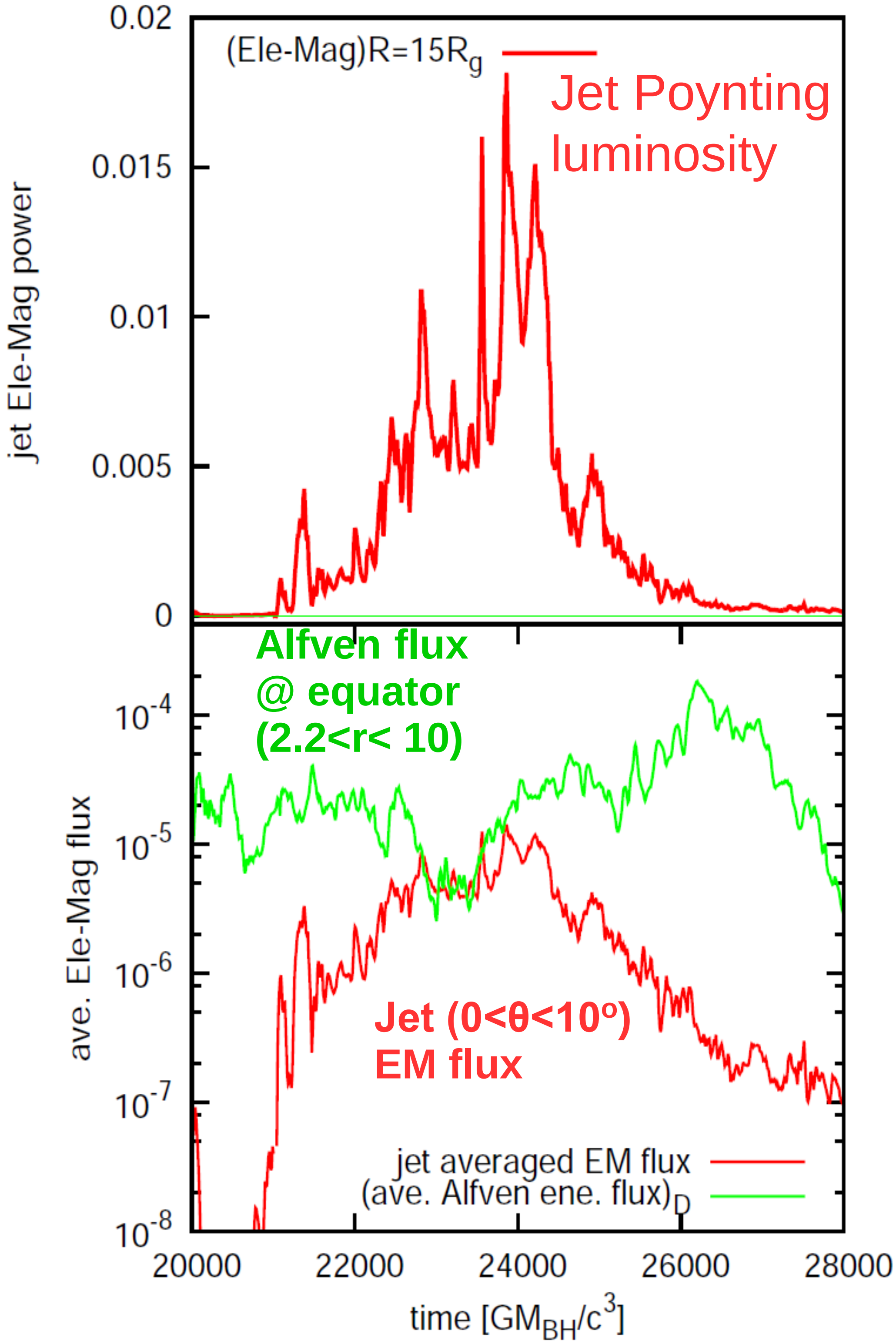


– B- filed amplification works as a viscosity
➔alpha viscosity in Shakura & Sunyaev 1973)

– B-field amplification via MRI (Balbus & Hawley 1991)
λ~0.5Rg ~8 grids size
~filamentaly structure
growth timescale ~ 50 GM/c^3

– Repeat cycle
~300 hundreds GM/c^3
~10 times orbital period
(Stone et al. 1996, Suzuki & Inutsuka 2009, O'Neill et al. 2011)

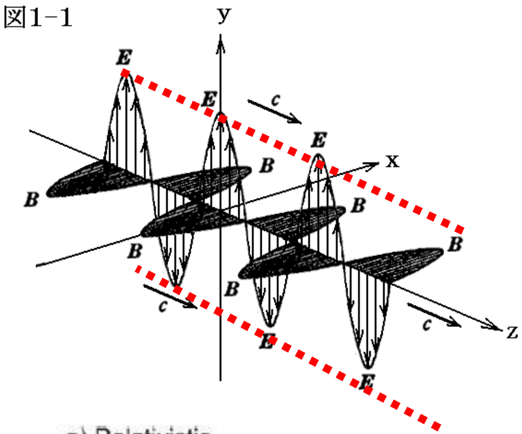
Large Alfven flares in the jet



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

Wakefield acceleration (Tajima & Dawson PRL 1979)

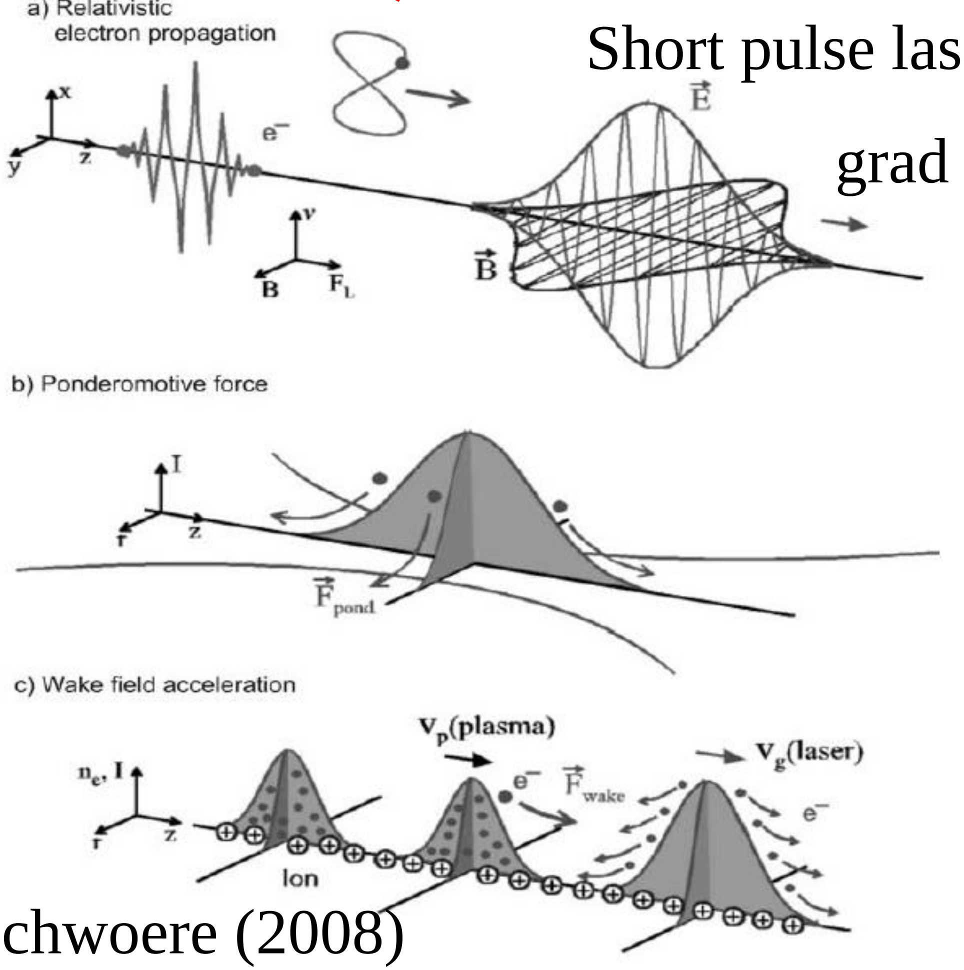
Acceleration mechnism by interaction between wave and plasma.



Laser plasma
interaction
⇒ 8 shape motion.

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

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



Short pulse laser

grad $\mathbf{E}^2$

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

Effective acceleration for $I \sim 10^{18}\mathrm{W/cm}^2$ (relativistic intensity).
Experimentally observed.

Relativistic Alfven wave can be applied to wakefield acceleration. (Takahashi+2000, Chen+2002, Lyubarusky 2006, Hoshino 2008)

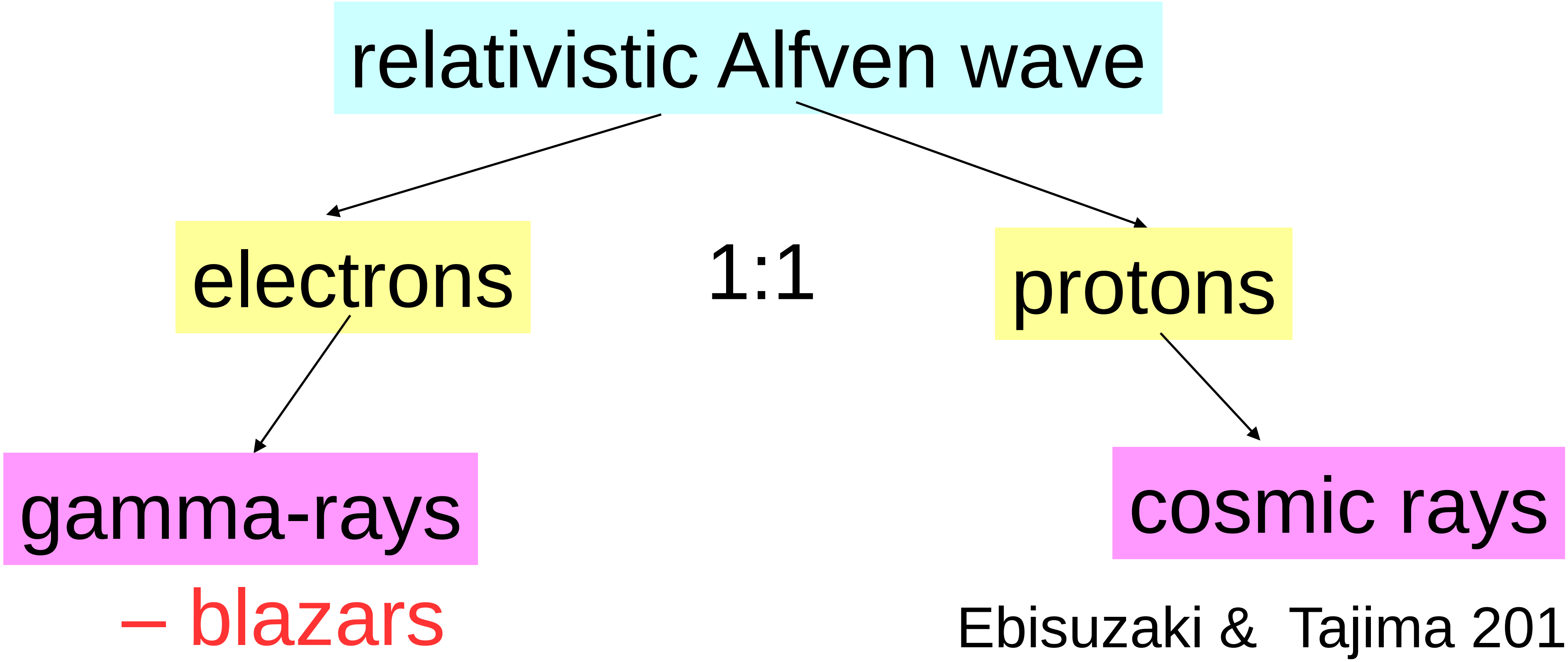
Schwoere (2008)

Particle Acceleration via relativistic waves

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

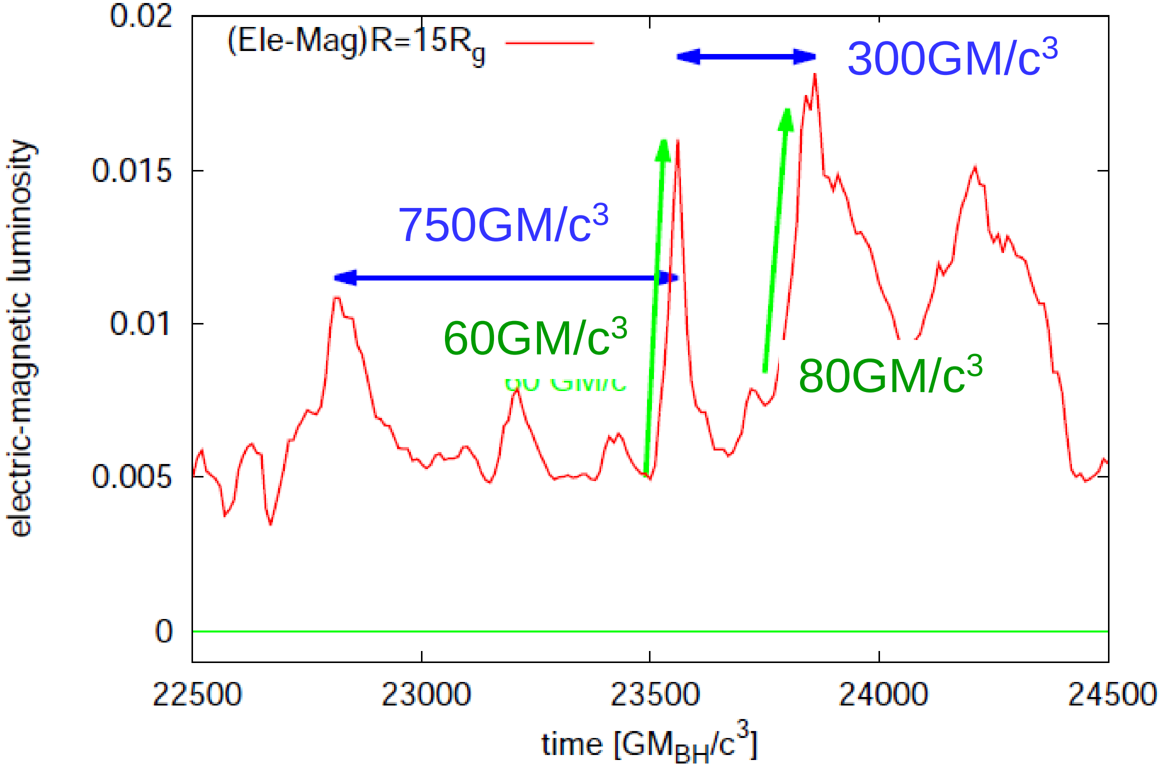
$$a_0 = \frac{eE}{m_e \omega_{\rm A} c} = 8.8 \times 10^{10} \left(\frac{M}{10^8 M_\odot}\right)^{1/2} \left(\frac{\dot{M}_{\rm av} c^2}{0.1 L_{\rm Ed}}\right)^{1/2}$$

– Particle acceleration (protons and electrons) via Ponderamotive force by relativistic EM waves



Ebisuzaki & Tajima 2014

Application to blazar gamma-ray flare by Fermi

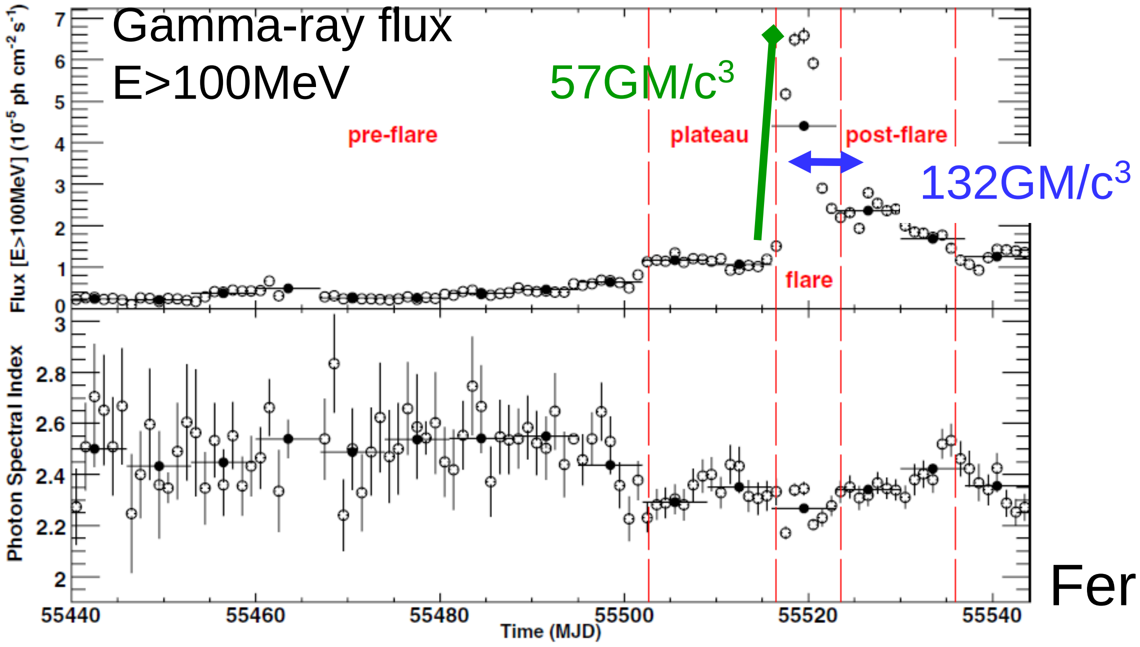


– Strong Alfven waves ($a_0 \gg 1$) in the jet.

– non-thermal electrons

==> blazar flares

– Essentially different from internal shock model (Rees 1978) + Fermi acc. model (Fermi 1954)



3C454.3 (M_{BH} ~$5 \times 10^8 M_{sun}$ Bonnoli et al. 2011)

Fermi observation Abdo + ApJ 2010

Conclusion

3D GRMHD simulations of rotating BH+accretion disk for the analysis of wakefield acc.

– B filefd amplification via MRI
– low beta disk ⇔ high beta disk transition
– Alfven wave burst in the jet when transition from low beta disk to high beta disk occurs
– $a_0 \sim 10^{10} >> 1$: effcient particle acceleration
– Timescalses of blazar flares are consistent with our simulation

Future works

– Higher resolution calculations to resolve the fastest MRI mode