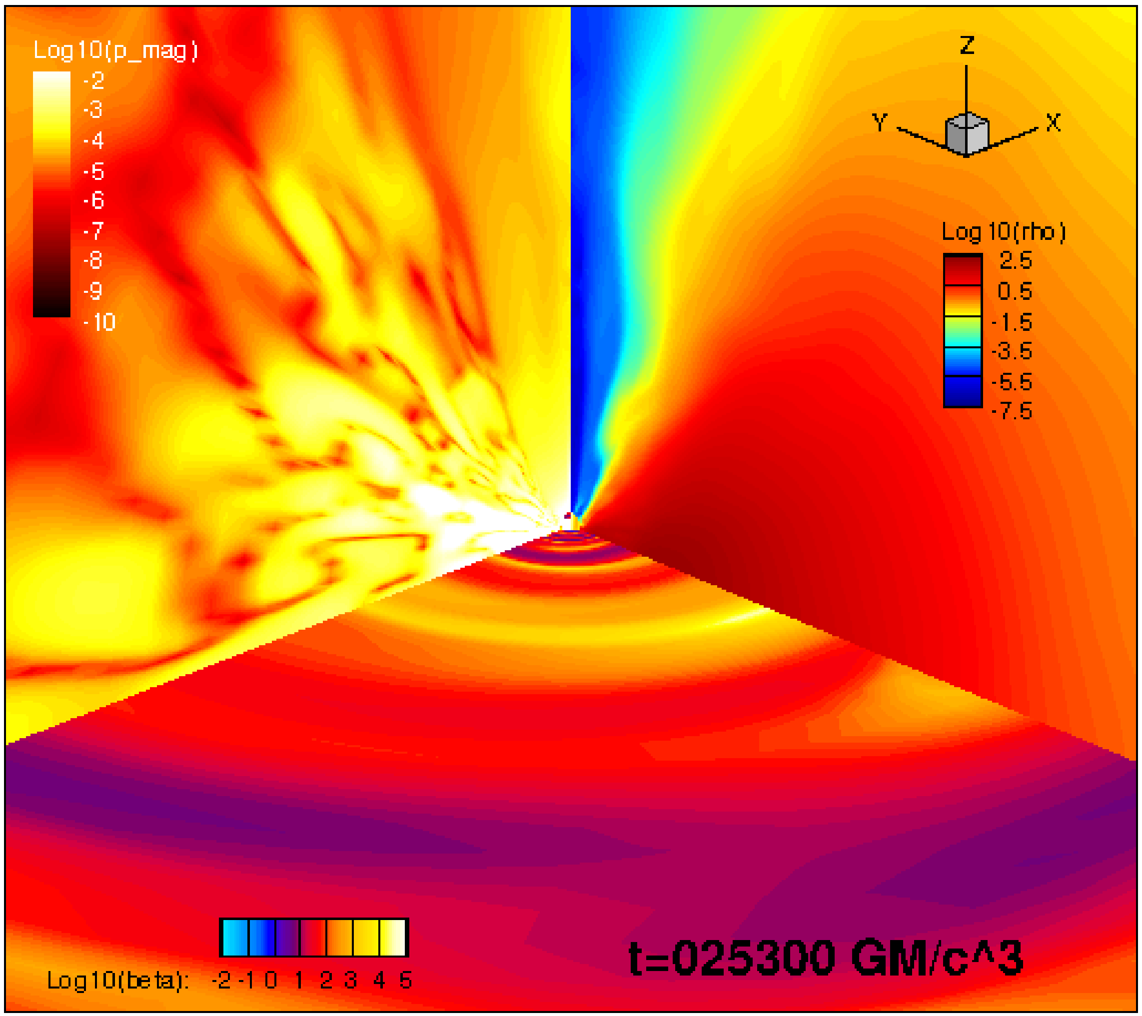
General Relativistic MHD simulation of a blackhole, accretion disk, and jets



Akira MIZUTA(RIKEN)

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

mini workshop on plasma astrophysics and extreme high energies@UC Irvine
17.02.06
Mizuta + in prep.

OUTLINE

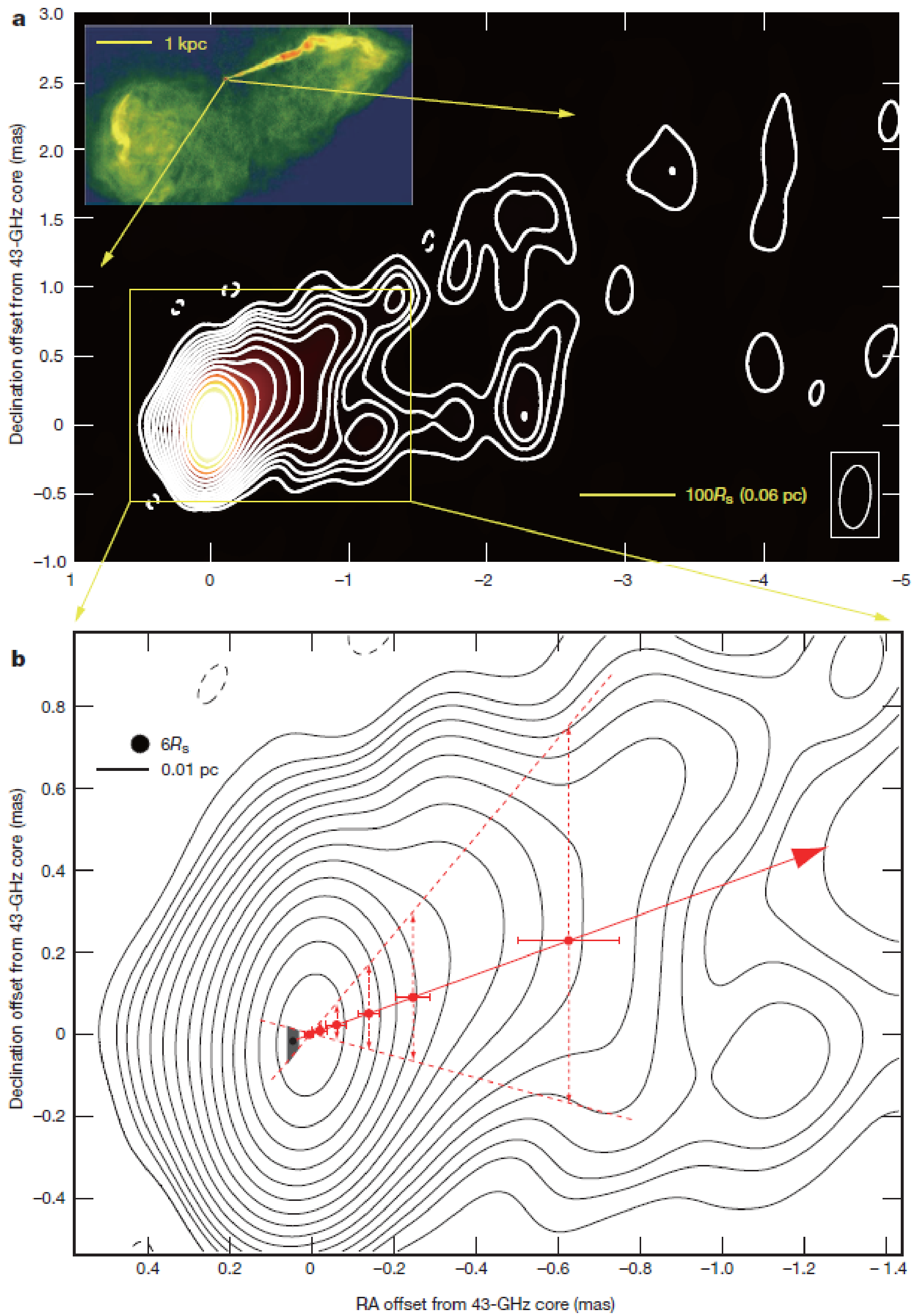
- Introduction
  AGN jets ; observations and theory

- GRMHD simulations of black hole and accretion disks

- Application :
  – Particle acceleration of ultra high energy cosmic rays
  – blazar flares

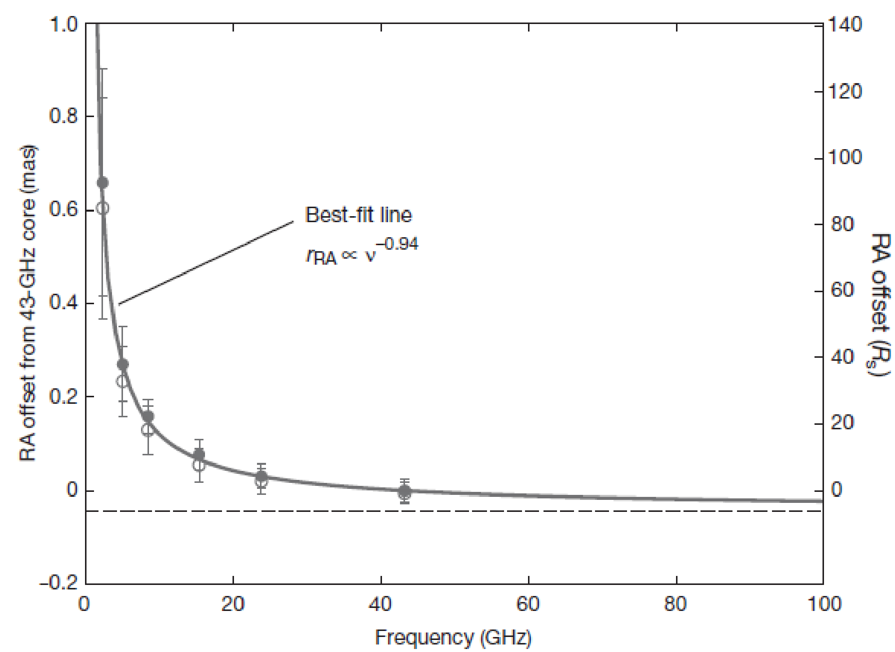
- Summary

AGN jet : M87 radio observations

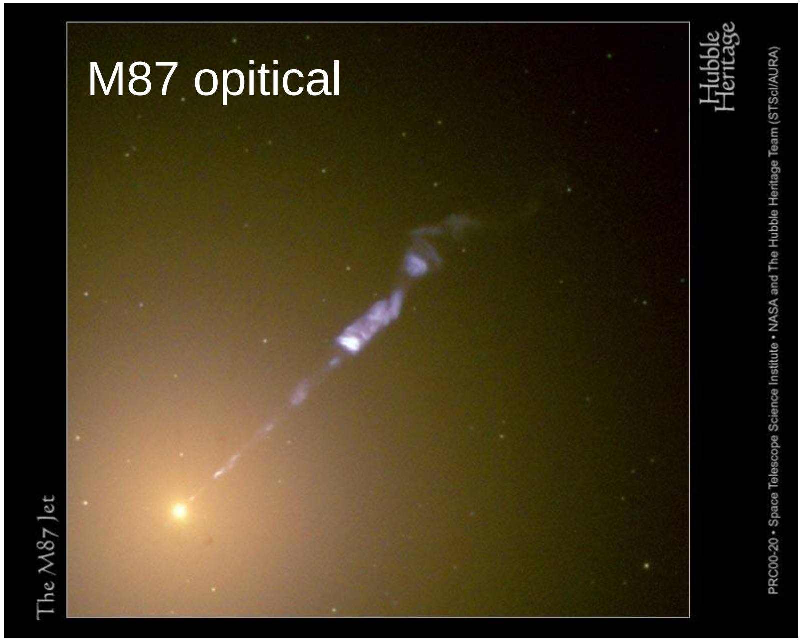


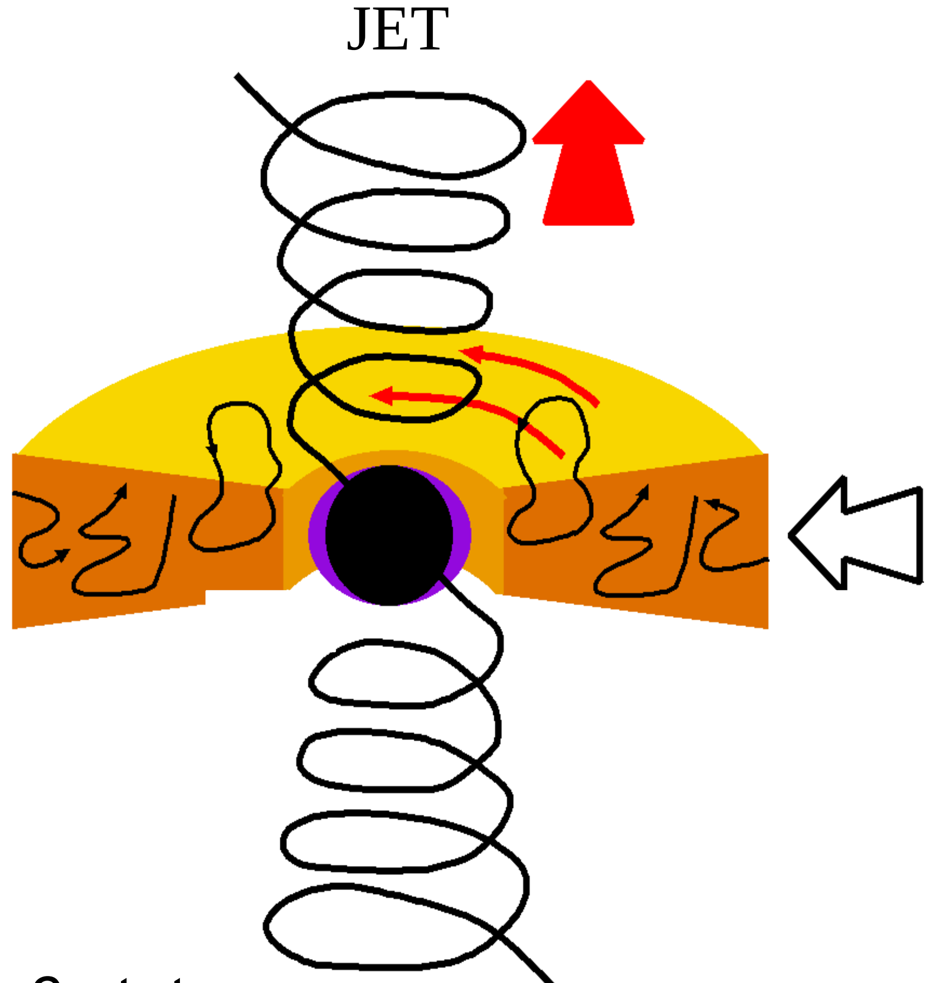
M87 radio observation Hada +(2011)

- M87 D=16.7Mpc
- M_{BH}~3.2-6.6x 10^9M_sun
- Location of the central BH (Hada + 2011)
- outer shape of the jet near the core ; parabola (Hada+2011)
- Rim brightening @ 100Rs



Relativistic jet launched from BH+accretion disk





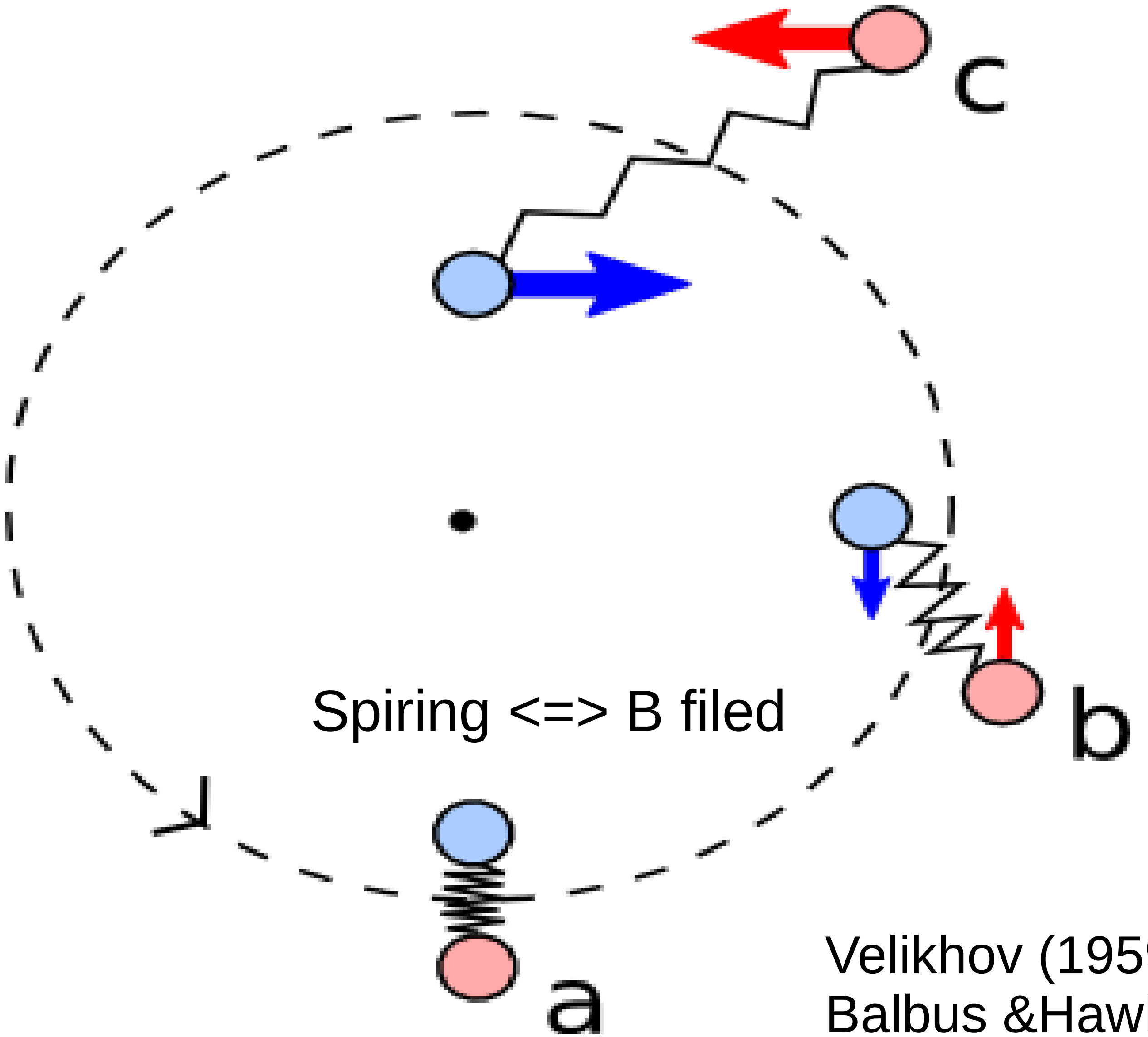
- Central Engine
  - -Black Hole(BH)＋accretion disk
  - -B filed amplification
- disk transition between from
  low plasma β state to high plasma β state.
- Strong Alfven burst at the transition from low β to high β.
  (Tajima+1987, Shibata, Matsumoto, Tajima 1990
  Haswell, Tajima, & Sakai 1992)
- Applied to cosmic-ray acceleration via wakefiled acc. Model
  Ebisuzaki & Tajima 2014

B-filed amplification inside the disk (1)

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

Magnetorotational instability (MRI)

MRI enhances angular momentum transfer



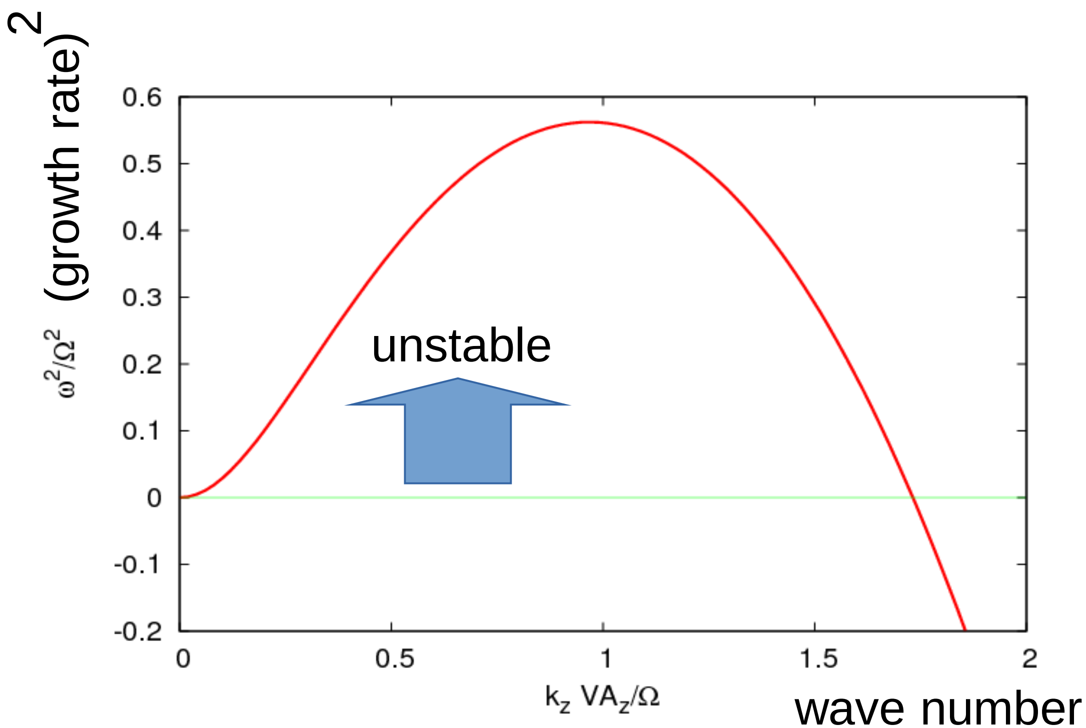
$B \propto \exp(i\omega t)$

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

B-filed amplification inside the disk (2)

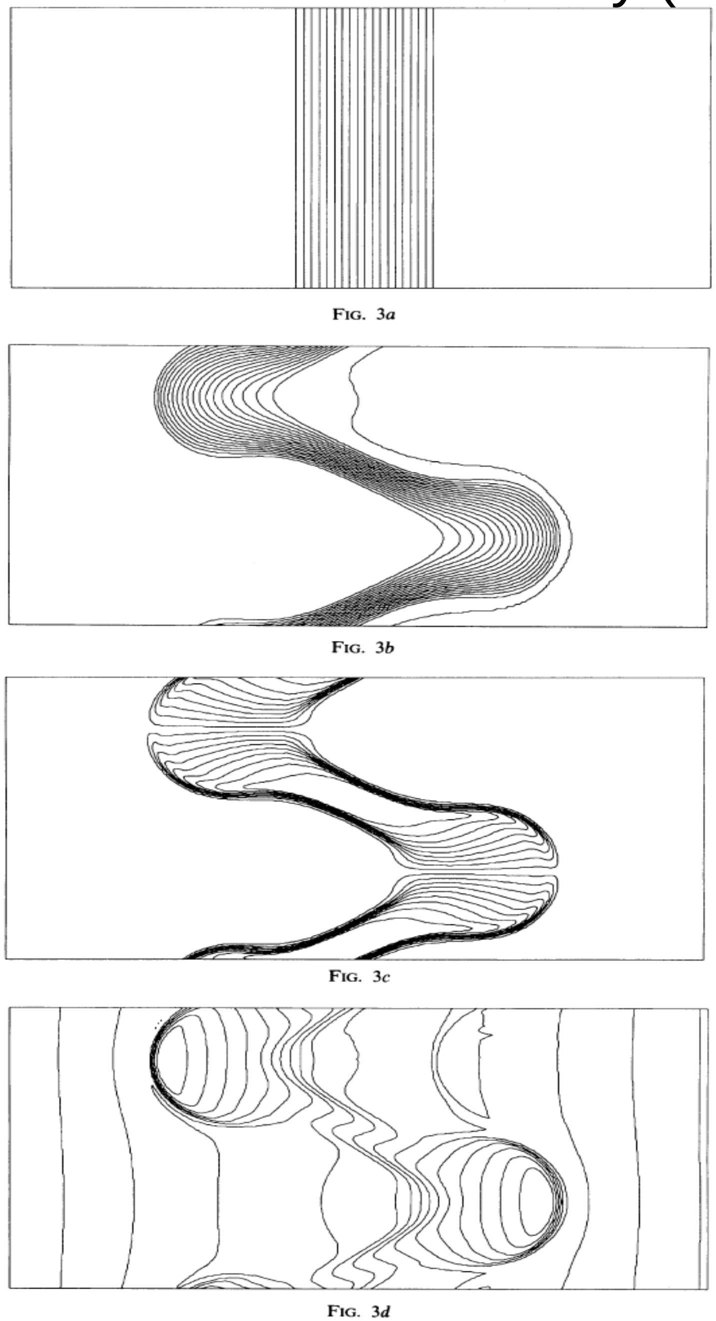
MRI growth rate depends on the wavelength.
For Kepler rotation, i.e., $\Omega_K \propto R^{-3/2}$,

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

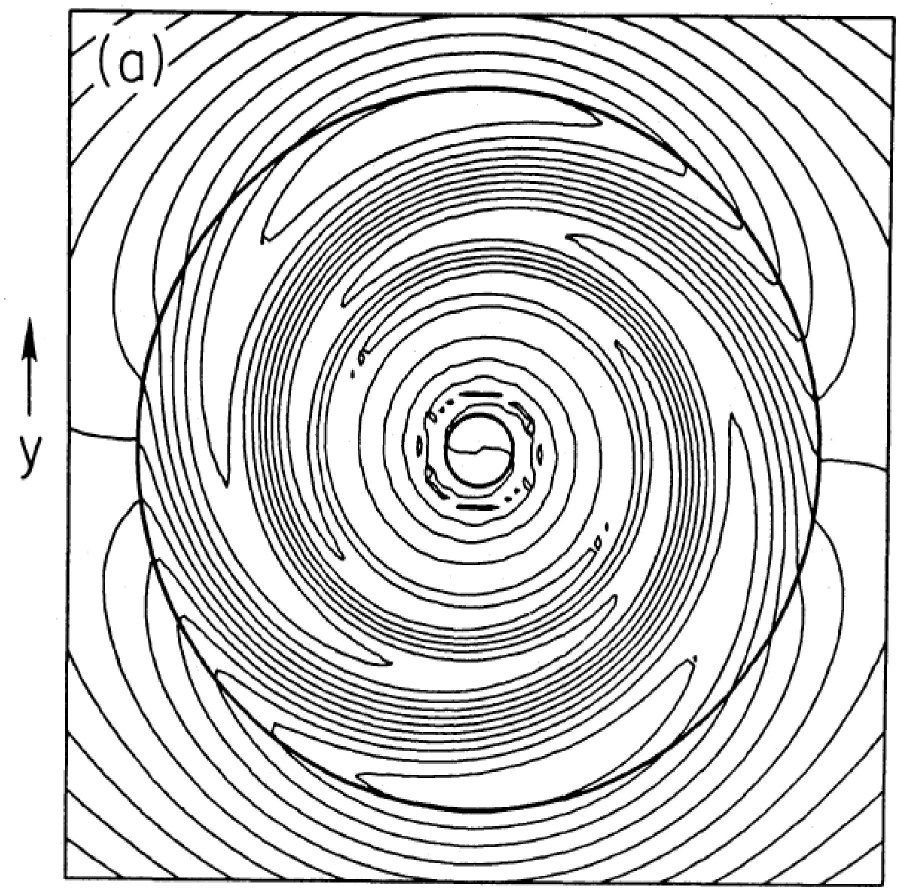


Unstable @ 0 <kV_a < 1.73 Ω_K
Most unstable @ $kV_a \sim \Omega_K$
$\omega \sim 0.75\Omega_K$

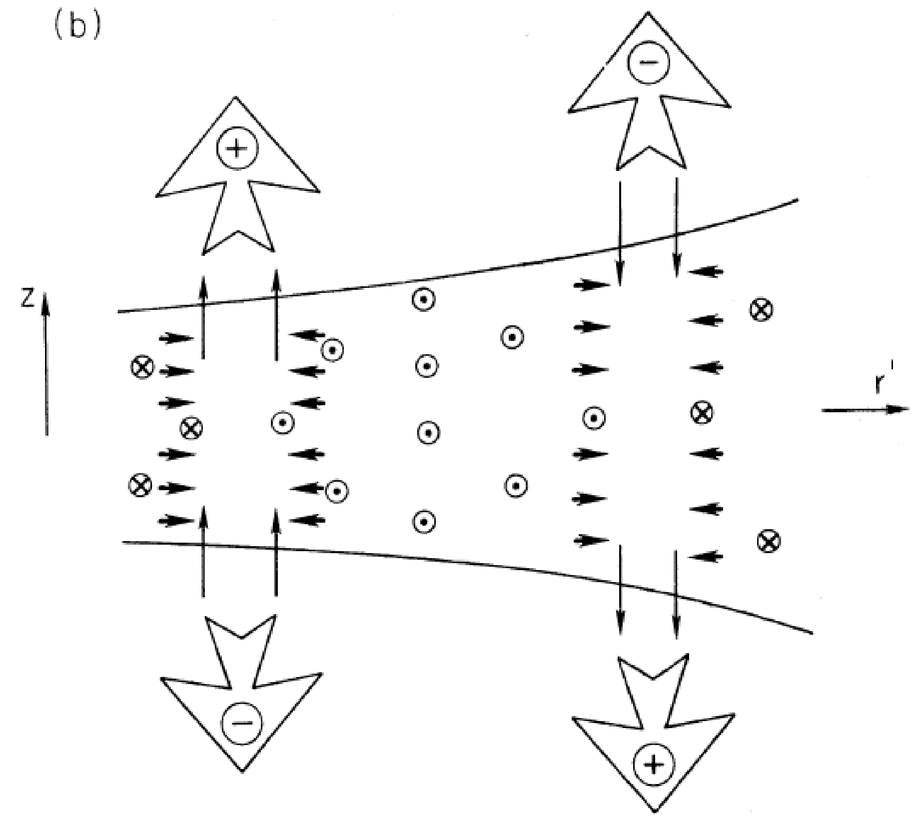
Balbus &Hawley (1991)



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))

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

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

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

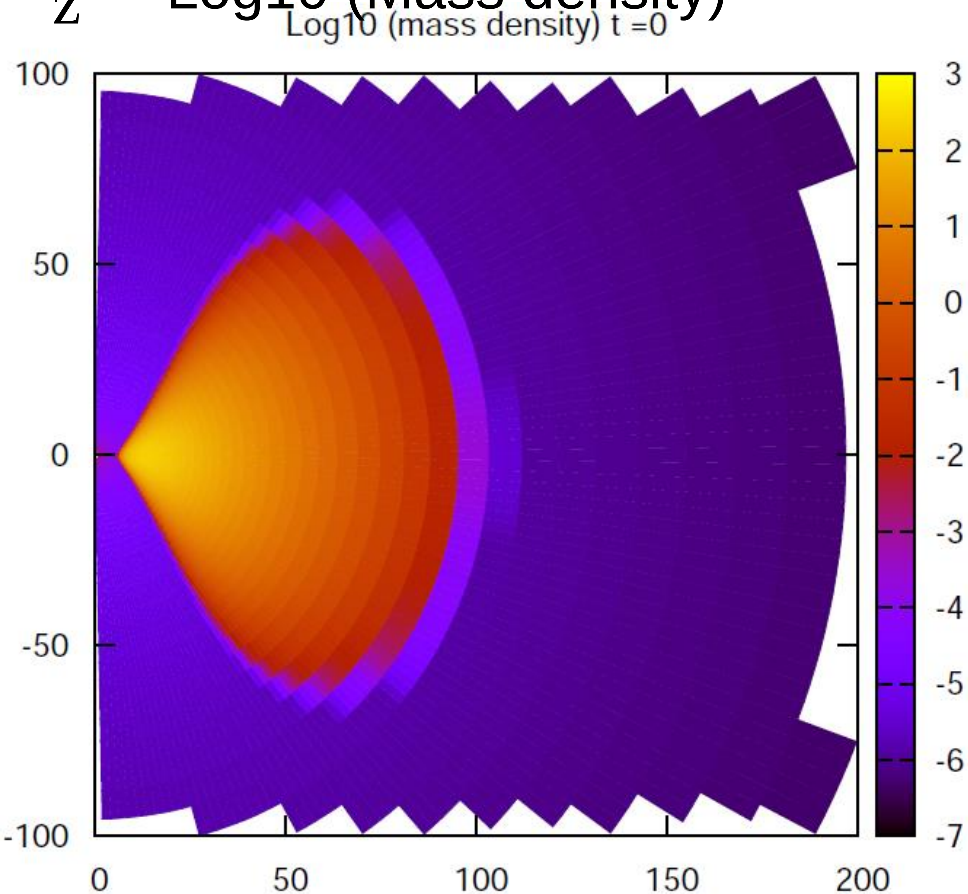
$$b^\mu \equiv \epsilon^{\mu\nu\kappa\lambda}u_\nu F_{\lambda\kappa}/2 \quad B^i = F^{*it}$$

GRMHD code (Nagataki 2009,2011)

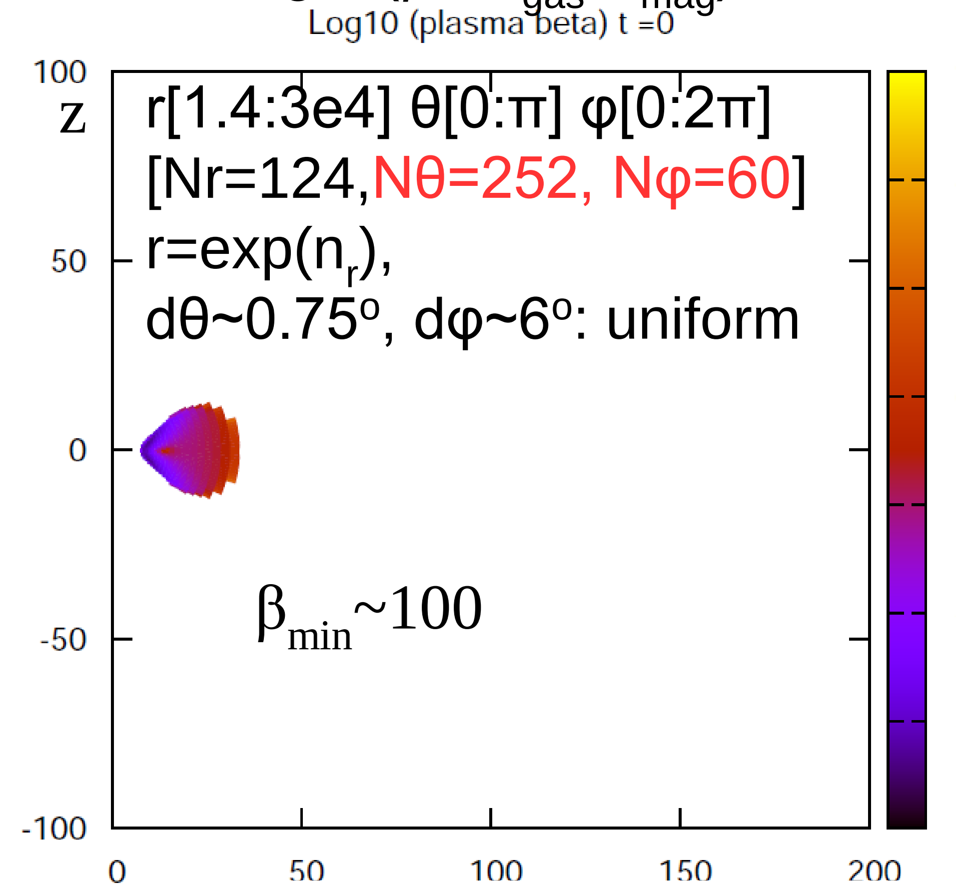
Kerr-Schild metric (no singular at event horizon)
HLL flux, 2nd order in space (van Leer), 2nd or 3rd order in time
See also, Gammie +03, Noble + 2006
Flux-interpolated CT method for divergence free

Initial Condition

Log10 (Mass density)



Log10(β= P_{gas}/P_{mag})



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

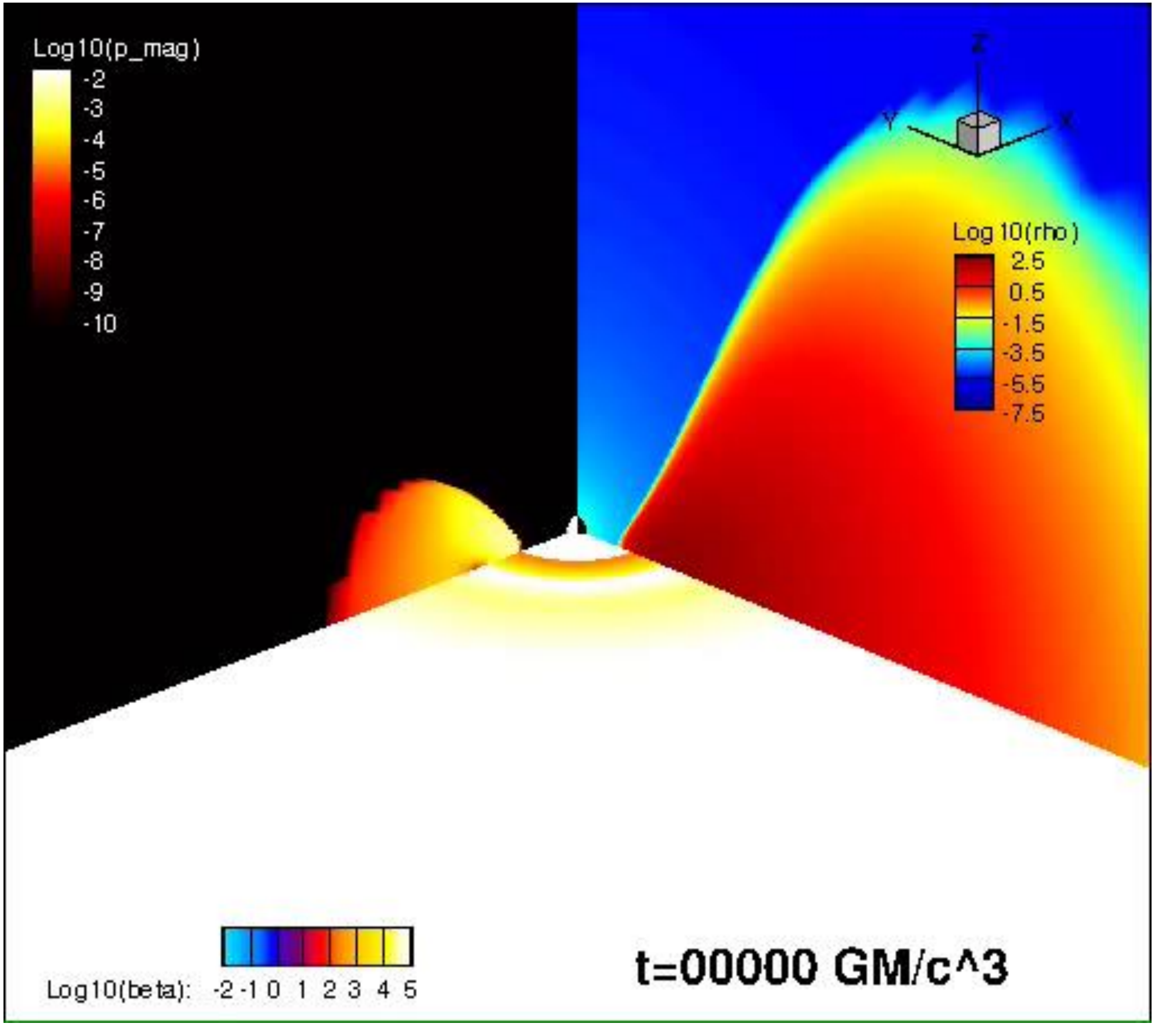
Fisbone-Moncrief (1976) solution – hydrostatic solution of tori around rotating BH (**a=0.9**, rH~1.44), $l_* \equiv -u^t u_\phi$ =const =4.45, r_{in}=6. > r_{ISCO}

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

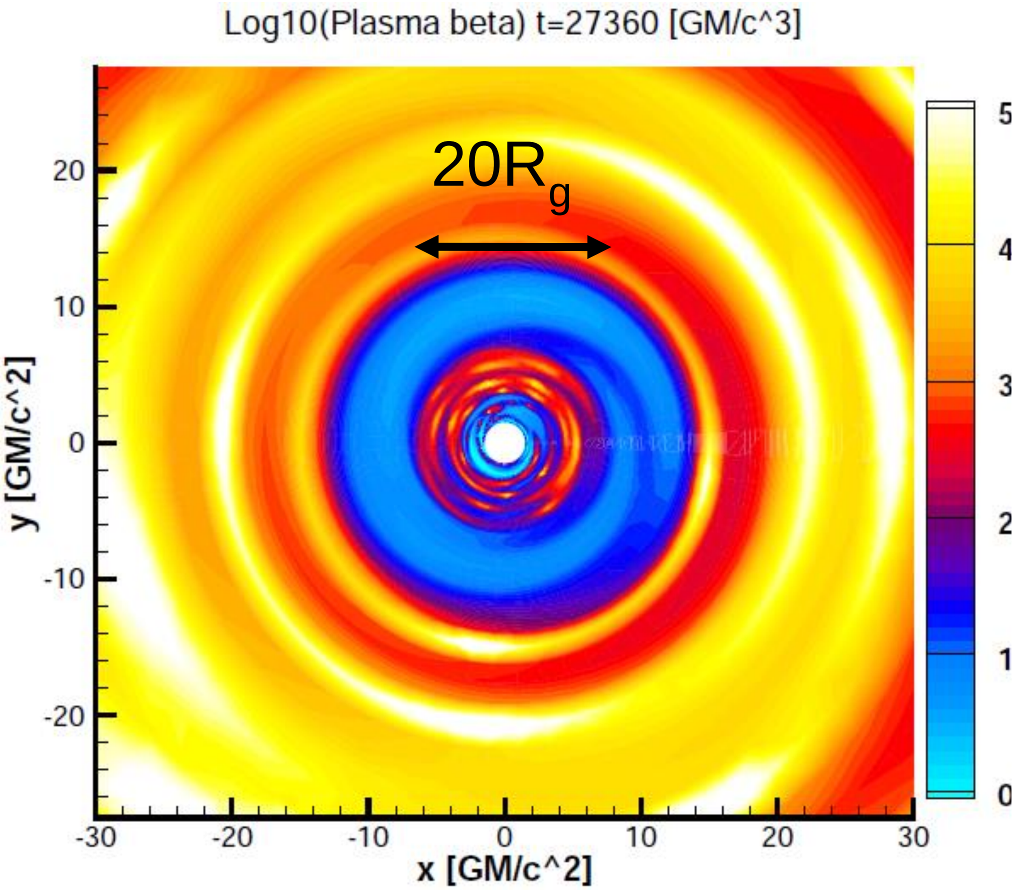
~1.5x10^{13}cm($M_{BH}/10^8 M_{sun}$) ~500s ($M_{BH}/10^8 M_{sun}$)

Magnetized jet launch

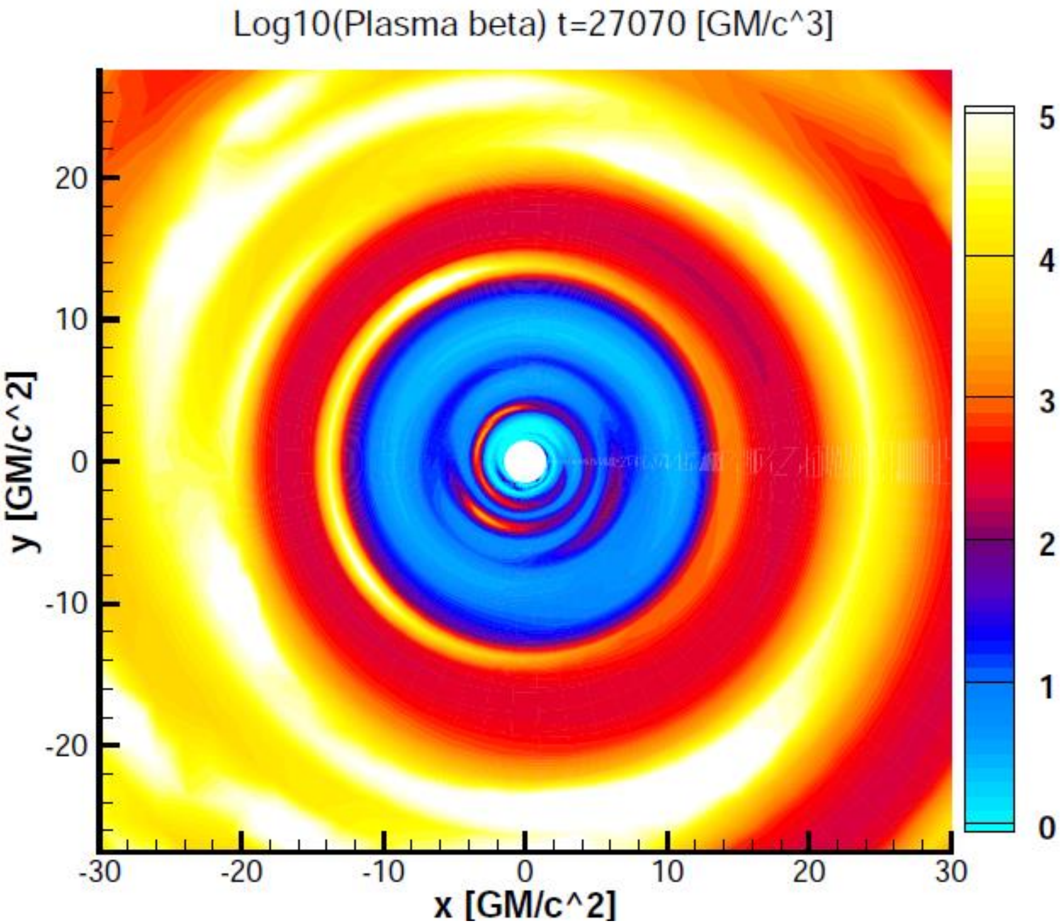


Low mass density and electromagnetic flux along the polar axis. Intermittent

Plasma β (P_{th} /P_{mag})



Plasma β @equator
t=273600



Plasma β @ equator
t=27070

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

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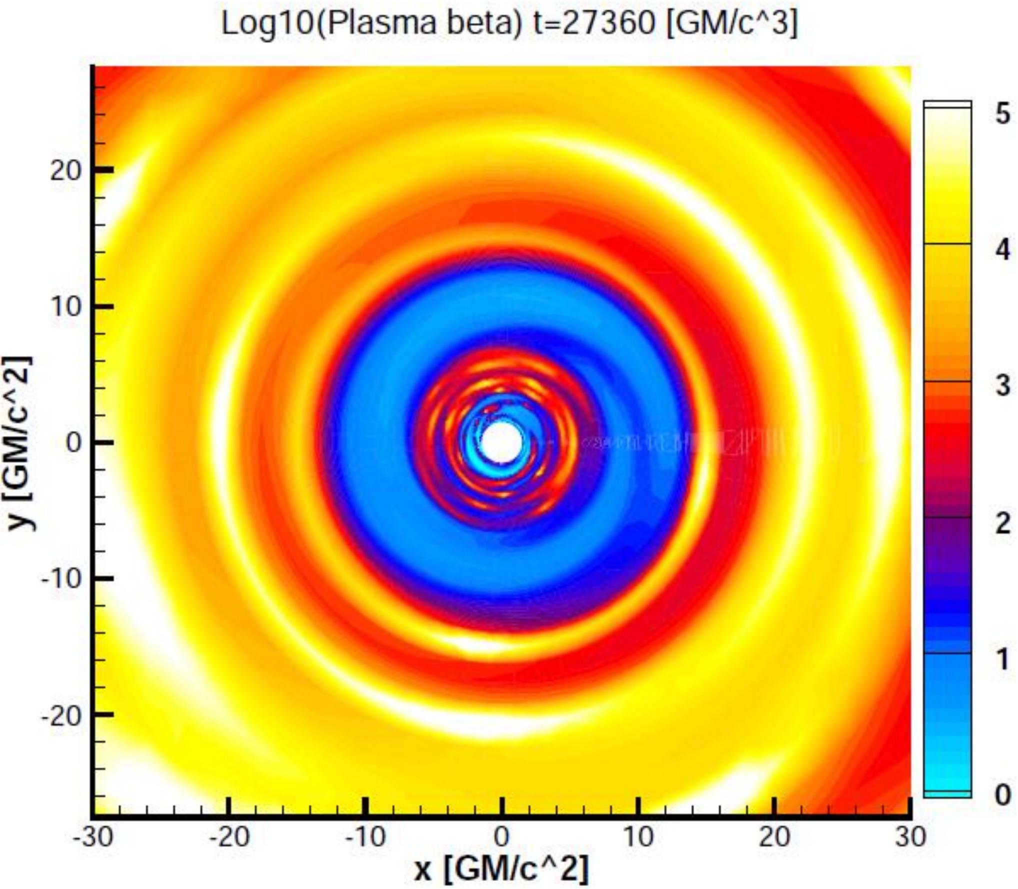
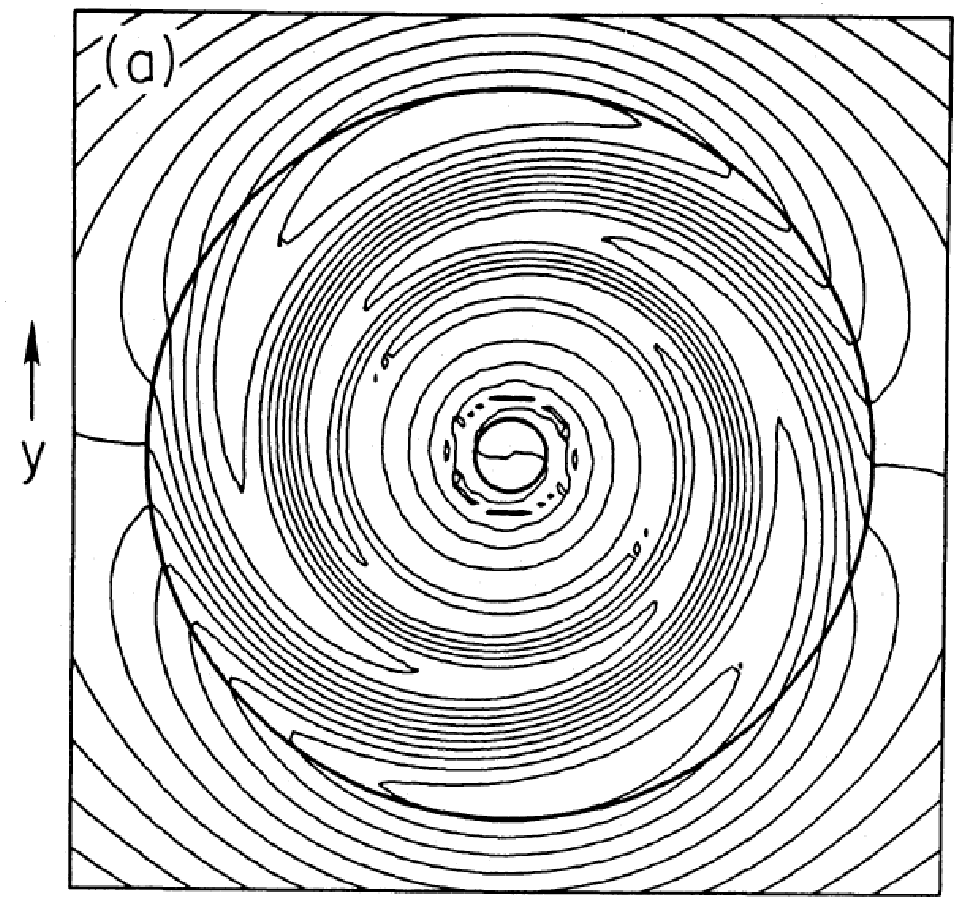
Plasma β (P_{th} /P_{mag})



Plasma β @equator



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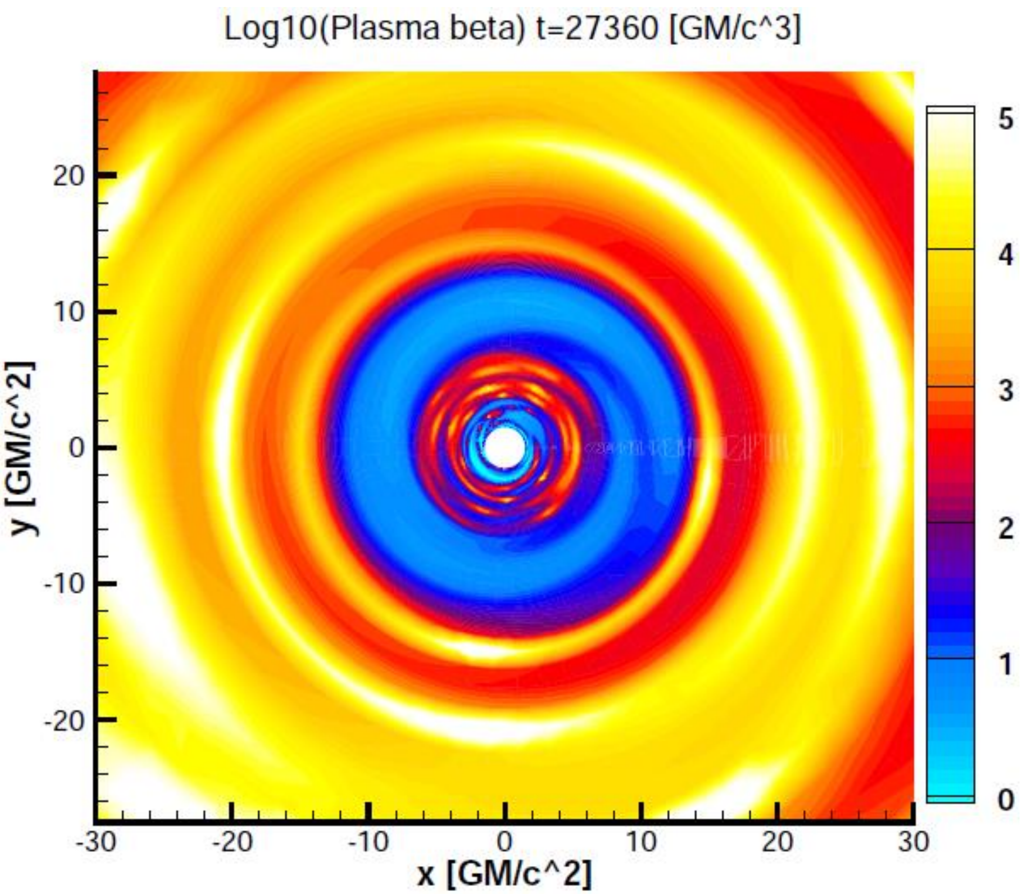
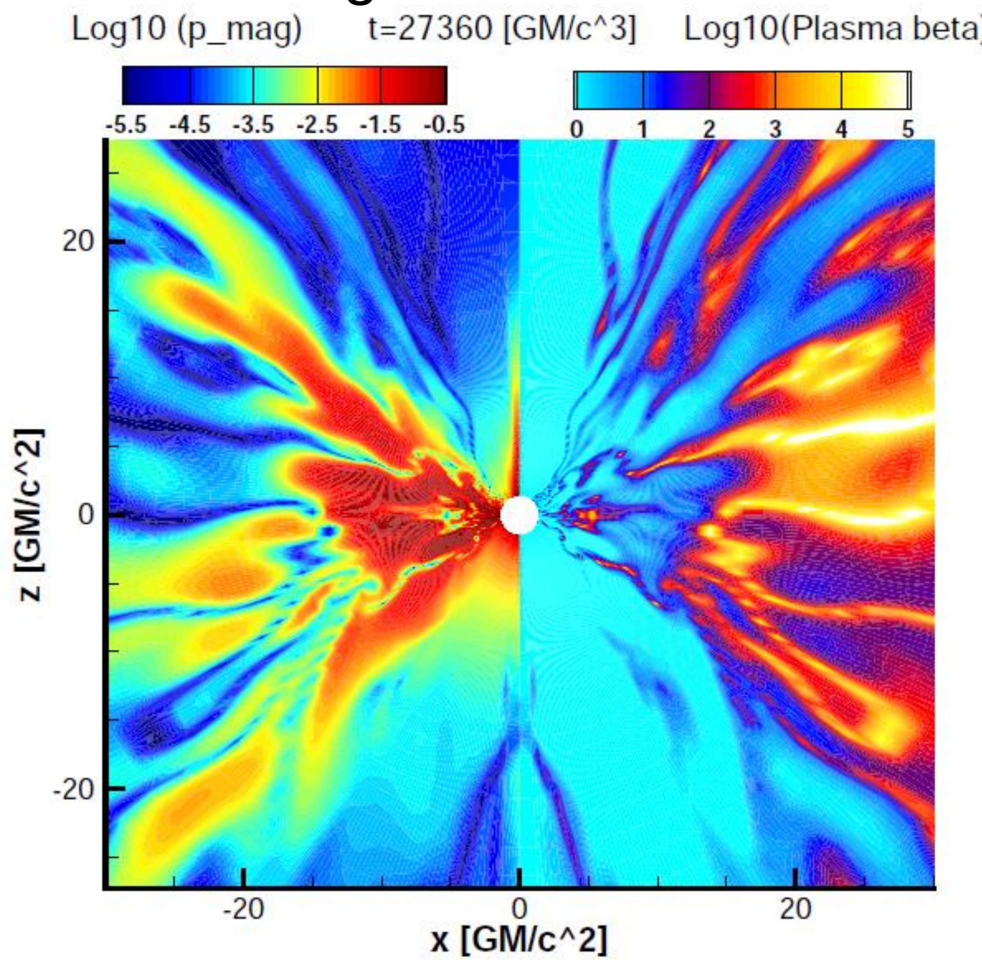


Plasma β @equator



Plasma β (right)
Magnetic pressure (left)

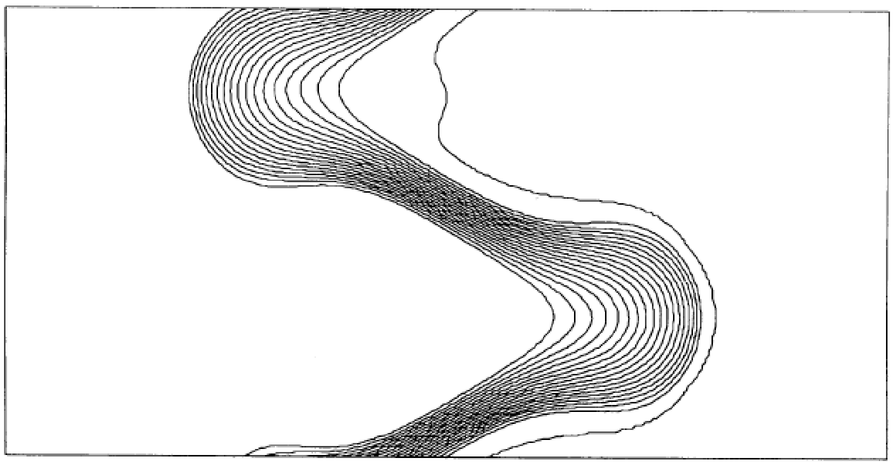
– transitions between low β starte and high beta state
Shibata, Mastumoto, & Tajima (1990) and MHD simulations).

– Highly non-axis symmetric

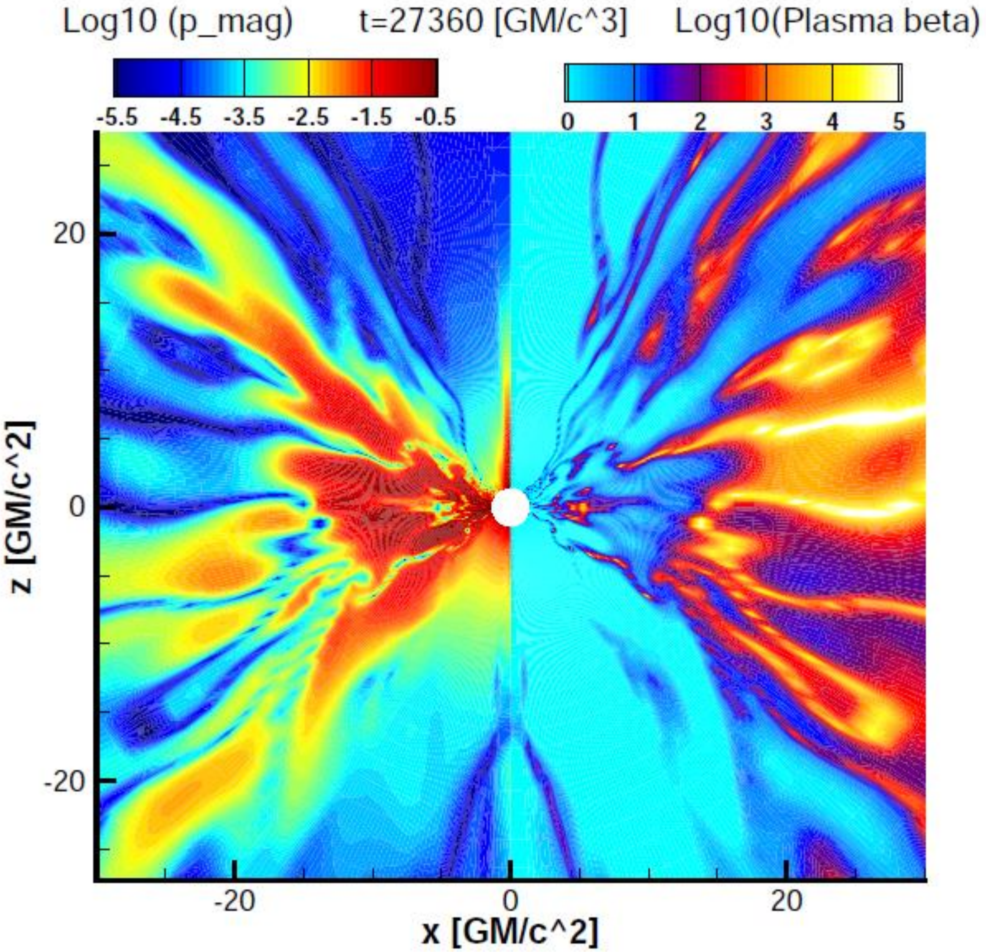
– Filamentaly structure ; thickness ~0.5 Rg

Mizuta + in prep.

Plasma β (P_{th} /P_{mag})



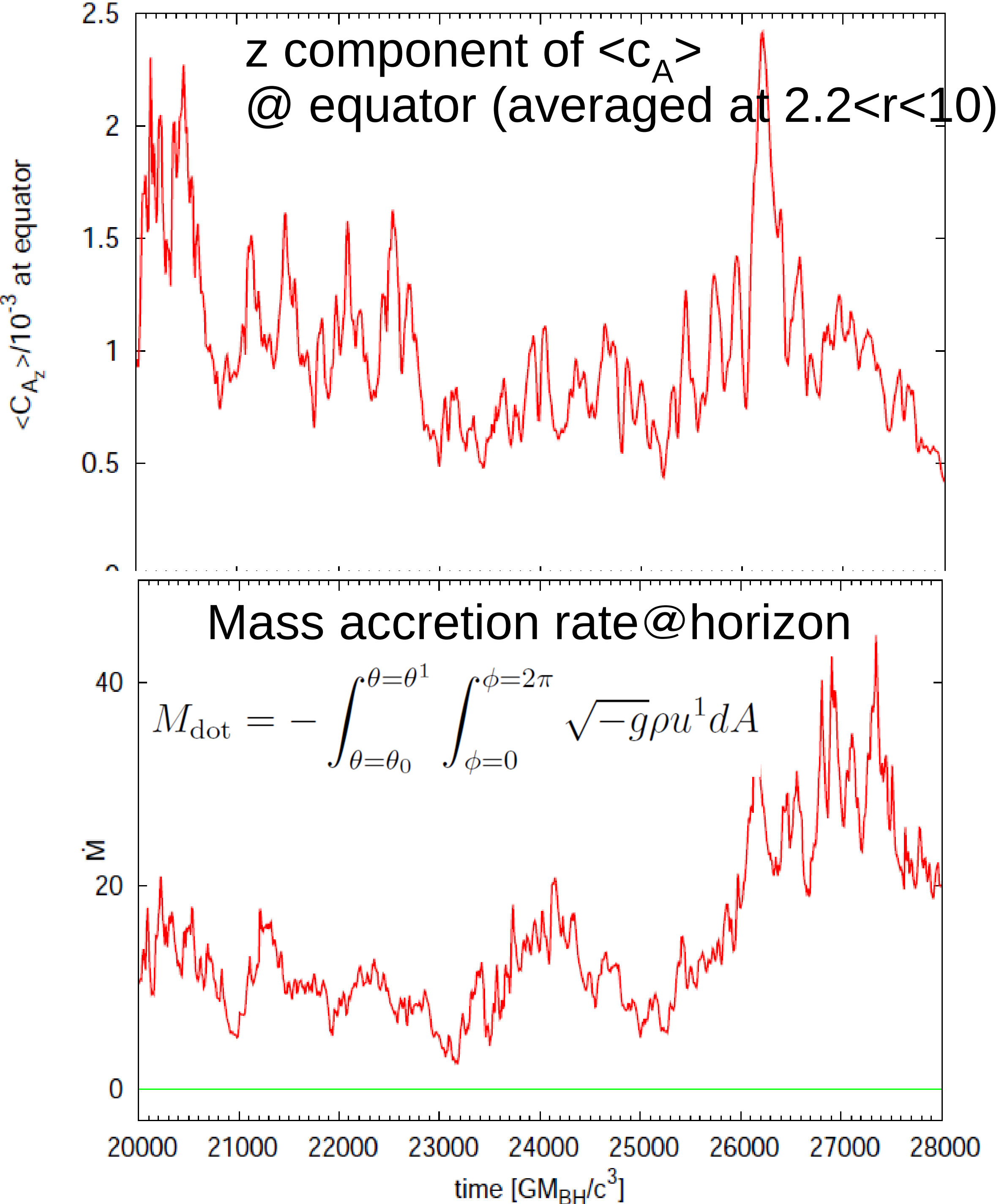
Poloidal B flled lines after growth of MRI
Balbus & Hawley (1991)



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

Mizuta + in prep.

B-filed amplification & mass accretion

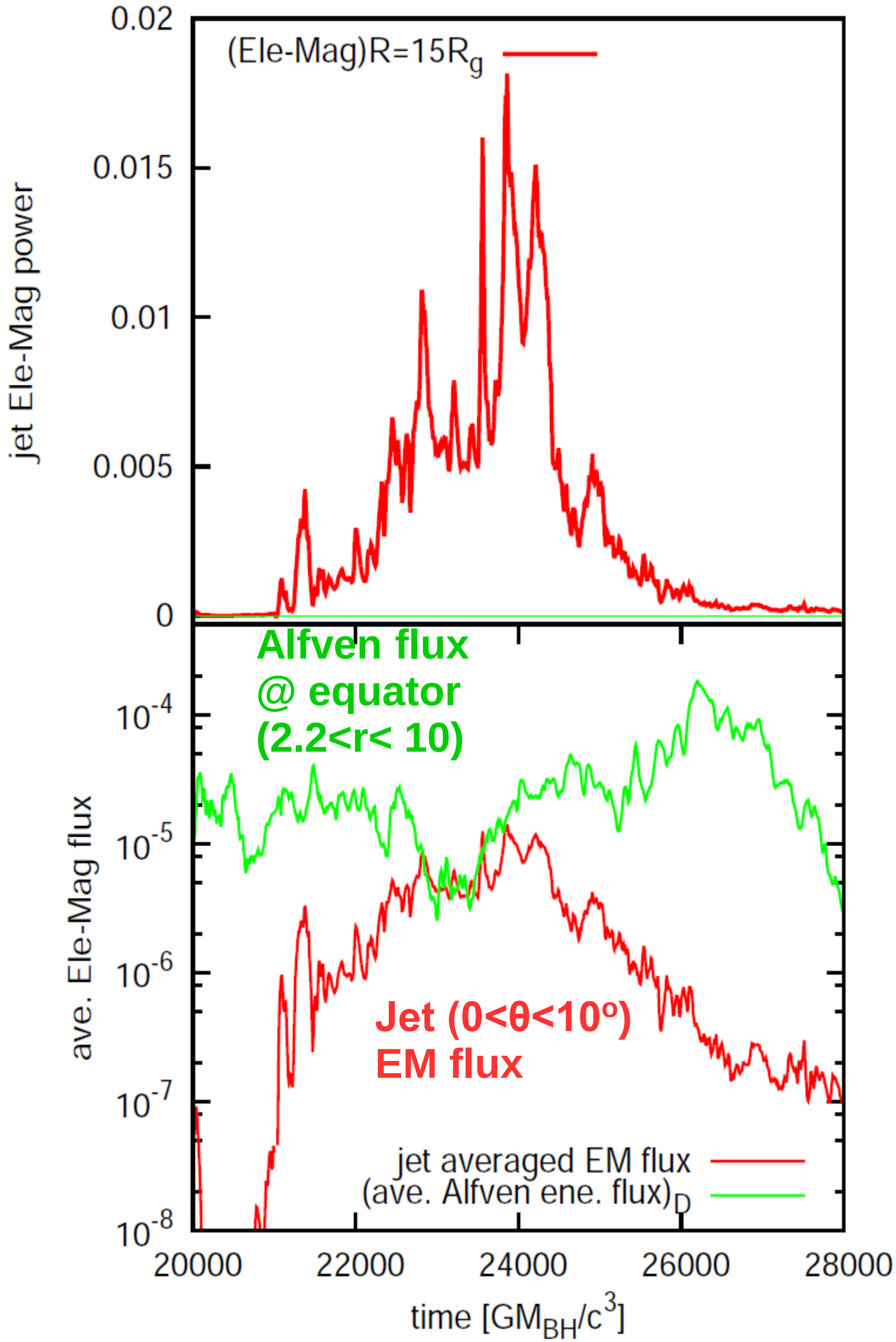


– B-field amplification via MRI λ~0.5Rg ~8 grids size
~filamentaly structure
~ a few tens GM/c^3

– Transitions high β state ⇔ low β state

– Repeat cycle
~A few hundreds GM/c^3
(Stone et al. 1996, Suzuki & Inutsuka 2009, O'Neill et al. 2011)

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



Large Alfven flares in the jet

– Short time variability

– Ele-Mag flux in the jet is comparable to Aflven flux in the disk when Ele-Mag jet is active.

Consistent with Ebisuzaki & Tajima model

Strength parameter a_0

strength parameter a_0 at maximum peak in Alfven flare ;

$$a_0 = \frac{eE}{m_e \omega_A c} = 1.7 \times 10^{12} \left(\frac{M}{10^8 M_\odot} \right)^{1/2} \left(\frac{\dot{M}_{\rm av} c^2}{6 \times 10^{-3} L_{\rm Ed}} \right)^{1/2}$$

Strength parameter highly exceeds unity as estimated
in Ebisuzaki Tajima (2014);

$$a_0 = 2.3 \times 10^{10} (\dot{m}/0.1)^{3/2} (m/10^8)^{1/2}$$

Comparison with Ebisuzaki Tajima model

Ebisuzaki Tajima (2014) | Our numerical simulation

Alfven flux conservation

$$\Phi_{AJ}(= cE \times B/4\pi) = \Phi_{AD}(= V_{AD}B_D^2/4\pi)$$

Consistent @ high Poyting flux flare

Rising timescale of flares

λ_{AD} / V_{AD}=480 GM/c^3

[~50 GM/c^3]

Recurrence rate

$$\nu_A = \eta V_{AD}/Z_D = 1.0 \times 10^2 \eta m^{-1} \text{ Hz},$$

~[2000 GM/c^3]$^{-1}$

[~500 GM/c^3]$^{-1}$

Comparison with Ebisuzaki Tajima model

Ebisuzaki Tajima (2014)

Estimated @ 10 Rs =20 Rg

Alfven flux conservation

$$\Phi_{AJ}(= cE \times B/4\pi) = \Phi_{AD}(= V_{AD}B_D^2/4\pi)$$

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λ_{AD} / V_{AD}=480 GM/c^3

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$$\nu_A = \eta V_{AD}/Z_D = 1.0 \times 10^2 \eta m^{-1}\ \mathrm{Hz},$$

~[2000 GM/c^3]$^{-1}$

Our numerical simulation

B amplification is active @ 6 Rg

Consistent @ high Poyting flux flare

[~50 GM/c^3]

[~500 GM/c^3]$^{-1}$

Comparison with Ebisuzaki Tajima model

Ebisuzaki Tajima (2014)

Estimated @ 10 Rs =20 Rg

Alfven flux conservation

$$\Phi_{\mathrm{AJ}}(=cE\times B/4\pi)=\Phi_{\mathrm{AD}}(=V_{\mathrm{AD}}B_{\mathrm{D}}^{2}/4\pi)$$

Rising timescale of flares

λ_{AD} / V_{AD}=480 GM/c^3

==> 82 GM/c^3

Recurrence rate

$$\nu_{\mathrm{A}}=\eta V_{\mathrm{AD}}/Z_{D}=1.0\times10^{2}\eta m^{-1}\ \mathrm{Hz},$$

~[2000 GM/c^3]$^{-1}$

==>[316 GM/c^3]$^{-1}$

Our numerical simulation

B amplification is active @ 6 Rg

Consistent @ high Poyting flux flare

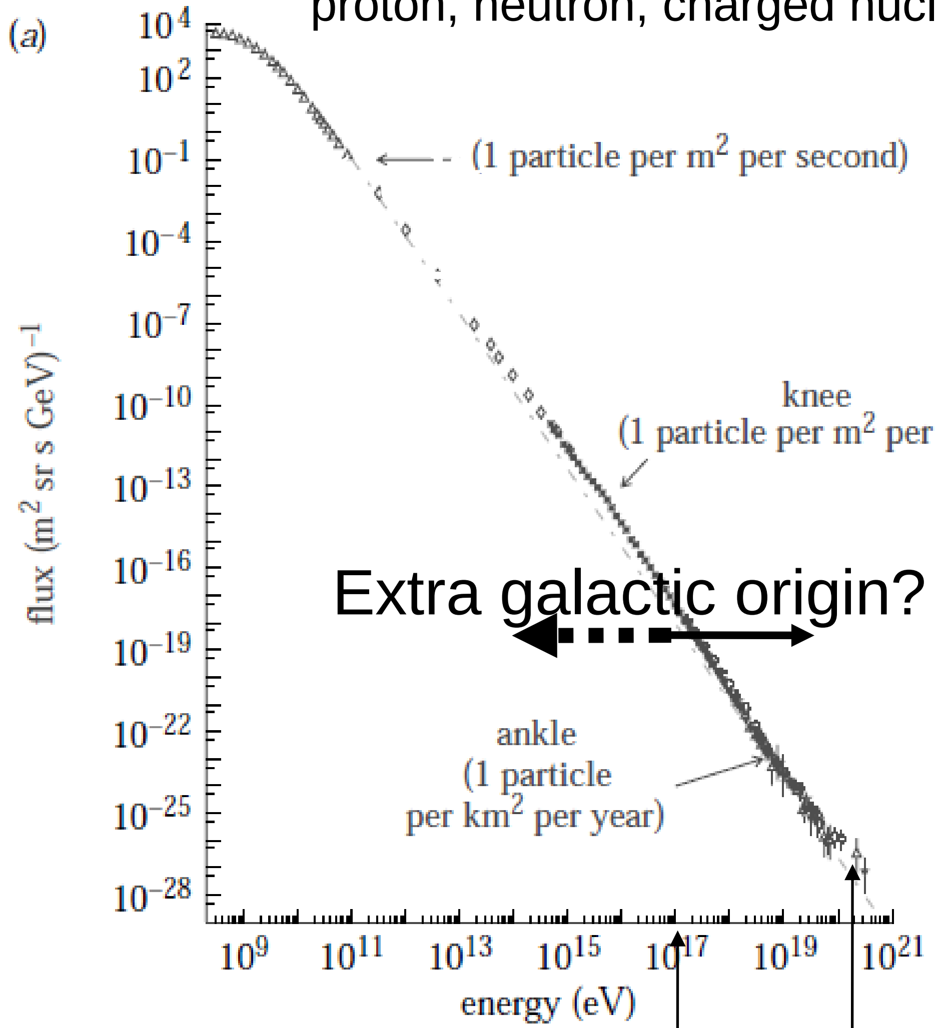
[~50 GM/c^3]

[~500 GM/c^3]$^{-1}$

Application to UHECR acceleration and blazar flare

Cosmic-ray up to ~10^{20}eV

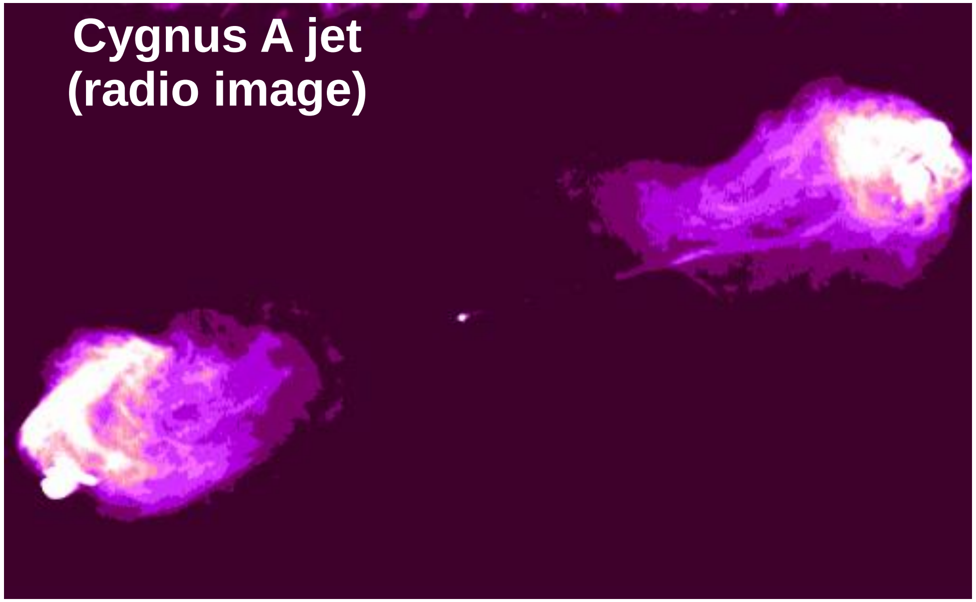
Cosmic-ray- electron, positron, proton, neutron, charged nuclei etc.



GZK cutoff

LHC(14TeV Center-of-mass system)

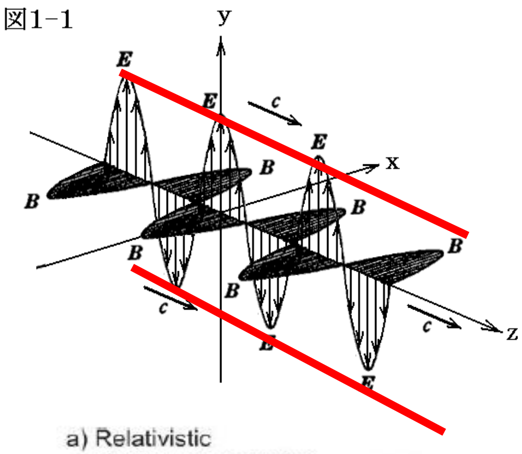
~10^{23}cm



Active galactic nuclei (AGN) jets are one of strong candidate objects for UHECR accelerator.

Wakefield acceleration (Tajima & Dawson PRL 1979)

Acceleration mechnism by interaction between wave and plasma.



Laser plasma interaction
$\Rightarrow$ 8 shape motion.

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

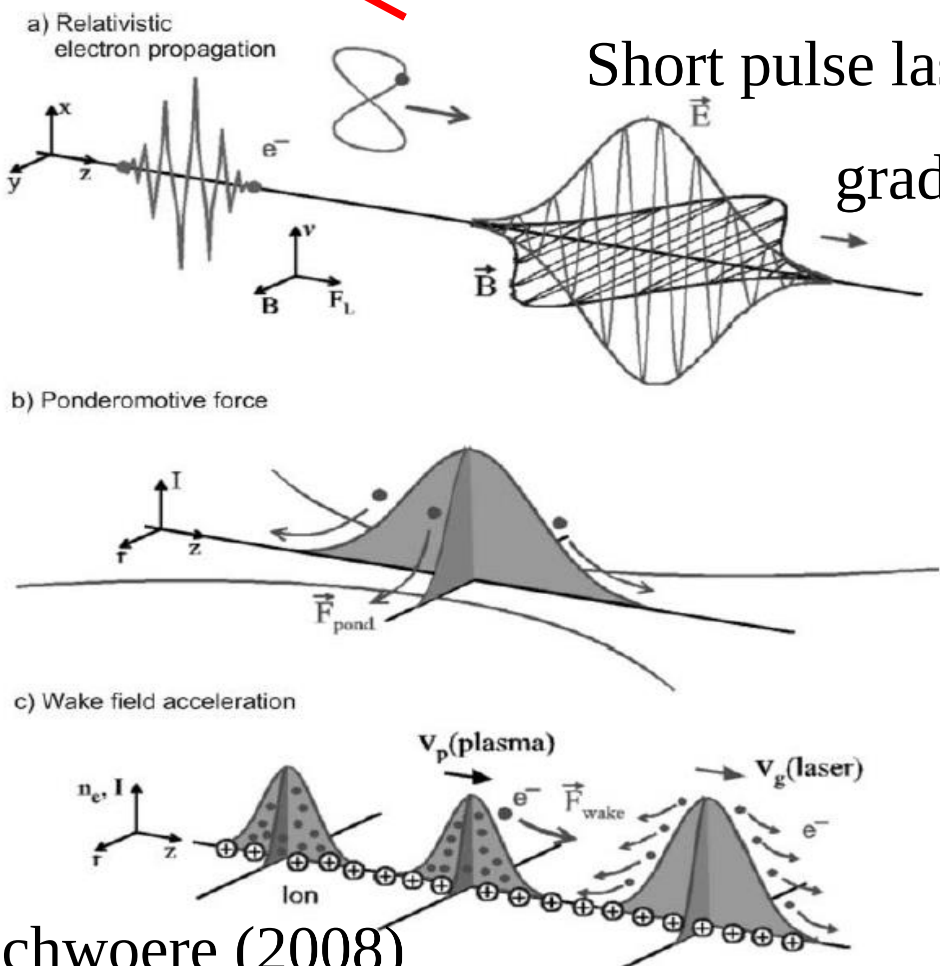
Osillation by Electrifield $\Rightarrow$ **v** **(ossilation up, down)**
vxB force $\Rightarrow$ ossilation forward and backward.
|**v**| ~ c => large amplification motion by **vxB. (8 shape motion).**

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"

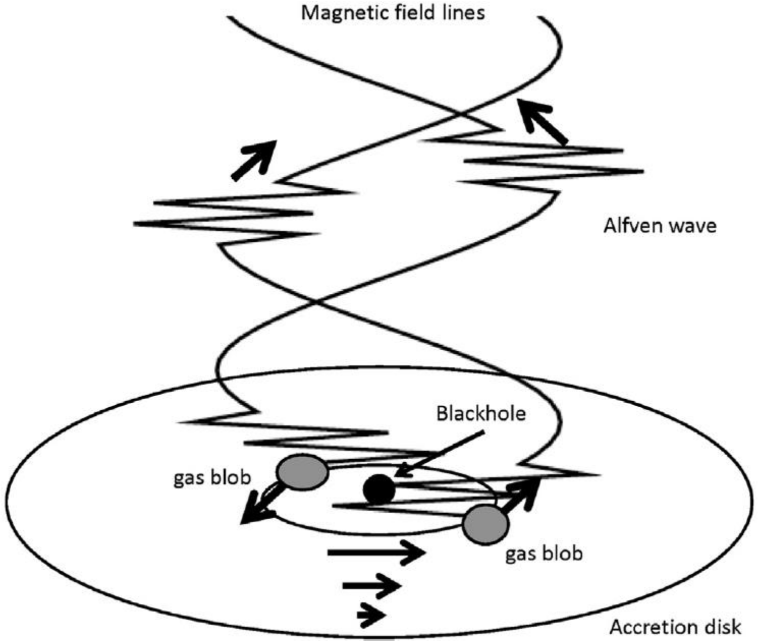
Effective acceleration for I~10^{18}W/cm^2 (relativistic intensity). Experimentally observed.

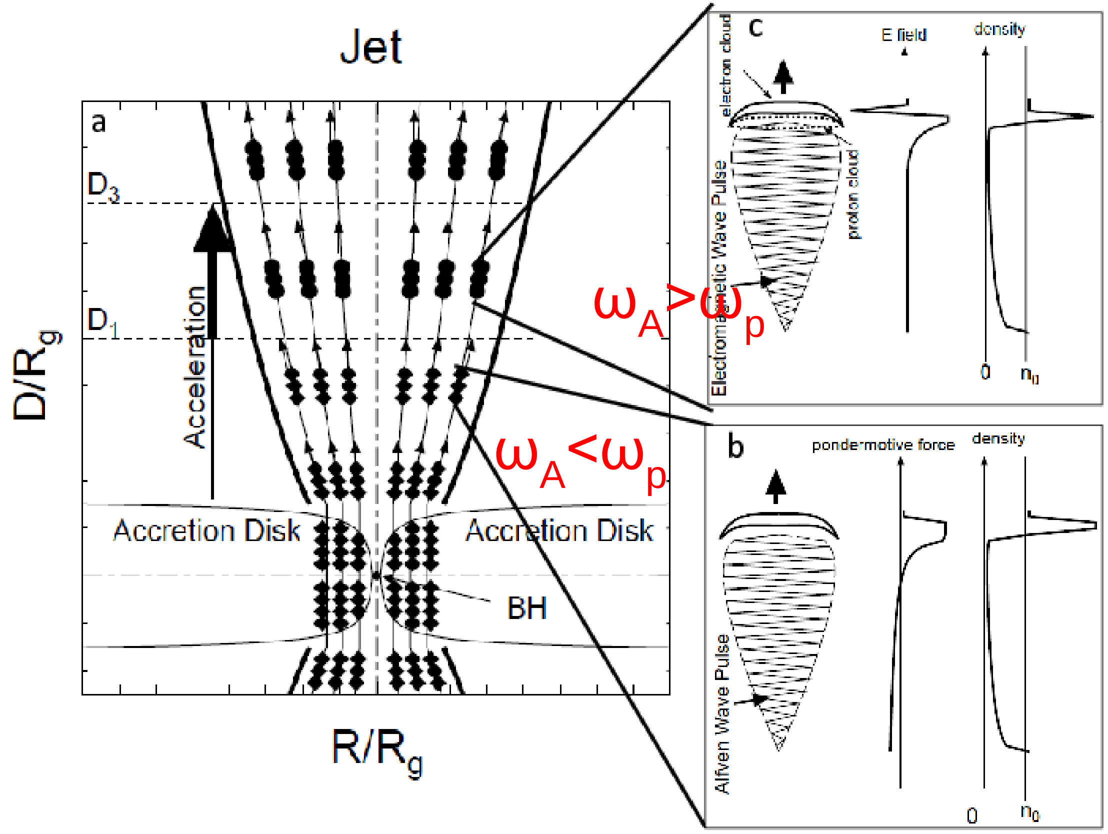


Schwoere (2008)

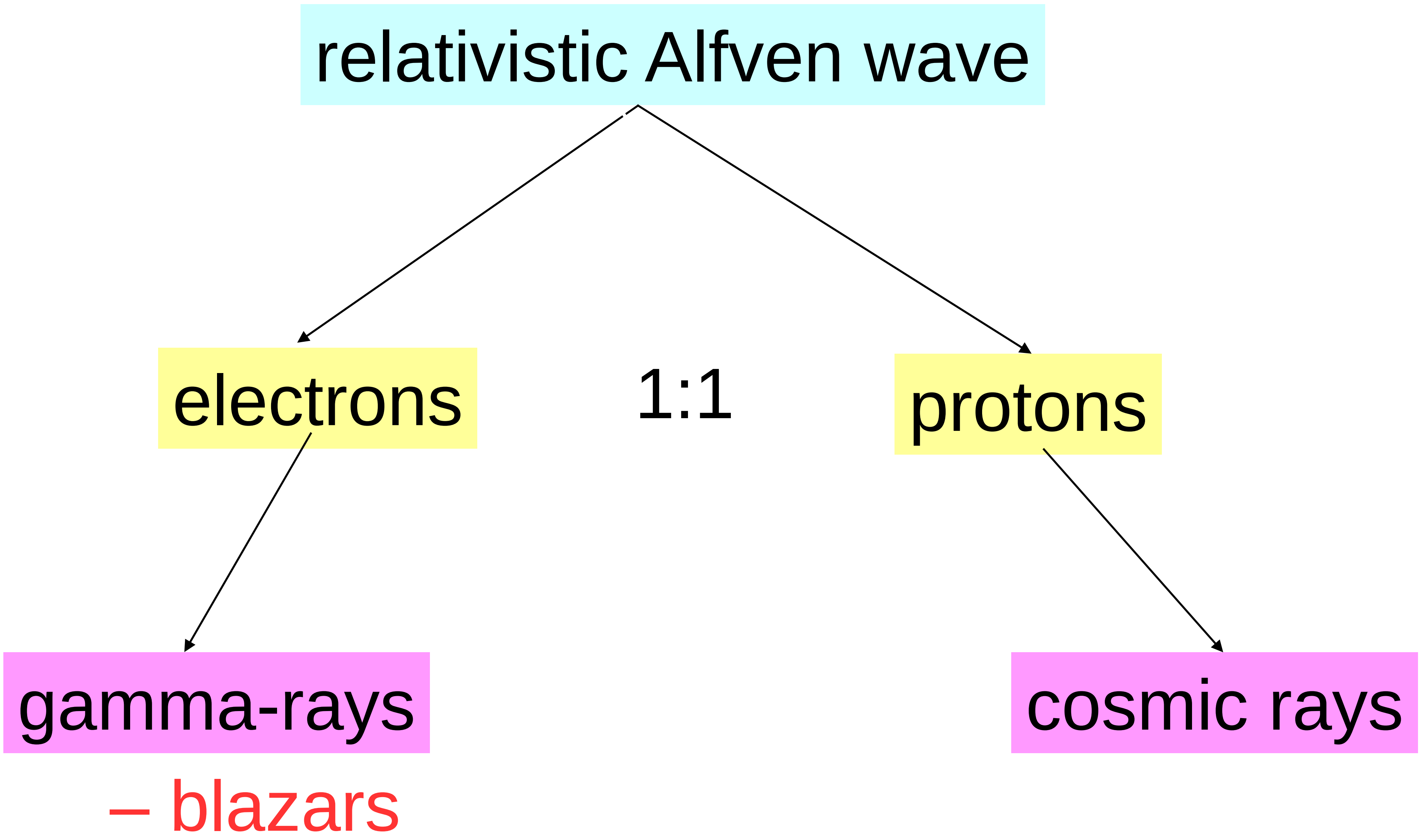
Relativistic Alfven wave can be applied to wakefield acceleration. (Takahashi+2000, Chen+2002, Lyubarusky 2006, Hoshino 2008)

AGN : UHECR accelarator ?

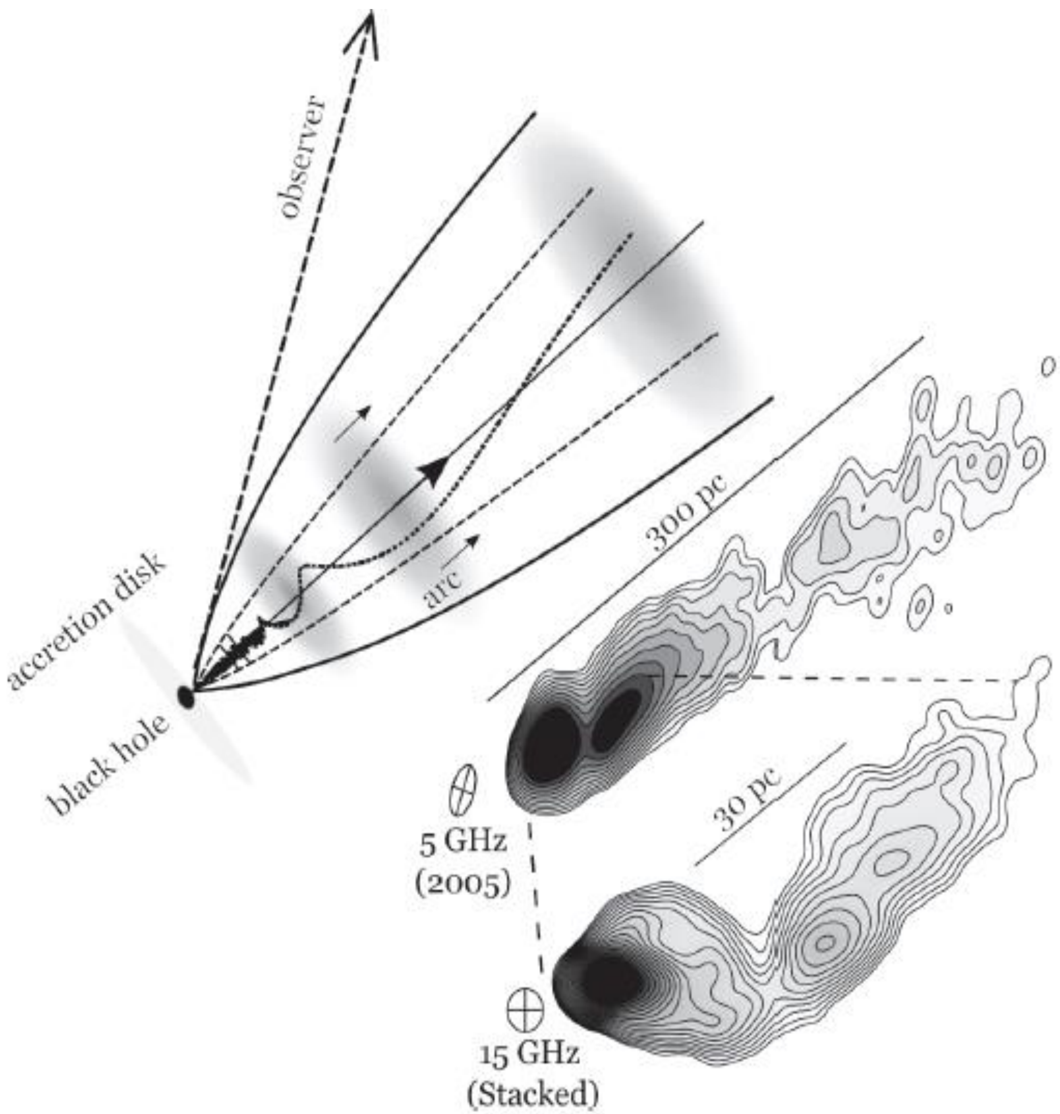




Ebisuzaki & Tajima 2014


relativistic Alfven wave
electrons
1:1
protons
gamma-rays
cosmic rays
– blazars

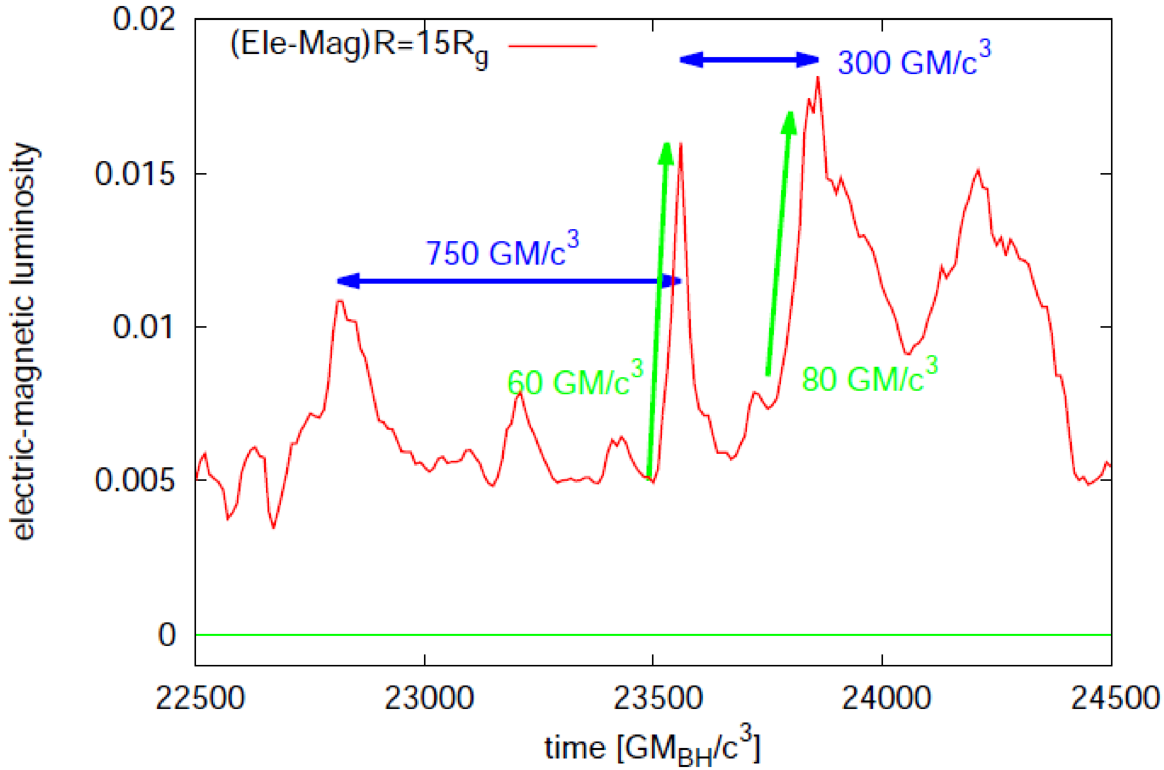
Blazar : 3C454.3



Blazars;
– relativistic jets almost on axis to us
– very blight gamma-ray sources

Zamaninasab+2013
Radio map (VLBA)

Application to blazar gamma-ray flare by Fermi

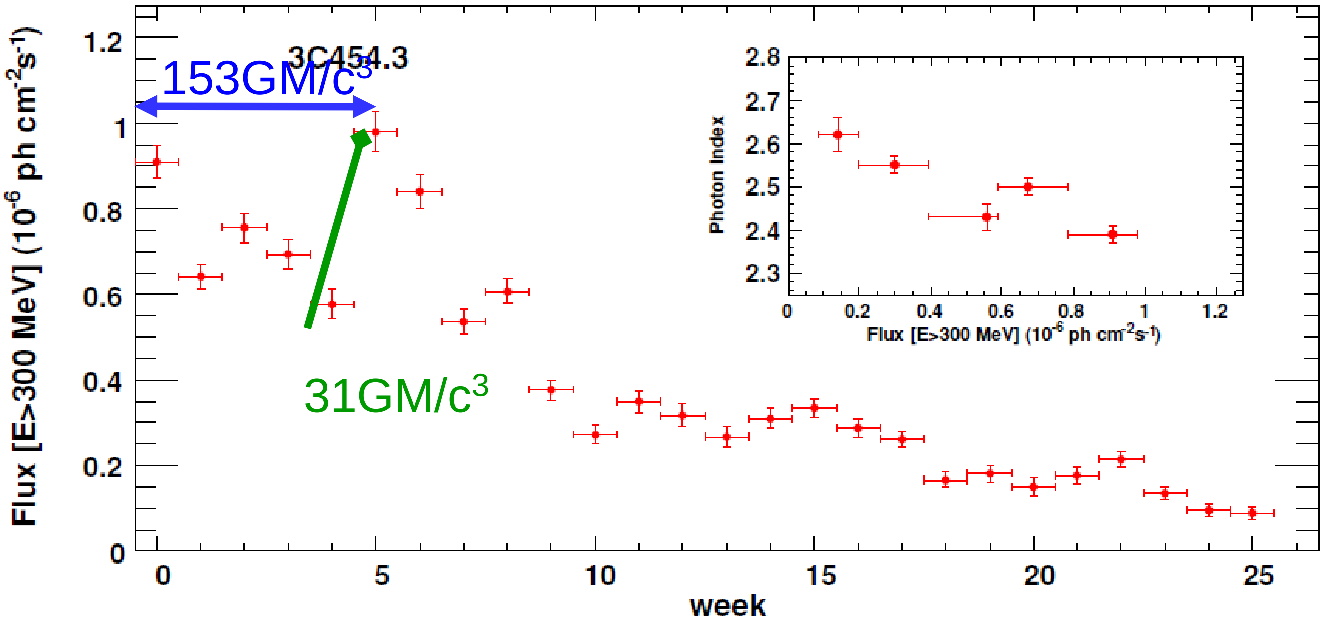


– Strong Alfven waves ($a_0 \gg 1$) in the jet.

– non-thermal electrons

==> blazar flares

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



3C454.3

(M_{BH} ~4x10^{9}M$_{sun}$ Gu +2001

Femi observation

Abdo + ApJ 2010

Summary

3D GRMHD simulations of rotating BH+accretion disk and jet launch

– 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
– Timescales are consistent with Ebisuzaki & Tajima model
– $a_0 \sim 10^{12} >> 1$: strong acceleration
– Timescalses of blazar flares are consistent with our simulation

Future works

– Higher resolution calculations to resolve the fastest MRI mode