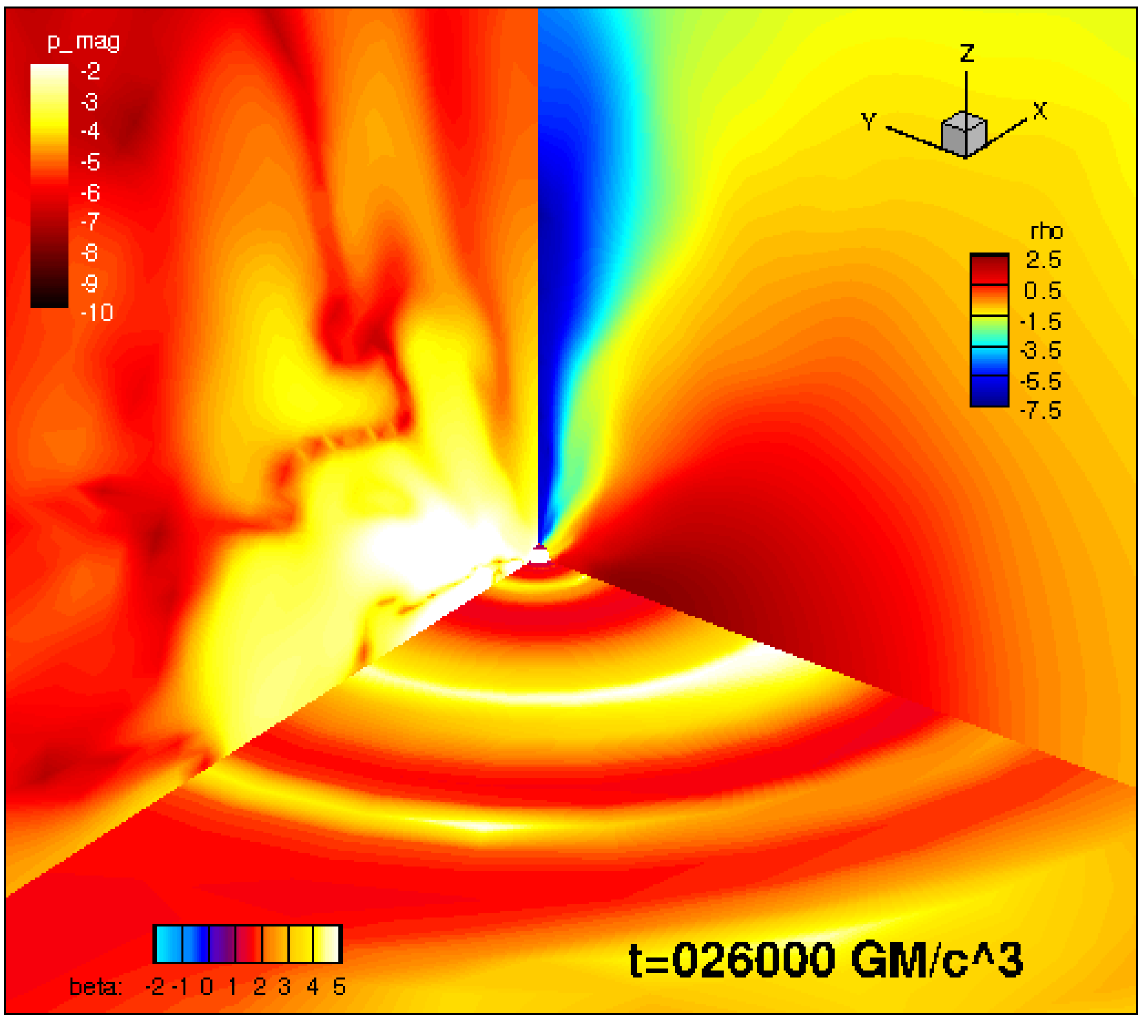
3D GRMHD simulations of accretion flows and relativistic jets – for cosmic ray accelaration



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@NAOJ 16.11.25
Mizuta + in prep.

OUTLINE

- Introduction
  AGN jet

- GRMHD simulations of black hole and accretion disks

- Particle acceleration by wakefield acceleration for ultra high energy cosmic rays (<--> Fermi acceleration model)

- Summary

AGN and AGN Jets are laboratories for….

- Supermassive black hole M~10^6-10^{10} M_sun

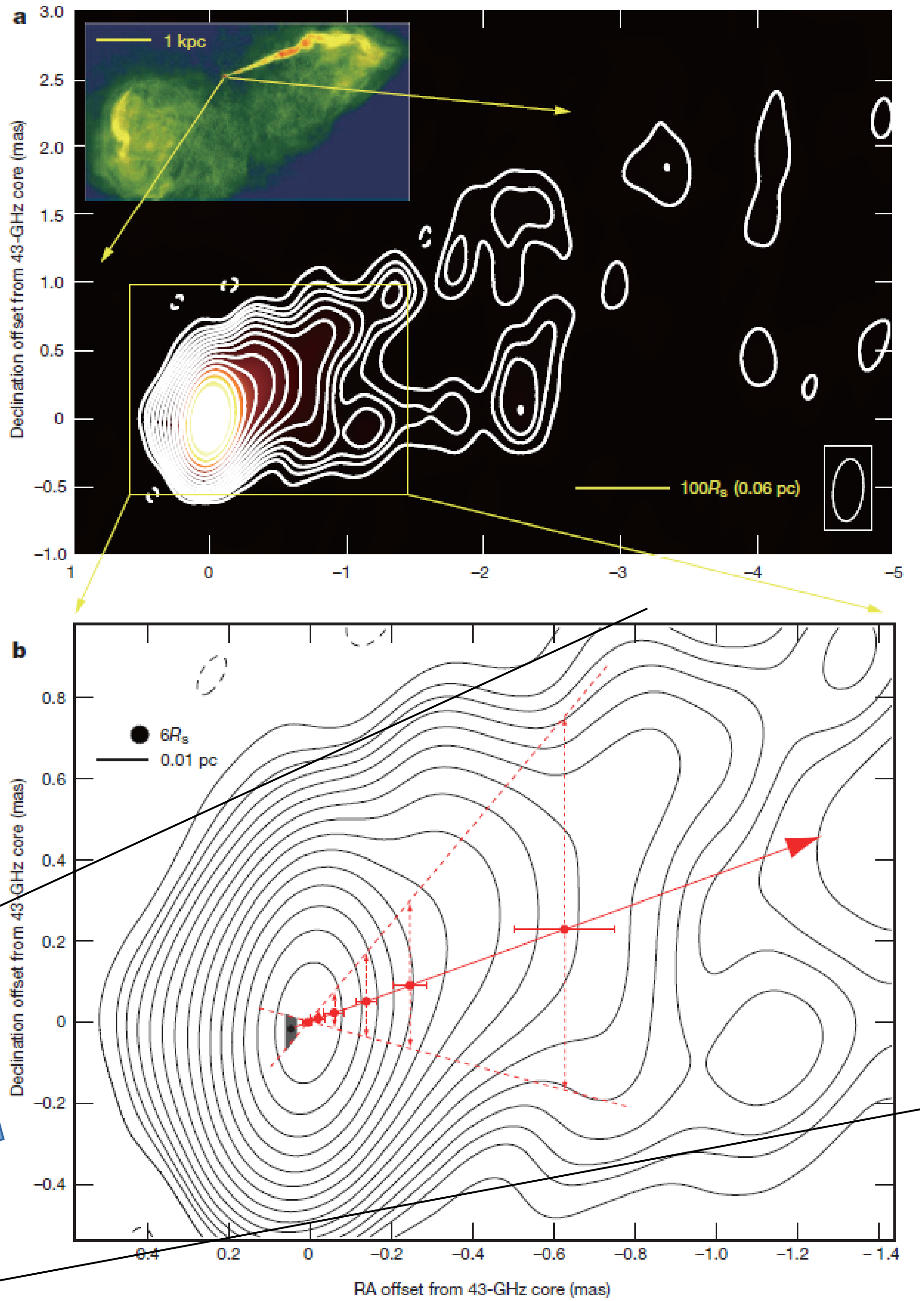
- Accretion disks
  - disk type & geometry (standard disk, ADAF, RIAF etc.)
  - angular momentum transport
    (B-filed amplification (Magnetorotational instability))

- jets
  - how to launch jets
  - how to collimate outflows and how to keep collimation
  - how to accelerate to relativistic bulk velocity (Γ~10)

- high energy astrophysics
  - gamma-ray blazars (on-axis view, multiwavelength
    radio to high energy gamma-ray)
  - candidate object for particle accelerator of ultra-high
    energy cosmic rays

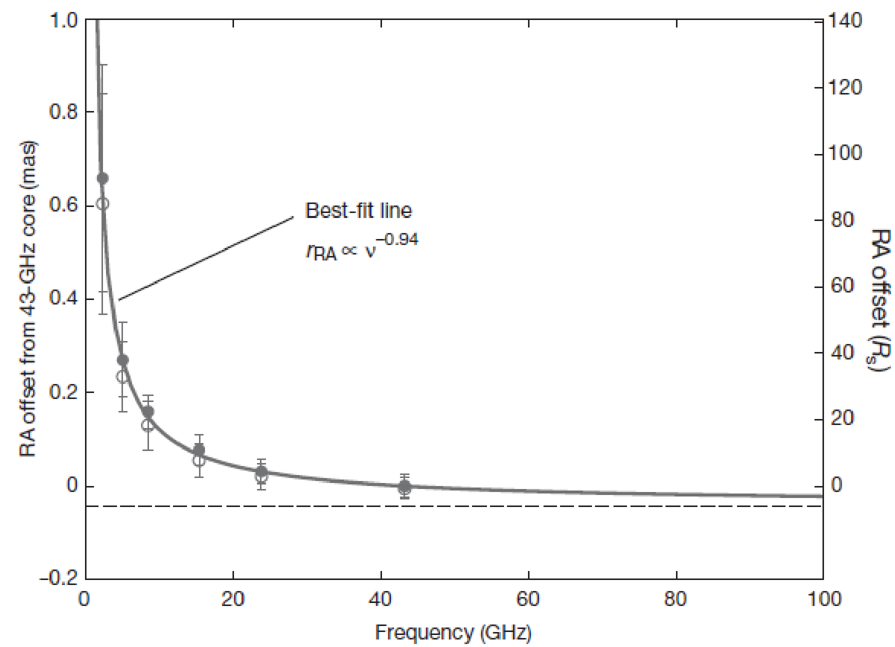
M87 radio observations

- 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

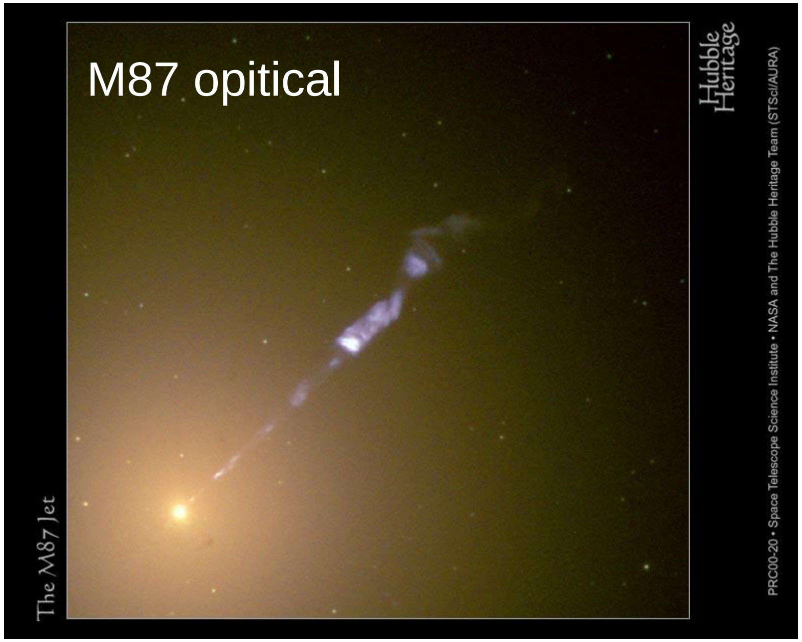


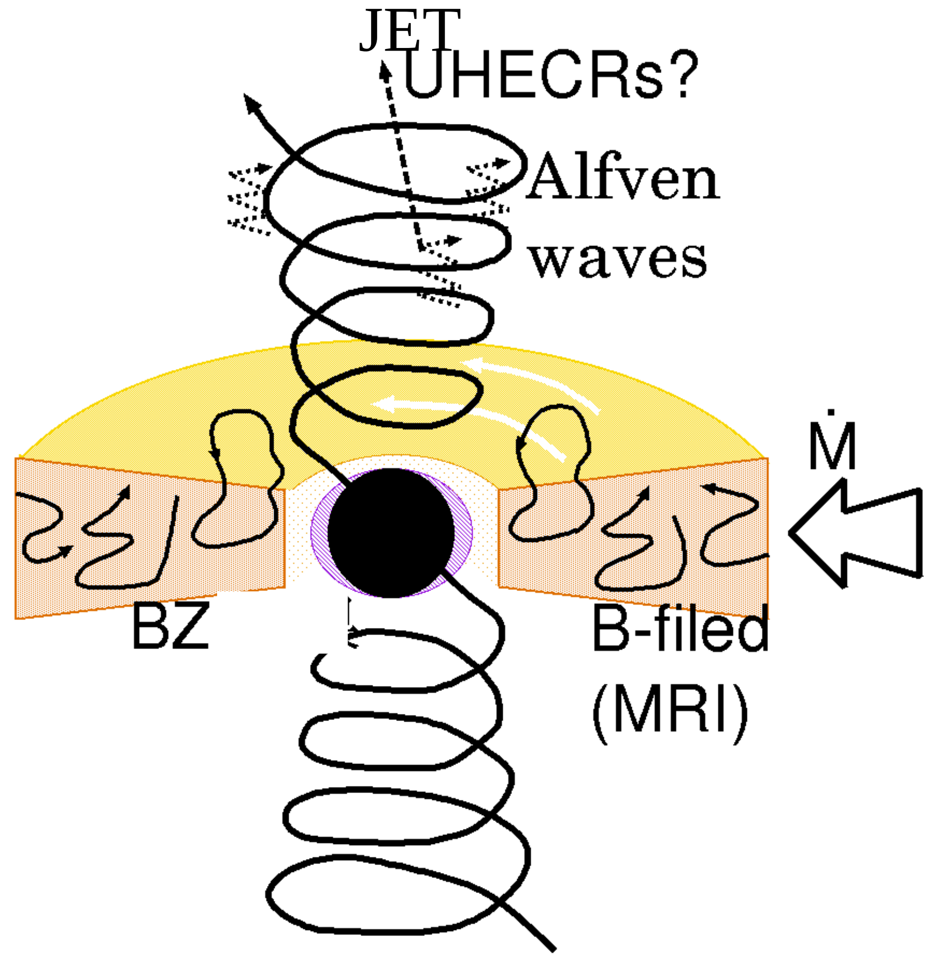
BH ?
No !

M87 radio observation   Hada +(2011)



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, B&P 1982)
    - Blandford-Znajek (general rela. + B filed effect, B&Z 1977)
      - or others ?

GRMHD simulations have been done in 2D & 3D (Koide+2002,McKinney, 2004,2006 Komissarov+2005 2009, Nagataki 2009, Takahashi (2016) etc...

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

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

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

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

GRMHD code (Nagataki 2009,2011)

Kerr-Schild metric (no singular at event horizon)

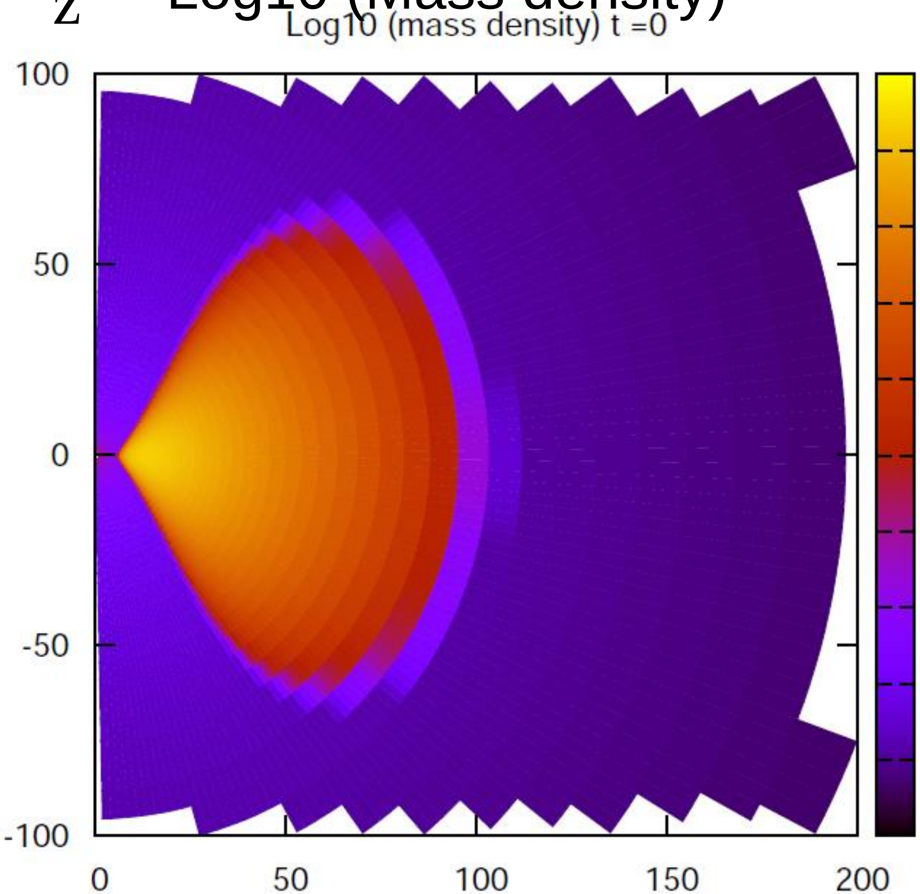
HLL flux, 2nd order in space (van Leer), 2nd or 3rd order in time

See also, Gammie +03, Noble + 2006

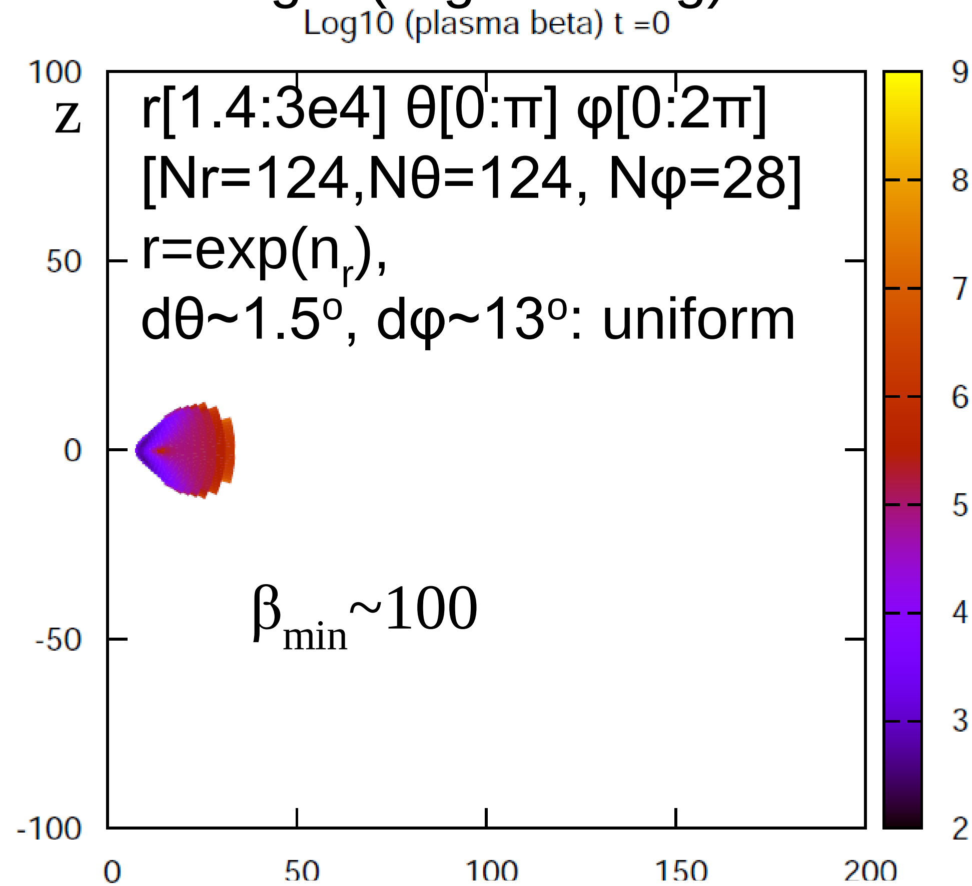
Flux-interpolated CT method for divergence free

Initial Condition

z Log10 (Mass density)



Log10(Pgas/Pmag)



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

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

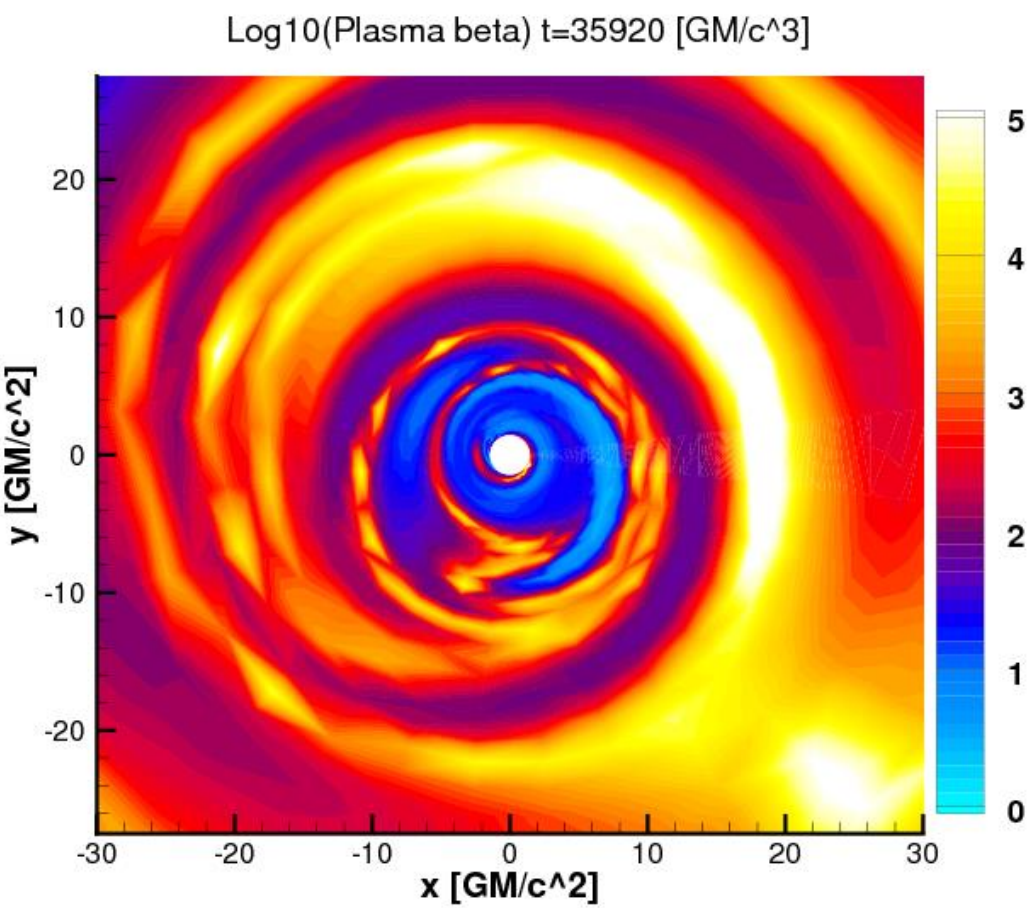
~1.5x10^{13}cm($M_{BH}/10^8 M_{sun}$) ~500s ($M_{BH}/10^8 M_{sun}$)

Magnetized jet launch

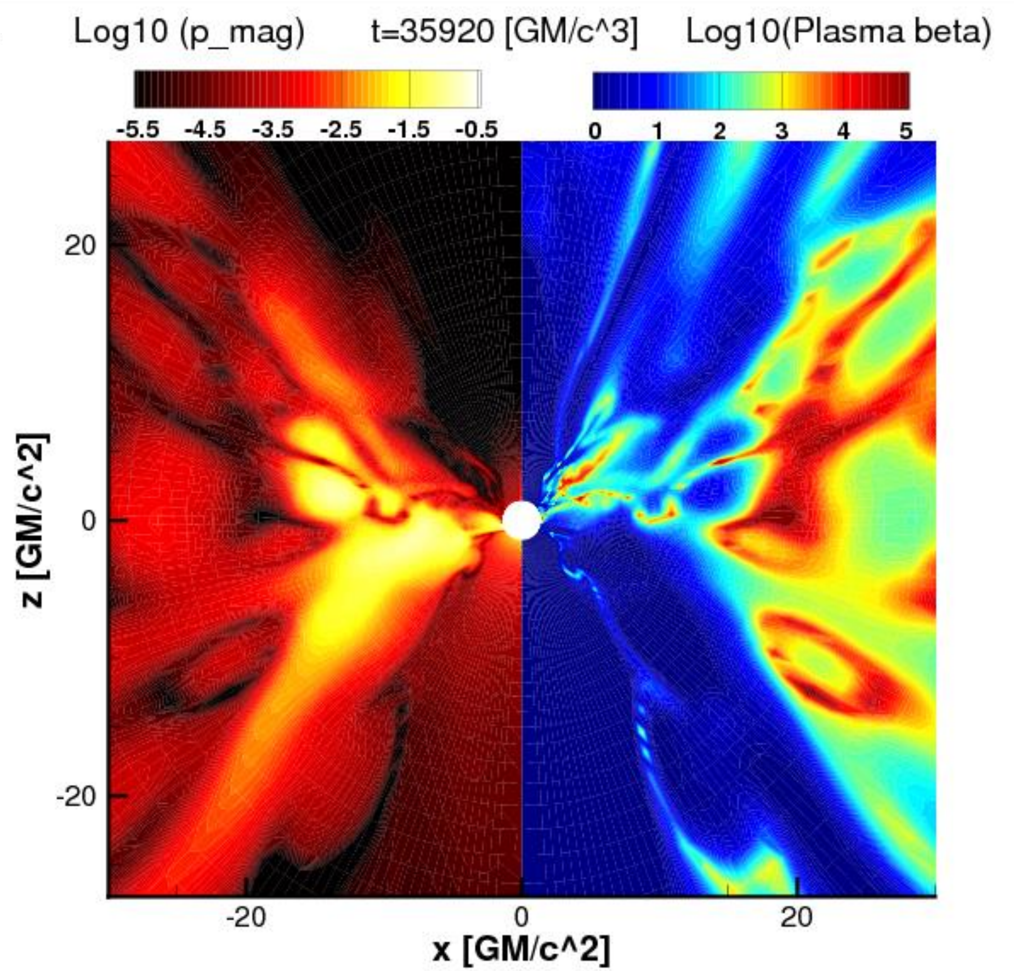
movie

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

Plasma beta(P_{th} /P_{mag}) & magnetic pressure



Plasma beta @equator



Plasma beta (right)
Magnetic pressure (left)

Highly non-axis symmetric mode is excited.
Filamentaly structure inside the disk with thickness ~0.5 Rg

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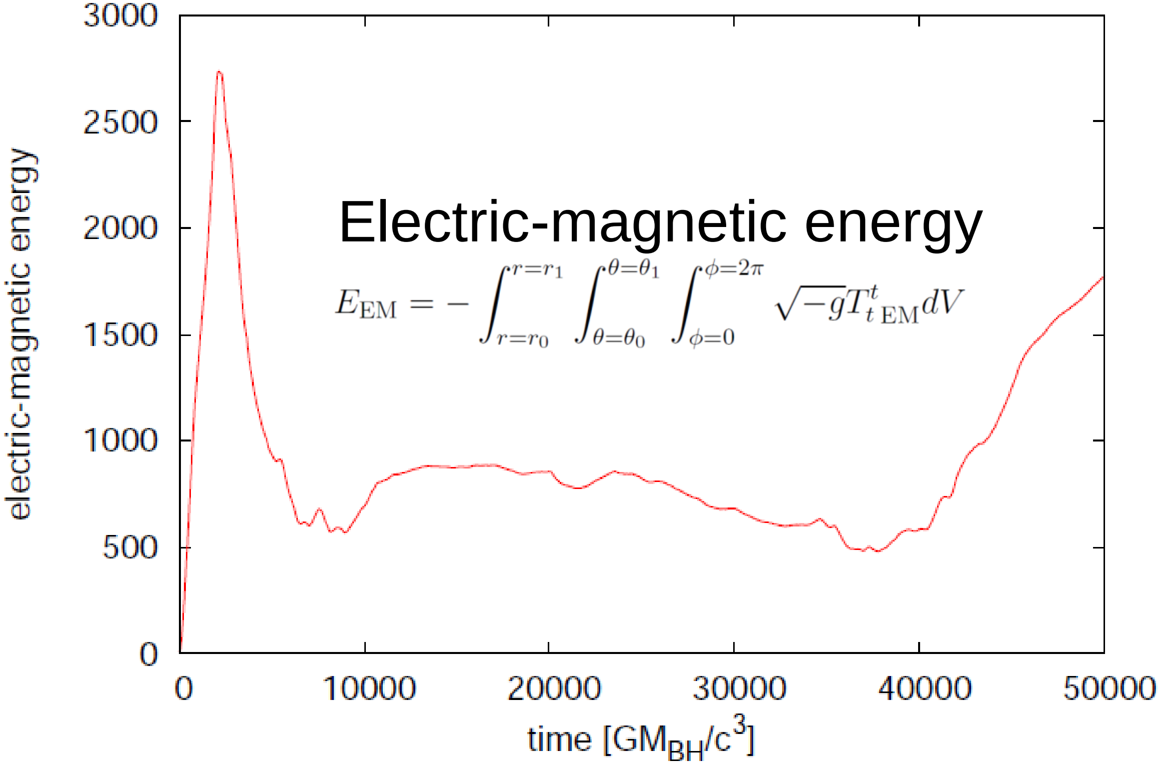
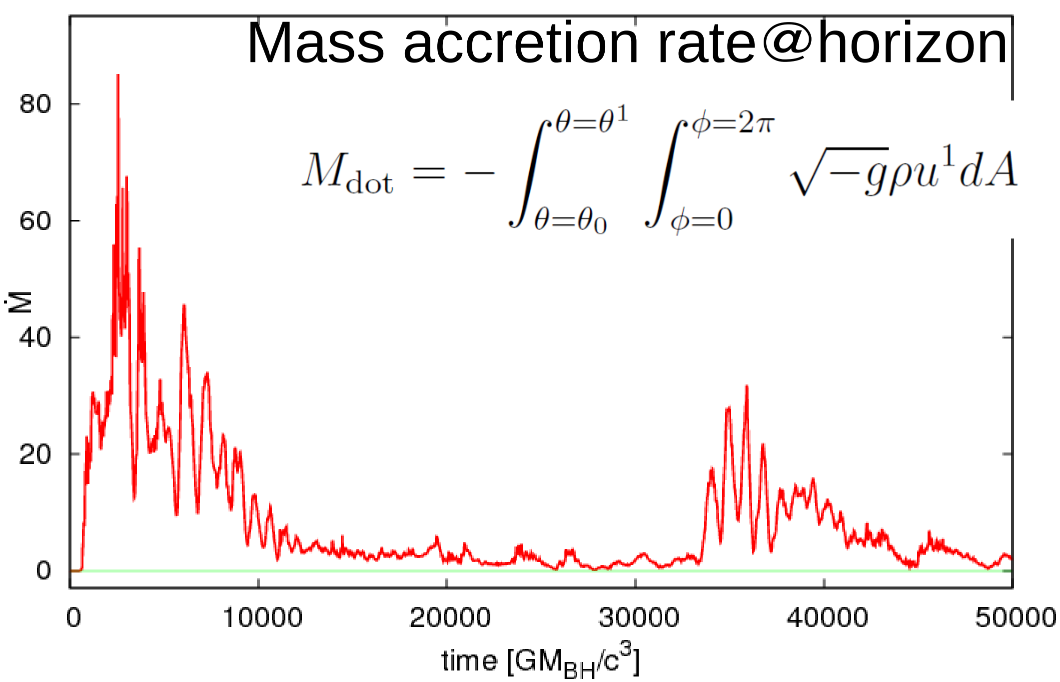




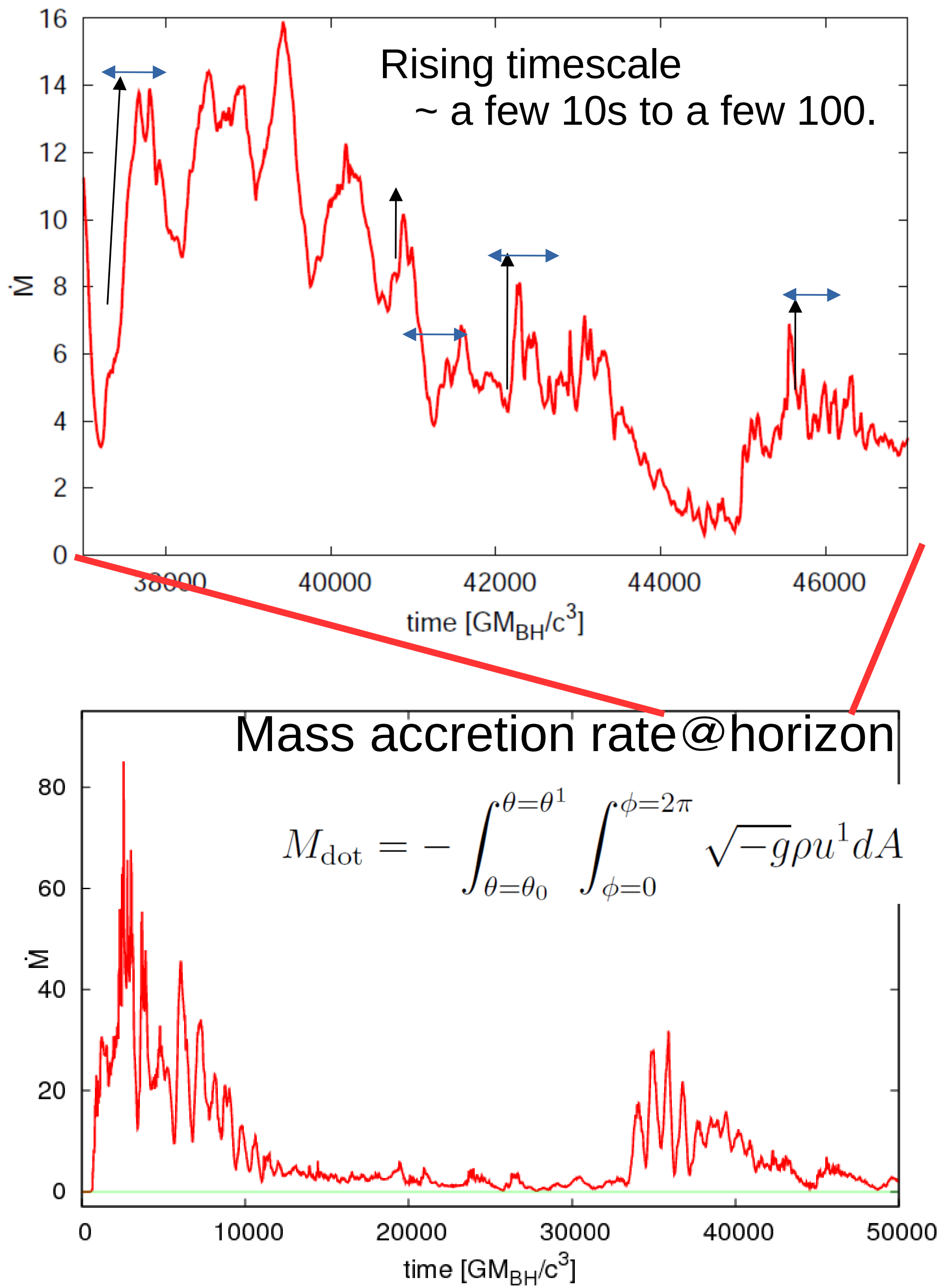
- B-filed is well amplified.

- Mass accretion rate shows short time variability (~ a few tens)
  => consistent with MRI growth rate for λ~0.5Rg ~8 grids size ~filamentaly structure

- Recurrence rate ~ a few hundreds
  => consistent with high resolution local shearing box simulations.
  (high β state ⇔ low β state)

$\tau \sim 10\ \Omega_K \sim 100$ Rg/c

(Stone et al. 1996, Suzuki & Inutsuka 2009, O'Neill et al. 2011)



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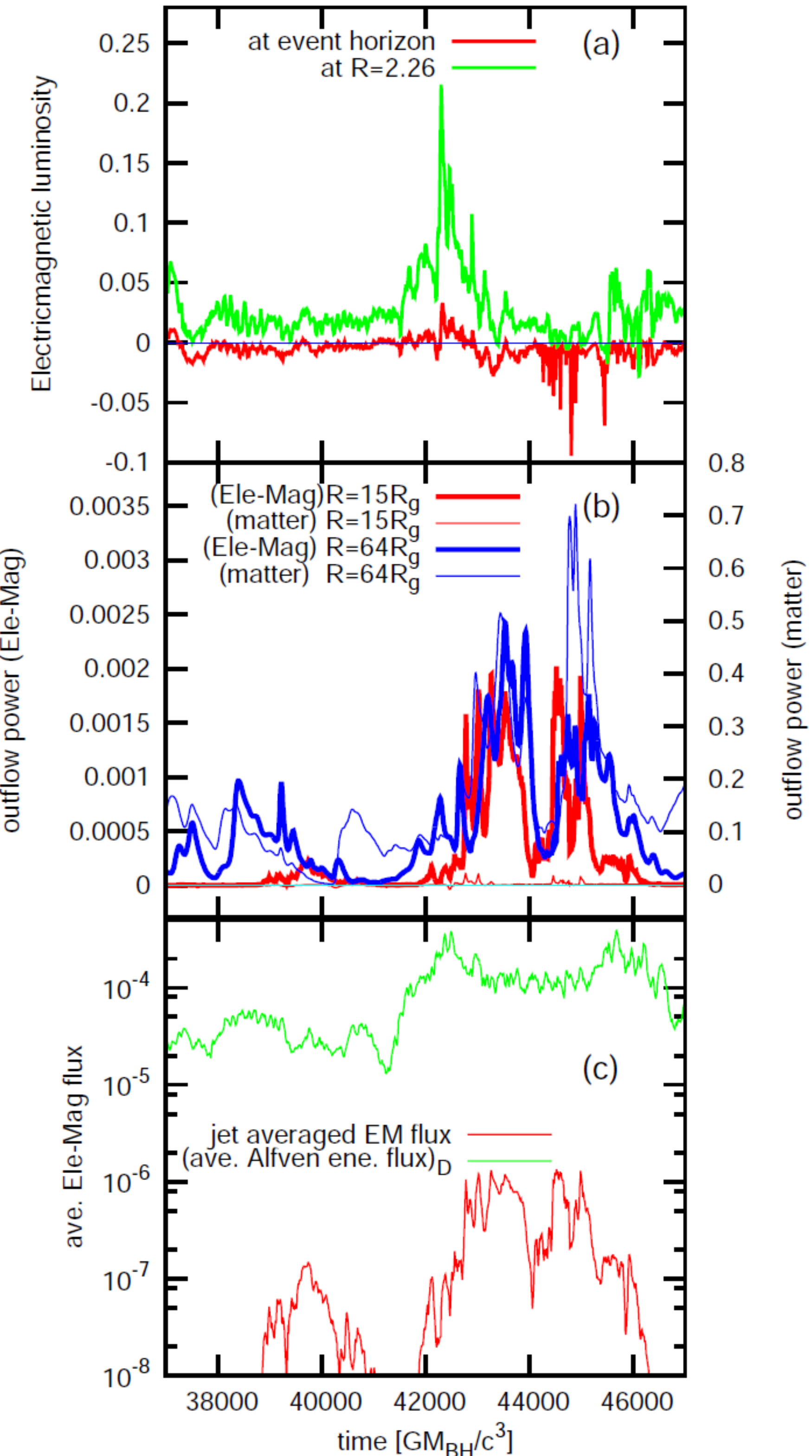


- BZ-effect & outflow properties

Electric-magnetic luminosity
@ horizon is sometimes positive.
==> BZ effect works.

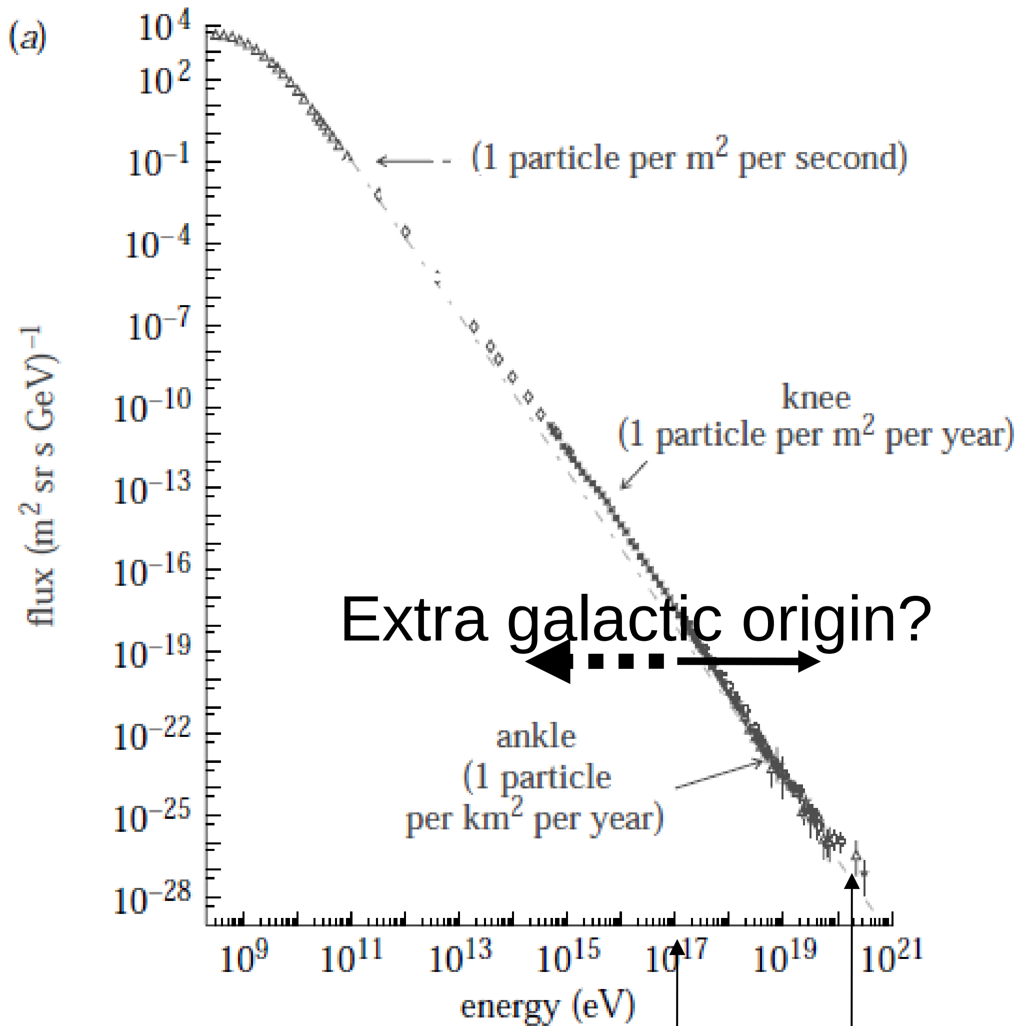
- But only ~1% in the jet

- Short time variability on electric-magnetic luminosity in the jet.
This is similar with mass accretion rate.

- About 1% of poloidal component of the Alfven flux (disk) goes to the jet.

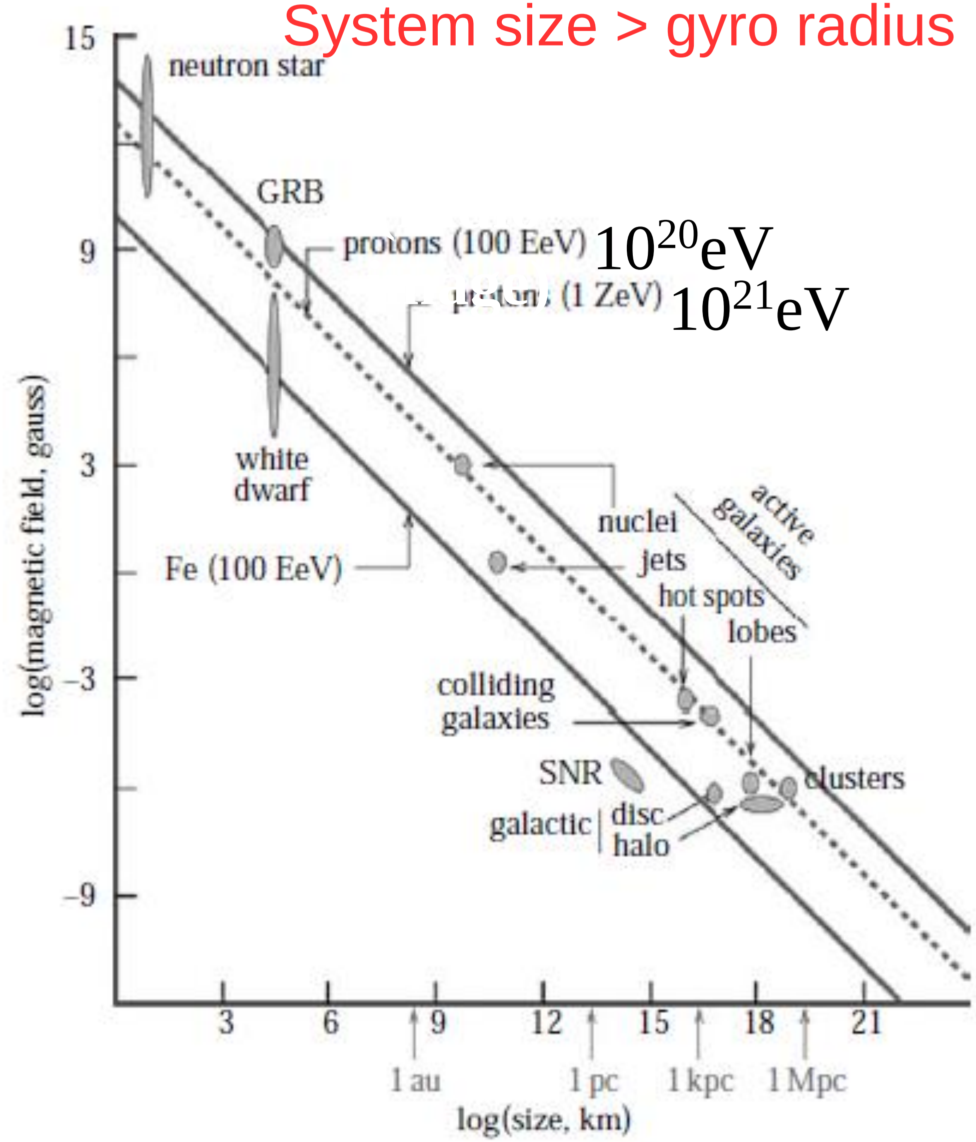
- Consistent with Ebisuzaki & Tajima model

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



Hillas plot : Emax~ZeBR

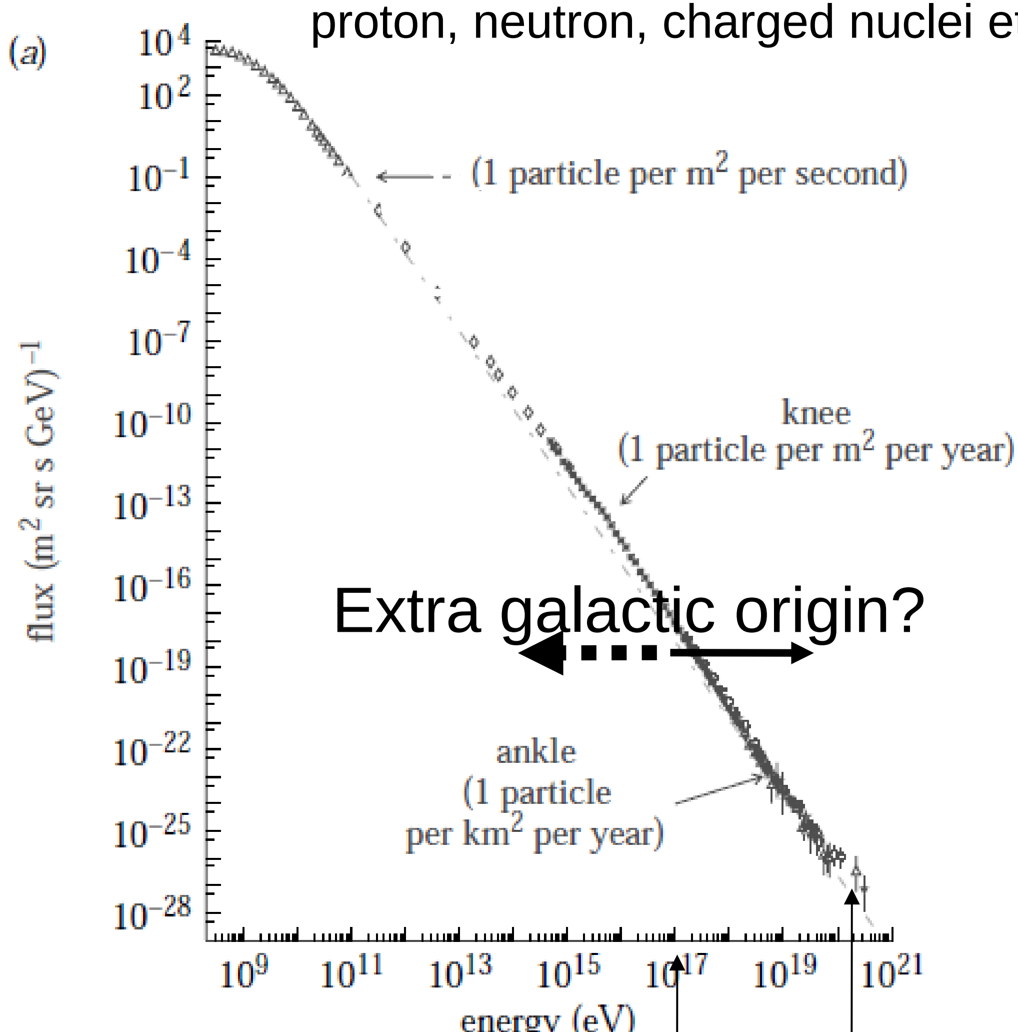
System size > gyro radius



LHC(14TeV Center-of-mass system)

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

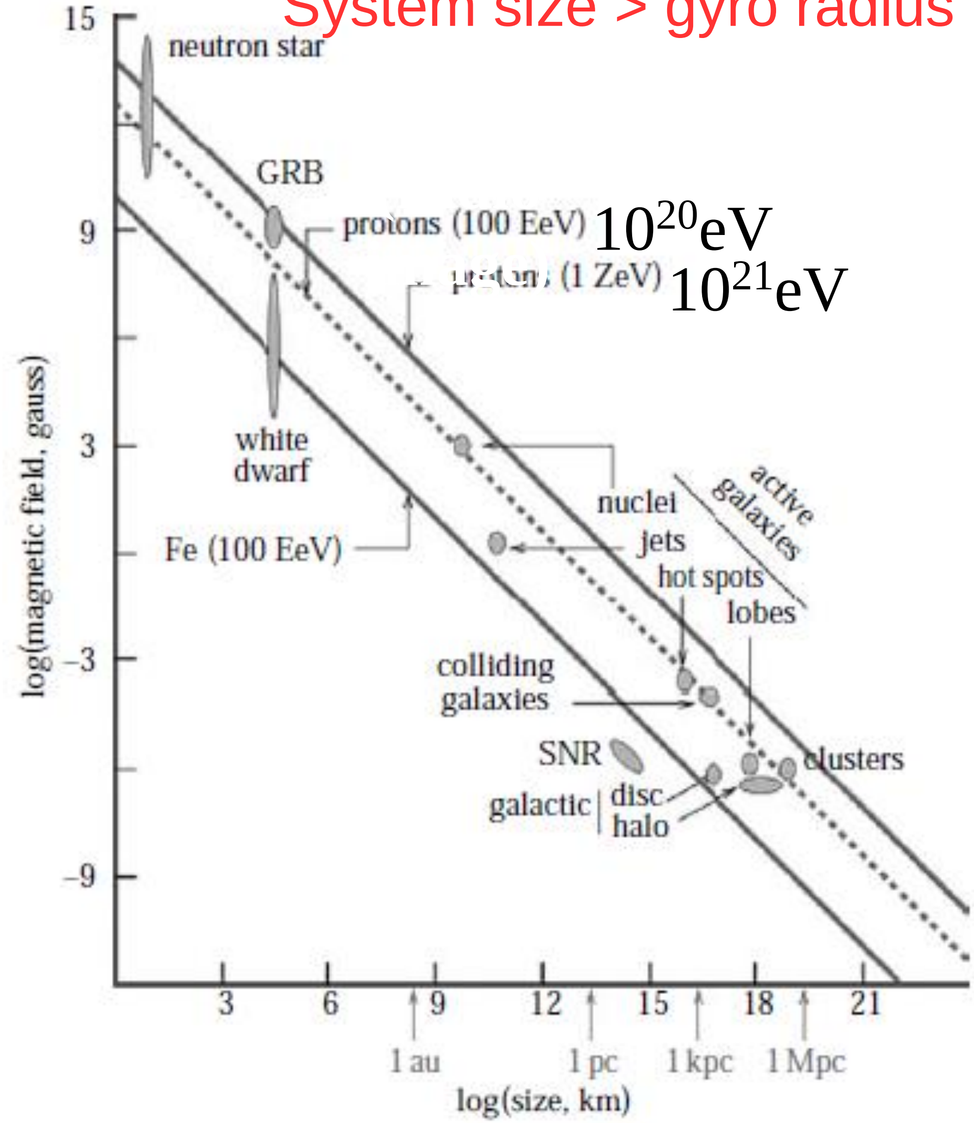
Cosmic-ray- electron, positron, proton, neutron, charged nuclei etc.



GZK cutoff

Hillas plot : Emax~ZeBR

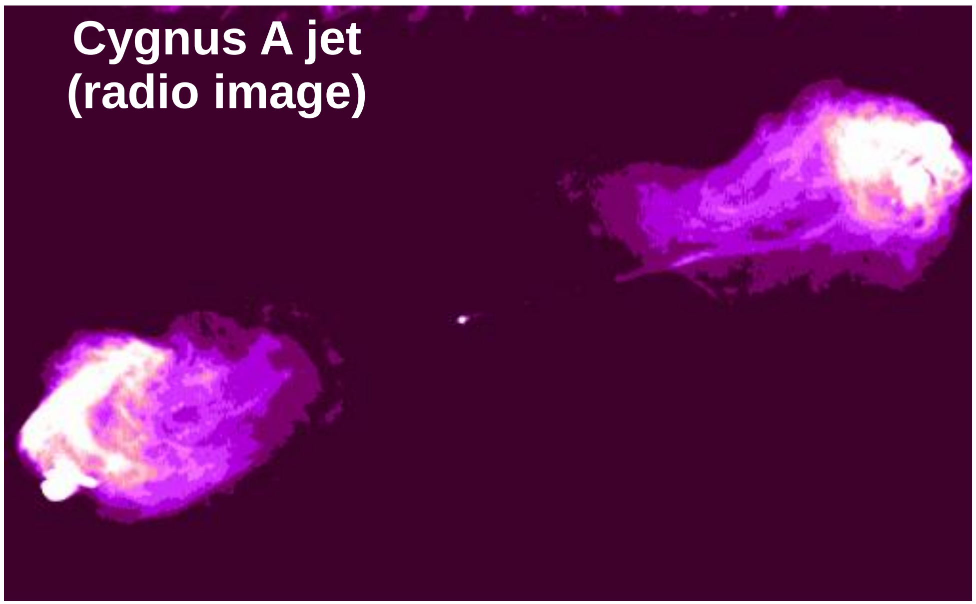
System size > gyro radius



LHC(14TeV Center-of-mass system)

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

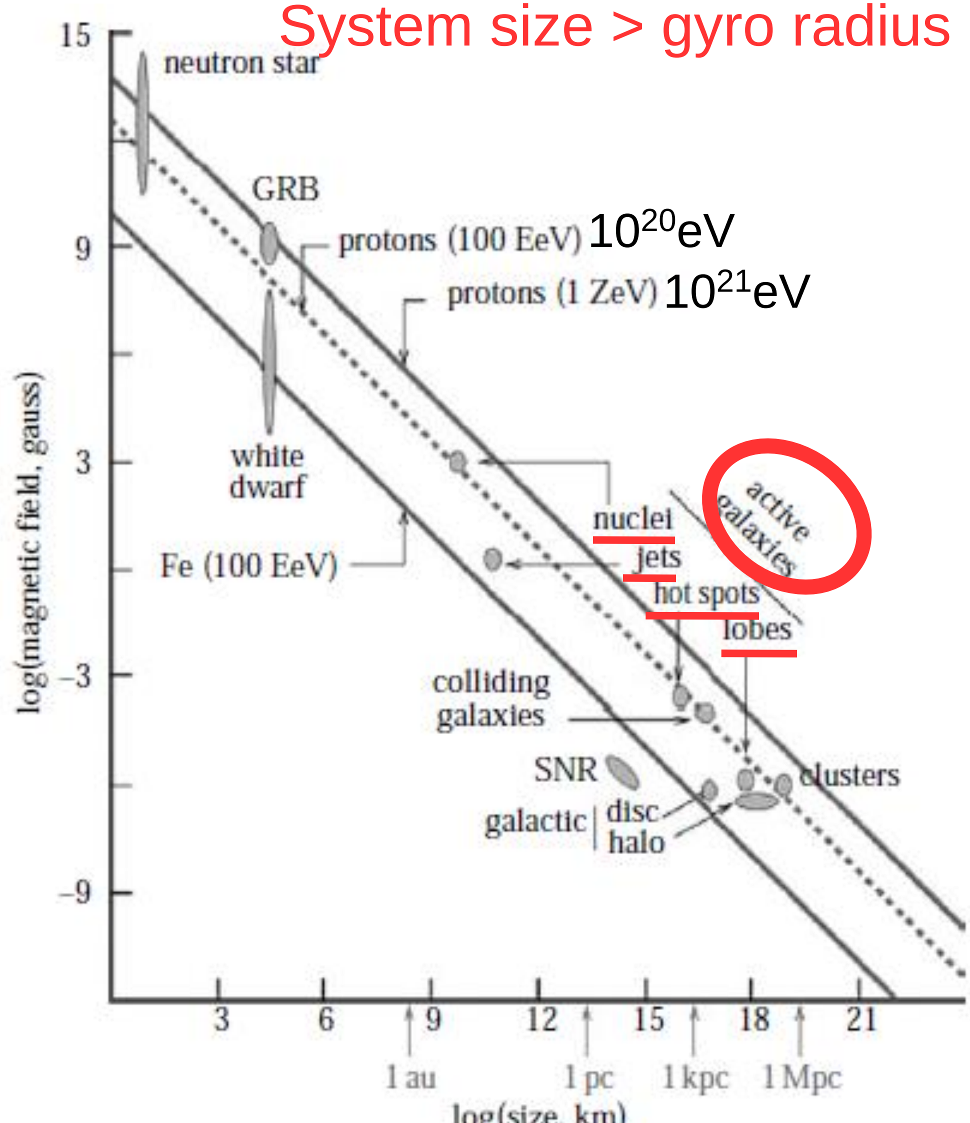
~10^{23}cm



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

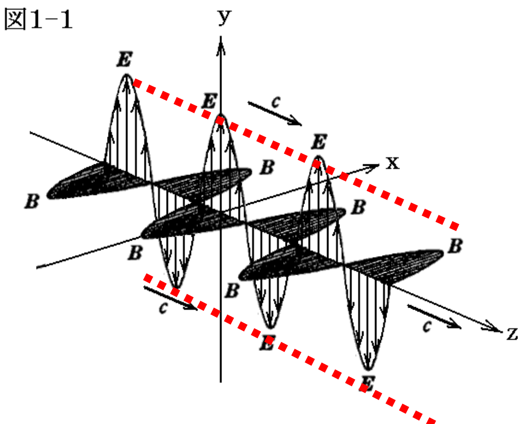
Hillas plot : Emax~ZeBR

System size > gyro radius



Wakefield acceleration (Tajima & Dawson PRL 1979)

Acceleration mechnism by interaction between wave and plasma.



Laser plasma interaction

⇒ 8 shape motion.

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

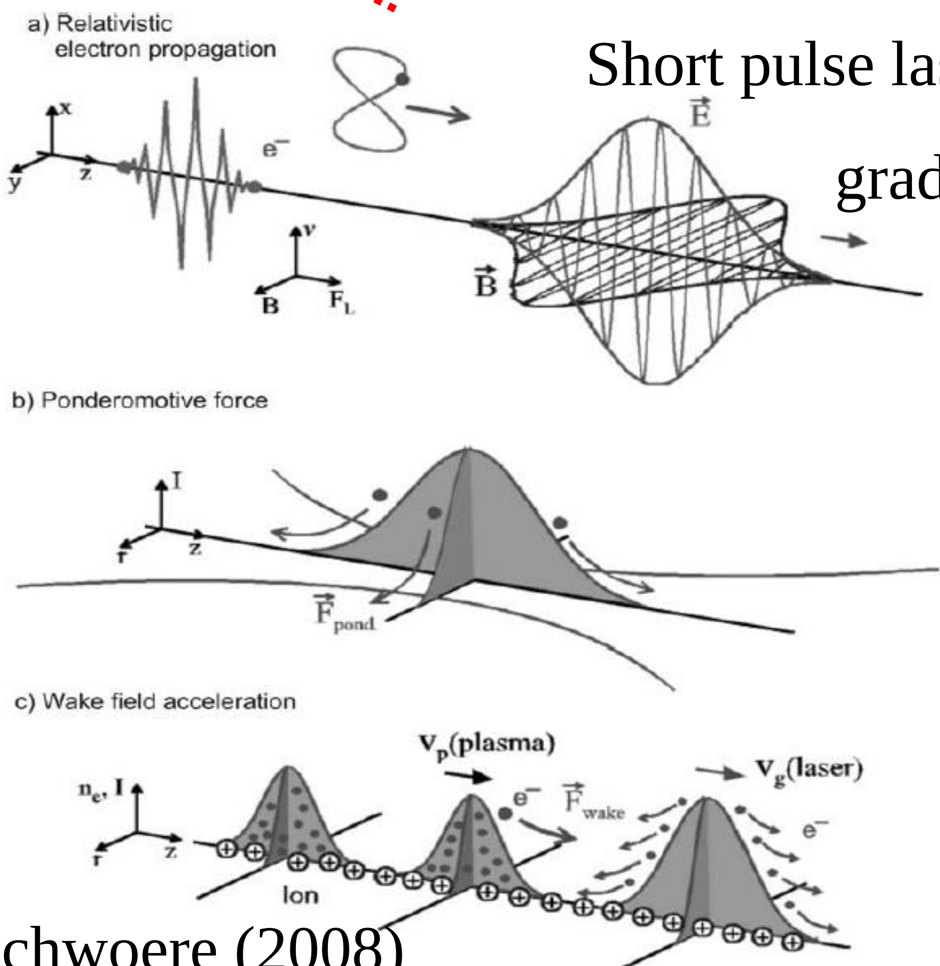
Osillation by Electrifield ⇒ **v** **(ossilation up, down)**

vxB force ⇒ ossilation forward and backward.

|**v**| ~ c => large amplification motion by **vxB. (8 shape motion).**

Short pulse laser

grad $\mathbf{E}^2$



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

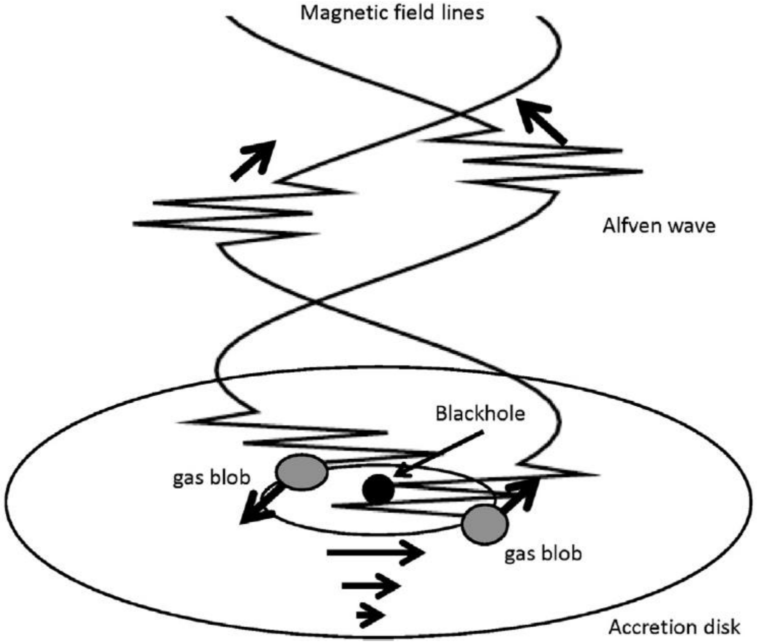
Relativistic Alfven wave can be applied to wakefield acceleration. (Takahashi+2000, Chen+2002, Lyubarusky 2006, Hoshino 2008)

AGN : UHECR accelarator ?

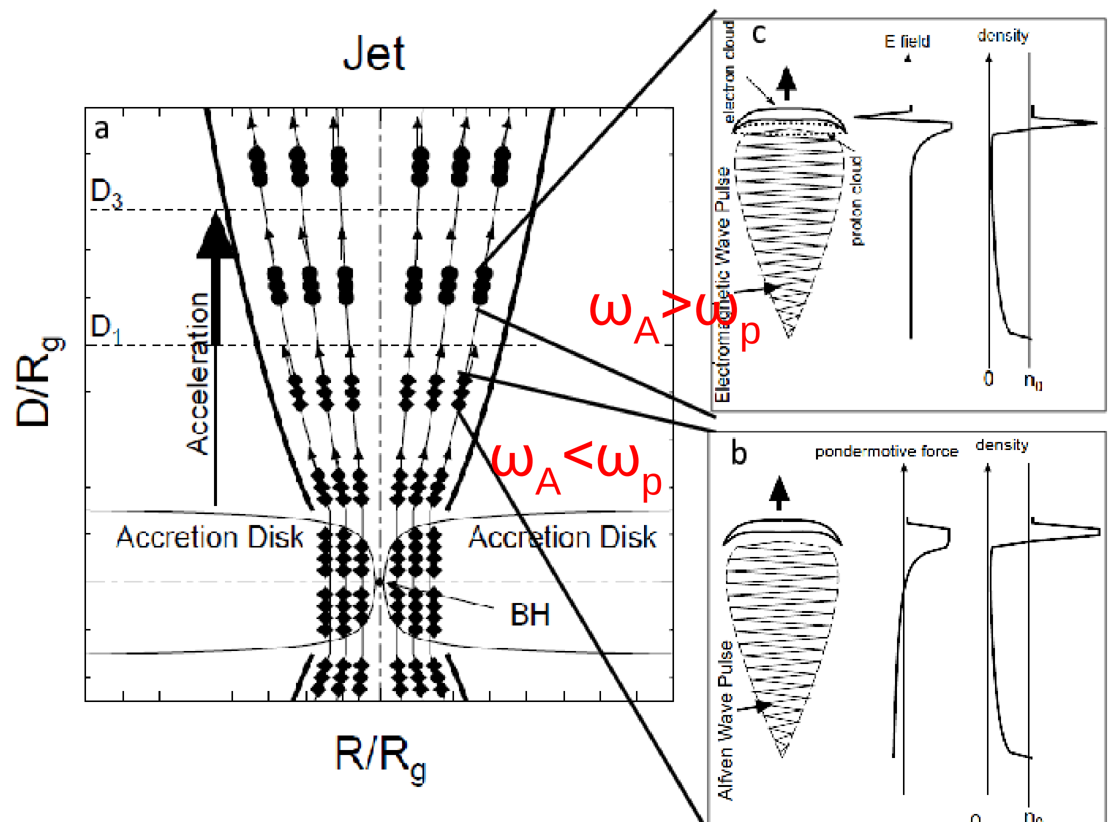
Wakefield acceleration model (excited by Alfven wave) (Ebisuzaki & Tajima 2014)
Relativistic Alfven wave in the jet => electric-magnetic wave

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

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



Ebisuzaki & Tajima 2014



Strength parameter a_0

In our numerical GRMHD simulation,

- – So many electric magnetic flares are observed in the jet.
- – Disk activities show MRI growth and eruption of Alfven waves.

We can estimate the strength parameter a_0 as,

$$a_0 = \frac{eE}{m_e \omega_{\rm A} c} = 7.6 \times 10^{12} \left(\frac{M}{10^8 M_\odot} \right)^{1/2} \left(\frac{\dot{M}_{\rm av}}{10^{-2} L_{\rm Ed}} \right)^{1/2}$$

Strength parameter highly exceeds unity.
The AGN jet can be good accelerator via wake-field acceleration.

Summary

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

– B filefd amplification
– Electromagnetic flux @ horizon (BZ effect)
– Electric magnetic flares in the jet
– consistent with Ebisuzaki & Tajima model
– $a_0 \sim 10^{12} >> 1$: good accelerator for UHECRs via wakefiled acceleration

Future works
– Higher resolution calculations are necessry to resolve fastest growing mode of MRI
– Different initial B-field topology