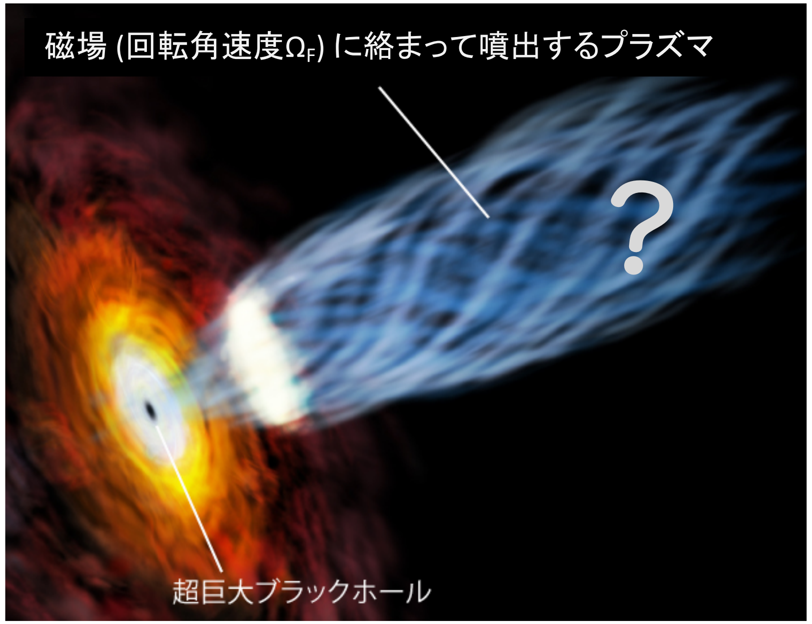
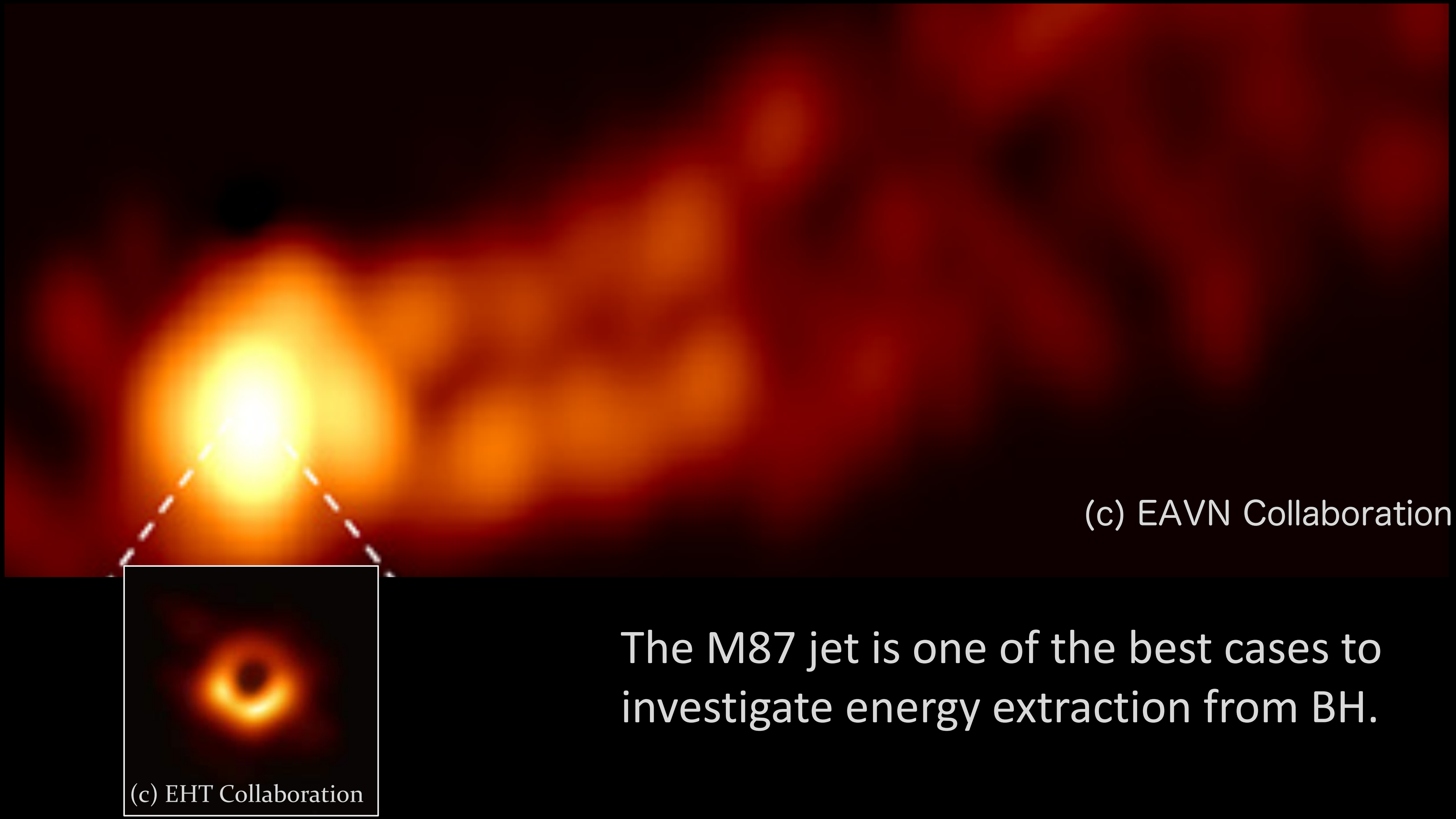
On BZ power in M87



Motoki Kino (Kogakuin Univ/NAOJ)
with M. Takahashi, M. Nakamura, K. Toma, T. Kawashima,
JH Park, K. Hada, HW Ro, Y Cui et al.

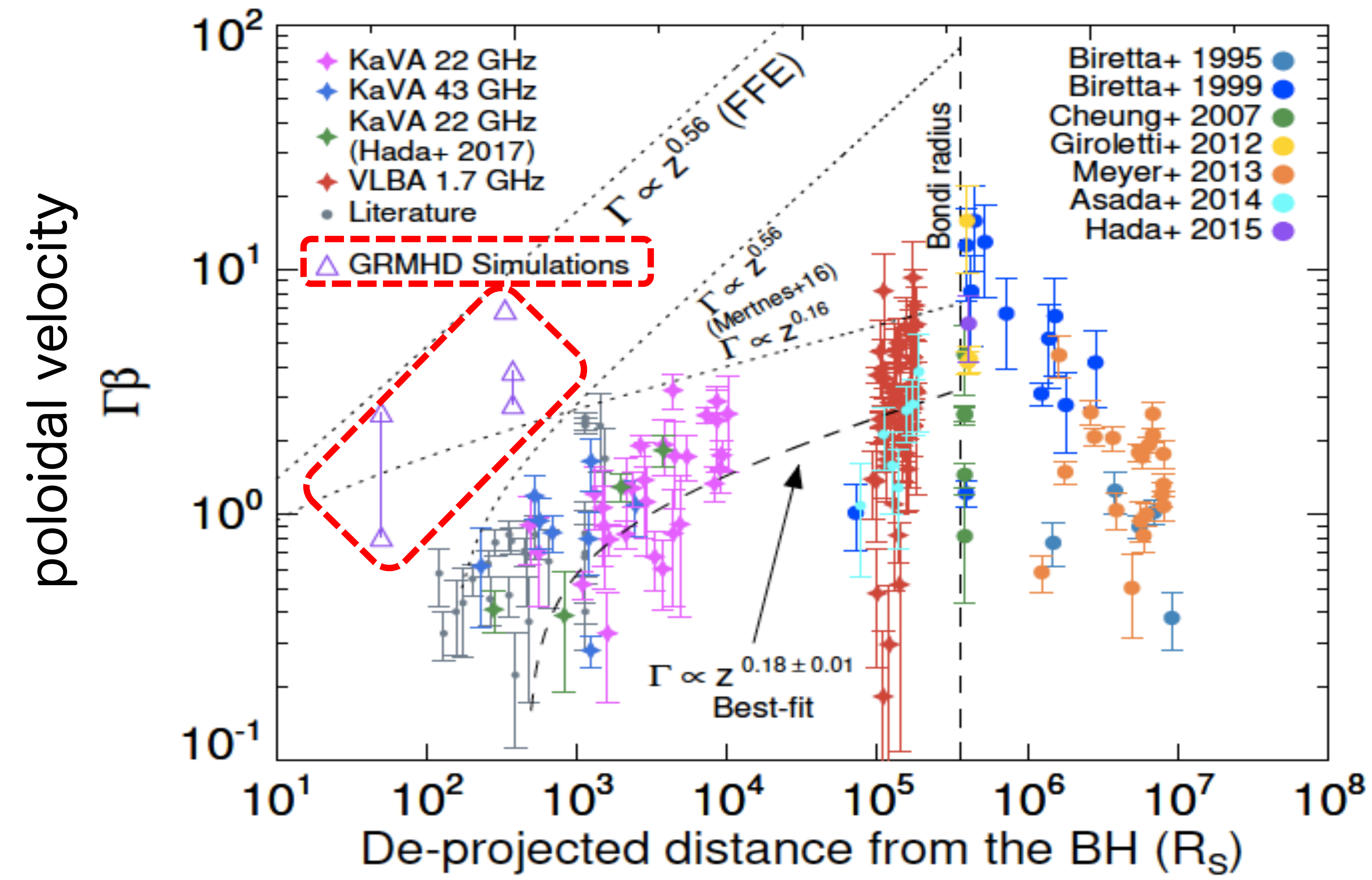
How to extract energy from black hole?



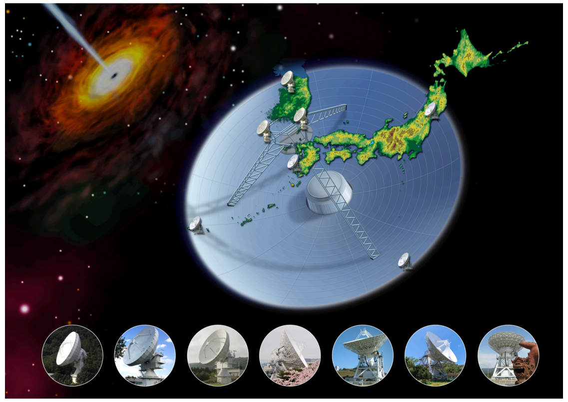
The M87 jet is one of the best cases to investigate energy extraction from BH.

Park, Hada, MK +2019

A new question
How to explain the discrepancy between obs. and model?!



Main observation was done



with KaVA array

by KaVA/EAVN AGN Science Working Group.

How to solve General Relativistic MHD?

Basic equations

The *ideal MHD* condition	$u^\beta F_{\alpha\beta} = 0$
The particle conservation law	$(nu^\alpha)_{;\alpha} = 0$
Maxwell equations	$F^{\mu\nu}_{;\nu} = -4\pi j^\mu \ , \quad F_{[\mu\nu;\sigma]} = 0$
Polytropic relation (*Tooper 1965*)	$P = K\rho_0^\Gamma$
The equation of motion	$T^{\alpha\beta}_{;\beta} = 0$

steady (∂_t=0) & axi-symmetric (∂_ϕ=0)

Bernoulli equation
Grad-Shafranov (GS) eq.

Here, we choose this way.

Easy comparison w/ VLBI data!

non-steady & 3D

GRMHD simulation

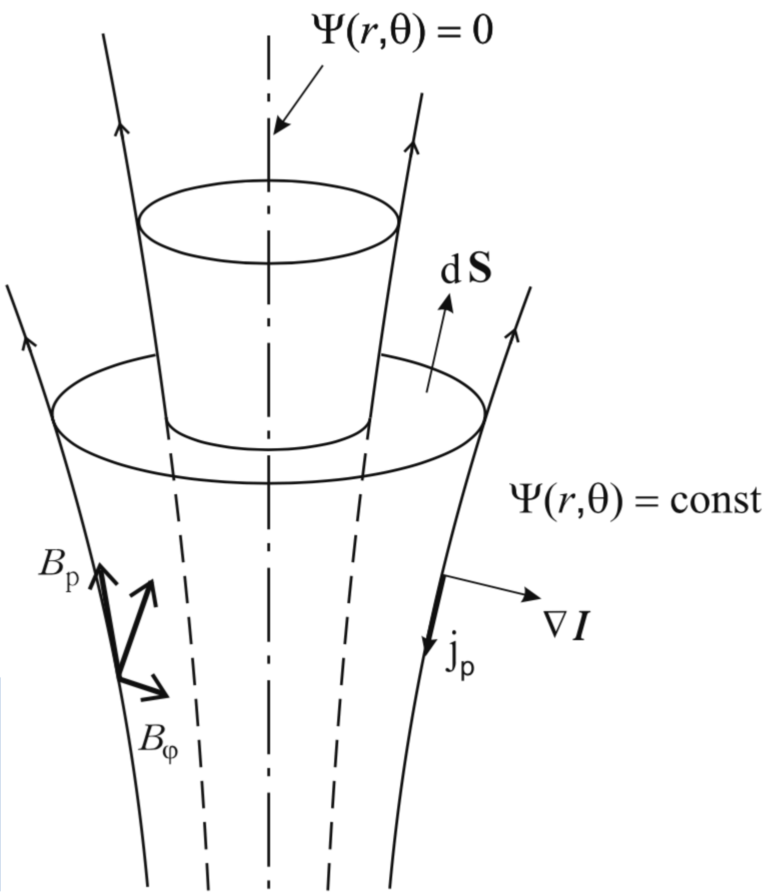
Steady and axisymmetric flow

Conserved quantities along the magnetic surface (Ψ=const.).

1.	Number flux per unit magnetic flux	$\eta(\Psi) = \frac{nu^p}{B^p}$
2.	Angular velocity of the field lines	$\Omega_F(\Psi) = -\frac{F_{tr}}{F_{\phi r}} = -\frac{F_{t\theta}}{F_{\phi\theta}}$
3.	Total energy of the magnetized flow	$E(\Psi) = \mu u_t - \frac{\Omega_F}{4\pi\eta} B_\phi$
4.	Total angular momentum	$L(\Psi) = -\mu u_\phi - \frac{1}{4\pi\eta} B_\phi$

Motion along Ψ=const surface <=> Bernoulli eq.
Balance between Ψ= const surface <=> GS eq.
(a.k.a. trans-field eq.)

magnetic-surface

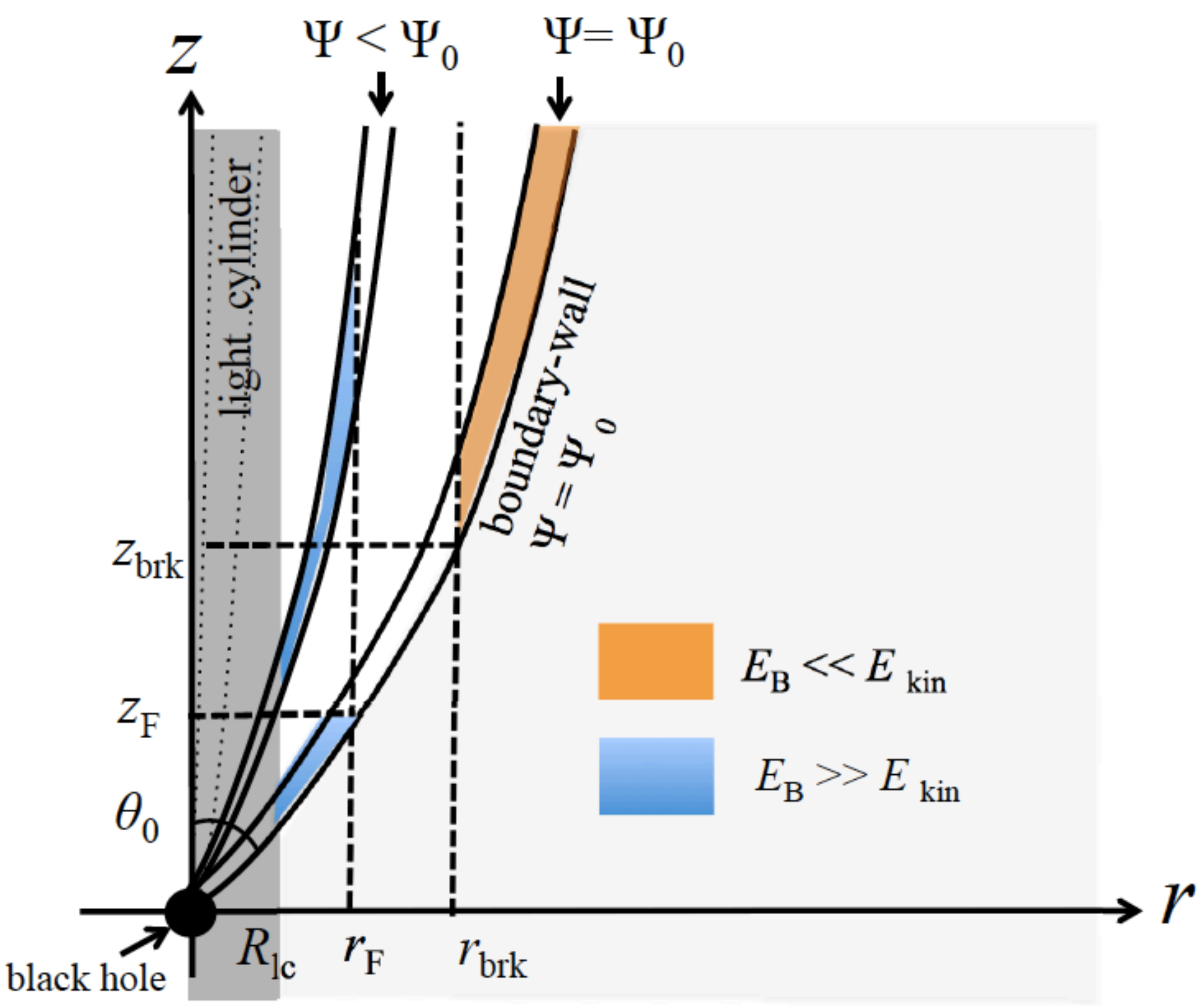


A well known approximated form of Ψ is

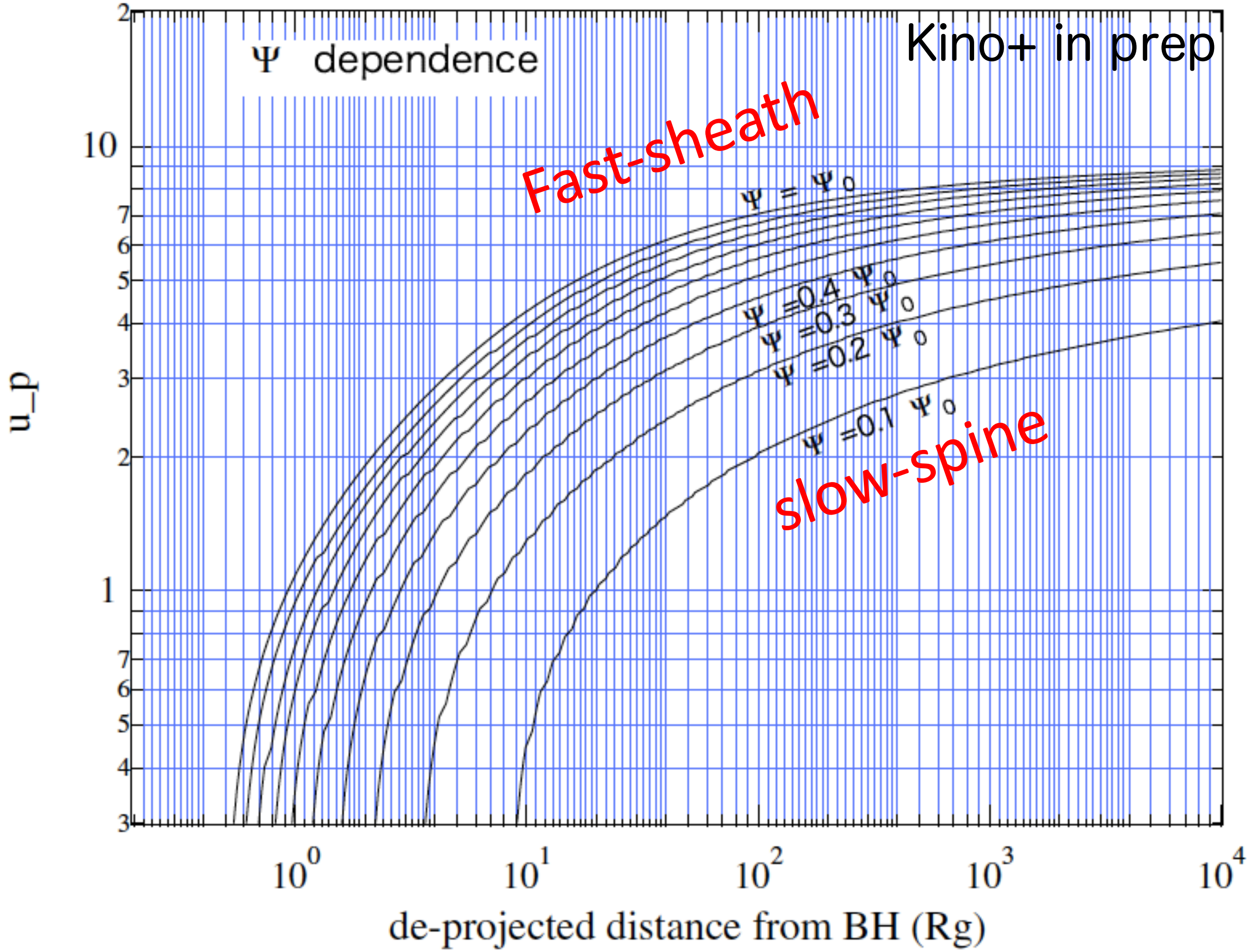
$$\Psi = \Psi_0 \left(\frac{r}{M_\bullet}\right)^p (1 - \cos\theta)$$

Tomimatsu & Takahashi (2003) model

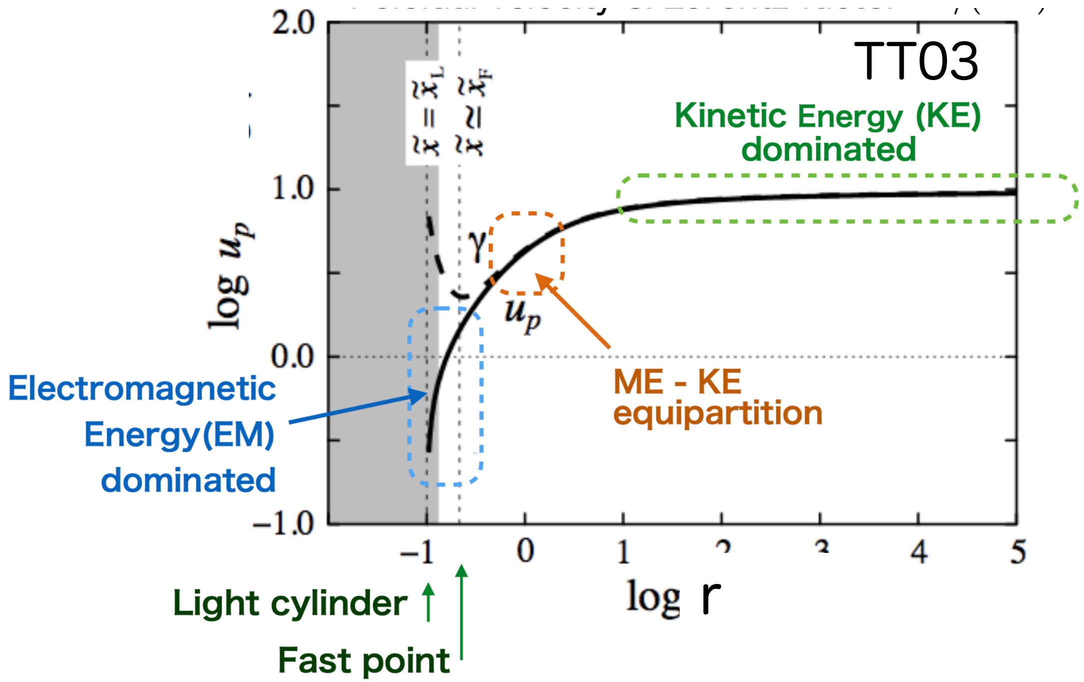
- Assumptions
  - ✓ Steady, axisymmetric
  - ✓ Special Relativistic (not GR)
  - ✓ A jet has relativistic speed and has a narrow opening-angle.
- Boundary condition
  - ✓ confined by outer boundary-wall
  - ✓ Inner-boundary = light-cylinder
  - ✓ At inlet-boundary, $\Omega_F(\Psi)$= const
- Advantages of TT03 model
  - ✓ Solving GS equation
  - ✓ Trans fast magnetosonic solution



Ψ-dependence can naturally explains a stratified velocity field.

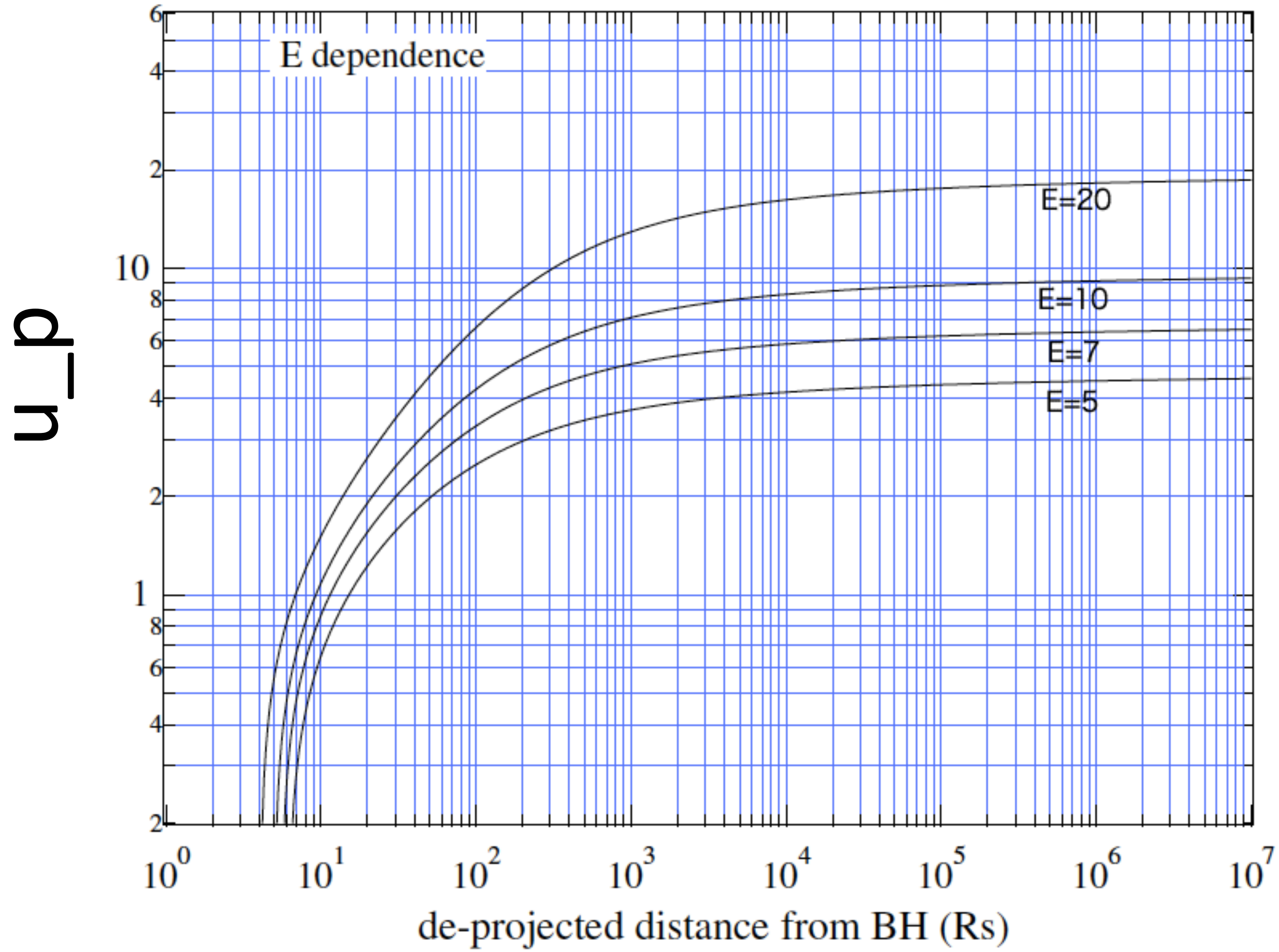


poloidal velocity (u_p) along a given Ψ=const. surface



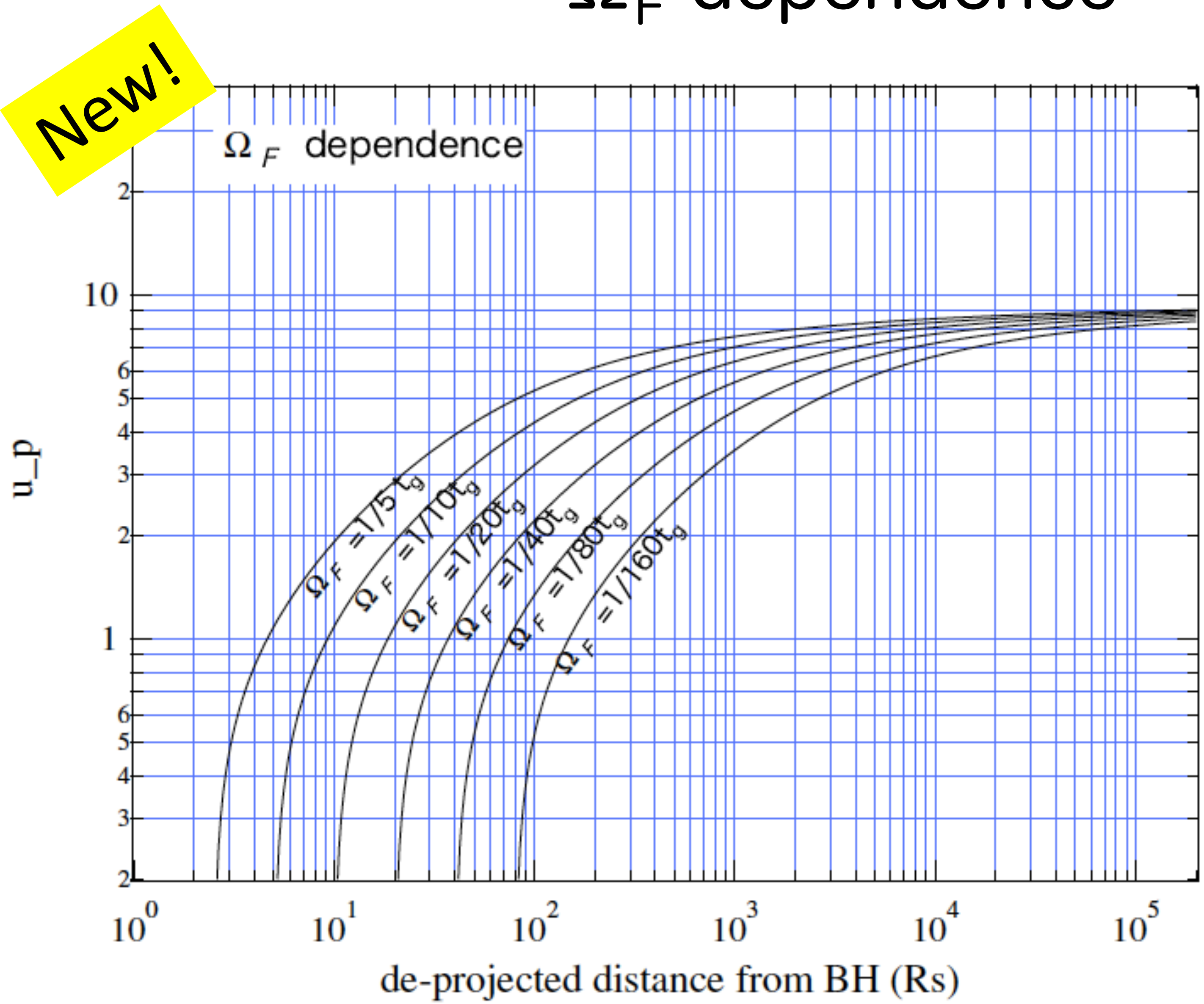
Kino+ in prep

E-dependence



Kino+ in prep

Ω_F dependence

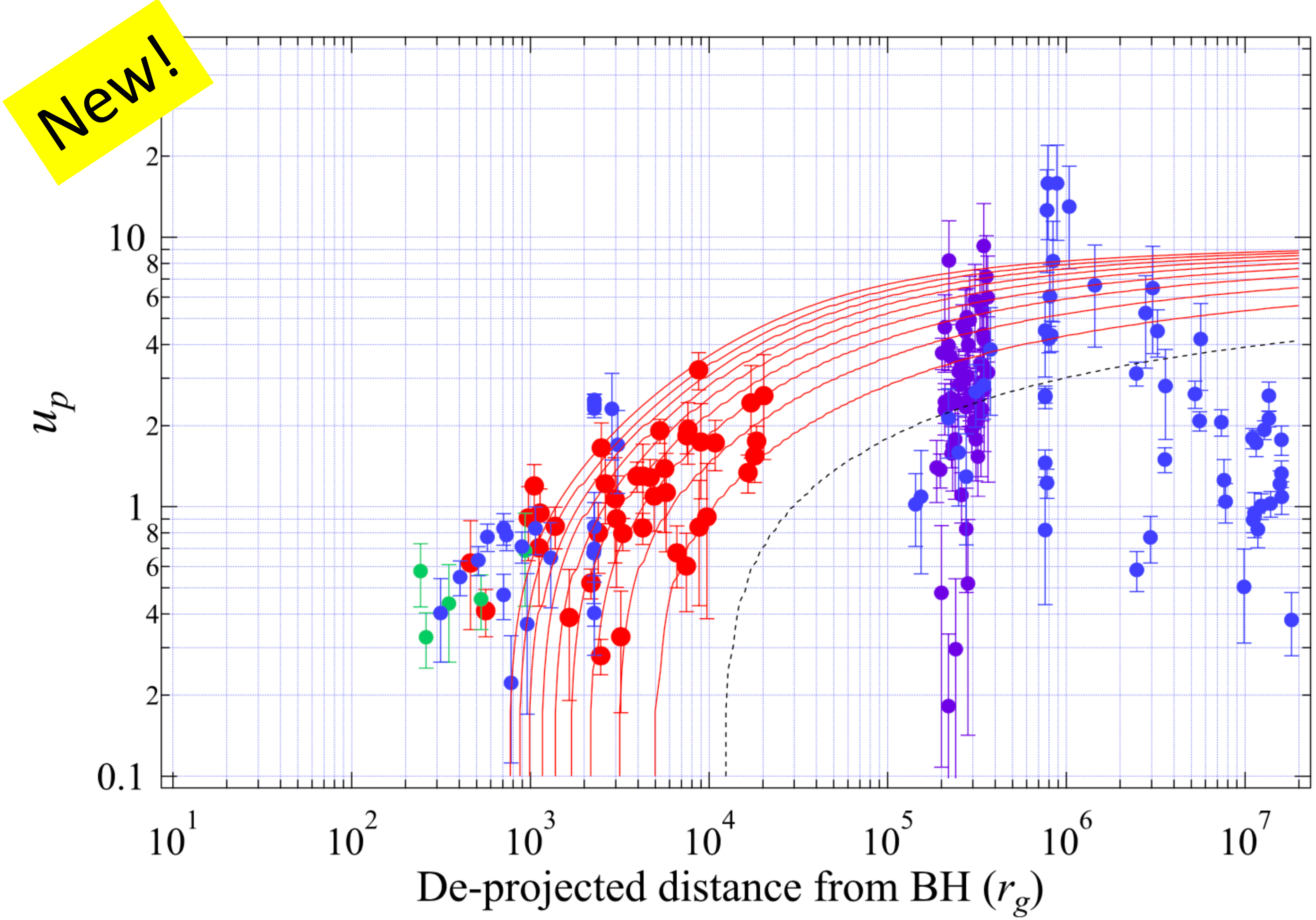


$$R_{\rm lc} = \frac{c}{\Omega_F}$$

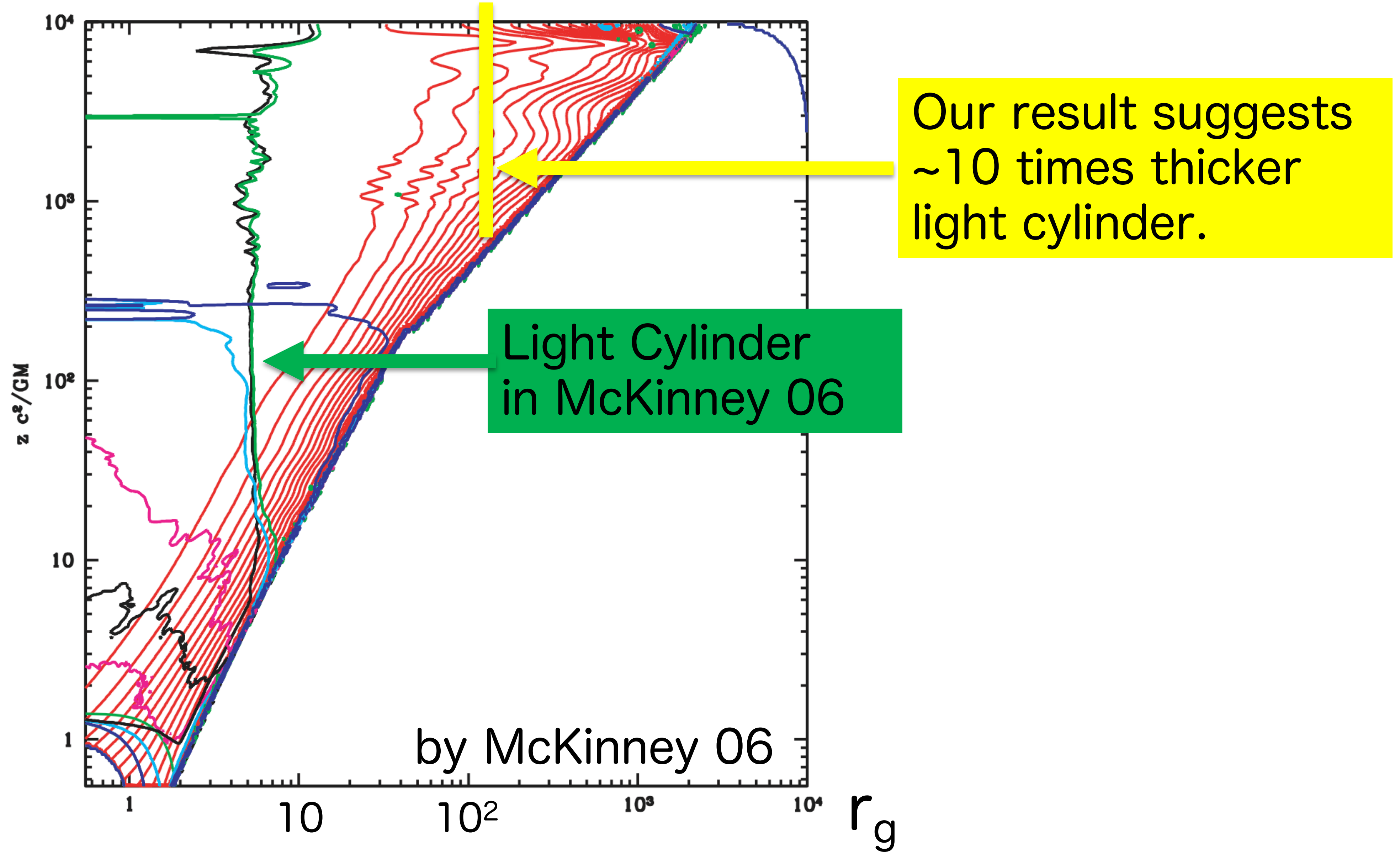
slower-Ω_F
-> thicker-R_{lc}
-> Jet acceleration starts from more distant point.

Kino+ in prep

Slower rotation of B-field $\Omega_F \sim c/100r_g$ (= larger light-cylinder radius ~$100r_g$) can explain u_p profile!



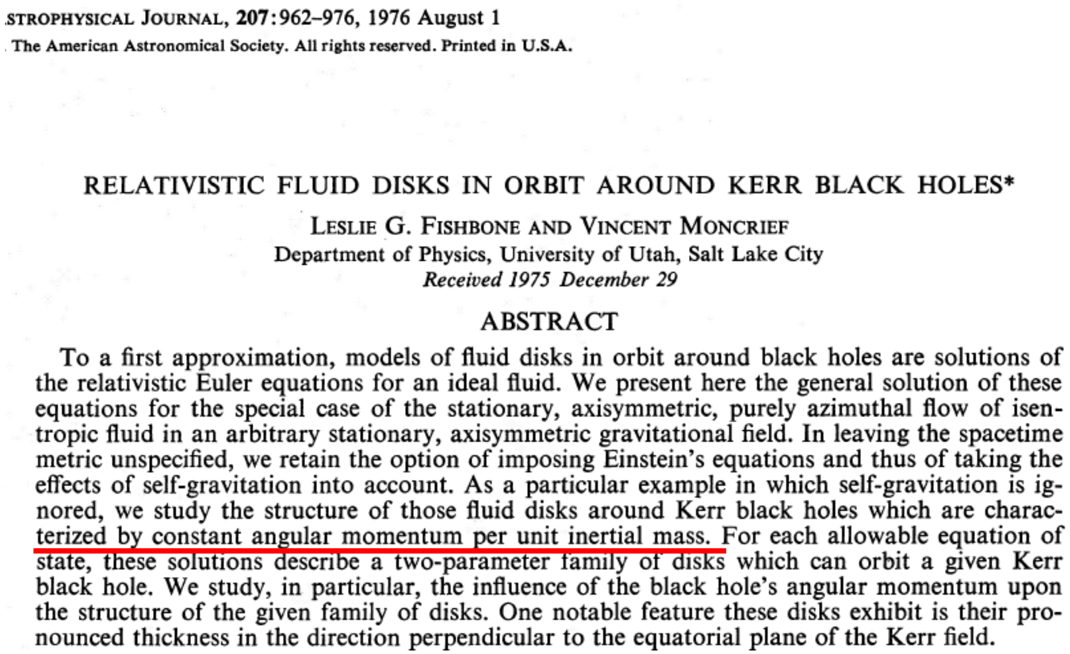
A difference between our result and GRMHD simulations.



Discussions
(1) How to realize slower Ω_F? (comments welcome)
(2) estimate of B-field on the horizon via BZ-power

How to realize slower Ω_F?

(1) Random ang-momentum accretion could make more slowly rotating magnetosphere.



STROPHYSICAL JOURNAL, 207:962–976, 1976 August 1

RELATIVISTIC FLUID DISKS IN ORBIT AROUND KERR BLACK HOLES*

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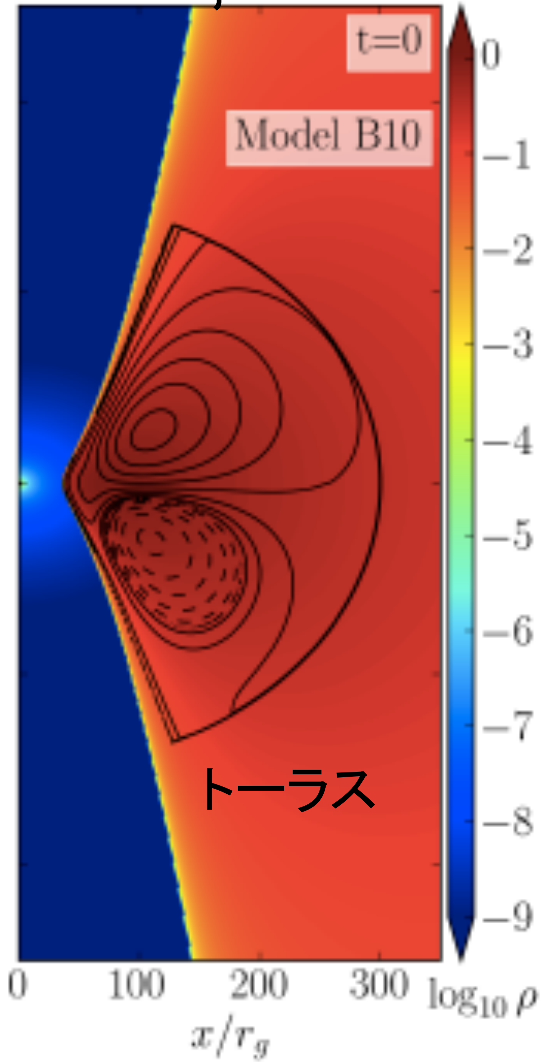
Received 1975 December 29

ABSTRACT

To a first approximation, models of fluid disks in orbit around black holes are solutions of the relativistic Euler equations for an ideal fluid. We present here the general solution of these equations for the special case of the stationary, axisymmetric, purely azimuthal flow of isentropic fluid in an arbitrary stationary, axisymmetric gravitational field. In leaving the spacetime metric unspecified, we retain the option of imposing Einstein's equations and thus of taking the effects of self-gravitation into account. As a particular example in which self-gravitation is ignored, we study the structure of those fluid disks around Kerr black holes which are characterized by constant angular momentum per unit inertial mass. For each allowable equation of state, these solutions describe a two-parameter family of disks which can orbit a given Kerr black hole. We study, in particular, the influence of the black hole's angular momentum upon the structure of the given family of disks. One notable feature these disks exhibit is their pronounced thickness in the direction perpendicular to the equatorial plane of the Kerr field.

Chatterjee+19



Accreting plasma with random angular-momentum rather than Fishbone-torus could realize smaller Ω_F.

How to realize slower Ω_F? (2) and (3)

(2) Floor conditions in GRMHD simulations may be different from the real case.

- ✓Need microscopic physics on particle creation and/or injection
- ✓Need GRMHD simulations w/ different floor condition

(3) The jet base is anchored to the accretion flow, rather than the black hole.

- ✓ It easily realizes slower Ω_F. However, it seems unlikely since an accretion flow is low σ, in which the flow does not accelerate sufficiently fast.

Ω_F (magnetoshare) vs Ω_H (Black Hole)

BZ process works when

$$0 < \Omega_F < \Omega_{\rm H}$$

Assuming reasonably high BH-spin i.e., $0.5 < a < 1$ in order to produce powerful jets, then we have

$$0.025 \lesssim \frac{\Omega_F}{\Omega_H} \lesssim 0.068.$$

OK, then let us assume BZ process in action in M87.

BZ power as the origin of jet power

The power of the M87 jet can be estimated as

$$1 \times 10^{43}\ \mathrm{erg\ s^{-1}} \lesssim L_{\mathrm{j}} \lesssim 5 \times 10^{44}\ \mathrm{erg\ s^{-1}}$$

The BH power is given by

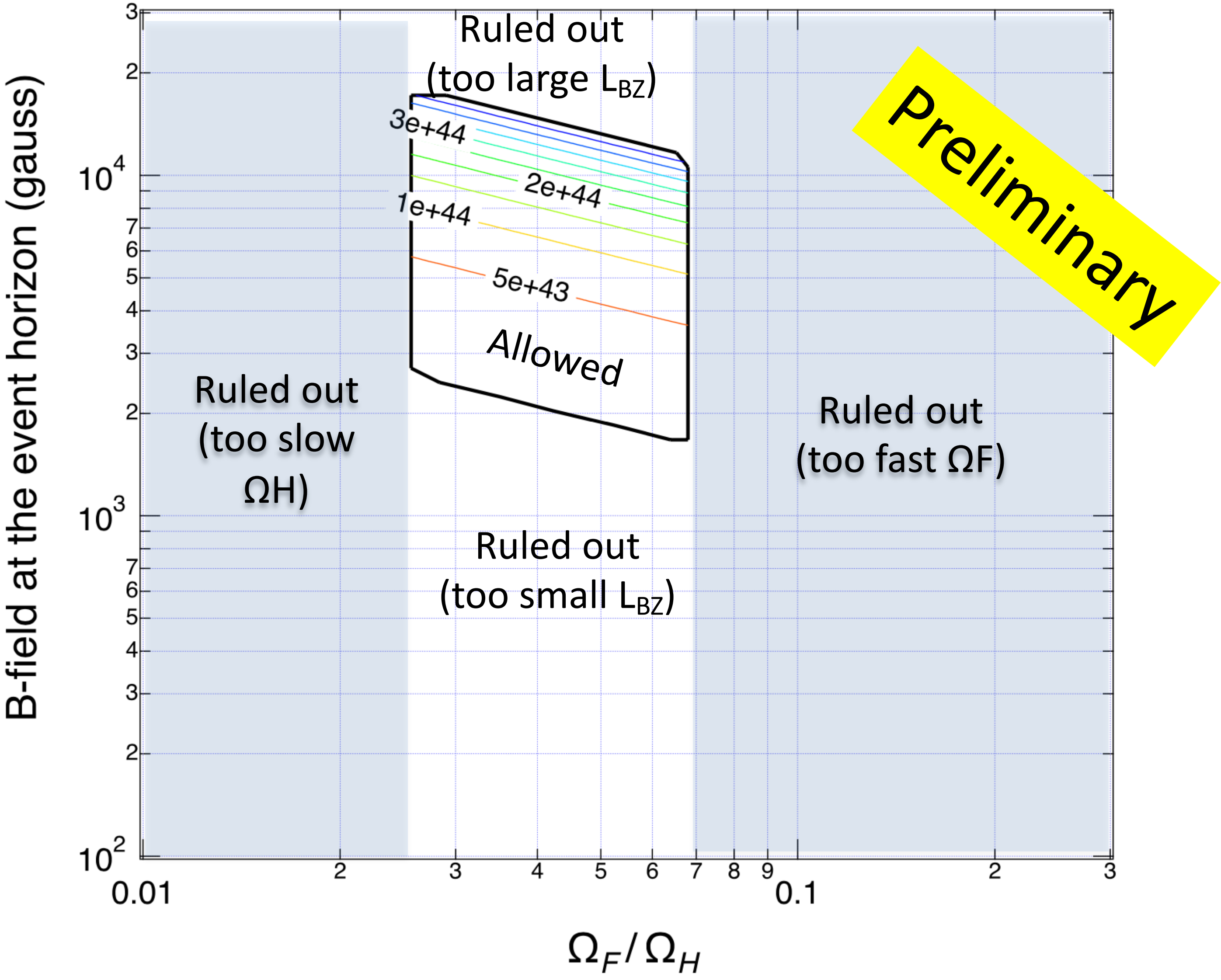
$$L_{\mathrm{BZ}} \approx 7.5 \times 10^{45} \chi_{-2} \frac{\Omega_F(\Omega_H - \Omega_F)}{\Omega_H^2} \left(\frac{B_H}{10^3\ \mathrm{G}}\right)^2 \left(\frac{r_H}{10^{15}\ \mathrm{cm}}\right)^2\ \mathrm{erg\ s^{-1}}$$

The condition here

$$L_{BZ} \approx L_{\mathrm{j}}$$

Allowed range of B_H on the horizon

$$2 \times 10^3 \ \text{gauss} \lesssim B_{\mathrm{H}} \lesssim 2 \times 10^4 \ \text{gauss}$$



Summary

- From the comparison of KaVA measured M87 jet velocity profile with steady-axisymmetric SRMHD model (TT03), we find that
  - ✓ velocity stratification (fast-sheath-slow-spine) is naturally expected
  - ✓ slower Ω_F ~ c/100 r_g (thicker light cylinder) can explain the data

- Possible reasons of slower Ω_F are discussed.
  - ✓ Outer boundary (torus) condition?
  - ✓ Inner boundary (floor) condition?

- An estimate of $B_{Horizon}$ is done based on required BZ-power (L_{BZ}).
  - ✓ Although smaller Ω_F makes L_BZ smaller, the estimated B-field strength $B_{Horizon}$~10^{3-4} G. The value looks to support MAD.