カーブラックホール・エルゴ領域に架かる磁気的橋の爆発的膨張と相対論的ジェット形成

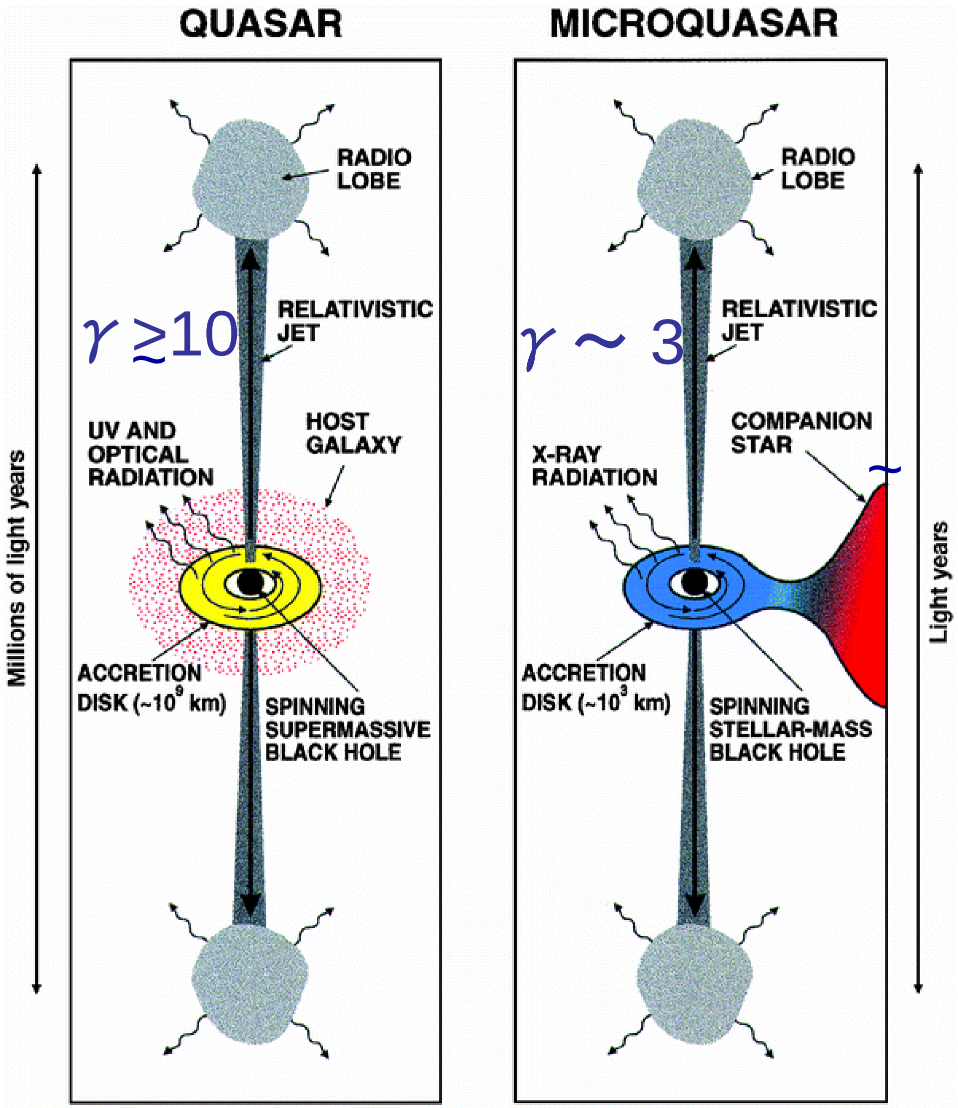
富山大学工学部　小出眞路
京都大学理学部　柴田一成
国立天文台　　　工藤哲洋

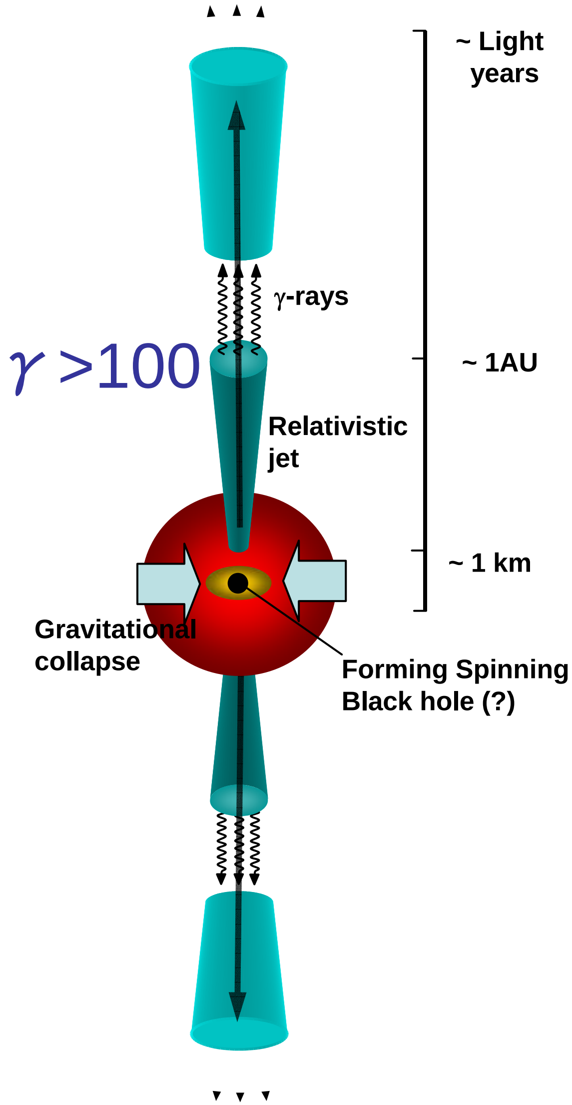
非常に速く回転するブラックホールのまわりの電流ループの作る磁場による相対論的ジェット形成:

- 降着円盤を伴うブラックホールのエルゴ領域付近に電流ループがある場合、エルゴ領域から降着円盤に架かる閉じた磁束管が存在するが、それはエルゴ領域と降着円盤をつなぐ「磁気的橋」と見なす。
- 磁気的橋はエルゴ領域の空間の引きずり効果により捩じり上げられ爆発的膨張をする。
- 爆発的膨張をしたプラズマは磁気張力により絞られて相対論的ジェットになる。

RMHD mini Workshop @千葉大学(2005.8.9)

Motivation: Relativistic Jets in the Universe





Mirabel, Rodriguez 1998

Relativistic Jets in the Universe

- Active galactic nuclei, Quasars:
  $\gamma \gtrsim 10$, $L_{jet} \sim$ several M ps
- Microquasars: $\gamma \sim 3$, $L_{jet} \sim$ several ps
- Gamma-ray bursts: $\gamma \gtrsim 100$, $L_{jet} \sim$ 1AU-several ps

Relativistic Jet Formation Mechanism

{ Acceleration of plasma/gas
  Collimation of plasma/gas outflow

1) Magnetic field
2) Radiation pressure
3) Gas pressure

Magnetic Formation of Relativistic Jet around Black Hole

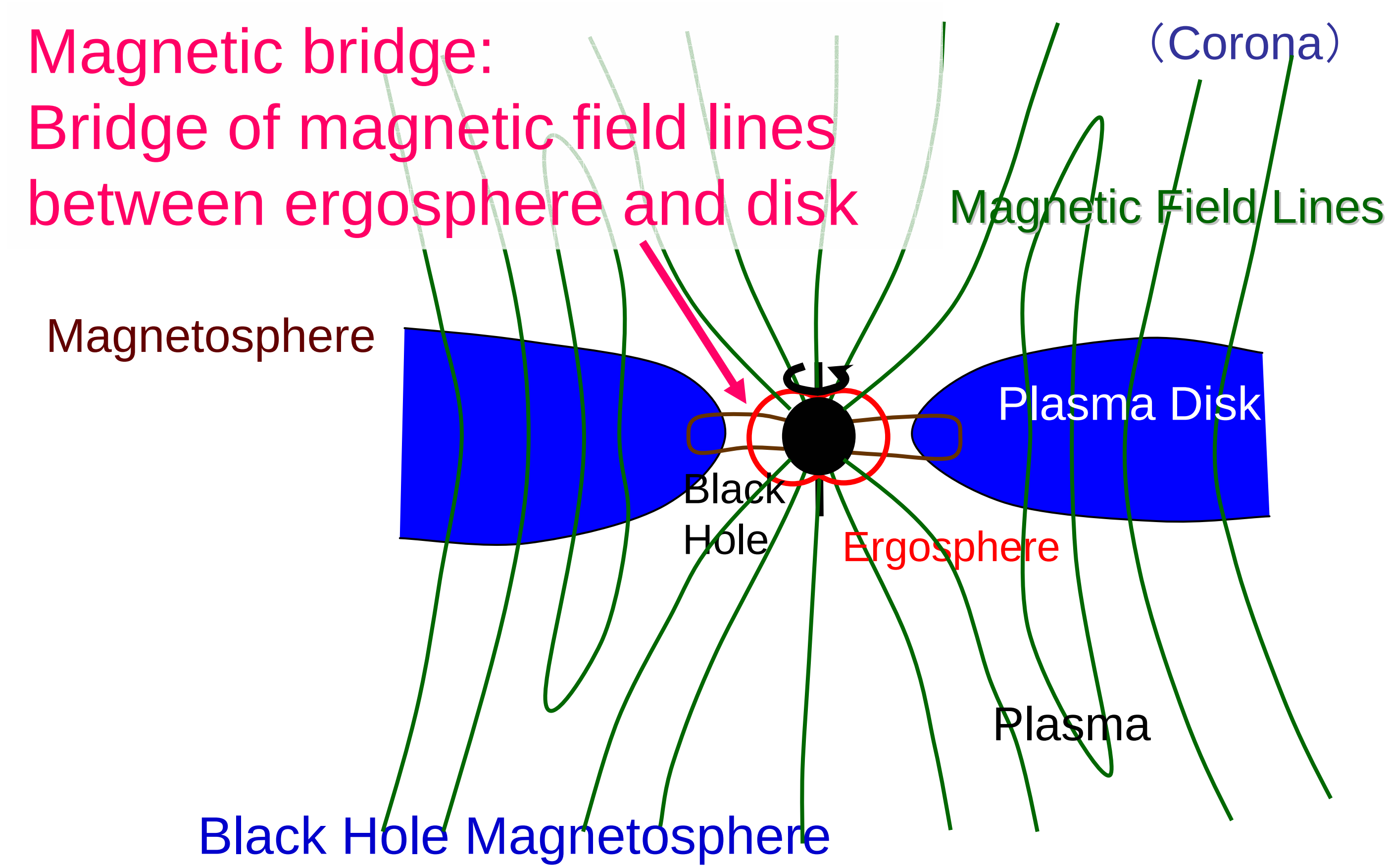
- Interaction between plasma and magnetic field around (near) black hole including general relativistic effects
- Most simple approximation: General Relativistic Magnetohydrodynamics (GRMHD)

Summary of OUR Previous Results with respect to Relativistic Jets

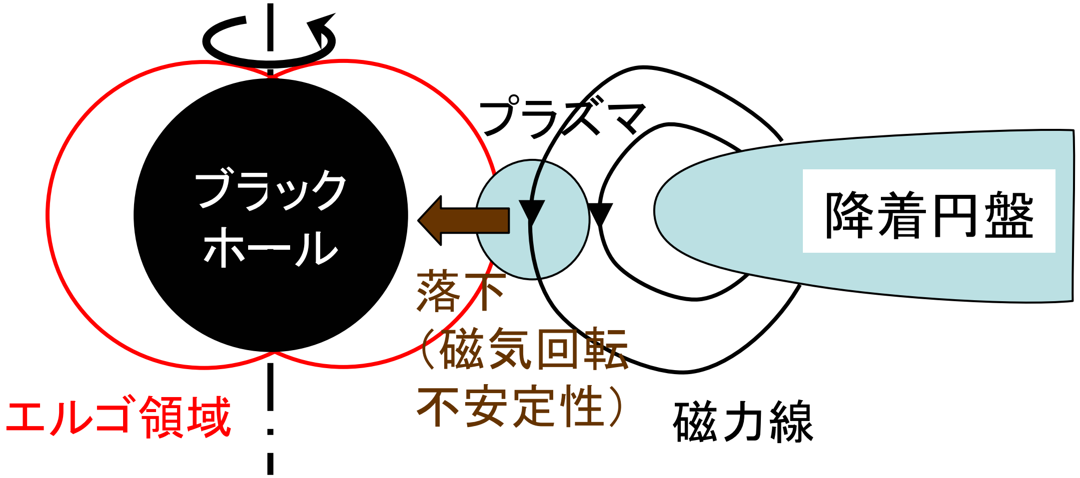
- Sub-relativistic jet
  (Disk case with Uniform magnetic field)
  1999
- 'Poynting flux jet', but No outflow
  (Uniform plasma with Uniform magnetic field)
  2002, 2003
- Relativistic outflow, but No colimated jet
  (radial magnetic field), 2004

  - No Clear Relativistic Jet

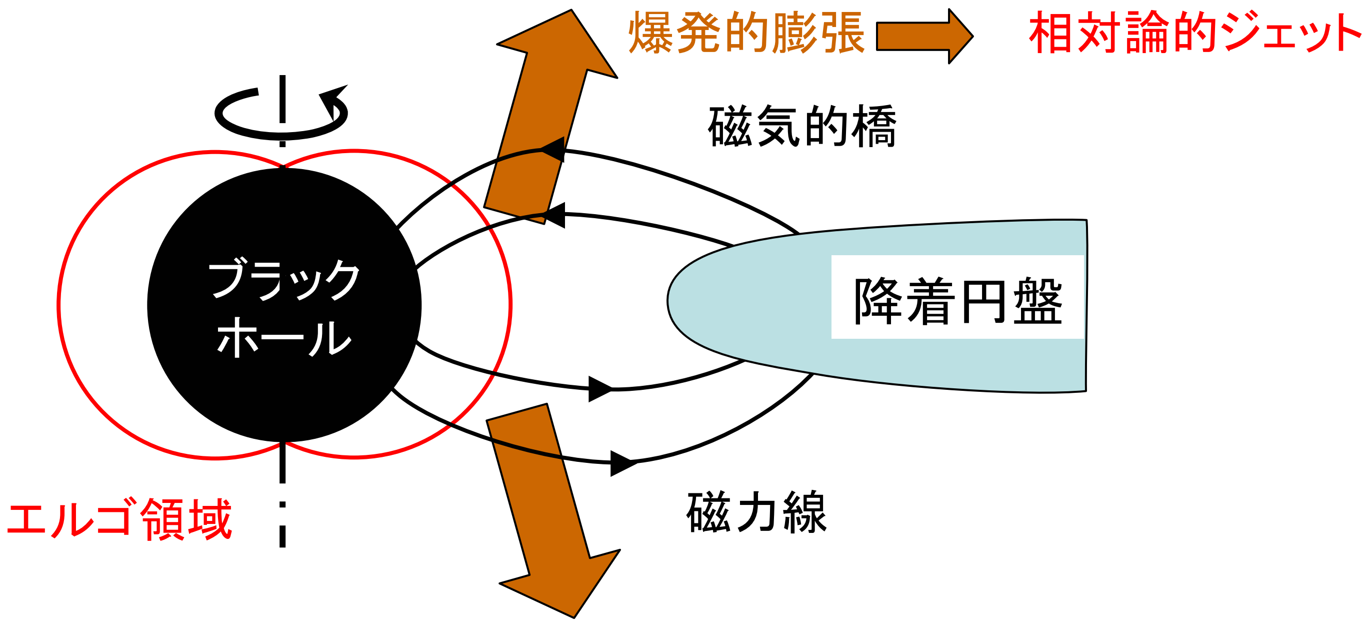
Realistic Magnetic Configuration of Black Hole Magnetosphere



磁気的橋の形成

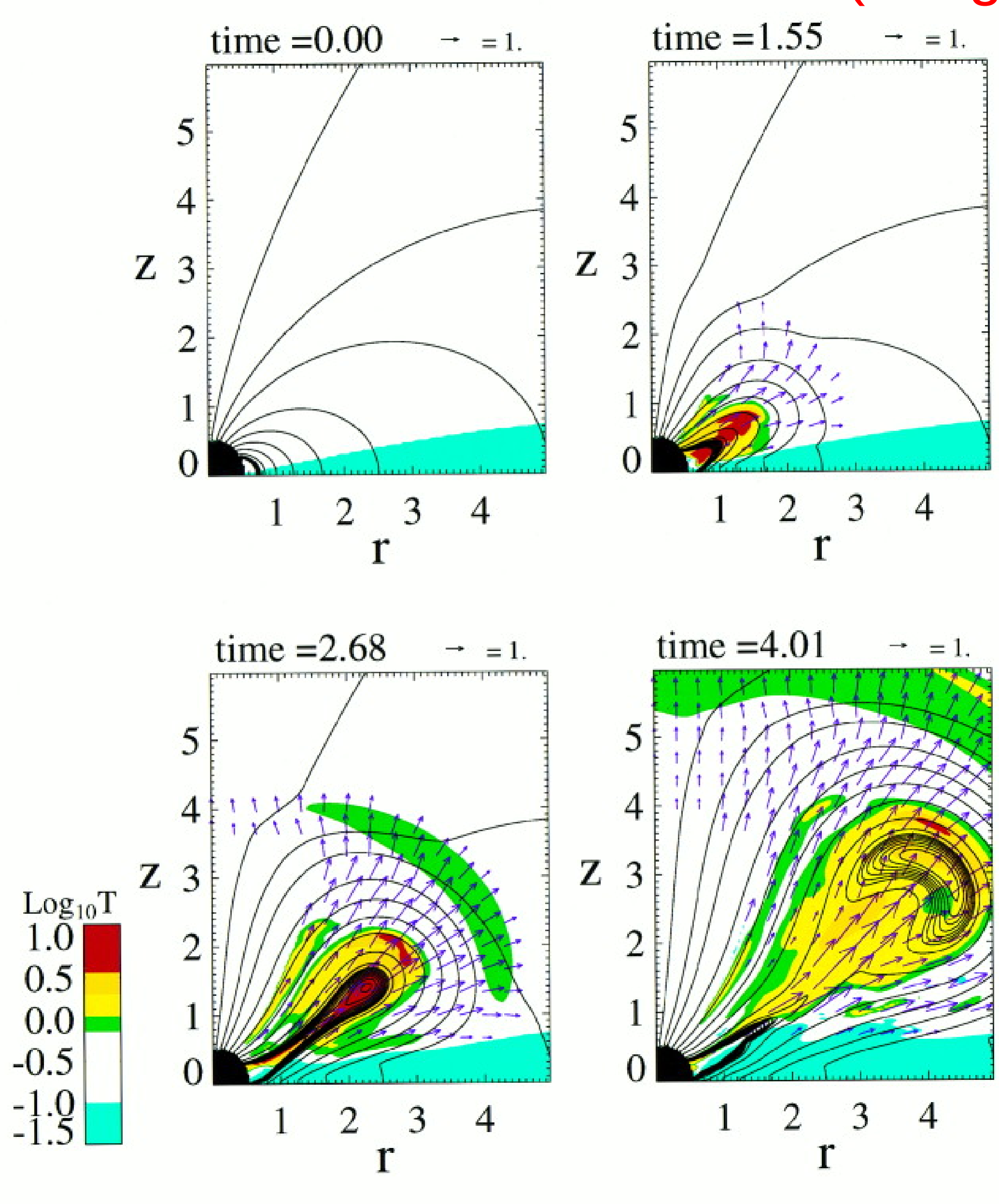


ブラック
ホール
プラズマ
降着円盤
落下
（磁気回転
不安定性）
エルゴ領域
磁力線

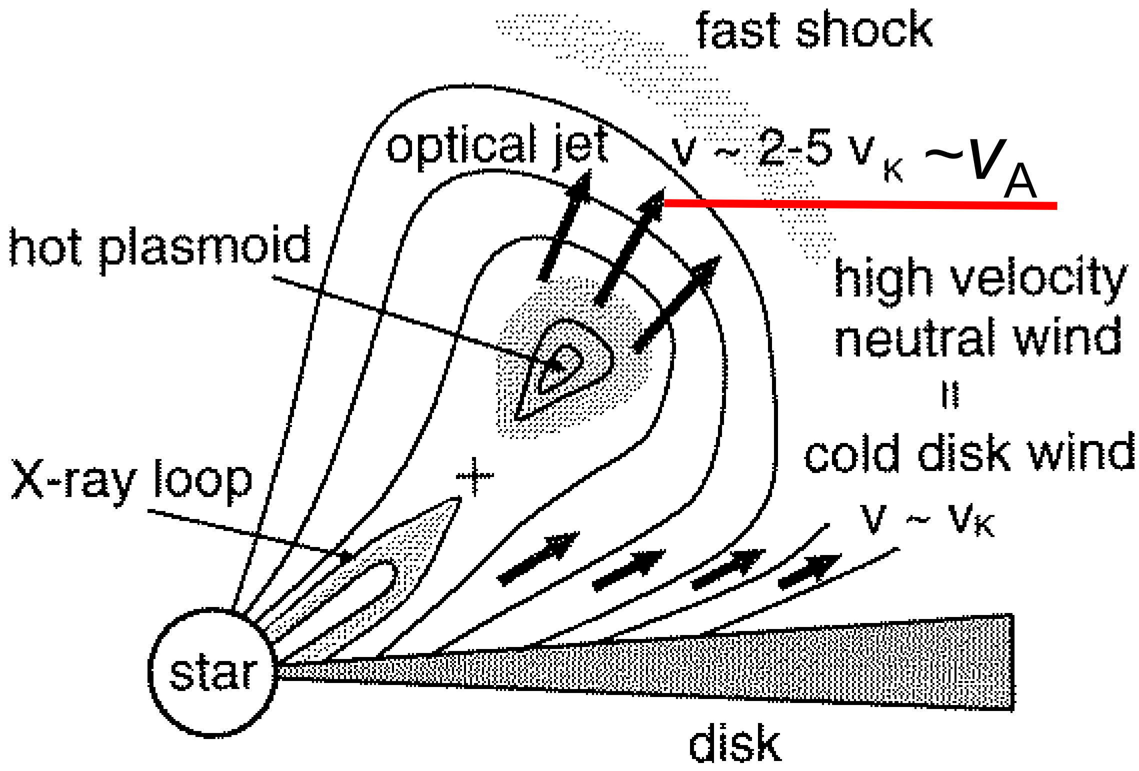


爆発的膨張
相対論的ジェット
磁気的橋
ブラック
ホール
降着円盤
エルゴ領域
磁力線

Non-Relativistic Simulation with Dipole-Magnetic Field and Disk
(bridge of magnetic field lines
between star and disk)



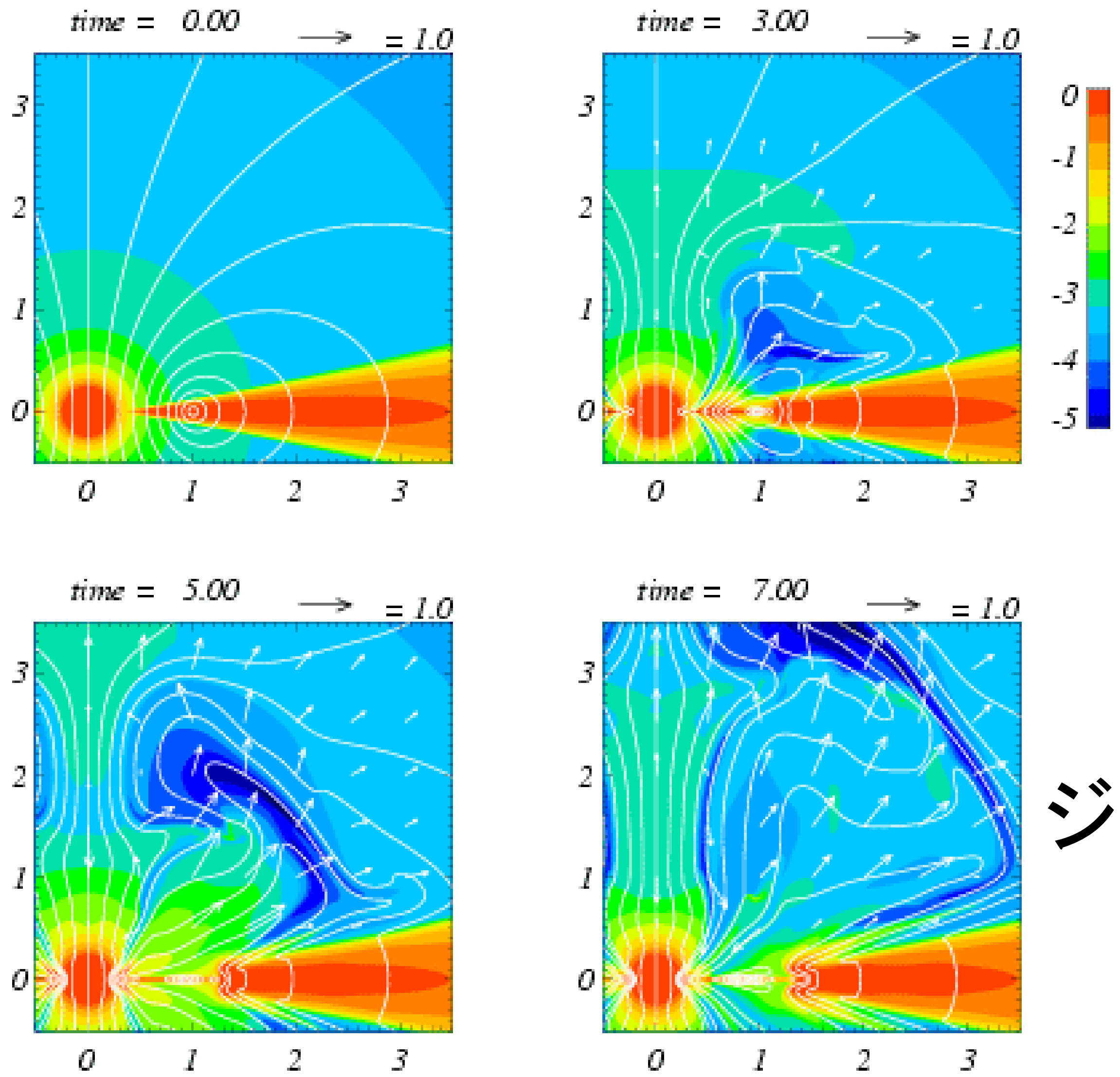
Hayashi,Shibata,
and Matsumoto
(1996)



Hayashi,Shibata, and Matsumoto (1996)

However, black hole does not sustain (dipole) magnetic field.

Non-relativistic Calculation of Current Loop Case



Kudoh, Matsumoto, & Shibata (2003)

ジェットの形成

ブラックホール近傍の電流ループが作る磁場配位について

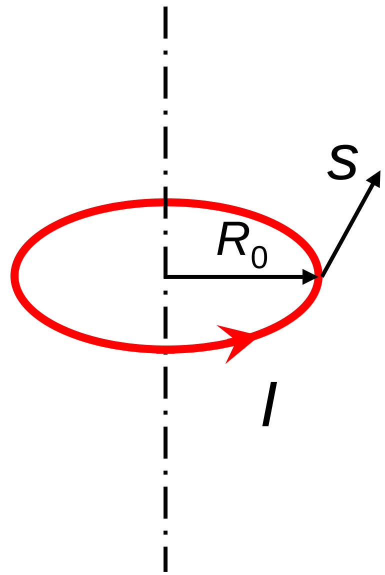
非相対論的電流ループの作る磁場のベクトル・ポテンシャル

$$A_\phi = \frac{\mu_0 I}{\pi}\frac{R_0}{\sqrt{R_0^2 + r^2 + 2R_0 r\sin\theta}}\left[\frac{\left(2-k^2\right)K(k) - 2E(k)}{k^2}\right]$$

$$k^2 = \frac{4R_0 r\sin\theta}{R_0^2 + r^2 + 2R_0 r\sin\theta}$$

$$K(k) = \int_0^{\frac{\pi}{2}}\frac{d\theta}{\sqrt{1-k^2\sin^2\theta}}$$:第1種完全楕円積分

$$E(k) = \int_0^{\frac{\pi}{2}}\sqrt{1-k^2\sin^2\theta}\,d\theta$$:第2種完全楕円積分



$s \to 0$ で$A_\phi \to \infty$なので電流ループ付近では滑らかに有界にする必要がある。

電流ループ近傍で滑らかなベクトル・ポテンシャル

$$A_\phi^{\text{nonrela, current loop}} = \frac{\mu_0 I}{\pi} \frac{R_0}{\sqrt{R_0^2 + r^2 + 2R_0 r \sin\theta}} \underbrace{\left[\frac{(2-k^2)K(k) - 2E(k)}{k^2} \right]}_{\Phi(k)}$$

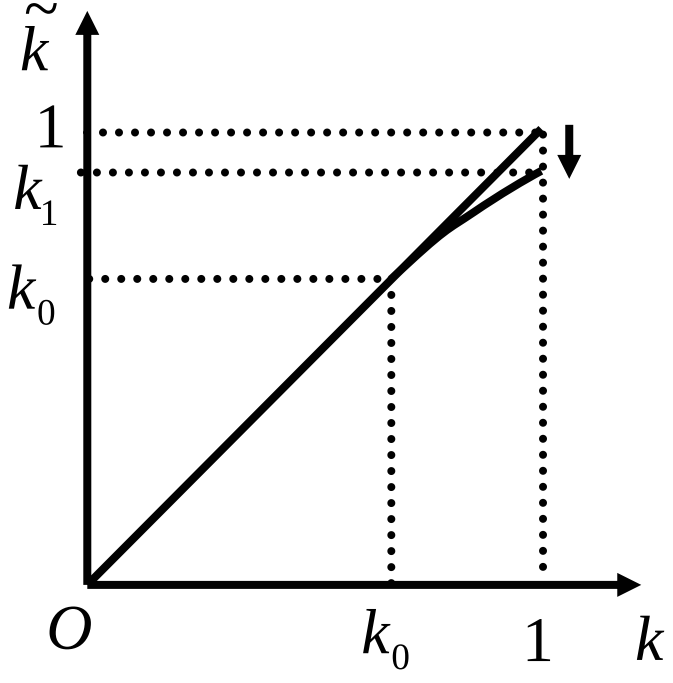
$$k^2 = \frac{4R_0 r \sin\theta}{R_0^2 + r^2 + 2R_0 r \sin\theta}$$

$s \to 0$ ($r \to R_0$, $\theta \to \pi/2$)

$k \to 1$

$\Phi \to \infty$

$A_\phi \to \infty$



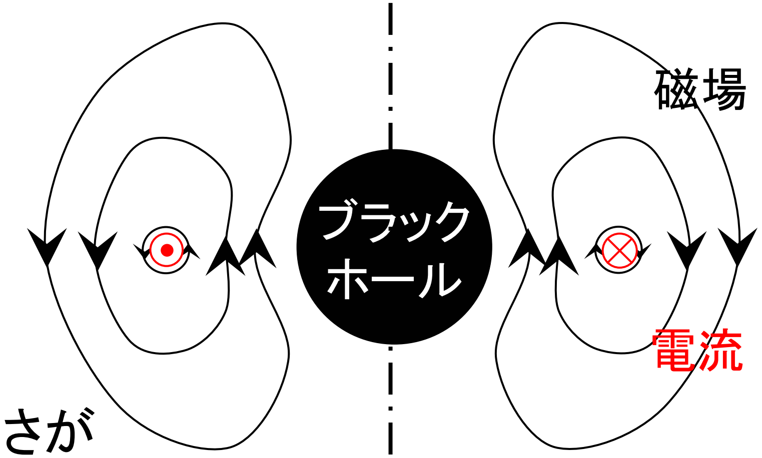
$$A_\phi = \frac{\mu_0 I}{\pi} \frac{R_0}{\sqrt{R_0^2 + r^2 + 2R_0 r \sin\theta}} \Phi(\tilde{k})$$

ブラックホールのまわりの電流ループが作る磁場のベクトルポテンシャル

- カー時空において次の条件を満たすBを与えたい:
  - ∇･B=0を満たす⇦ベクトルポテンシャル，B＝∇×A
  - 電流ループの外ではcurrent-freeに近い，∇×(αB)＝0
  - 電流ループの作る磁場のベクトルポテンシャルは次のような性質を持つ。

$$A_\phi \to A_\phi^{\text{nonrela, current loop}} \qquad (r >> r_{\rm H})$$

$$A_\phi \to A_\phi^{\text{uniform}} \qquad (r \to r_{\rm H})$$



A_ϕ^{uniform}はブラックホールの十分遠方で磁場の強さがB_0の一様磁場を与えるベクトルポテンシャルの方位角成分:

$$A_\phi^{\text{uniform}} = \frac{B_0}{2} h_\phi \left(1 - \frac{2ar_{\rm g}\alpha\beta^\phi}{h_\phi} \right) = \frac{B_0}{2} h_\phi \left(1 - \frac{4r_{\rm g}(ar_{\rm g})^2 r}{A} \right)$$

ここで,

$$A_\phi^{\text{uniform}} \to \frac{B_0}{2} h_\phi^{\text{nonrela}} \qquad \left(r >> r_{\text{H}}\right)$$

$$h_i^2 \equiv g_{ii}$$

$$A_\phi^{\text{nonrela, current loop}} \to \frac{1}{2}\frac{\mu_0 I}{2R_0} h_\phi^{\text{nonrela}} \qquad \left(r \to r_{\text{H}} << R_0\right)$$

なので,

$$A_\phi = 2\frac{A_\phi^{\text{uniform}} / B_0}{h_\phi^{\text{nonrela}}} A_\phi^{\text{nonrela, current loop}}$$

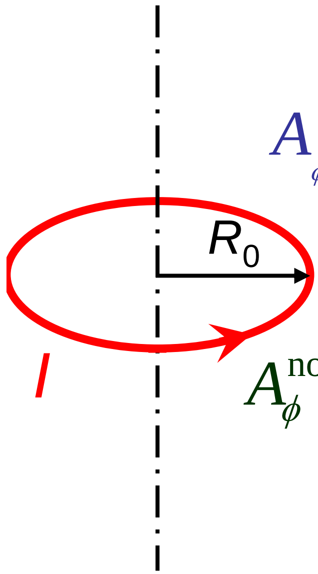
$$= \frac{h_\phi}{h_\phi^{\text{nonrela}}}\left(1 - \frac{4r_{\text{g}}\left(ar_{\text{g}}\right)^2 r}{A}\right) A_\phi^{\text{nonrela, current loop}}$$

とすればよい。

Magnetic Field induced by Current Loop around Kerr Black Hole

$\mathbf{B} = \nabla \times \mathbf{A}$ ⟵ Vector potential

$\mathbf{A} = A_\phi \hat{\phi}$



$$A_\phi = \frac{h_\phi}{h_\phi^{\text{nonrela}}}\left(1 - \frac{4 r_g (a r_g)^2 r}{A}\right) A_\phi^{\text{nonrela, current loop}}$$

Elliptic integrals of first and second kinds

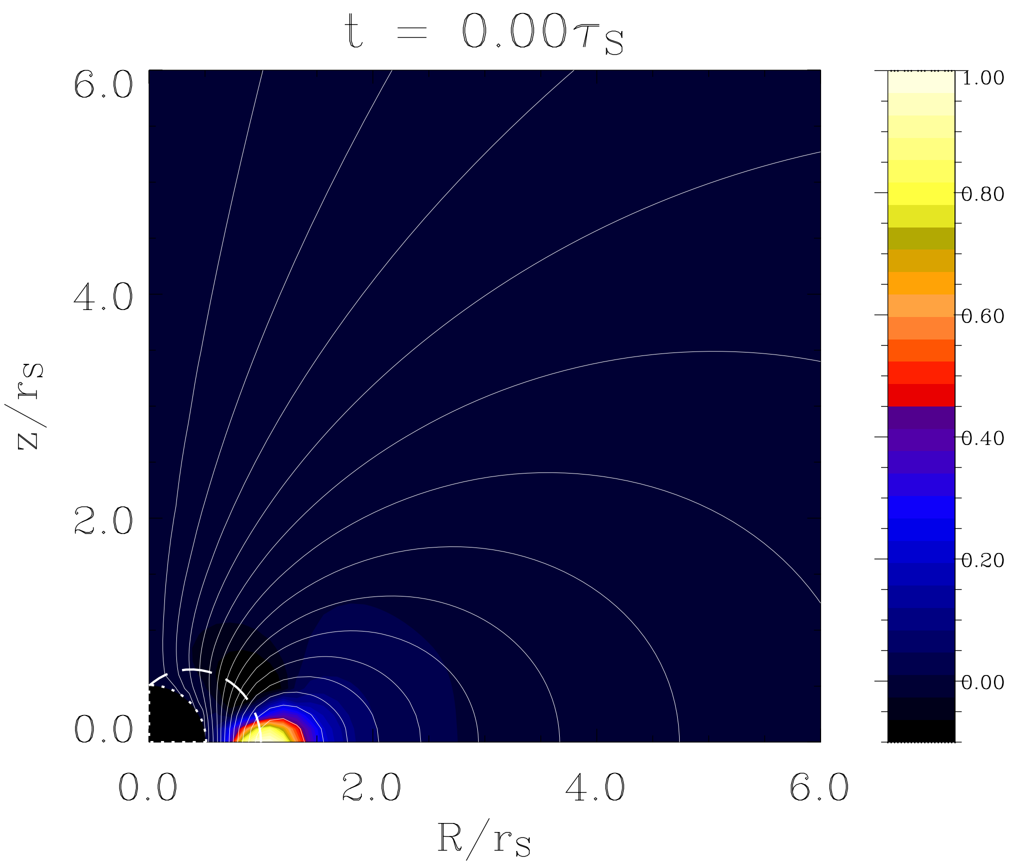
$$A_\phi^{\text{nonrela, current loop}} = \frac{\mu_0 I}{\pi} \frac{R_0}{\sqrt{R_0^2 + r^2 + 2R_0 r \sin\theta}} \left[\frac{(2 - k^2)K(k) - 2E(k)}{k^2}\right]$$

$$k^2 = \frac{4R_0 r \sin\theta}{R_0^2 + r^2 + 2R_0 r \sin\theta}$$

But, $A_\phi^{\text{nonrela}} \to \infty \quad (r \to R_0,\ \theta \to \pi/2)$

We smooth A_ϕ^{nonrela} around $r = R_0,\ \theta = \pi/2$

Current Density of Initial Magnetic Field



$R_0 = R_S$

$\delta = 0.5 R_S$

Solid line:
Magnetic field line

Color: J_ϕ

ブラックホールのまわりの
プラズマの平衡解・準平衡解

Quasi-hydrostatic Equilibrium of Plasma around Kerr Black Hole

Hydrostatic Equilibrium of Plasma

$$\rho = \rho_0 \left(\alpha^{-\frac{\Gamma}{(\Gamma_0+1)(\Gamma-1)}} - 1 \right)^{\Gamma_0}$$

$$p = \frac{\Gamma - 1}{\Gamma} \rho_0 c^2 \left(\alpha^{-\frac{\Gamma}{(\Gamma_0+1)(\Gamma-1)}} - 1 \right)^{\Gamma_0+1}$$

α : lapse function

Γ : Specific heat ratio, 5/3

Γ_0 : Positive constant

But, these variables are infinite at horizon.
Modification to finite variables at horizon
→ Quasi-hydrostatic equilibrium

$$\alpha \rightarrow \alpha(\tilde{r}, \theta)$$

$$\tilde{r} = r + (r_{\mathrm{smt}} - r_{\mathrm{H}}) \exp\left(-(r - r_{\mathrm{H}})/(r_{\mathrm{smt}} - r_{\mathrm{H}})\right)$$

$$\tilde{r} \rightarrow r_{\mathrm{smt}} \qquad (r \rightarrow r_{\mathrm{H}})$$

GRMHD方程式

- 放射冷却効果を無視。
- 放射圧を無視。
- 電気抵抗はゼロ。
- ホール効果は無視。
- プラズマの粘性を無視。
- プラズマの自己重力無視。
- ブラックホールは定常とする。
- 原子核・素粒子反応は無視する。

大須賀さん
廣瀬さん
町田さん
→ 渡邊さん
仰木さん
柴田大さん
→ 滝脇さん

Base of General Relativistic MHD in Kerr Space-Time

- General relativistic equation of conservation laws and Maxwell equations:

$$\nabla_\nu (n U^\nu) = 0$$ (conservation of particle number)

$$\nabla_\nu T^{\mu\nu} = 0$$ (conservation of energy and momentum)

$$\partial_\mu F_{\nu\lambda} + \partial_\nu F_{\lambda\mu} + \partial_\lambda F_{\mu\nu} = 0$$

$$\nabla_\mu F^{\mu\nu} = - J^\nu$$

(Maxwell equations)

- Frozen-in condition: $F_{\nu\mu} U^\nu = 0$
- Kerr Metric: $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$;

$$g_{00} = - h_0^2 ; \quad g_{ii} = - h_i^2 ;$$

$$g_{0i} = - h_i^2 \omega_i \ (i=1,2,3) ; \quad g_{ij} = 0 \ (i \neq j)$$

n: proper particle number density. p : proper pressure. c: speed of light.
e : proper total energy density, $e=mnc^2 + p / (\Gamma -1)$.
m : rest mass of particles. Γ: specific heat ratio.
$U^{\mu\upsilon}$: velocity four vector. $A^{\mu\upsilon}$: potential four vector. $J^{\mu\upsilon}$: current density four vector.
$\nabla^{\mu\nu}$: covariant derivative. $g_{\mu\nu}$: metric.
$T^{\mu\nu}$: energy momentum tensor, $T^{\mu\nu} = pg^{\mu\nu} + (e+p)U^\mu U^\nu + F^{\mu\sigma} F^\nu{}_\sigma - g_{\mu\nu} F^{\lambda\kappa} F_{\lambda\kappa}\}/4$.
$F_{\mu\nu}$: field-strength tensor, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

Vector Form of General Relativistic MHD Equation
(3+1 Formalism) ~ similar to Classical MHD

Special relativistic mass density, γρ

$$\frac{\partial D}{\partial t} = -\nabla \cdot [\alpha D(\mathbf{v} + \mathbf{v}_{\mathrm{H}})]$$ (conservation of particle number)

general relativistic effect

Special relativistic total momentum density

$$\frac{\partial \mathbf{P}}{\partial t} = -\nabla \cdot [\alpha(\mathbf{T} + c\beta\mathbf{P})] - \left(D + \frac{\varepsilon}{c^2} \right) \nabla (c^2 \alpha) + \alpha \mathbf{f}_{\mathrm{curv}} - \mathbf{P} : \boldsymbol{\sigma}$$ (equation of motion)

special relativistic effect

Special relativistic total energy density

$$\frac{\partial \varepsilon}{\partial t} = -\nabla \cdot [\alpha(c^2 \mathbf{P} - Dc^2 \mathbf{v} + e\mathbf{v}_{\mathrm{H}})] - (\nabla \alpha) \cdot c^2 \mathbf{P} - \mathbf{T} : \boldsymbol{\sigma}$$ (equation of energy)

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times [\alpha(\mathbf{E} - c\boldsymbol{\beta} \times \mathbf{B})] \qquad \mathbf{J} + \rho_e c \boldsymbol{\beta} + \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} = \nabla \times \left[\alpha \left(\mathbf{B} + \frac{\boldsymbol{\beta}}{c} \times \mathbf{E} \right) \right]$$

$$\nabla \cdot \mathbf{B} = \mathbf{0} \qquad \rho_e = \frac{\alpha}{c^2} \nabla \cdot \mathbf{E}$$ (Maxwell equations)

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \mathbf{0}$$ (ideal MHD condition)

where

$$\alpha = \sqrt{h_0^2 + \sum_{i=1}^{3} \left(\frac{h_i \omega_i}{c} \right)^2}$$: (Lapse function)

$$\beta^i = \frac{h_i \omega_i}{c\alpha}$$: (shift vector)

$$\mathbf{v}_{\mathrm{H}} = c\boldsymbol{\beta}$$: (shift velocity)

$$f_{\mathrm{curv}}^{i} = \sum_{j=1}^{3} \left(G_{ij} T^{ij} - G_{ji} T^{jj} \right) \qquad G_{ij} = -\frac{1}{h_i h_j} \frac{\partial h_i}{\partial x^j} \qquad \sigma_{ij} = \frac{h_i}{h_j} \frac{\partial \omega_i}{\partial x^j}$$

準静水圧平衡コロナでの計算
テスト計算→数値計算

Initial Condition

- Black Hole: $a \equiv \dfrac{J}{J_{\max}} = 0.99995$ (Almost maximally rotating)
- Magnetic Field: Magnetic field induced by current loop around black hole (J_0=1.5π/2, R_0=r_S, δ=0.5r_S)
- Plasma:
  - Corona
    quasi-hydrostatic equilibrium (Γ_0=5, ρ_0=0.018, r_{smt}=0.8r_S)
    $\hat{\mathbf{v}} = 0$
  - Disk
    $\rho_{disk} = 100\,\rho_{corona}$, $p_{disk} = p_{corona}$
    $\hat{\mathbf{v}}_P = 0,\qquad v_\phi = \pm v^{\pm}_{Kepler}$ { Co-rotating disk / ~~Counter-rotating disk~~

Boundary Condition

- Calculation region:

$$1.016 r_{\mathrm{H}} \leq r \leq 80 r_{\mathrm{H}}$$

$$0.01 \leq \theta \leq \pi / 2$$

- Boundary condition:

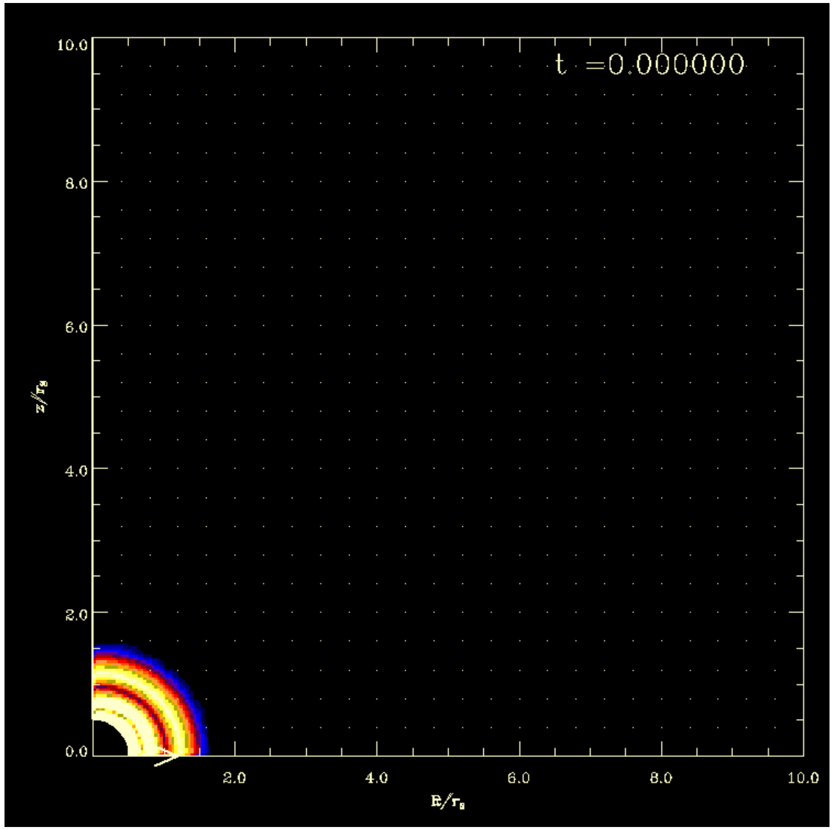
Radial boundary condition: free boundary condition

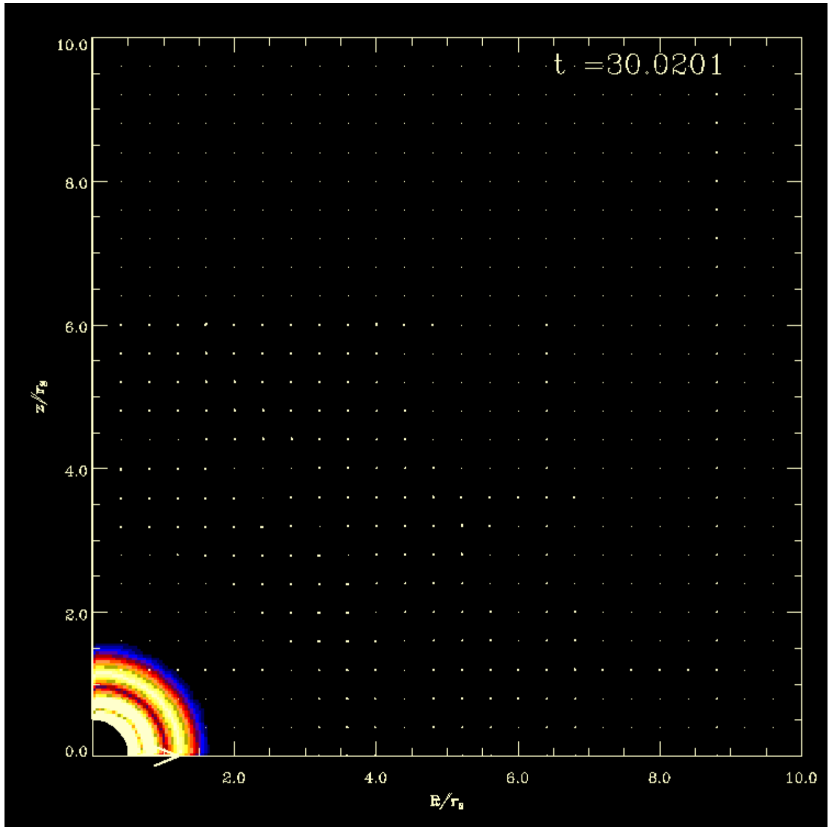
Axi-symmetric and mirror boundary conditions
at $\theta = 0.01,\ \pi/2$

完全静水圧平衡のテスト

$\tau_S = r_S / c$

$t = 0$ $t = 30\tau_S$

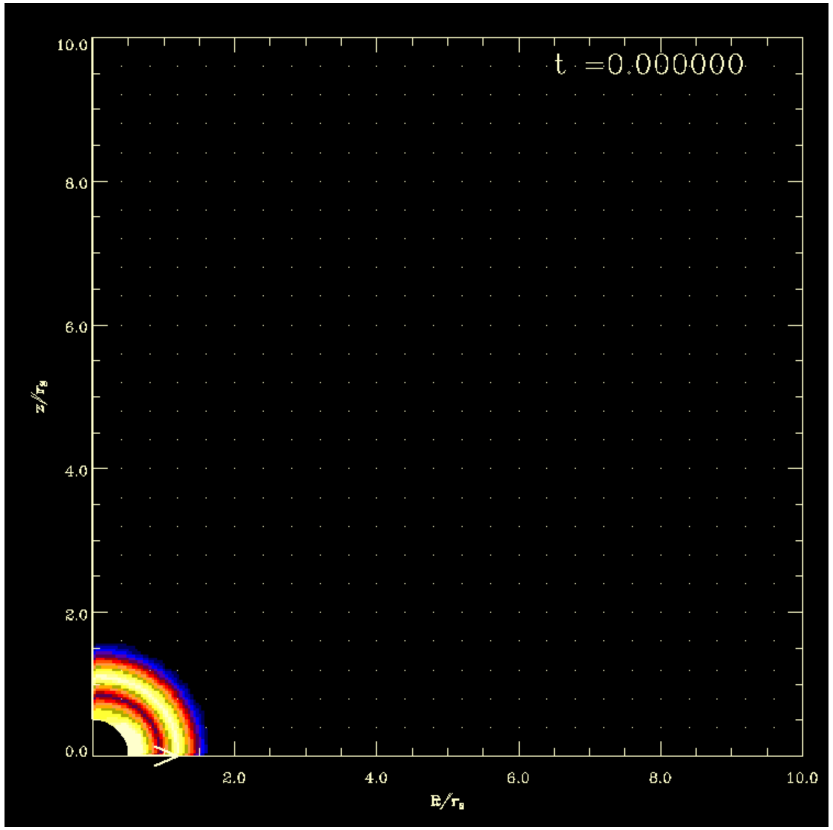




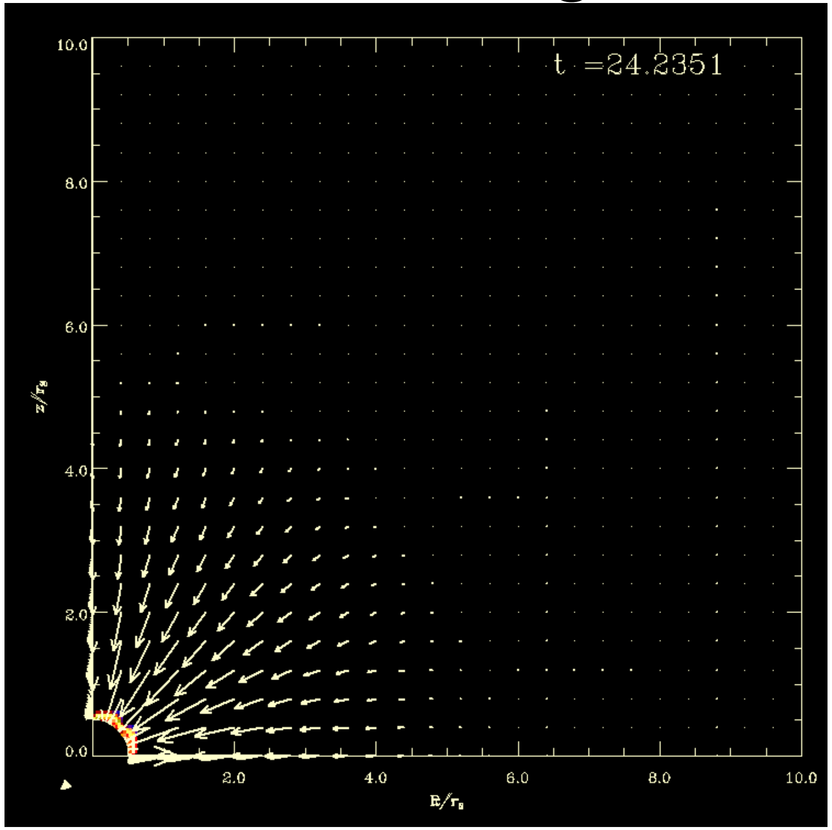
Color: log ρ , Arrows: Velocity

準静水圧平衡のテスト

t =0



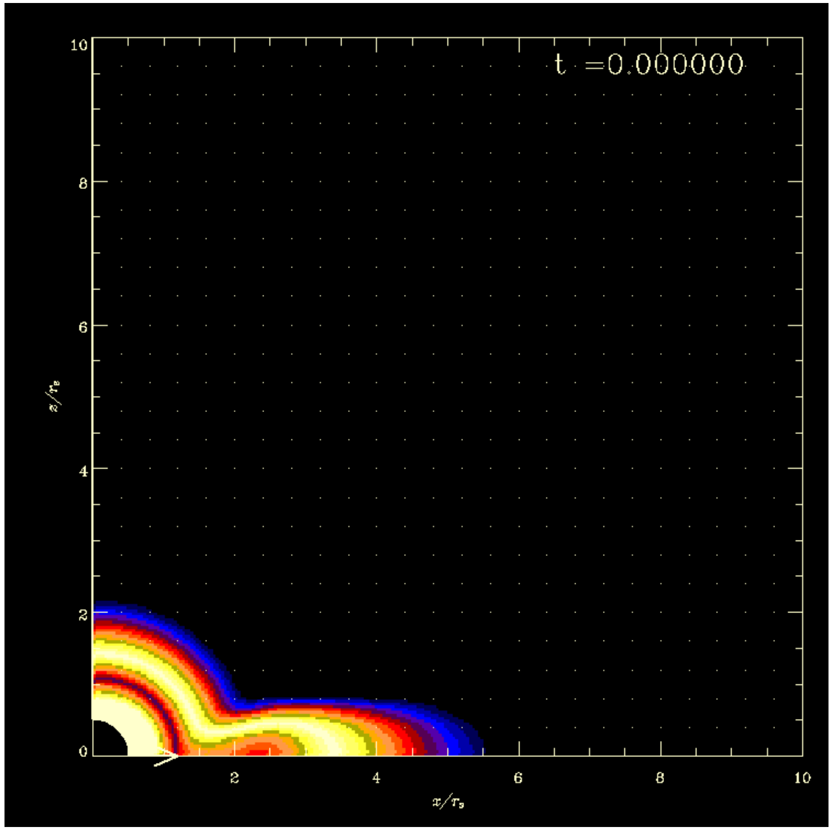
t =24.23τ_S



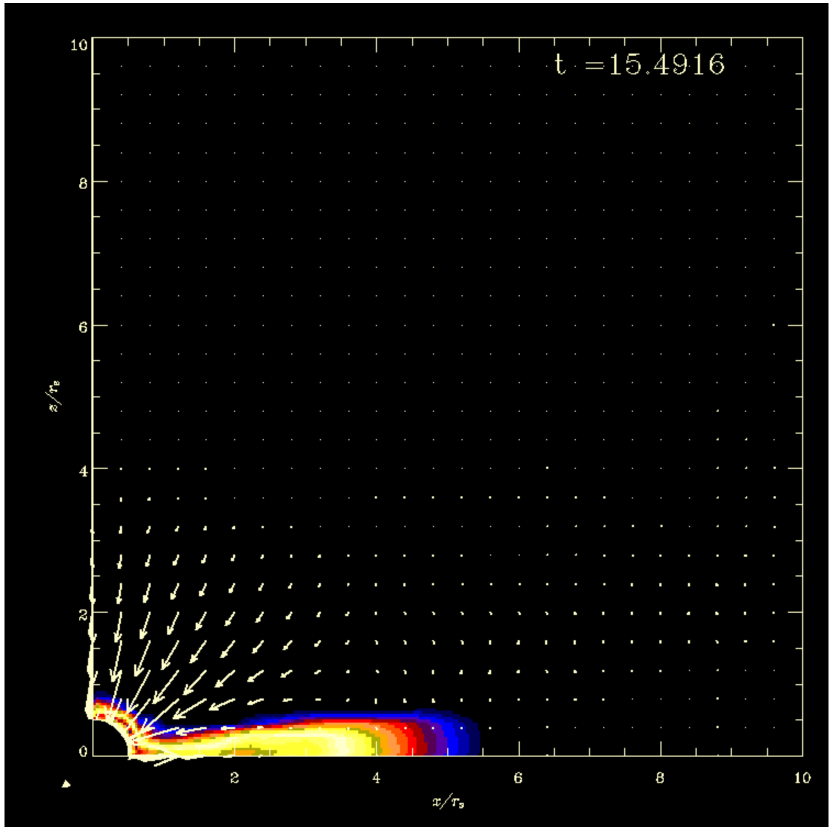
Color: log ρ , Arrows: Velocity

順方向回転円盤

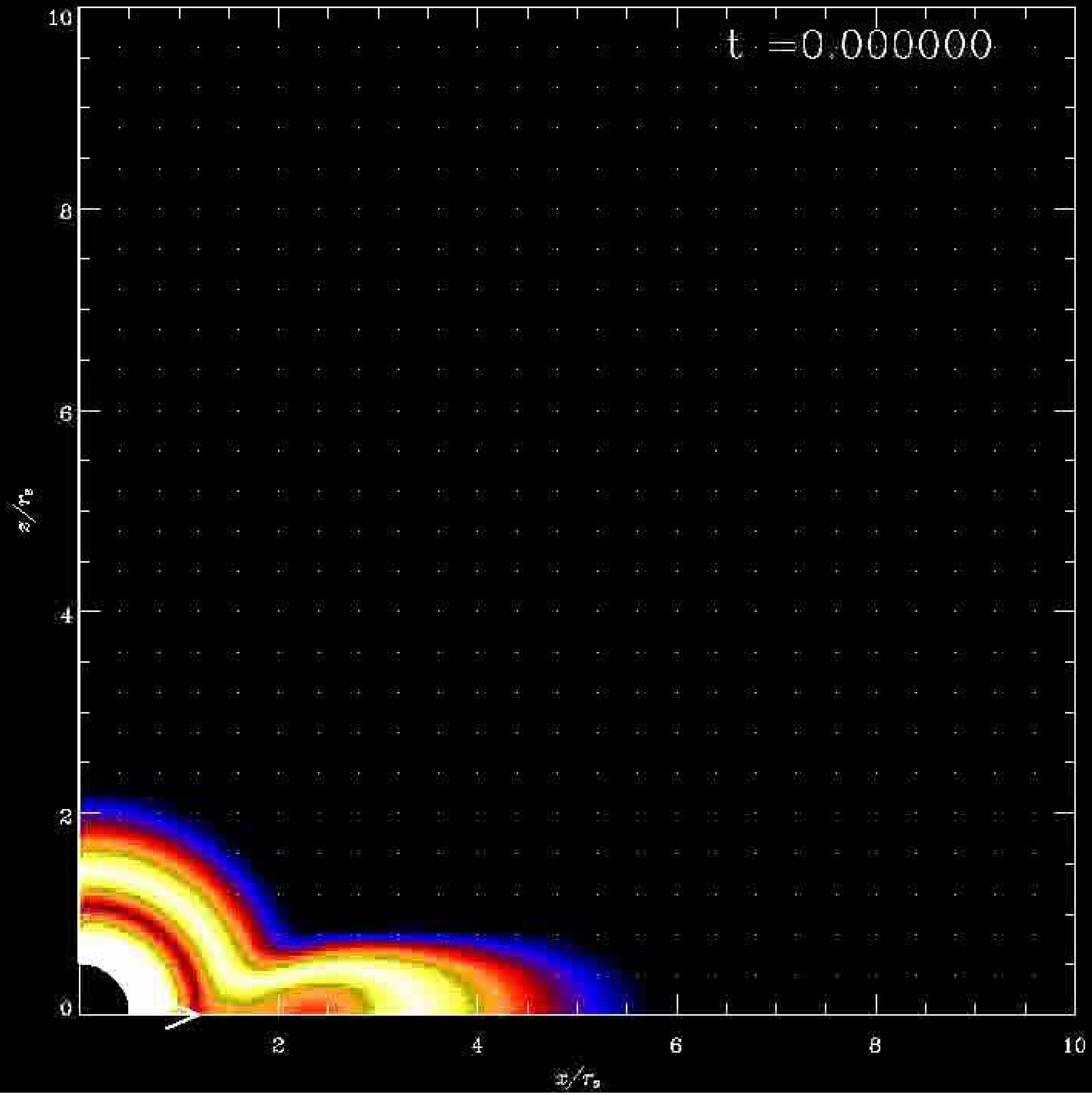
t =0



t =15.49τ_S



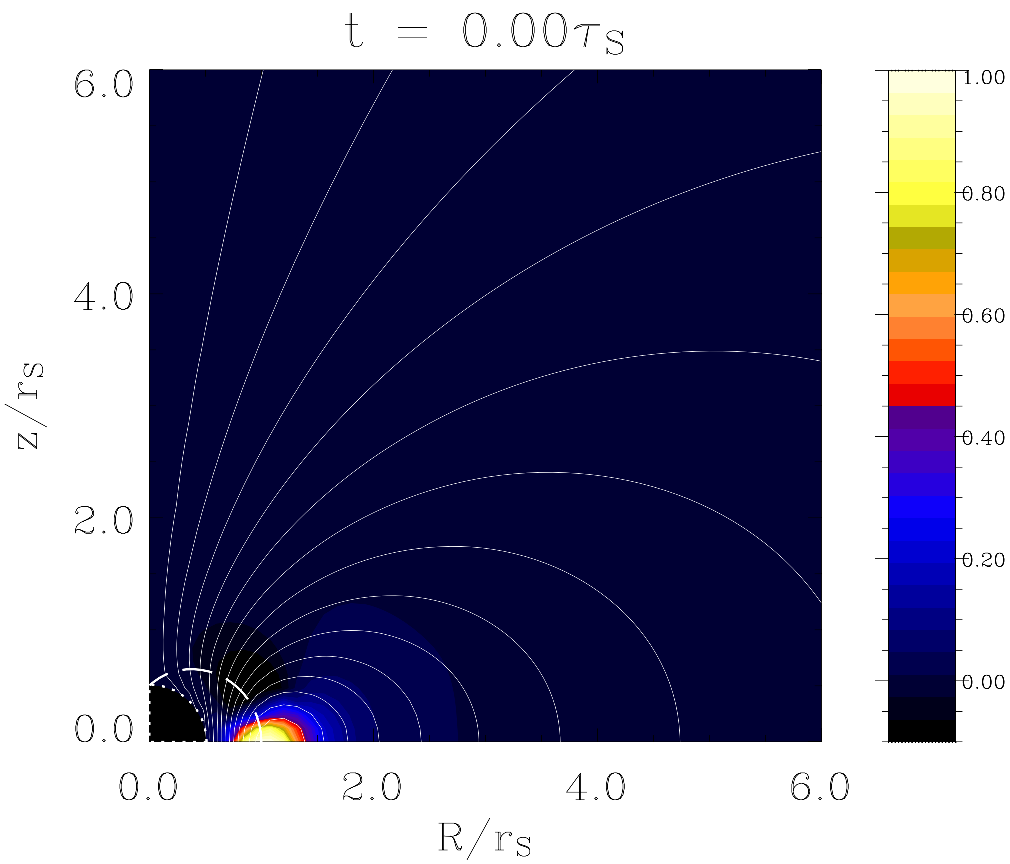
Color: log ρ , Arrows: Velocity



Color: log ρ
Arrows:
Velocity

電流ループ磁場印加

Current Density of Initial Magnetic Field

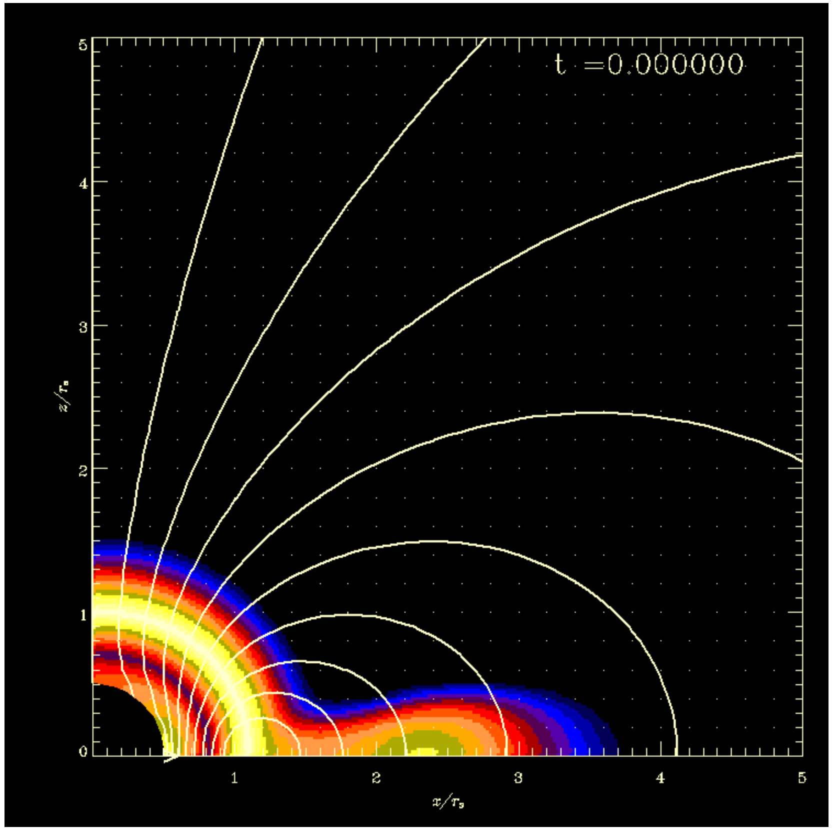


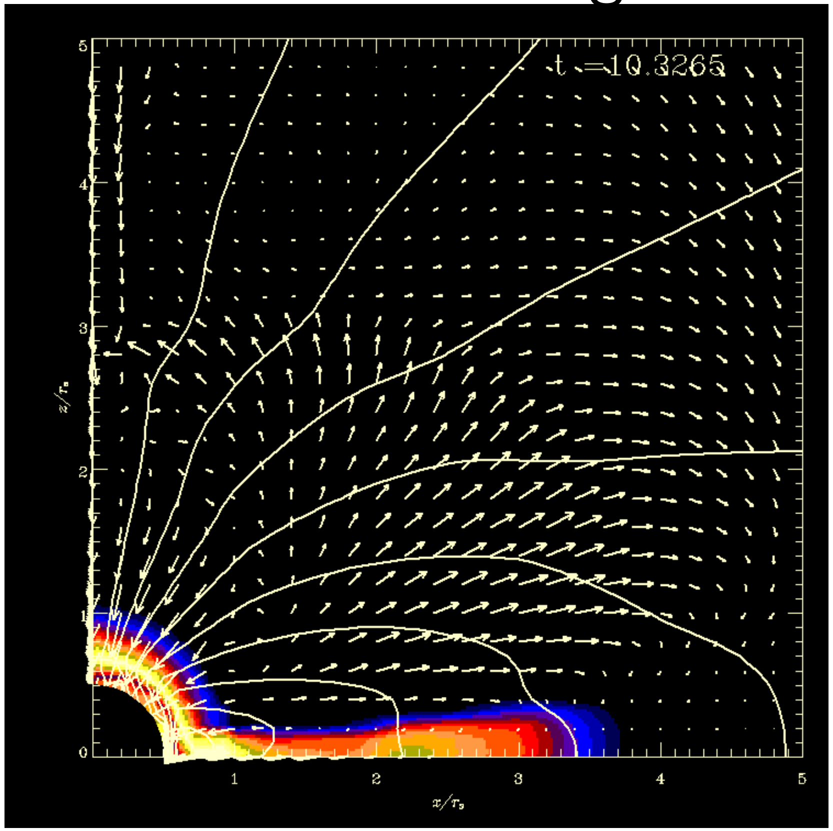
Solid line:
Magnetic field line

Color: J_ϕ

電流ループ磁場印加

$t = 0$ $\qquad$ $t = 10.33\tau_S$



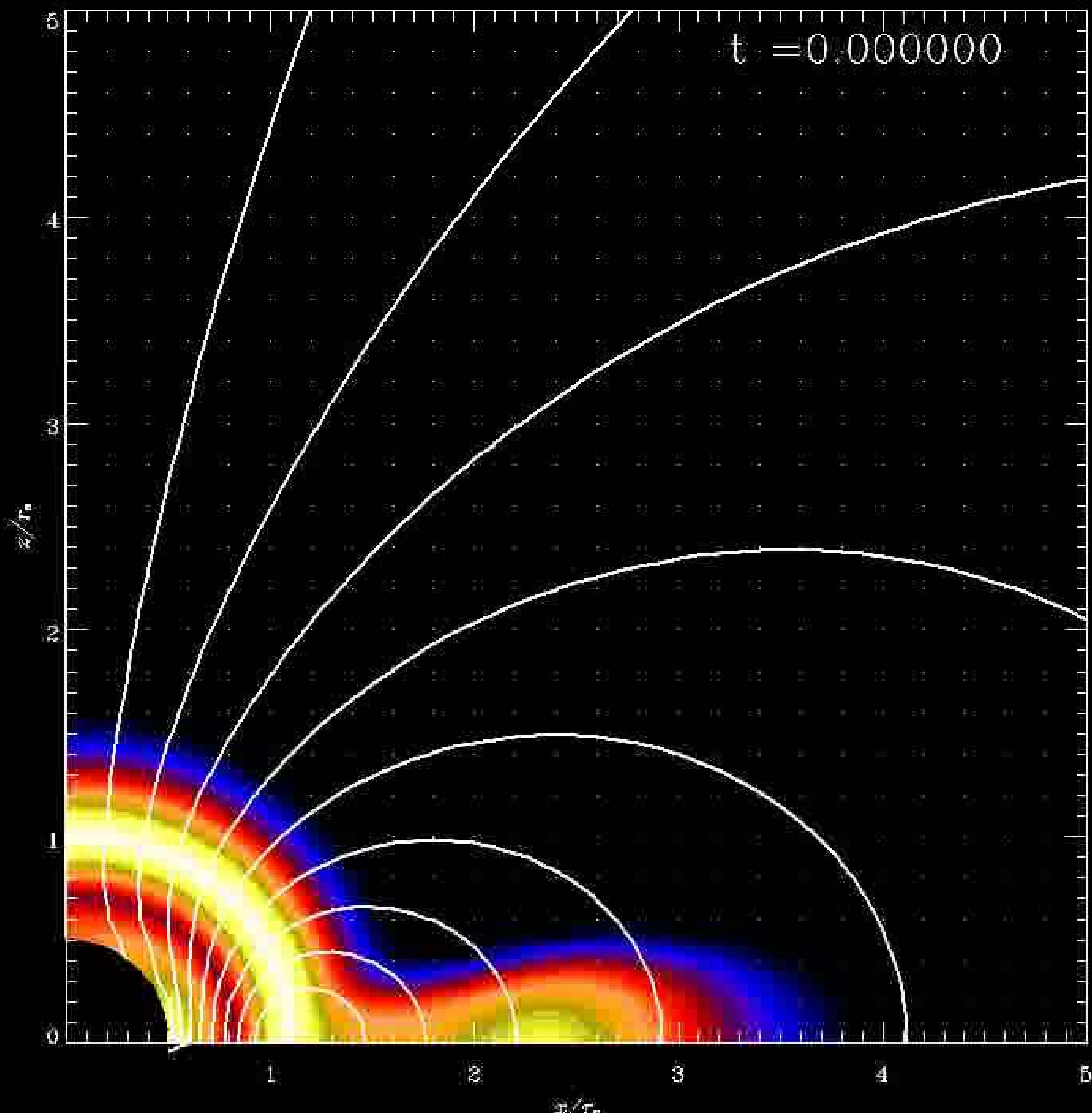


Solid line: Magnetic field line

Color: $\log \rho$, Arrows: Velocity

$v^{max} = 0.580c$

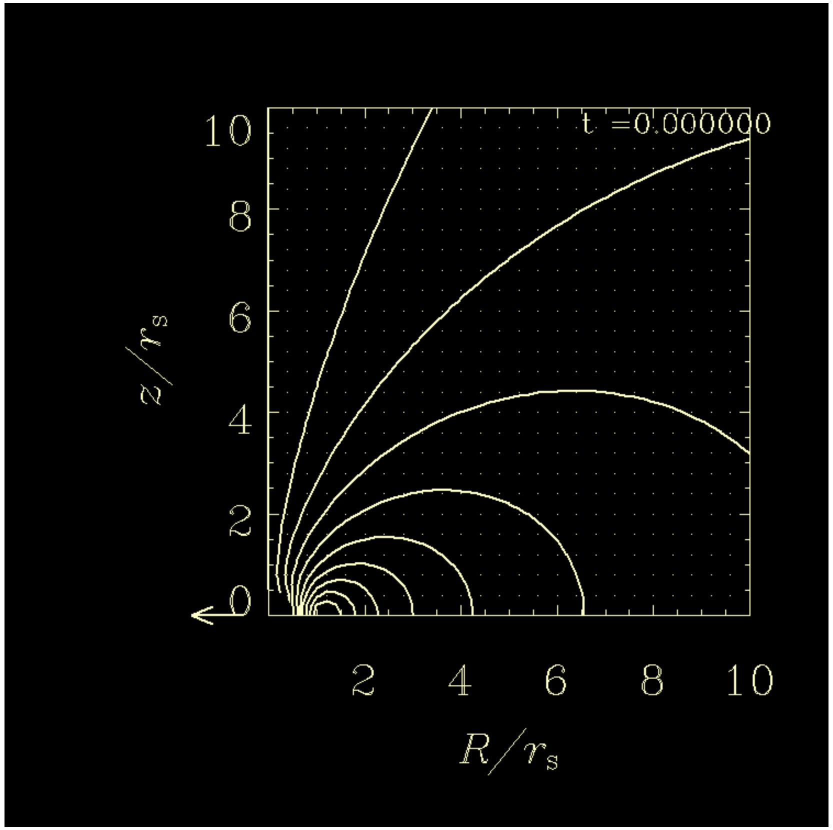
$v_P^{max} = 0.370c$

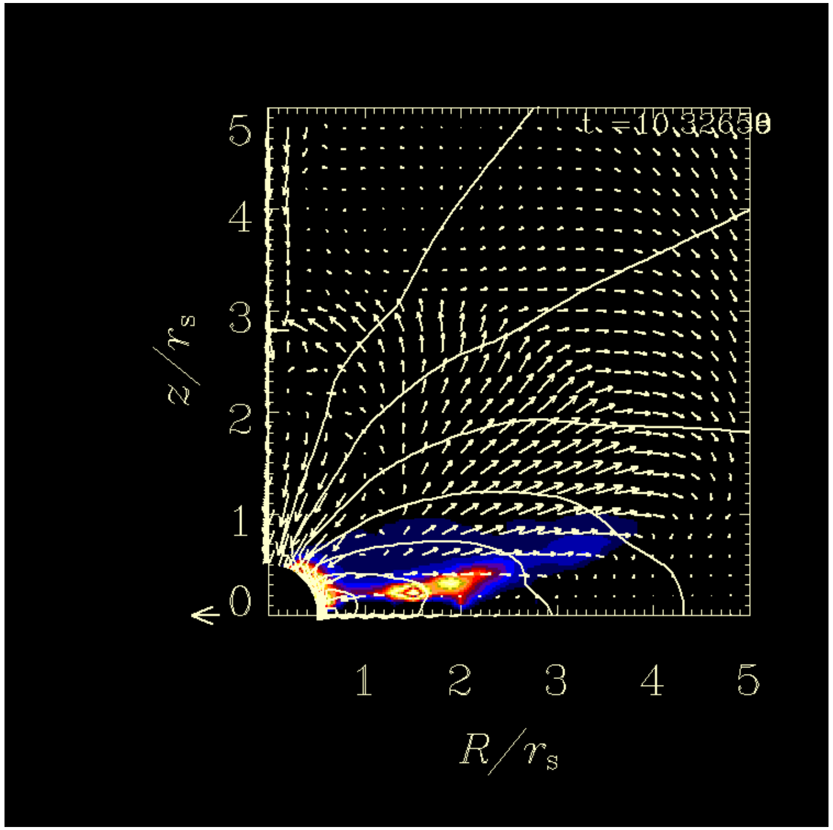


Solid line:
Magnetic
Field line
Color: log ρ
Arrows:
Velocity

Azimuthal component of Magnetic Field

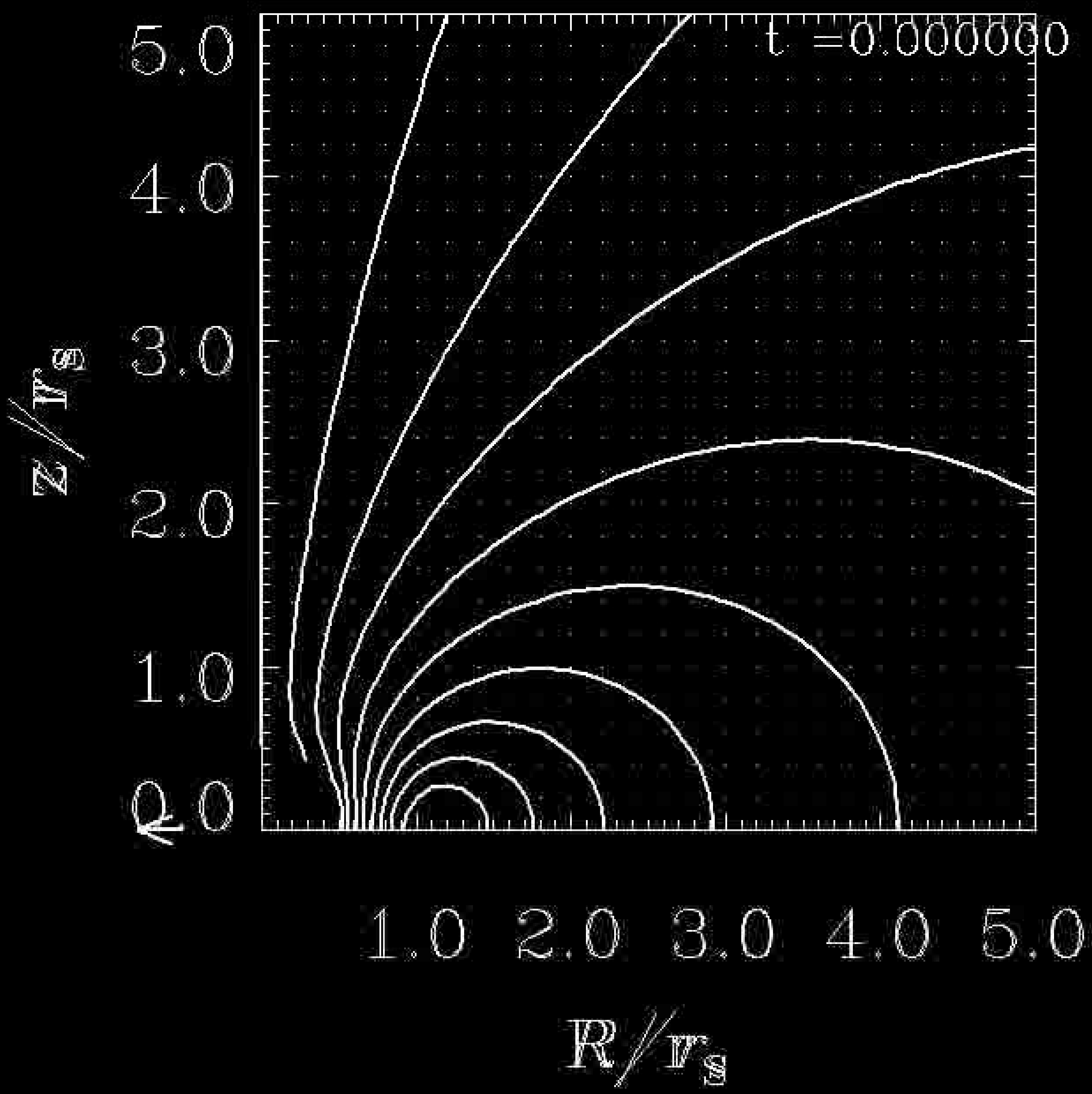
t =0 t =10.33τ_S





Color: $B_\phi{}^2/\rho c^2$

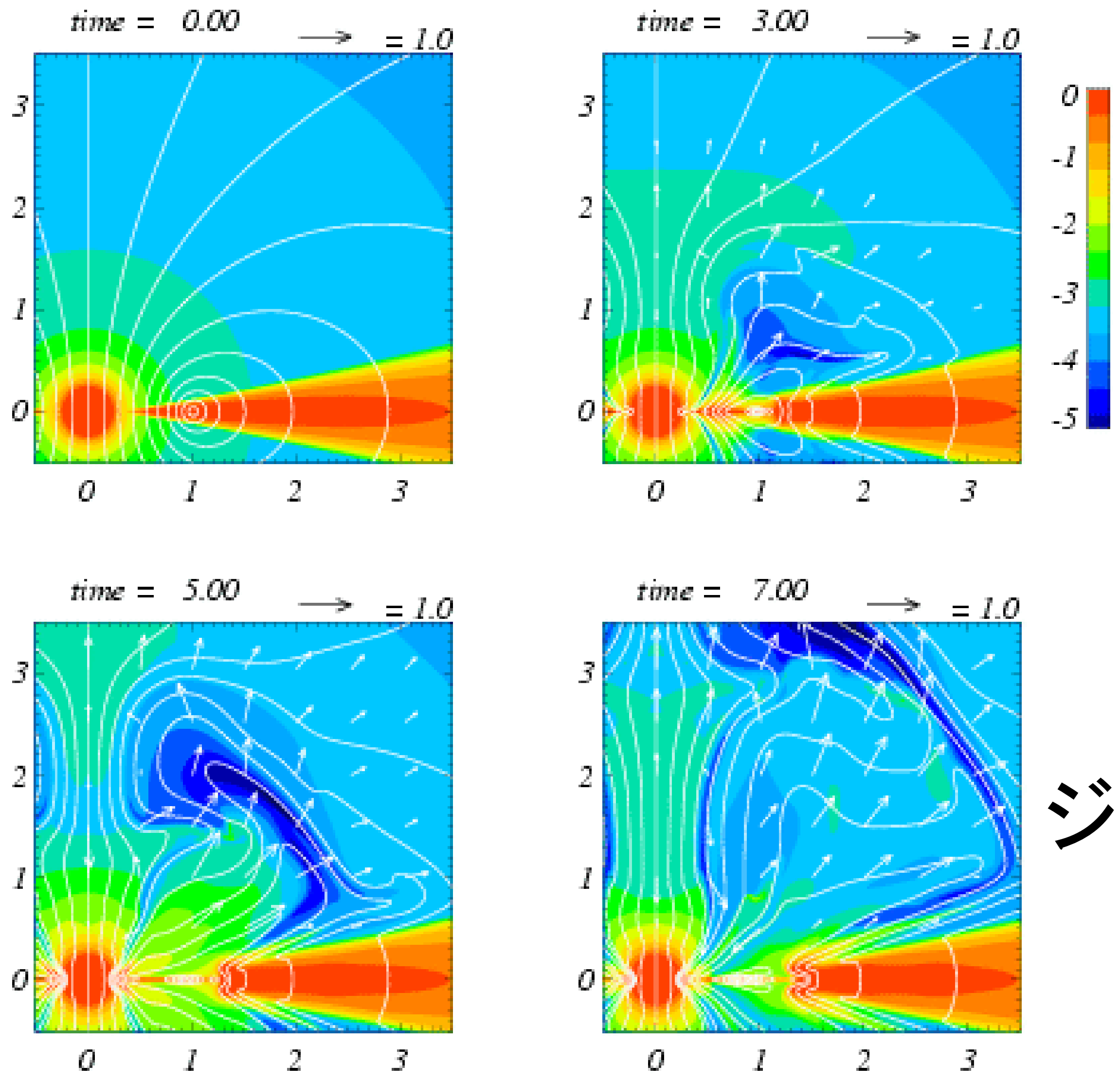
Solid line: Magnetic field line



Solid line:
Magnetic field line
Color: $B_\phi^2/\rho c^2$
Arrows:
Velocity

What happen after the final time of present calculations?

Non-relativistic Calculation of Current Loop Case



Kudoh, Matsumoto, & Shibata (2003)

ジェットの形成

静水圧平衡コロナでの計算
計算結果
（長時間の追跡が可能）

Initial Condition

- Black Hole: $a \equiv \frac{J}{J_{\max}} = 0.99995$ (Almost maximally rotating)
- Magnetic Field: Magnetic field induced by current loop around black hole (J_0=1.5π/2, R_0=r_S, δ=0.5r_S)
- Plasma:
  - Corona

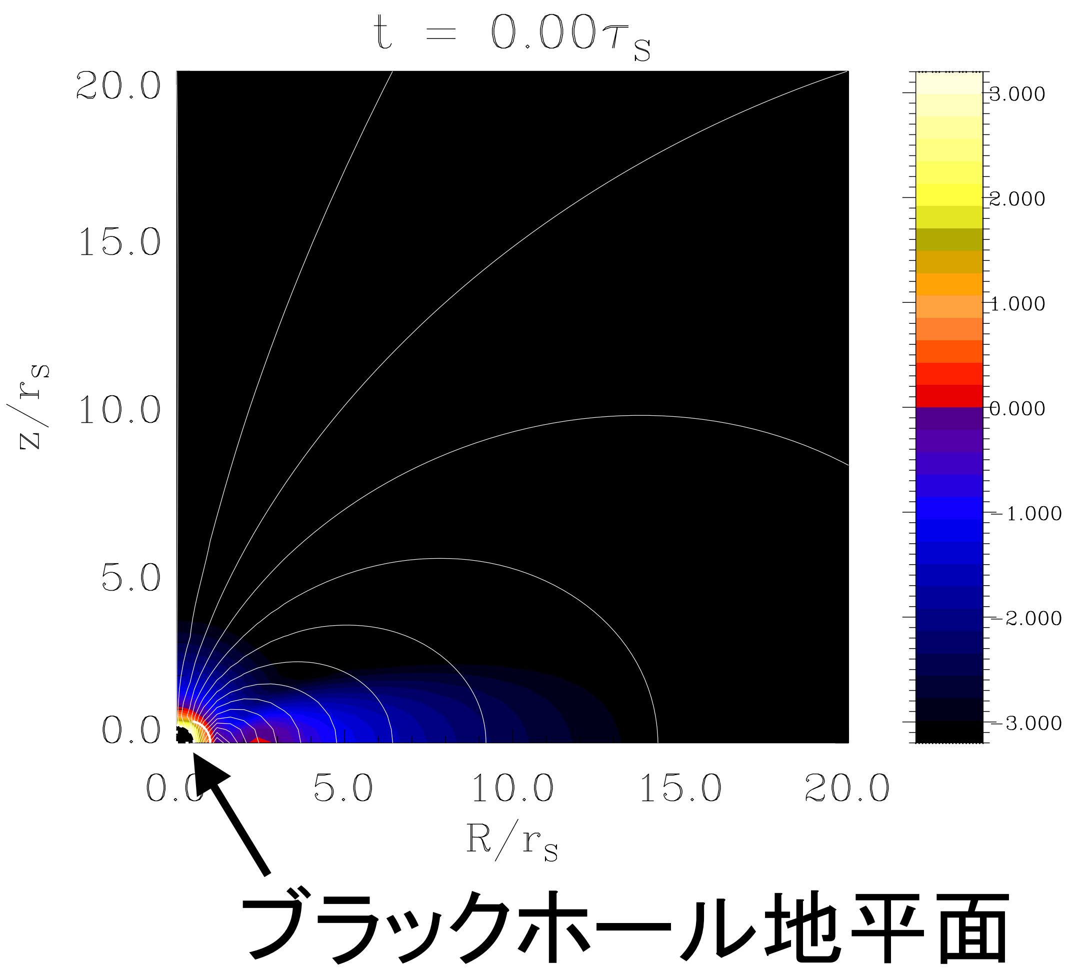
    hydrostatic equilibrium (Γ_0=4, ρ_0=0.018)

    $\hat{\mathbf{v}} = 0$
  - Disk

    $\rho_{\text{disk}} = 300\,\rho_{\text{corona}}$, $p_{\text{disk}} = p_{\text{corona}}$

    $\hat{\mathbf{v}}_{\mathrm{P}} = 0,\quad v_\phi = v^{\pm}_{\text{Kepler}}$ { Co-rotating disk / ~~Counter-rotating disk~~

初期条件：
磁気配位，質量密度分布

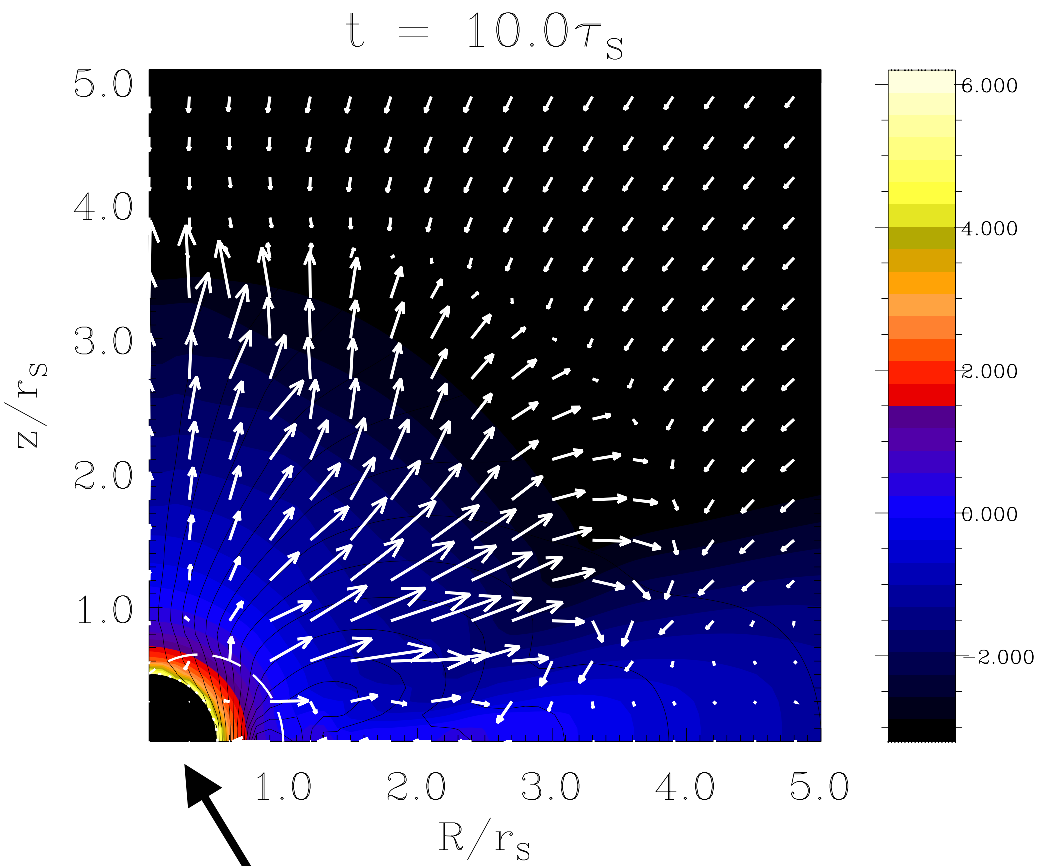


t =0

Solid line:
Magnetic field line

Color: log ρ

磁気配位，速度，質量密度分布



ブラックホール地平面

$t = 10\tau_S$

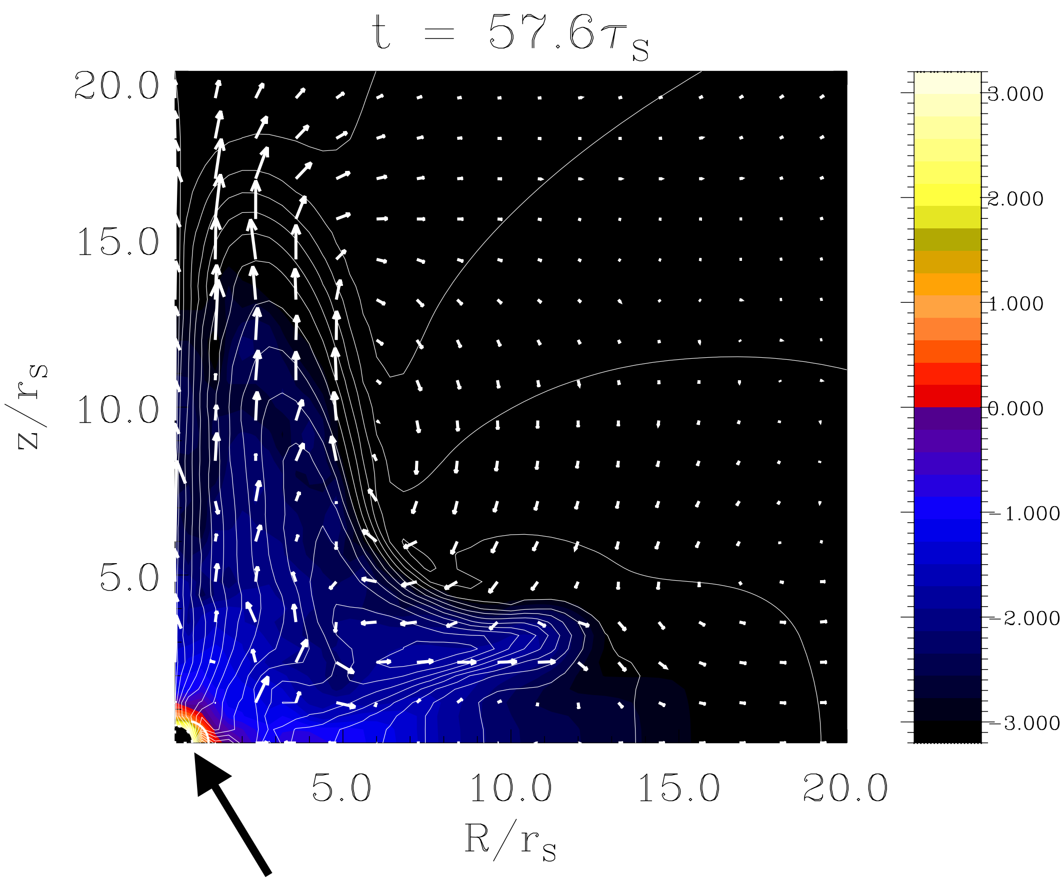
Solid line:
Magnetic field line

Color: $\log \rho$

Arrow: Velocity

$v^{max} = 0.664c$
$v_P^{max} = 0.387c$

計算の最終状態：
磁気配位，速度，質量密度分布



ブラックホール地平面

$t = 57.6\tau_S$

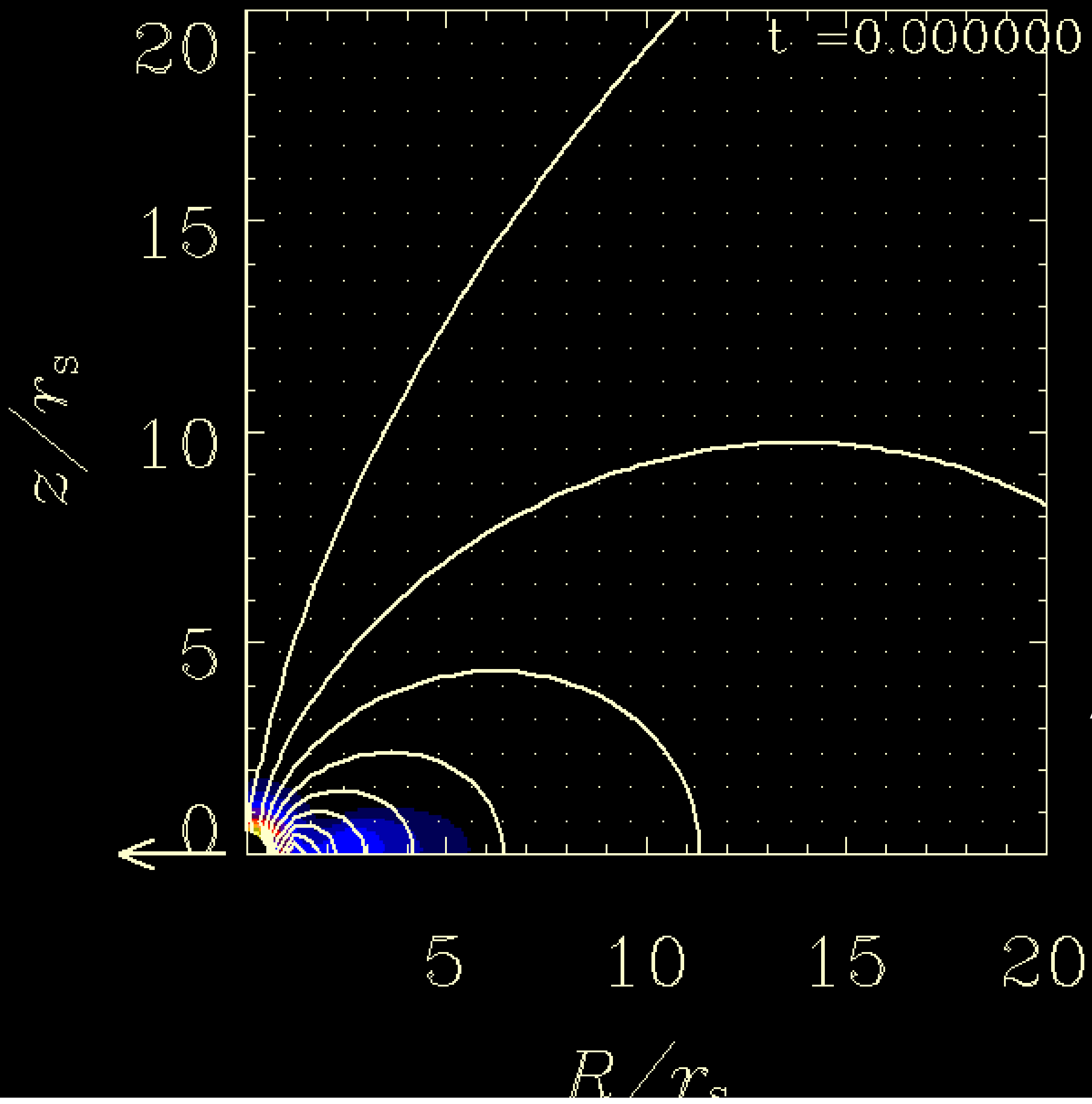
Solid line:
Magnetic field line

Color: $\log \rho$

Arrow: Velocity

$v^{max} = 0.502c$

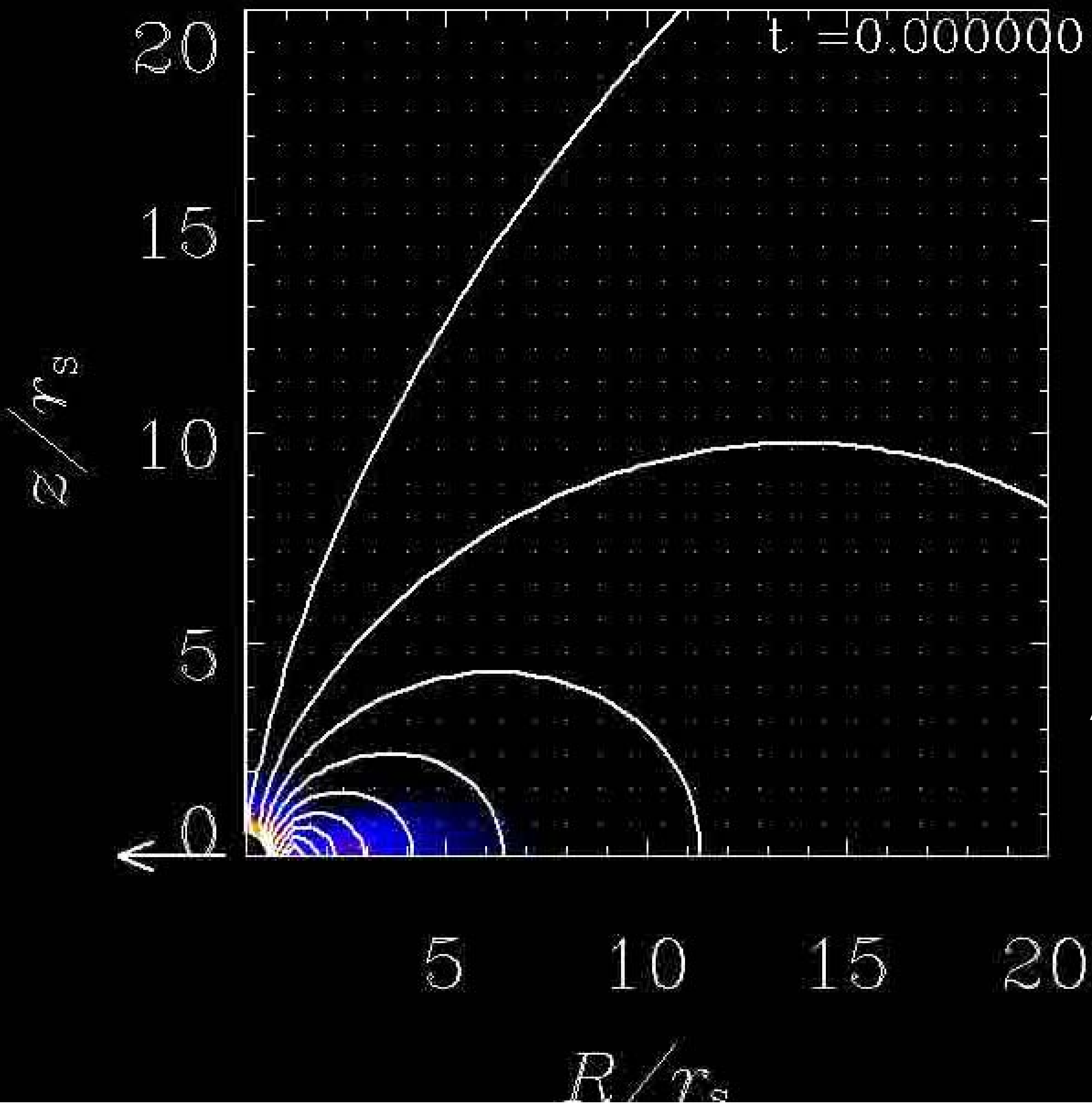
$v_P^{max} = 0.367c$



Solid line:
Magnetic field line

Color: log ρ

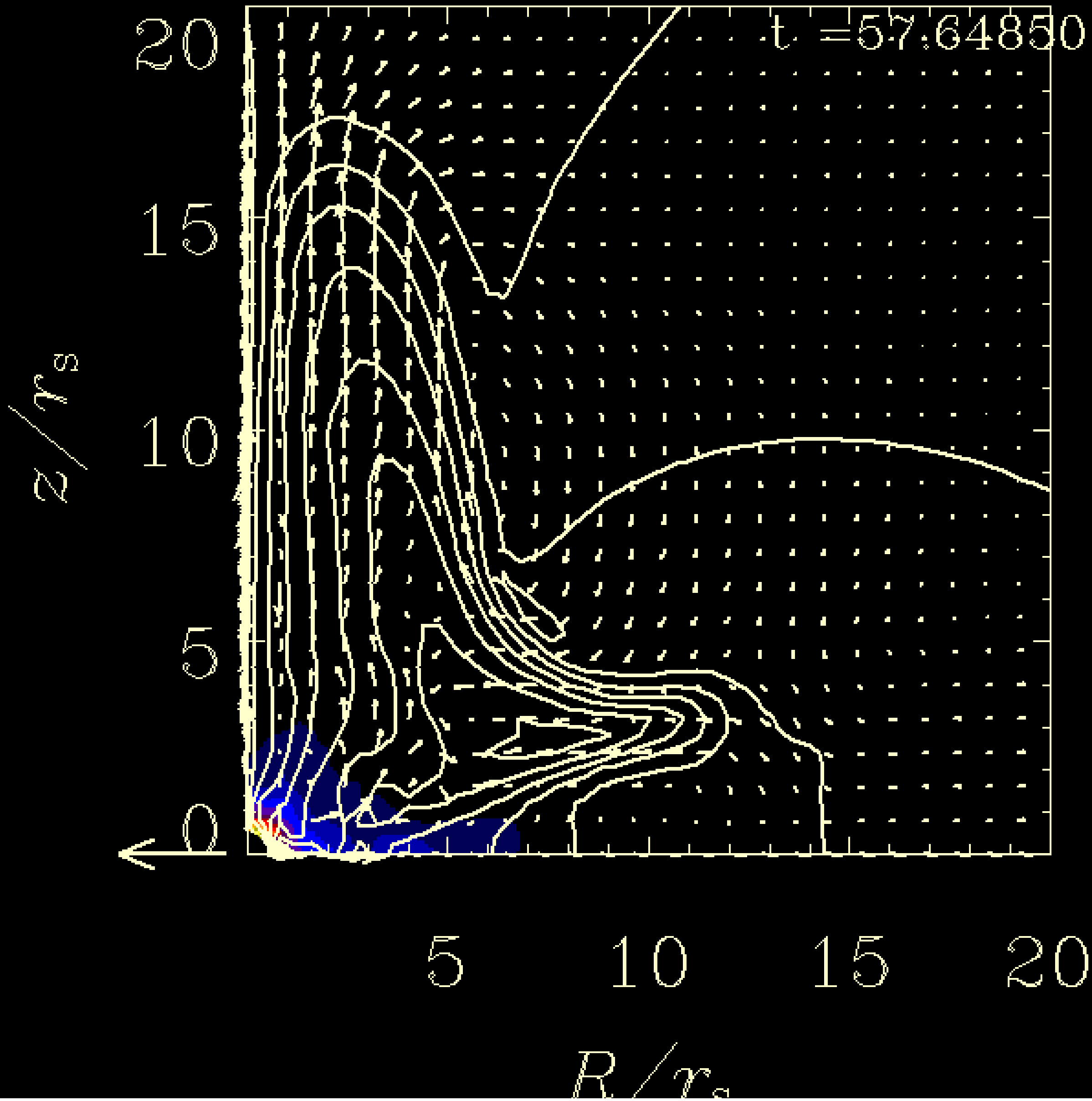
Arrow: Velocity



Solid line:
Magnetic field line

Color: log ρ

Arrow: Velocity

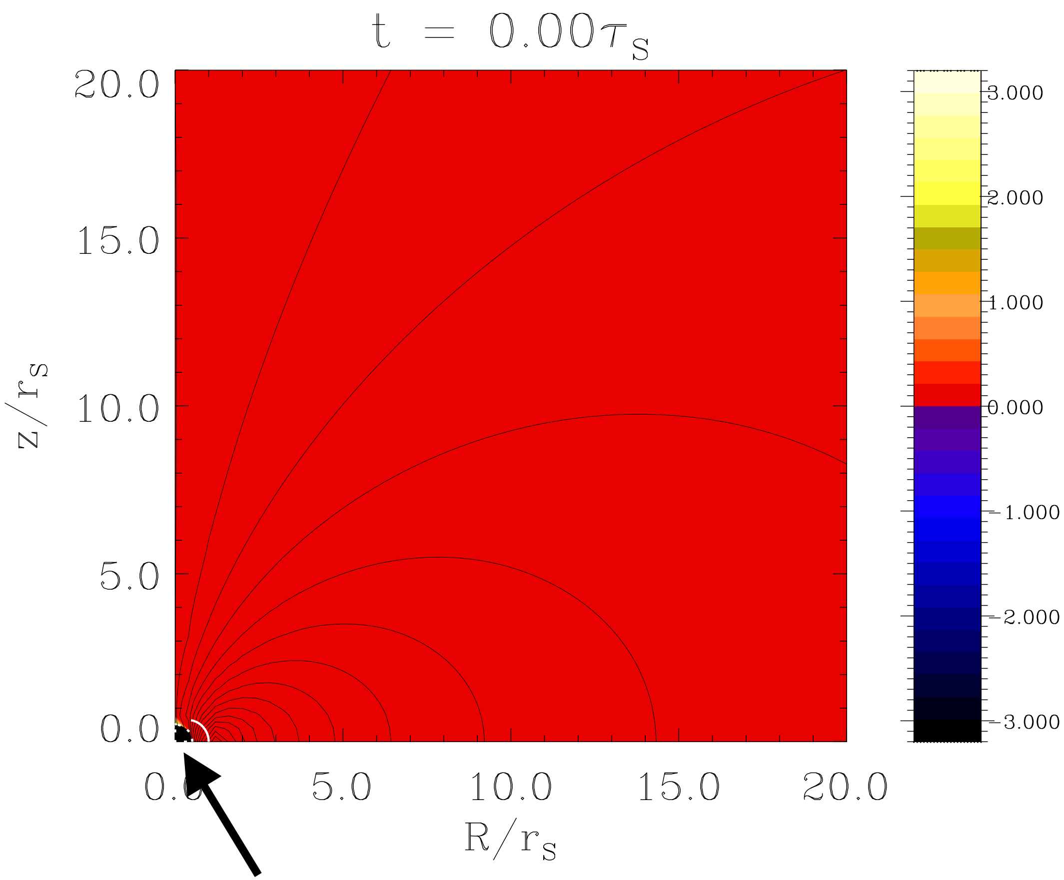


Solid line:
Magnetic field line

Color: log ρ

Arrow: Velocity

磁気配位，磁場の方位角成分



ブラックホール地平面

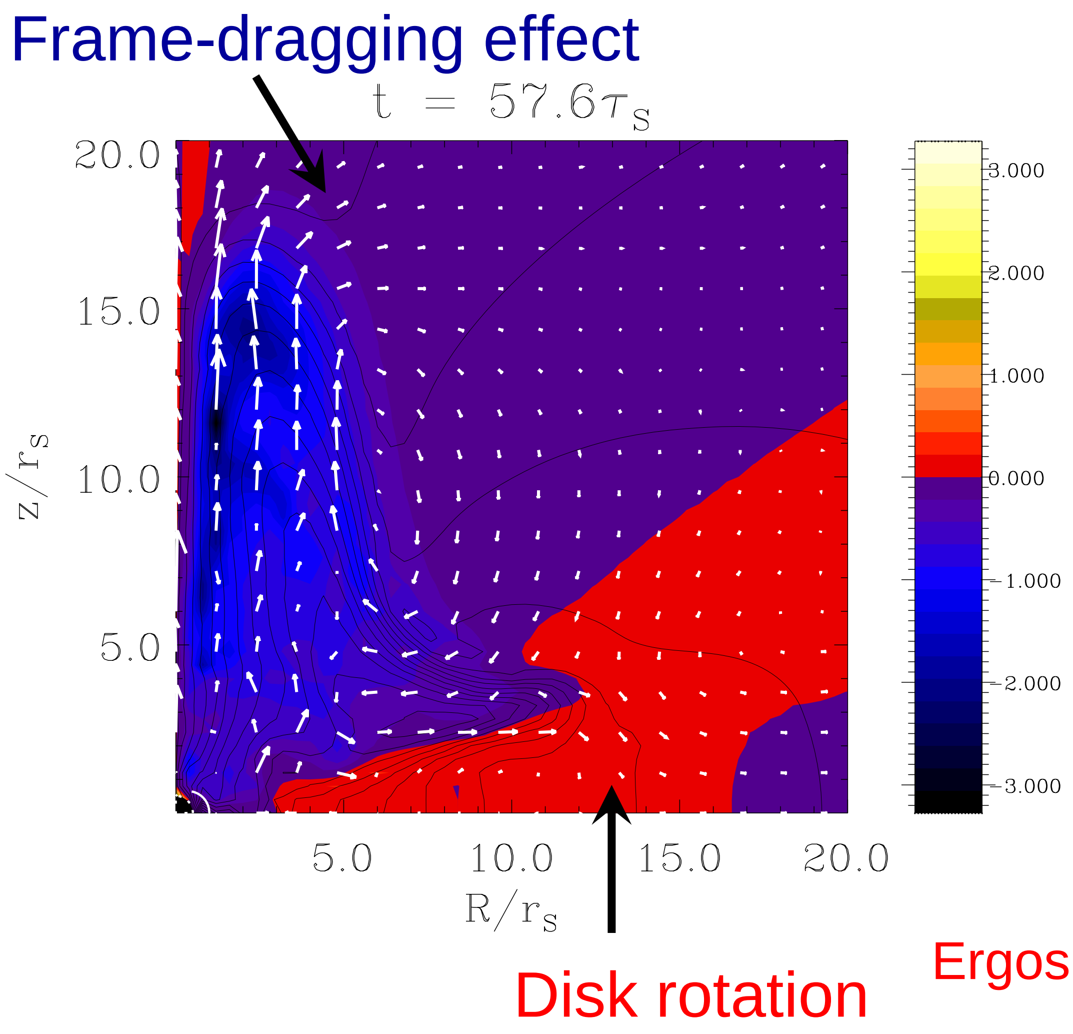
t =0

Solid line:
Magnetic field line

Color: $B_\phi/\rho^{1/2}$

磁気配位，磁場の方位角成分

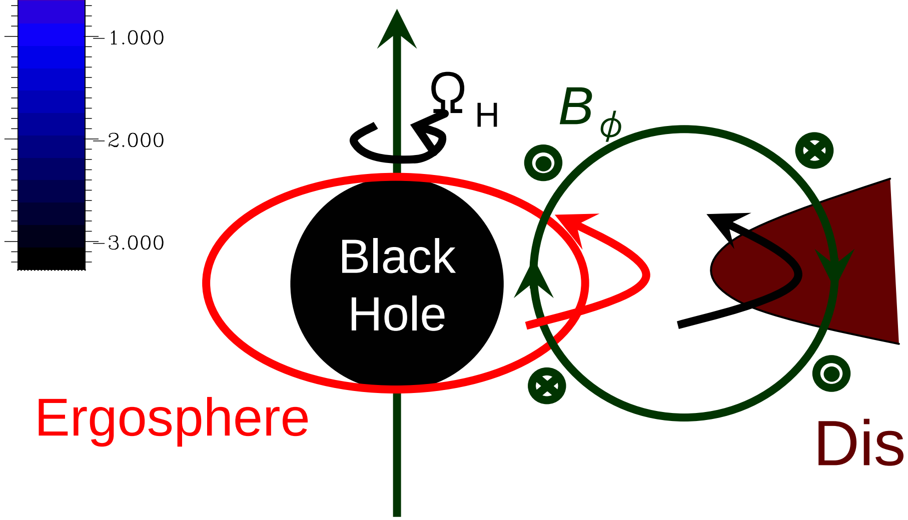
$t = 57.6\tau_S$

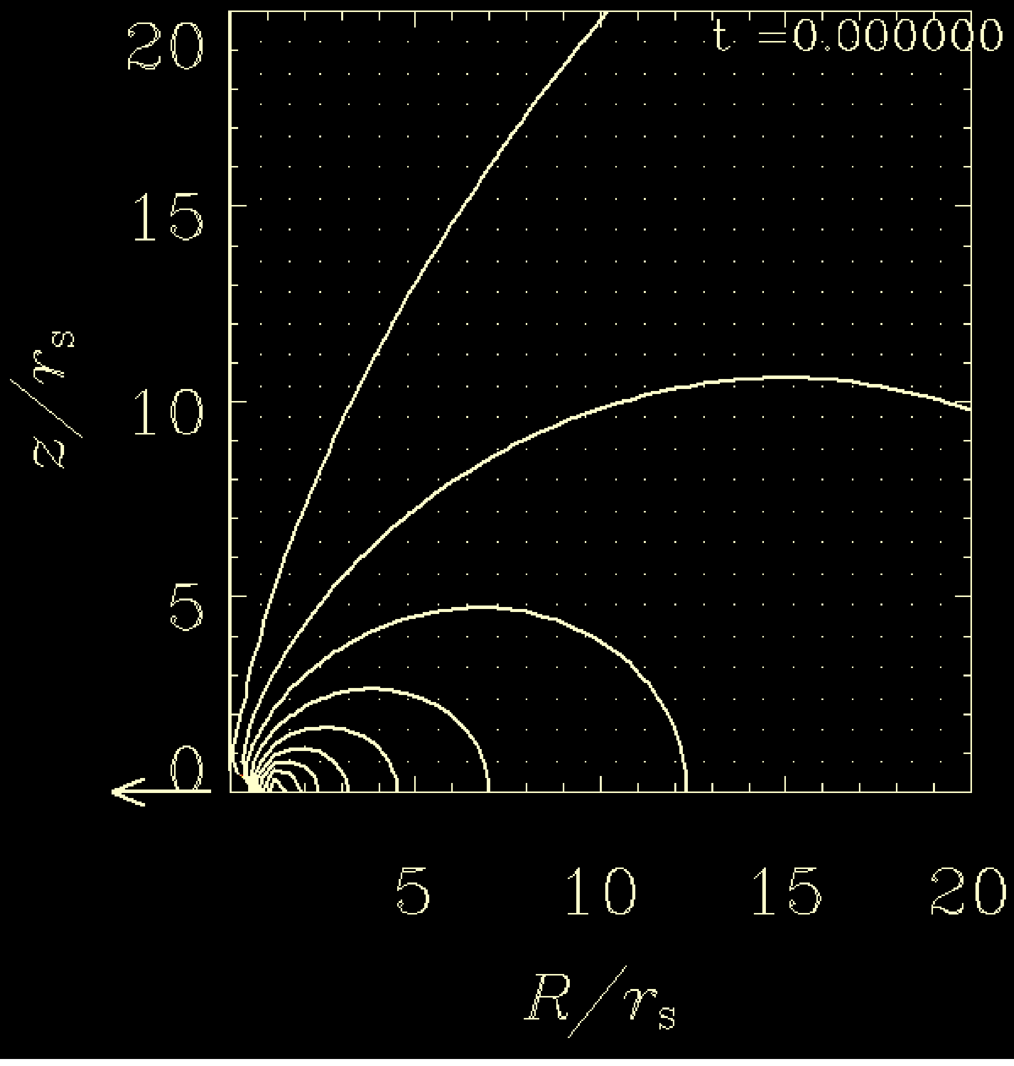


Solid line:
Magnetic field line

Color: $B_\phi/\rho^{1/2}$

Arrow: Velocity

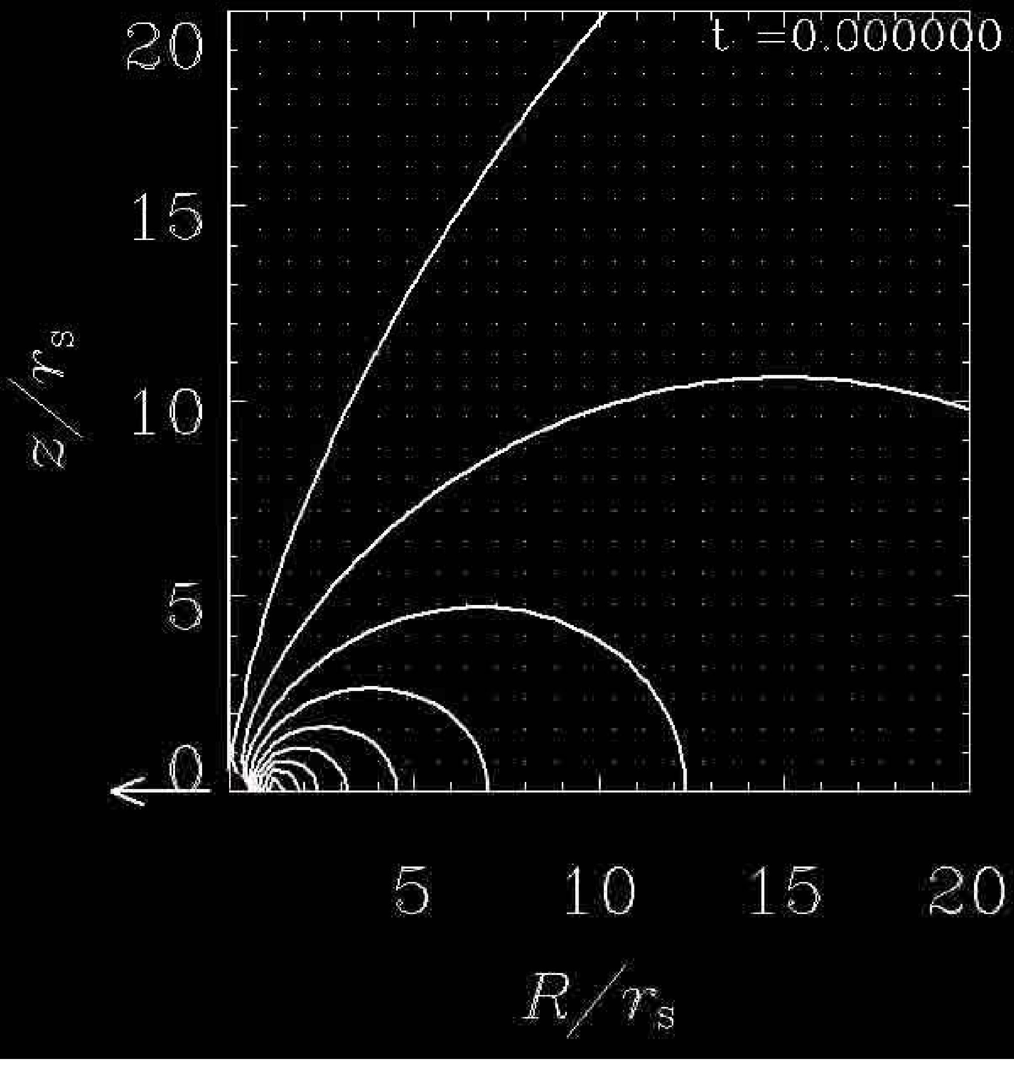




Solid line:
Magnetic field line

Color: $B_\phi^2/\rho c^2$

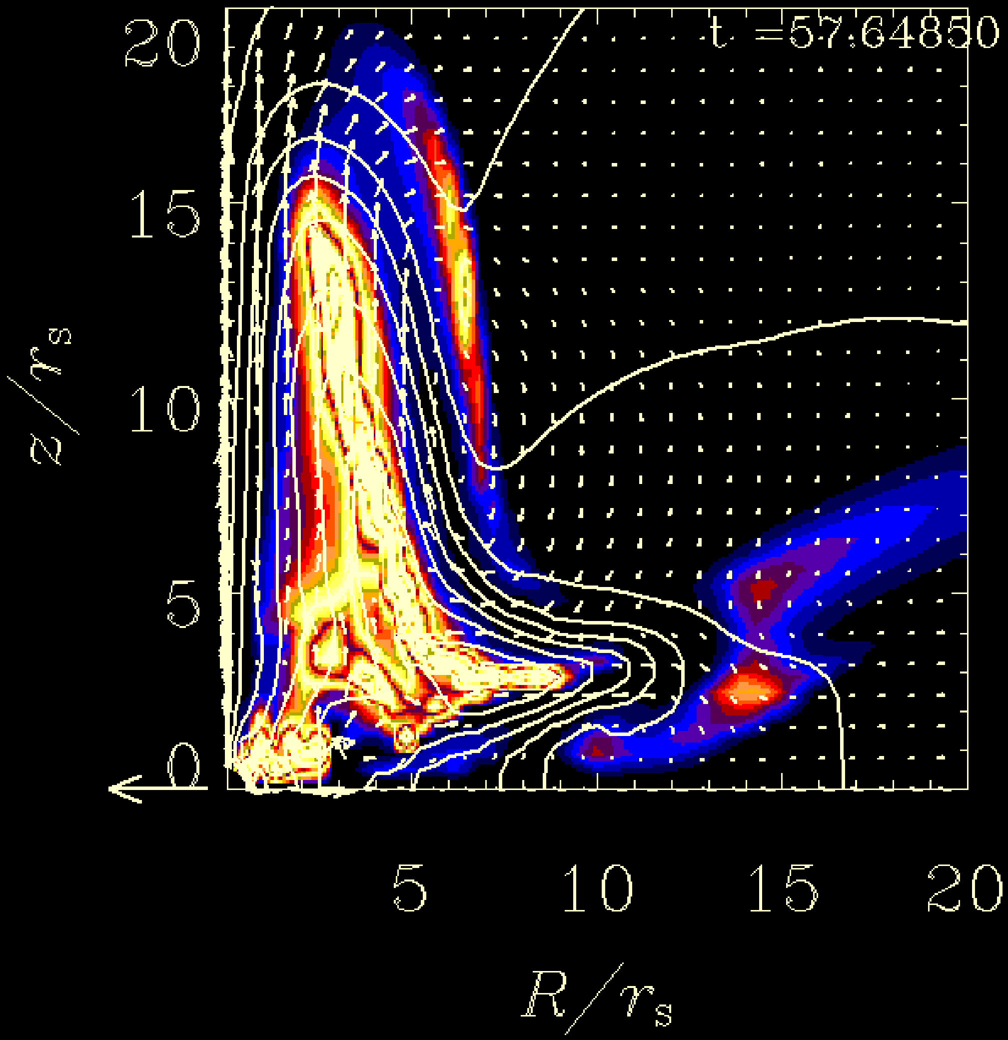
Arrow: Velocity



Solid line:
Magnetic field line

Color: $B_{\phi}^2/\rho c^2$

Arrow: Velocity



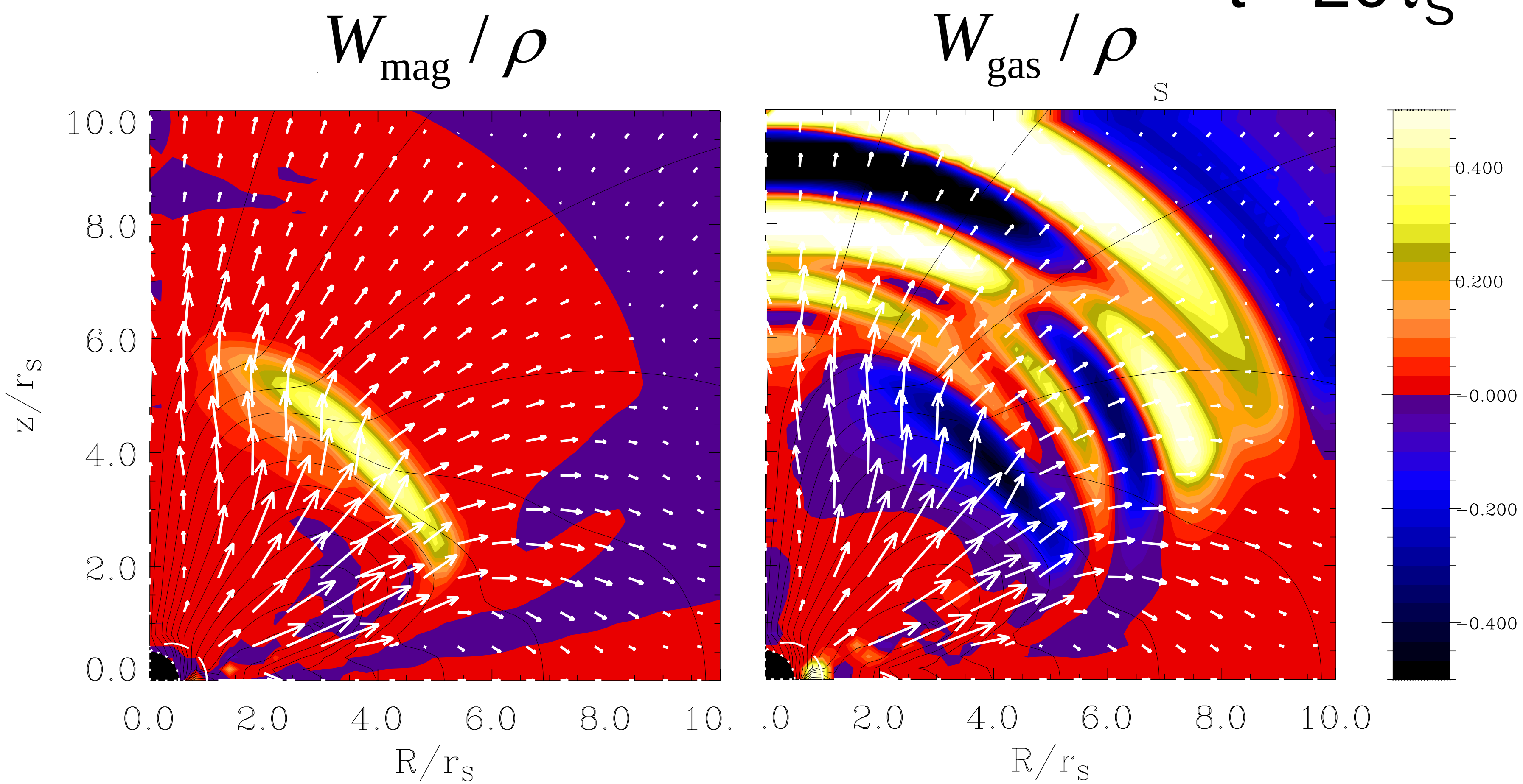
Solid line:
Magnetic field line

Color: $B_\phi^2/\rho c^2$

Arrow: Velocity

加速機構の同定

$t = 20\tau_S$



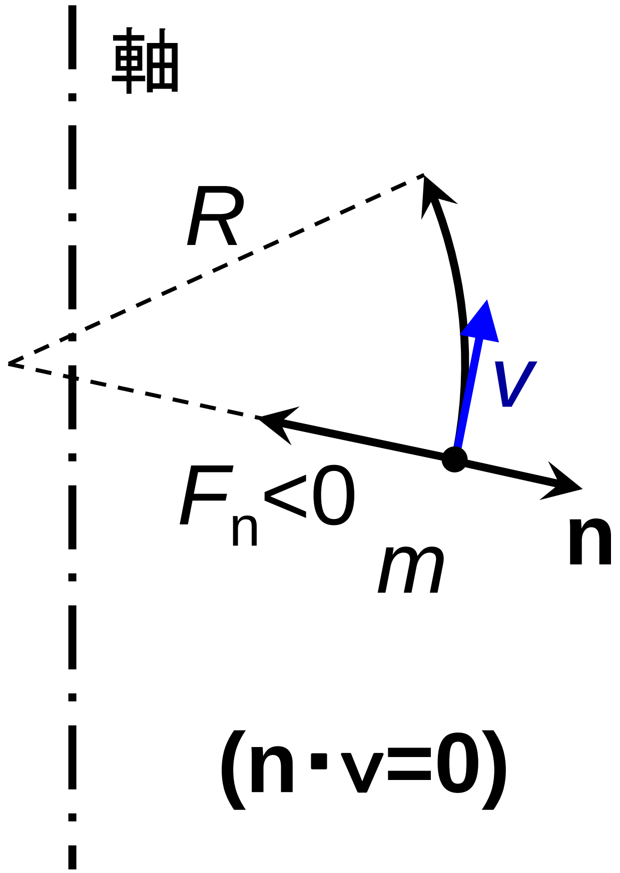
$$W_{mag} = \alpha \mathbf{v} \cdot \underbrace{(\rho_e \mathbf{E} + \mathbf{J} \times \mathbf{B})}_{\text{ローレンツ力}}$$

$$W_{gas} = \mathbf{v} \cdot (-\nabla(\alpha p))$$

ジェット絞込みの機構の同定:
ジェット収束の曲率 (非相対論)

$$F_{\mathrm{n}} = m\frac{v^2}{R}$$

R ← 曲率半径



曲率

$$\kappa = \frac{1}{R} = \frac{F_{\mathrm{n}}}{mv^2} = \frac{f_{\mathrm{n}}}{\rho v^2}$$

曲率の測定

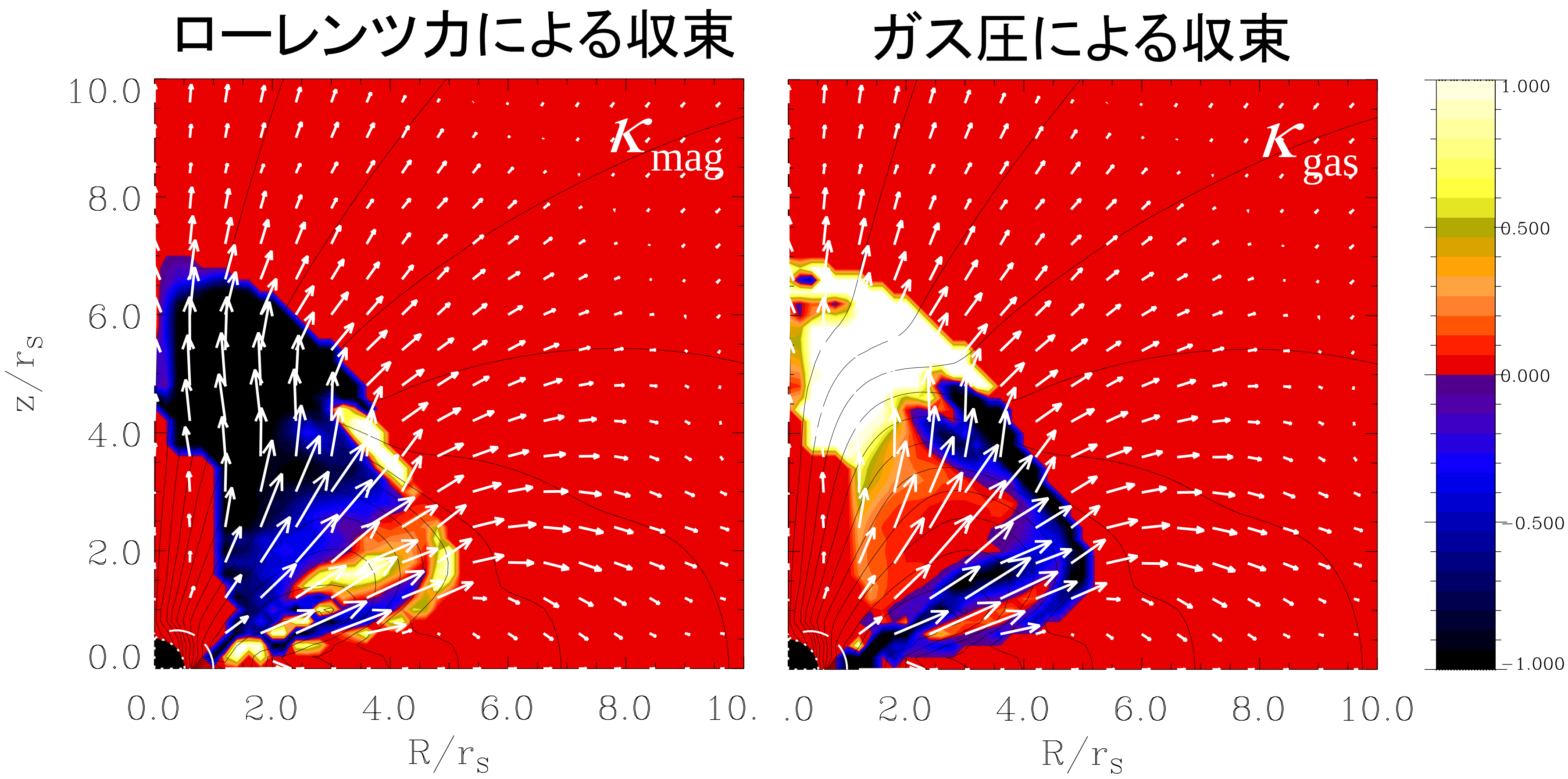
$$\kappa = \begin{cases} \dfrac{f_{\mathrm{n}}}{\rho v^2} & (v > v_{\mathrm{crit}} = 0.1c) \\ 0 & (v \le v_{\mathrm{crit}} = 0.1c) \end{cases}$$

$$f_{\mathrm{n}} = (\underbrace{\rho_{\mathrm{e}}\mathbf{E} + \mathbf{J}\times\mathbf{B}}\underbrace{-\nabla p})\cdot\mathbf{n}$$

$$\kappa_{\mathrm{mag}} \leftarrow \mathbf{f}_{\mathrm{Lorentz}} \qquad \mathbf{f}_{\mathrm{gas}} \rightarrow \kappa_{\mathrm{gas}}$$

収束機構の同定

$t = 20\tau_S$

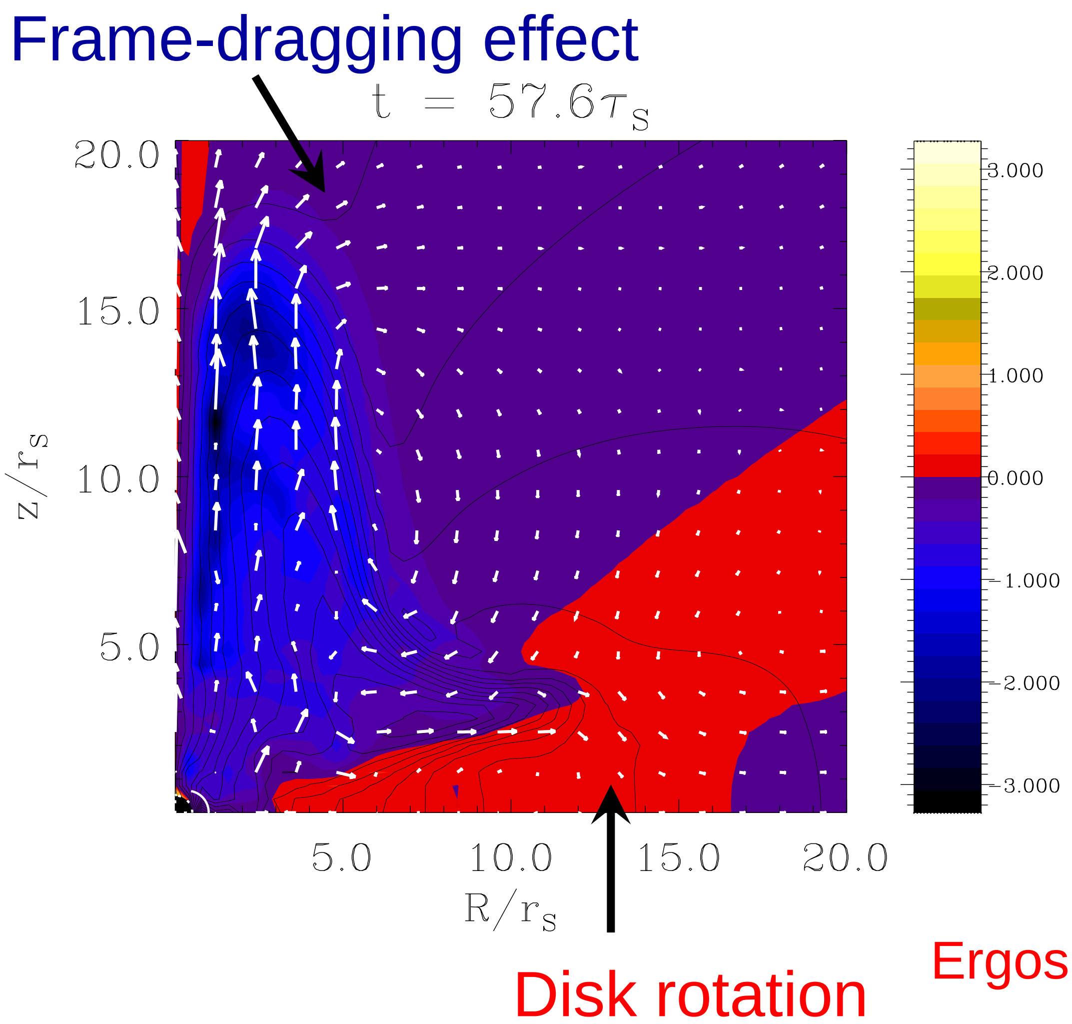


κ_{mag} ：ローレンツ力によるジェットの収束の曲率半径

κ_{gas} ：ガス圧によるジェットの収束の曲率半径

磁気配位，磁場の方位角成分

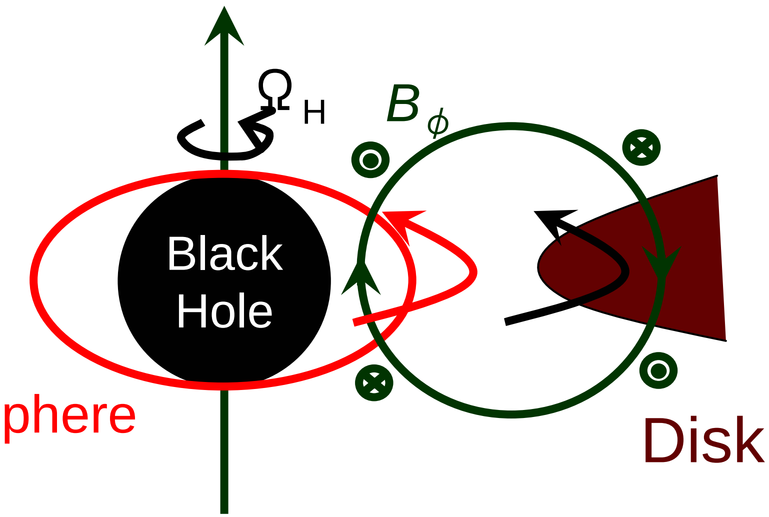
$t = 57.6\tau_S$



Solid line:
Magnetic field line

Color: $B_\phi/\rho^{1/2}$

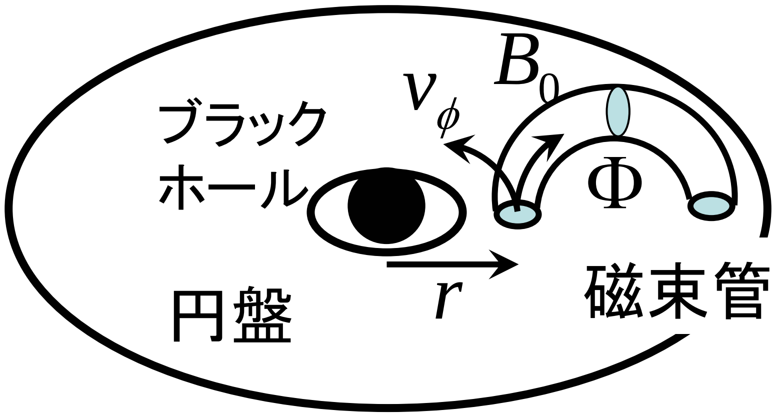
Arrow: Velocity



なぜ磁気的橋は内側の端で主にねじられるのか？#1

単位時間単位面積当たりの円盤から磁束管へ注入されるエネルギーの流入量は

$$P = \frac{B_0^2}{v_A} v_\phi^2$$ （定常の場合）



$$v_A = \frac{B_0}{\sqrt{\rho}} \qquad \Phi = B_0 S$$

$$P = B_0 \sqrt{\rho} v_\phi^2 = \frac{\Phi}{S} \sqrt{\rho} v_\phi^2$$

単位時間当たりの磁束管へのエネルギー流入量：

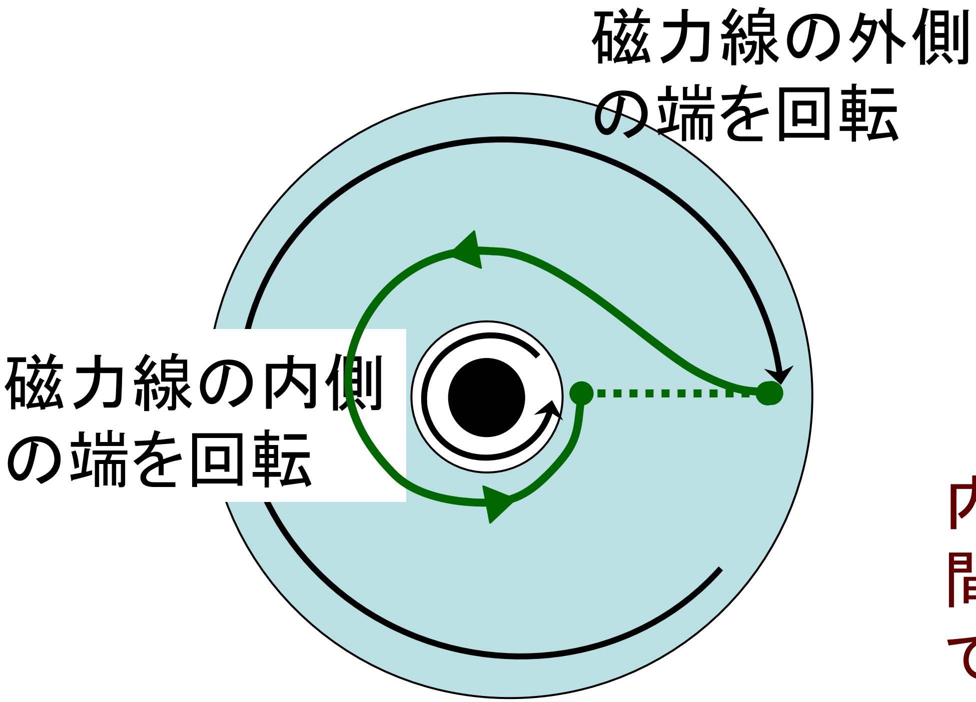
$$PS = \Phi \sqrt{\rho} v_\phi^2 \quad \propto \frac{1}{r}$$ （ρ一定の場合）

r→大：ρ→小

$$v_\phi^2 = v_\mathrm{K}^2 = \frac{GM}{r}$$

なぜ磁気的橋は内側の端で主にねじられるのか？#2

- force-free の場合



$$PS \propto \frac{1}{T} = \frac{1}{T_{\mathrm{K}}} = \frac{v_{\mathrm{K}}}{2\pi r} \propto \frac{1}{r^{3/2}}$$

磁力線の外側の端で
回転しようと，内側の
橋で回転しようと同じ
磁場配位になる。

内側を回転させるほうが単位時
間当たり回転数が大きく出来るの
で内側の端を回転させるほうが
磁場を効率よく捩じることになる。

すなわち，磁気的橋はエルゴ領域で
捩じられることになる。

パラメータ依存性

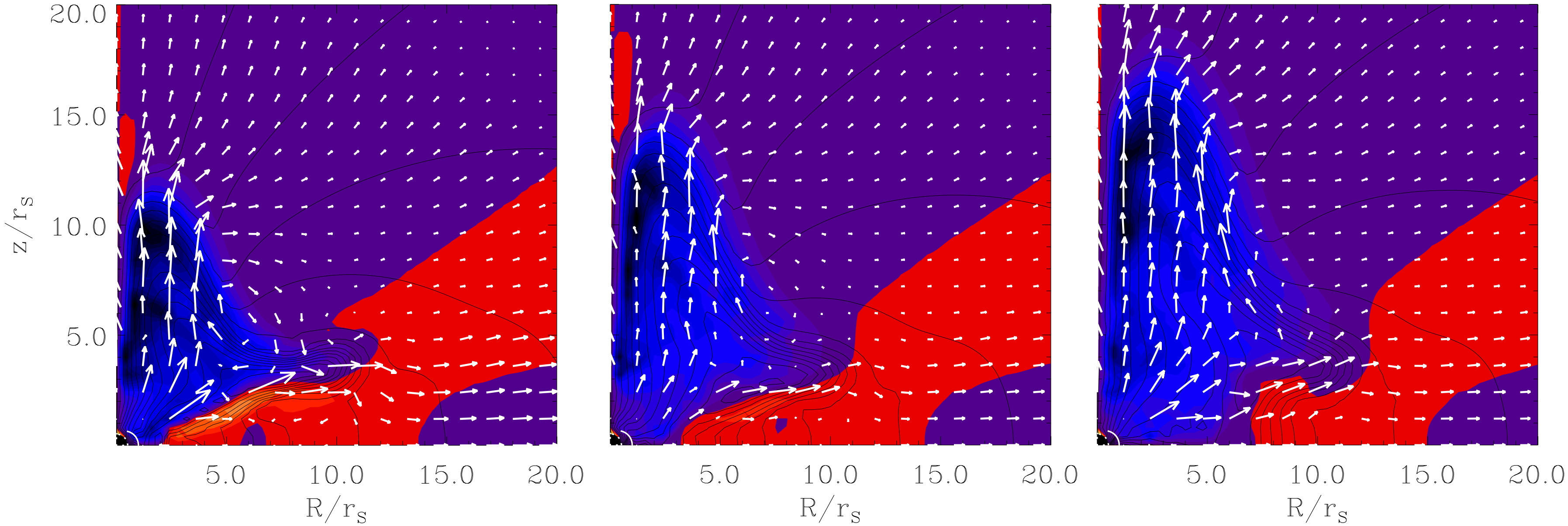
静水圧平衡コロナ・順方向回転

電流ループの電流密度の依存性

カラー： $B_\phi/\rho^{1/2}$ $t = 47\tau_S$

標準の場合

$J_0 = 1.0\pi/2$ $J_0 = 1.5\pi/2$ $J_0 = 2.0\pi/2$



$J_0 = 1.0\pi/2$	$J_0 = 1.5\pi/2$	$J_0 = 2.0\pi/2$
$v^{max} = 0.473c$	$v^{max} = 0.502c$	$v^{max} = 0.552c$
$v_P^{max} = 0.325c$	$v_P^{max} = 0.367c$	$v_P^{max} = 0.427c$

実線： 磁束面， 矢印： 速度

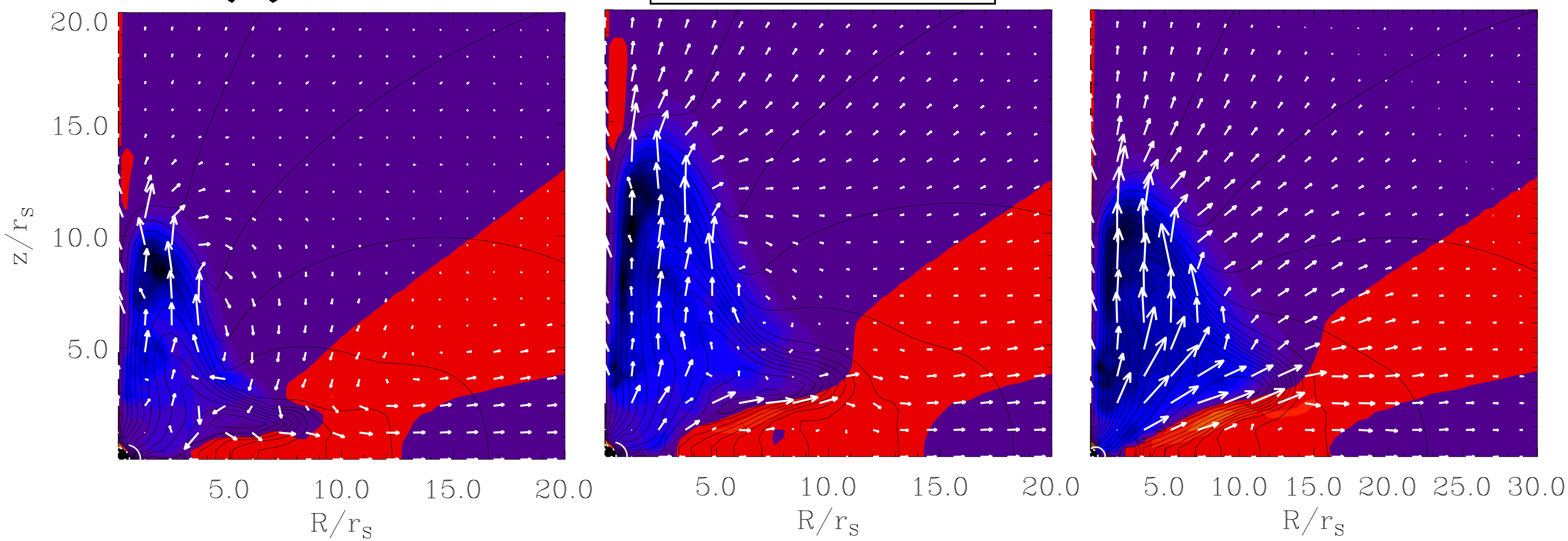
コロナの圧力の依存性

カラー：$B_\phi/\rho^{1/2}$

$p = p_{\mathrm{equil}} + p_{\text{ゲタ}}/\alpha$

$t = 47\tau_S$

$P_{\text{ゲタ}} = 3\times10^{-3}$　　$P_{\text{ゲタ}} = 10^{-3}$　　$P_{\text{ゲタ}} = 3\times10^{-4}$



$v^{\max} = 0.654c$	$v^{\max} = 0.502c$	$v^{\max} = 0.538c$
$v_P^{\max} = 0.292c$	$v_P^{\max} = 0.367c$	$v_P^{\max} = 0.538c$

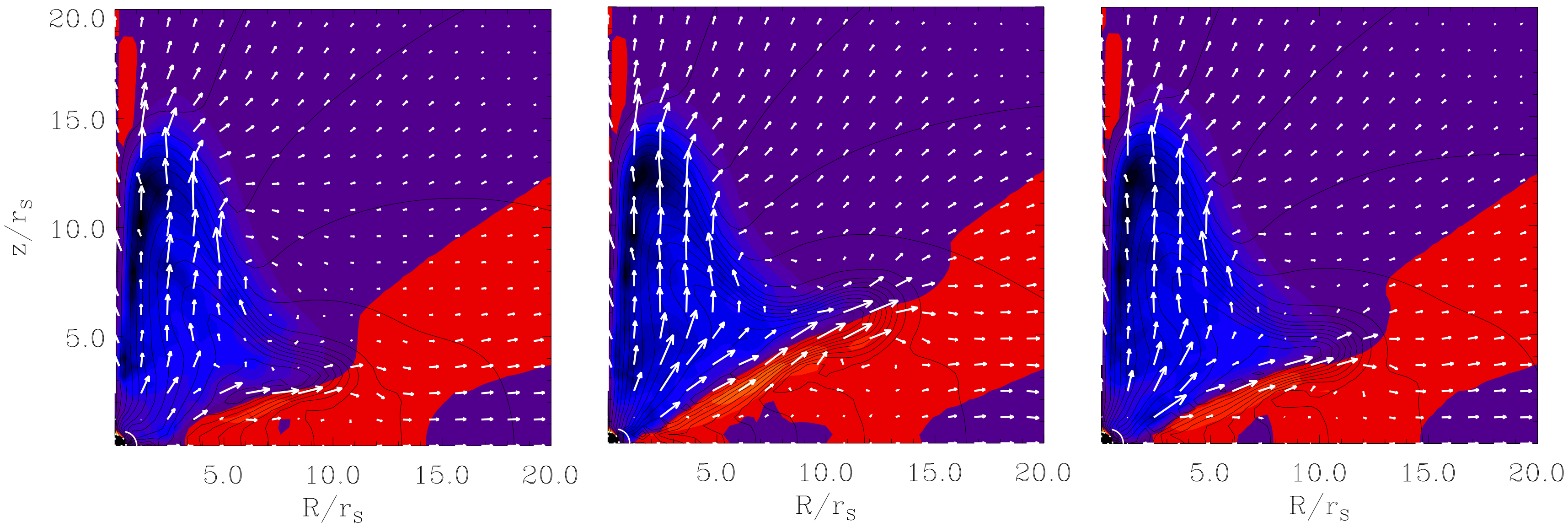
実線：　磁束面，　矢印：　速度

円盤の質量密度の依存性

カラー： $B_\phi/\rho^{1/2}$

$t = 47\tau_S$

$\eta_{disk}=300$ $\eta_{disk}=500$ $\eta_{disk}=1000$



$v^{max} = 0.502c$ $v^{max} = 0.511c$ $v^{max} = 0.489c$

$v_P^{max} = 0.367c$ $v_P^{max} = 0.384c$ $v_P^{max} = 0.394c$

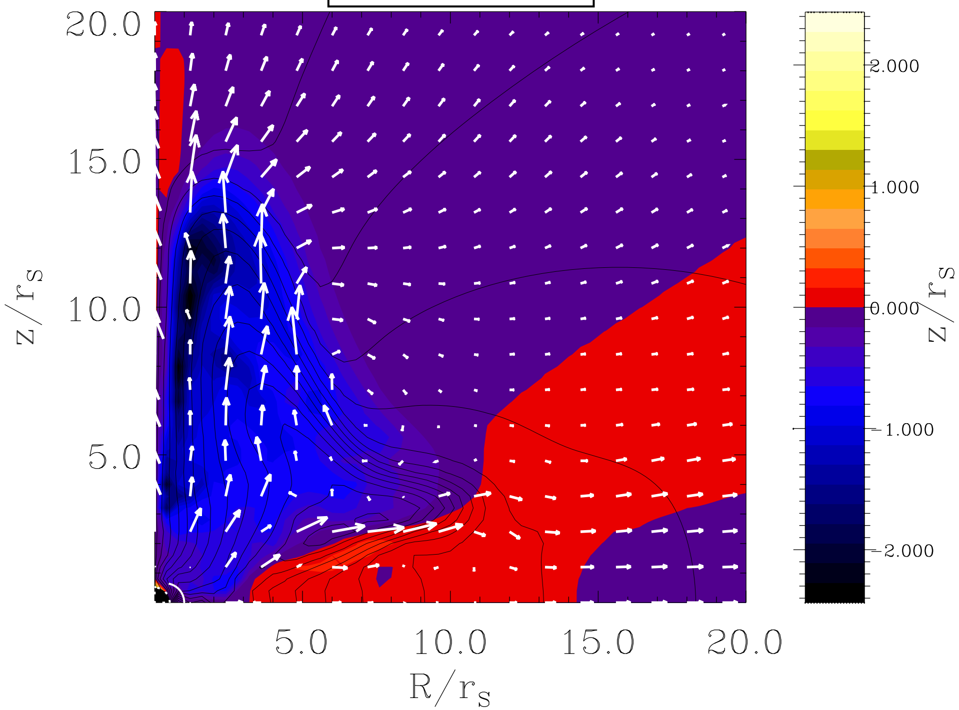
実線： 磁束面， 矢印： 速度

コロナの圧力・密度分布の依存性

カラー: $B_\phi/\rho^{1/2}$

$t = 47\tau_S$

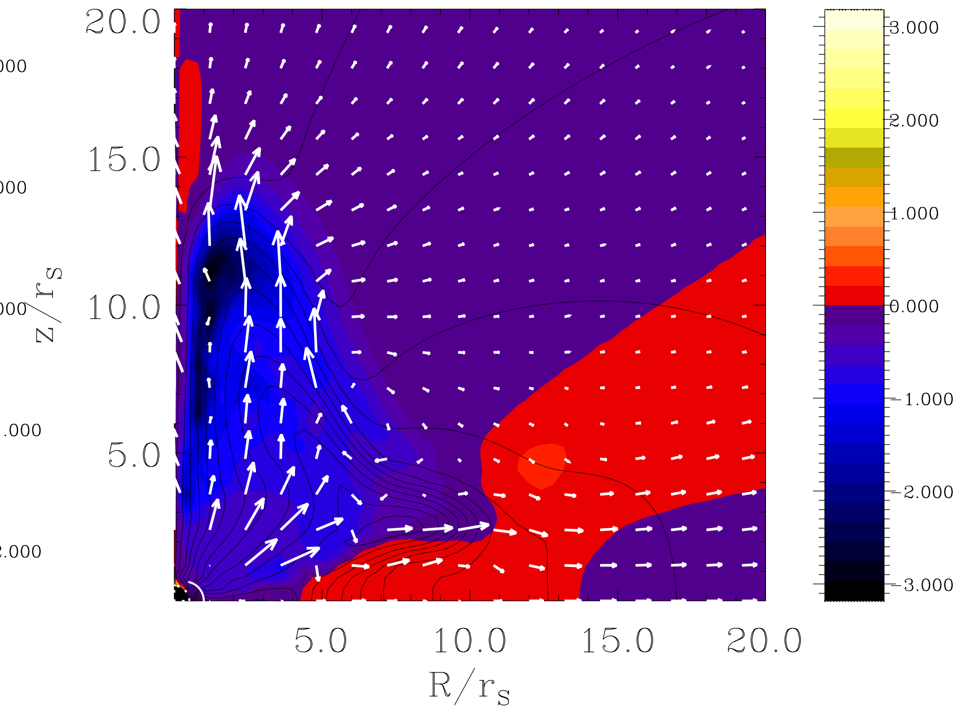
$\Gamma_0 = 4$



$v^{max} = 0.502c$

$v_P^{max} = 0.367c$

$\Gamma_0 = 4.5$



$v^{max} = 0.544c$

$v_P^{max} = 0.369c$

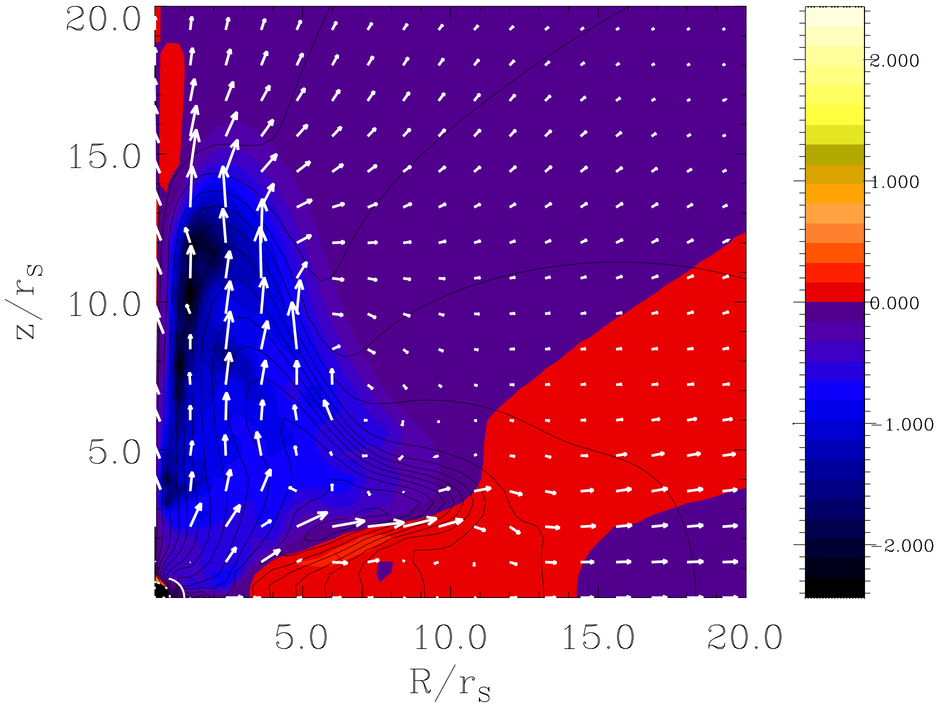
実線: 磁束面, 矢印: 速度

コロナの質量密度の依存性

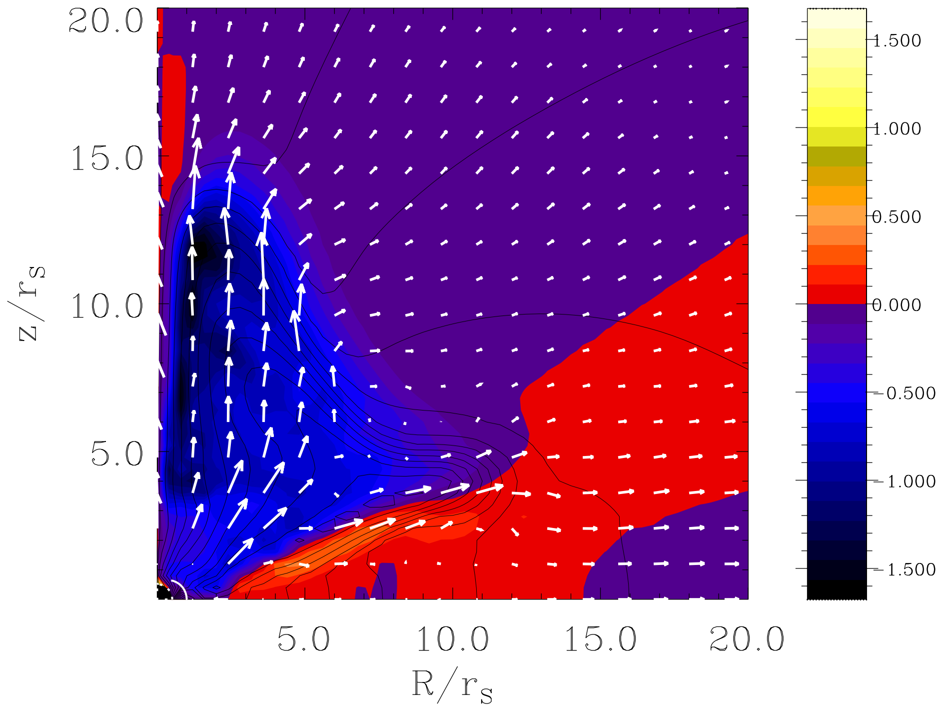
カラー： $B_\phi/\rho^{1/2}$

$t = 47\tau_S$

$\rho_0 = 0.0018$



$\rho_0 = 0.027$



$v^{max} = 0.502c$
$v_P^{max} = 0.367c$

$v^{max} = 0.488c$
$v_P^{max} = 0.422c$

実線： 磁束面， 矢印： 速度

Summary and Speculation

Sub-relativistic jets were formed from the magnetic bridge between the ergosphere and disk around rapidly rotating black hole.

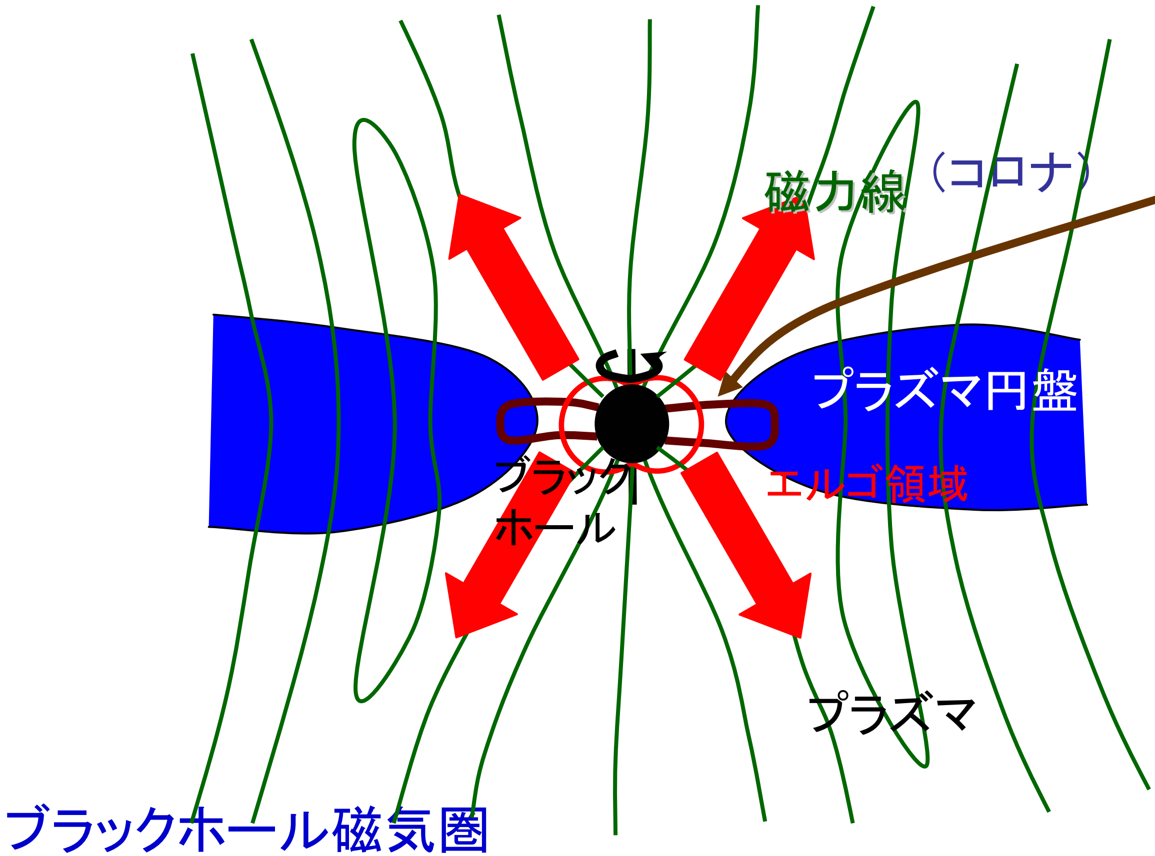
- The magnetic bridges between the ergosphere and the disk are twisted by the frame-dragging effect in the ergosphere. The twist by the disk is negligible in the present cases.
- The magnetic pressure of the twisted magnetic flux tubes brows off the plasma around the black hole.
- The outflow is collimated by the magnetic force to become (sub-relativistic) jet.

Speculation for further work toward relativistic jet:

•Stronger magnetic field → Relativistic acceleration (parameter scan with respect to J_0)

⇒ Relativistic Jet!

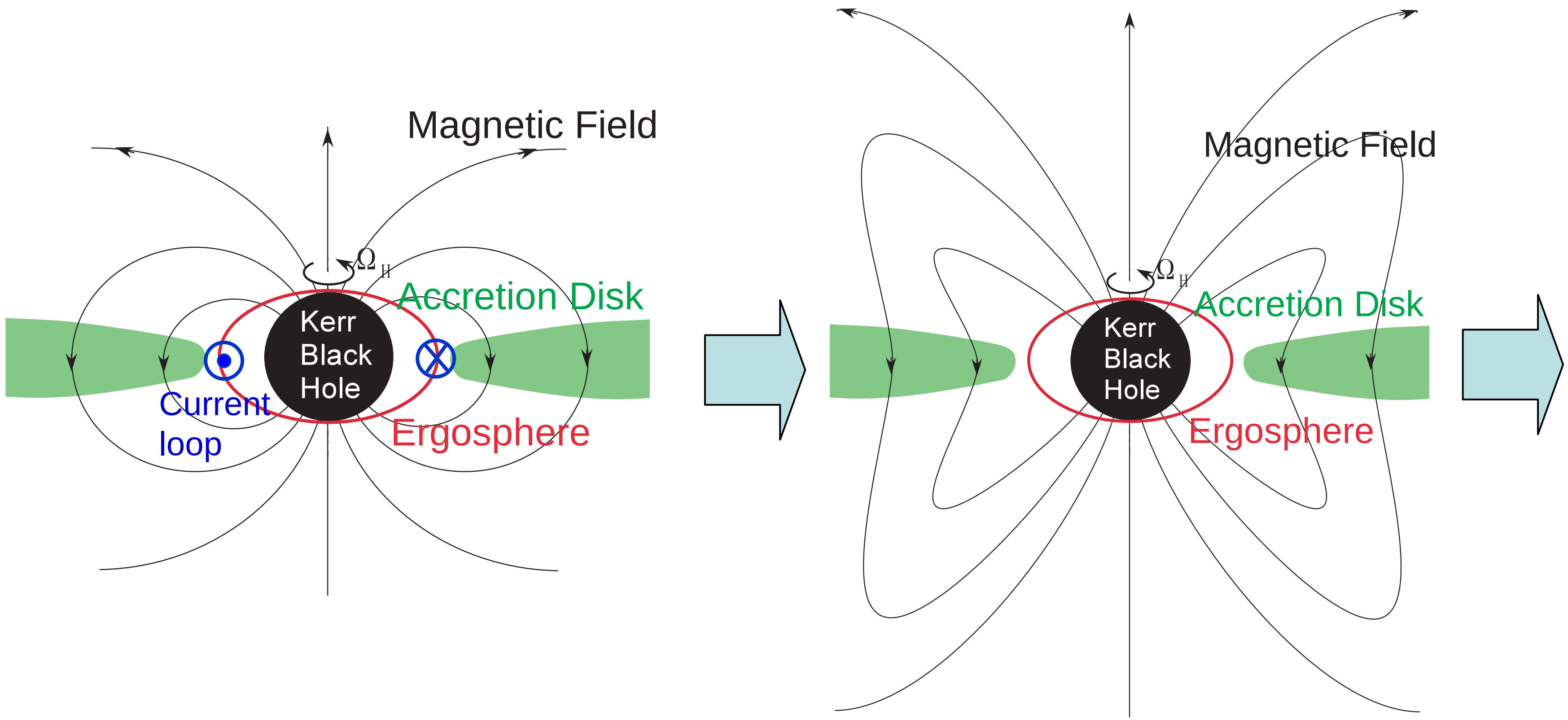
ブラックホール磁気圏:
宇宙で最もダイナミックで活発な領域！

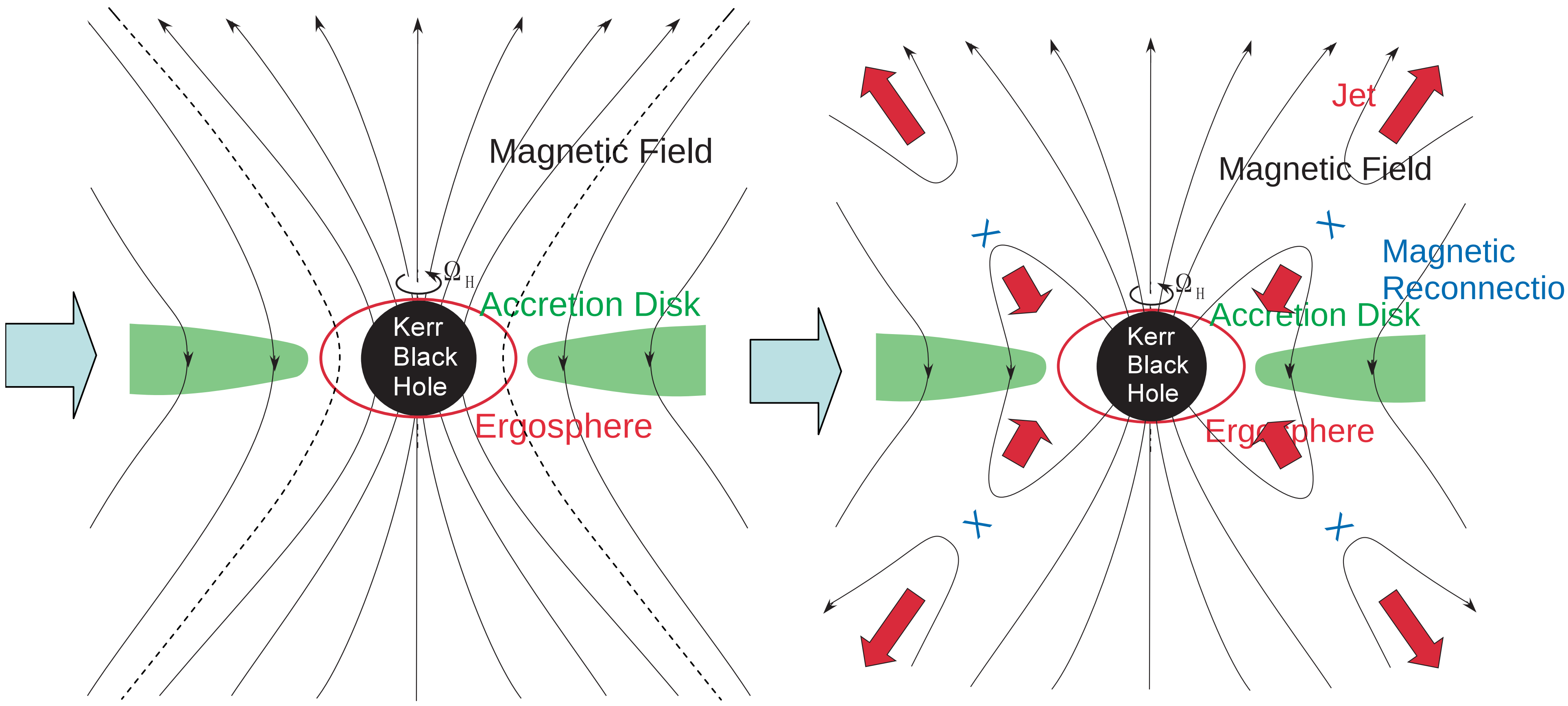


ブラックホールからプラズマ円盤に架かる磁気的橋はエルゴ領域で強力にねじられ，急速に膨張する

相対論的ジェット

Expected phenomena caused by closed magnetic field of current loop near rotating black hole



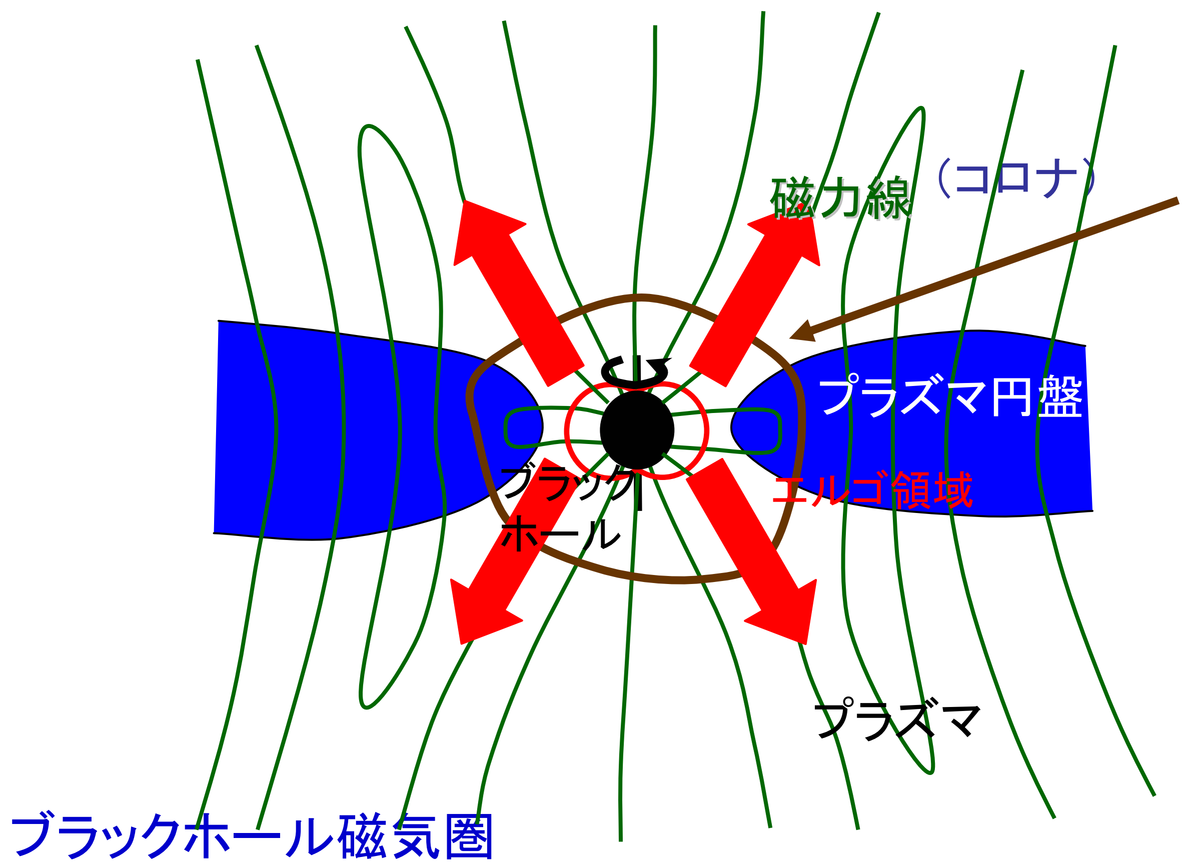


Magnetic reconnection should be important near black hole horizon!

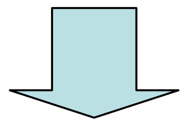
- Magnetic reconnection
  - Electric resistivity

  → Resistive relativistic MHD:

ブラックホール磁気圏:
宇宙で最もダイナミックで活発な領域！



ブラックホールからプラズマ円盤に掛かる磁力線（磁気的橋）のある領域:
最も活発な領域



相対論的ジェット