GRMHD Simulation of BH & Magnetic Fields

prepared by Koide-san

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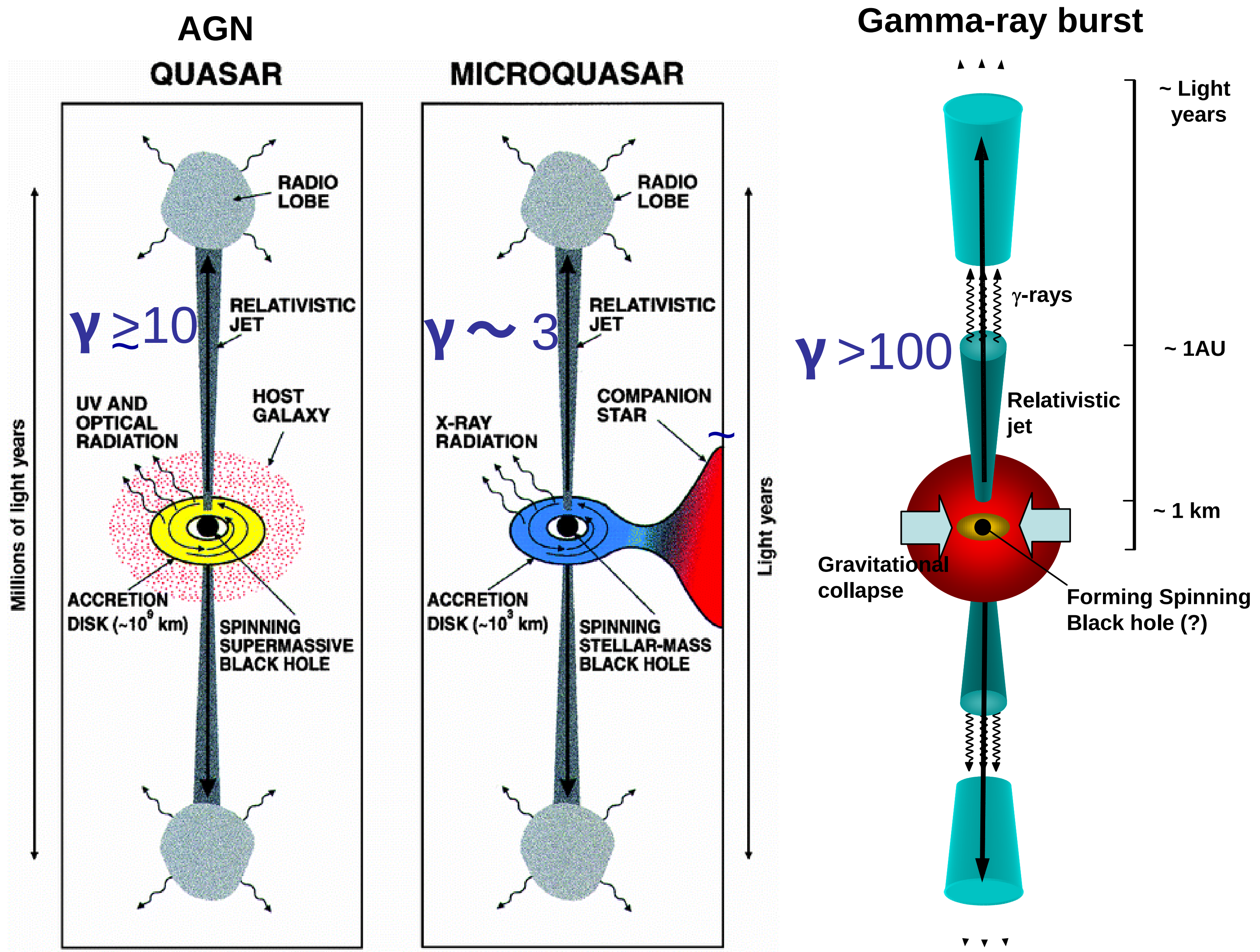
Motivation: Relativistic Jets in the Universe



Mirabel, Rodriguez 1998

Base of General Relativistic MHD in Kerr Space-Time

- General relativistic equation of conservation laws and Maxwell equations:

$$\nabla_\nu (n U^\nu) = 0 \qquad \text{(conservation of particle number)}$$

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

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

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

(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, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

Kerr black hole, Uniform magnetic field, No Accretion disk : Initial condition

(1) Kerr black hole

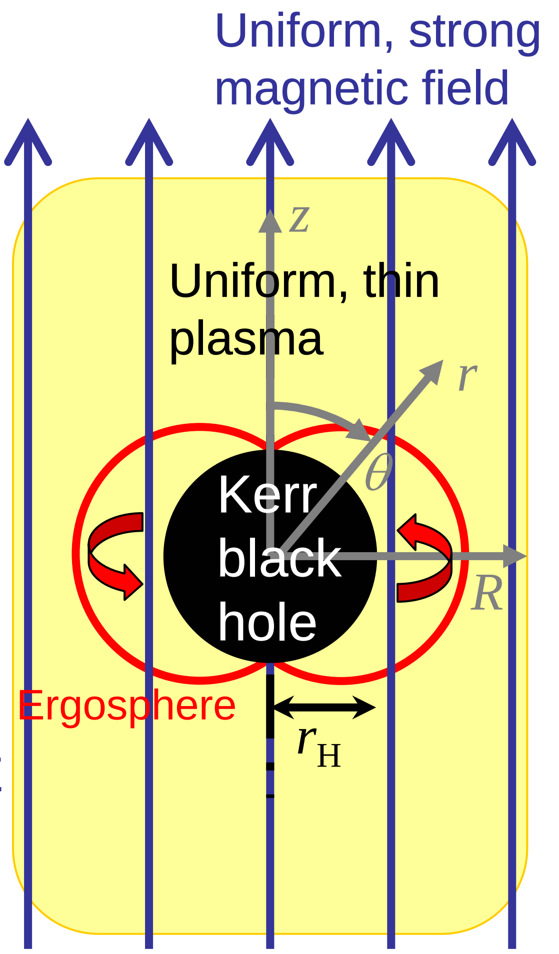
(2) Magnetic field: Uniform around Kerr black hole

(3) Plasma: uniform, low density and pressure

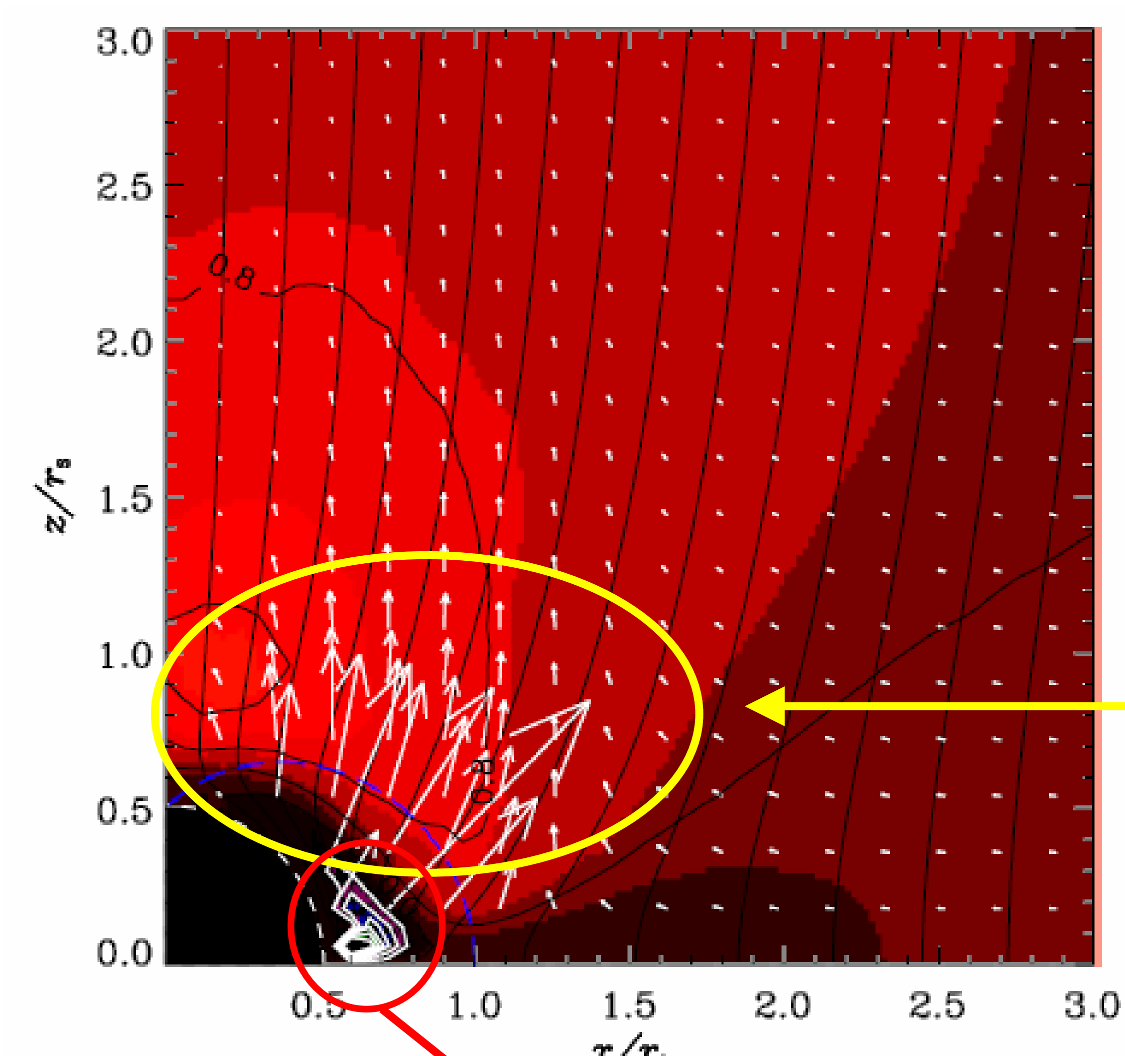
$$\rho_0=0.1B_0^2/c^2,\ p_0=0.06\rho_0 c^2$$

(4) Calculation region:
$1.01\ r_H \leqq r \leqq 40\ r_H$,
$0.01 \leqq \theta \leqq \pi/2$

- Axisymmetry, symmetry with respect to equatorial plain



Result(1)

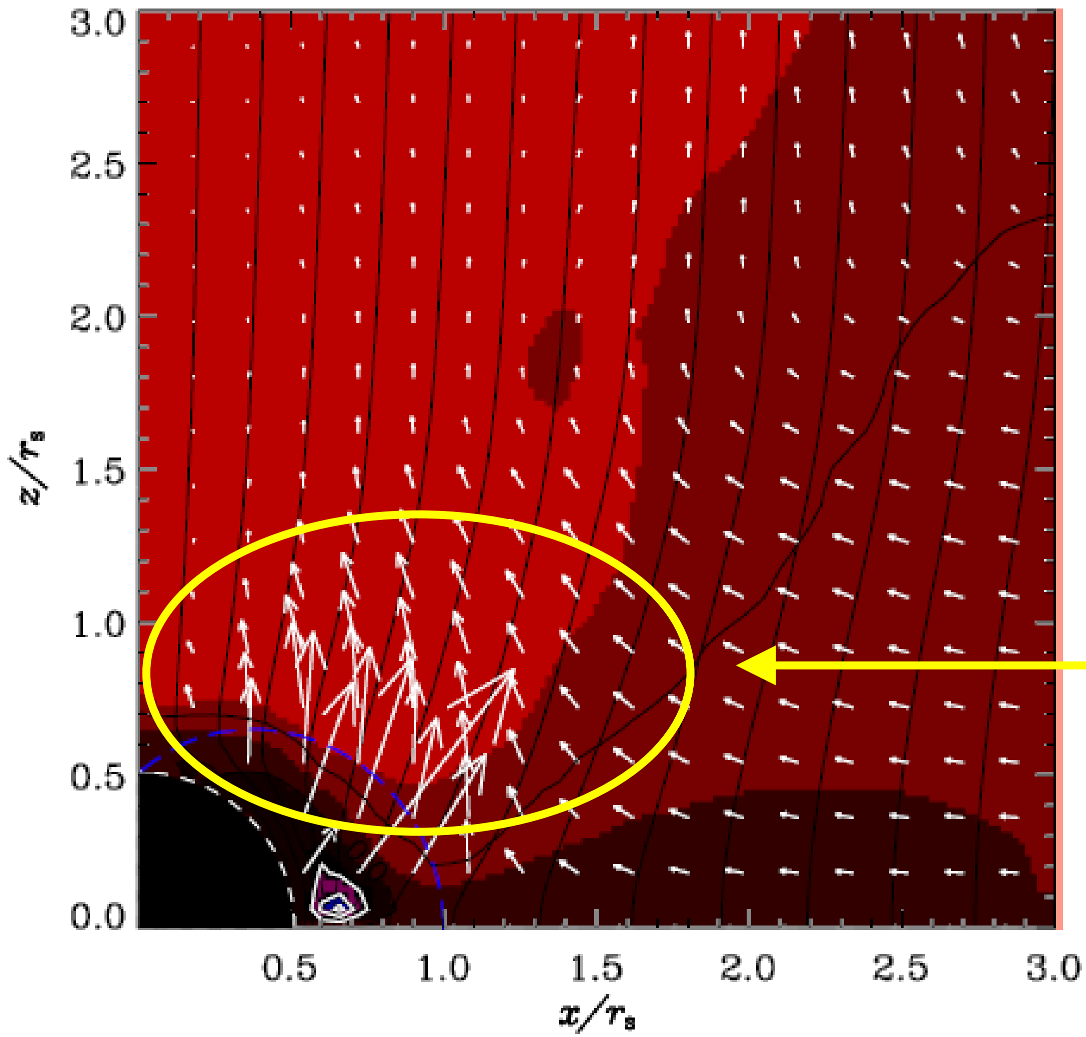


a=0.9995
V_matter=0
(no motion initially)

Poynting flux direct outward!

negative energy region

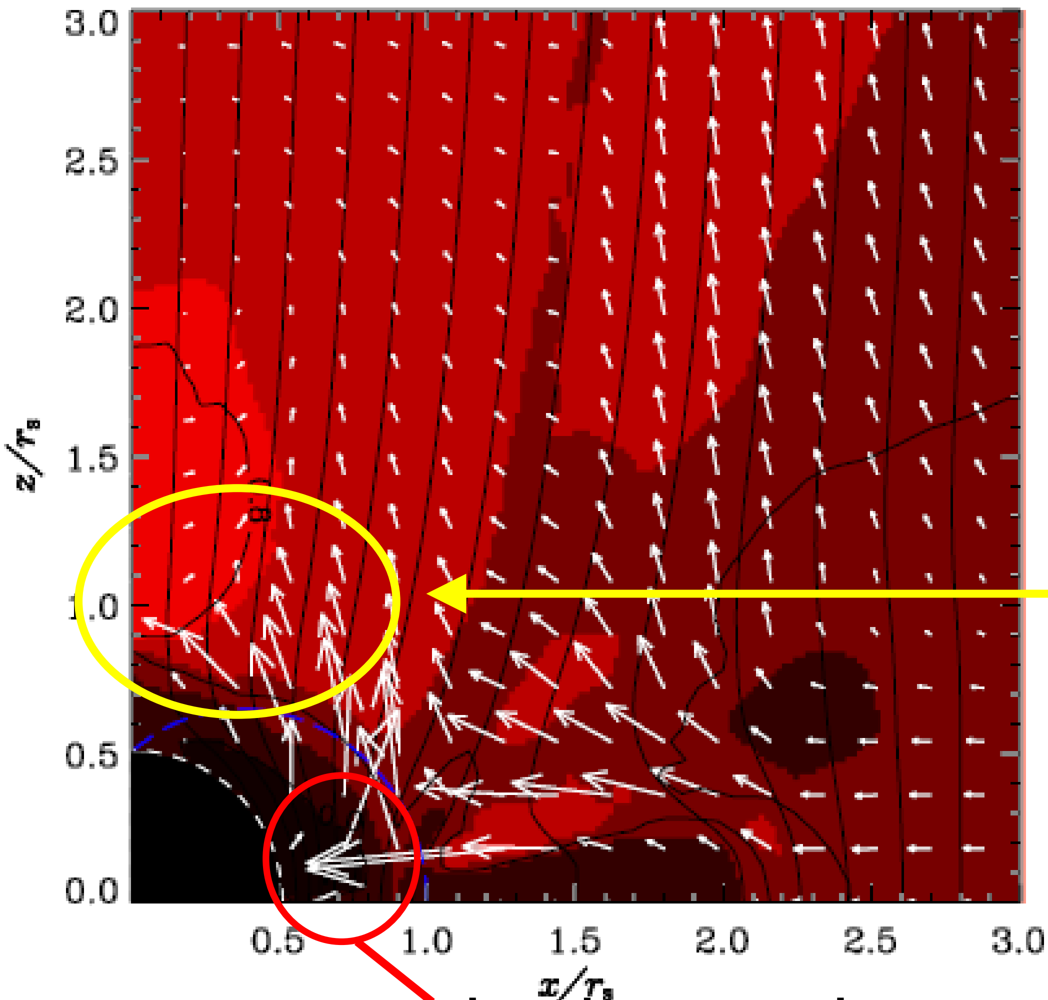
Result(2)



a=0.9995
V_matter=1
(co-rotation)

Similar feature

Result(3)

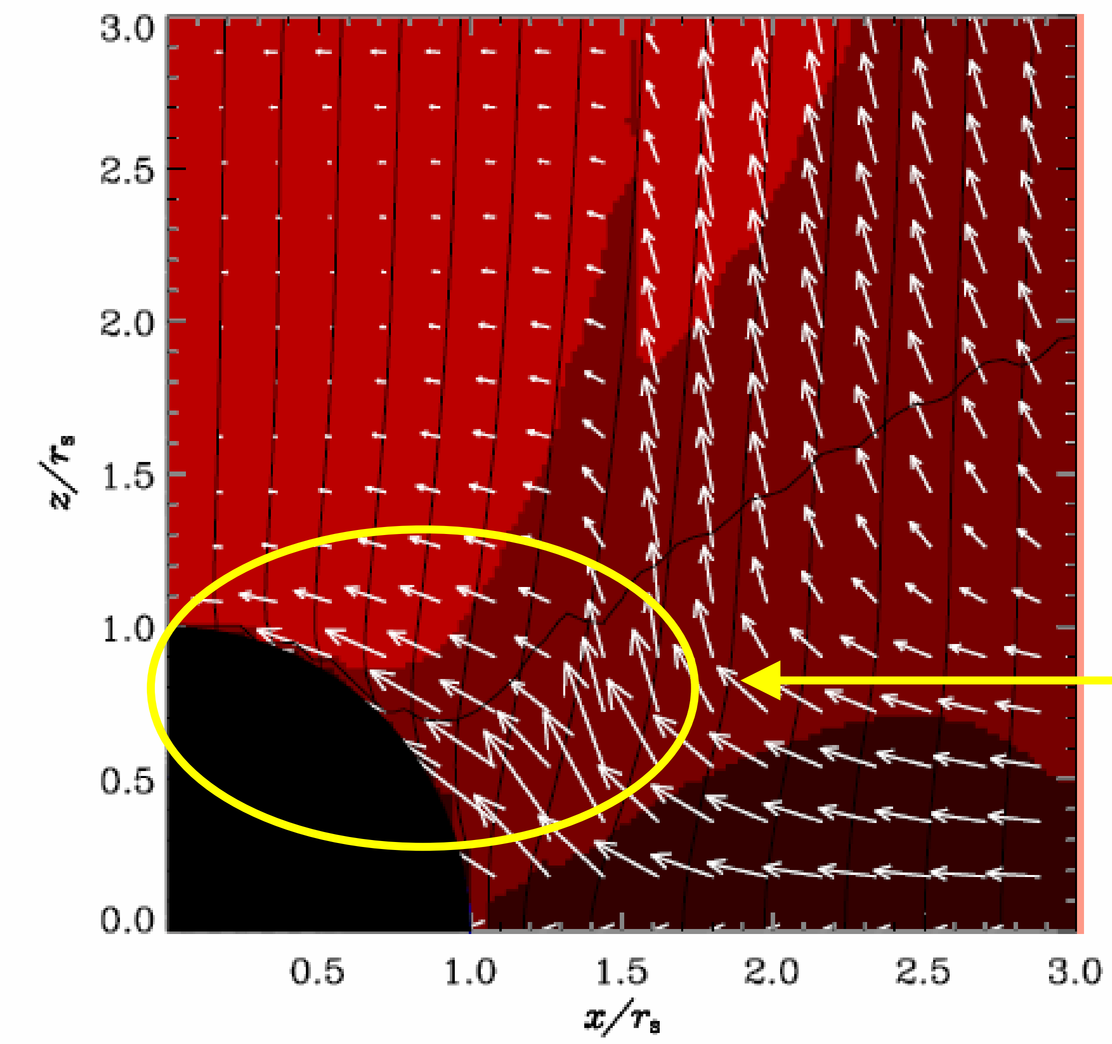


a=0.9995
V_matter=-1
(anti-rotation)

Poynting flux direct
rotation axis

there is no negative energy region

Result(4)



a=0.0 (Schwarzshild)
V_matter=1

No outward poynting flux!!

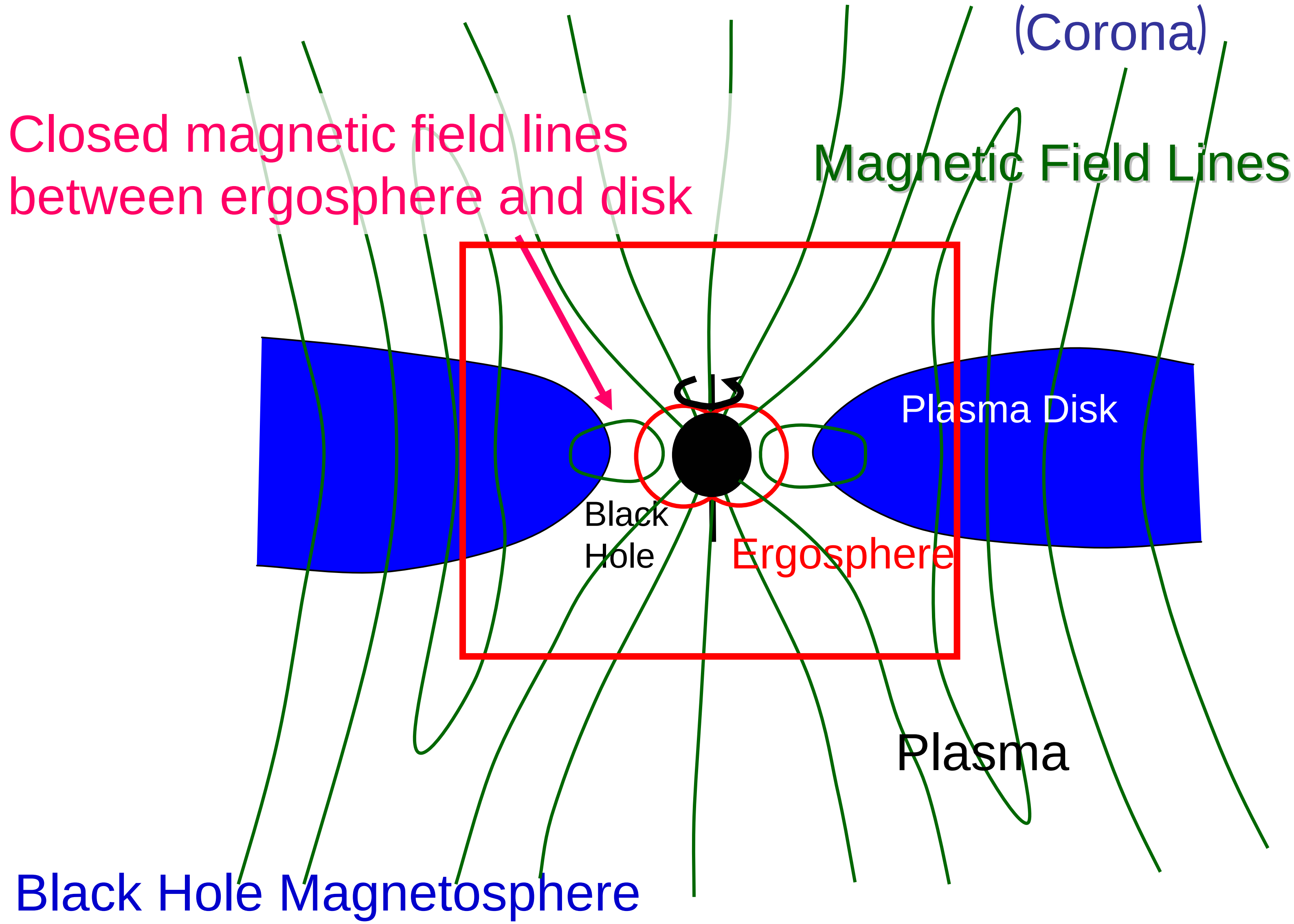
Summary

- We performed GRMHD simulation and calculated the evolution of BH+ uniform magnetic field models.
- The strong outward poynting flux produced in the ergo region of Kerr BH.
- The motion of surrounding material has correlation of the degree of extraction from the BH.

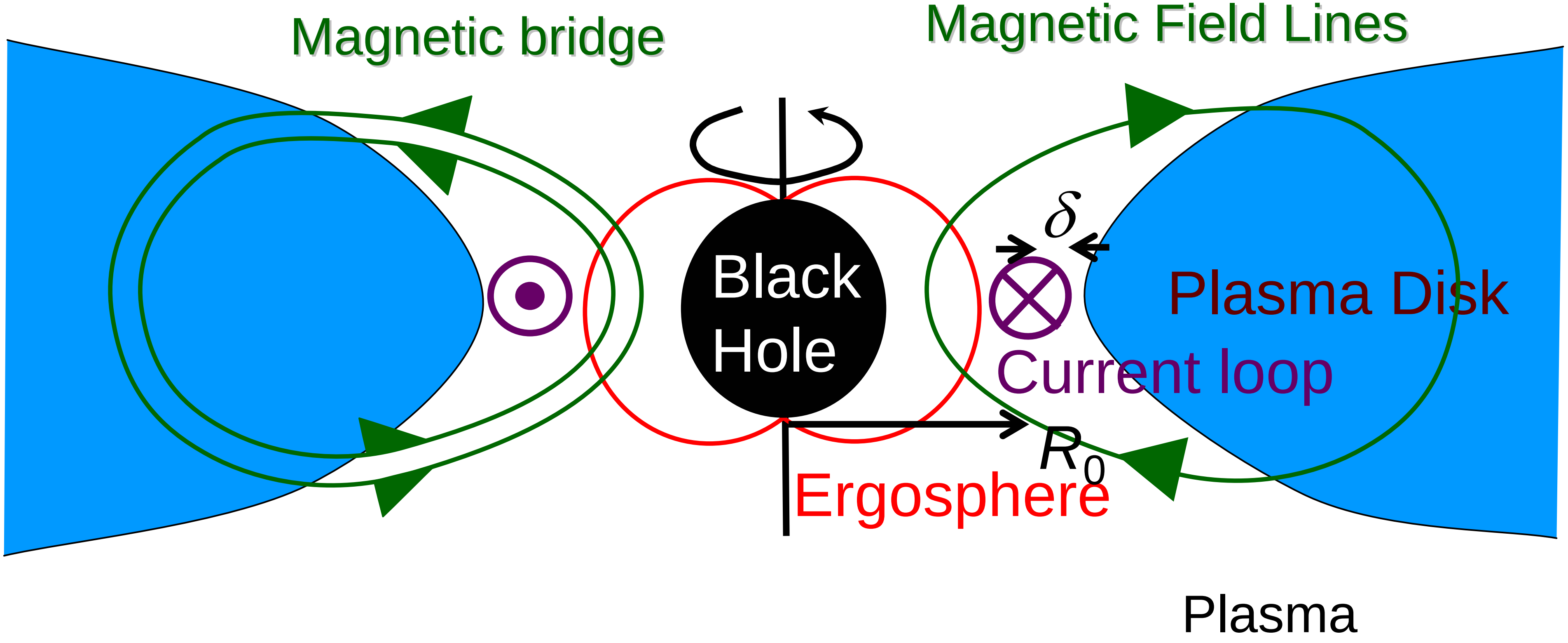
GRMHD Simulation: magnetic field of current loop near rotating black hole

Nobuya Nishimura
(Kyushu University)

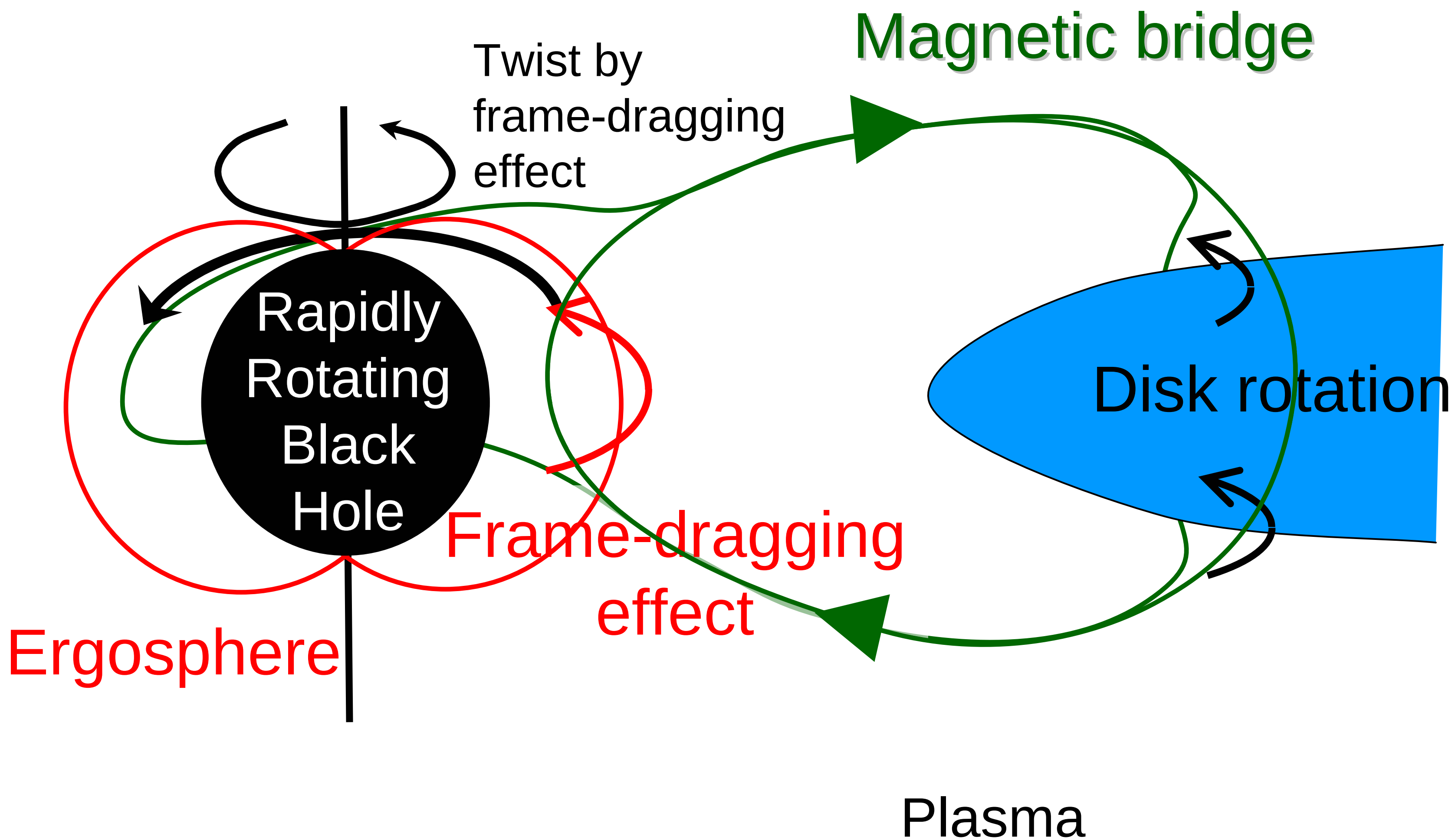
Black Hole Magnetosphere



Magnetic Field induced by Current Loop around Black Hole



Twist of magnetic bridge by ergosphere



Numerical Models

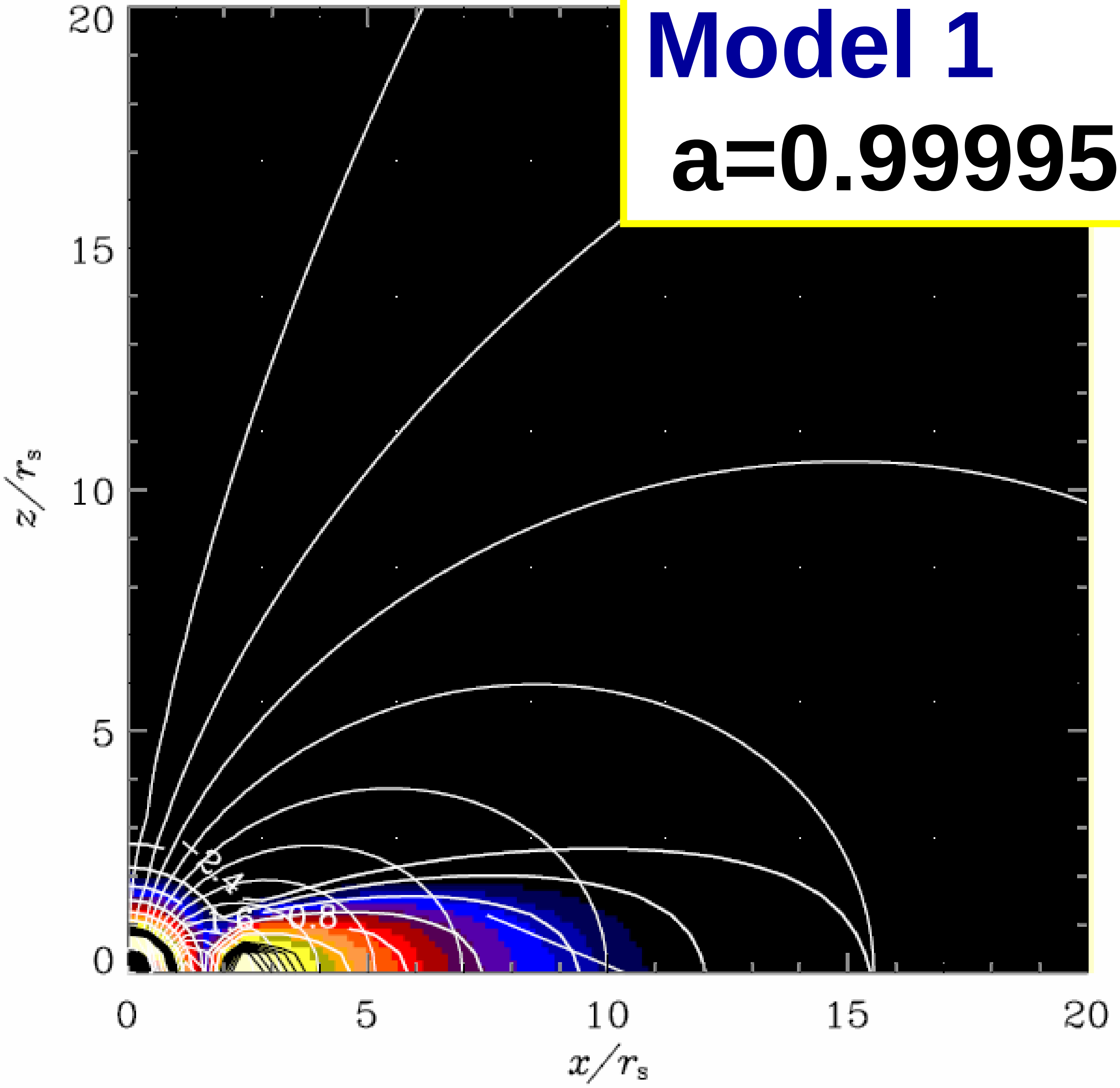
We performed GRMHD simulation for

two types of parameters.

a: rotation parameter

Model 1	**Model 2**
a=0.99995	**a=0.5**

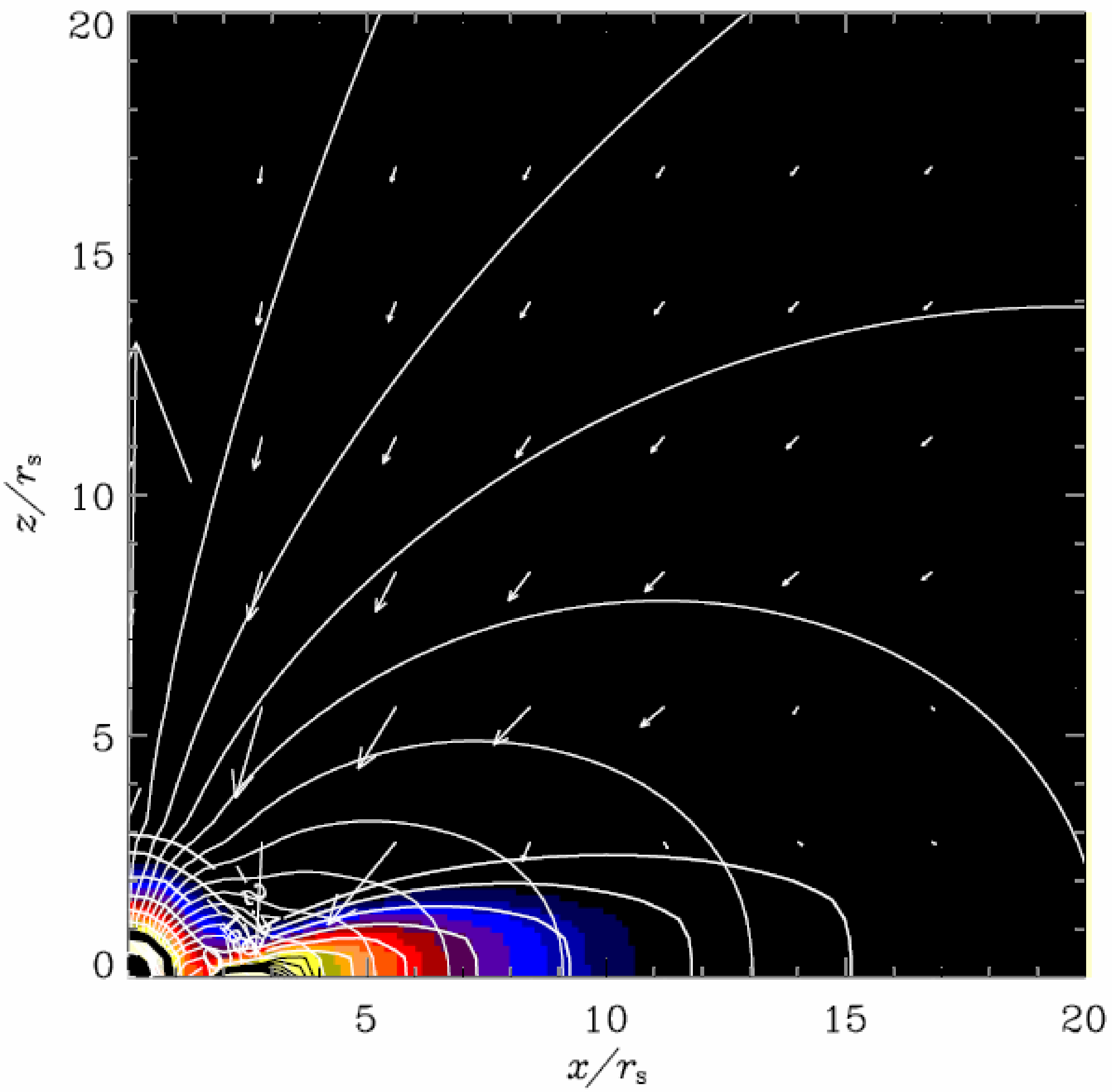
T=0



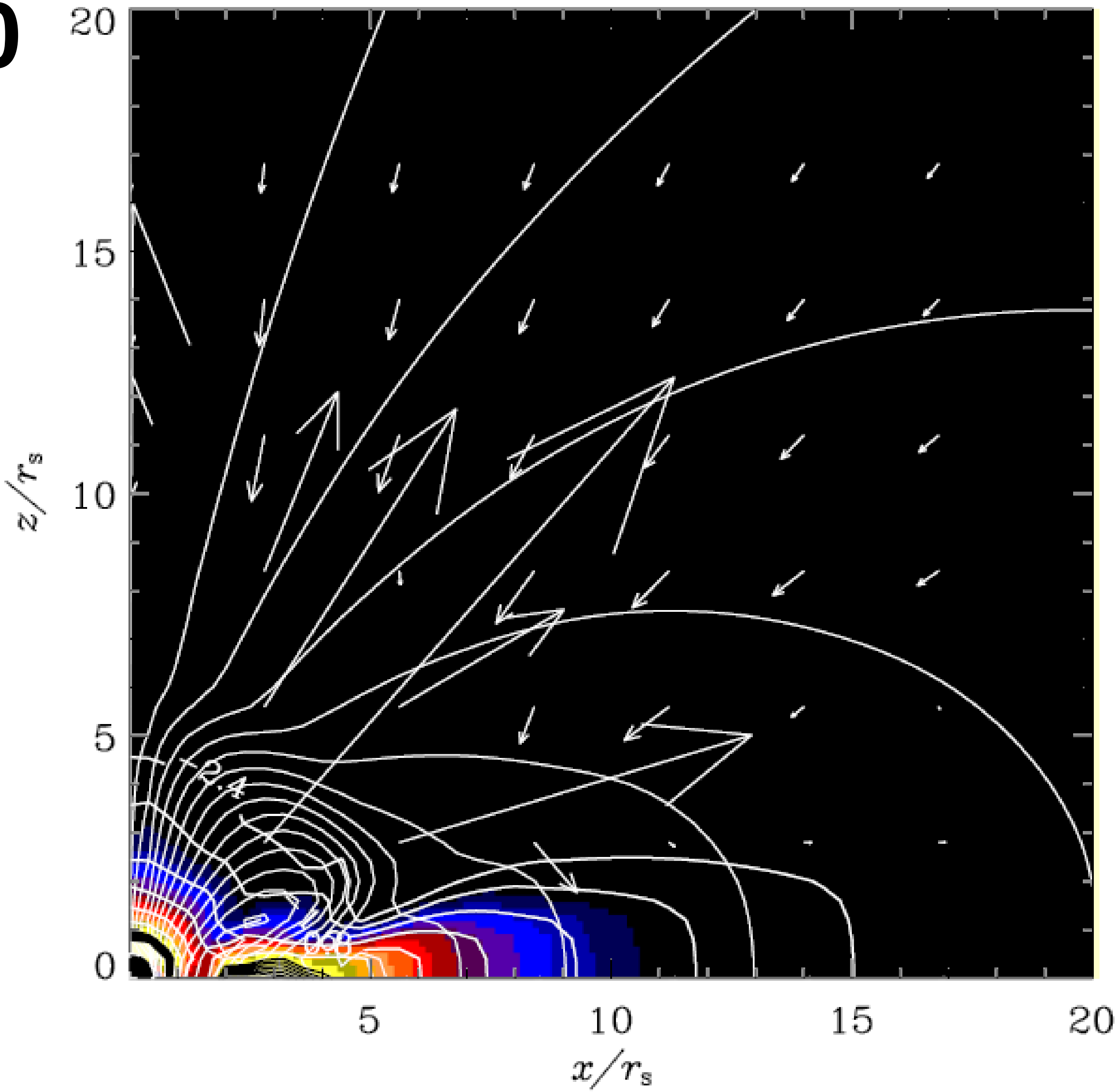
Model 1

a=0.99995

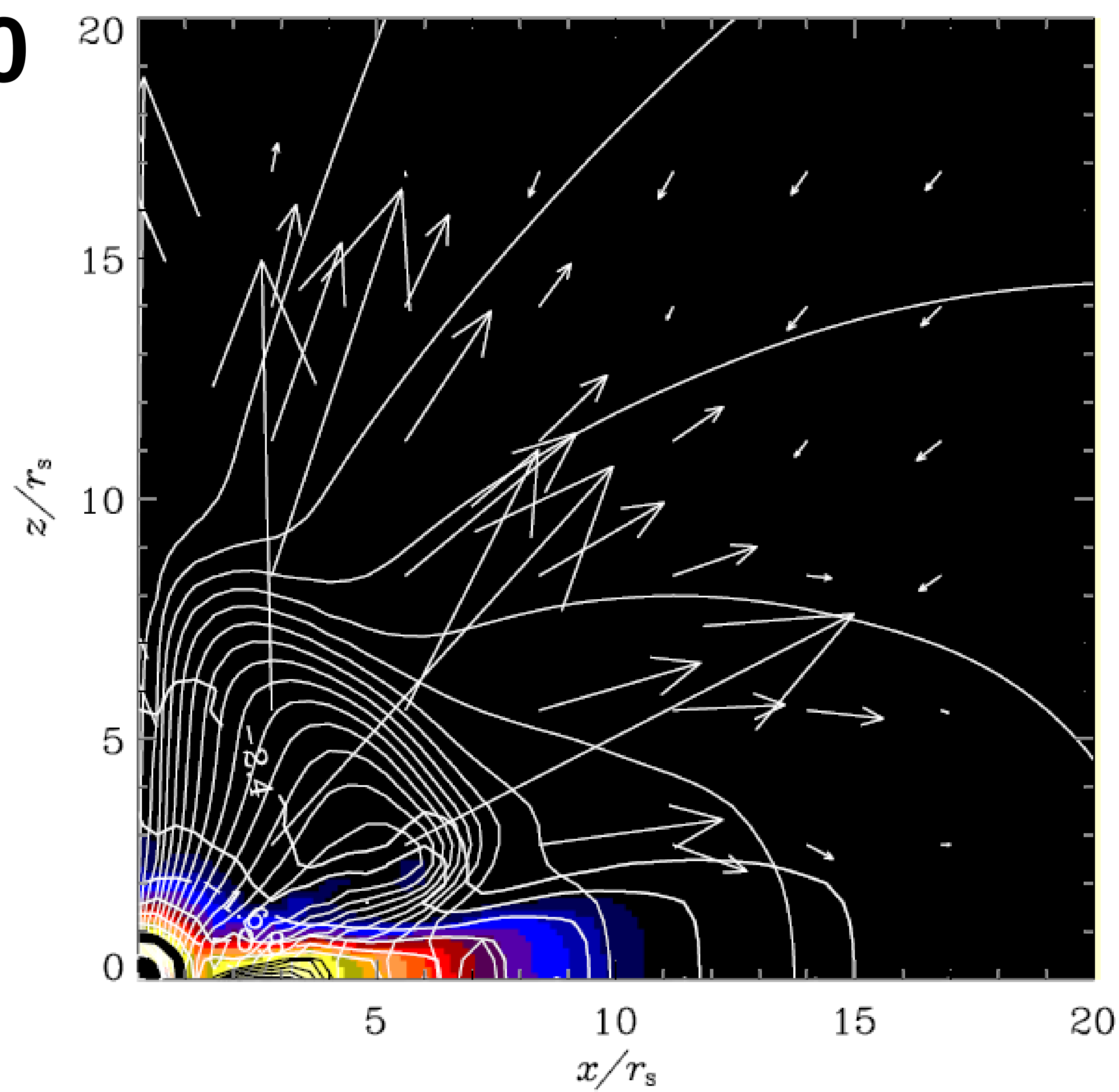
T=8



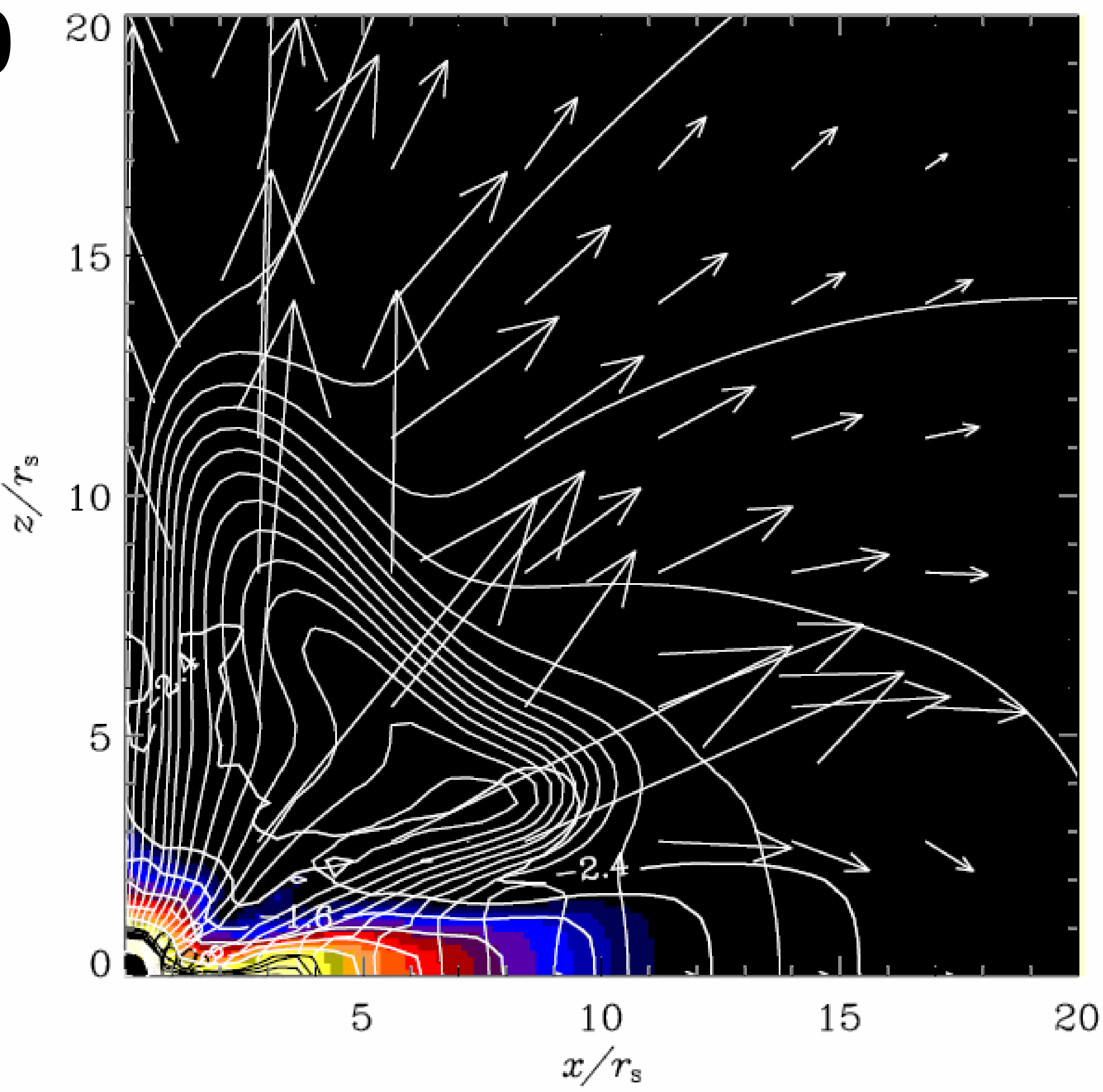
T=20



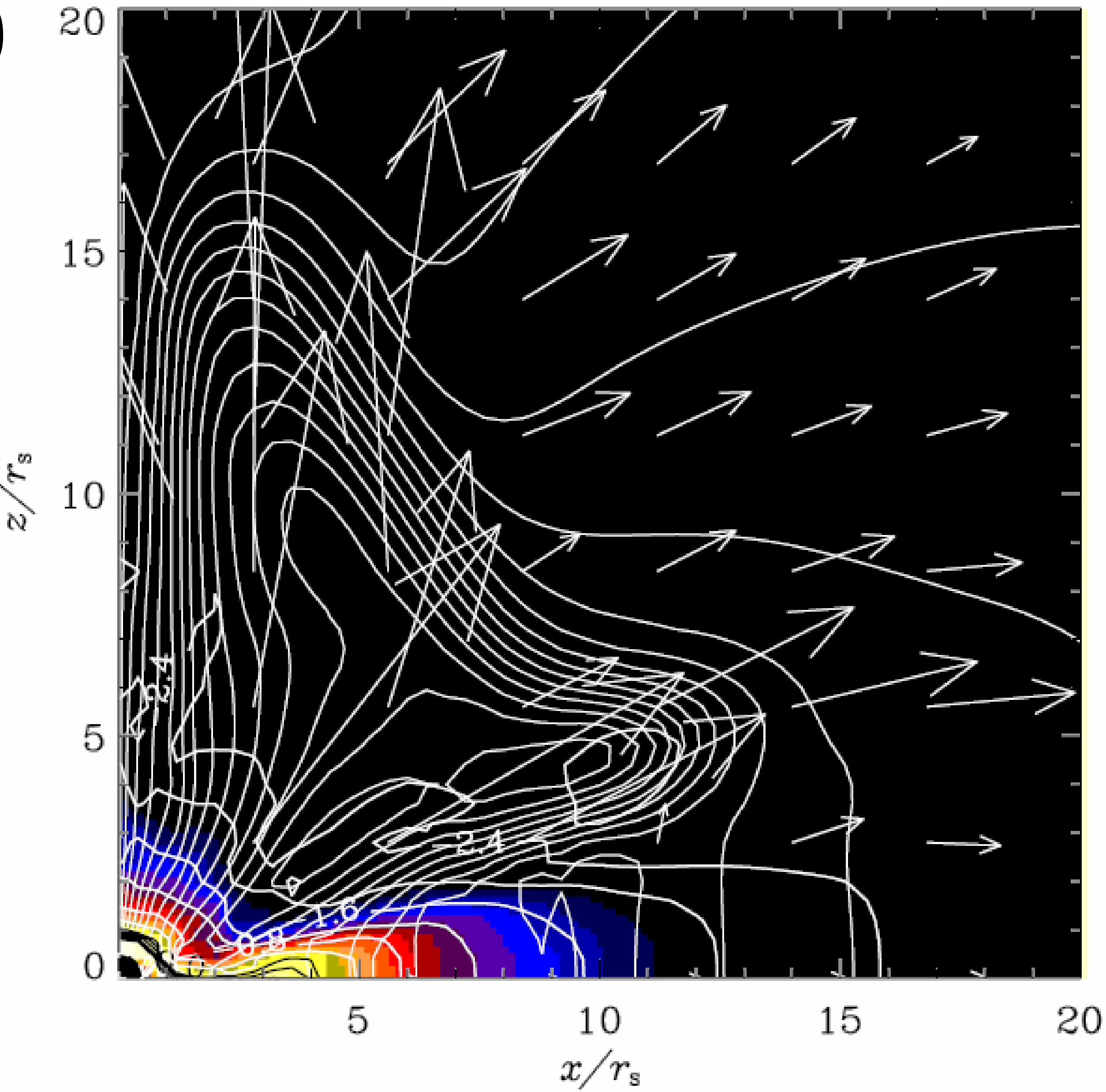
T=30



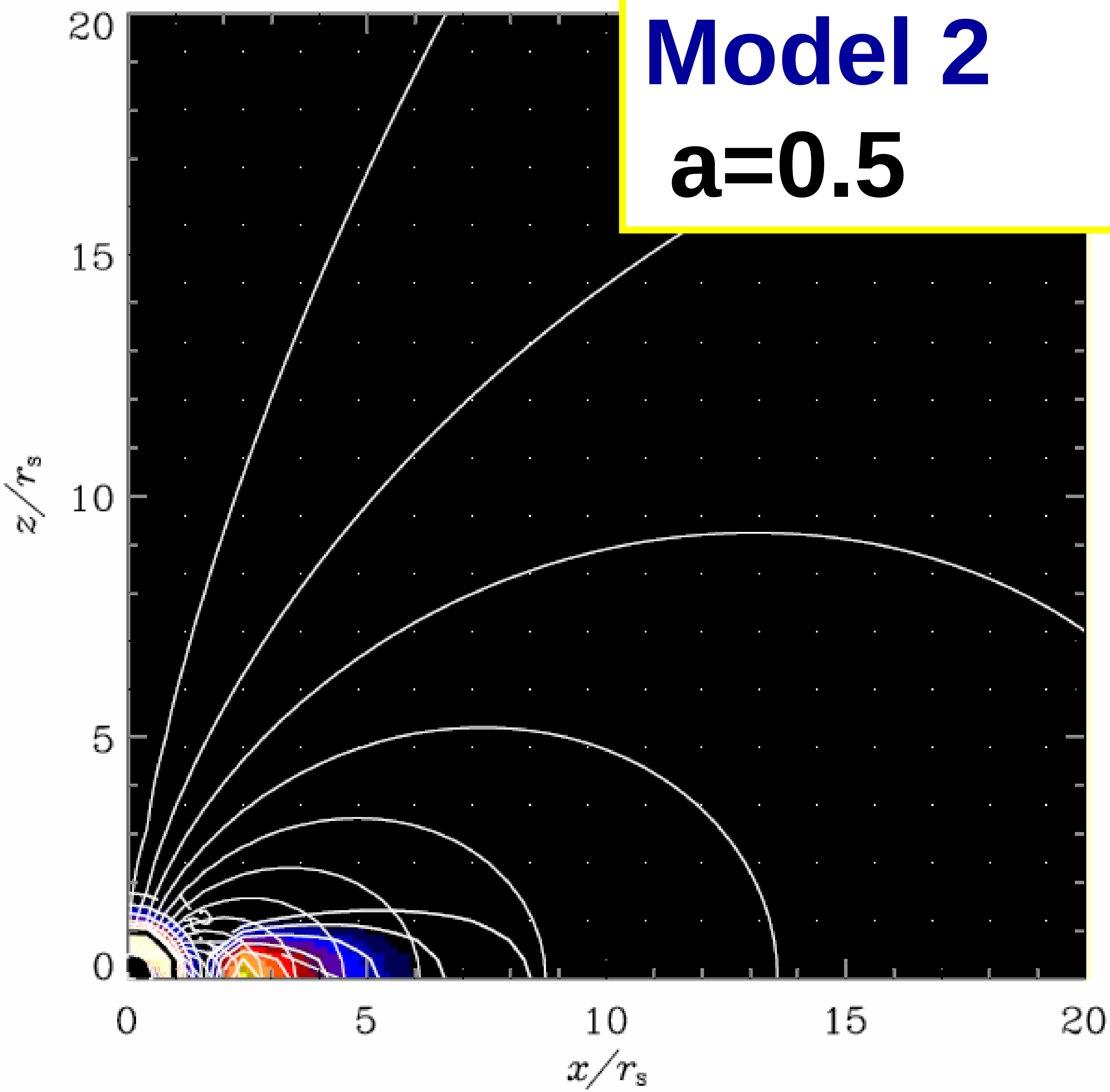
T=40



T=50



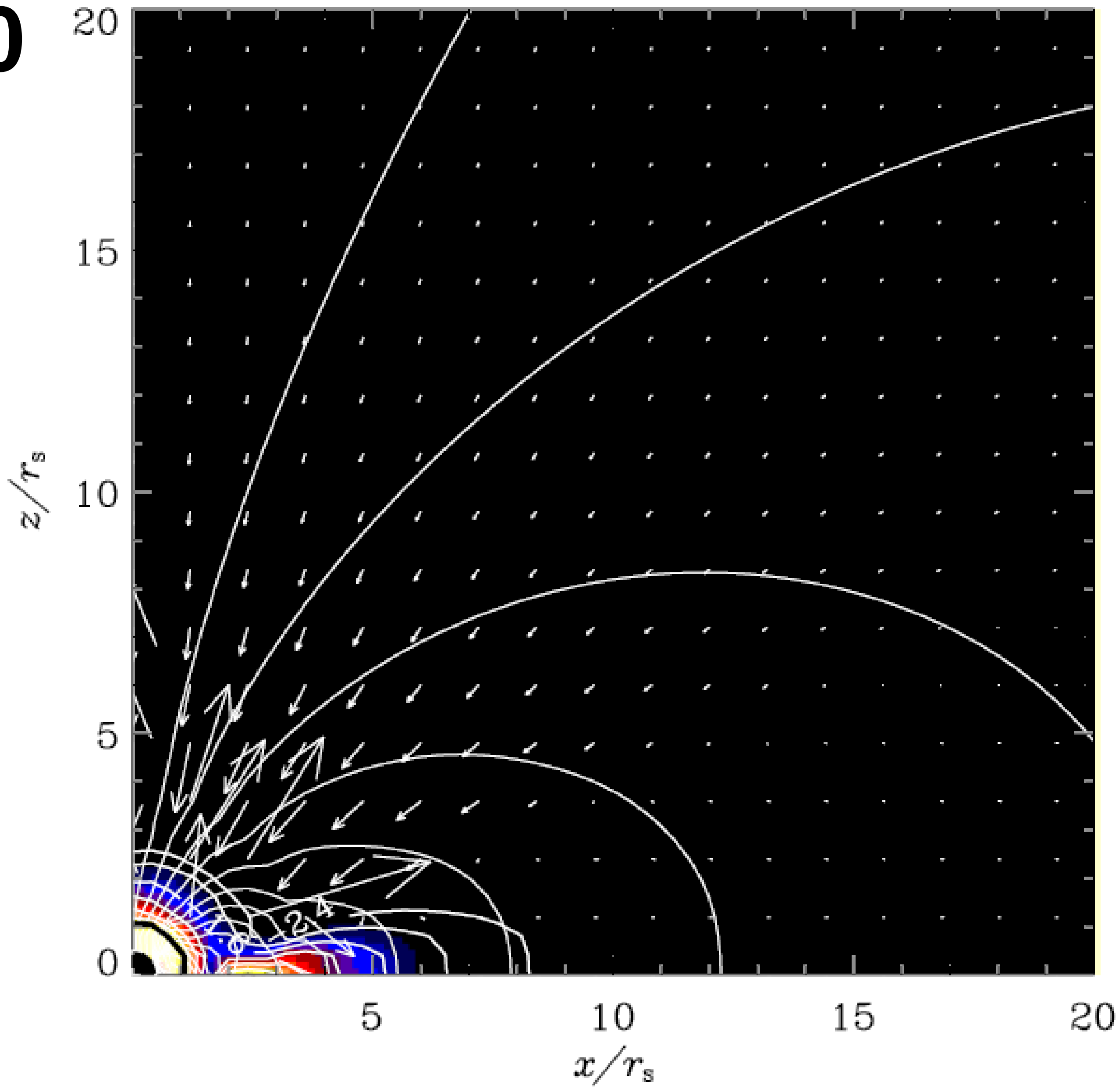
T=0



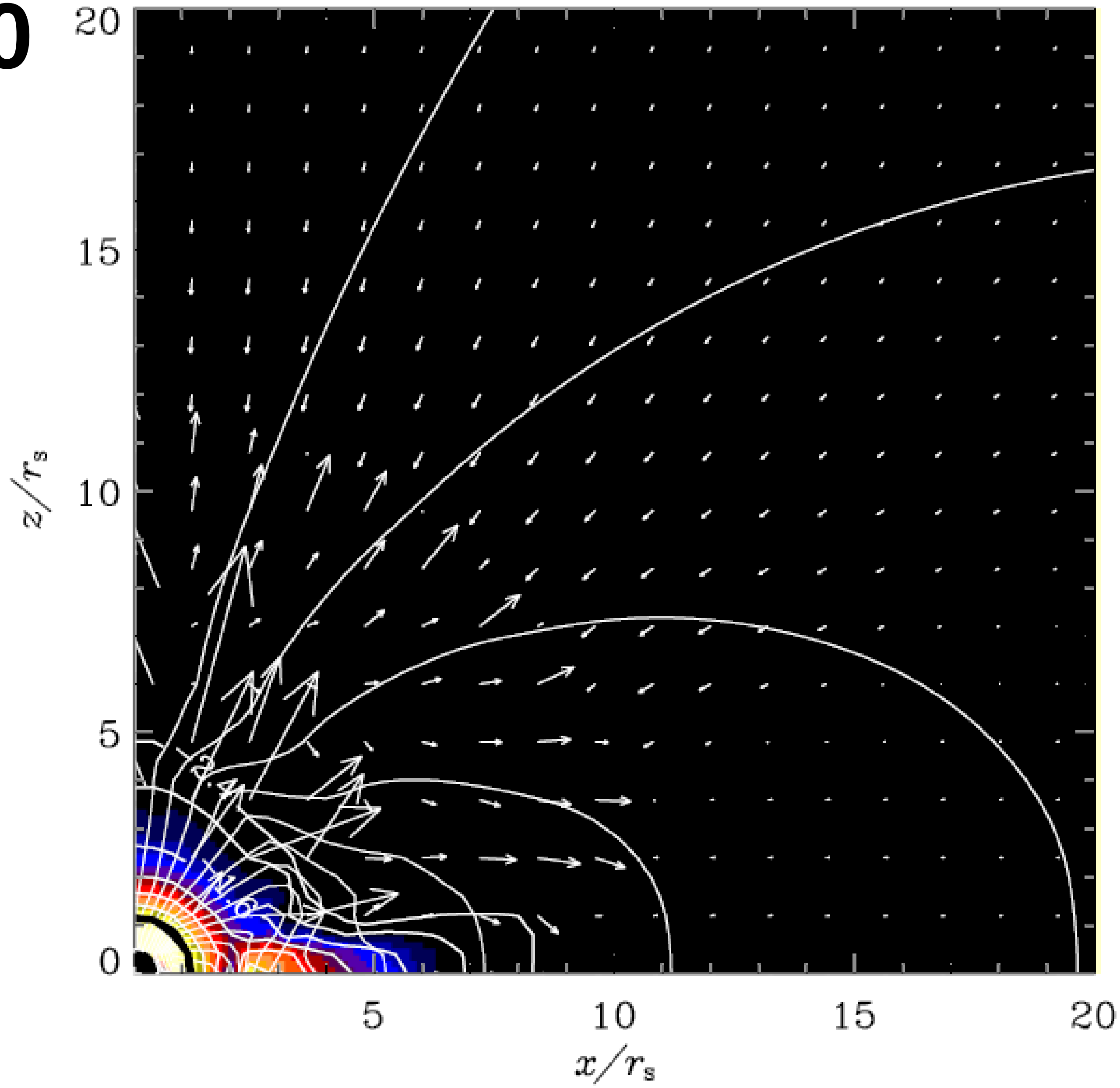
Model 2

a=0.5

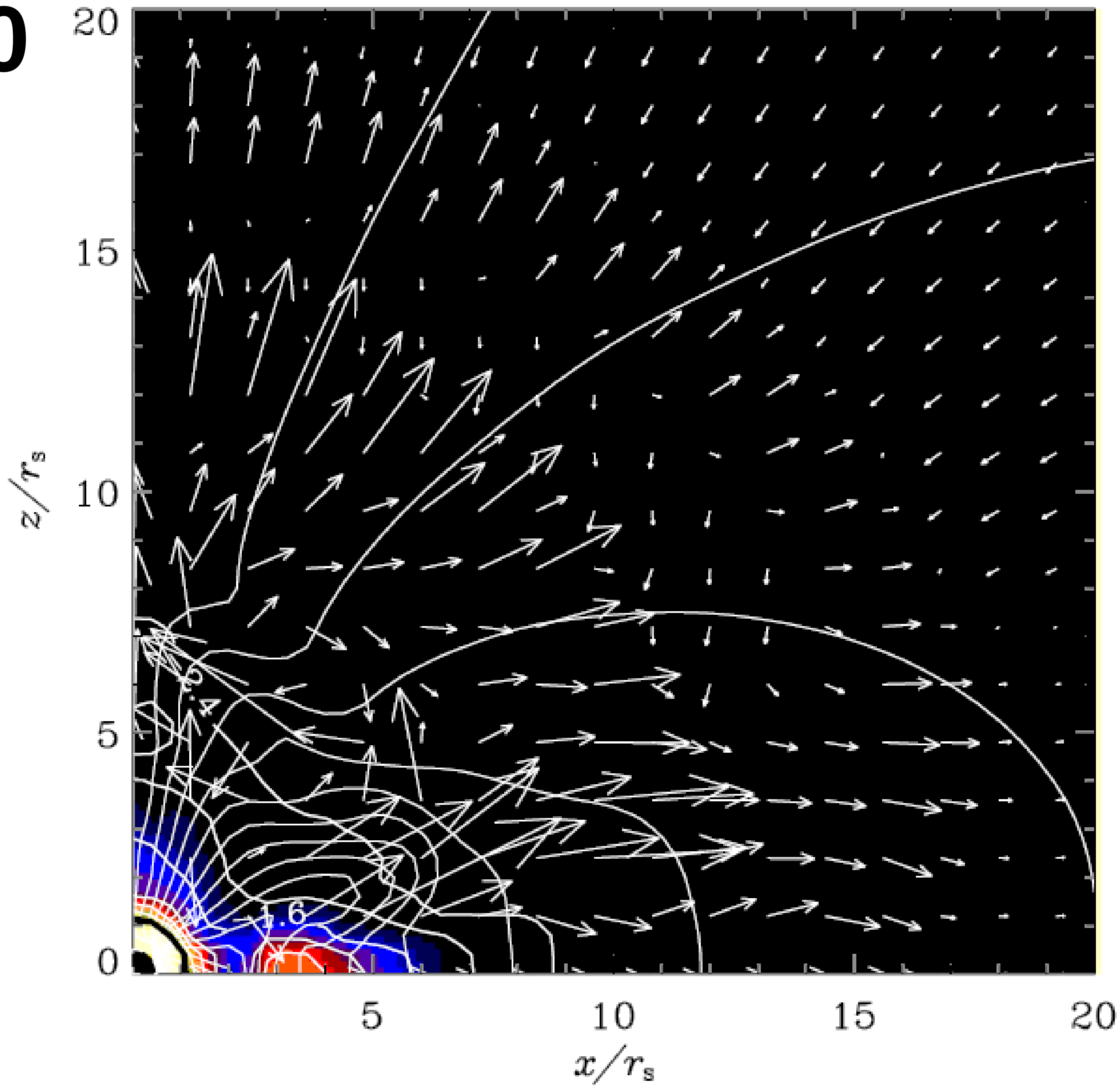
T=10



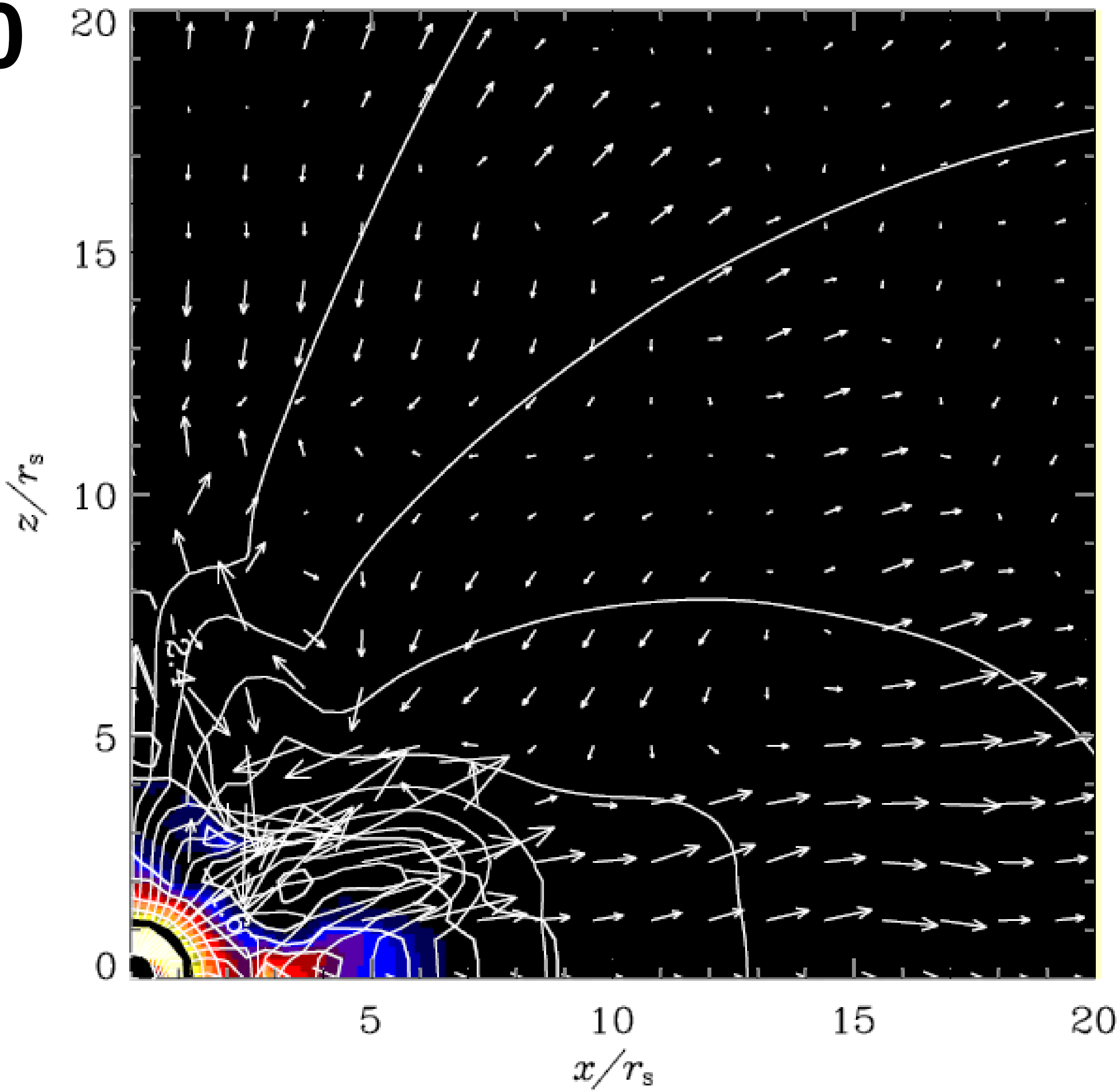
T=20



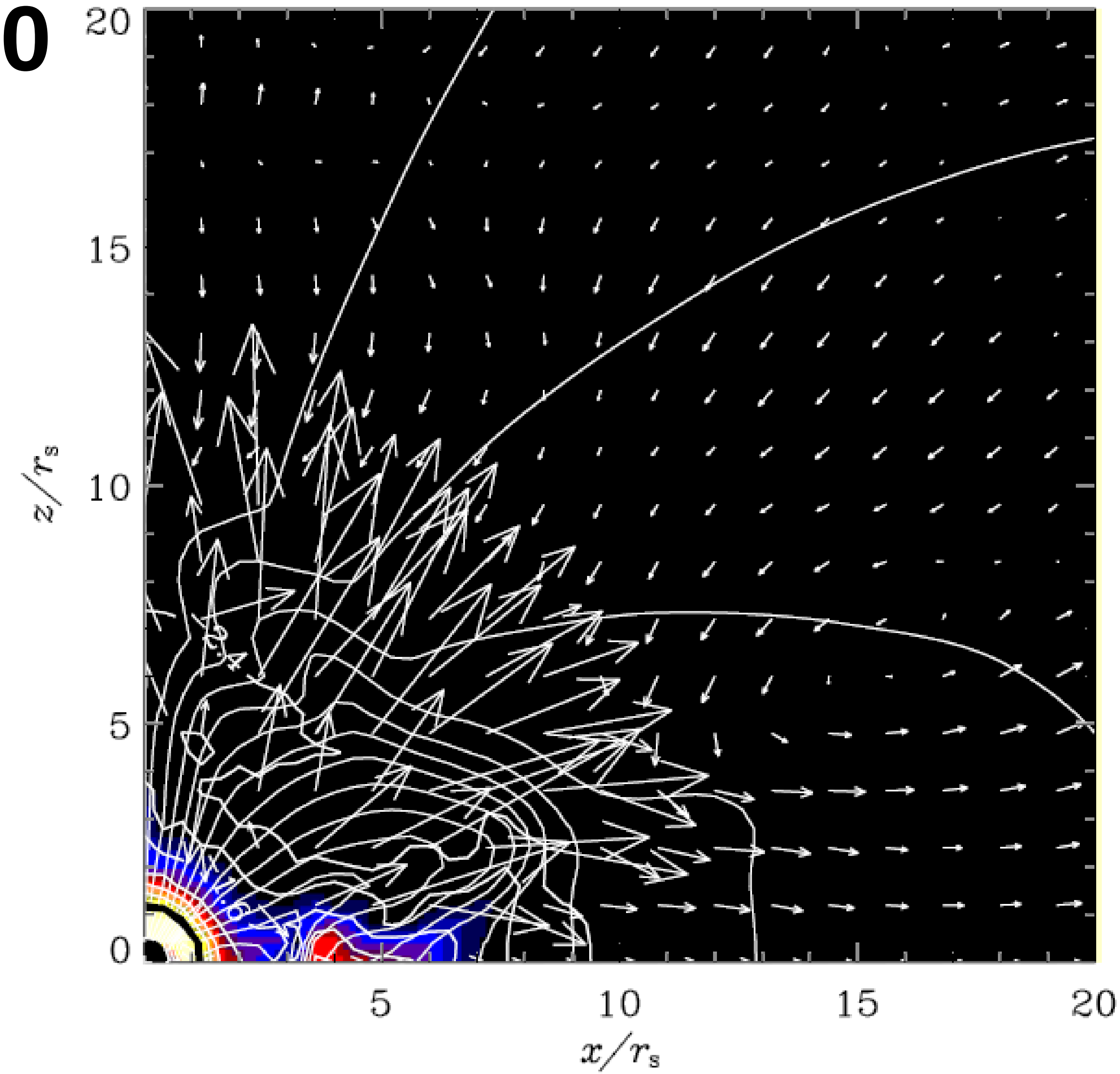
T=30



T=40

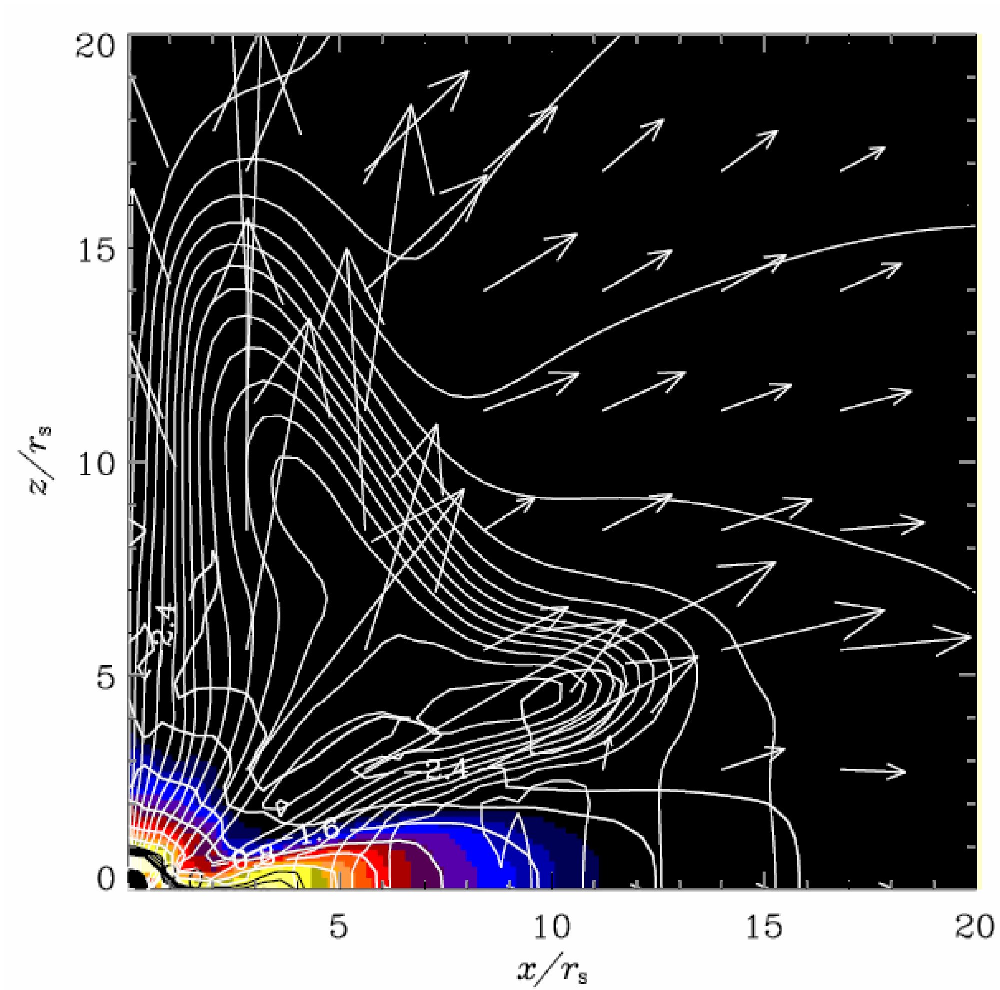


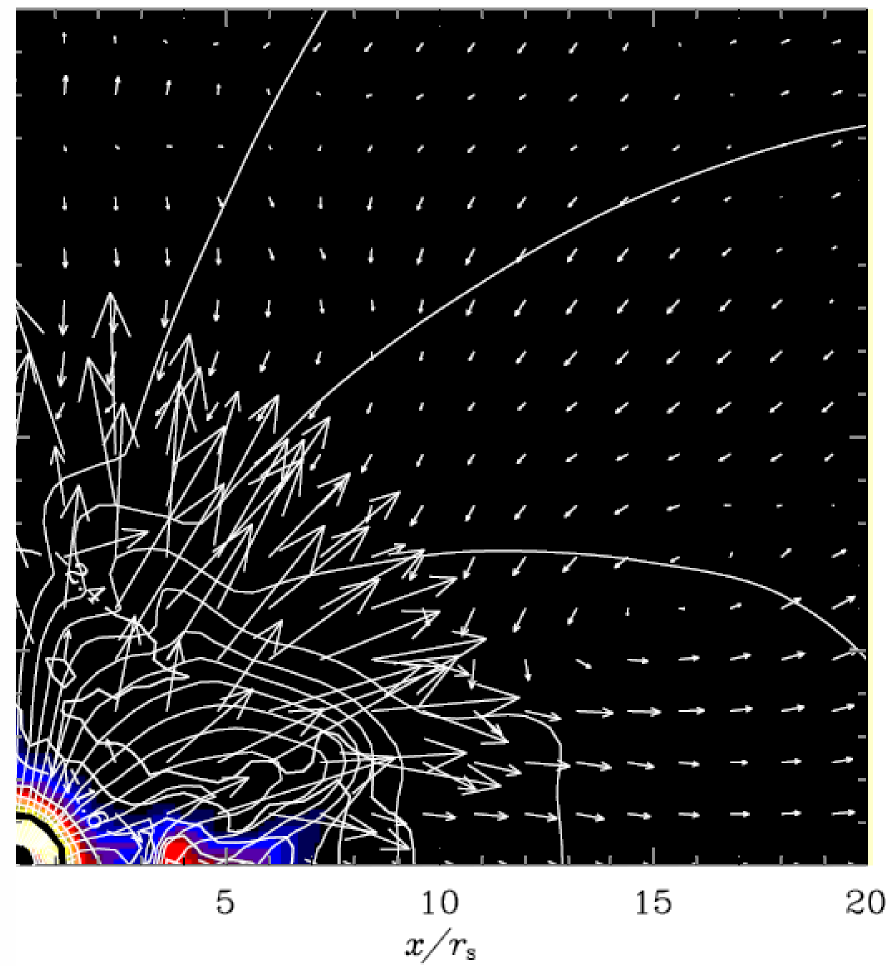
T=50



Model 1
a=0.99995

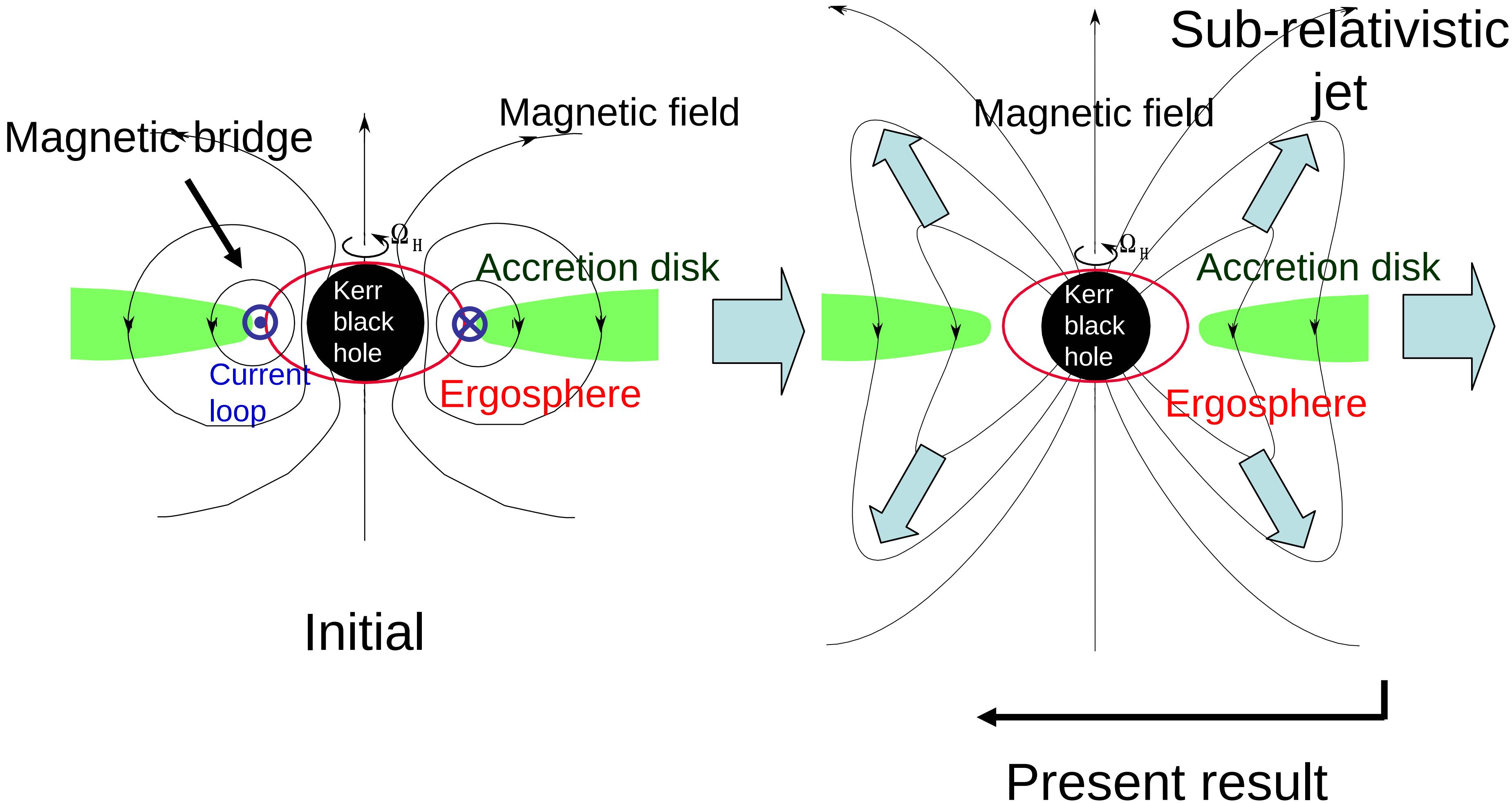
Model 2
a=0.5 (t=50)

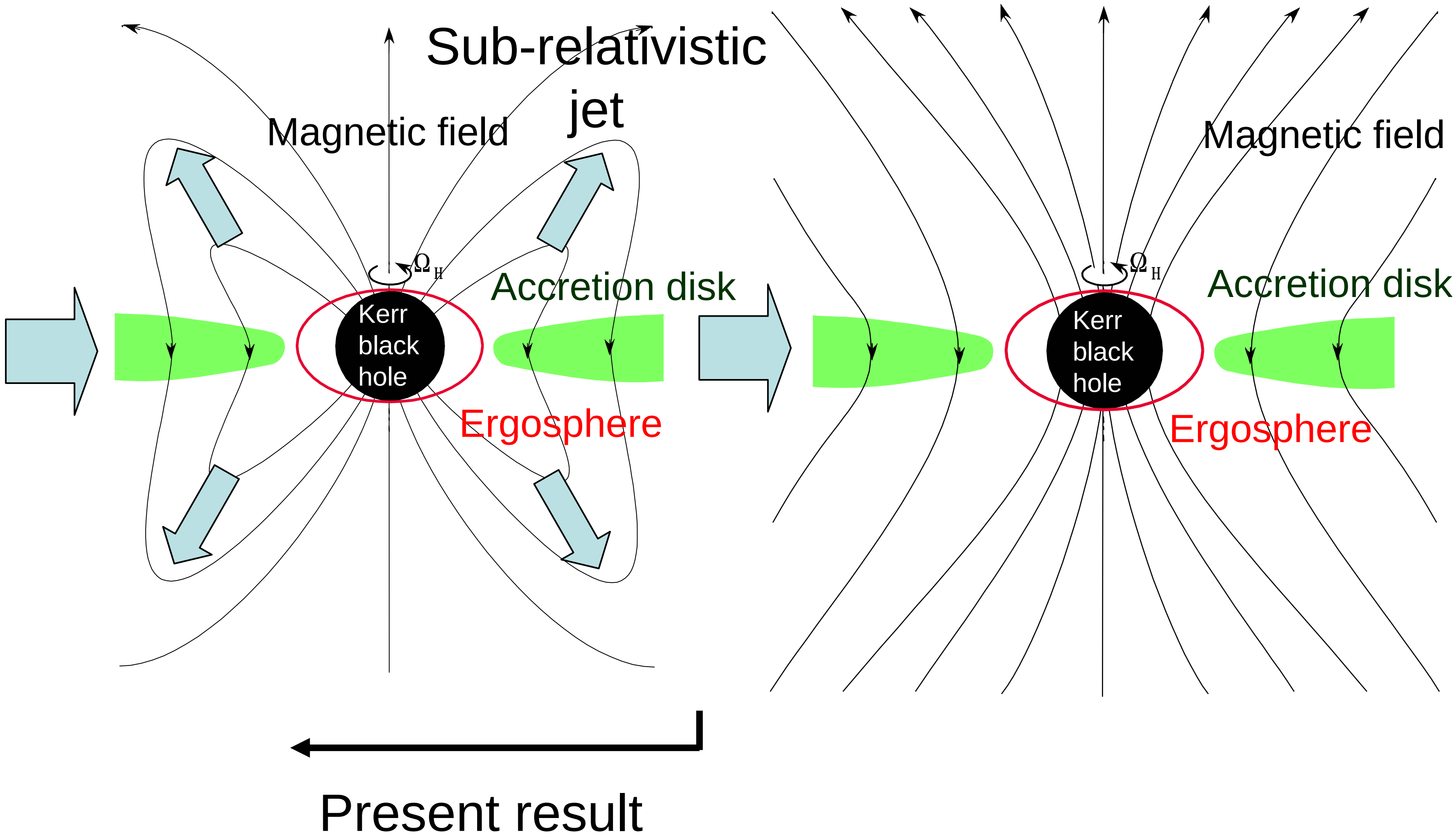


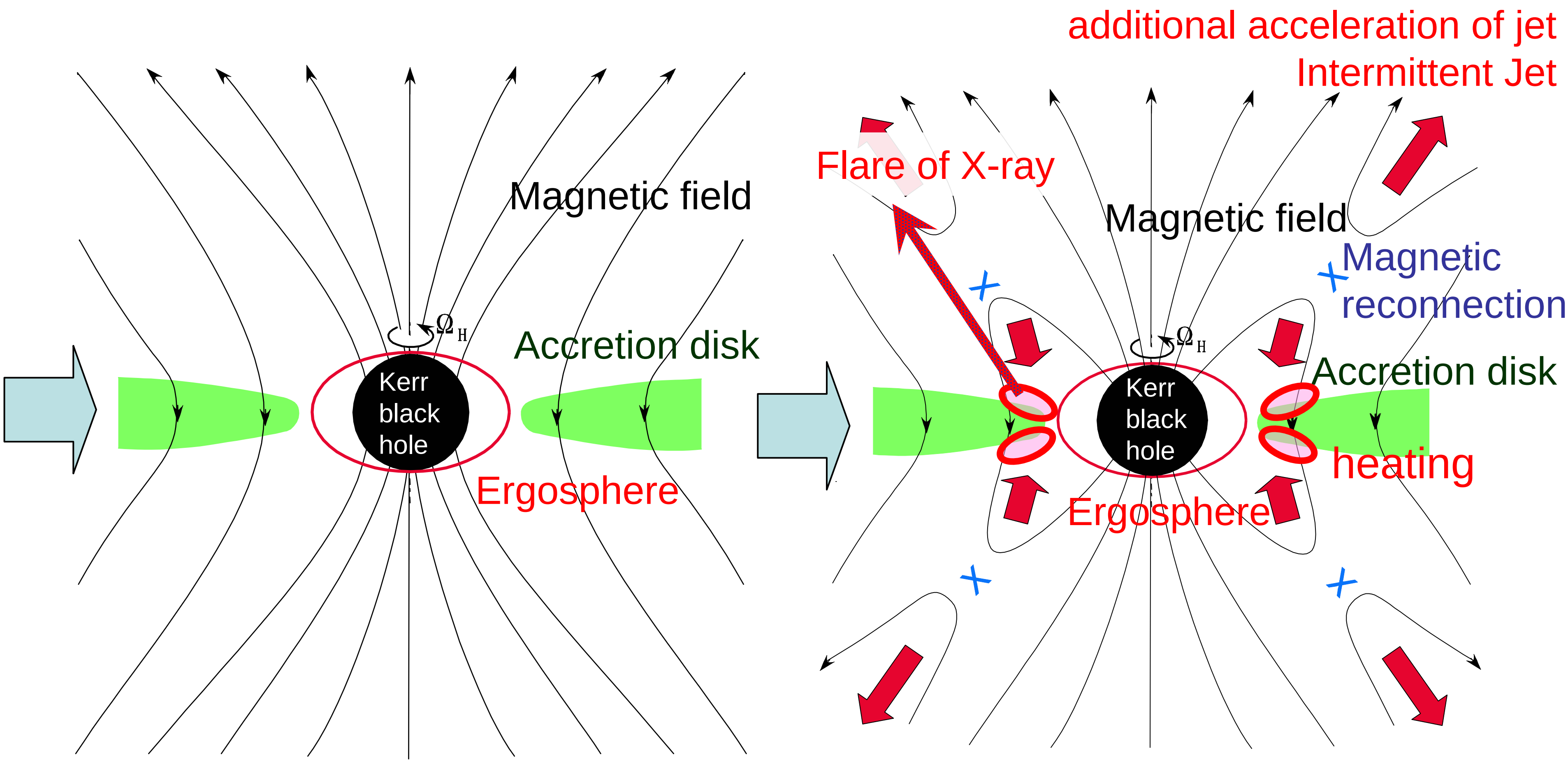


Thank You

Expected phenomena caused by the magnetic bridge in longer-term calculation




Sub-relativistic
jet
Magnetic field
Ω_H
Accretion disk
Kerr
black
hole
Ergosphere
Magnetic field
Ω_H
Accretion disk
Kerr
black
hole
Ergosphere
Present result



Magnetic reconnection should be important near black hole horizon!

Electric resistivity should be considered

Future important subject

Summary of Numerical Results

- When the black hole rotates rapidly, the magnetic bridge between the ergosphere and the disk is twisted by the plasma in the ergosphere due to the frame-dragging effect.
- The magnetic pressure of the magnetic bridge increases rapidly by the twist of the magnetic bridge, and the high magnetic pressure blows off the plasma near the ergosphere outwardly.
- The outflow of the plasma is collimated by the magnetic tension to form the jet.

In conclusion, the magnetic bridge between the ergosphere and the disk can not be steady, and expands explosively and forms the jet.