28th Texas Symposium on Relativistic Astrophysics

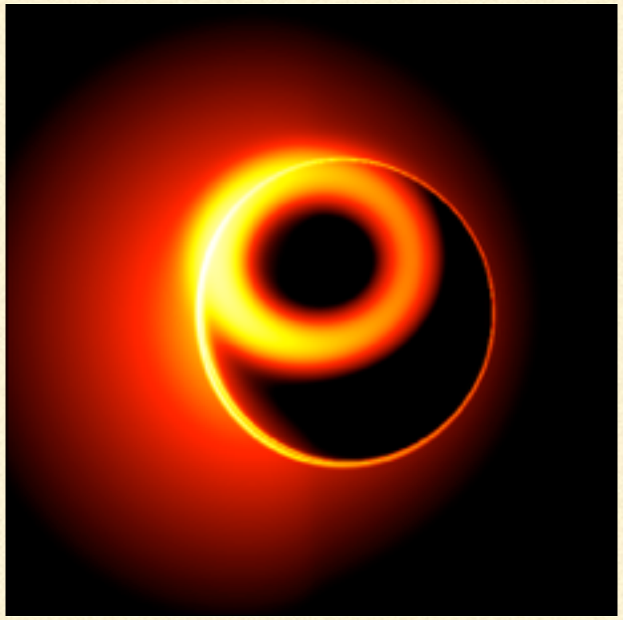
13-18 December 2015

$$G_{\mu\nu} - \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

MHD SHOCKS IN ACCRETION ONTO A ROTATING BLACK HOLE

Masaaki TAKAHASHI

Aichi University of Education



The formation of standing magnetohydrodynamical (MHD) shocks by accreting plasma in a black hole magnetosphere is studied. The black hole magnetosphere would be formed around a black hole with an accretion disk. The global magnetic field lines would be originated by currents in the accretion disk and its corona, and then some part of magnetic field lines would lead to the event horizon. Along such magnetic field lines magnetized plasma streams from the disk surface to the horizon, and on the way to the horizon MHD shock can be generated. Although the postshock plasma becomes very hot, the MHD shock can be expected as a source of high-energy radiation, which is generated very close to the horizon and then carry to us a lot of information of the black hole spacetime. We also discuss the huge energy release at the MHD shock front, where the plasma's kinetic energy and the black hole's rotational energy can convert to radiative energy by considering negative energy postshock MHD flows (Takahahi & Takahashi 2010). This means that the Blandford-Znajek (1977) power can convert to radiative energy at the MHD shock generated very close to the horizon.

Where is the black hole power transported to?

Hada et al. (2011)

Relativistic Jet : Its origin is still unknown.

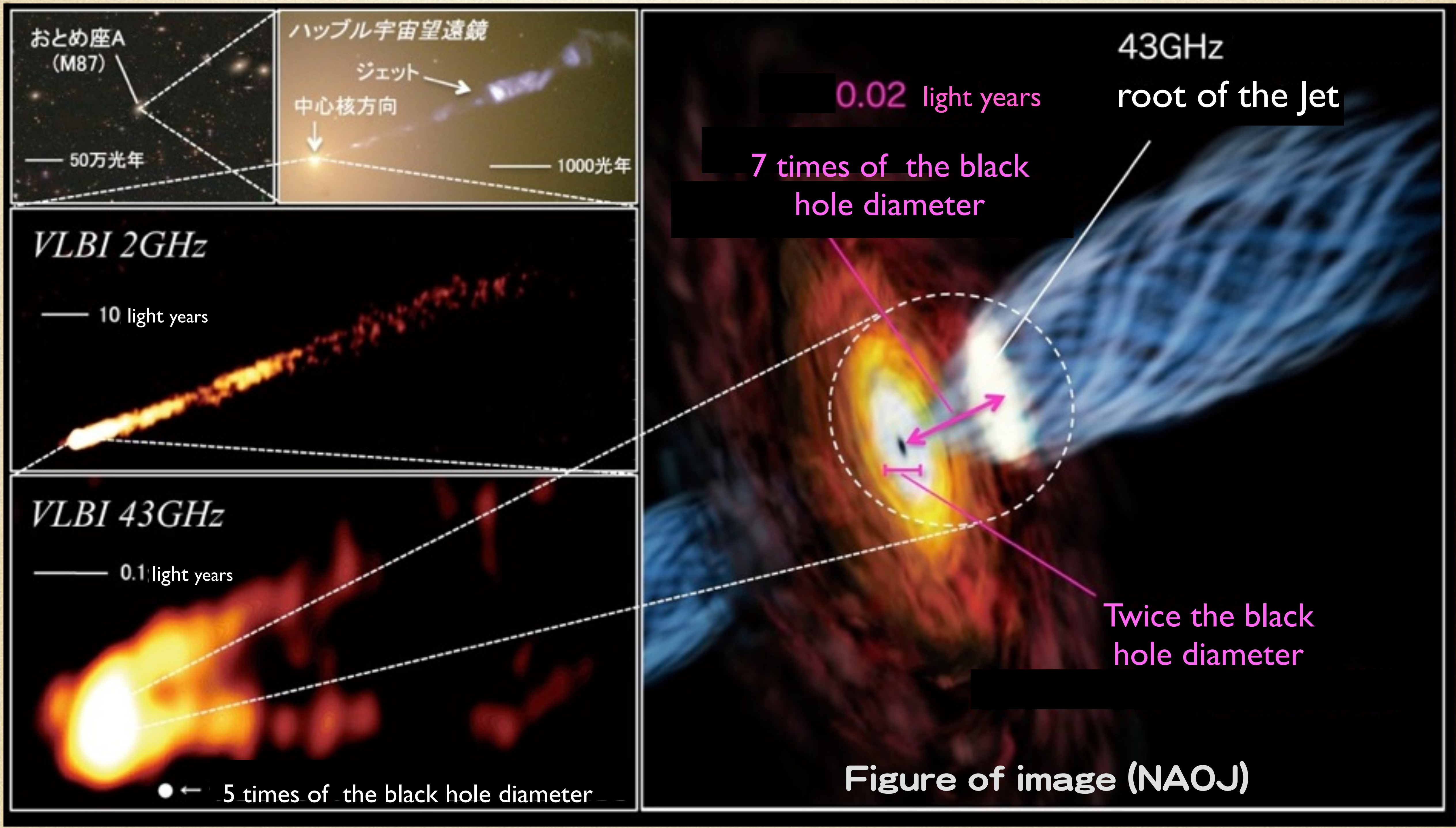
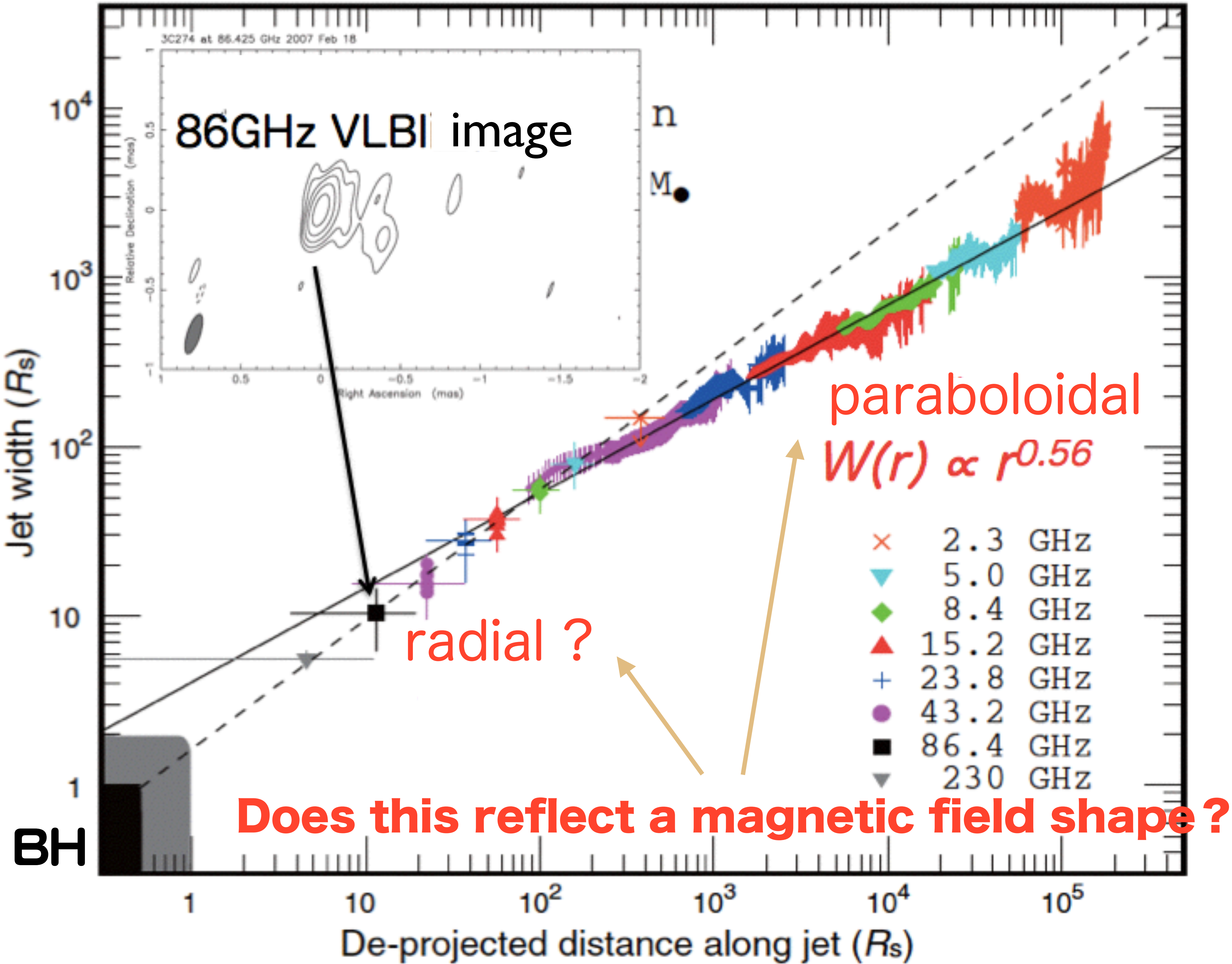


Figure of image (NAOJ)

(TopLeft) Sloan Digital Sky Suvey, (TopRight) NASA and the Hubble Heritage Team.

Jet convergence profile

(Hada et al. 2013, ApJ)



86GHz VLBI image

paraboloidal

$W(r) \propto r^{0.56}$

radial ?

Does this reflect a magnetic field shape?

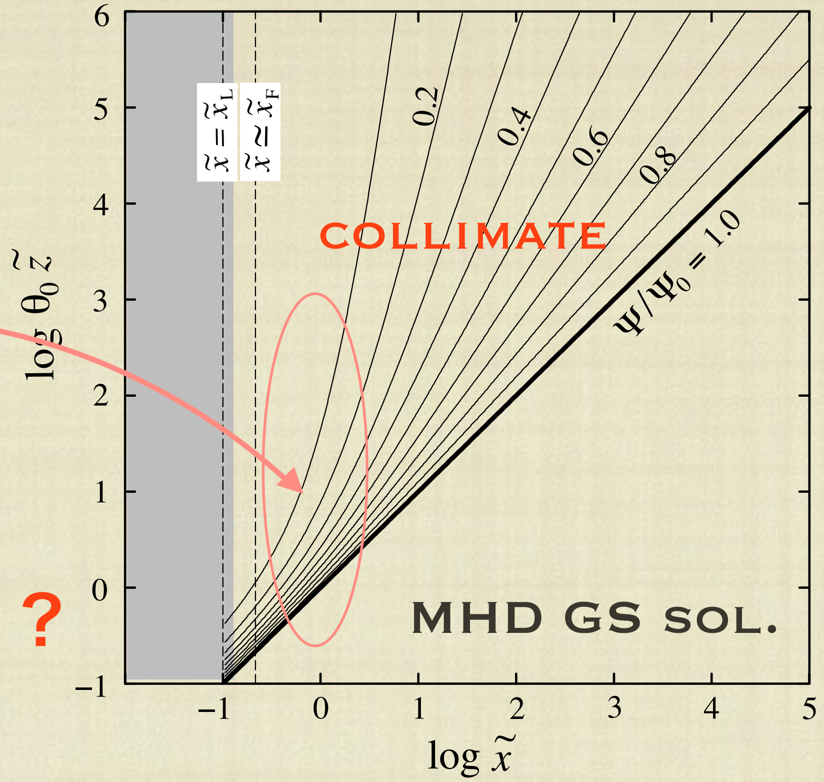
Black Hoke Magnetosphere : Jets

- **OUTER REGION**

$E_k \sim E_m$
bending

How about in M87 ?

TOMIMATSU & MT 2003

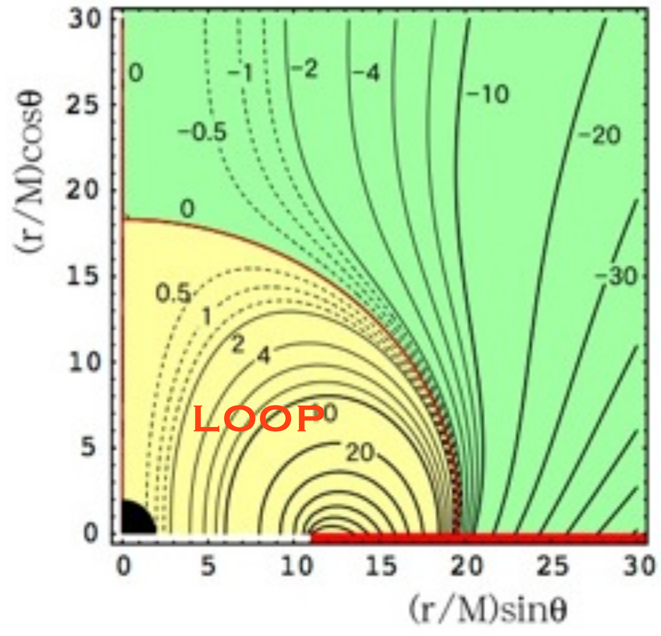


COLLIMATE

MHD GS SOL.

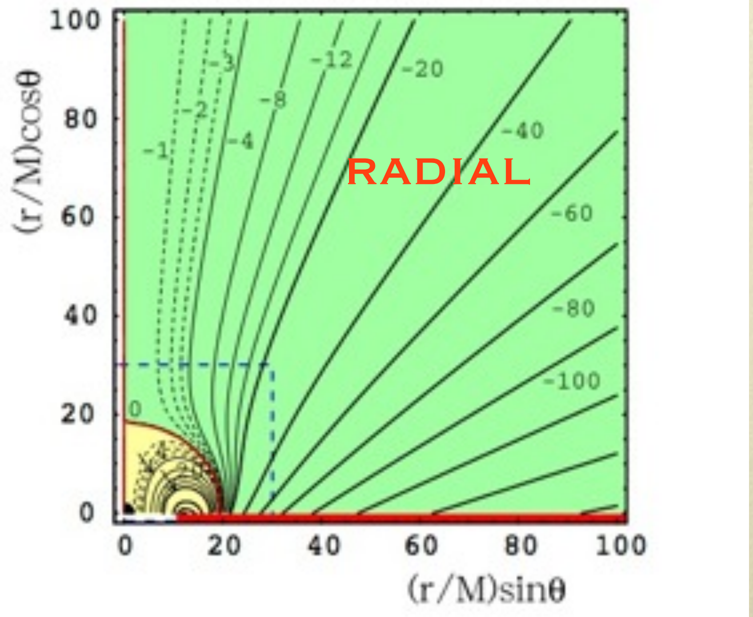
- **INNER REGION**

VACUUM MAXWELL SOL.



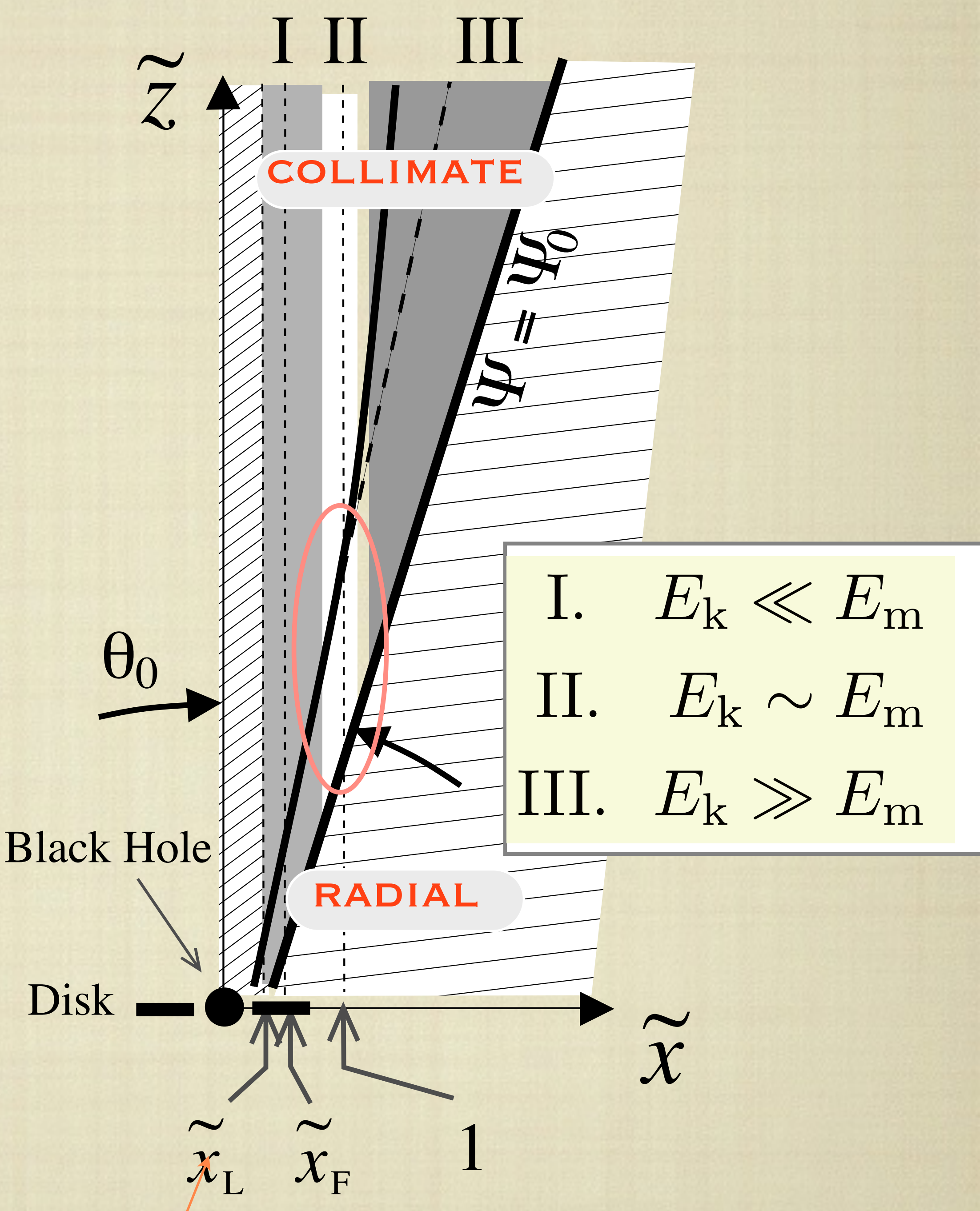
LOOP

TOMIMATSU & MT 2000



RADIAL

MHD Jet Model



COLLIMATE

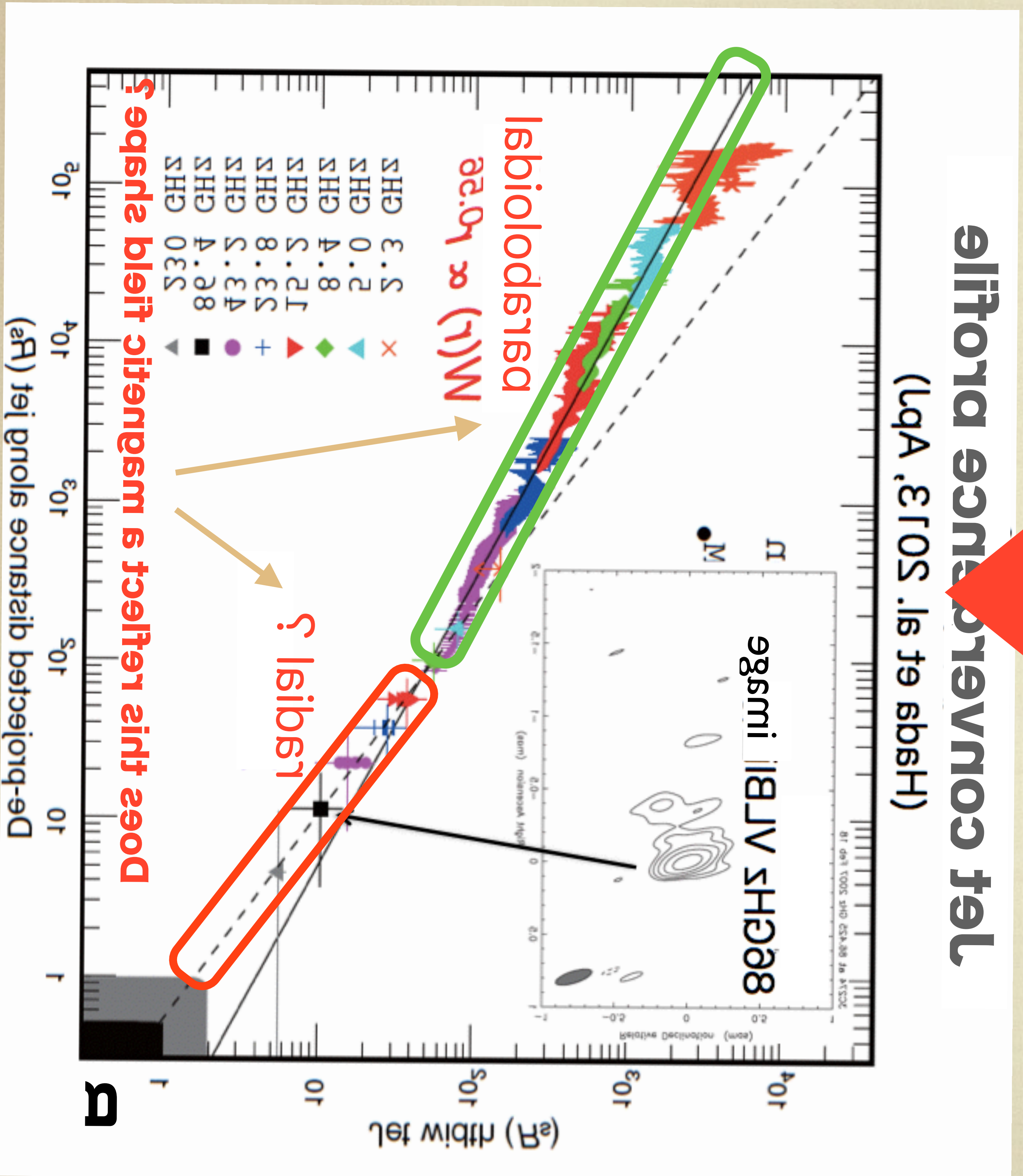
RADIAL

I. $E_k \ll E_m$
II. $E_k \sim E_m$
III. $E_k \gg E_m$

FAST MAG. SURFACE

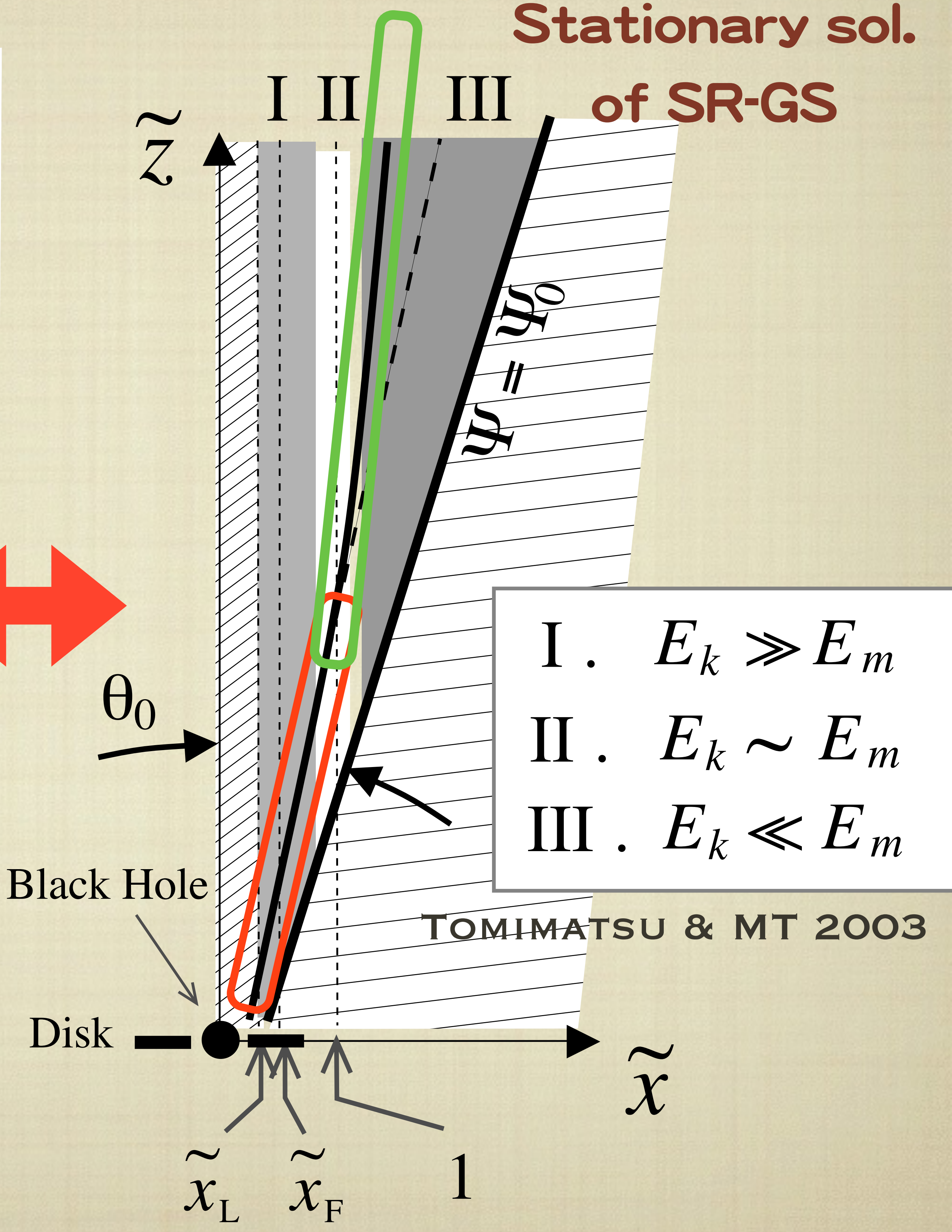
LIGHT SURFACE

Collimation (Radial → Paraboloidal) **came to be observed !?**



Jet convergence profile (Hada et al. 2013, ApJ)

Stationary sol. of SR-GS



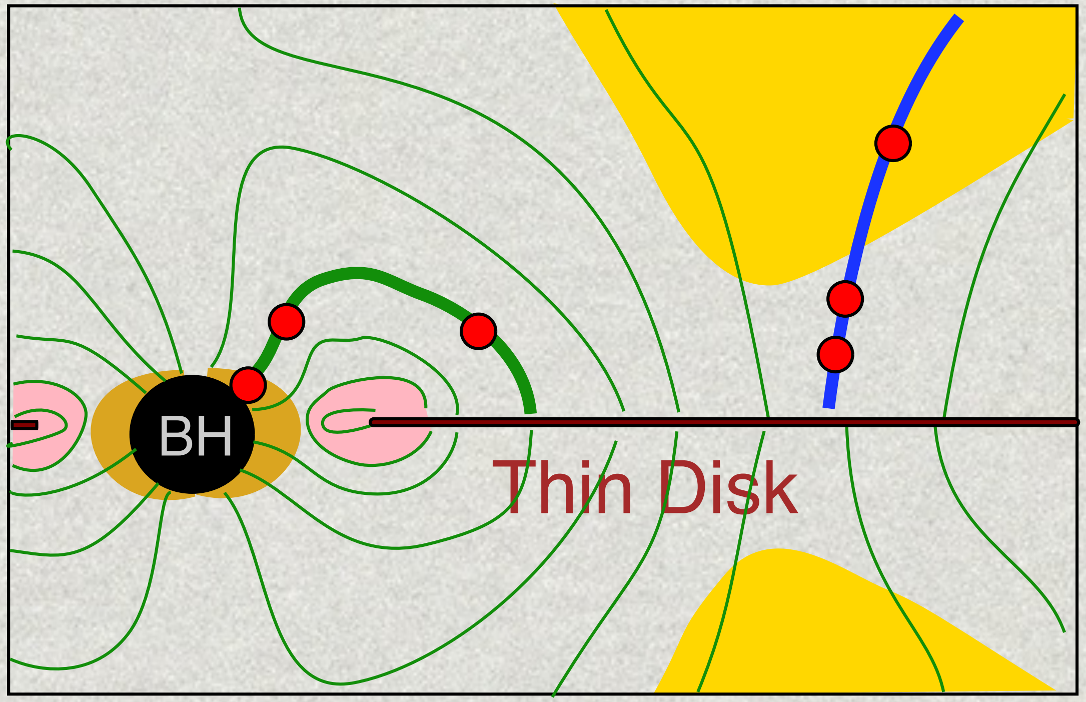
I. $E_k \gg E_m$

II. $E_k \sim E_m$

III. $E_k \ll E_m$

TOMIMATSU & MT 2003

BLACK HOLE MAGNETOSPHERE

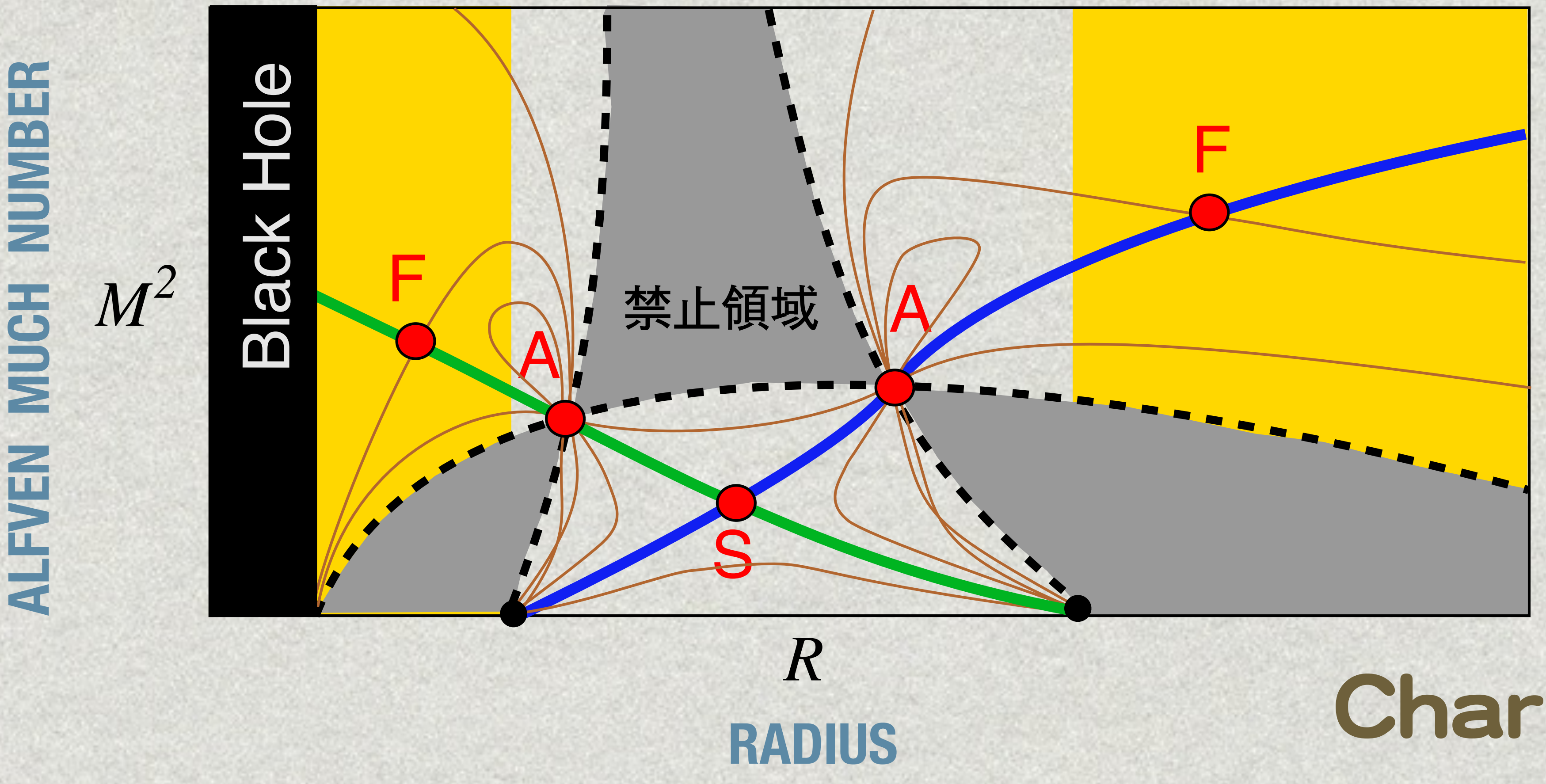


INFLOWS & OUTFLOWS

What are Relativistic Effects?

LIGHT SURFACE

FORBIDDEN REGION($E^2 < 0$)



- **Plasma spurce**
- **Slow point**
- **Alfven point**
- **Fast point**
- **Event Horizon**

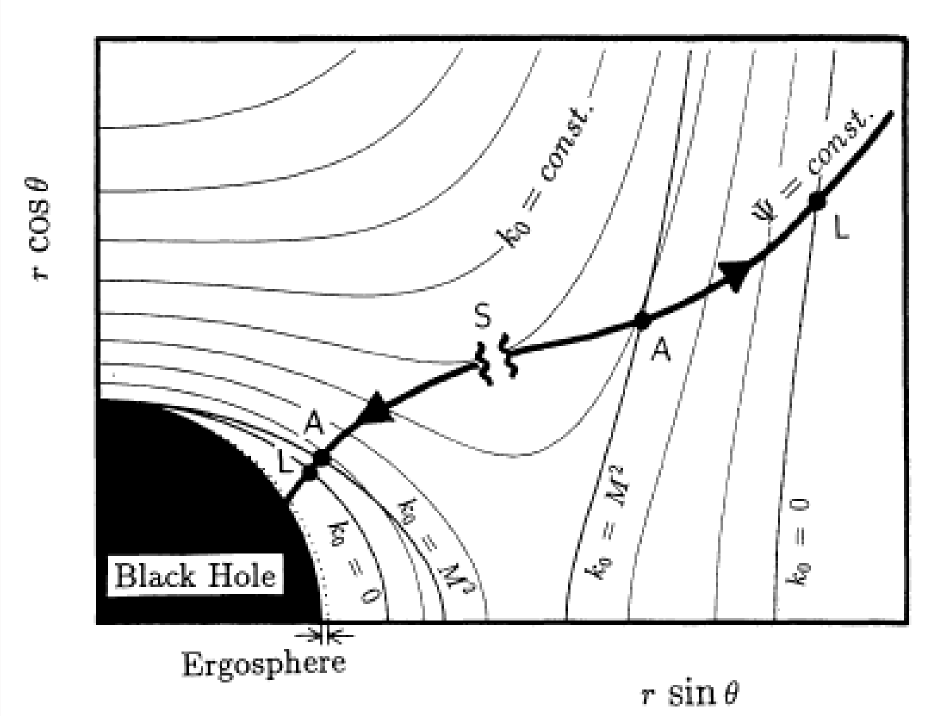
Characteristic radii

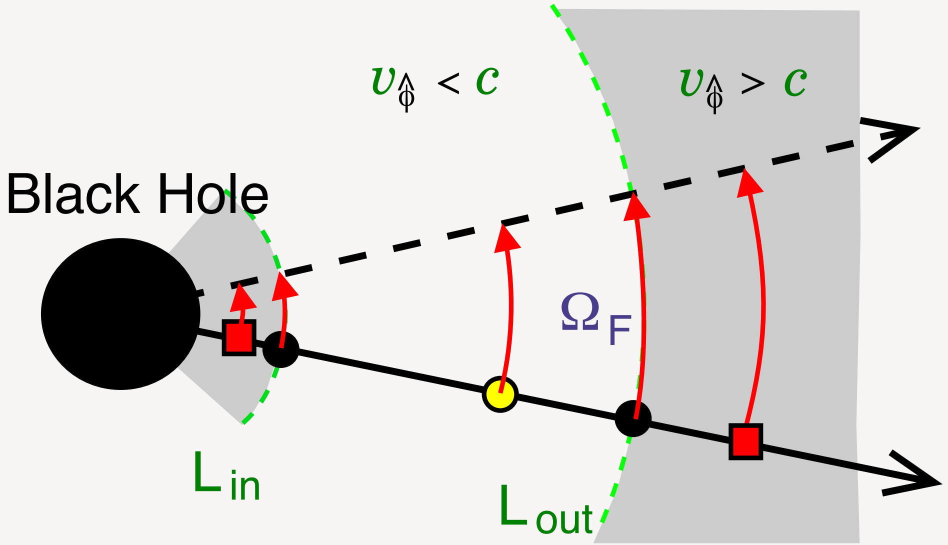
MHD FLOWS IN A BLACK HOLE MAGNETOSPHERE

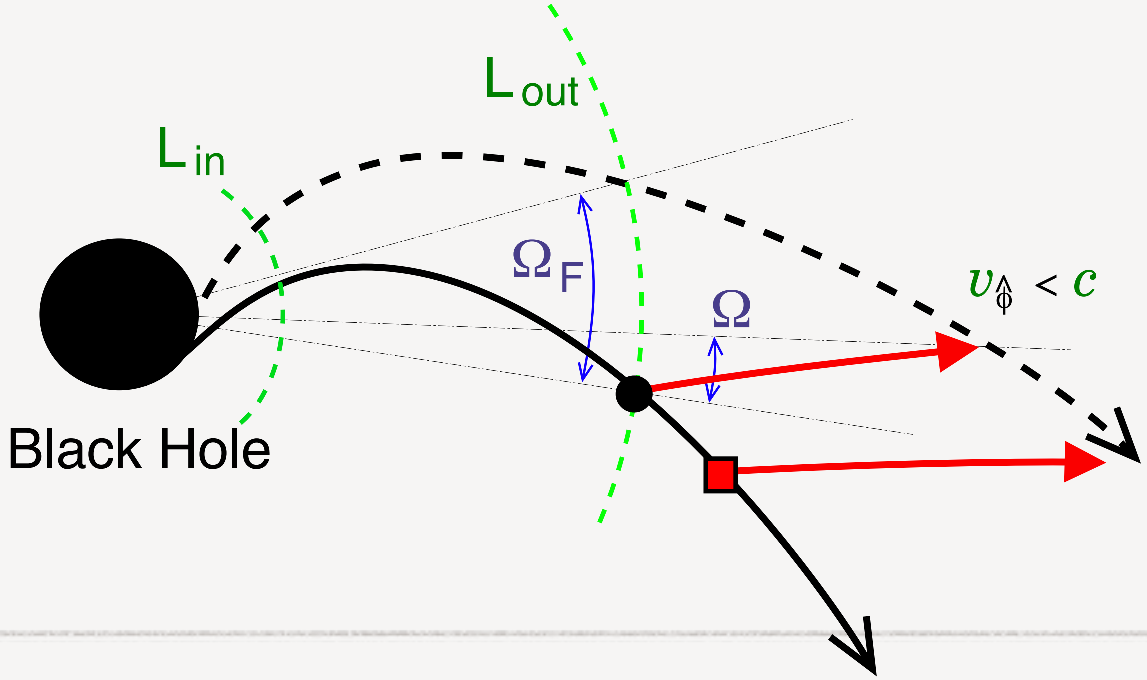
inner/outer Light surfaces

Alfven points

Magnetosonic points







General Relativistic Magneto-hydrodynamic Flows

GRMHD

Basic Equations

The *ideal MHD* condition	$u^{\beta} F_{\alpha\beta} = 0$
The particle conservation law	$(n u^{\alpha})_{;\alpha} = 0$
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	$T^{\alpha\beta}_{;\beta} = 0$

Field-aligned ``conserved quantities''

flow's parameters

1.	Number flux per unit magnetic flux	$\eta(\Psi) = \frac{n u^p}{B^p}$
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	$L(\Psi) = -\mu u_\phi - \frac{1}{4\pi\eta} B_\phi$
5.	Entropy	$S(\Psi)$

GRMHD Flows

- **1. Relativistic Bernoulli equation**

energy in corotation frame

gtavitational Lorentz factor

poloidal magnetic field

$$\boxed{(E-\Omega_F L)}^2 = \mu^2\alpha + M^2(\alpha B_p^2 + B_\phi^2)$$

→ PLOT Solution

enthalpy

(rest mass energy + internal energy)

Alfven Mach number

$$M^2 \equiv \frac{u_p^2}{u_{\rm AW}^2}\alpha$$

toroidal magnetic field

- **2. total Energy of MHD Flow**

$$E(\Psi) = \mu u_t \boxed{-\frac{\Omega_F}{4\pi\eta}B_\phi}$$

energy conversion

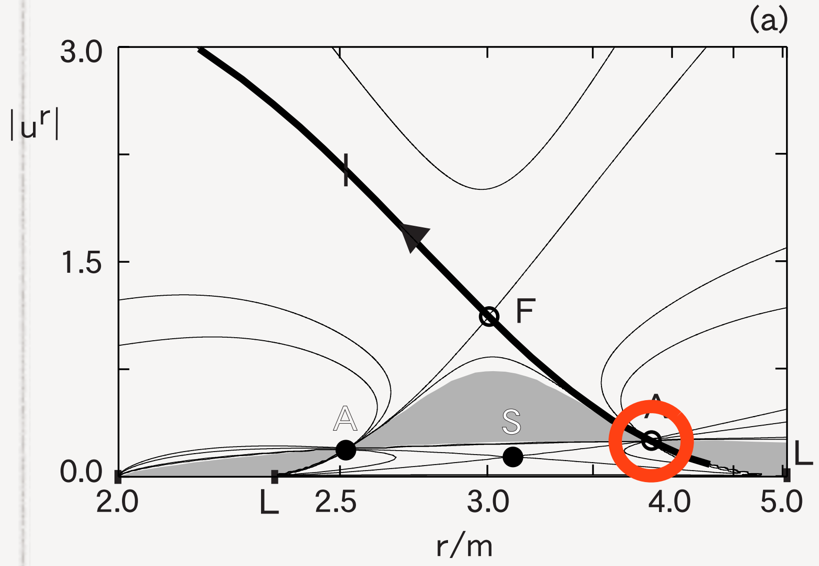
KE <--> ME

the fluid part of energy

Poynting flux per the particle number flux

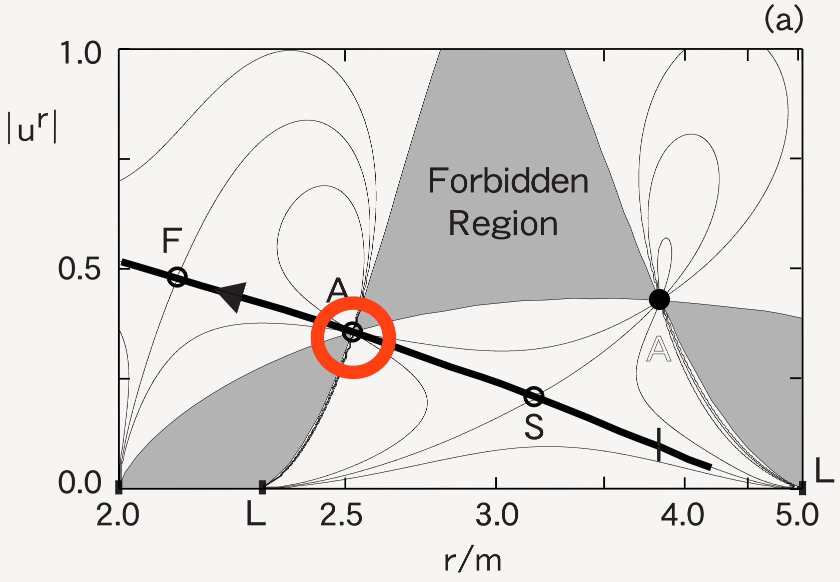
MHD ACCRETION ONTO A BLACK HOLE

BH: slowly rotating



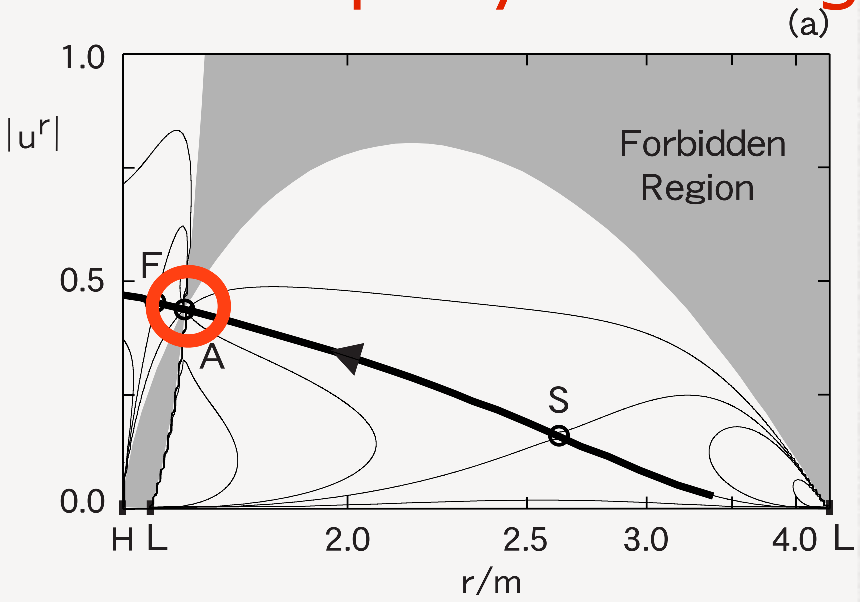
hydro-like

BH: slowly rotating



magneto-like

BH: rapidly rotating



magneto-like

weak-magnetic field limit
=> Hydro Dynamical Flow

strong-magnetic field limit
=> Force-free magnetosphere

Some critical points make regularity conditions.

Plasma source => Slow Point => Alfven P. => Fast P. => Event Horizon
(boundary conditions)

NEGATIVE ENERGY MHD INFLOWS

Total-Energy of MHD flow

$$E = \left(\frac{g_{tt} + g_{t\phi}\Omega_F}{\alpha} \right)_{\mathrm{A}} e$$

Angular Momentum of MHD flow

$$L = \left(\frac{-g_{\phi\phi}}{\alpha} \right)_{\mathrm{A}} (\Omega_F - \omega_{\mathrm{A}})\ e$$

Total-energy in rotational frame

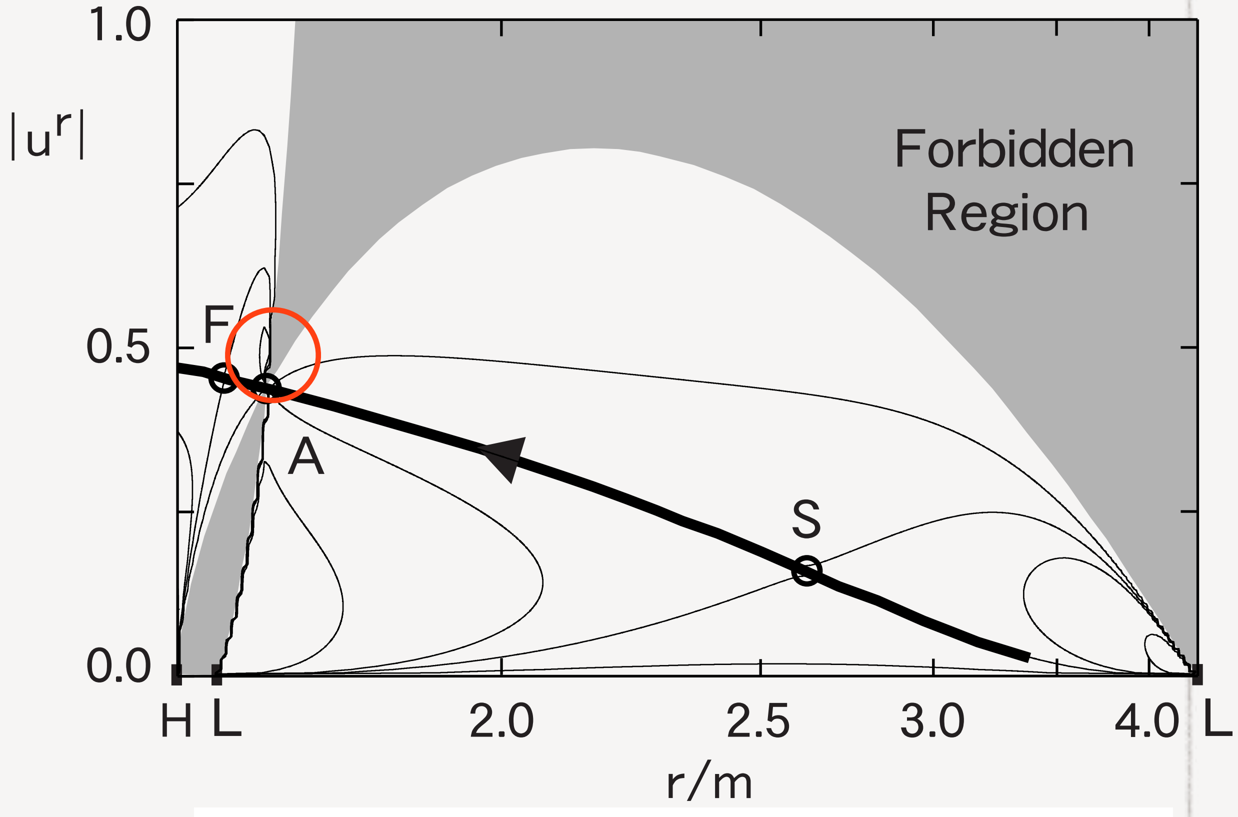
$$e \equiv E - \Omega_F L > 0$$

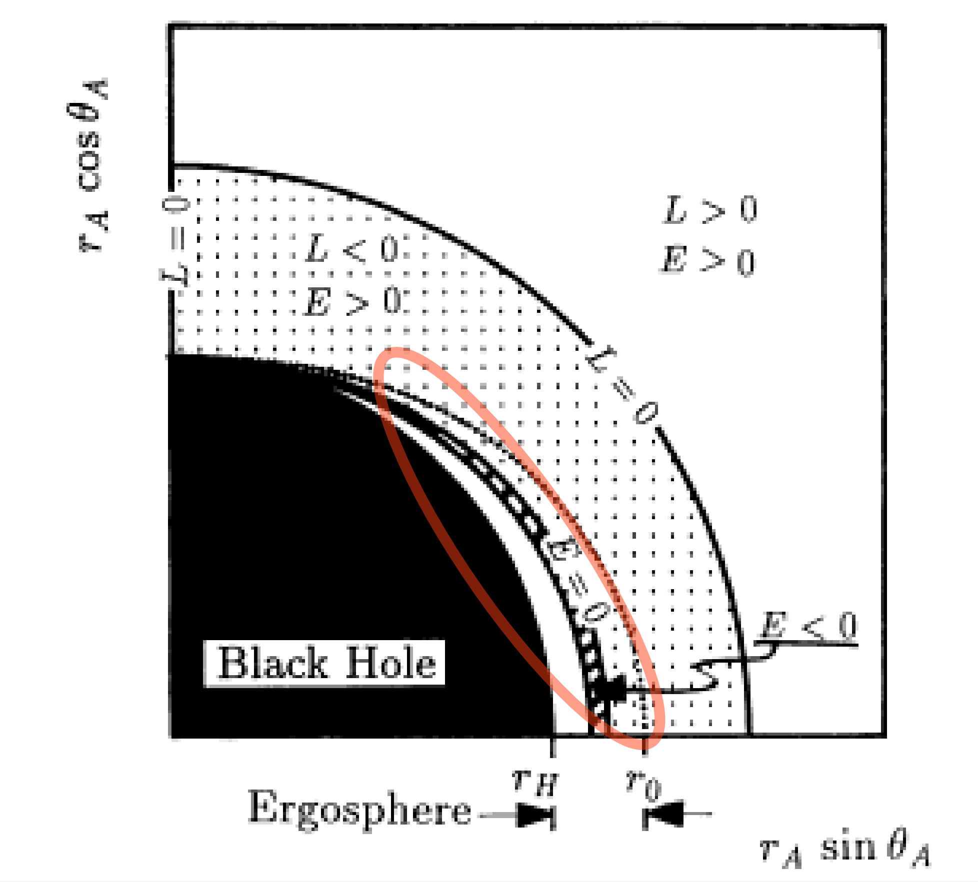
Gravitational-Lorentz factor

$$\alpha \equiv g_{tt} + 2g_{t\phi}\Omega_F + g_{\phi\phi}\Omega_F^2$$

$$(g_{tt} + g_{t\phi}\Omega_F)_{\mathrm{A}} < 0 \quad \Rightarrow \quad \boxed{E < 0}$$

TAKAHASHI ET AL. 1990





When the Alfven point locates inside the Ergosphere,

Energy Extraction from a Rotating BH by MHD Inflows is possible.

Takahashi + 1990

fluid part **EM part**

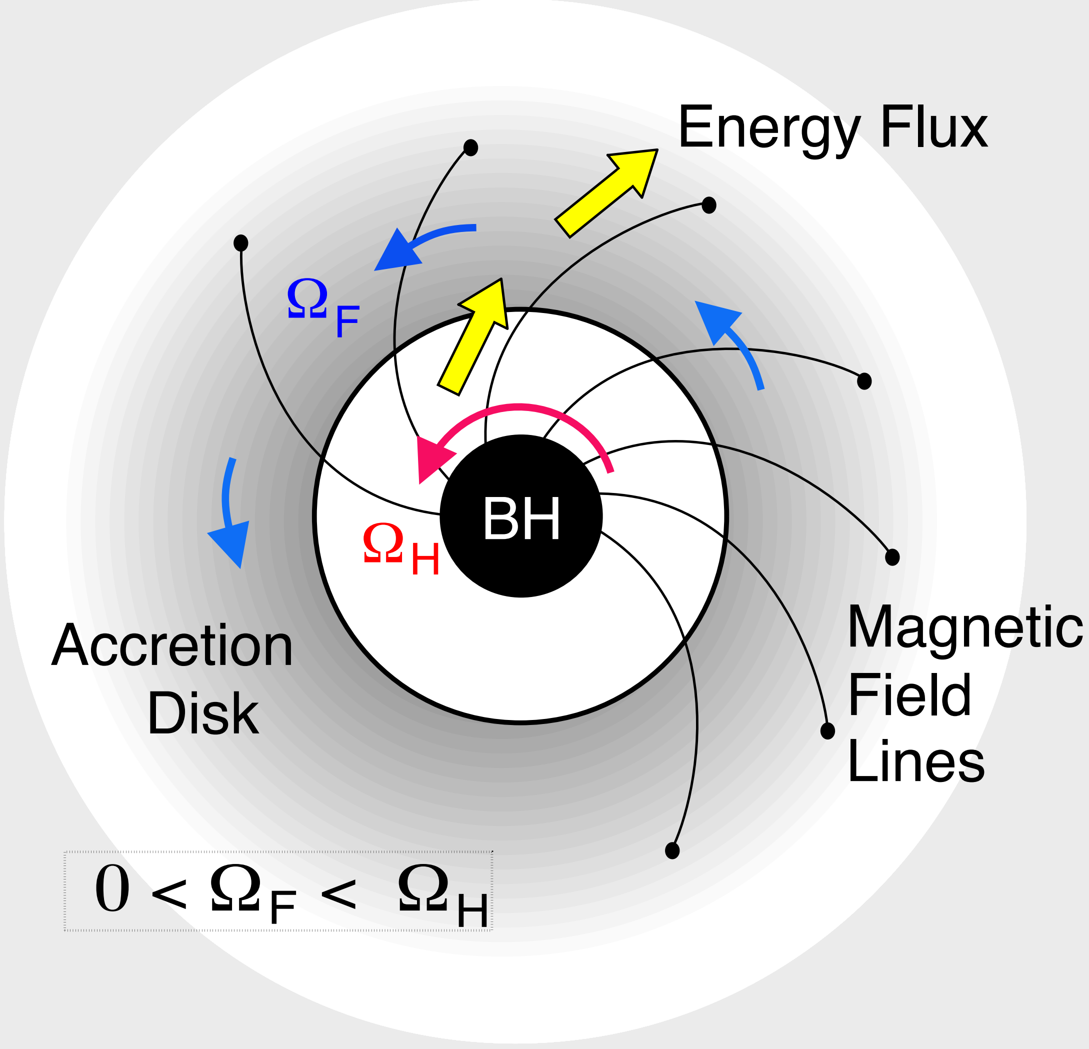
$$\underbrace{E(\Psi)}_{-} = \underbrace{\mu u_t}_{+/-} - \underbrace{\frac{\Omega_F}{4\pi\eta} B_\phi}_{-}$$

Negative energy inflow

gas accretion

BZ process

is possible !



$0 < \Omega_F < \Omega_H$

This situation would be possible in the magnetically-dominated BH magnetosphere .

Rankine-Hugoniot conditions

the relationship between the states on both sides of a shock wave front

- **PARTICLE NUMBER FLUX**

number density

four-velocity

$$U \equiv n u^{\alpha} \ell_{\alpha}$$

the unit vector perpendicular to a shock front

- **NORMAL COMP. OF THE MAGNETIC FIELD**

$$B_{\perp} \equiv B^{\alpha} \ell_{\alpha}$$

magnetic field

- **ENERGY-MOMENTUM FLUX**

relativistic enthalpy

$$W \equiv \frac{\mu}{n} U^2 + P + \frac{B^2}{8\pi}$$

pressure

$$B^2 \equiv \alpha B_p^2 + \frac{B_\phi^2}{\rho_w^2}$$

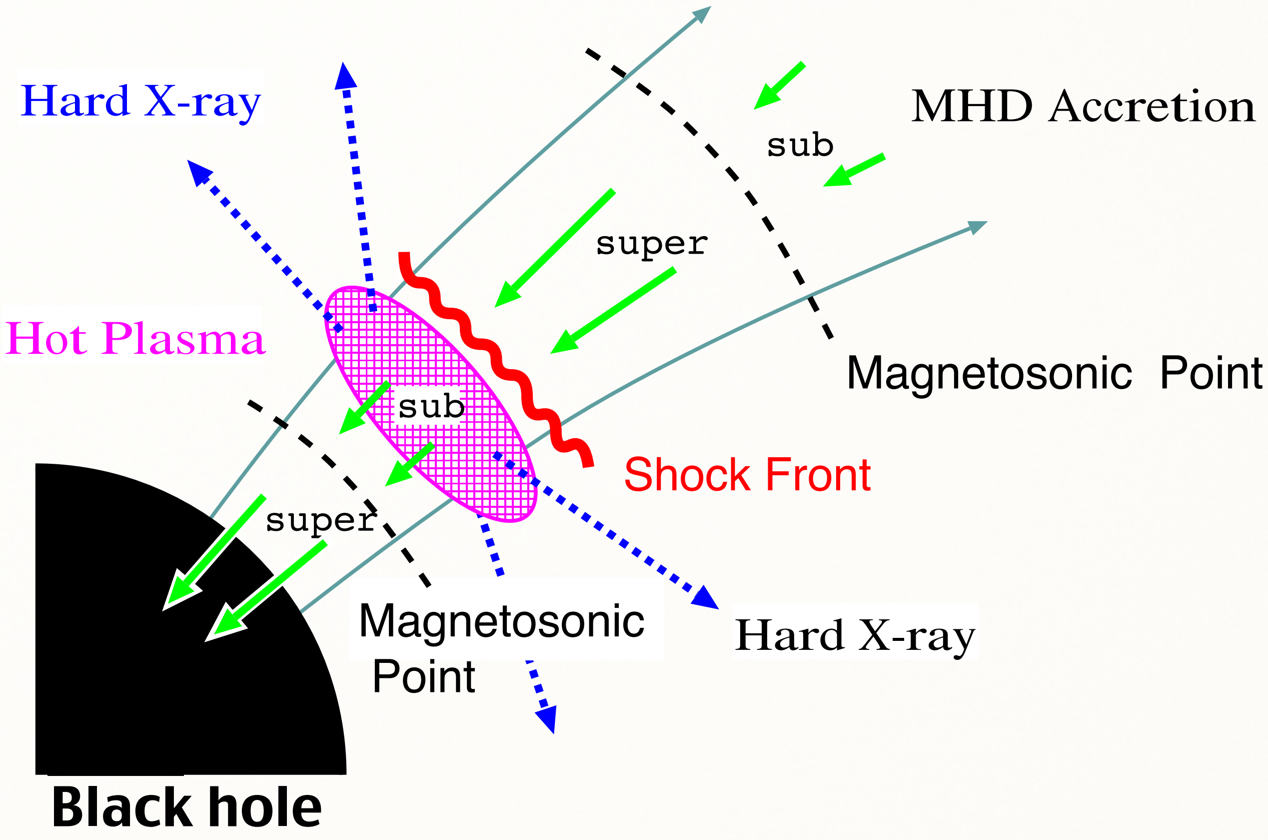
gravitational Lorentz factor

$U, \; B_{\perp}, \; W$ are conserved across the shock front.

When an up-stream is specified → down-stream is determined

Shock Heating : High-energy emission from the vicinity of BH (observable)

Plasma Source
(accretion disk / corona)
↓
Slow magnetosonic point
↓
Alfven point
↓
Fast magnetosonic point → MHD Shock



shocked flow
↓
2nd Fast magnetosonic point

shock-free flow ↓

Event Horizon ← *2nd Fast magnetosonic point*

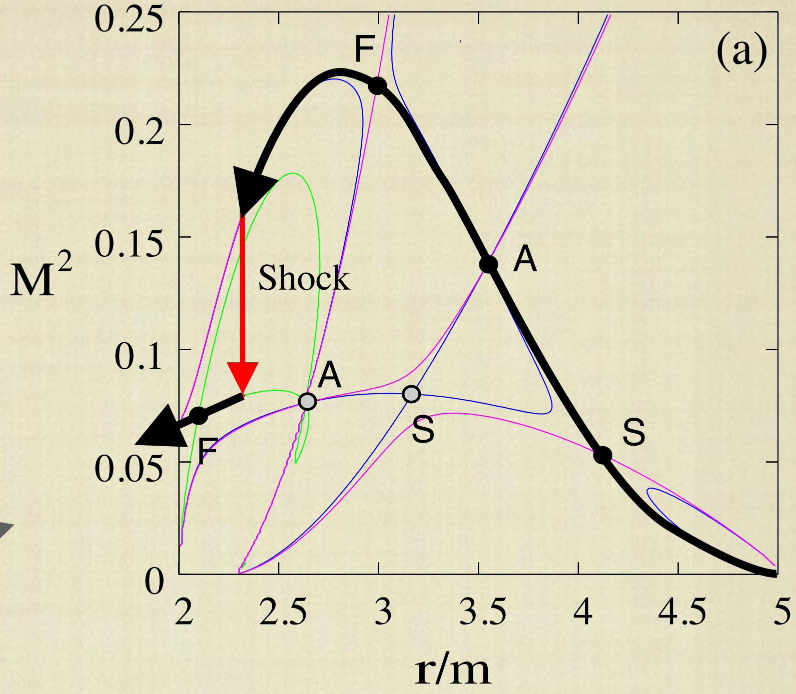
MHD Accretion onto BH

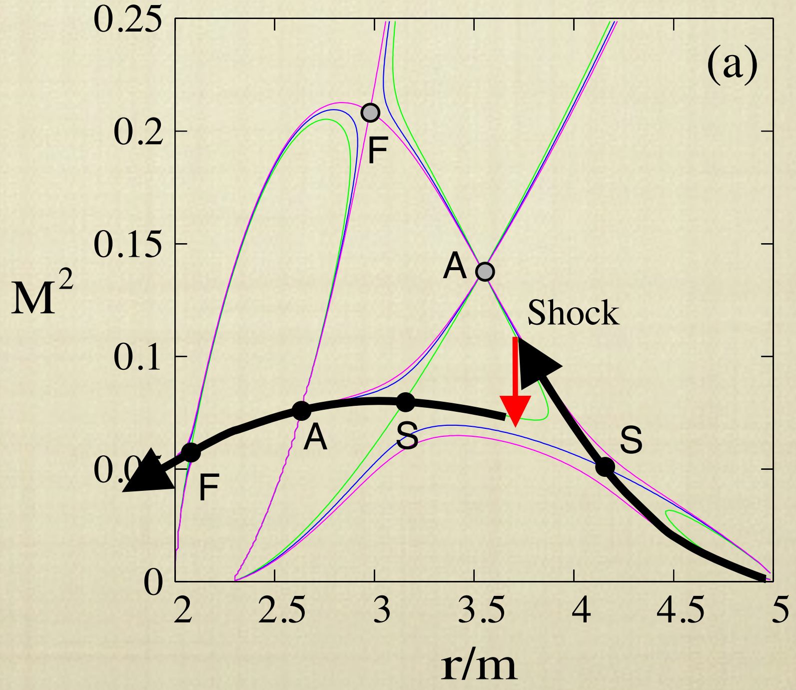
Takahashi et al. 2006

Hot Plasma region

for high energy radiation

- Fast magnetosonic Shock
  - Hydro-like
  - Magneto-like
- Slow magnetosonoc Shock



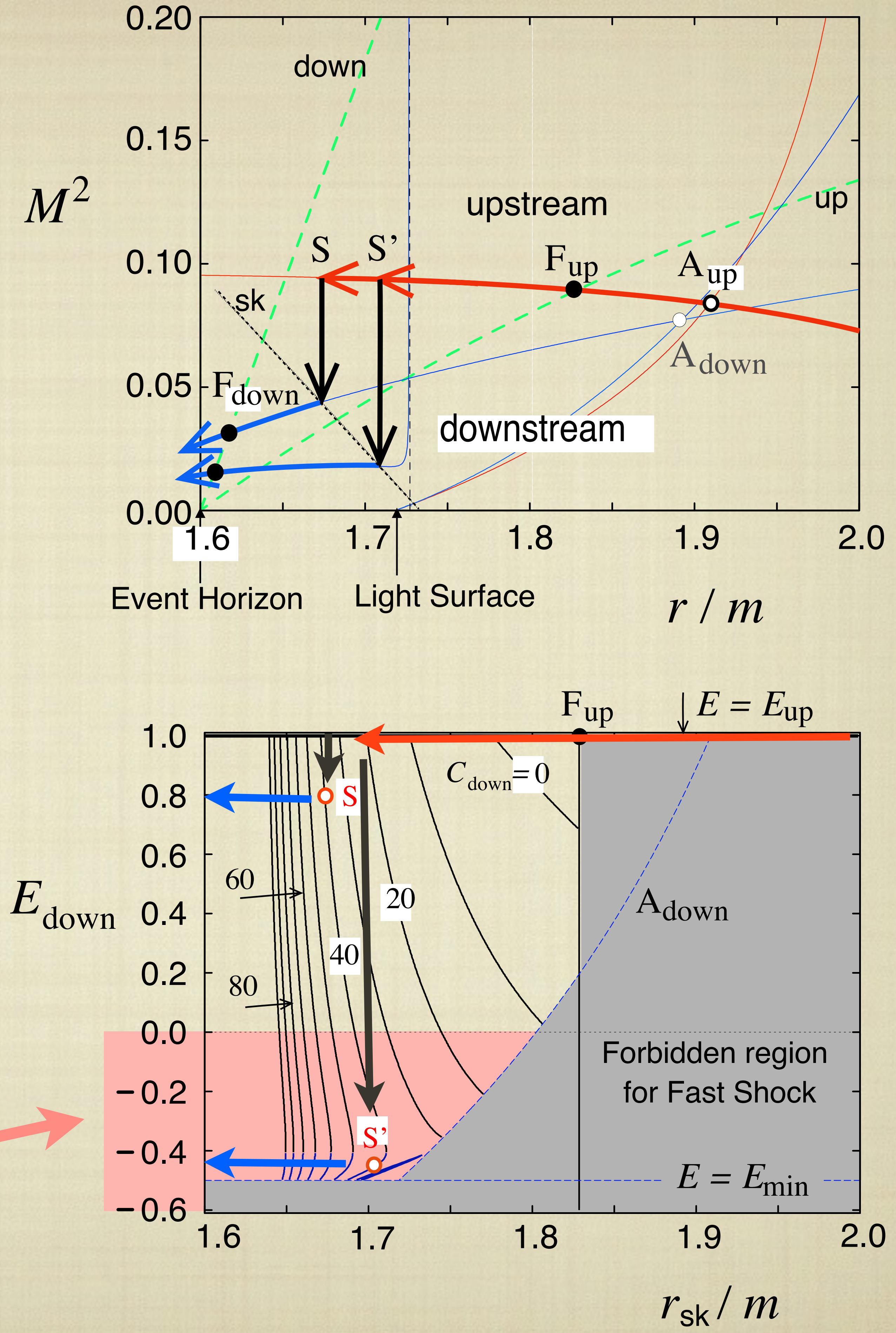


Black Hole MHD Shock

- FAST MAGNETOSONIC SHOCK IN ERGOSPHERE
- COLD UPSTREAM → COLD DOWNSTREAM
- S' : $\Delta E > mc^2$

NEGATIVE ENERGY INFLOW

MT & TAKAHASHI . 2010



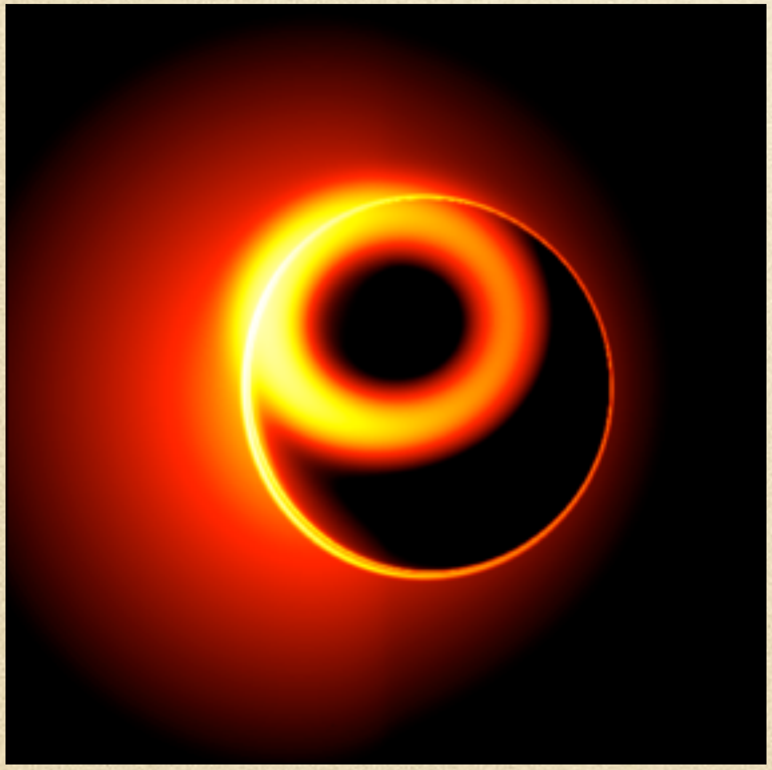
MHD Shock

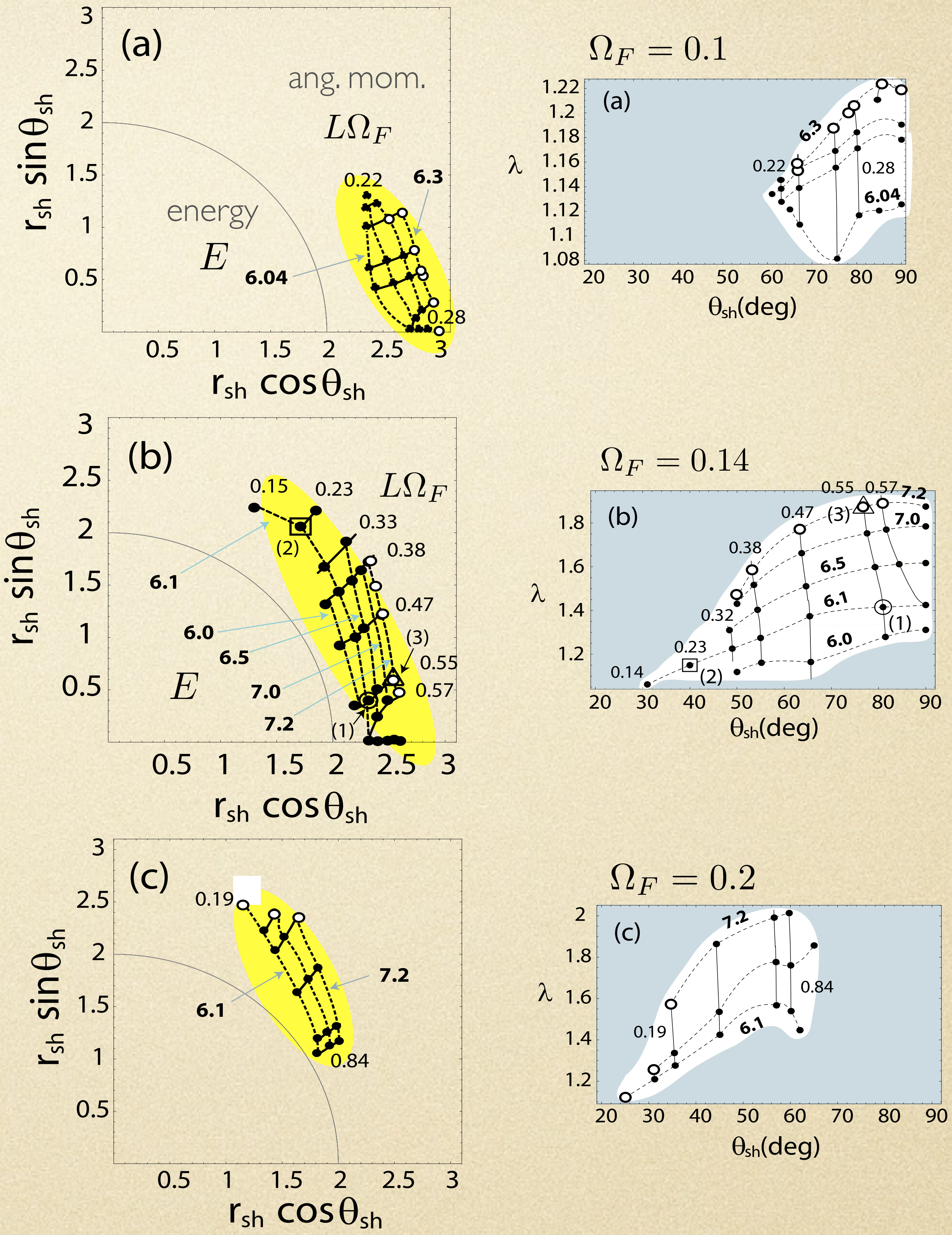
Adiabatic cases

Takahashi et al. (2006)
Fukumura et al. (2007)

θ -dependence

for example , , , ,

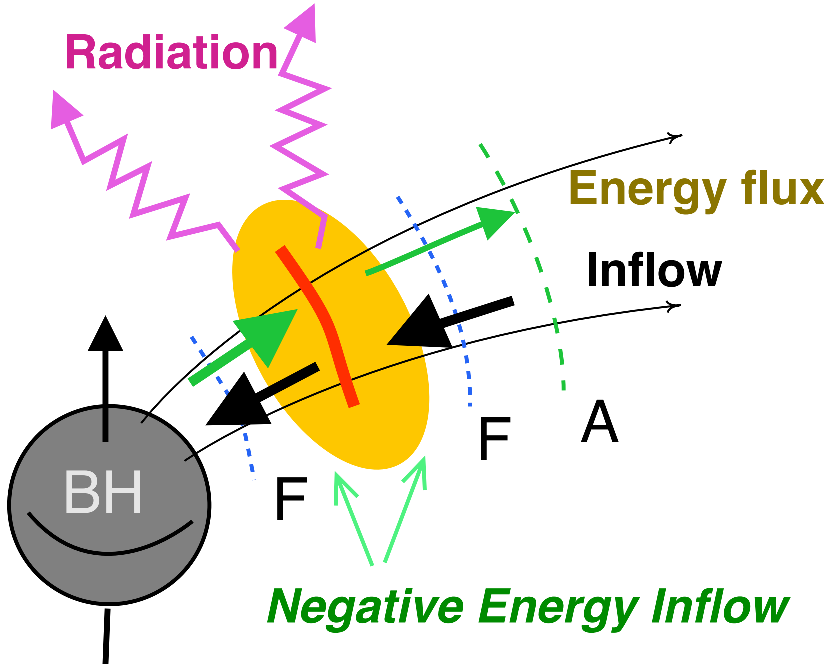


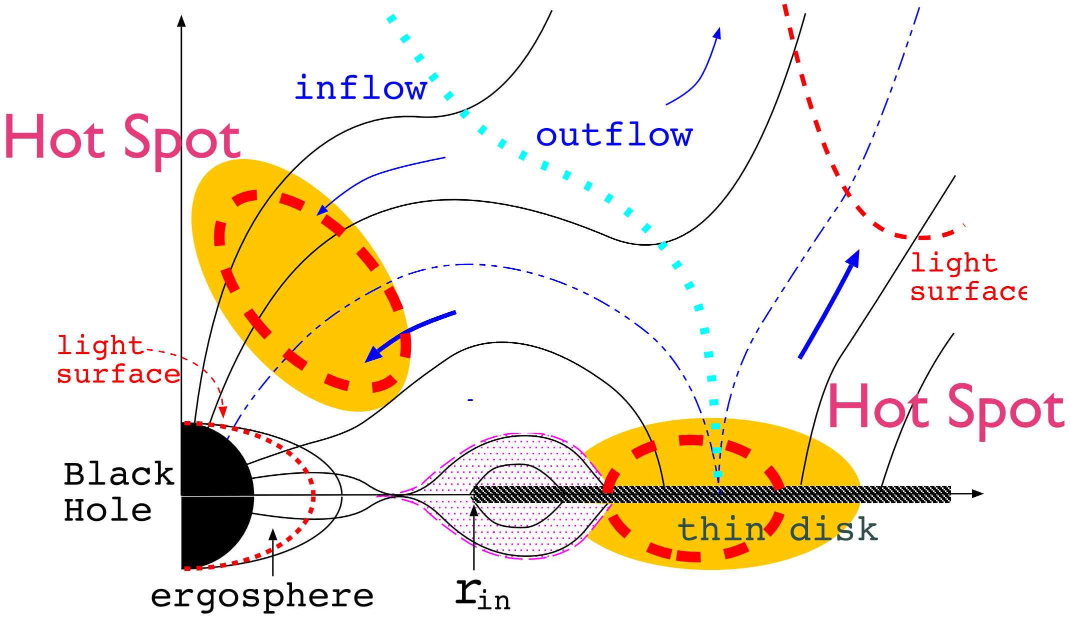


Acceptable shock locations

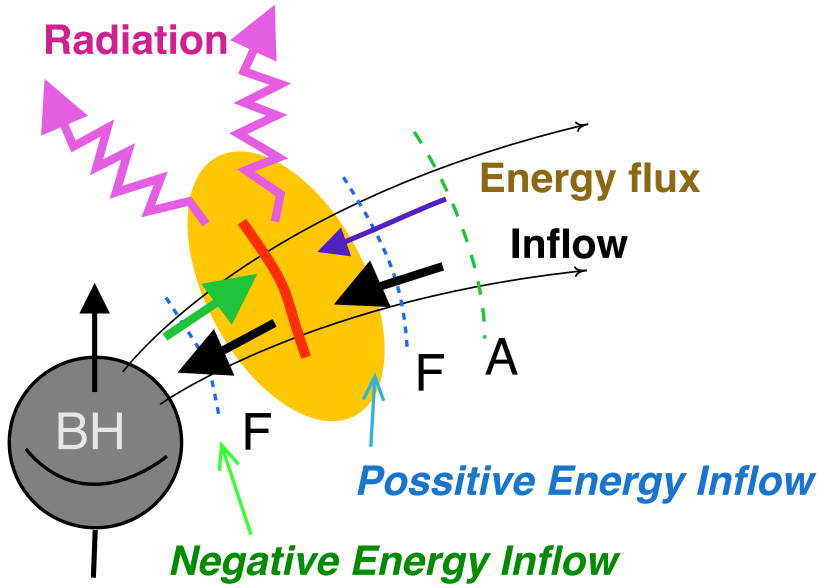
Hot Spot powered by Rotating BH

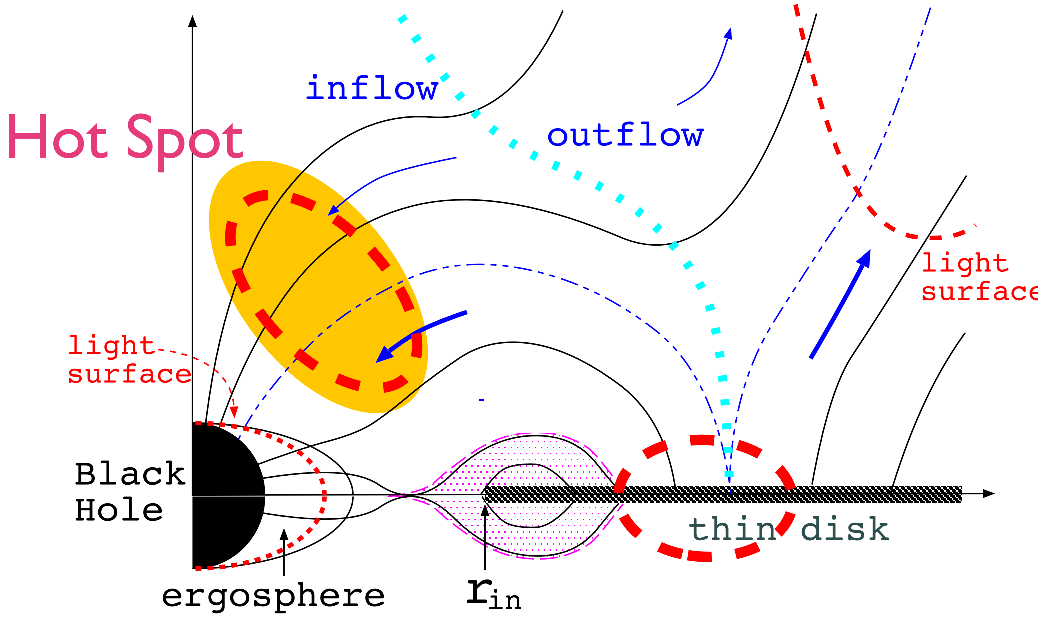
High-energy radiation including the information of space-time.





The extracted energy from BH can radiate at Shock front.





SOURCE - REFRECTOR

Theoretical Toy-Model

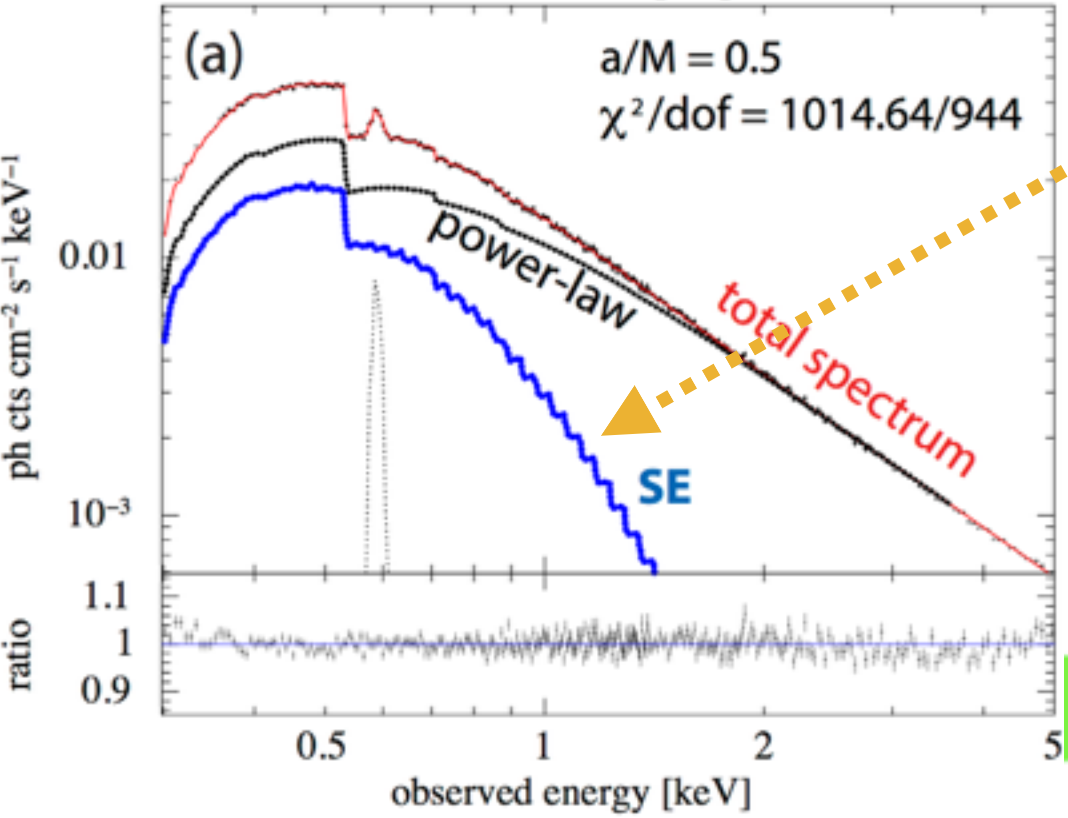
Near the BH Horizon…

Source : MHD Shock

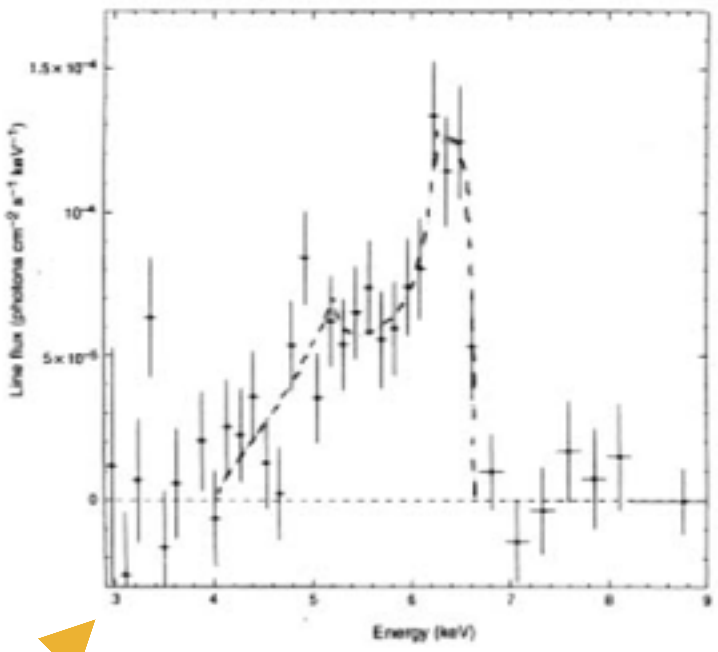
Hot plasma region = BH Aurora

Seyfert 1 (NLS1) : Arc 120

60 ks *XMM–Newton*/EPIC–pn spectrum of Ark120

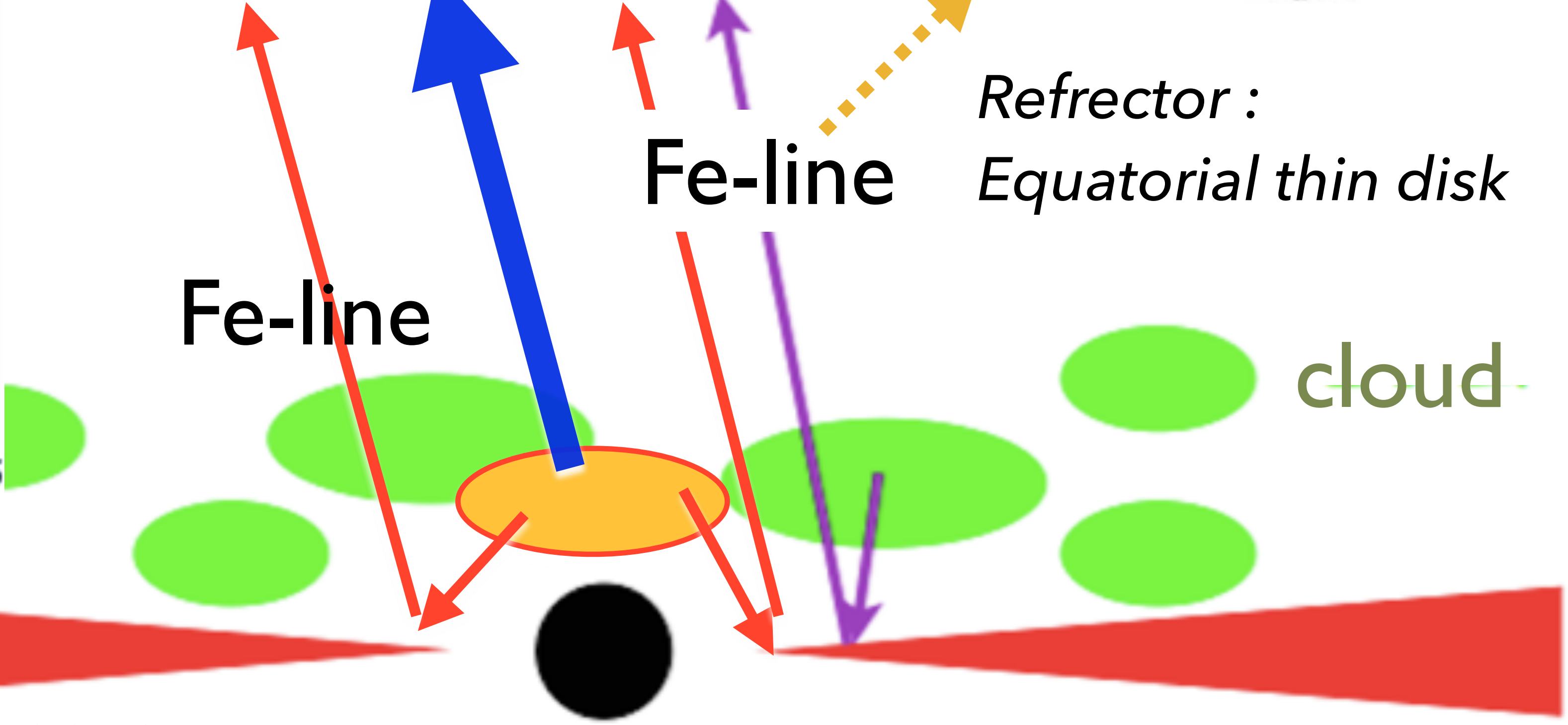


Fukumura, MT + 2016



Soft X-ray Excess !?

continuum



Fe-line

Fe-line

Refrector :
Equatorial thin disk

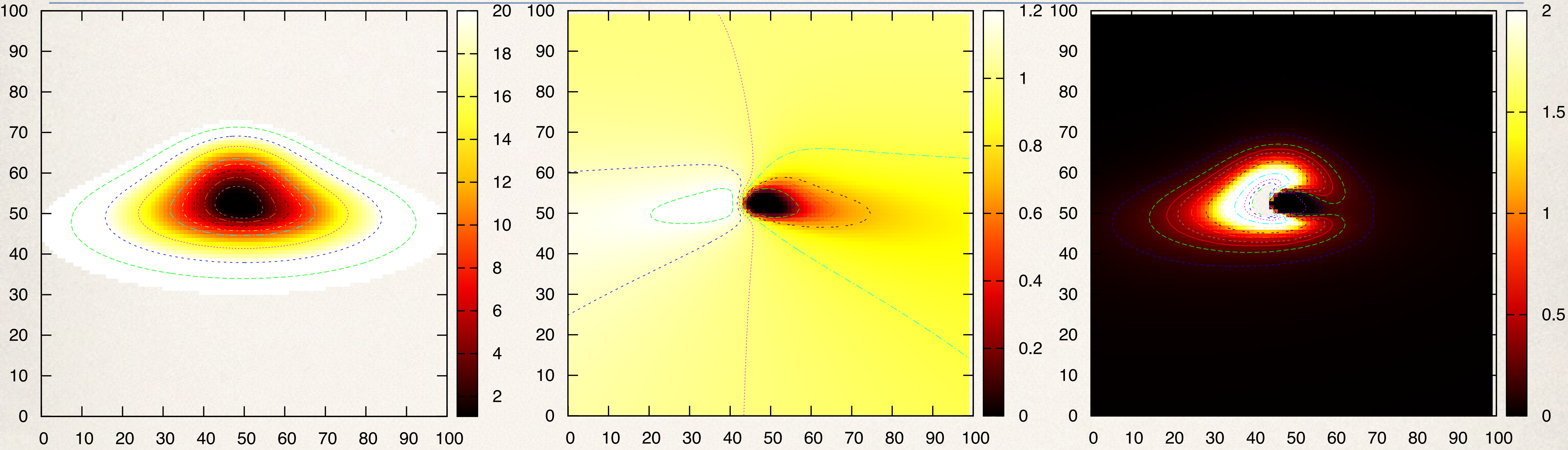
cloud

Haba2013

Black Hole

Accretion Disk

Thin disk near a Black Hole



isoradius

redshift

Obs. Flux

Page-Thorne (1974) model

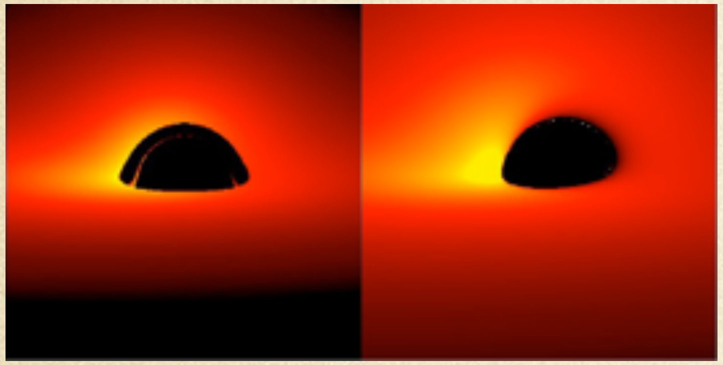
Gravitational red-shift ／ Dopplar effect ／ Beaming effect

／ Gravitational lens effect

Information of the black hole spacetime

Accretion Disk --- **Image** of the Black Hole Shadow and Accretion Plasma

(sub-mm VLBI)



BH - Aurora --- **HE-emission** from very close to the Event Horizon

MT & R.Takahashi 2010

(X-ray, γ-ray)

BH - Van Allen radiation belt --- The plasma can be trapped in this zone, which may be related to a **cosmic ray** .

MT & H.Koyama 2009