Disk modelling by global radiation-MHD simulations

~Confrontation of inflow & outflow~

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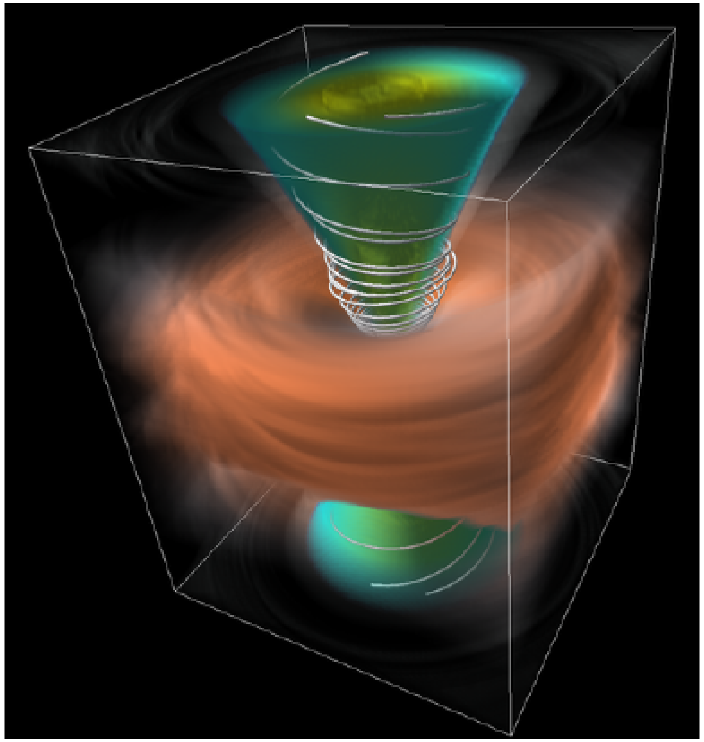


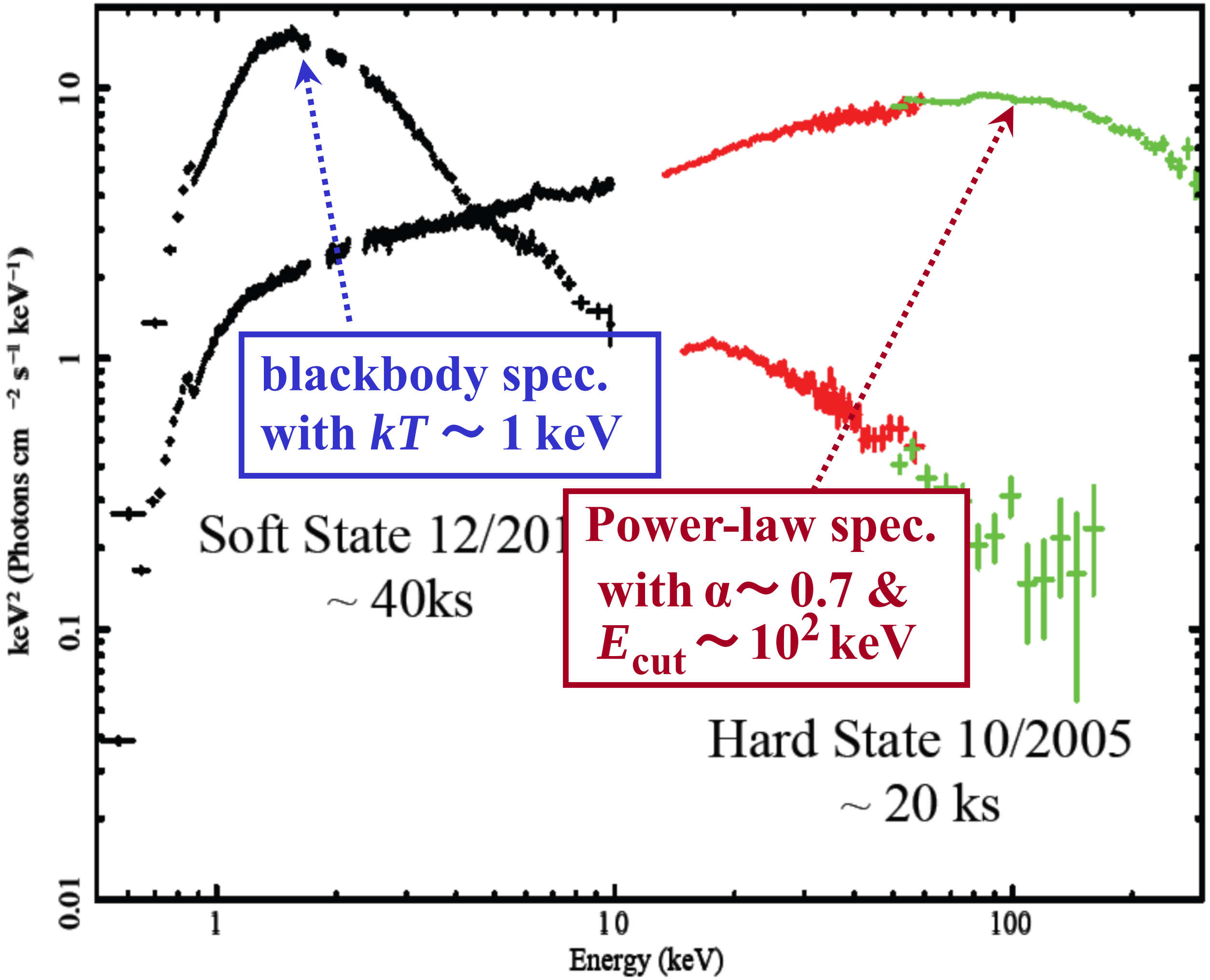
Magnetic tower jet
by RMHD simulation
(Takeuchi+11)

Outline

- Introduction
  - Various states and/or spectral components
  - Basic theory of black hole accretion
- Global R-MHD simulations of super-critical flow
  - Motivation: why global radiation-MHD simulations?
  - Three distinct regimes of accretion flow
  - P_{rad}-driven jet & clumpy outflow
  - Comptonization (?)

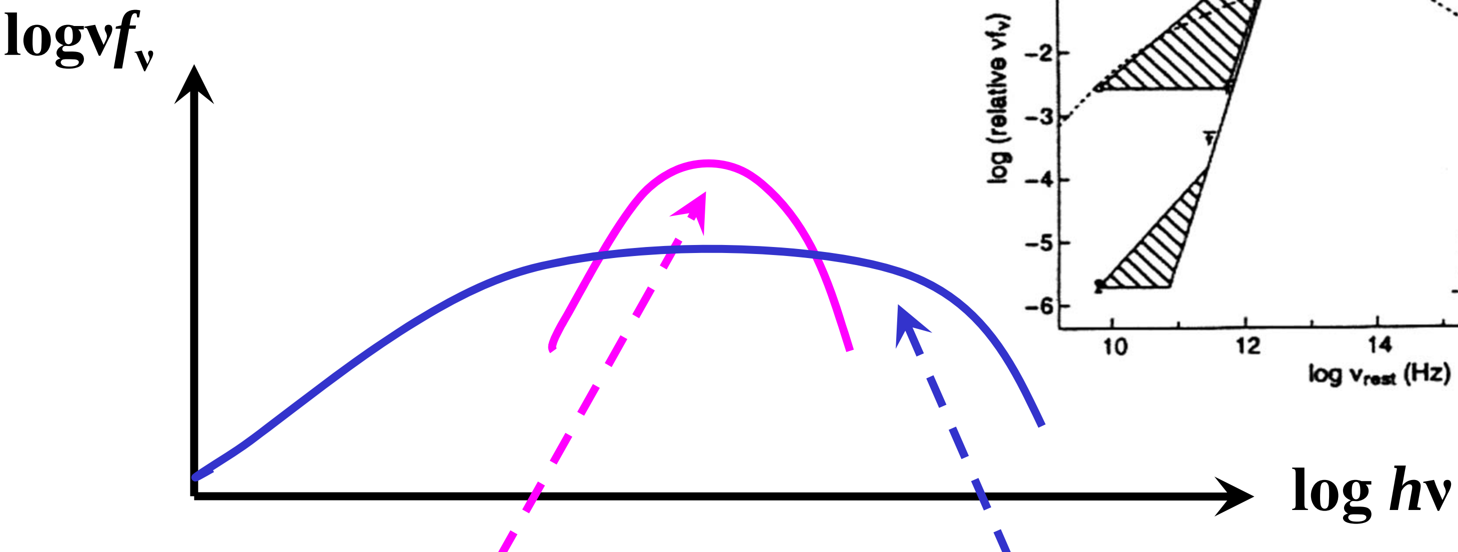
BH binaries: two (basic) spec. states

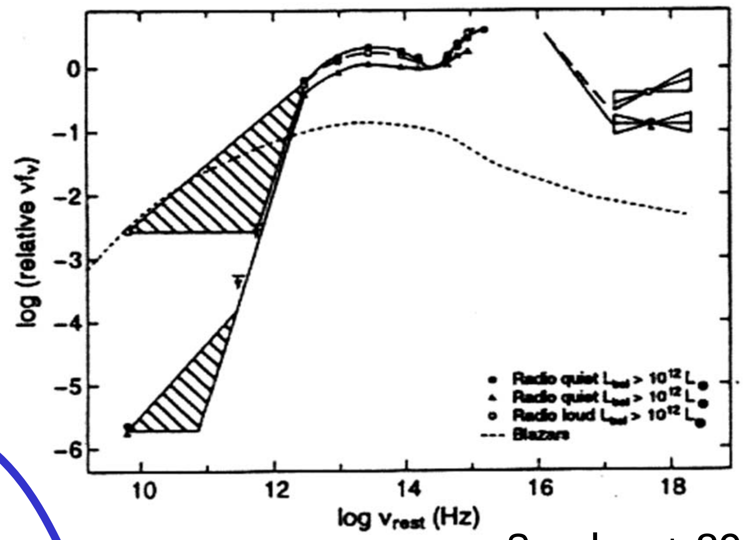
(S. Yamada/ Suzaku data)



⇒ **Combination of Hot flow (T~10^9 K) & Cool disk (~10^7 K)**

AGN: two spectral components





Sanders+ 89

Big Blue Bump (UV)

blackbody with

$T_{eff} \sim 10^5$ K (10 eV)

borad-band comp. (radio ~γ)

$f_\nu \propto \nu^{-\alpha}$ with $\alpha \sim 0.7$, cutoff

with $T_{elec} \sim 10^9$ K + self-abs.

⇒ **coexistence of hot (~10^9 K) and 'cool' (~10^5 K) material** (indicated by Fe fluorescence line)

Two basic solutions!

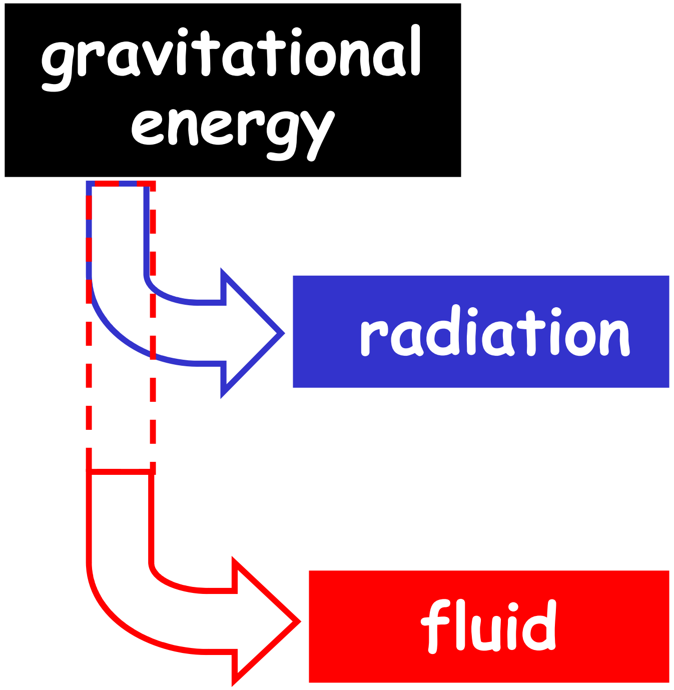
Kato, Fukue & Mineshige (2008)

Energy equation: $Q_{adv} = Q_{vis} - Q_{rad}$

$Q_{adv} \sim \Sigma T v_r \,(ds/dr)$ = advection term

Q_{vis} = viscous heating

Q_{rad} = radiative cooling



<u>*standard disk*</u>: $Q_{vis} = Q_{rad} \gg Q_{adv}$

→ cool bright disk

→ $T \sim 10^7\,K\,(M_{BH}/M_{sun})^{-1/4}$

<u>*RIAF*</u> : $Q_{vis} = Q_{adv} \gg Q_{rad}$

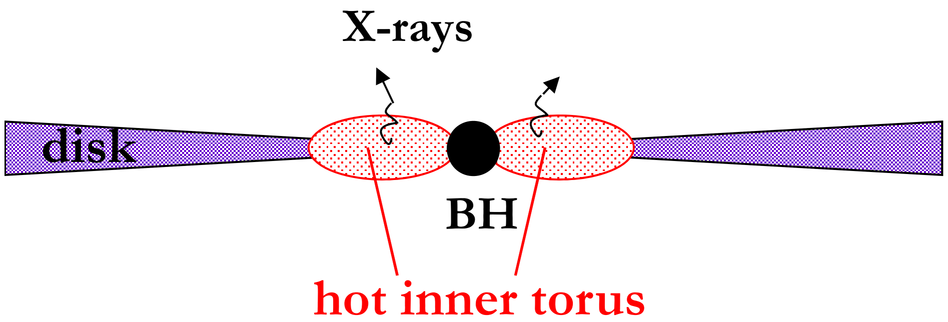
→ hot faint flow → $T \sim 10^9\,K$

(RIAF=Radiatively Inefficient Accretion Flow)

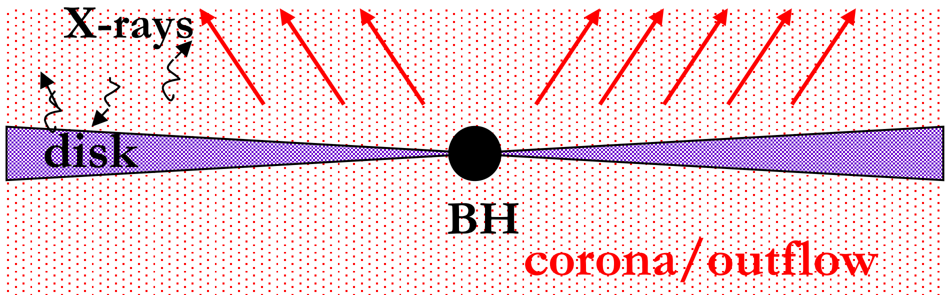
Situations may not be so simple…

Cool disks and hot corona/outflow

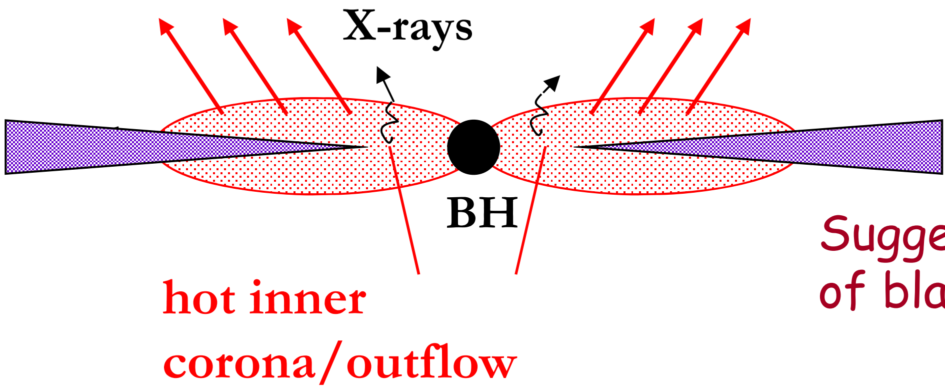
(a) horizontal separation



(b) vertical separation



(c) mixture type



Suggested by X-ray obs. of black hole binaries.

Why global radiation-MHD simulations?

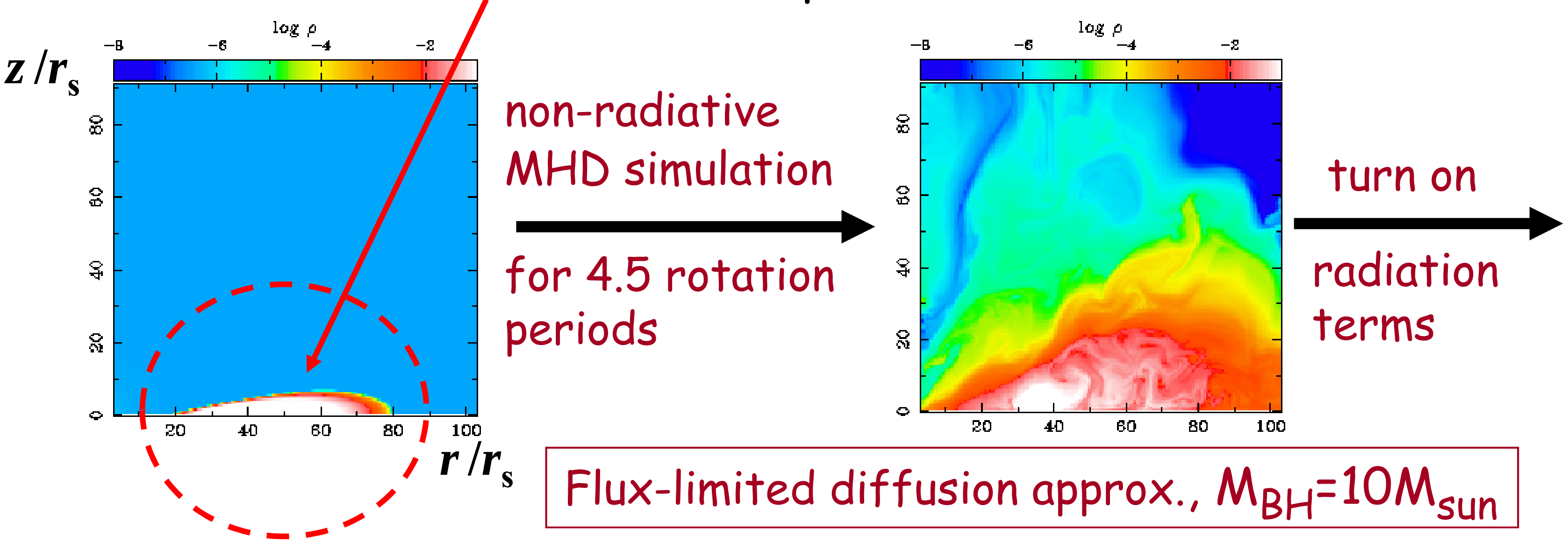
One-dimensional models (e.g. standard disk, slim disk, ADAF) are quite useful for understanding the basics of different modes of accretion. However…

- Multi-dimensional gas motions, such as circulation, convection, outflow… are totally neglected.
  → Need 2D/3D simulations
- Disk viscosity was treated by the phenomenological α model. Its validity needs to be examined. → Need MHD simulations
- Strong radiation-matter interactions expected at high luminosities are not properly treated.
  → Need radiation-hydrodynamical (RHD) simulations

Our global 2D RMHD simulations

Ohsuga, SM, et al. (2009, PASJ 61, L7)

- Start with a torus threaded weak poloidal fields:



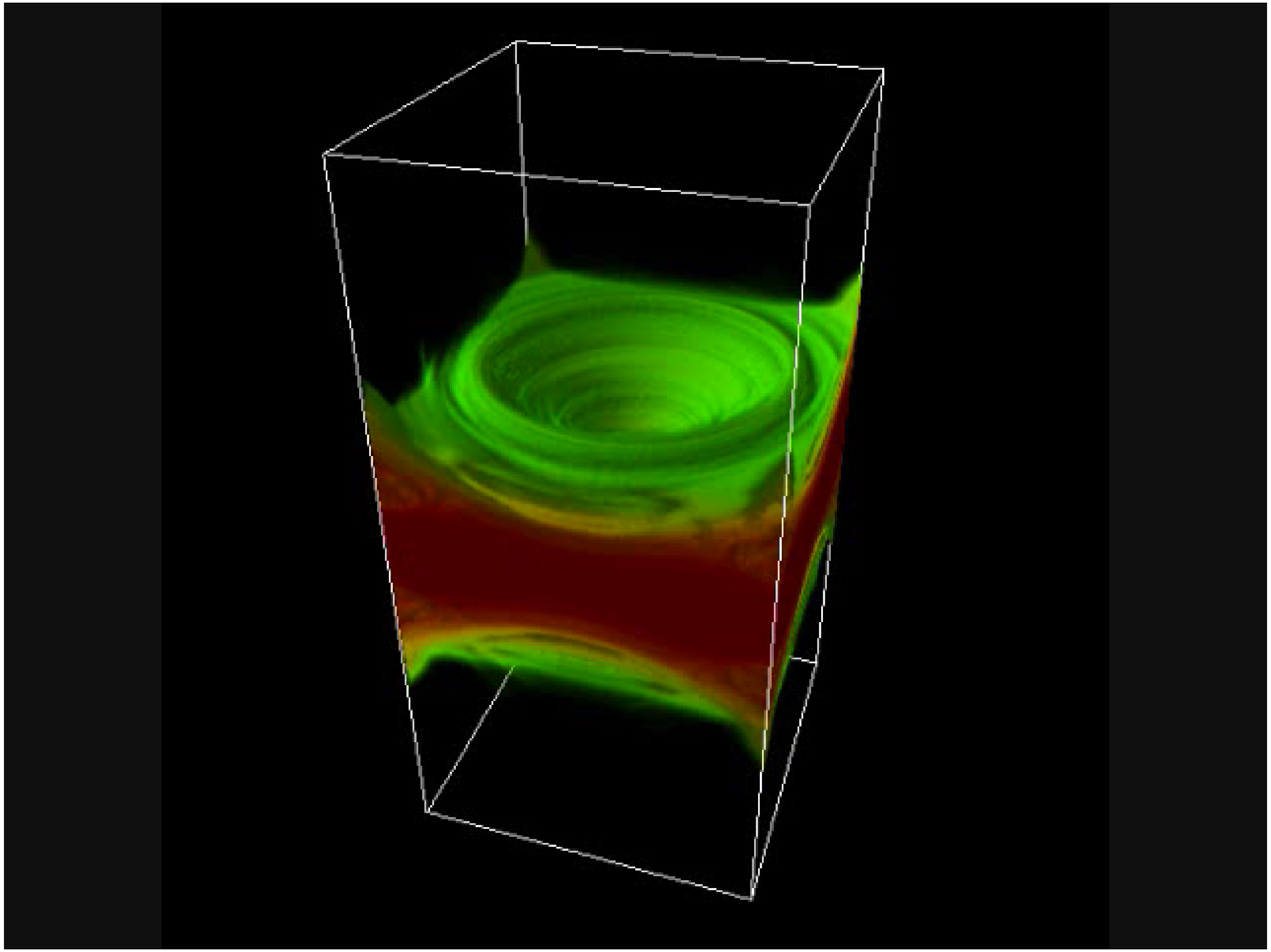
Flux-limited diffusion approx., $M_{BH}=10M_{sun}$

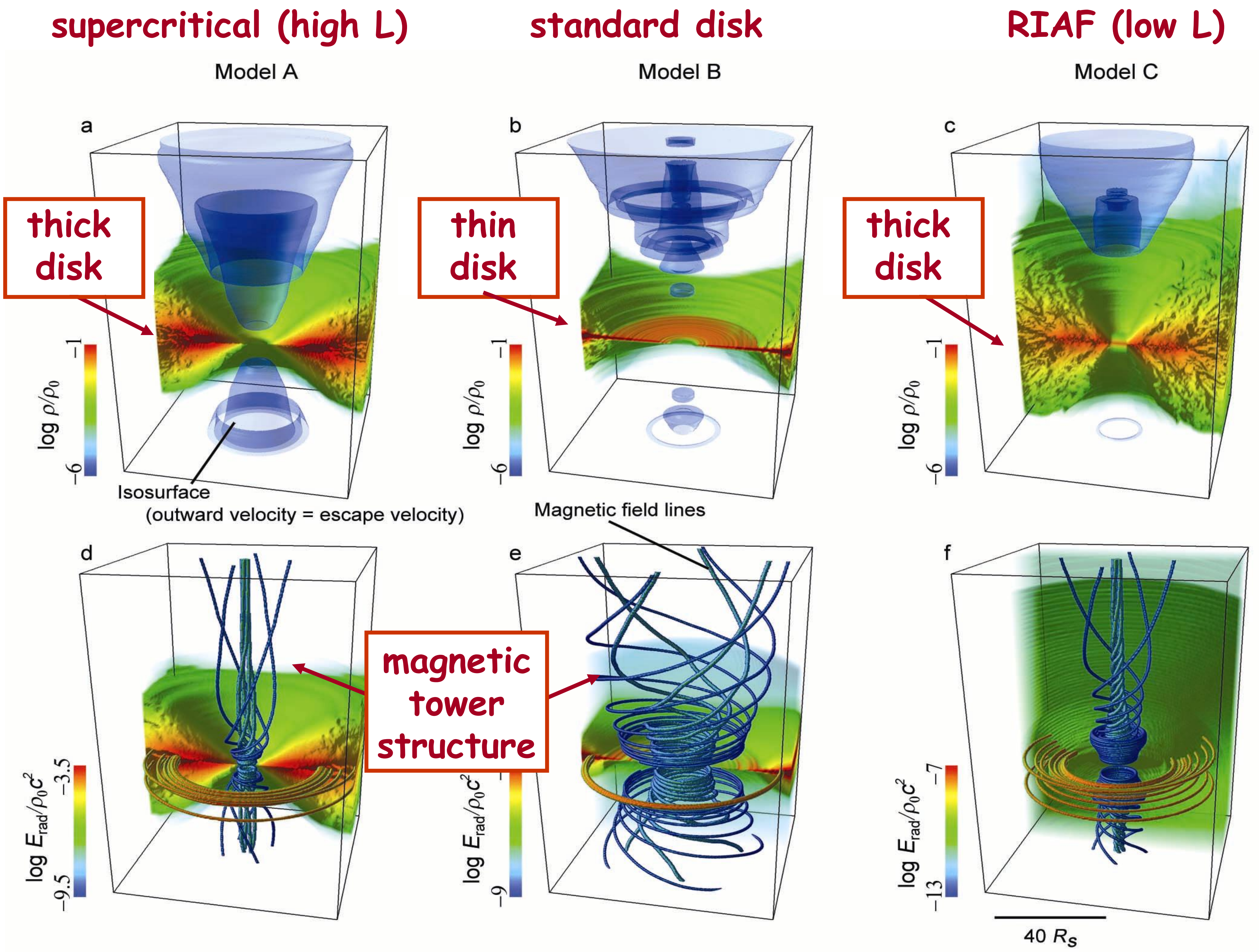
- Results depend on the initial density normalization (ρ_0)

- **Model A ($\rho_0=10^0$ g/cm^3) : supercritical state (P_{rad} force)**
  Model B ($\rho_0=10^{-4}$ g/cm^3) : standard-disk state (rad. cooling)
  Model C ($\rho_0=10^{-8}$ g/cm^3) : radiatively inefficient flow state

⇒ Three distinct states can be modelled by one code.

Radiation-MHD simulation: model A





supercritical (high L)
standard disk
RIAF (low L)
Model A
Model B
Model C
a
b
c
thick disk
thin disk
thick disk
log ρ/ρ0
−1
−6
Isosurface
(outward velocity = escape velocity)
Magnetic field lines
d
e
f
magnetic tower structure
log Erad/ρ0c2
−3.5
−9.5
−9
−7
−13
40 Rs

Summary of radiation-MHD simulations

Ohsuga & SM (2011, ApJ 237)

Model	density & temperature	luminosity, L/L_E	Energetics	kin. luminosity, L_{kin}/L
Model A (supercritical)	$\rho \sim 10^{-2}$ g/cm^3 $T \sim 10^8$ K	$\sim 10^0$	Erad > Emag > Egas	~1
Model B (standard)	$\rho \sim 10^{-5}$ g/cm^3 $T \sim 10^6$ K	$\sim 10^{-2}$	Egas $\gtrsim$ Emag ~ Erad	~0.003
Model C (RIAF)	$\rho \sim 10^{-9}$ g/cm^3 $T \sim 10^{10}$ K	$\sim 10^{-8}$	Egas > Emag >> Erad	~3

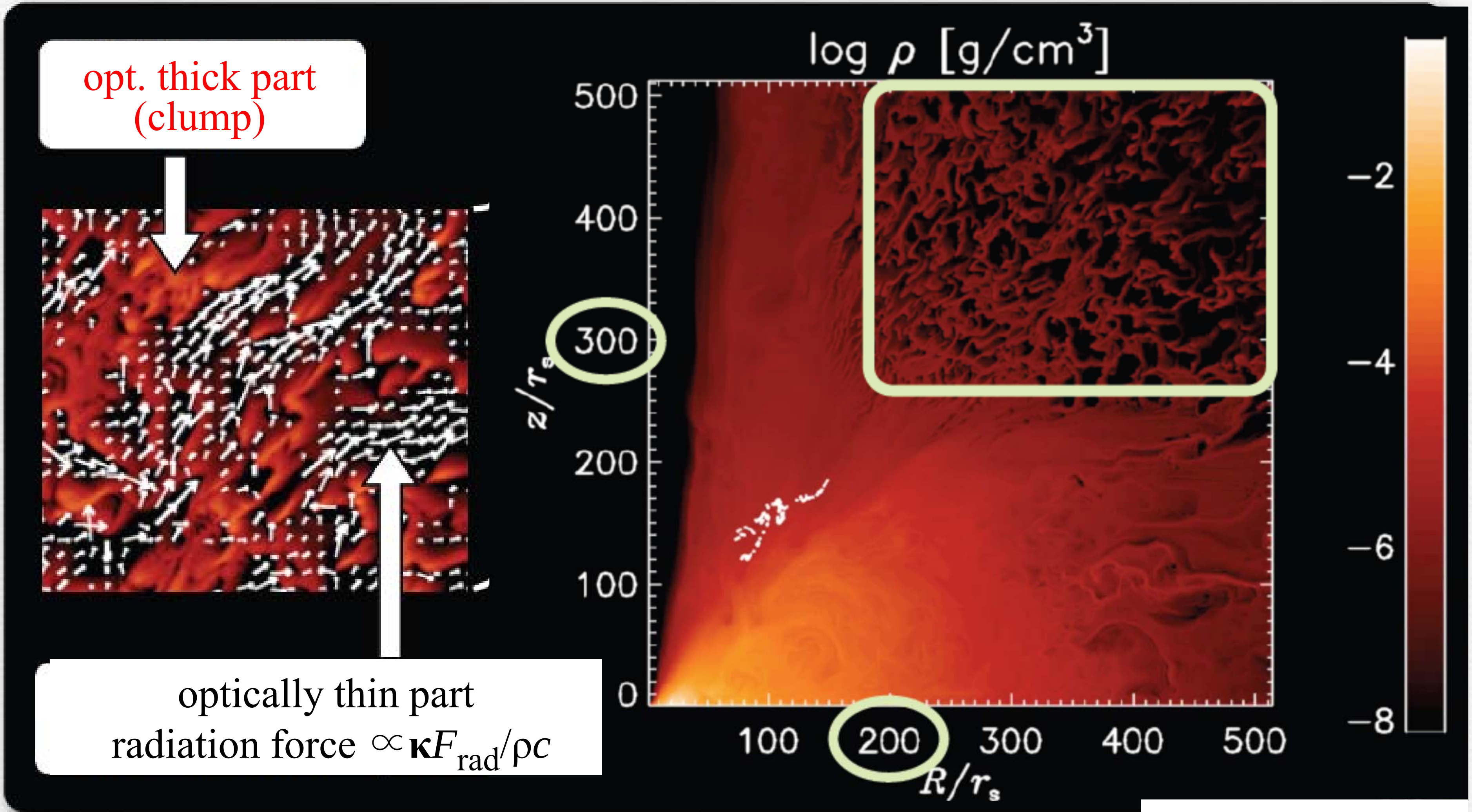
⇨ **Model A (supercritical): thick disk with P_{rad}-driven jet & outflow**

Model B (standard) : thin disk with weak outflow

Model C (RIAF) : thick disk with P_{mag}-driven jet & outflow

Remark 1. Clumpy outflows → variability

(Outflow speed $\lesssim$ 0.1c, $\dot{M}$(outflow) ~ L_E/c^2, opening angle = 20-50 deg)



clump size ~ 5 r_S, τ~1

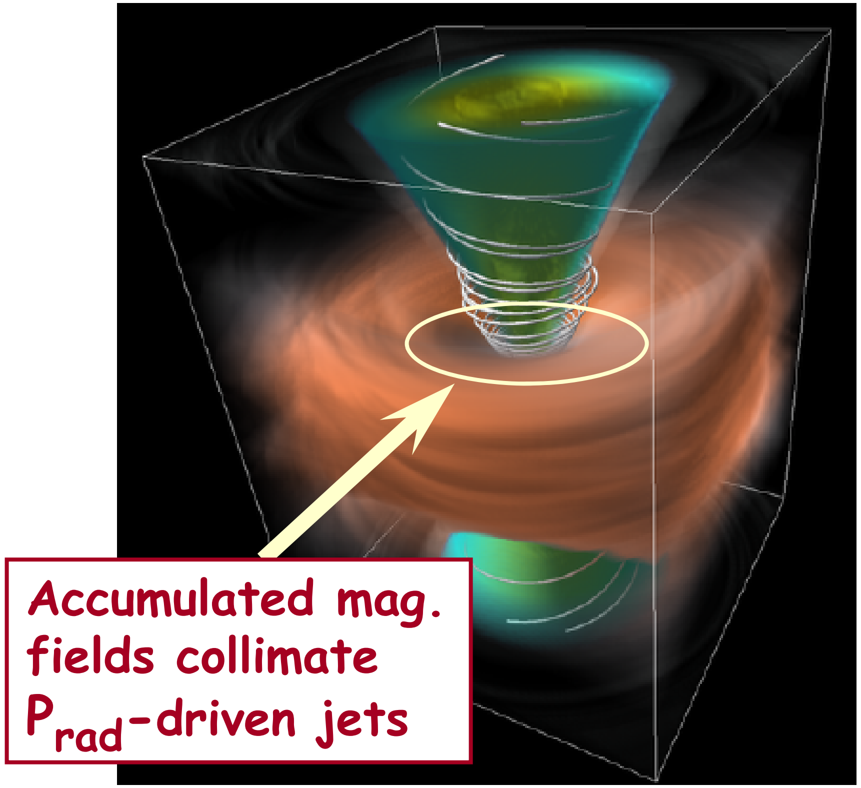
Remark 2. Radiation-MHD jets

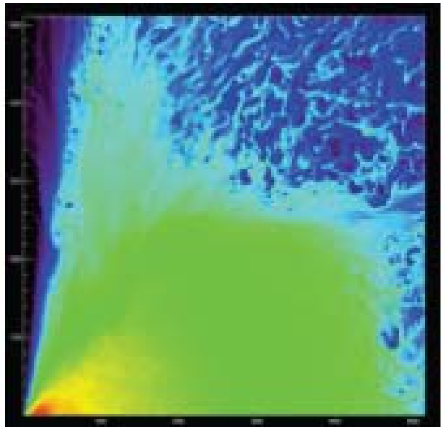
(jet speed ~ 1 c, opening angle < 10 deg)

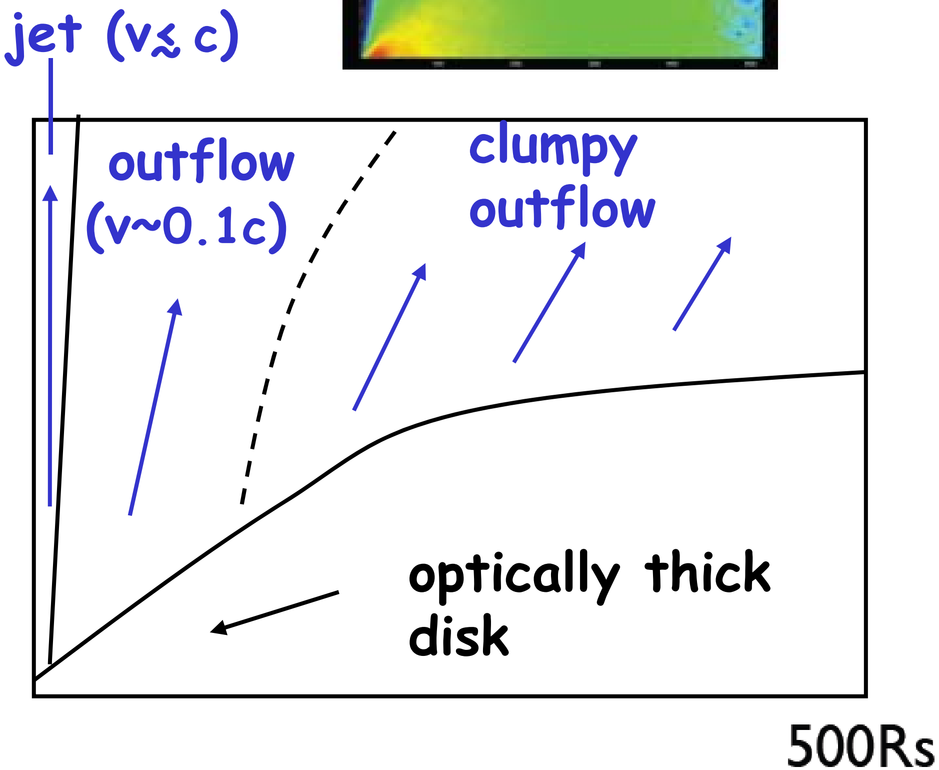
(Takeuchi+11)

Powerful P_{rad}-driven magnetic tower jets are produced at high luminosities ($L \gtrsim L_E$).

Bird's eye view ↓







Remark 3. Comptonization (?)

(RHD simulations by Kawashima et al. 2009, 2012)

Compton cooling

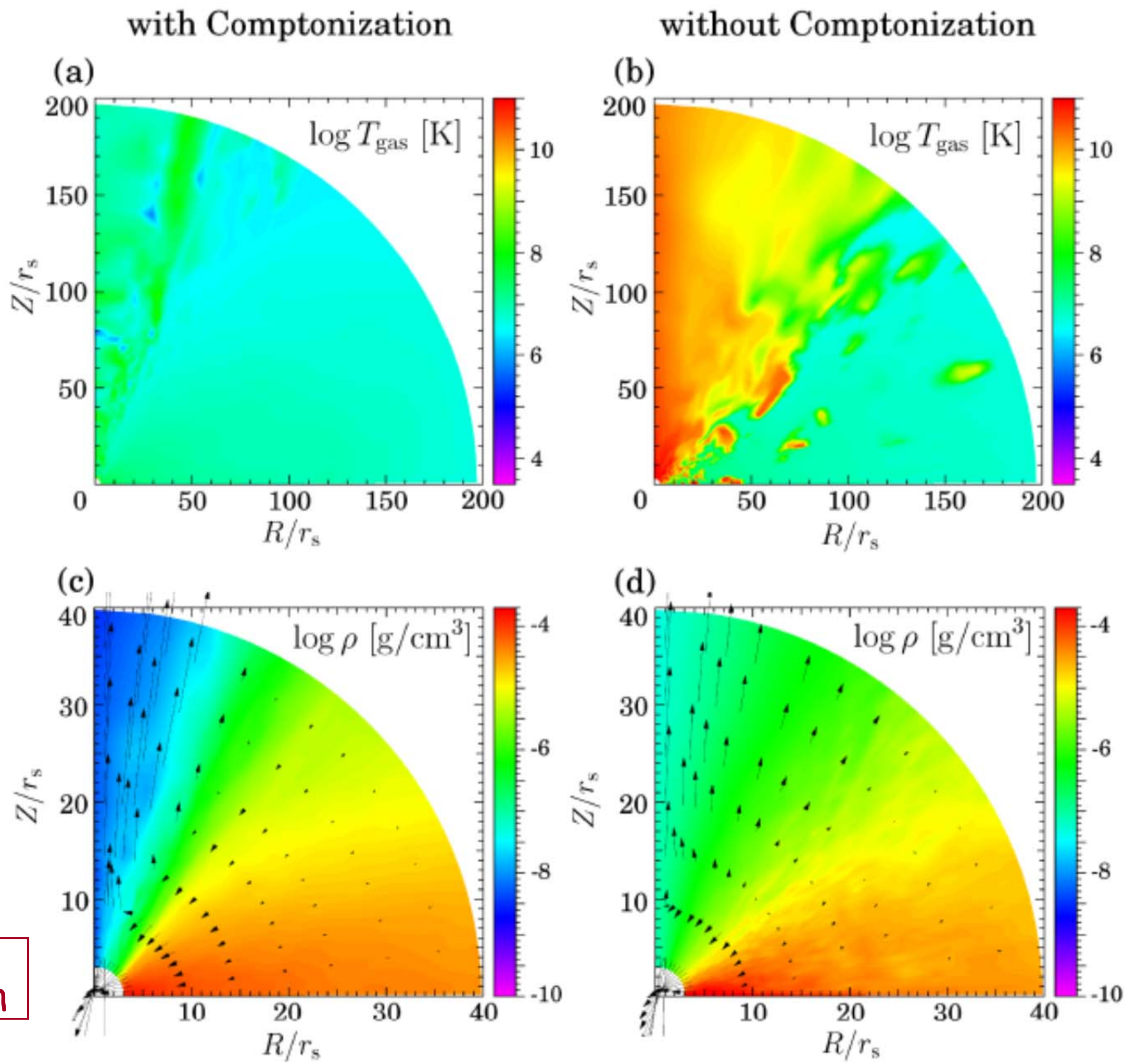
y-parameter > 1

→ significant cooling

→ also bulk Compton

Should be important for BHBs (& ULXs).

How about the cases with supermassive BHs?



$M_{BH}=10M_{sun}$

Summary

- Variety of accretion modes are observed in BH objects. The flow is composed of hot ($\sim 10^9$K) plasmas and cool disk (10^{5-7}K) but their locations are unknown.
- For making a unified view of various accretion modes, we are performing global radiation-MHD simulations.
- By controlling a density normalization we could for the first time reproduce three distinct modes of accretion flow and outflow by one code.
- Outflow is quite ubiquitous. At high luminosities ($\gtrsim L_E$), in particular, powerful P_{rad}-driven jets and clumpy outflows are produced. Comptonization may be important.