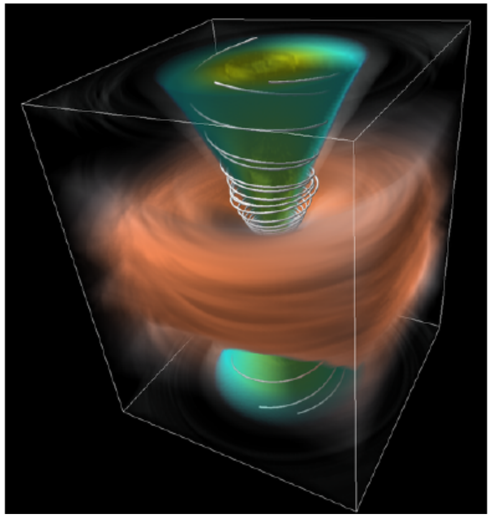
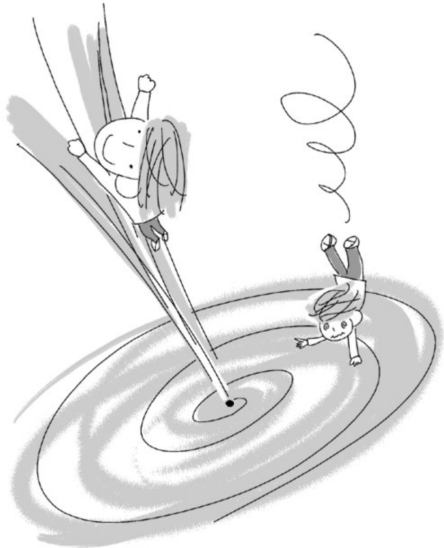
Slim Disc Model and Numerical Simulations of Super-Eddington Accretion Flow



© Shun Takeuchi



© Takao Ochiai

Shin Mineshige (Kyoto U.)

K. Ohsuga (Tsukuba), T. Kawashima, Y. Asahina, H. Kobayashi, (NAOJ), H. Takahashi (Chubu), T. Ogawa, T. Kitaki (Kyoto)

Outline

1. Introduction: super-Eddington accretion and key questions

2. Slim disc model vs. numerical simulation

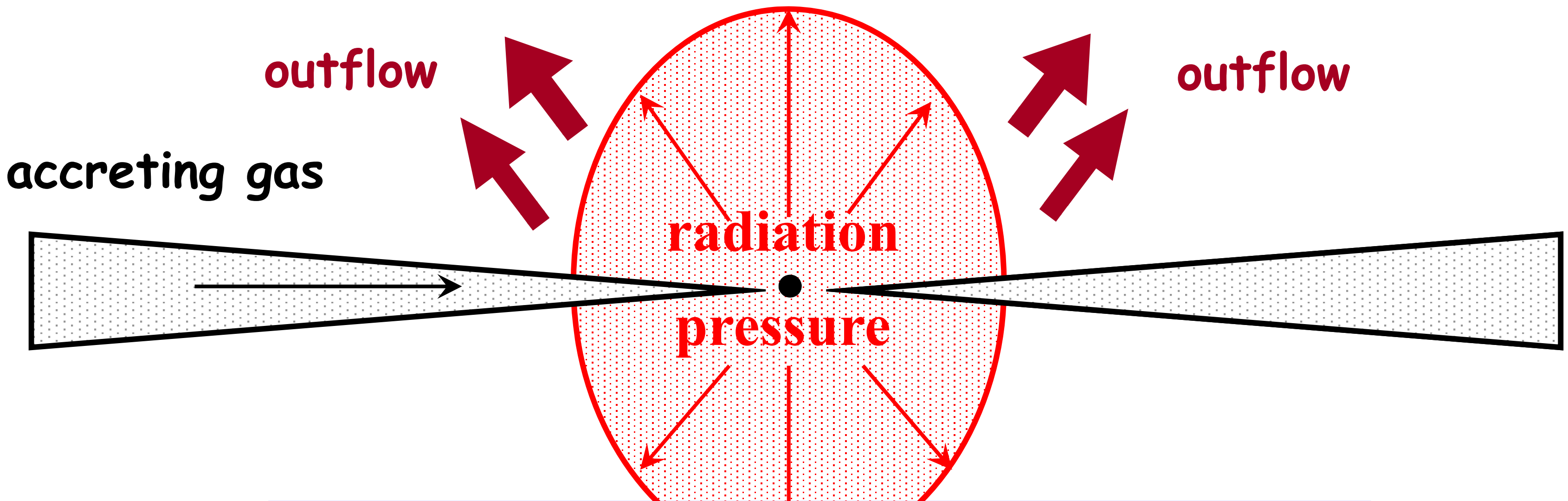
3. 3D structure of clumpy outflow from super-Eddington accretion flow

Super-Eddington accretion

$$\dot{M}_{\rm acc} \gg \dot{M}_{\rm E} \equiv L_{\rm E}/(\eta c^2) \quad (\eta = \text{efficiency} \sim 0.1)$$

Classical limit can be exceeded by disc accretion

($\because$ directions of gas inflow & out-going radiation are different)



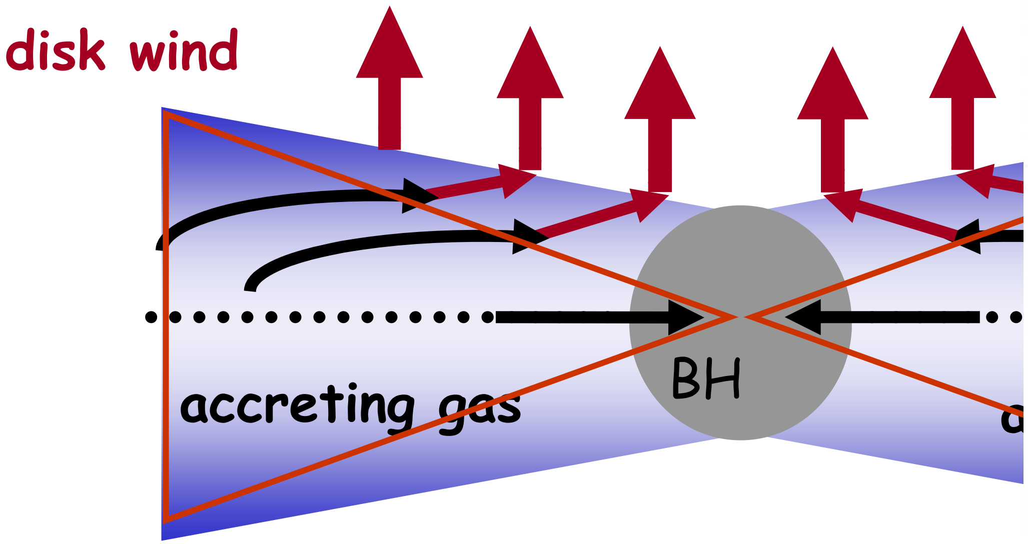
Apparent luminosity can exceed L_E!

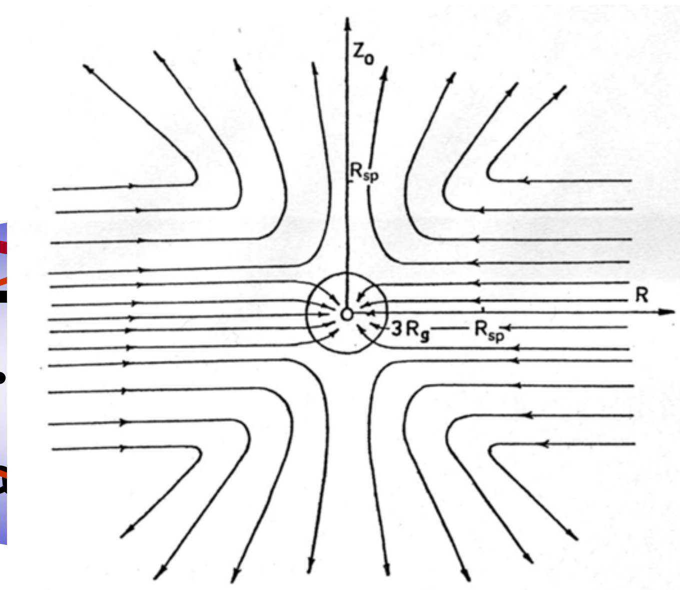
Key process 1. Outflow

(Shakura & Sunyaev 1973; Poutanen+ 2007, ...)

Significant outflow from disc surface

Radiation pressure-driven outflow inevitably occurs.





Shakura & Sunyaev (1973)

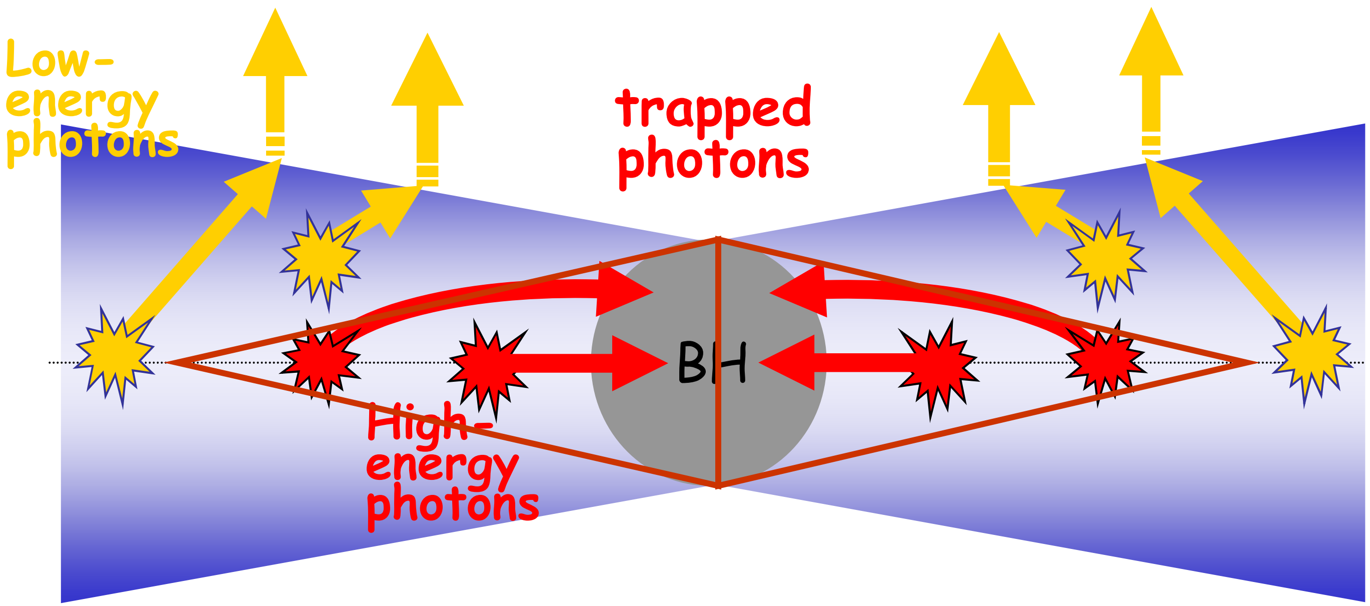
- **Critical radius = spherization radius:** $r_{sp} \sim (\dot{M}c^2/\eta L_E)\, r_s$
- **Inside this radius: flatter temp. profile:** $T \propto r^{-1/2}$

Key process 2. Photon trapping

Begelman (1978), Ohsuga et al. (2002)

Photon trapping within disc

Photons are trapped within luminous accretion flow.



- Critical radius = trapping radius: $r_{trap} \sim (\dot{M}c^2/L_E)(H/r)\, r_s$
- Inside this radius: flatter temp. profile: $T \propto r^{-1/2}$

Key questions !!

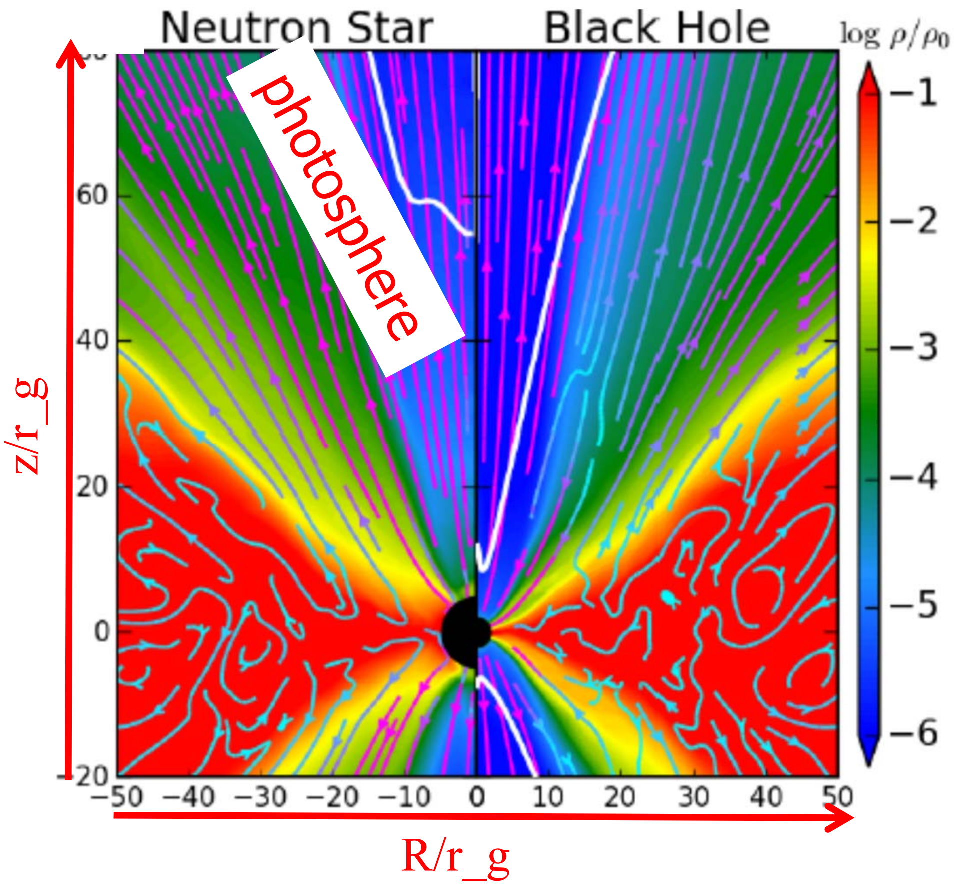
1. Why is super-Eddington accretion feasible?
   In case of BH, in case of NS??

2. Is the slim disc model a good model?
   Or just a "historical" model?

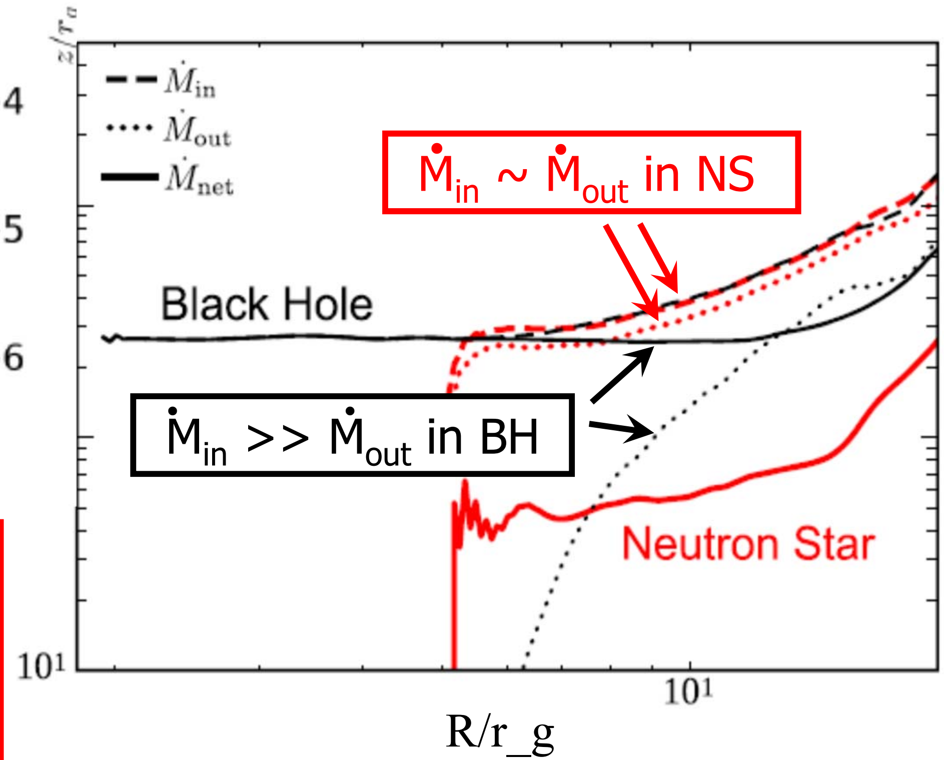
3. What is a key signature of super-Eddington flow?

Why is super-Eddington accretion feasible?

GR-R-MHD simulation by Takahashi+2017



	NS	BH
$\dot{M}_{\rm acc}c^2/L_{\rm E}$	690	390
$L_{\rm kin}/L_{\rm E}$	4.9	0.20
$L_{\rm rad}/L_{\rm E}$	3.2	3.0



Two-dimensional flow pattern with
(BH) photon trapping (or advection)
(NS) powerful outflow

Outline

1. Introduction: super-Eddington accretion and key questions

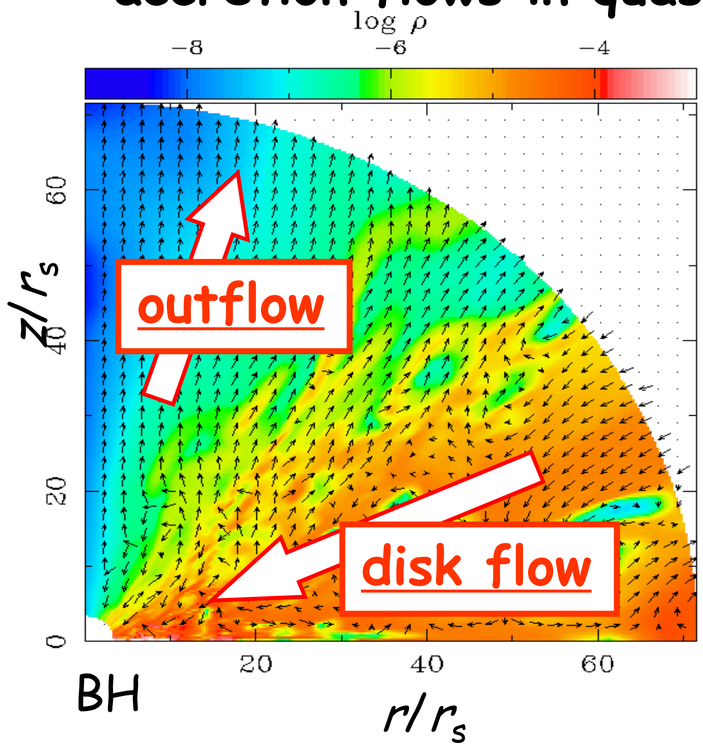
2. Slim disc model vs. numerical simulation

3. 3D structure of clumpy outflow from super-Eddington accretion flow

RHD simulation of super-Eddington accretion & outflow:

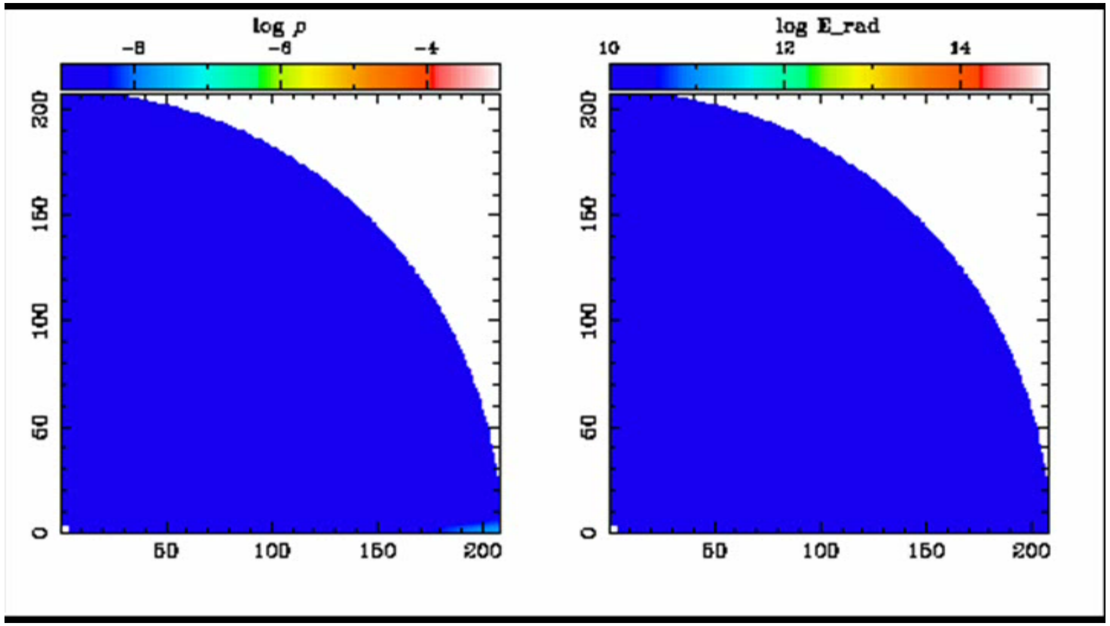
(Ohsuga+ 05)

- First radiation-hydrodynamical simulations of supercritical accretion flows in quasi-steady regimes with α viscosity (α=0.1).



density contours & velocity fields

$M = 10\,M_{sun}$ & $\dot{M} \sim 350\,L_E/c^2 \rightarrow L \sim 3\,L_E$



gas density

radiation energy density

Problems in the past simulations

We wish to compare with the slim disc model

Simulations show two step evolution:

(1) free fall until r_{Kep} (at which $F_{cent}=F_{grav}$)

(2) viscous accretion flow inside r_{Kep}

→ Need large $r_{Kep} \gtrsim r_{trap} \sim (\dot{M}c^2/L_E)\, r_S$

Large r_{Kep} → long computational time → difficult

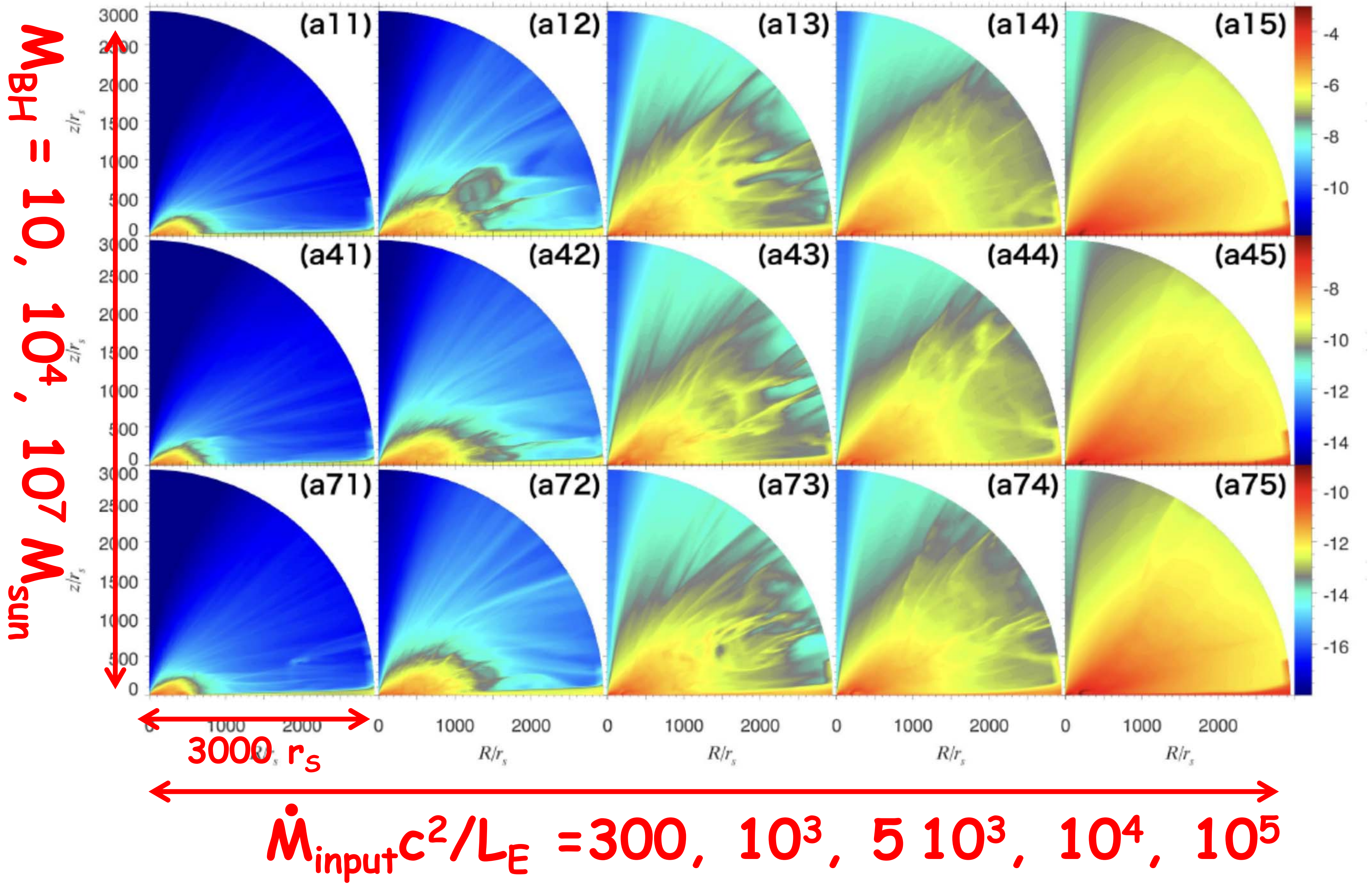
(cf. Previously $r_{Kep} \sim 30\, r_S$)

➔ New simulations with $r_{Kep} \sim 300\, r_S$

Box size ~ $3000\, r_S$

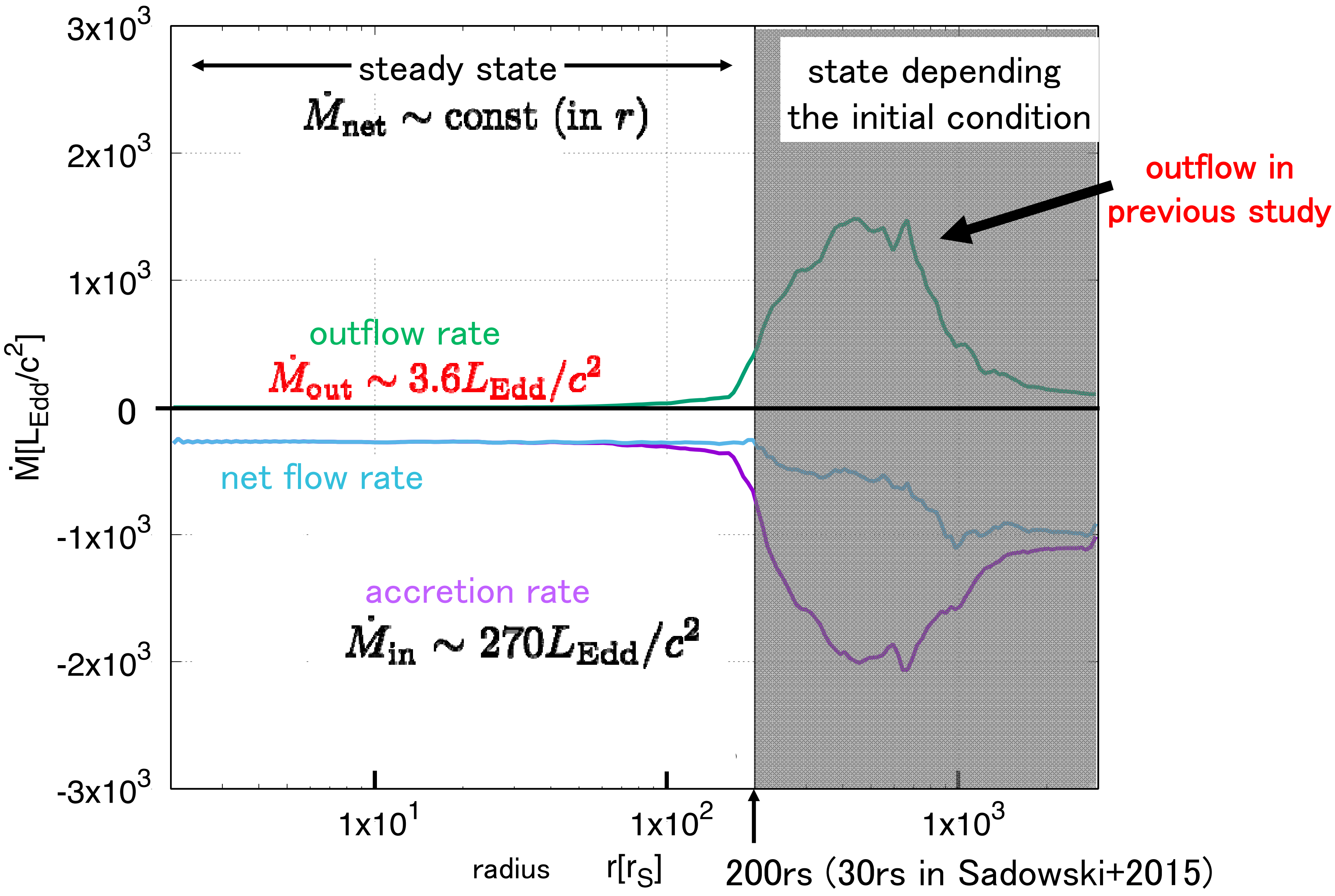
Summary: density contours

(density normalization $\rho_0 \propto M_{BH}^{-1}$) Kitaki, SM+ 2018



The region of steady state and the outflow

Outflow rate is negligible near BH => consistent with slim disc model



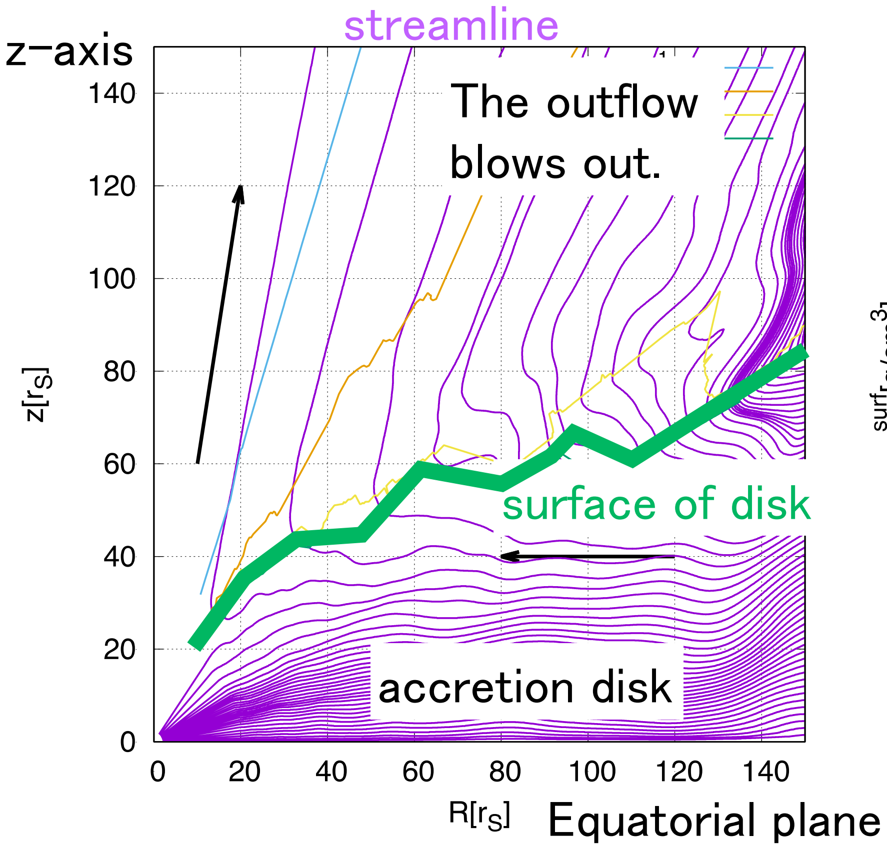
Why is the outflow so weak?

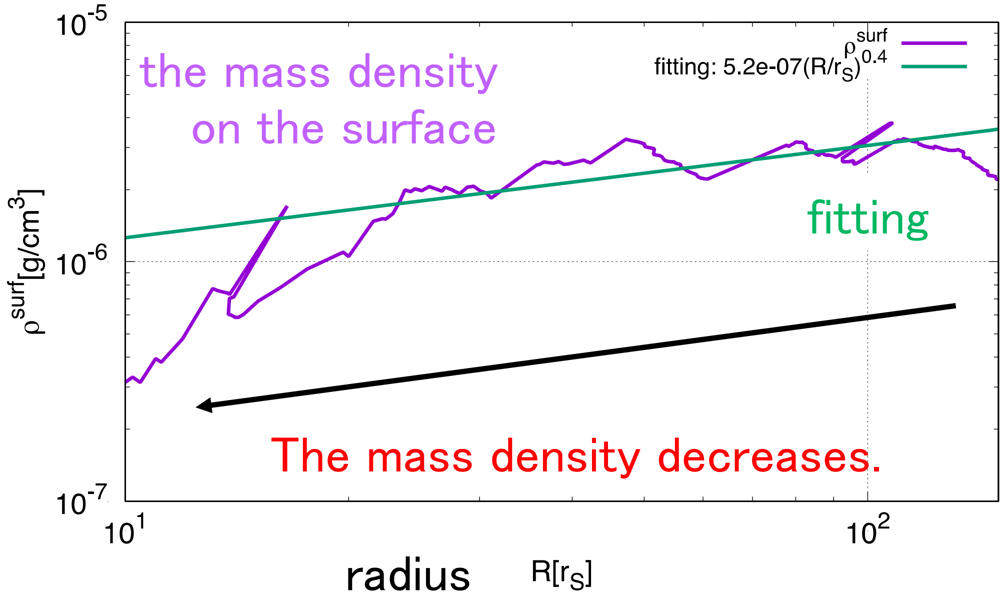
- Outflow rate is proportional to mass density and velocity.

$$\dot{M}_{out}(r) = \int_{4\pi} d\Omega\, r^2 \rho(r,\theta) \max\{v_r(r,\theta), 0\}$$

- From streamline, outflow blows out ($v_r \geq 0.1c$) near the black hole.
- The mass density on the disc surface decreases, as *r* decreases;

$\rho^{surface} \propto r^{0.4}$ (cf. $\rho^{surf}_{slim} = \rho_{slim}(r) \exp(-\frac{z^2}{2H^2}) \propto \rho_{slim}(r) \propto r^{-1.5}$)





Results of parameter fittings

- Compare the parameter dependences of the physical quantities between the simulated accretion flow and the slim disc:
- Dependences on M_{BH} & $\dot{M}_{BH}$ => Good agreement
- Dependences on r => Differences in ρ, v_r profiles

- Density and velocity profiles of the simulated flow are close to those of the CDAF (Convection Dominated Accretion Flow).

our simulations

$$\rho = 9.1 \cdot 10^{-6} m^{-1.0} \dot{m}^{1.0} (r/r_S)^{-0.73}$$

$$T_{gas} = 3.9 \cdot 10^{7} m^{-0.24} \dot{m}^{0.24} (r/r_S)^{-0.54}$$

$$v_r / c = -0.36 m^{0.0} \dot{m}^{0.0} (r/r_S)^{-1.11}$$

$$v_\phi / c = -0.81 m^{0.0} \dot{m}^{0.0} (r/r_S)^{-0.50}$$

slim disc (Watarai 2006)

$$\rho = 2.6 \cdot 10^{-5} m^{-1} \dot{m}^{1} (r/r_S)^{-1.5}$$

$$T_{gas} = 5.3 \cdot 10^{7} m^{-0.25} \dot{m}^{0.25} (r/r_S)^{-0.63}$$

$$v_r / c = -0.11 m^{0} \dot{m}^{0} (r/r_S)^{-0.5}$$

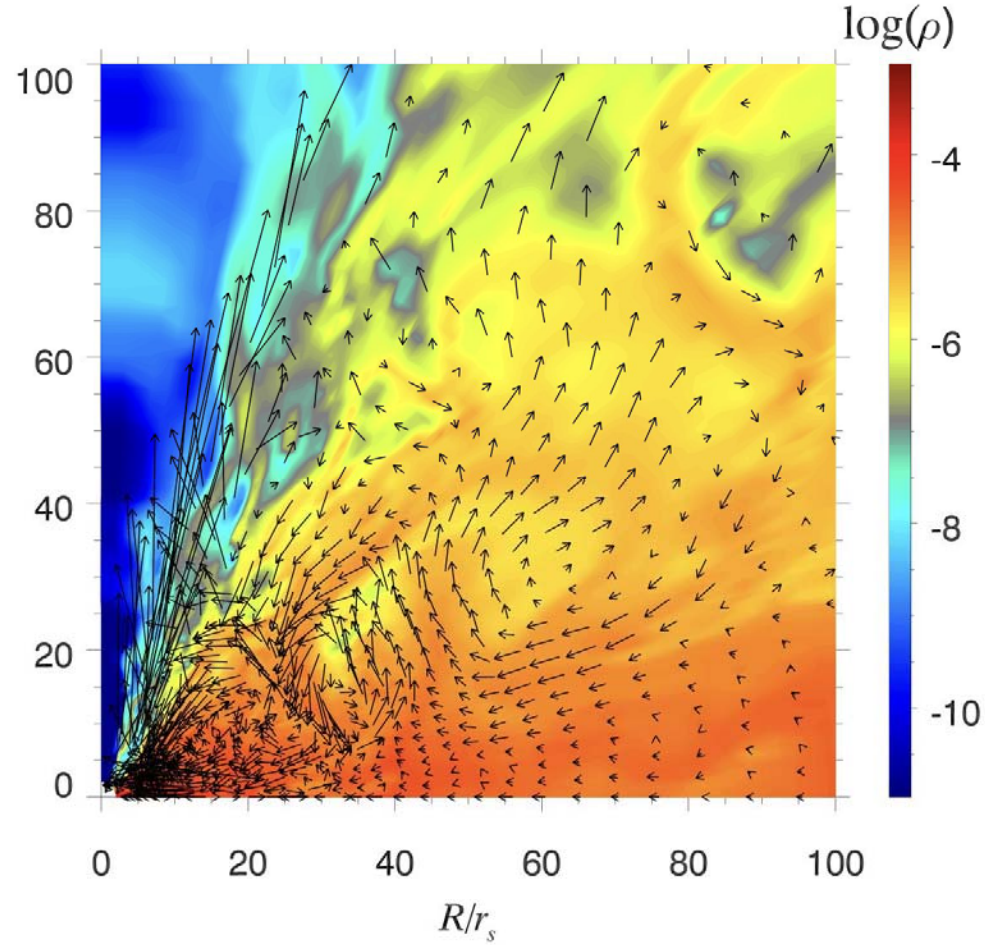
$$v_\phi / c = -0.71 m^{0} \dot{m}^{0} (r/r_S)^{-0.5}$$

$$m \equiv M_{BH} / M_{sun}, \quad \dot{m} \equiv \dot{M} c^2 / L_E$$

Convection in super-Eddington accretion

- Entropy increases toward the center (direction of the gravitational force) => convectively unstable
- Timescales of convective motion and radiative diffusion

$$t_{\rm conv} = D/v \sim 0.54[{\rm s}] \quad < \quad t_{\rm diff} = 3\tau_{\rm e} H/c \sim 15[{\rm s}]$$



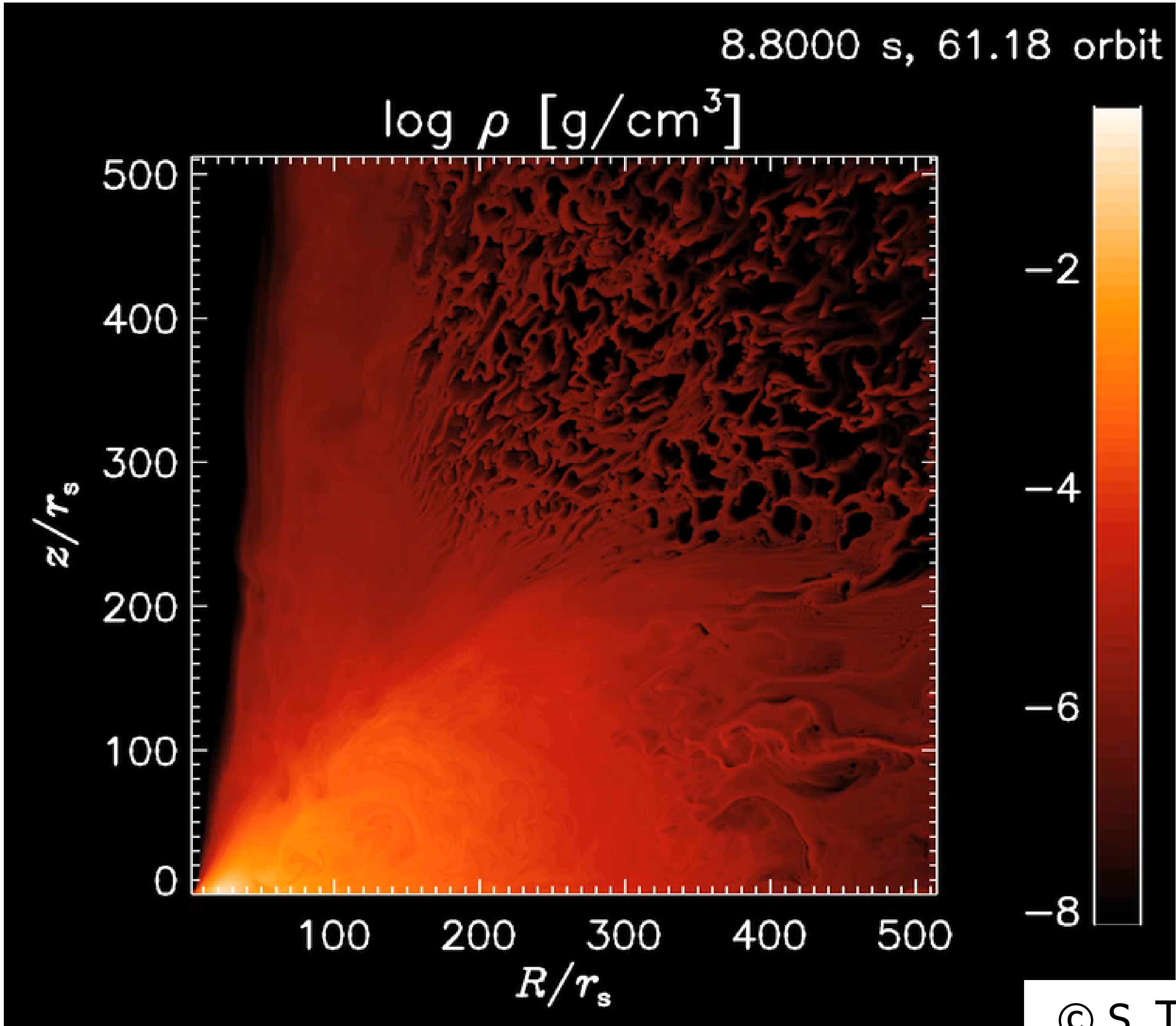
Outline

1. Introduction: super-Eddington accretion and key questions

2. Slim disc model vs. numerical simulation

3. 3D structure of clumpy outflow from super-Eddington accretion flow

Discovery of clumpy outflow



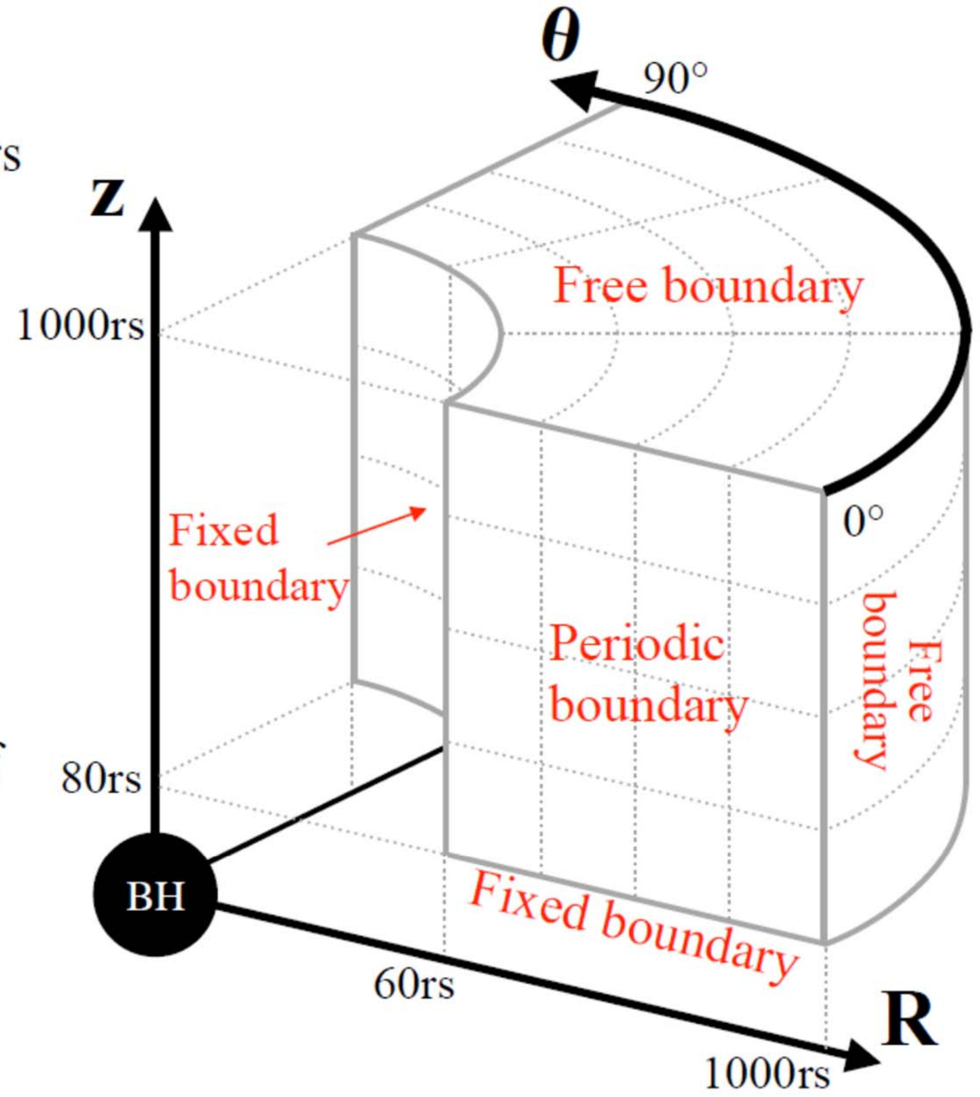
© S. Takeuchi

3D calculated model

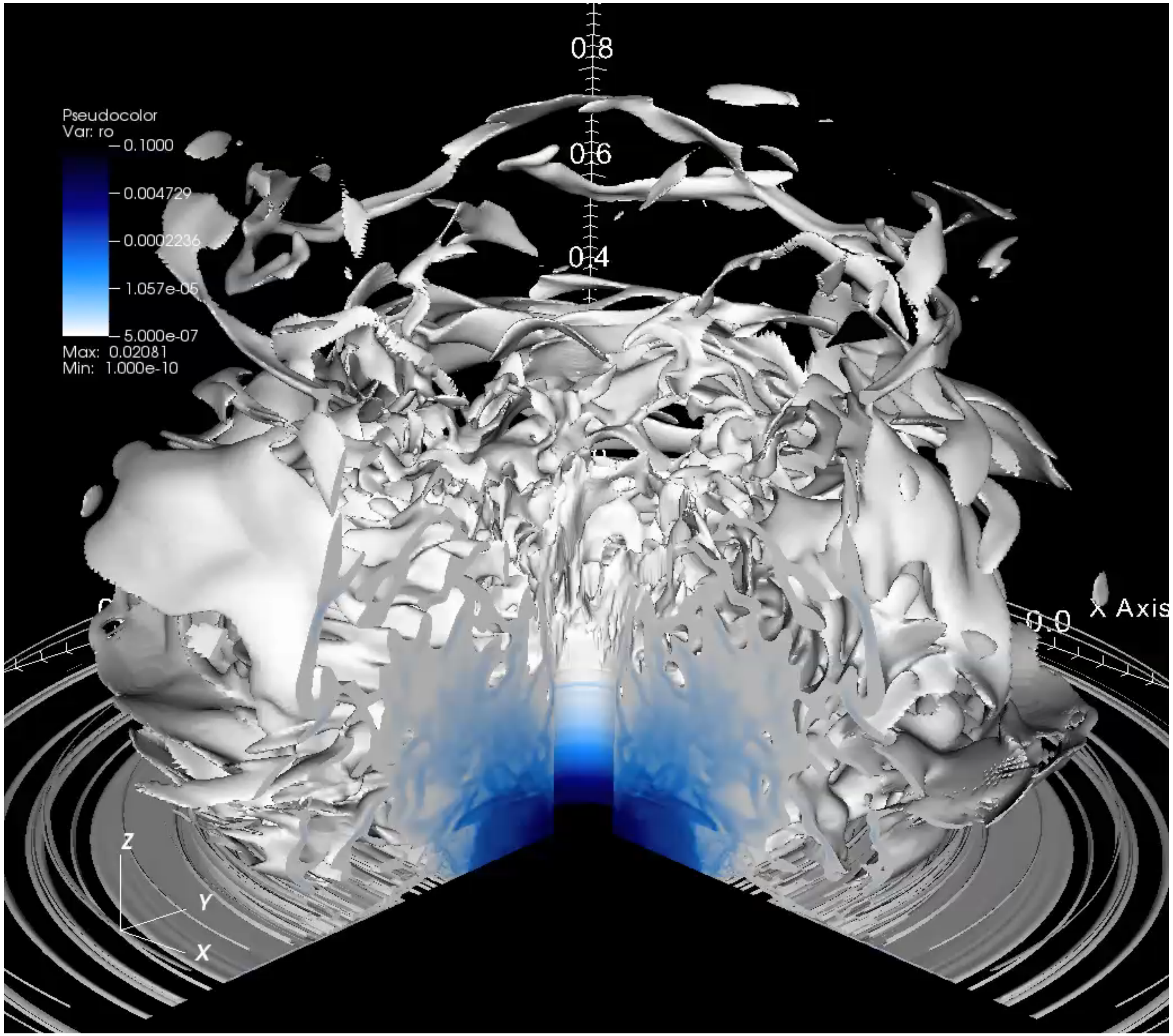
- Computational domain
  R=60-1000rs：θ=0-90°：z=80-1000rs
- Grid spacing
  ΔR=Δz=4.0rs：Δθ=0.9°
- Initial condition of physical quantity

  Data from Takeuchi et al. 2013 with fluctuation for one wave of ±10% SIN curve in θ-direction, and ignore the magnetic fields (magnetic fields do not affect to make clumpy structure).

  $(\propto [1 + 0.1\sin(4\theta)])$

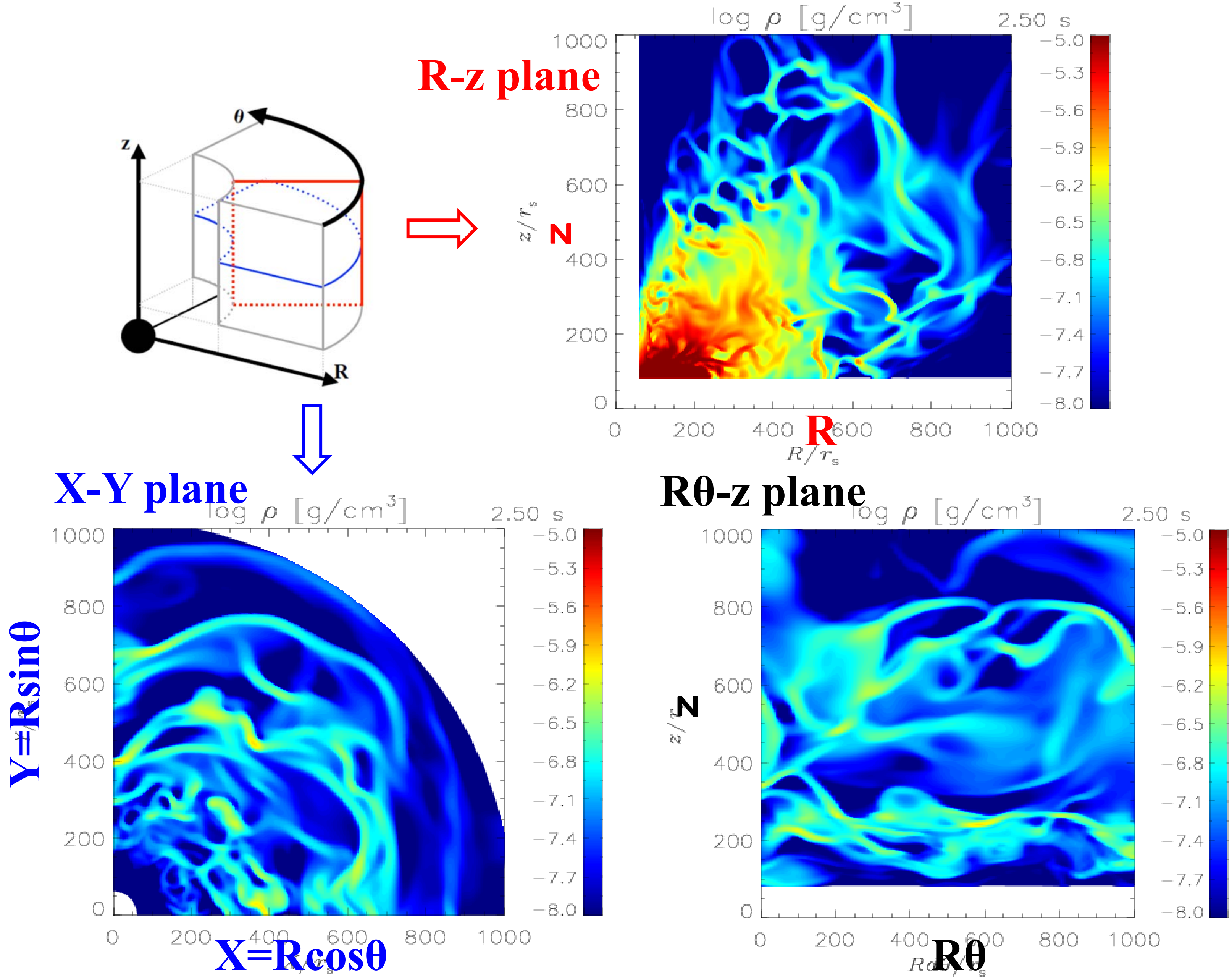


3D Structure of clumpy outflow



© H. Kobayashi

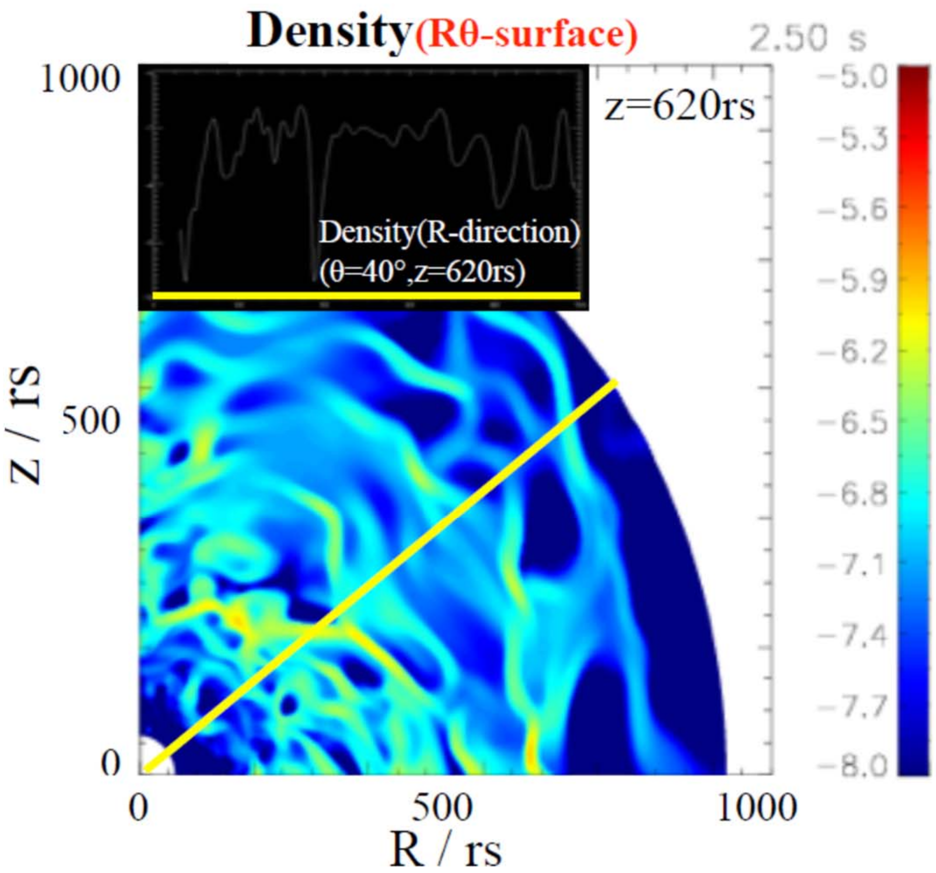
Density contours on the 2D planes

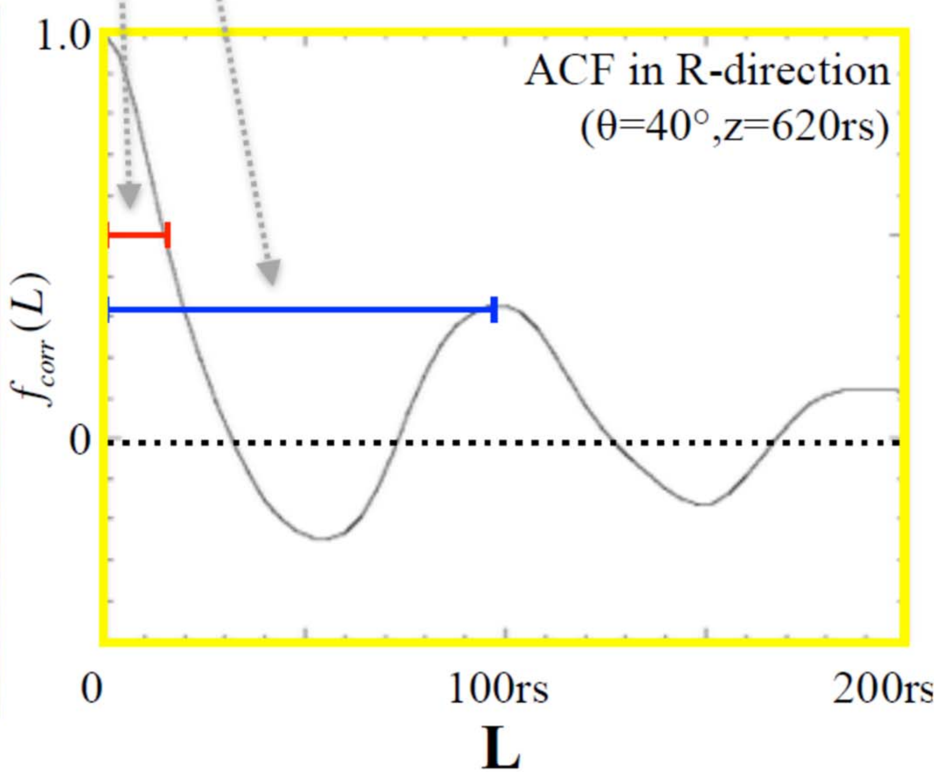


Auto-Correlation Analysis

$$f_{corr}(L) = \frac{\sum_{k=0}^{N-L-1} (\rho_{k+L} - \bar{\rho})(\rho_k - \bar{\rho})}{\sum_{k=0}^{N-1} (\rho_k - \bar{\rho})^2}$$

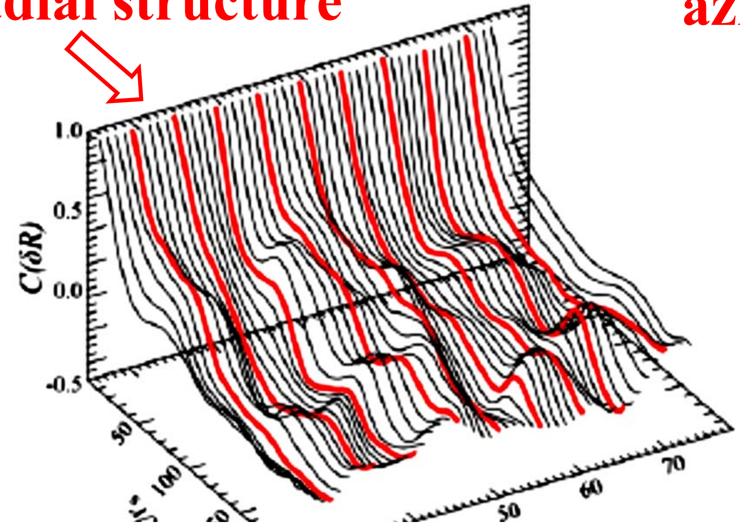
- Typical size of clump
  ~30rs(optical depth~several)
- Separation between clumps
  ~100rs



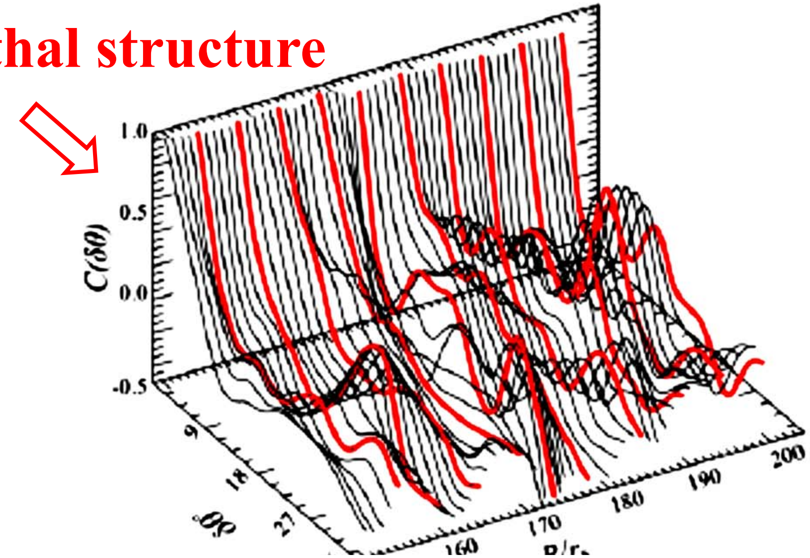


ACF analysis (R and θ direction)

Radial structure

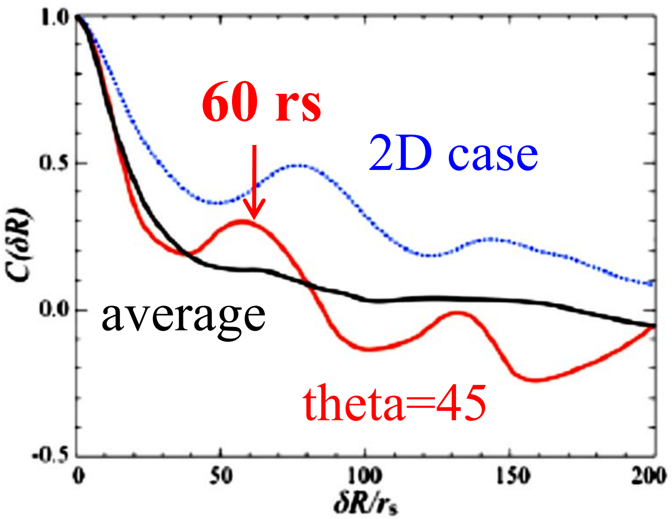


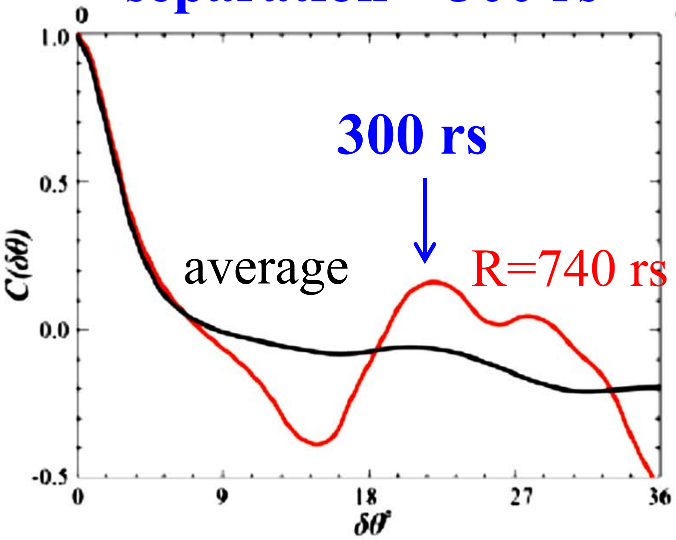
azimuthal structure



clump width ~ 30 rs
separation = 50 – 150 rs

clump width ~ 100 rs
separation ~ 300 rs



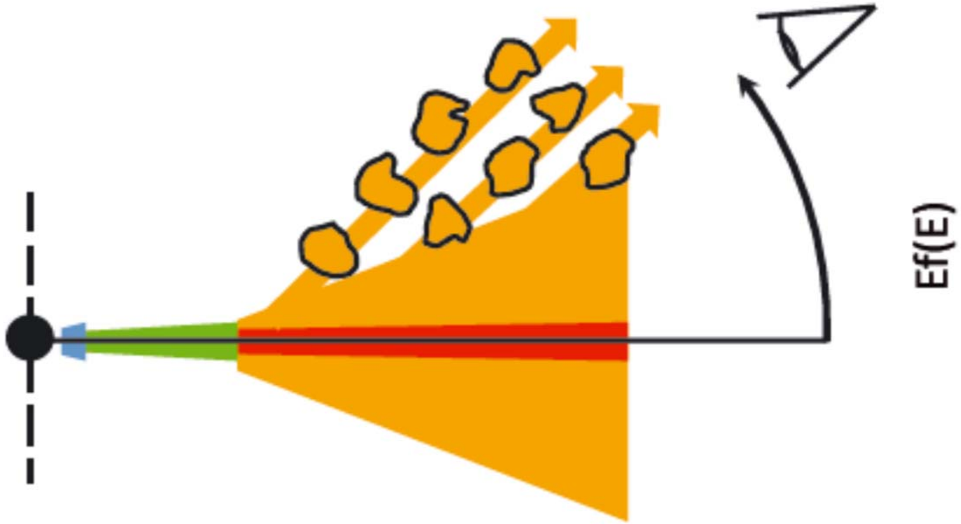


Clumpy outflow (?) from ULXs

(Middleton+11)

Energy dependent time variations in NGC5408 X-1 on ~10 s

→ variability at low energies is diluted by a constant soft comp.



Covering factor (fraction of sky covered by clumps):

$$f \sim 0.1 \left(\frac{\dot{M}_{\rm out}}{10 L_{\rm E}/c^2}\right) \tau_{\rm c}^{-1} \left(\frac{r_0}{1000\, r_{\rm s}}\right)^{-1}$$

Basic time scale:

$$t \sim 10 \left(\frac{M_{\rm BH}}{30 M_{\rm sun}}\right) \left(\frac{r_0}{1000\, r_s}\right) \text{sec}$$

⇧

$2\pi r_0 / 0.3\, V_K$

Key questions: Revisited

1. Why is super-Eddington accretion feasible?

→ 2-D effects with photon trapping/outflow

2. Is the slim disc model a good model?

→ Yes, it is !!

3. What is a key signature of super-Eddington flow?

→ clumpy outflow, producing variability & spectral hump (see a next talk)