Outflow from super-Eddington flow around various mass classes of Black Holes: Dependence of the luminosity on the accretion rate

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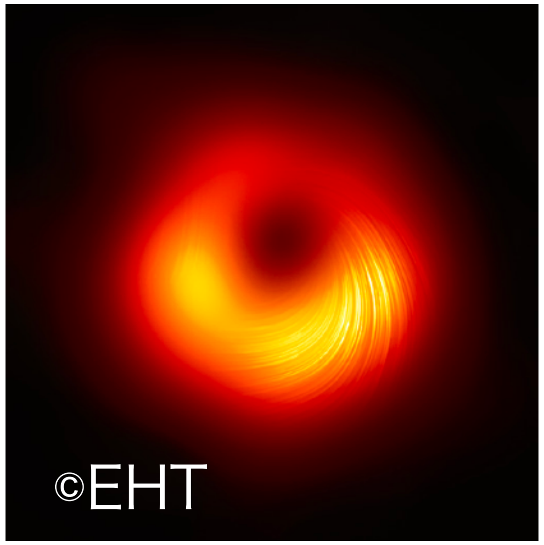
Yoshioka et al. 2022
Yoshioka et al. 2024, PASJ in press

Why studying Black Holes ?

Black holes + accretion disks can give enormous impacts to their environment

feedback
(outflow, radiation)

Black Hole (BH) scale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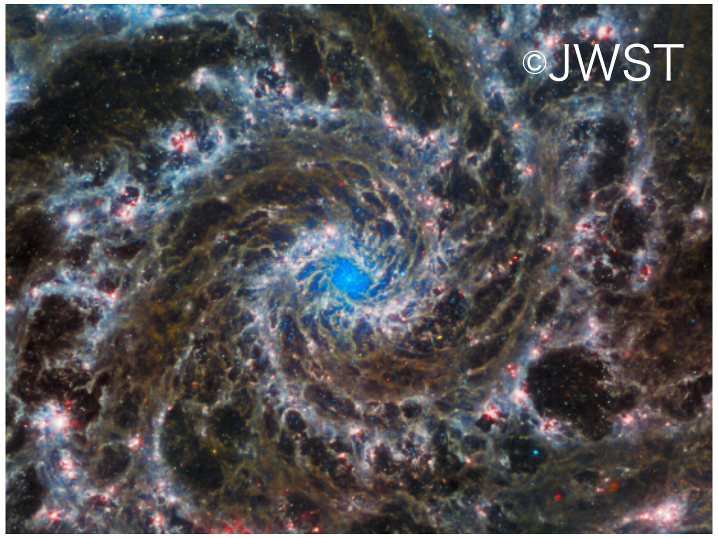
AGN/Galactic scale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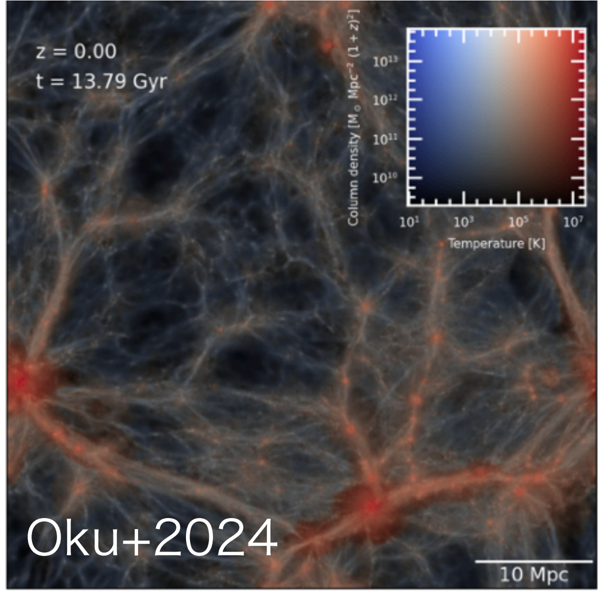
Galactic/cosmological scale



Oku+2024

mass loading

Motivation:
Quantification of feedback from black holes to galaxies/the universe

The super-Eddington accretion flow

Eddington luminosity $L_{\rm Edd}$

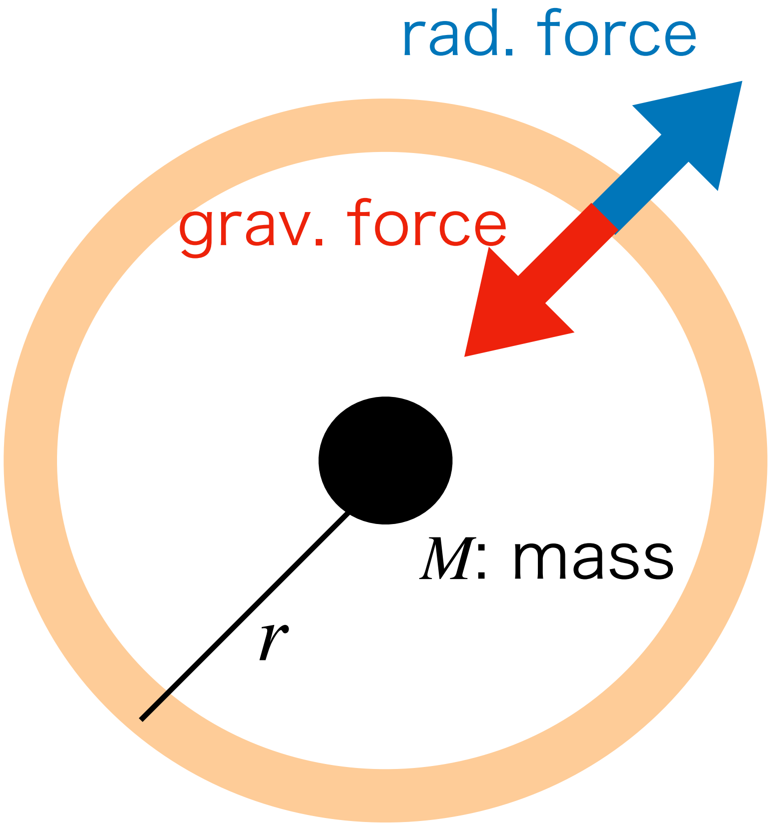
- Spherical symmetric model

force balance $$\rho\frac{GMm_p}{r^2}=\frac{\sigma_T L}{4\pi r^2 c}$$

$$\Rightarrow L_{\rm Edd}\equiv\frac{4\pi GMm_p c}{\sigma_T}\sim 1.26\times10^{39}\left(\frac{M}{10_\odot}\right)\ {\rm erg\ s^{-1}}$$

- classical limit of luminosity

ρ: density, m_p: proton mass,
L: luminosity, σ_T: Tomthon scatt.,
G: gravitational constant
c: speed of light

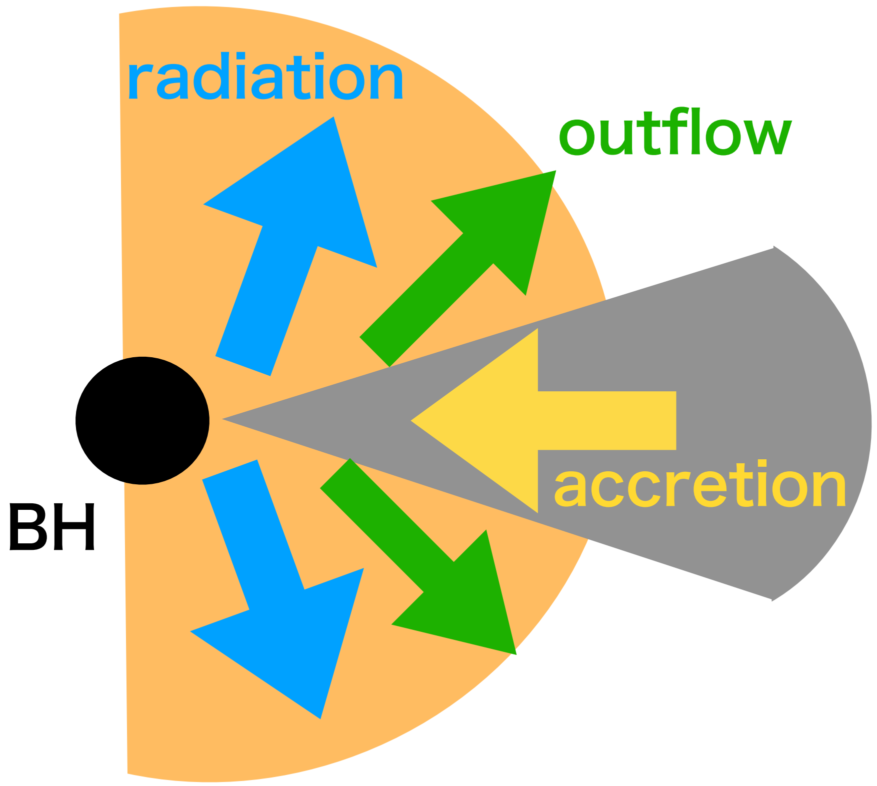


Super-Eddington accretion

The accretion rate is very high

$$\dot{M}\gg L_{\rm Edd}/c^2\equiv\dot{M}_{\rm Edd}$$

- Luminosity can be bright beyond $L_{\rm Edd}$
- Photon trapping effect
- Launching powerful outflows

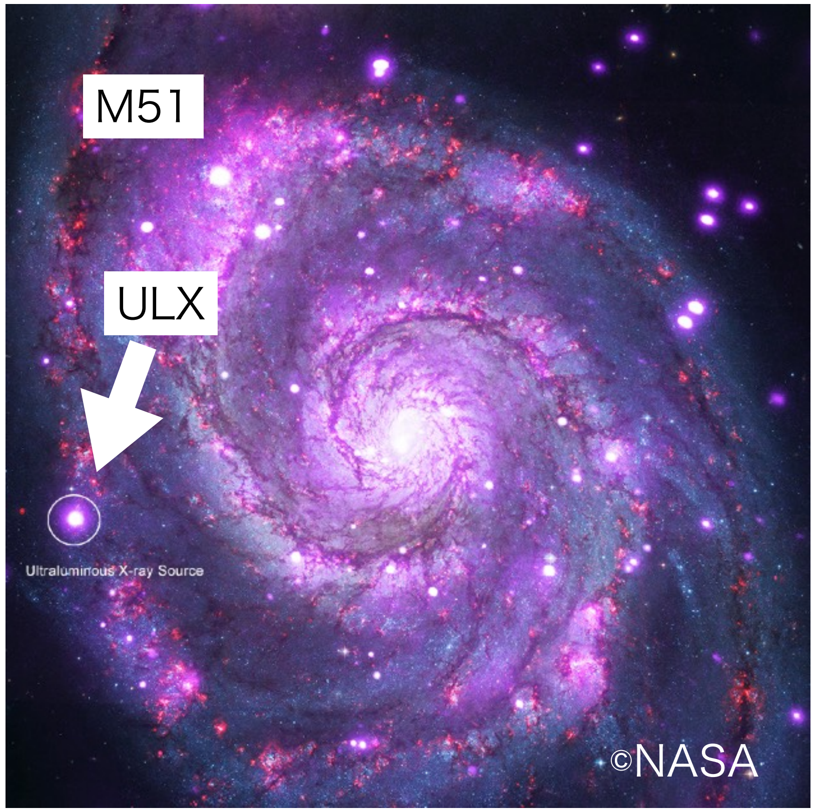


Candidate of super-Eddington flow ① : ULXs

ULXs…Ultra Luminous X-ray sources

- $L_X > 10^{39}\ \mathrm{erg\ s^{-1}}$ at the far from center of Galaxy
- They are often found in galaxies with high star formation rates.
- Three candidates of the central objects

1. **stellar mass BH+super-Eddington**
2. Nutron Star+super-Eddington
3. Intermediate BH+sub-Eddington



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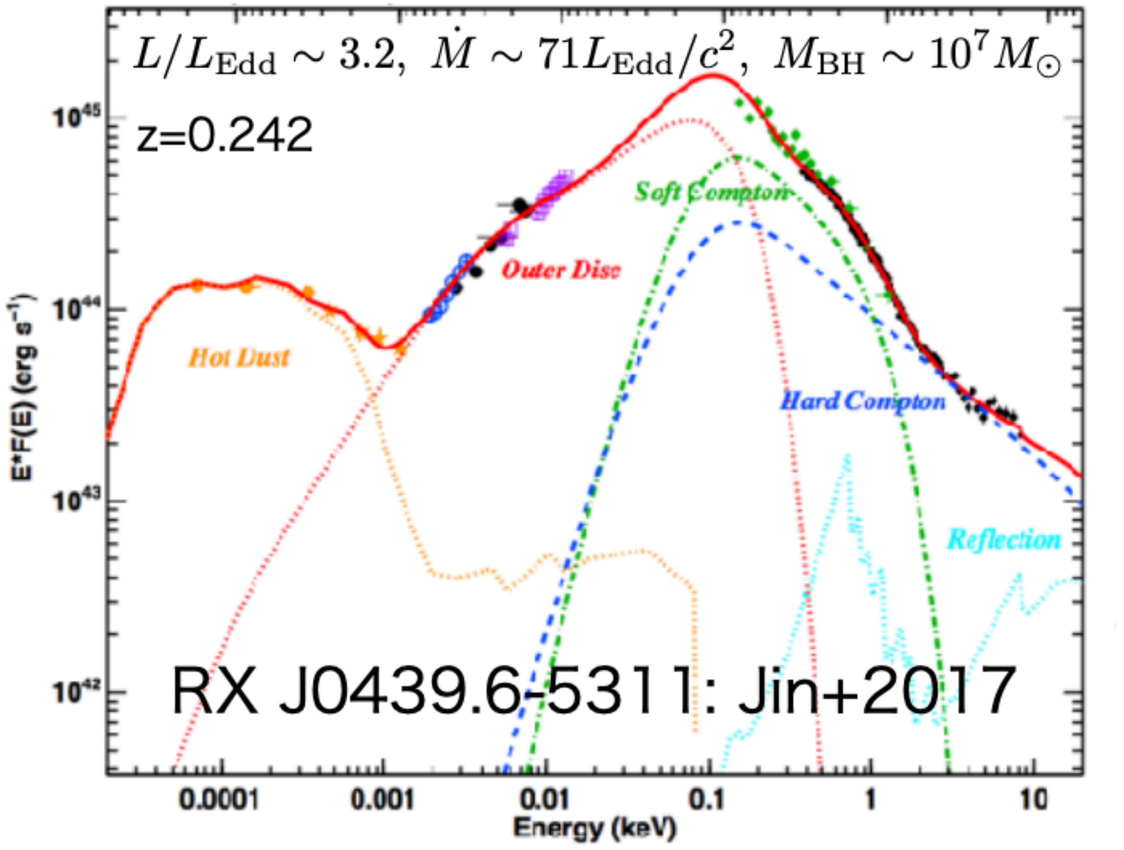
Galaxy	Milky way	M82	IZw18
Type	Barred spiral	Star burst	Blue Compact Dwarf
star formation rate	1-5	10	0.074
Number of ULX	0	6	1
ratio of metalicity	1	1	1/20

Candidate of super-Eddington flow ② : NLS1

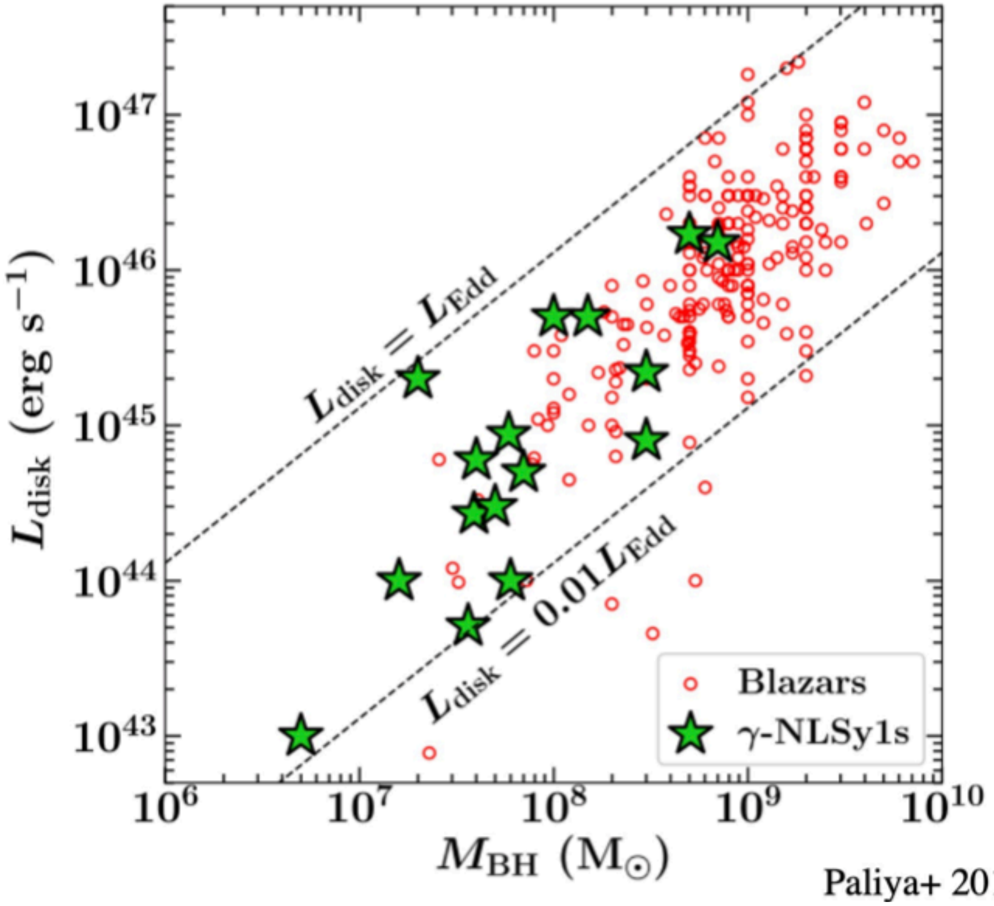
NLS1…Narrow line Seyfert1 Galaxy

- Defined by optical properties (Osterbrock & Pogge 1985)
  (i.e., FWHM(Hβ) < 2000 km/s, [O III]/Hβ < 3)
- High Eddington ratio & <u>low BH mass</u> $M_{\rm BH}$ ($\sim 10^{6-8} M_\odot$)
- Powerful outflow (e.g., Komassa+2018)

➡ rapidly evolving SMBH and strong AGN feedback



RX J0439.6-5311: Jin+2017



Paliya+ 2019

Importance of high ang. mom. simulations

Kitaki+2021

- **high** angular momentum ($r_K \sim 2430\ r_S$)

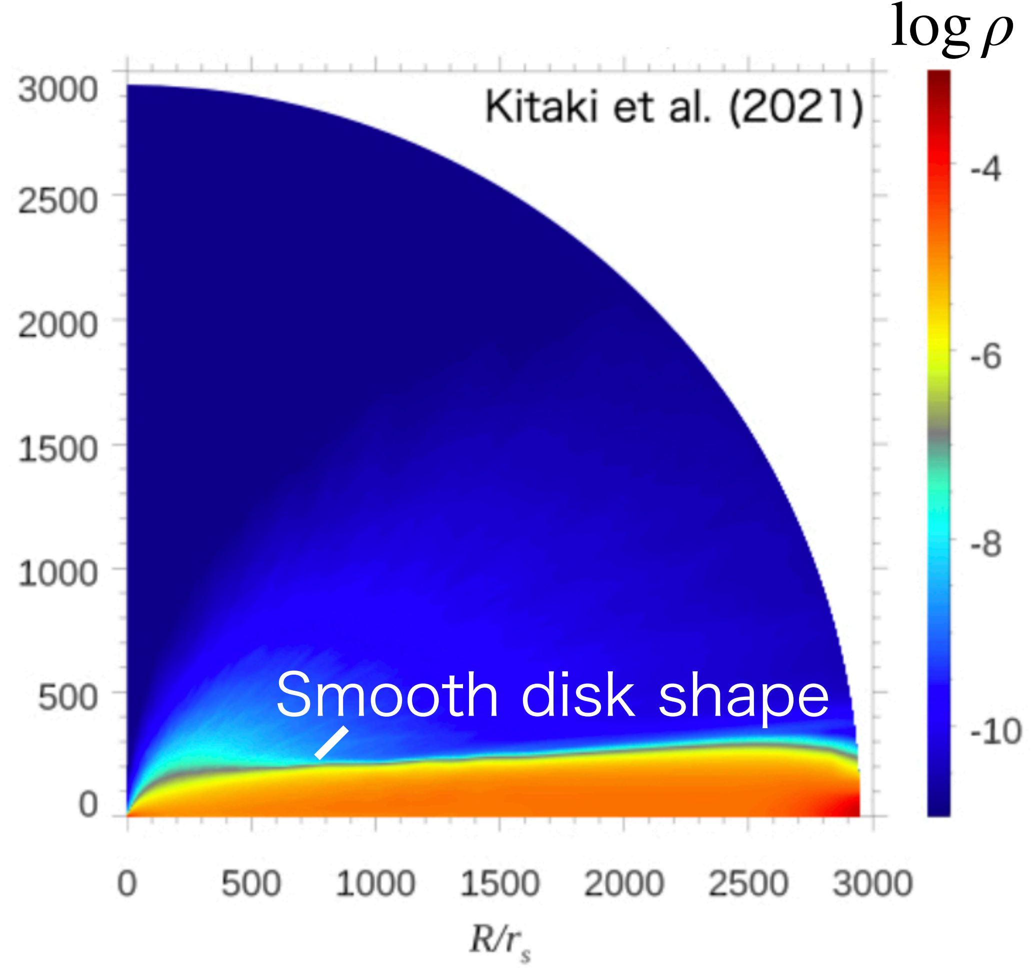
  ($r_{trap} < r_K$) r_K ··· Keplerian radius
  r_{trap} ··· Photon trapping radius

  - outer radius of the accretion disk in NLS1 ~ several hundred r_S

    cf. previous simulations set r_S at several tens to a few hundred r_S

- Accurate estimation of outflow rate and luminosity

$\dot{M}_{BH} \sim 180\ L_{Edd}/c^2,\ r_K \sim 2430\ r_S$



$\dot{M}_{BH}$ ··· black hole accretion rate

→ **but only one parameter set**

Purpose：Thorough investigation of outflow structure

Our work

Quantifying outflow and radiation properties of super-Edd. flow as function of $(m_{\rm BH}, \dot{m}_{\rm BH})$

➡ high ang. mom. simulations in a large simulation box

Key Questions:

Q1.What is the large-scale outflow structure？

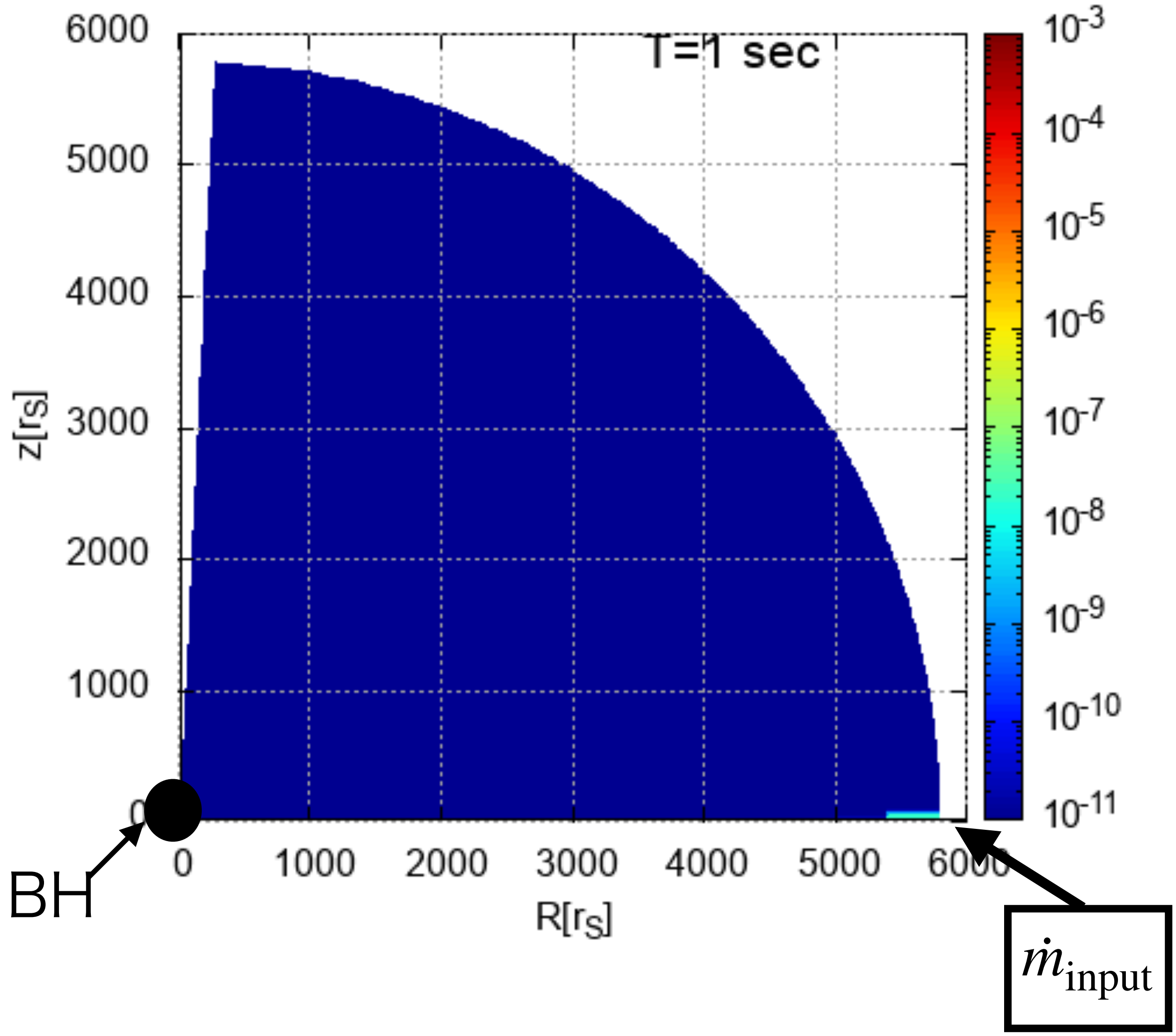
Q2. How do the radiation and mechanical luminosities depend on $(m_{\rm BH}, \dot{m}_{\rm BH})$？

normalized BH mass: $m_{\rm BH} \equiv \dfrac{M_{\rm BH}}{M_\odot}$, normalized accretion rate: $\dot{m}_{\rm BH} \equiv \dfrac{\dot{M}_{\rm BH}}{L_{\rm Edd}/c^2}$

Set up of RHD simulations

Simulation setup

- Symmetric 2D Radiation HydroDynamics (RHD) simulation
- High angular momentum
- alpha viscosity model： $\alpha = 0.1$
- Initial conditions:
  empty region with gas injection $\dot{m}_{\rm input}$
- Radiation processes:
  - flux-limited diffusion
  - Compton heating/cooling, free-free



Parameter

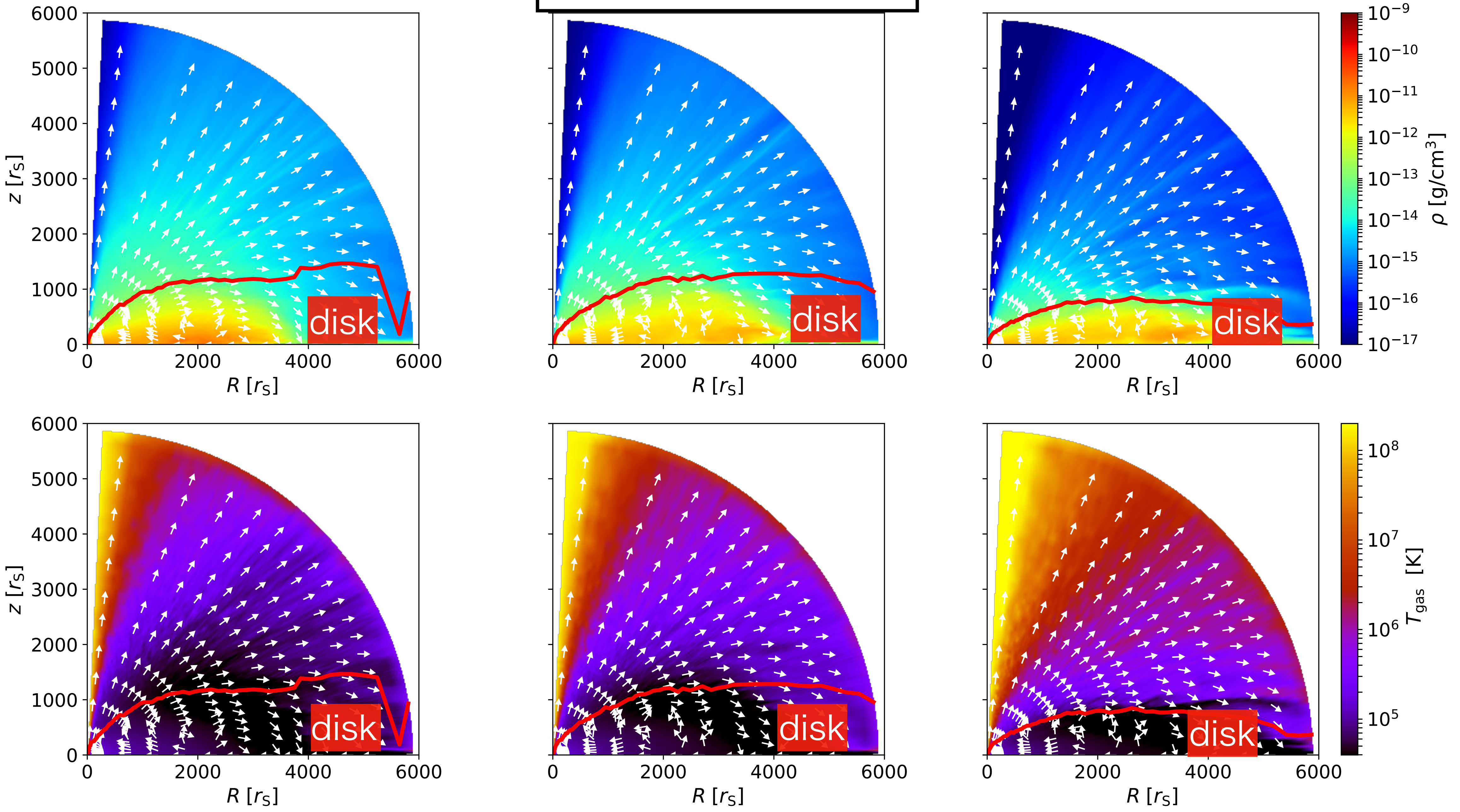
- black hole mass $m_{\rm BH} = 10,\ 10^4,\ 10^7$
- mass injection ratio $\dot{m}_{\rm input} = 350 - 2000$
- Kepler radius： $r_{\rm K} \sim 1000,\ 2430\ r_{\rm S}$
- outer boundary： $r_{\rm out} = 6000\ r_{\rm S}$
- accretion ratio $\dot{m}_{\rm BH} = 130 - 730$

$\dot{m}_{\rm input}$: normalized injection ratio

$r_{\rm out}$: outer boundary radius

Overall flow structure

$m_{\rm BH} = 10^7$, $\dot{m}_{\rm input} = 1000$

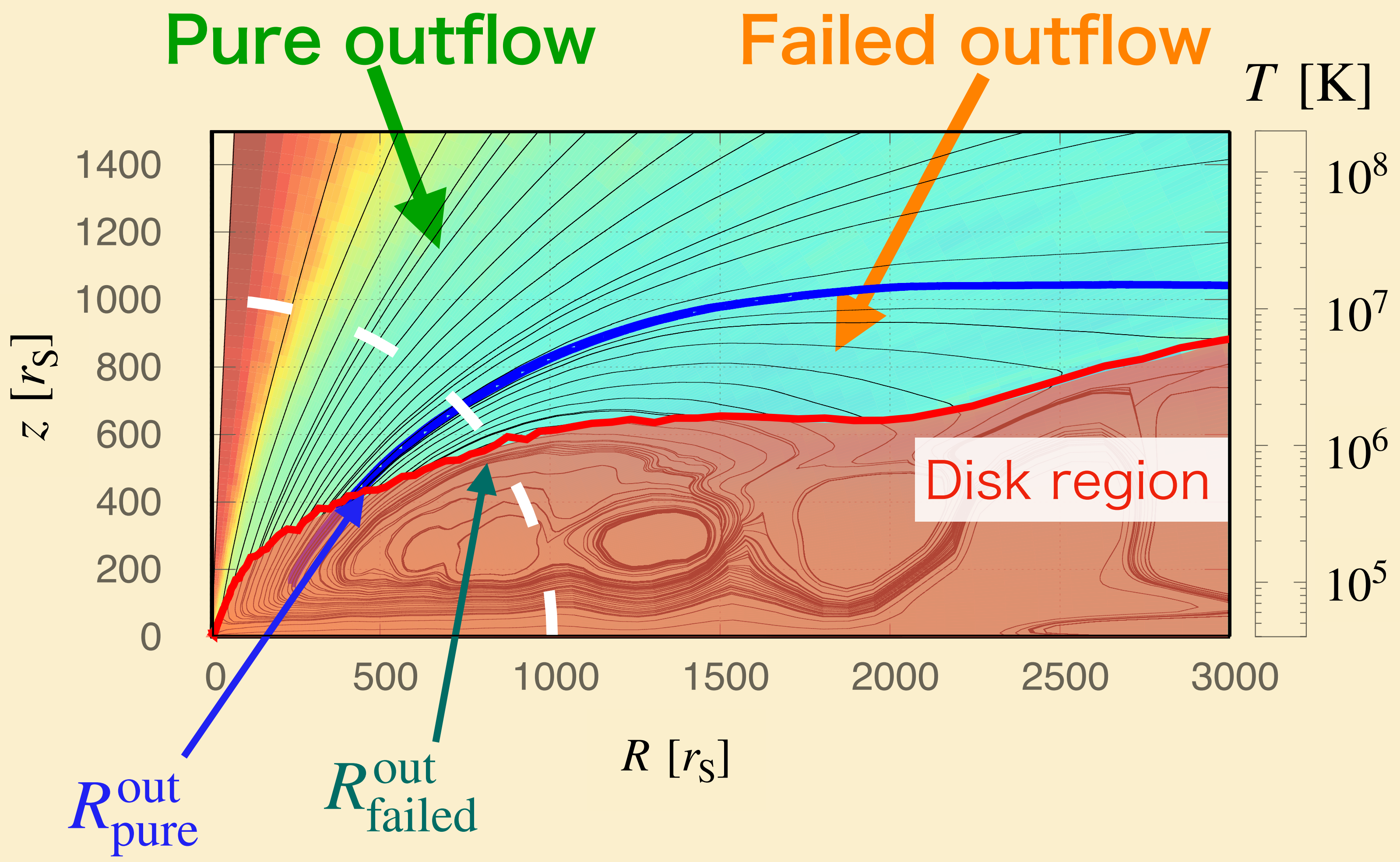


high $\dot{m}_{\rm BH}$ ← low $\dot{m}_{\rm BH}$

high-$\dot{m}_{\rm BH}$: disk inflate & high-density outflow eject at a wide angle

low-$\dot{m}_{\rm BH}$: disk flatten & the high-temperature outflow erupts at a wide angle

Two types of outflow structures: Pure & Failed outflow



Distribution of temperature and streamline

$R^{\rm out}_{\rm pure}$: farthest launching radius of pure outflow

$R^{\rm out}_{\rm failed}$: farthest launching radius

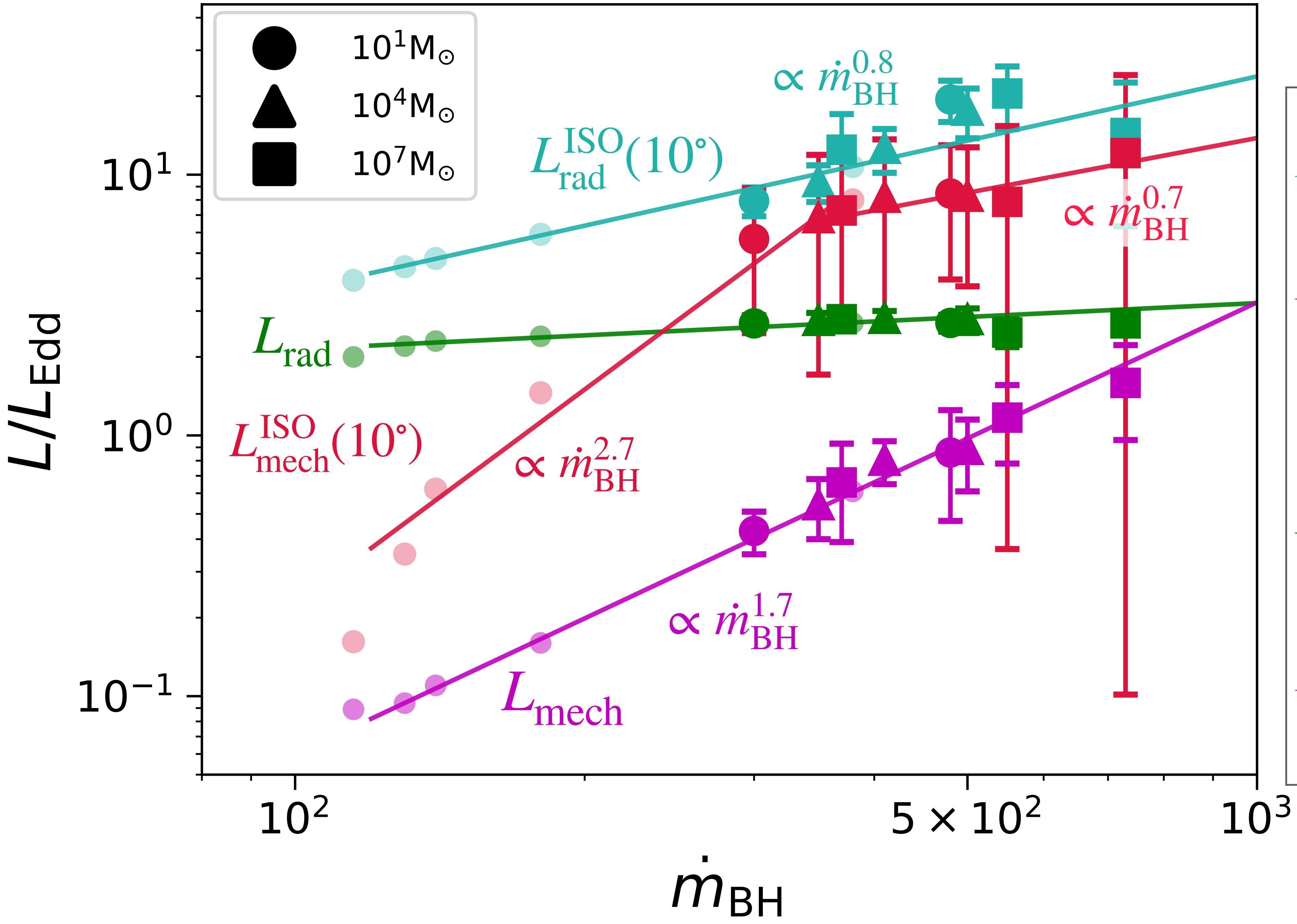
- **Pure outflow:**

  gas flow which reaches the outer boundary of the simulation box

- **Failed outflow:**

  gas flow which eventually falls back onto the disk surface

How do luminosities $L_{\rm rad}$ and $L_{\rm mech}$ depend on $(m_{\rm BH}, \dot{m}_{\rm BH})$?



$$L^{\rm ISO}_{\rm rad}(\theta) \equiv 4\pi r^2 F^r_{\rm lab}$$

$$L^{\rm ISO}_{\rm mech}(\theta) \equiv 4\pi r^2 \left(\frac{1}{2}\rho v^2 v_r\right)$$

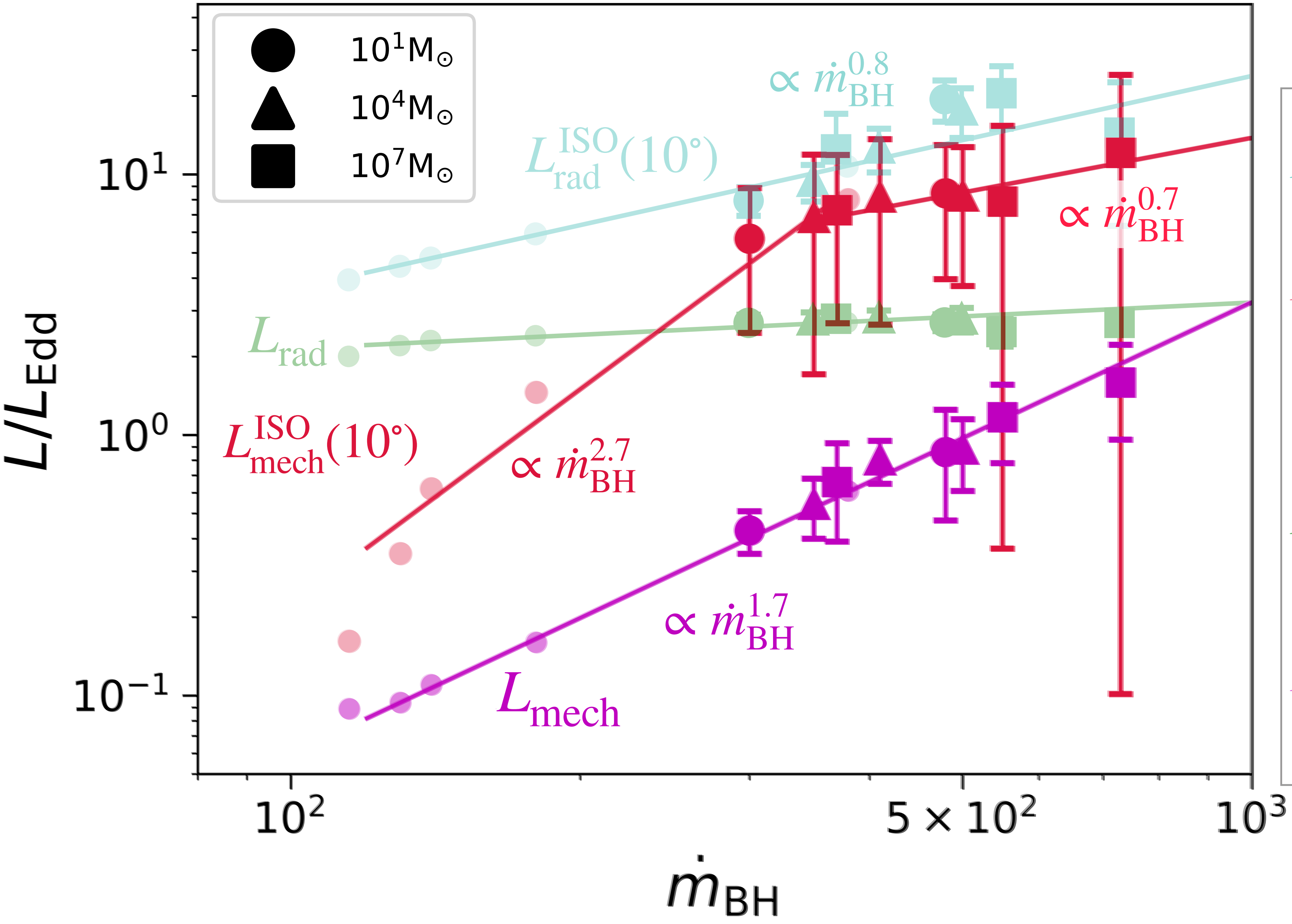
(Assuming $\theta \sim 10^\circ$)

$$L_{\rm rad} \equiv 4\pi \int_0^{\theta_{\rm surf}} r^2 F^r_{\rm lab} d\theta$$

$$L_{\rm mech} \equiv 4\pi \int_0^{\theta_{\rm surf}} r^2 \left(\frac{1}{2}\rho v^2 v_r\right) d\theta$$

- $\dot{m}_{\rm BH}$-dependence of outflow power larger than radiation ones
- **$\dot{m}_{\rm BH}$-dependence of luminosities is independent on the $m_{\rm BH}$**

$\dot{m}_{\rm BH}$-dependence of mechanical luminosity



$L^{\rm ISO}_{\rm rad}(\theta) \equiv 4\pi r^2 F^r_{\rm lab}$

$L^{\rm ISO}_{\rm mech}(\theta) \equiv 4\pi r^2 \left(\frac{1}{2}\rho v^2 v_r\right)$

(Assuming $\theta \sim 10^\circ$)

$L_{\rm rad} \equiv 4\pi \int_0^{\theta_{\rm surf}} r^2 F^r_{\rm lab} d\theta$

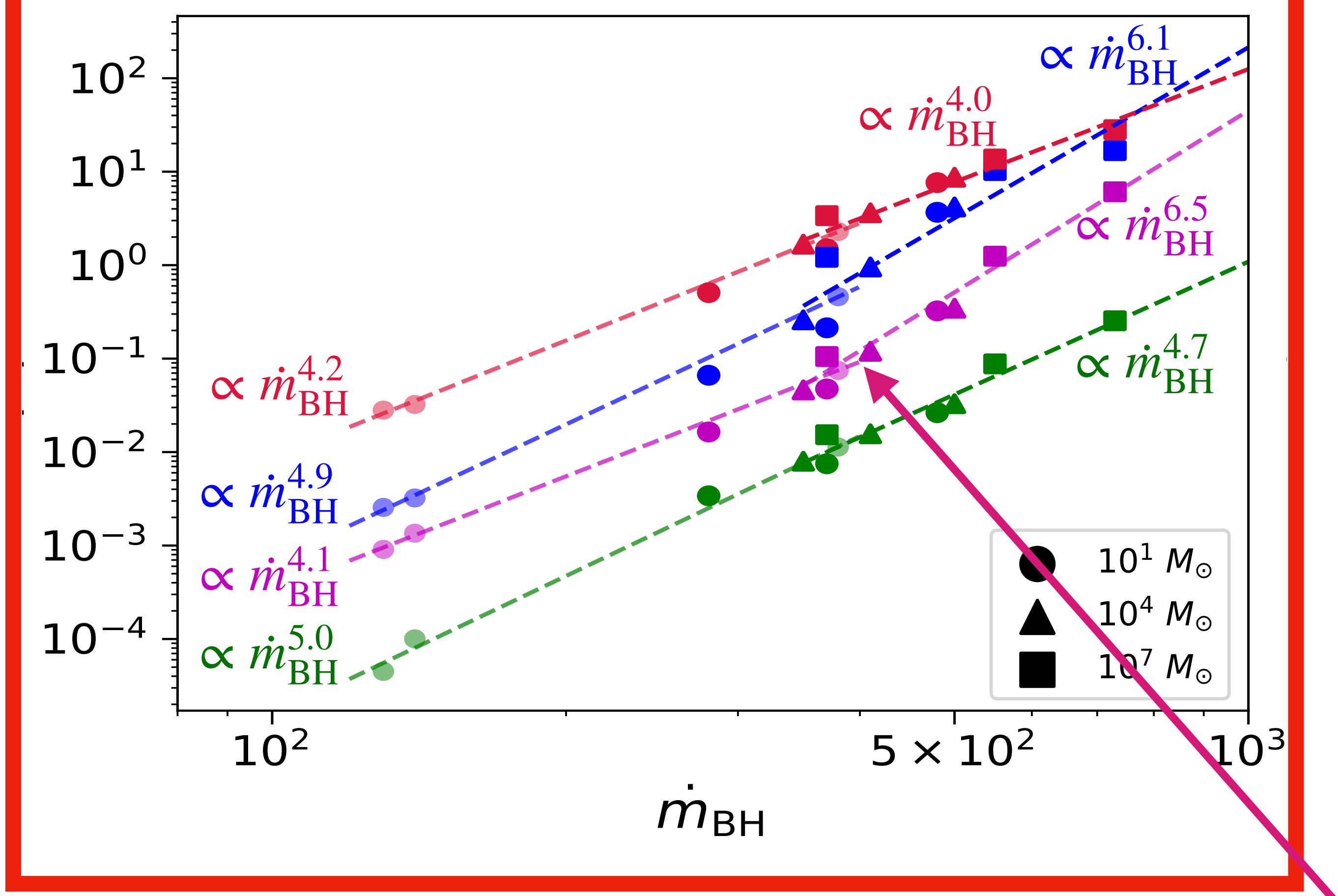
$L_{\rm mech} \equiv 4\pi \int_0^{\theta_{\rm surf}} r^2 \left(\frac{1}{2}\rho v^2 v_r\right) d\theta$

- **$\dot{m}_{\rm BH}$-dependence of $L^{\rm ISO}_{\rm mech}$ show broken-power law**

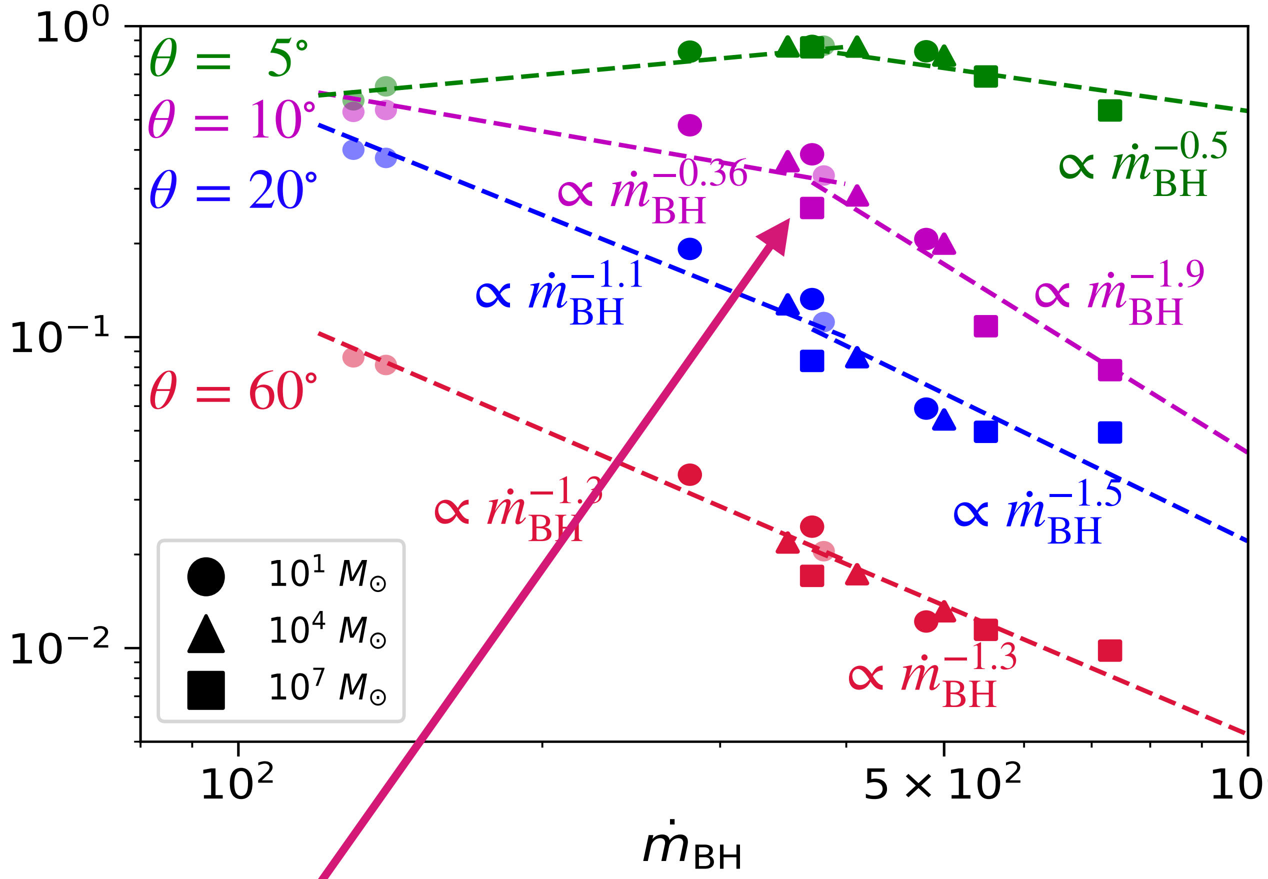
➡ $L^{\rm ISO}_{\rm mech}(10^\circ) \propto \dot{m}_{\rm BH}^{2.7}$ **($\dot{m}_{\rm BH} \le 400$), $\propto \dot{m}_{\rm BH}^{0.7}$ ($\dot{m}_{\rm BH} \ge 400$)**

Why does $\dot{m}_{\rm BH}$-dependence of $L^{\rm ISO}_{\rm mech}$ show a break ?

normalized **density**



normalized **velocity**



- For $\theta = 10^\circ$, the density and velocity also break at $\dot{m}_{\rm BH} \sim 400$

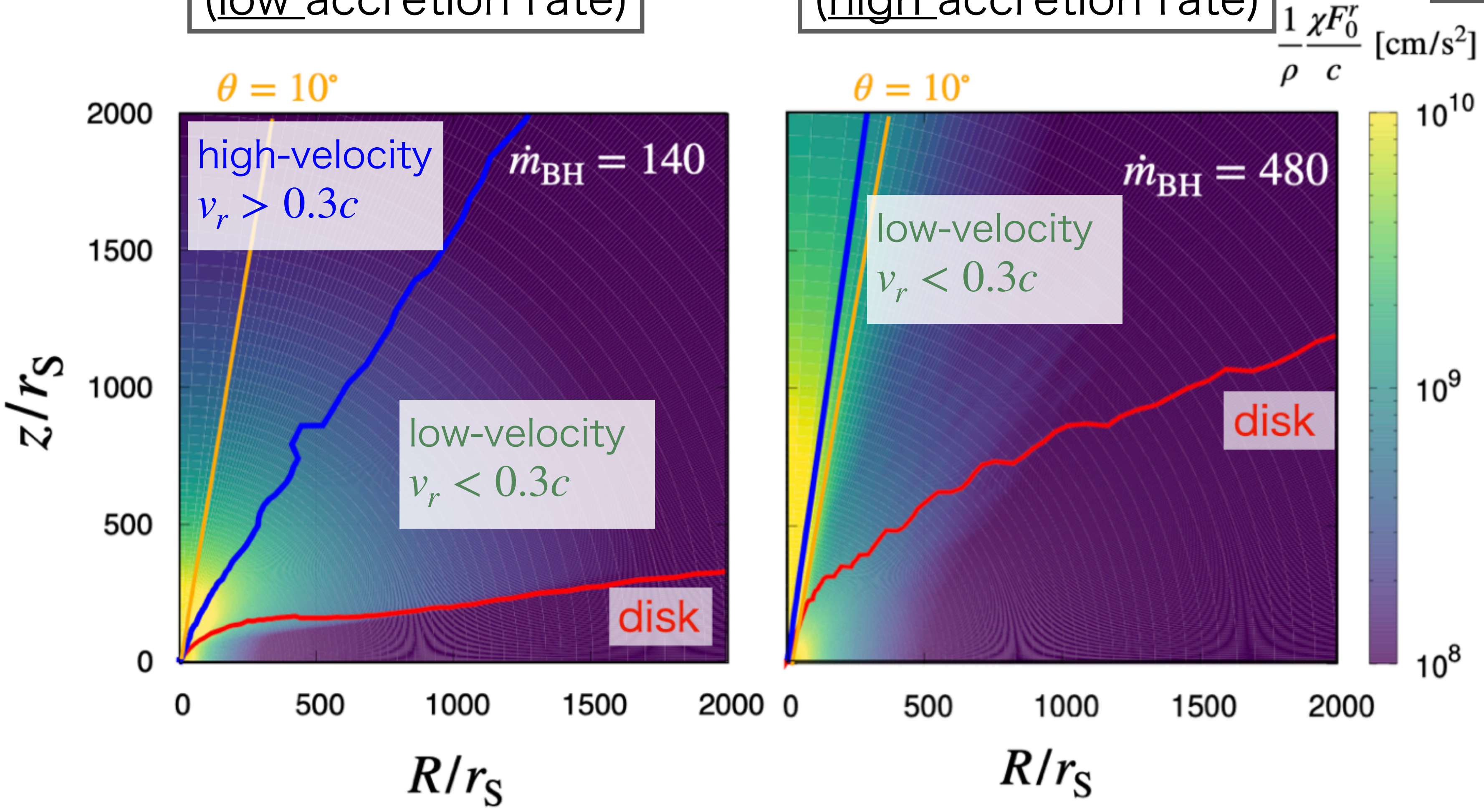
  ➡ **At high accretion rates, a slow and dense outflow is ejected in the polar direction**

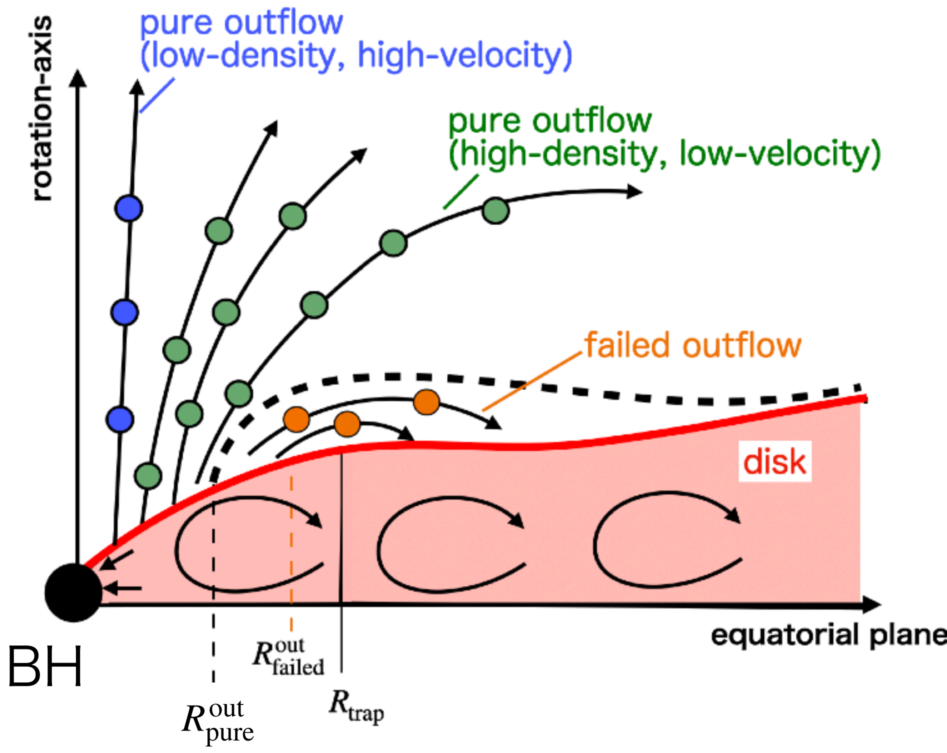
Disk inflation and outflow structure

below break
(low accretion rate)

above break
(high accretion rate)

χ :opacity, F_0^r :radiation flux at lab. frame





As mass accretion rate increases, the disk expands

➡Radiation is concentrated in the rotational axis

➡The ejection region of the high-velocity and low-density outflow is collimated in the polar direction

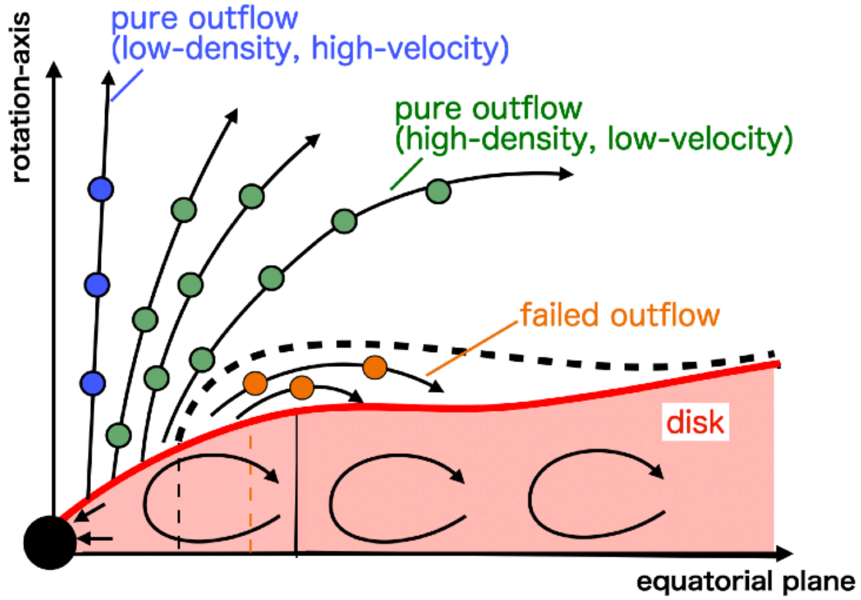
Summary

Aim & method

Perform global and high angular momentum, 2D axisymmetric RHD simulations to investigate

(1) large-scale outflow structure

(2) $(m_{\rm BH}, \dot{m}_{\rm BH})$-dependence of luminosities



Results

Q1. What is the large-scale outflow structure？

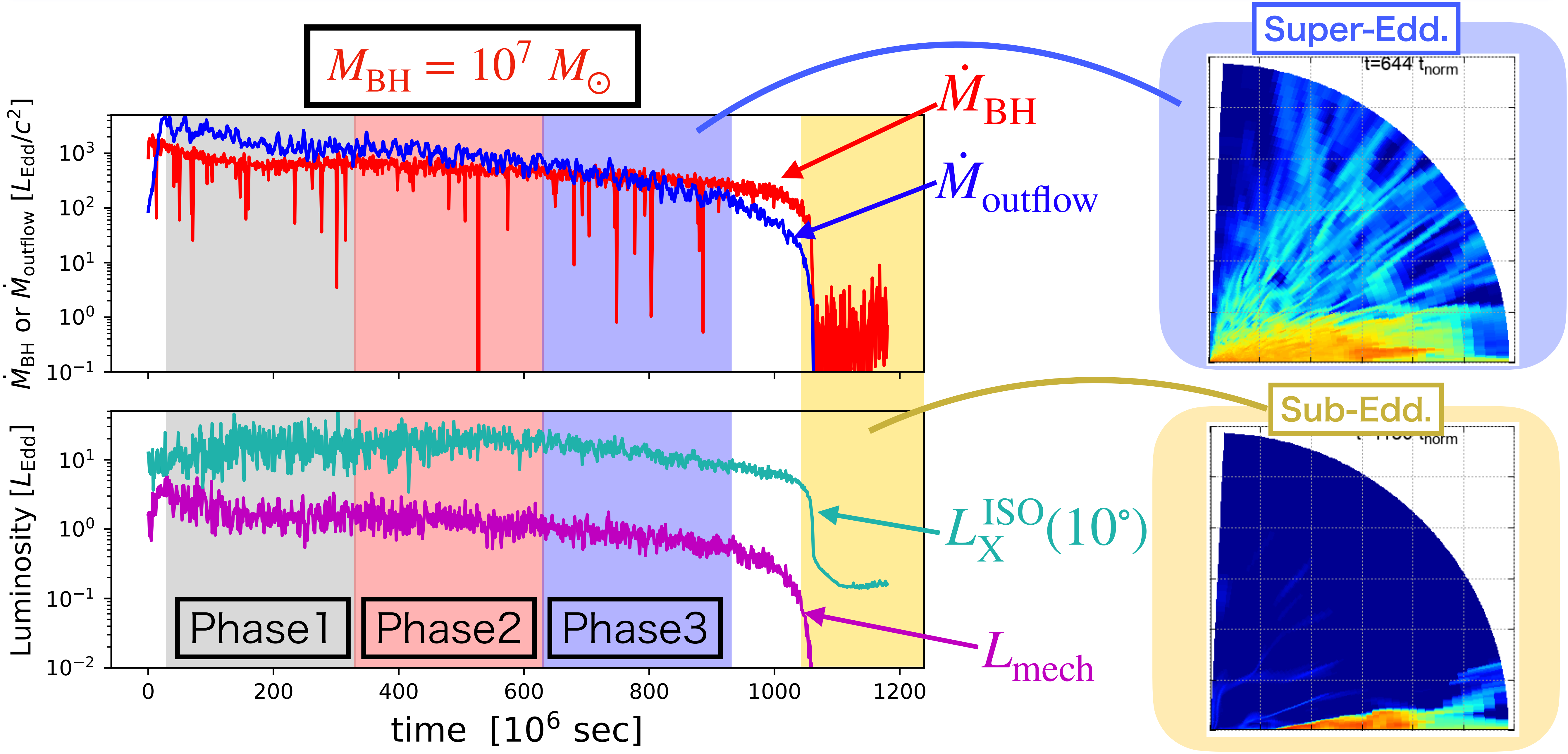
A1. Two types of outflow structures: Pure & Failed outflow

Q2. How do the radiation and mechanical luminosities depend on $(m_{\rm BH}, \dot{m}_{\rm BH})$?

A2.
- **$\dot{m}_{\rm BH}$-dependence of luminosities is independent of $m_{\rm BH}$**
- **$\dot{m}_{\rm BH}$-dependence of $L^{\rm ISO}_{\rm mech}(10^\circ)$ show broken-power law**

➡ $L^{\rm ISO}_{\rm mech}(10^\circ) \propto \dot{m}_{\rm BH}^{2.7}$ **(**$\dot{m}_{\rm BH} \leq 400$**),** $\propto \dot{m}_{\rm BH}^{0.7}$ **(**$\dot{m}_{\rm BH} \geq 400$**)**

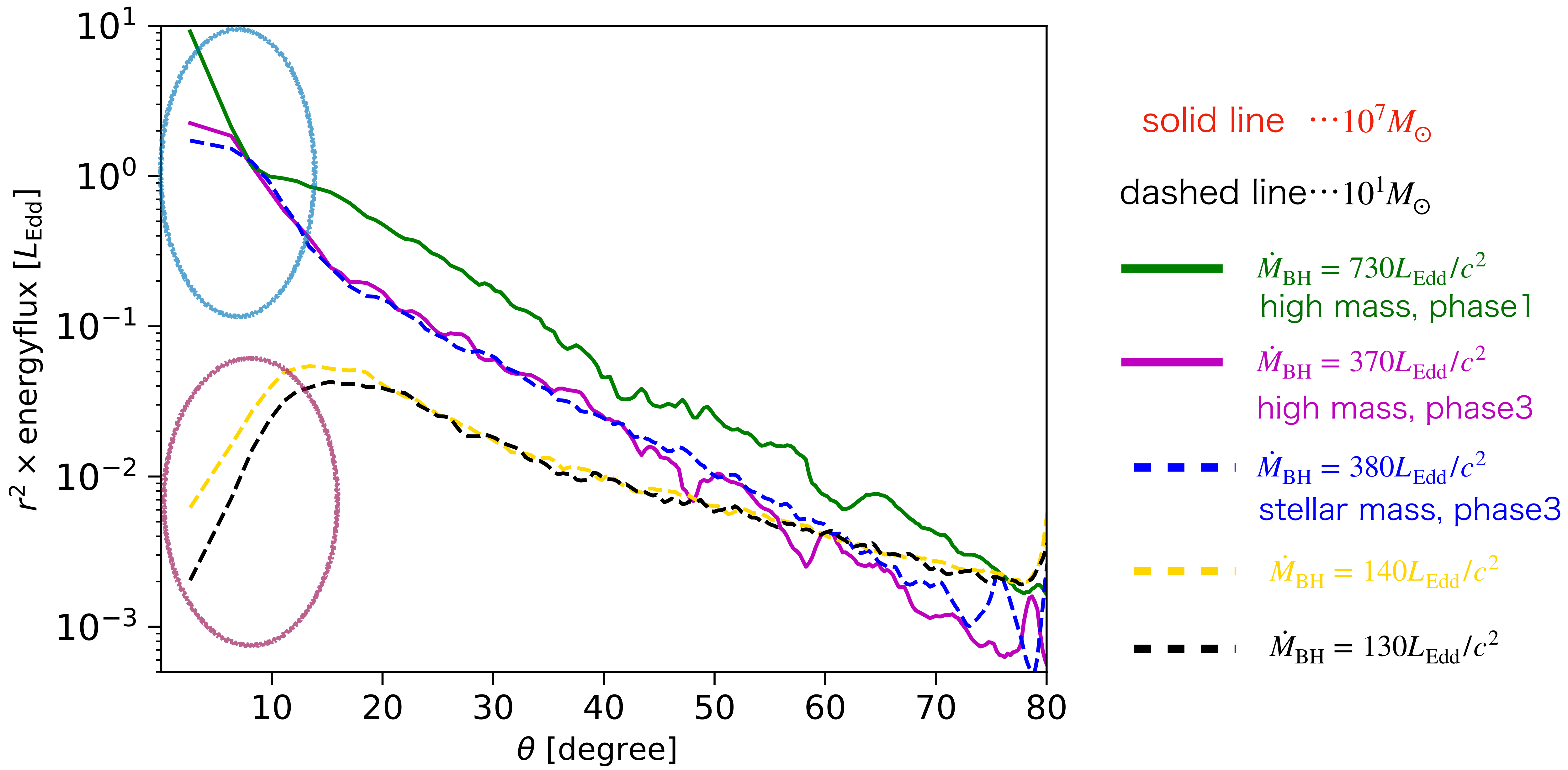
Time evolution of the accretion rate and luminosity



- Disk transitions between super-Edd. and sub-Edd. state

➡ We divided the super-Eddington state into three phase and analyzed physical quantities for each phase

θ dependence of Impact by the outflow

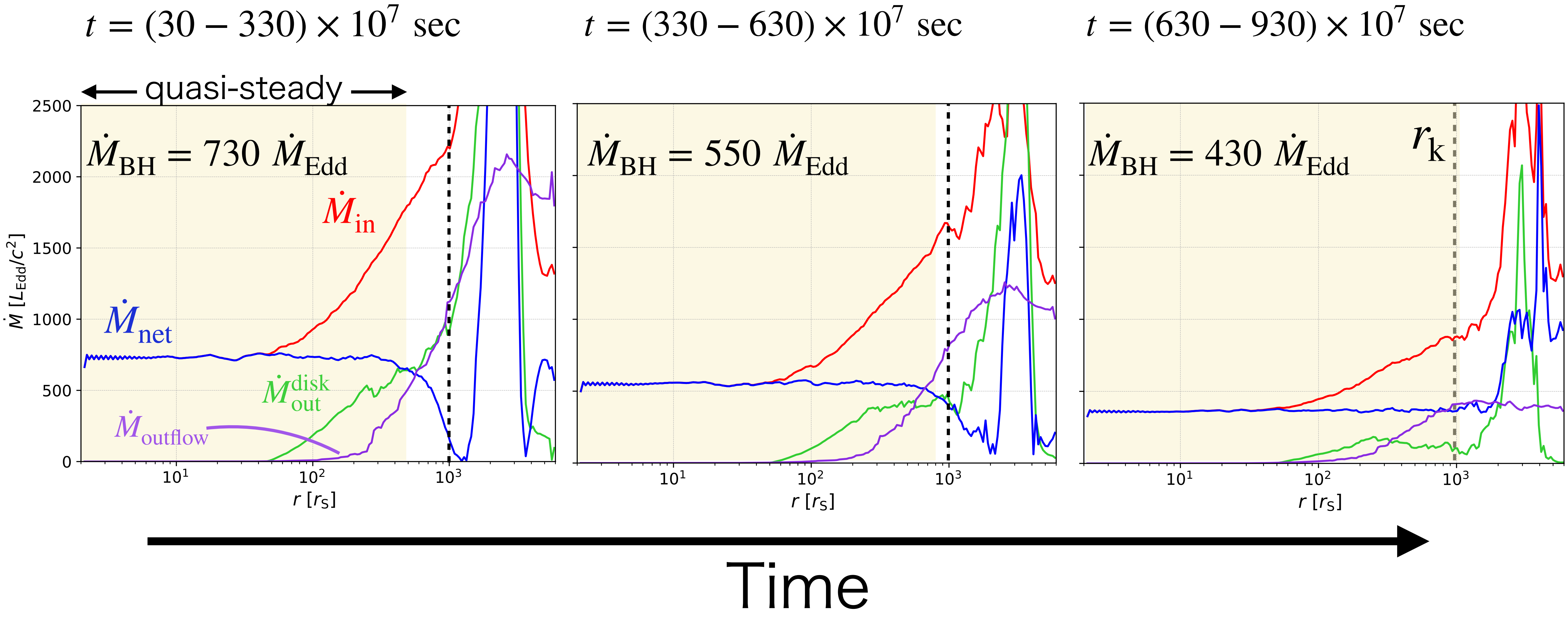


- Maximum angle of energy flux approaches poleward as $\dot{M}_{\rm BH}$ increases
- Two component of outflow at polar axis

  high-velocity & low-density outflow (low accretion rate)

  low-velocity & high-density outflow (high accretion rate)

Time evolution of flow



$t = (30 - 330) \times 10^7$ sec

$t = (330 - 630) \times 10^7$ sec

$t = (630 - 930) \times 10^7$ sec

- Phase1: Large amounts of outflow eject from far away $(r > r_{\rm K})$
- Phase3: Outflow eject from inside $r_{\rm K}$