ブラックホール超臨界降着
モーメンタムフィードバックの効果

Super-Eddington accretion to black holes: Effects of mechanical feedback

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Supermassive black holes (SMBHs) in high-z Universe

Observation

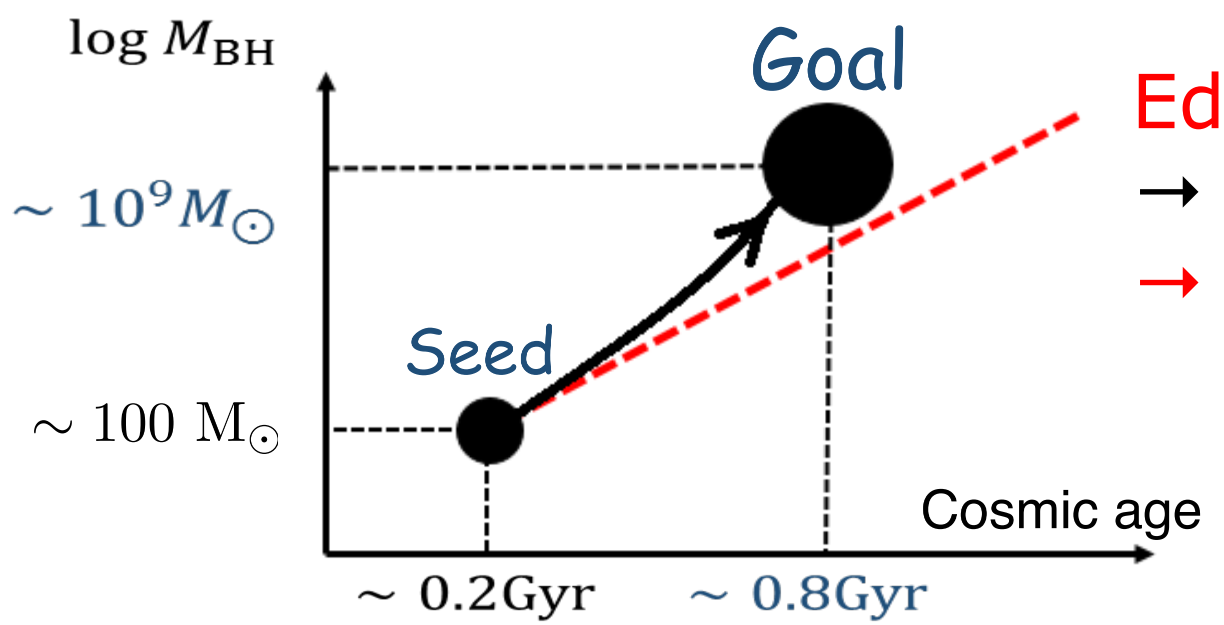
Cosmic age < 1Gyr (z > 6), SMBHs with $M_{\rm BH} \gtrsim 10^9\ {\rm M}_\odot$

(Mortlock et al. 2011)

One possible pathway to high-z SMBHs: Rapid accretion

BH seeds (light seed $\sim 100\ {\rm M}_\odot$, heavy: $\sim 10^3 - 10^5\ {\rm M}_\odot$)

Rapid growth via gas accretion



Eddington limited growth

→ growth time > Cosmic age of SMBHs

→ Super-Eddington accretion is required.

Possibility of super-Eddington accretion

- Low mass BH : Eddington limited

Gas accretion → Disk → Radiation feedback

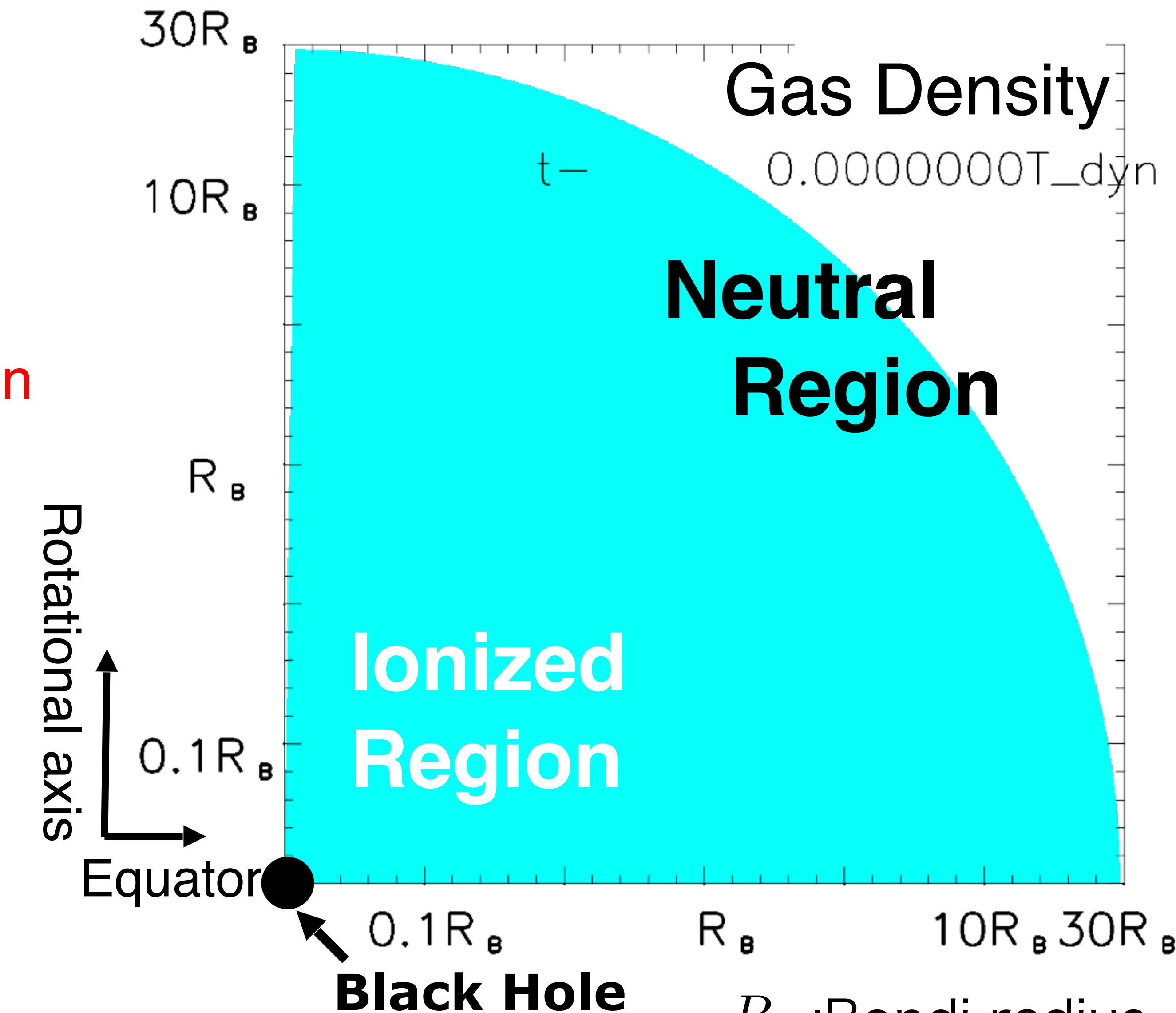
Hot & Ionized region → Suppression of Accretion

$$\dot{M} \propto M_{\rm BH}^2 n_\infty T_\infty^{-3/2}$$

Sub-Eddington accretion

$$\dot{M} \le L_{\rm Edd}/(\eta c^2)$$

(e.g., Milosavljevic et al. 2009)



$R_{\rm B}$:Bondi radius

- High mass BH $M_{\rm BH} \gtrsim 10^4 M_\odot$

Bondi radius $R_{\rm B} = GM_{\rm BH}/c_\infty^{3/2}$ > Ionization radius $R_{\rm HII}$ (Inayoshi et al. 2016)

$$\left(\frac{M_{\rm BH}}{10^4\ {\rm M_\odot}}\right)\left(\frac{n_\infty}{10^5\ {\rm cm^{-3}}}\right) \gtrsim \left(\frac{T_\infty}{10^4\ {\rm K}}\right)^{3/2}$$

High BH mass or high gas density

→ **Transition** to Super-Eddington accretion phase.

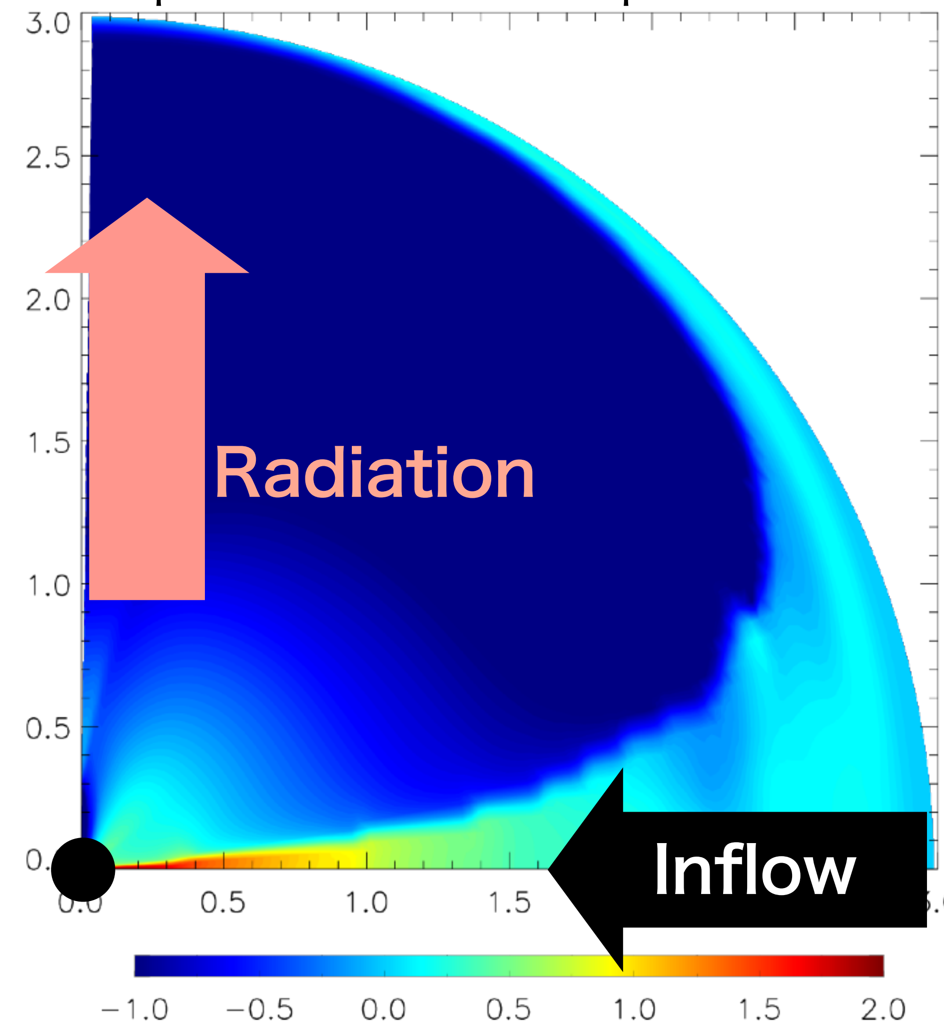
Our study: Effects of Mechanical feedback

Previous studies on super-Eddington transitions do not include mechanical feedback.

cf. studies on accretion flows @ Bondi scale (e.g., Novak+2012, Ciotti+2017)

cf. effects of jets in atomic-cooling halo (Regan+2019)

Gas Density distribution exposed to anisotropic radiation



- Mechanical feedback has the potential to shut off the inflowing gas and blow out the surrounding medium.
- Bipolar outflows
  → Anisotropic flow structure forms
  → Inflowing motion round the equator?
  cf. anisotropic radiation feedback cases (Sugimura+2017, Takeo+2018)

Our aim;

Derivation of the criterion required for the super-Eddington transition

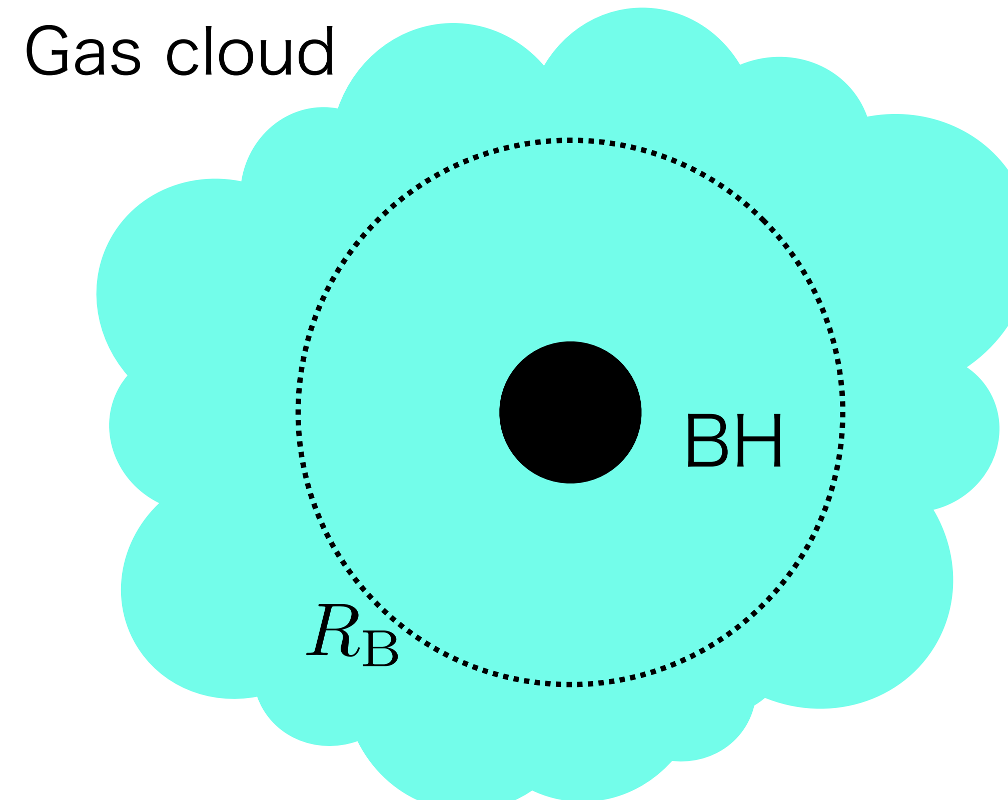
Simulation setups

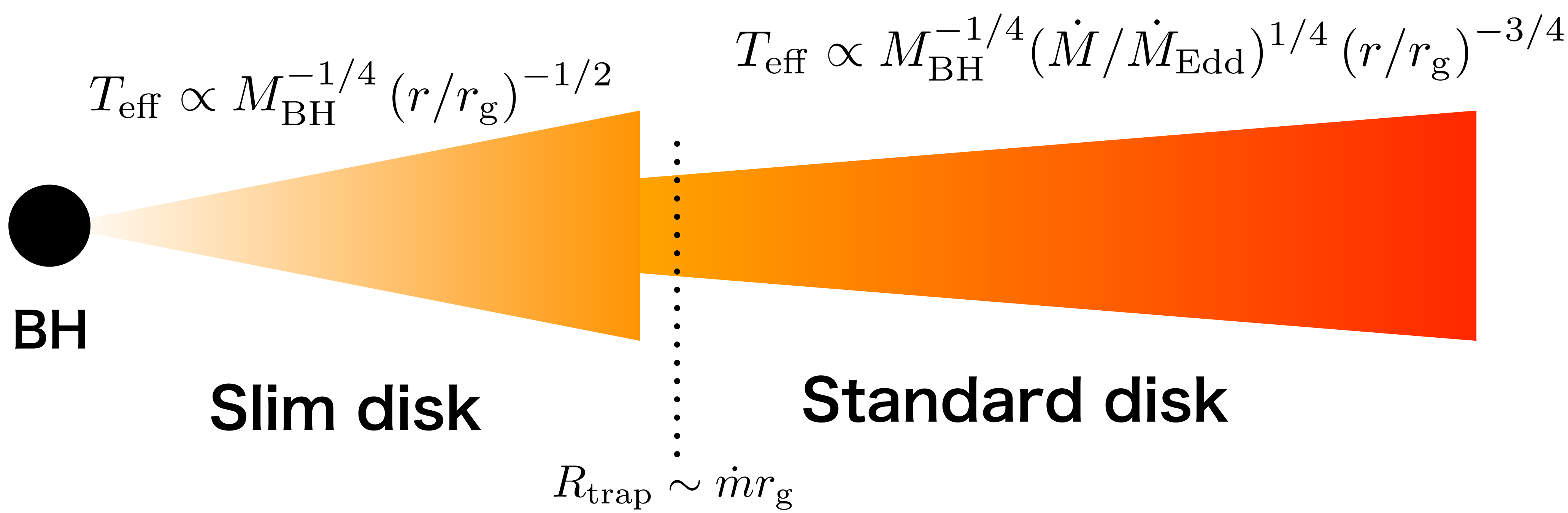
BH embedded in an uniform, metal-free gas cloud.
Two-dimensional radiation hydrodynamical simulation.

- Disk spectrum model as a function of $\dot{m}$ and $M_{\rm BH}$ (Watarai 2006)
- Computational domain

$$0.006R_{\rm B} \le r \le 6R_{\rm B}$$

- Frequency range $13.6\ {\rm eV} \le h\nu \le 100\ {\rm keV}$
- Isotropic radiation field





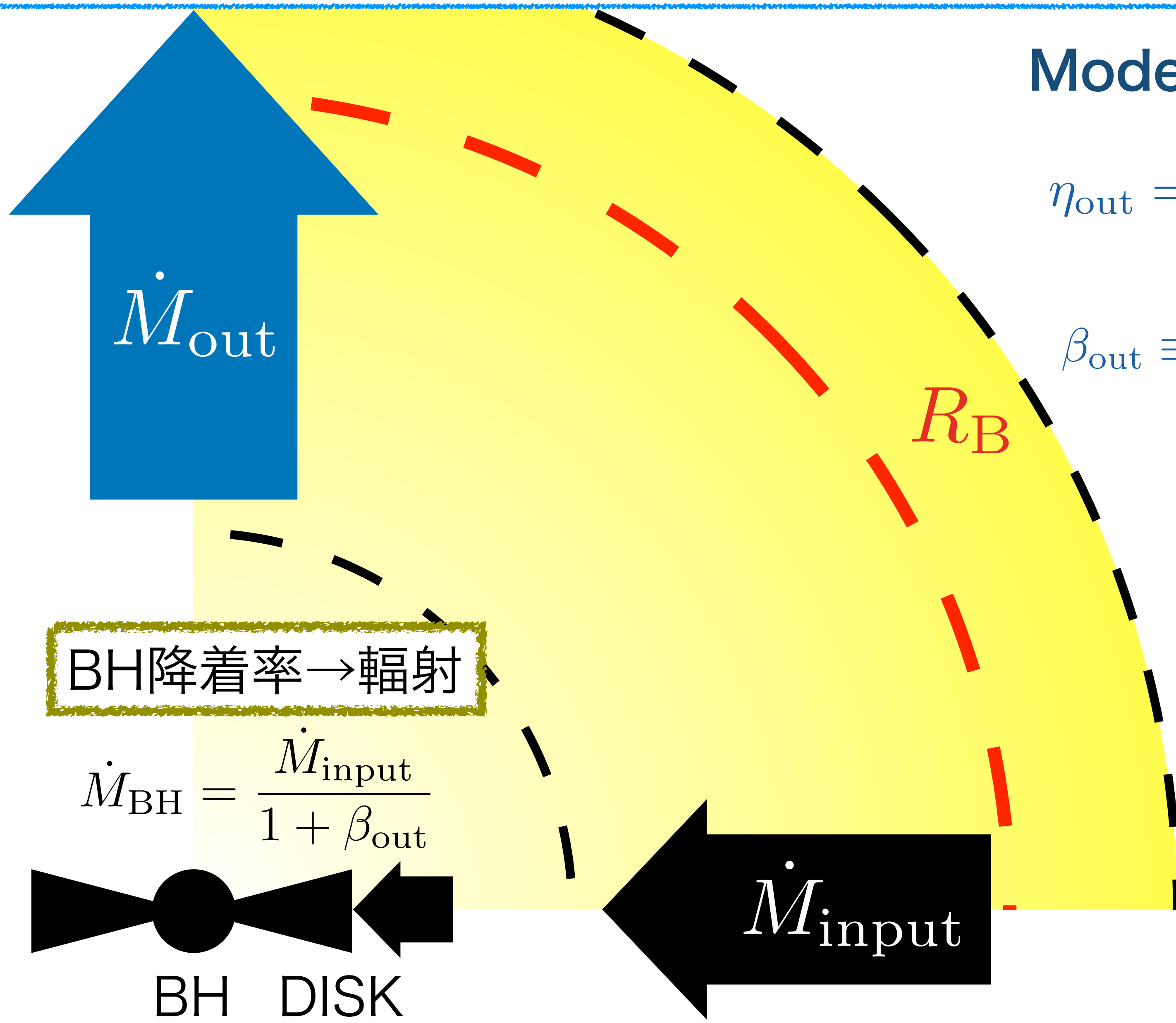
Outflow model

$$\dot{M}_{\rm out} = \frac{\beta_{\rm out}}{1+\beta_{\rm out}} \dot{M}_{\rm input}$$ Outflow mass rate

$$\dot{P}_{\rm out} = \dot{M}_{\rm out} v_{\rm out}$$ Outflow kinetic power

$$L_{\rm out} \equiv \eta_{\rm out} \dot{M}_{\rm BH} c^2 = \frac{1}{1+\beta_{\rm out}} \eta_{\rm out} \dot{M}_{\rm input} c^2$$ Outflow kinetic energy

Ostriker et al. (2010)



Model parameters;

$$\eta_{\rm out} = \frac{\beta_{\rm out}}{2} \frac{v_{\rm out}^2}{c^2}$$: Outflow energy efficiency

$$\beta_{\rm out} \equiv \frac{\dot{M}_{\rm out}}{\dot{M}_{\rm BH}}$$: Mass loading factor (outflow/accretion)

$$\beta_{\rm out} = 1 \rightarrow \dot{M}_{\rm out} = \dot{M}_{\rm BH} = \frac{1}{2} \dot{M}_{\rm input}$$

$v_{\rm out}$: Outflow velocity 1,000km/s

Outflow model

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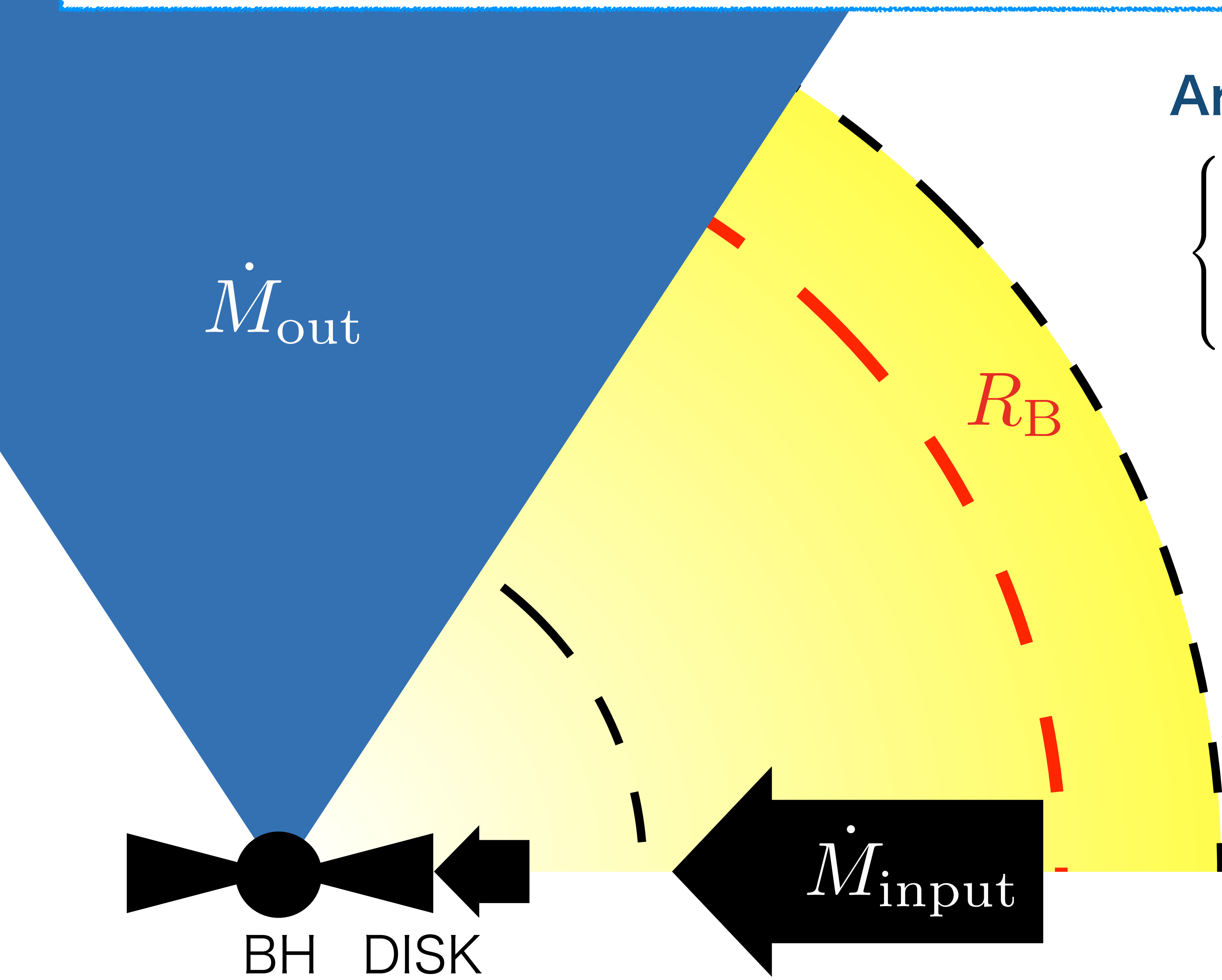
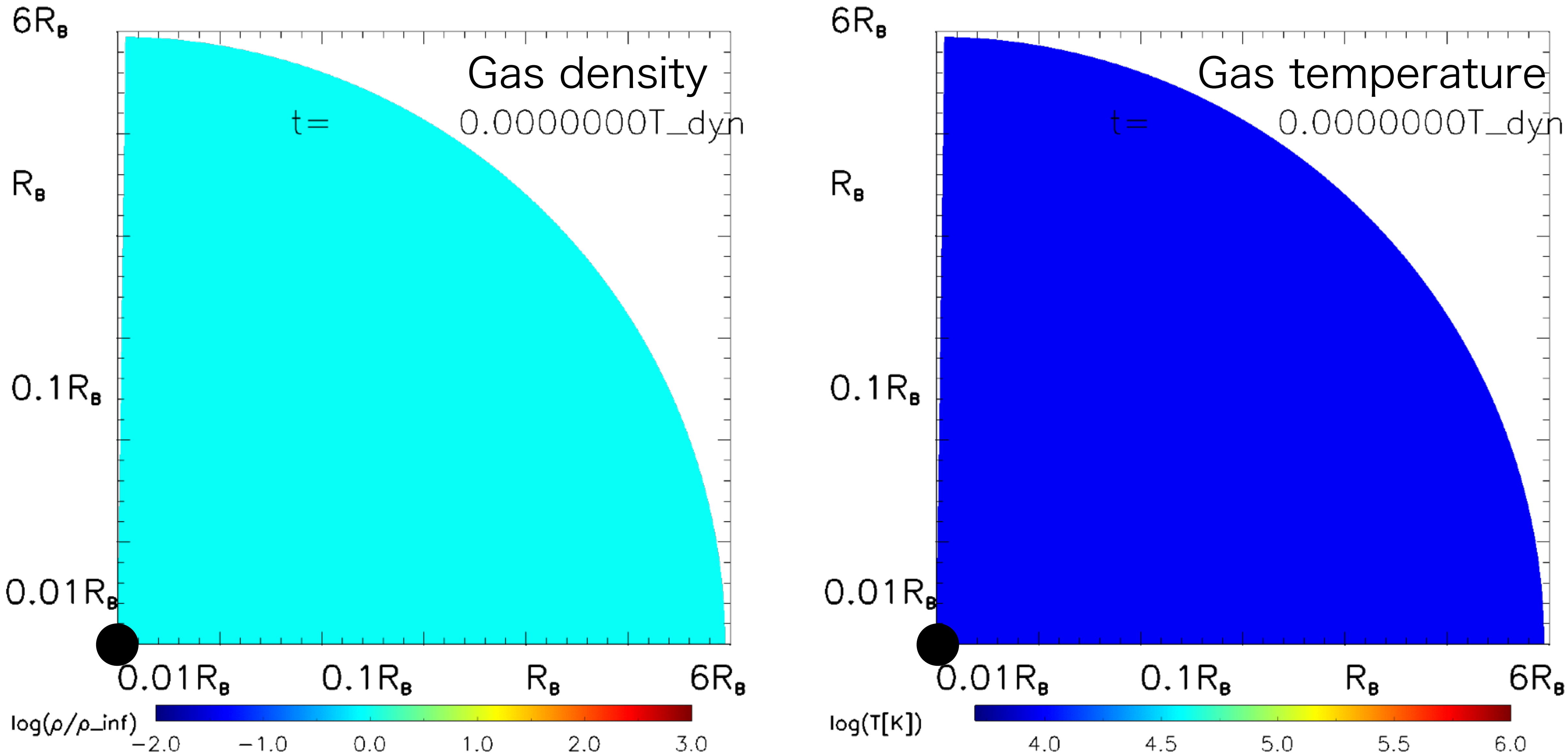


Angular dependence;

$$\begin{cases} 1 & , \quad 0^\circ \leq \theta \leq \tilde{\theta}_{\rm shadow} \\ \exp\left(-\left(\frac{\theta - \tilde{\theta}_{\rm shadow}}{\delta\theta}\right)^2\right) & , \quad \tilde{\theta}_{\rm shadow} \leq \theta \leq 90^\circ \end{cases}$$

cf. Sugimura+2017

Results: Time evolution of flow structure (Outflow angle $\theta_{\rm out} = 80^\circ$)



- Isotropic radiation → Spherical ionized region
- Outflowing region along the polar axis / Inflowing region around the equator
- Ionization radius is confined within the Bondi radius

  → Ionized region shrinks

  → **Transition**

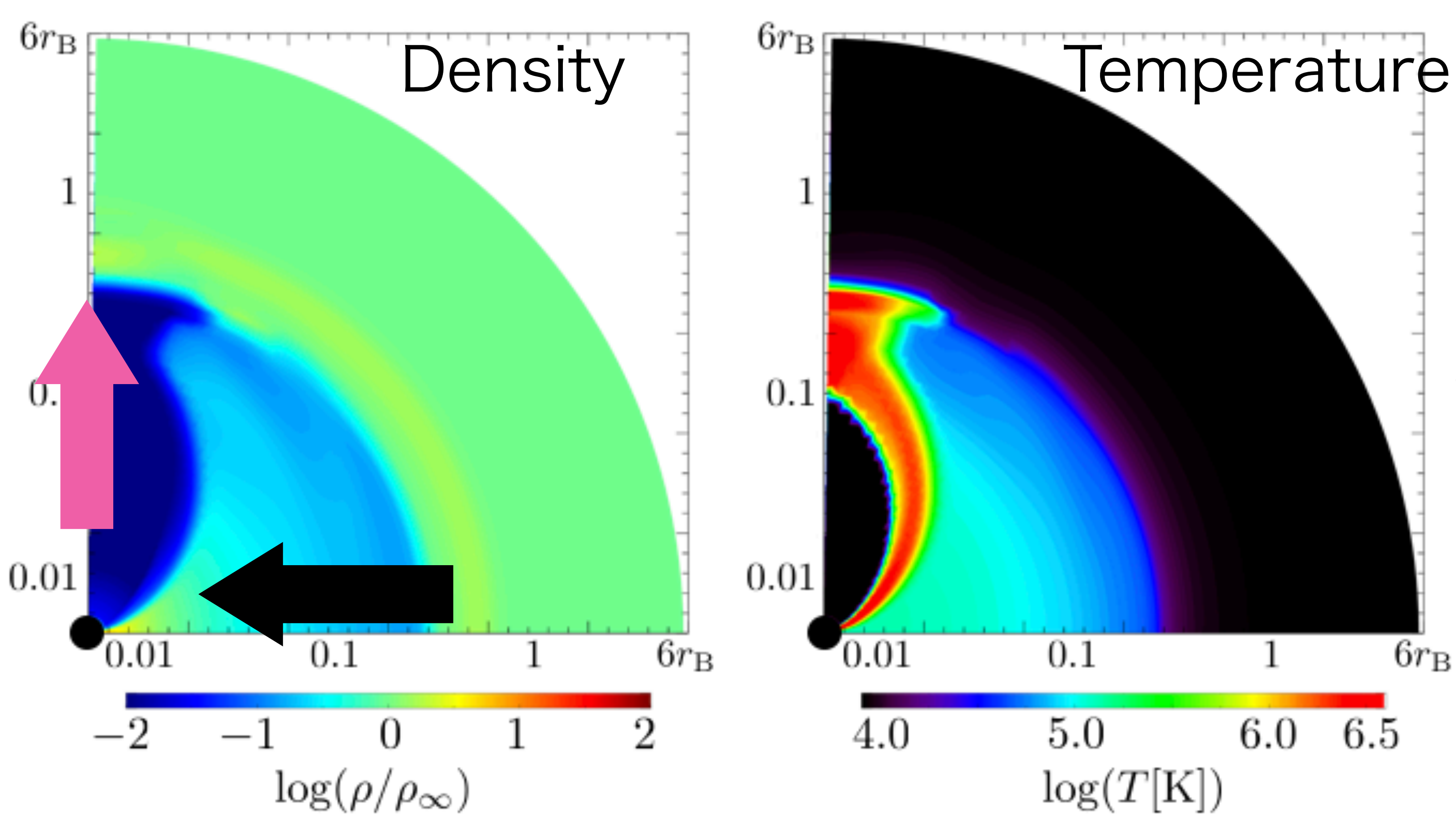
Radial structure of outflows along the rotational axis

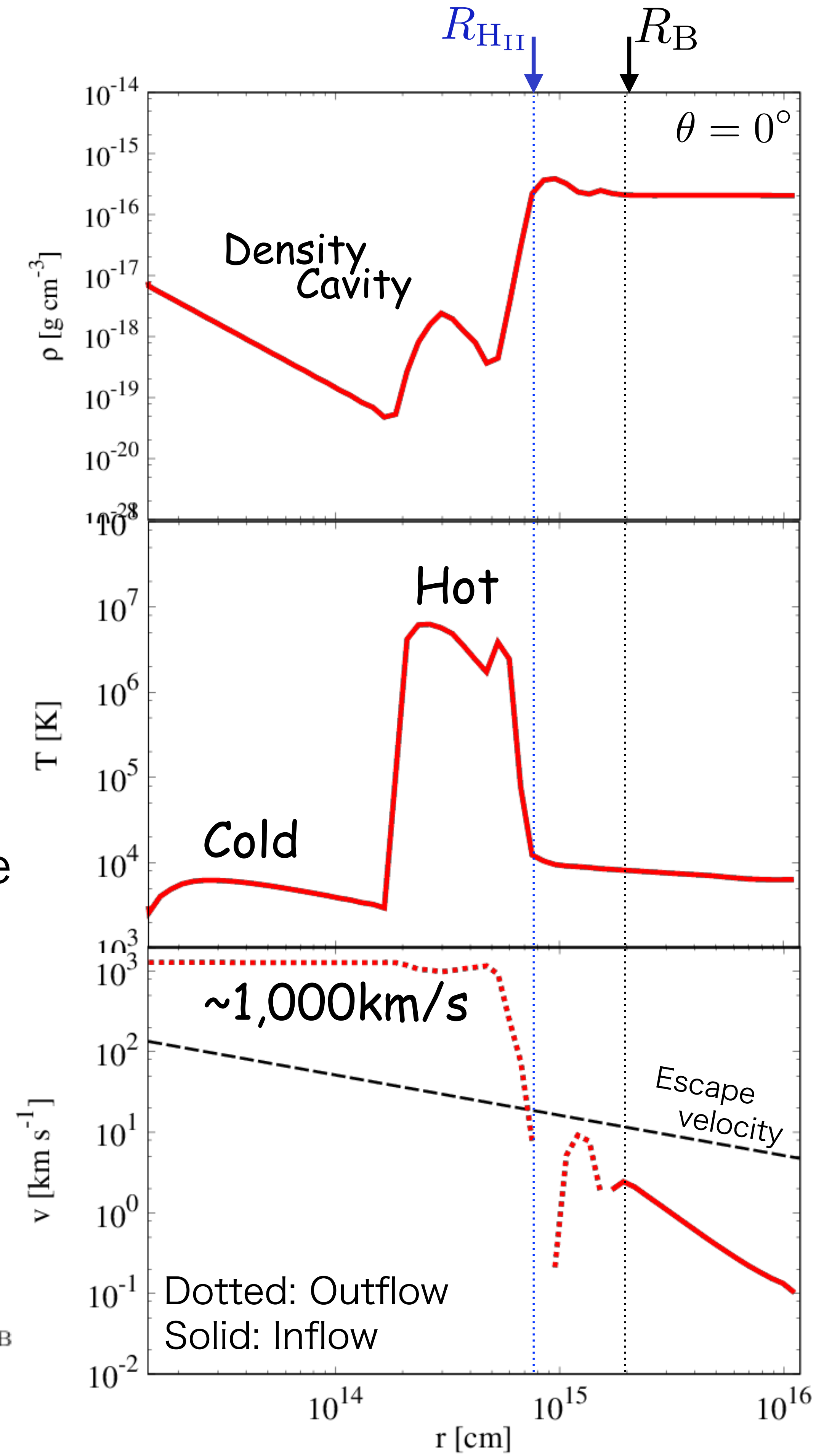
- Ionized gas is evacuated by outflows.
- Cold region due to expansion cooling: $r \lesssim 2\times10^{14}$ cm

  Hot region due to shock: $2\times10^{14} \lesssim r \lesssim 10^{15}$ cm
- Outflow speed is nearly constant.

$$v_{\rm out} = 1,000\ {\rm km\ s^{-1}}$$

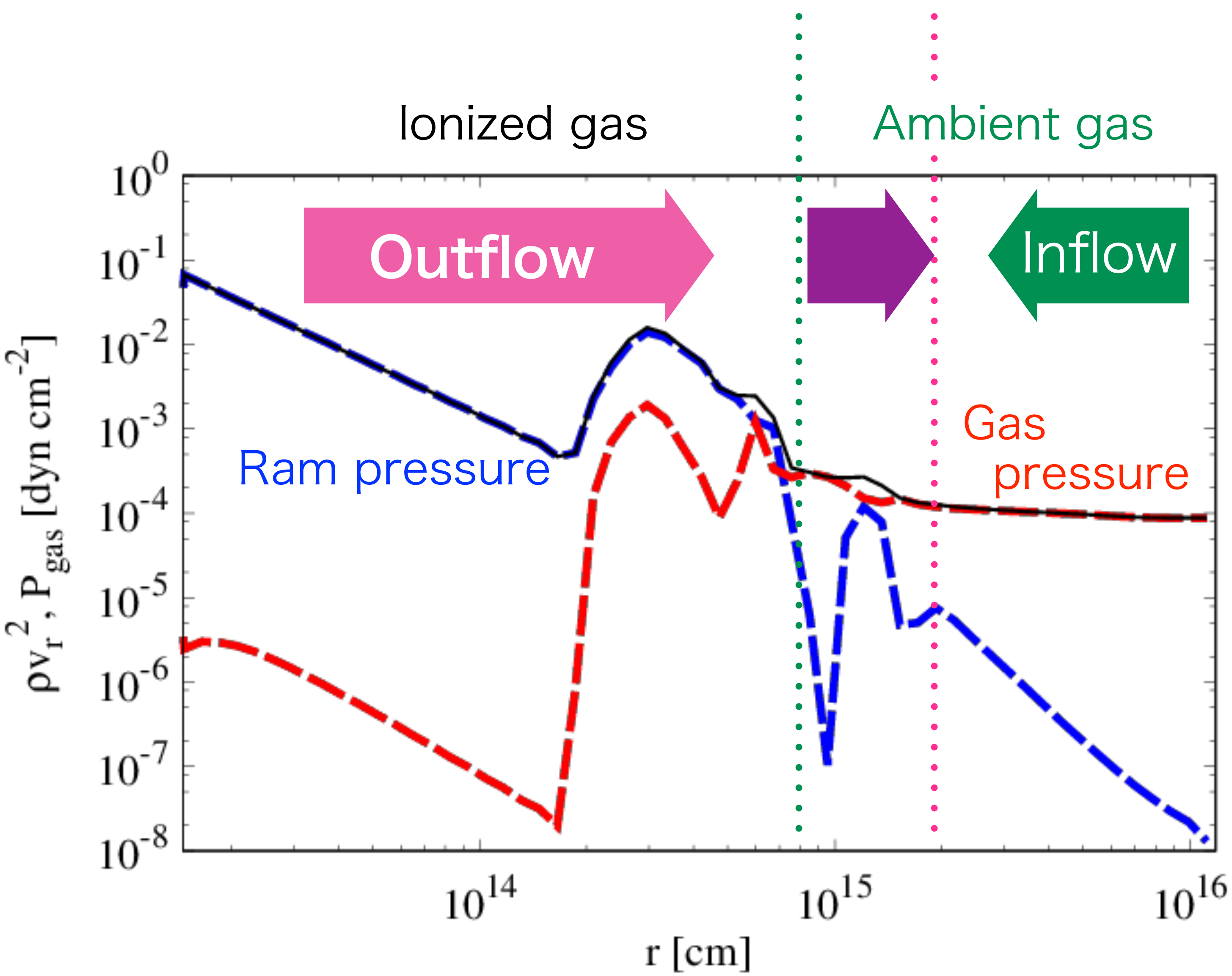
(cf. $v_{\rm esc} = 134\ {\rm km\ s^{-1}}$)

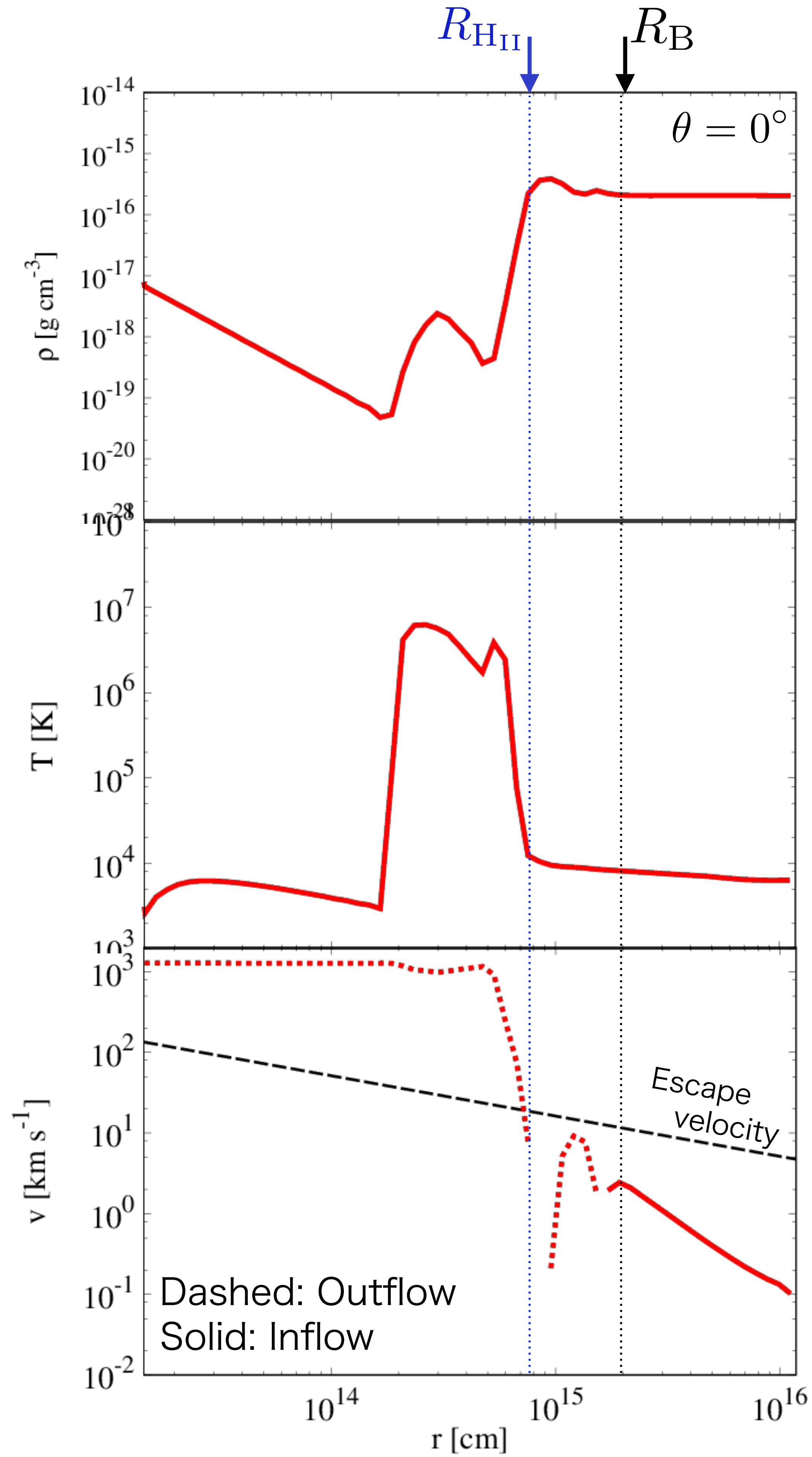




Radial structure of outflow velocity along the rotational axis

- Fast outflow with 1,000 km/s.
- Mild outflowing region driven by pressure gradient.
- Inflowing motion by the BH gravity.





Radial structure of outflows around the equatorial plane

Same as radiation-regulated accretion flows.

e.g., Park & Ricotti (2011,2012)

- Gas is photo heated up to $\sim 10^5\ \mathrm{K}$
- Ionized gas is depleted due to both accretion to the central BH and outflow driven by thermal pressure.

Gas depletion

↓

Accretion rate, Luminosity ↓

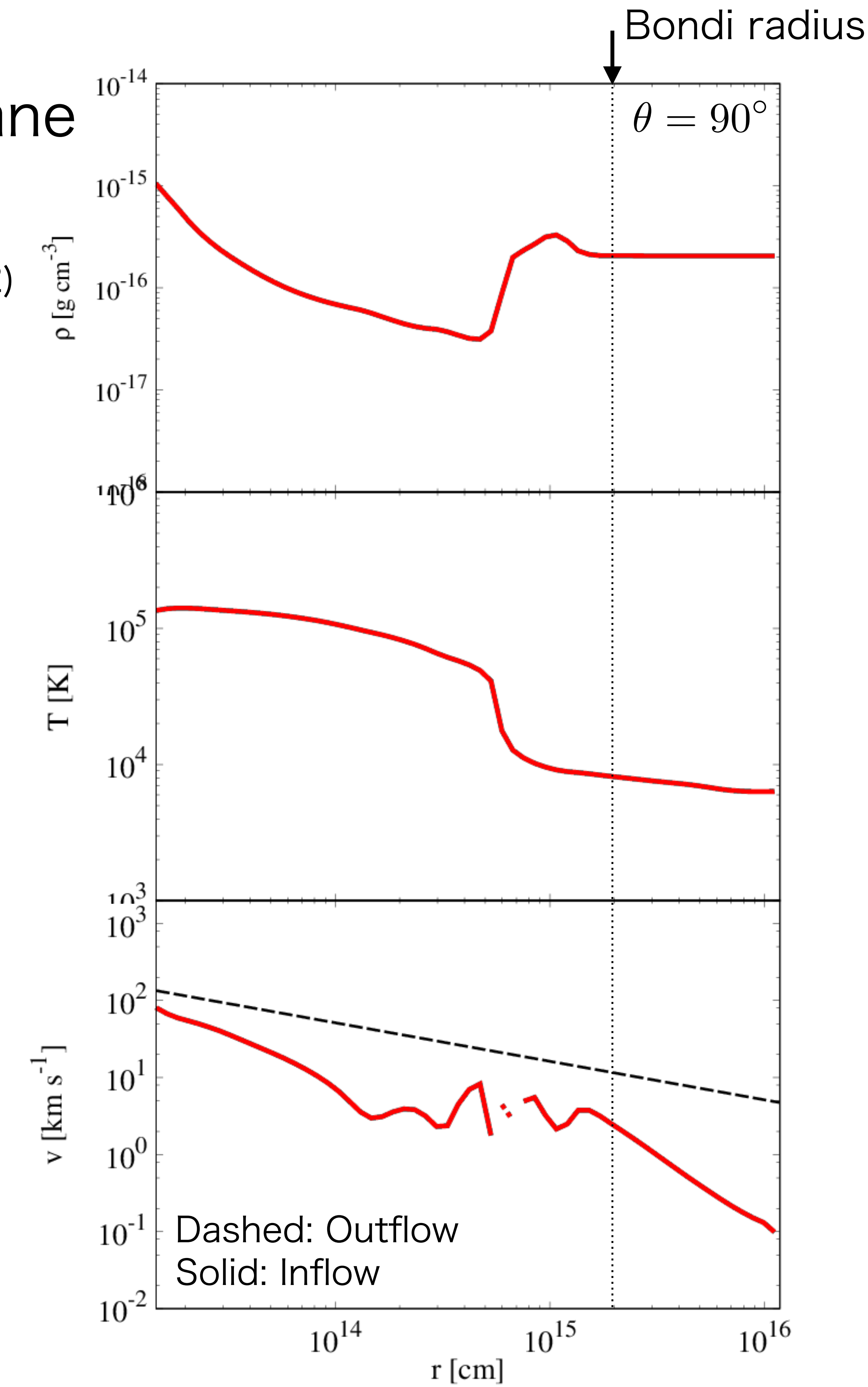
↓

Dense gas at the ionization front falls into the central BH.

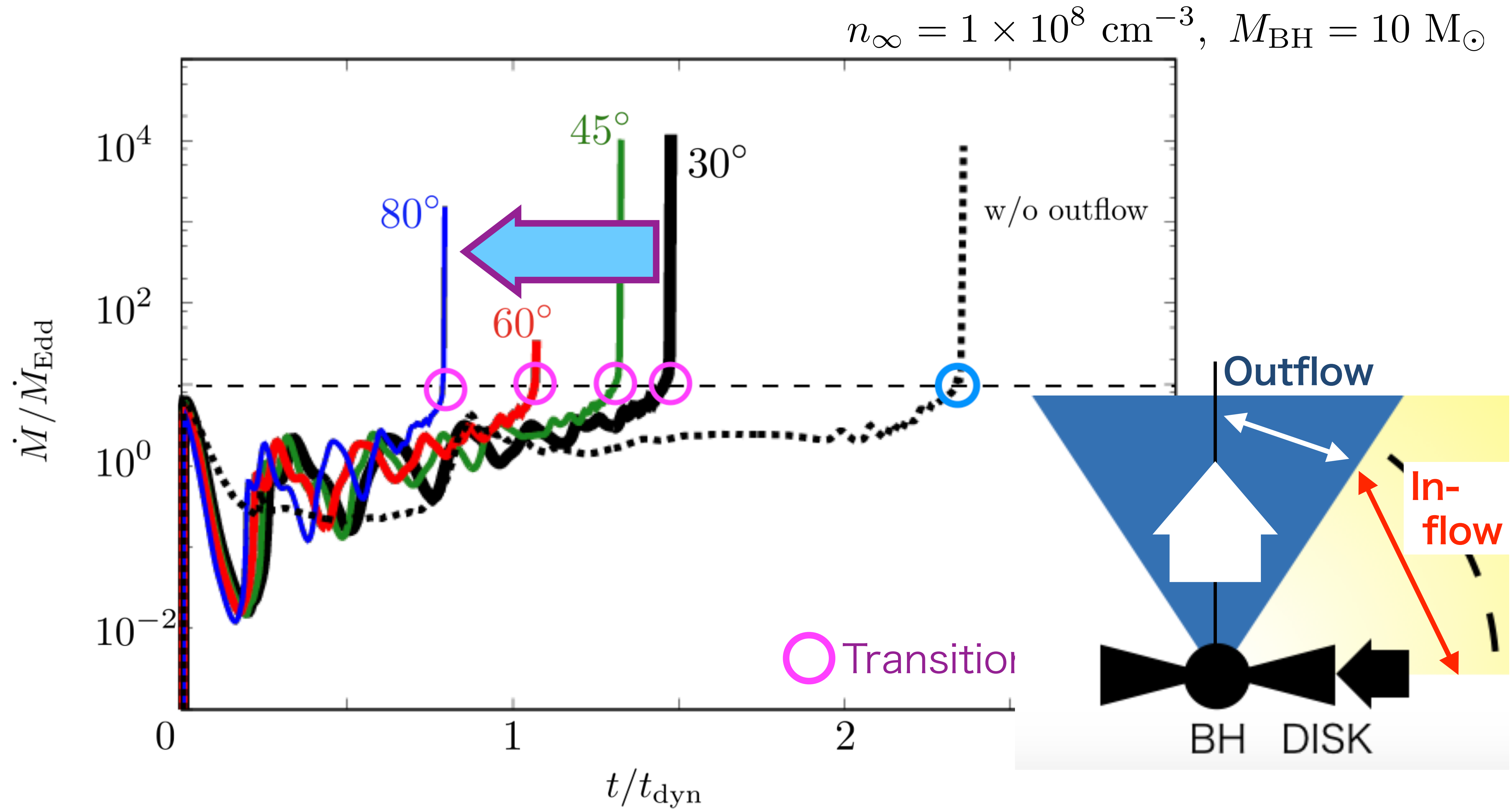
↓

Accretion rate, Luminosity ↑

Episodic Accretion



Outflow opening angle ↗ → Transition epoch becomes earlier

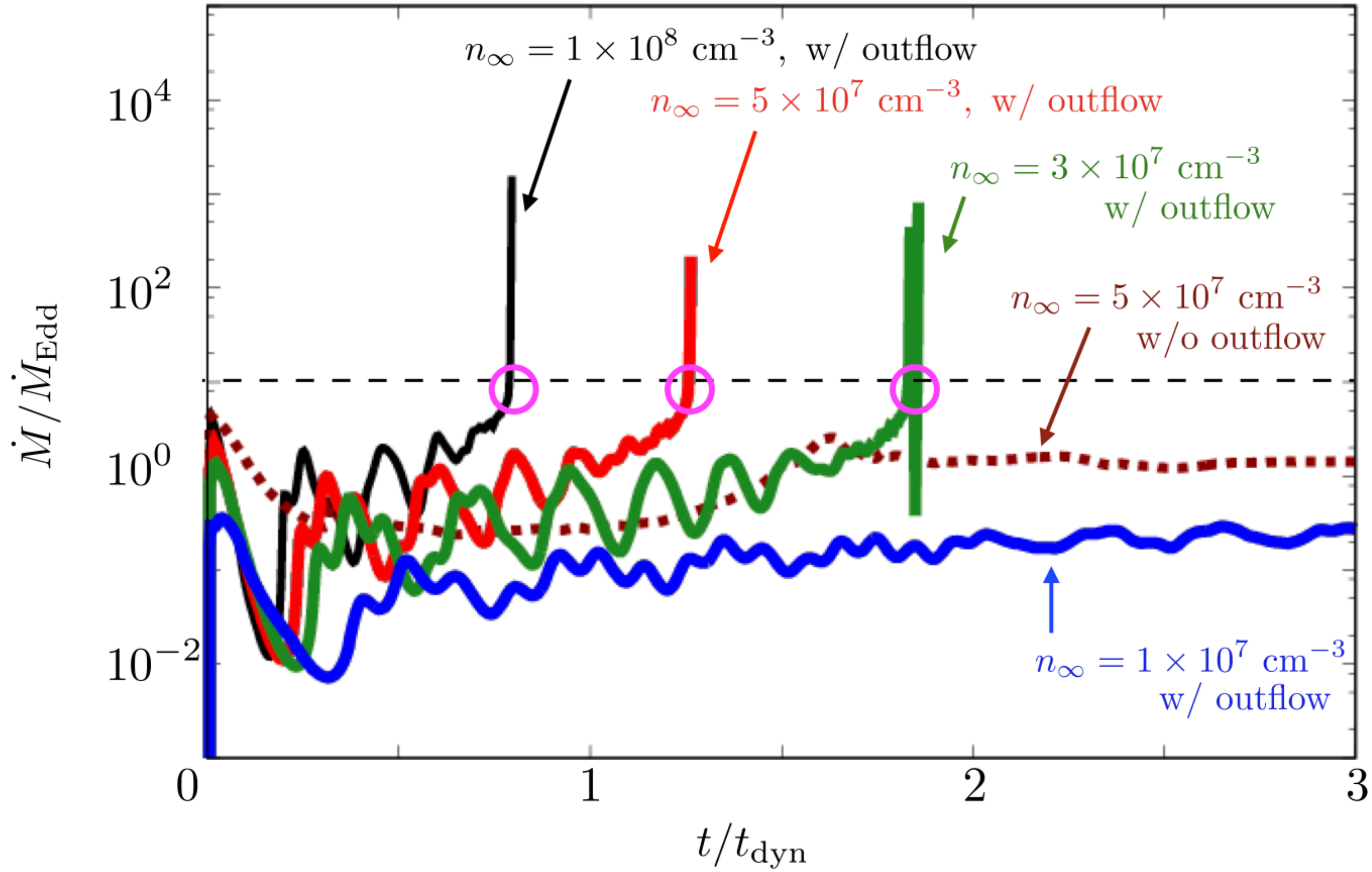


- Outflow opening angle ↗ → Solid angle of the inflowing region ↘
- Mass inflow rate reduces due to outflows $\dot{M}_{\rm BH} = (1+\beta_{\rm out})^{-1}\dot{M}_{\rm input}$

BH accretion rate $\dot{M}_{\rm BH}$ ↘ → Radiation feedback ↘ → $R_{\rm H_{II}}$ ↘ → **Transition**

Transition criterion is alleviated owing to outflows

$M_{\rm BH} = 10\ {\rm M}_\odot$
$\dot{M}_{\rm out}/\dot{M}_{\rm BH} = 1$
$\theta_{\rm out} = 80^\circ$



Critical density above which the transition occurs

$n_\infty \gtrsim 1 \times 10^8\ {\rm cm}^{-3}$ (w/o outflow)

$n_\infty \gtrsim 3 \times 10^7\ {\rm cm}^{-3}$ (w/ outflow)

Transition criterion is alleviated owing to outflows

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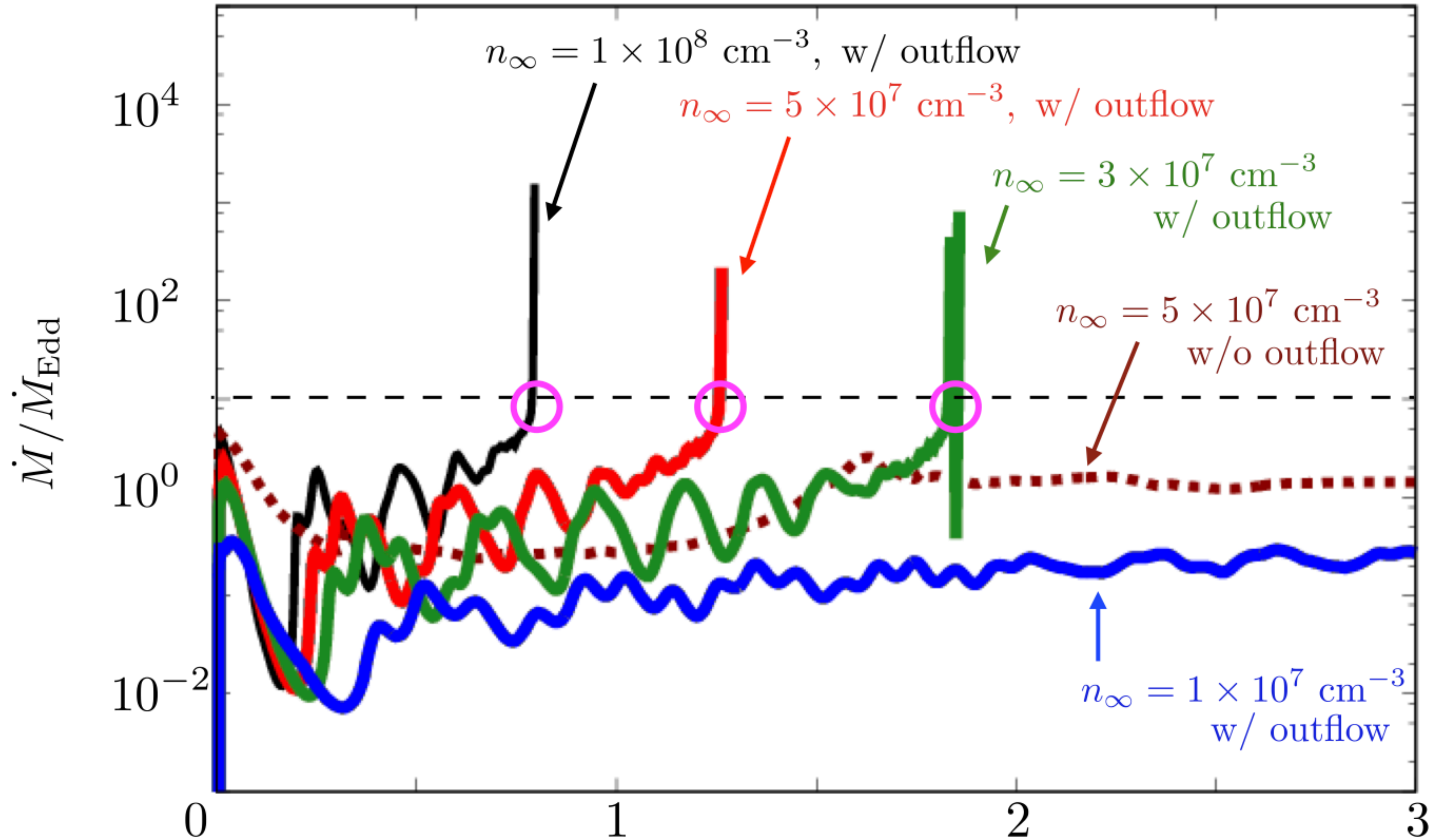

- Solid angle of inflowing region $\Delta\Omega_{\rm in}$ ↘
- Mass loss due to outflows

→ Ionization radius ↘ $\dfrac{r_{\rm HII}^{\rm out}}{r_{\rm HII}^{\rm rad}} \propto \cos^{1/3}\theta_{\rm out}(1+\beta_{\rm out})^{-1/3}$

Critical density

$$n_\infty \gtrsim \cos^{1/2}\theta_{\rm out}(1+\beta_{\rm out})^{-1/2} \times n_{\rm crit,rad} \approx 2\times 10^7\ {\rm cm^{-3}}$$

→ agrees with our numerical results.

Summary

Effects of mechanical feedback on the super-Eddington transition

cf. Only radiation feedback is considered in previous works. (e.g., Inayoshi+2016)

2D radiation hydrodynamical simulation + chemical + mechanical feedback model (Ostriker+2010).

Our Results

- New transition criterion

$n_\infty \gtrsim 1 \times 10^8 \ \mathrm{cm}^{-3}$ (w/o outflows) → $n_\infty \gtrsim 3 \times 10^7 \ \mathrm{cm}^{-3}$ (w/ outflows) $M_{\mathrm{BH}} = 10 \ \mathrm{M}_\odot$

- Transition criterion is alleviated because
  - accretion rate reduces due to significant mass-loss
  - solid angle of inflowing region ↘

[Future work]

- Long-term simulation (after the transition)
- Survey in broader range of BH masses