ブラックホール降着円盤からのアウトフローの金属量依存性とSMBH形成過程への影響

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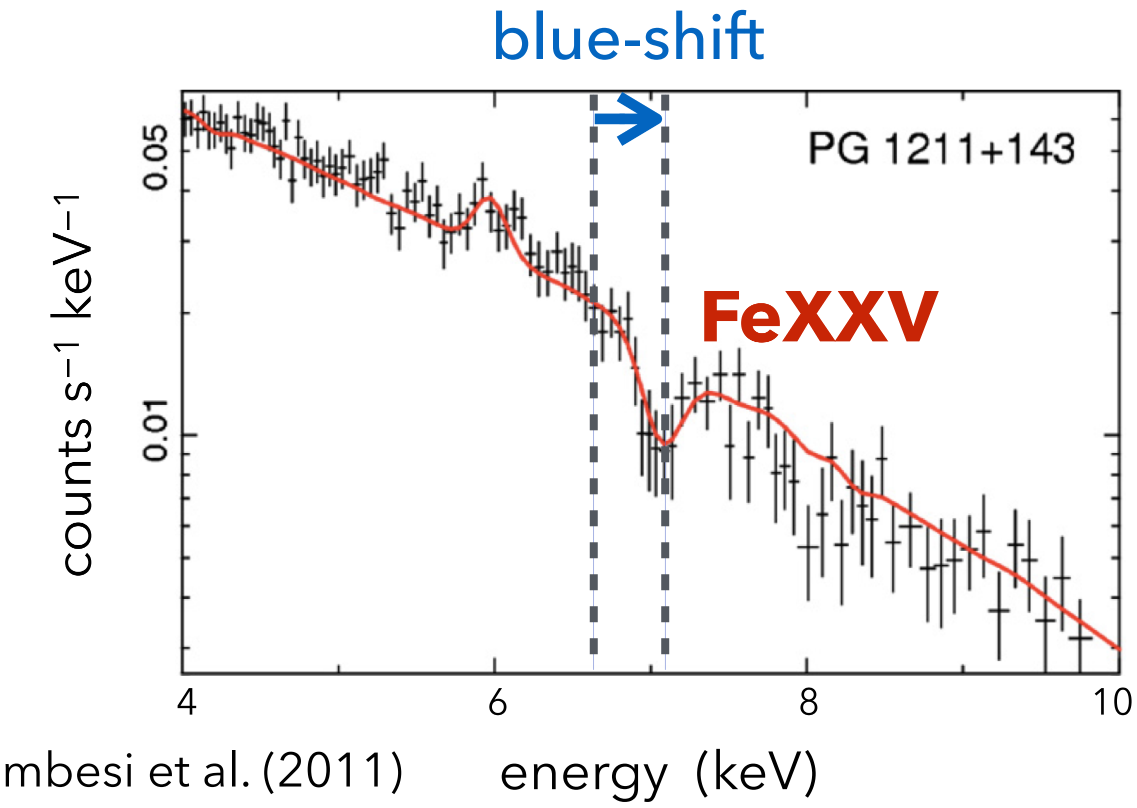
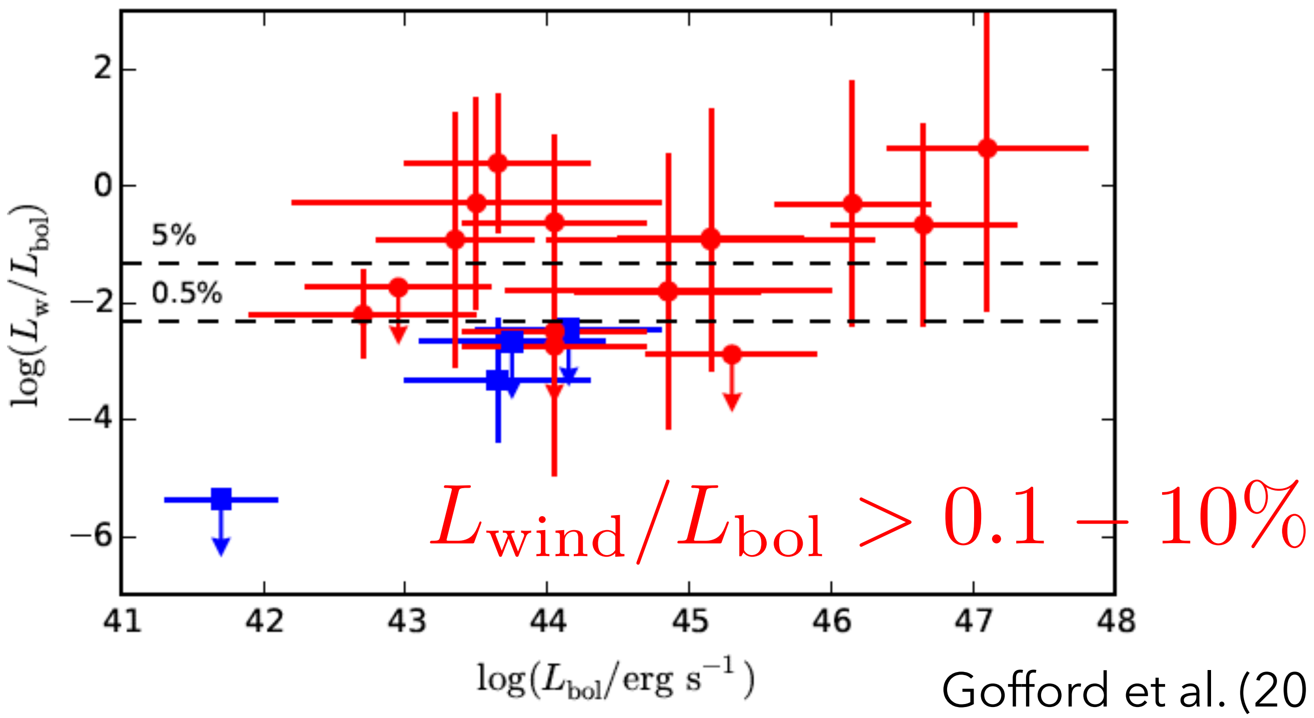
SMBH evolution and outflows

- Outflow may have an important role in SMBH evolution.
  - **decrease mass accretion rate → suppress SMBH growth**
  - **feedback onto host galaxy → SMBH-galaxy co-evolution**
  - e.g., **Ultra-fast outflow (UFOs)** detected in some AGNs
    - outflow speed ~0.1–0.3c
    - detected in ~40% AGN samples
    - large mass loss rate and kinetic energy → feedback & control of BH growth



Tombesi et al. (2011)

kinetic luminosity/bolometric luminosity



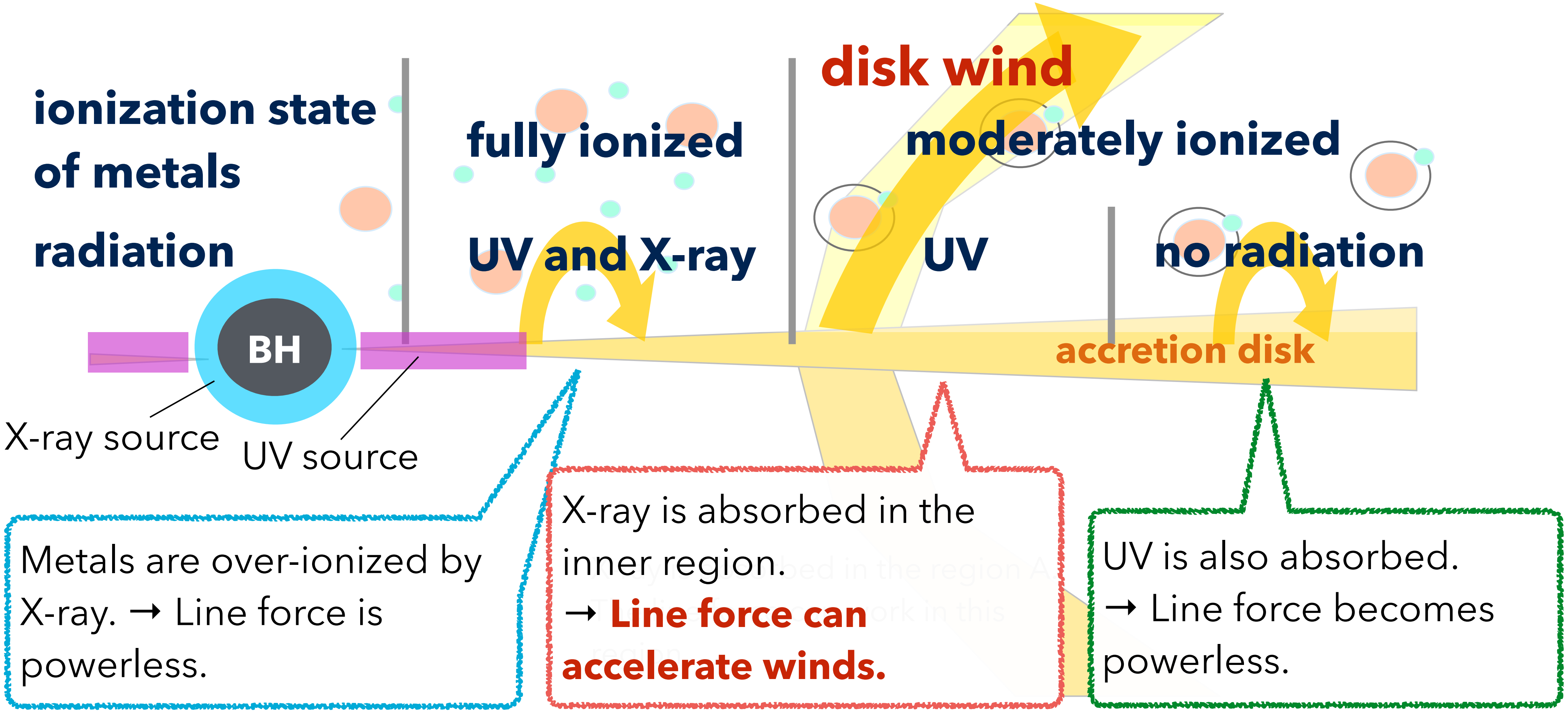
$L_{\rm wind}/L_{\rm bol} > 0.1-10\%$

bolometric luminosity

Gofford et al. (2015)

Line-driven disk wind

- accelerated by radiation force due to absorbing UV radiation through the bound–bound transition of metals (**line force**).
- Line force can be **~1000 times larger** than the radiation force due to electron scattering for moderately ionized matter.
  → **effective in sub-Eddington sources**



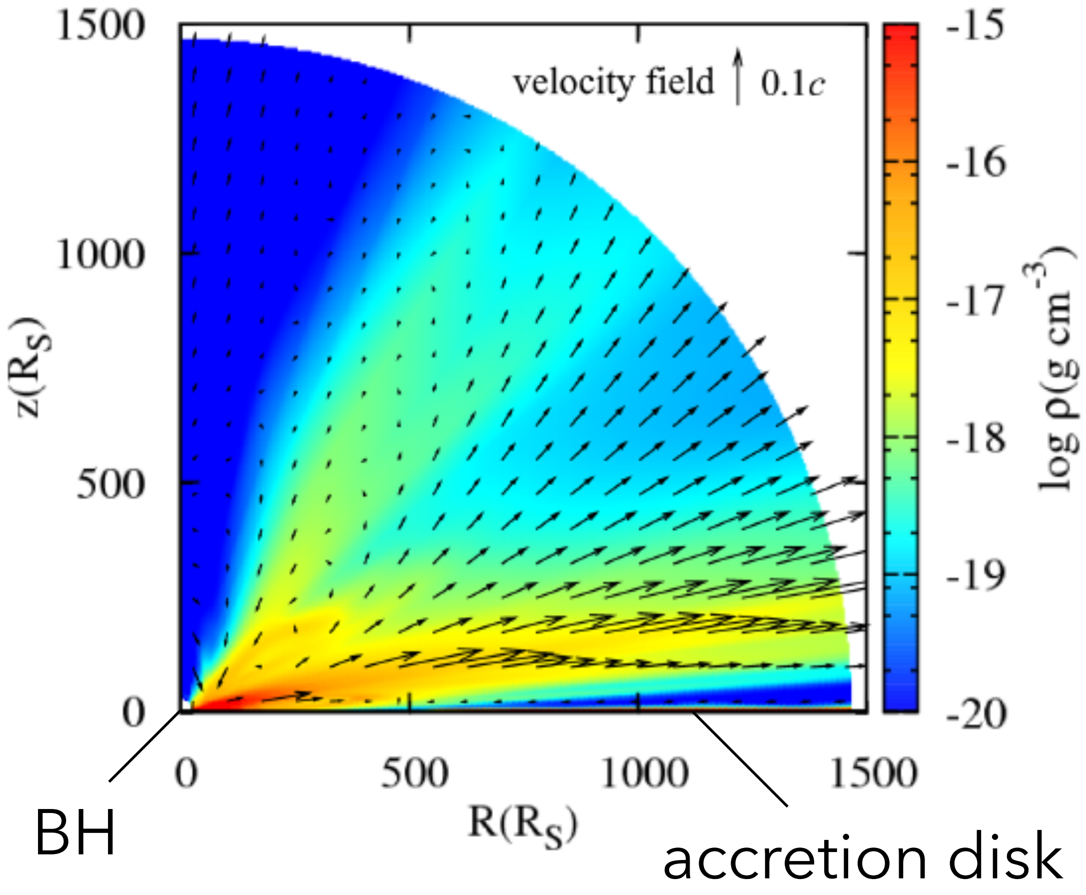
Metals are over-ionized by X-ray. → Line force is powerless.

X-ray is absorbed in the inner region.
→ **Line force can accelerate winds.**

UV is also absorbed.
→ Line force becomes powerless.

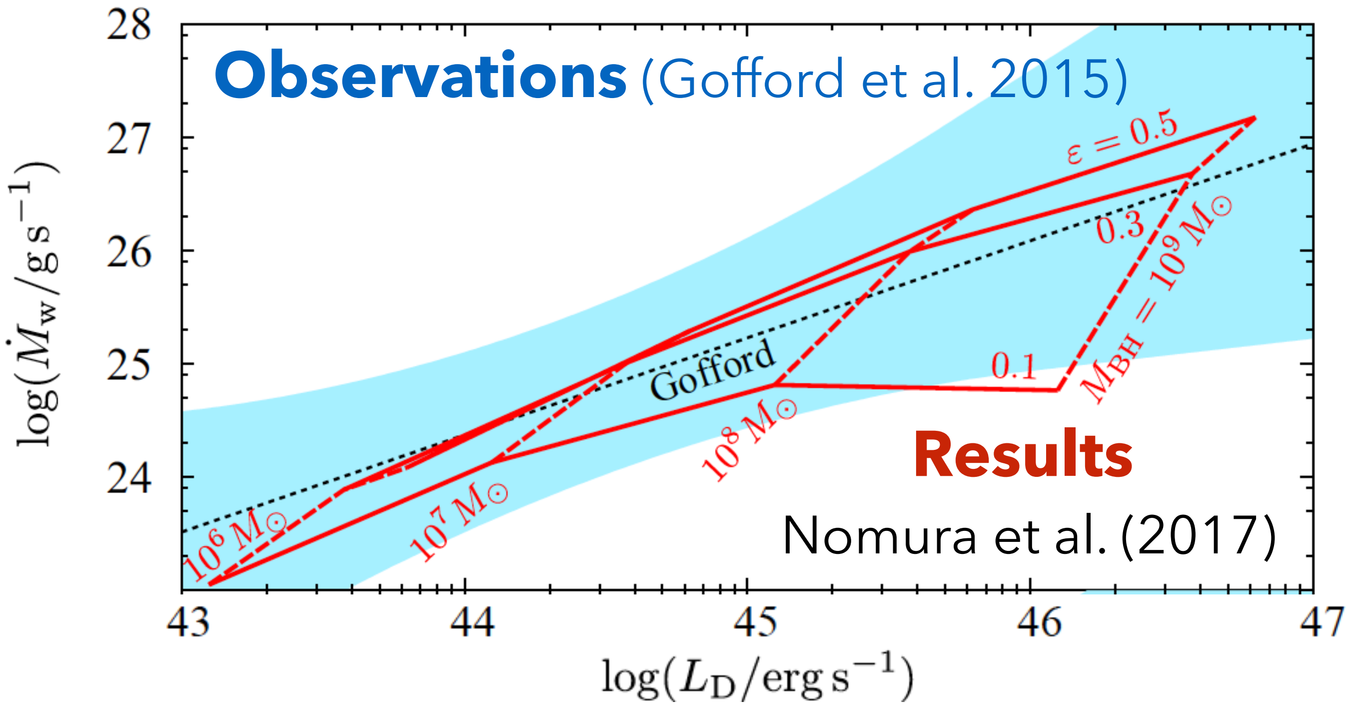
Previous works

- Numerical simulations are developed.
  - Proga et al. (2000), Proga & Kallman (2004): focus on typical BH mass and mass accretion rate of AGNs
  - Nomura et al. (2016), Nomura et al. (2017): perform simulations in wide parameter range and reproduce observational features of UFOs.



BH

accretion disk



Observations (Gofford et al. 2015)

Results

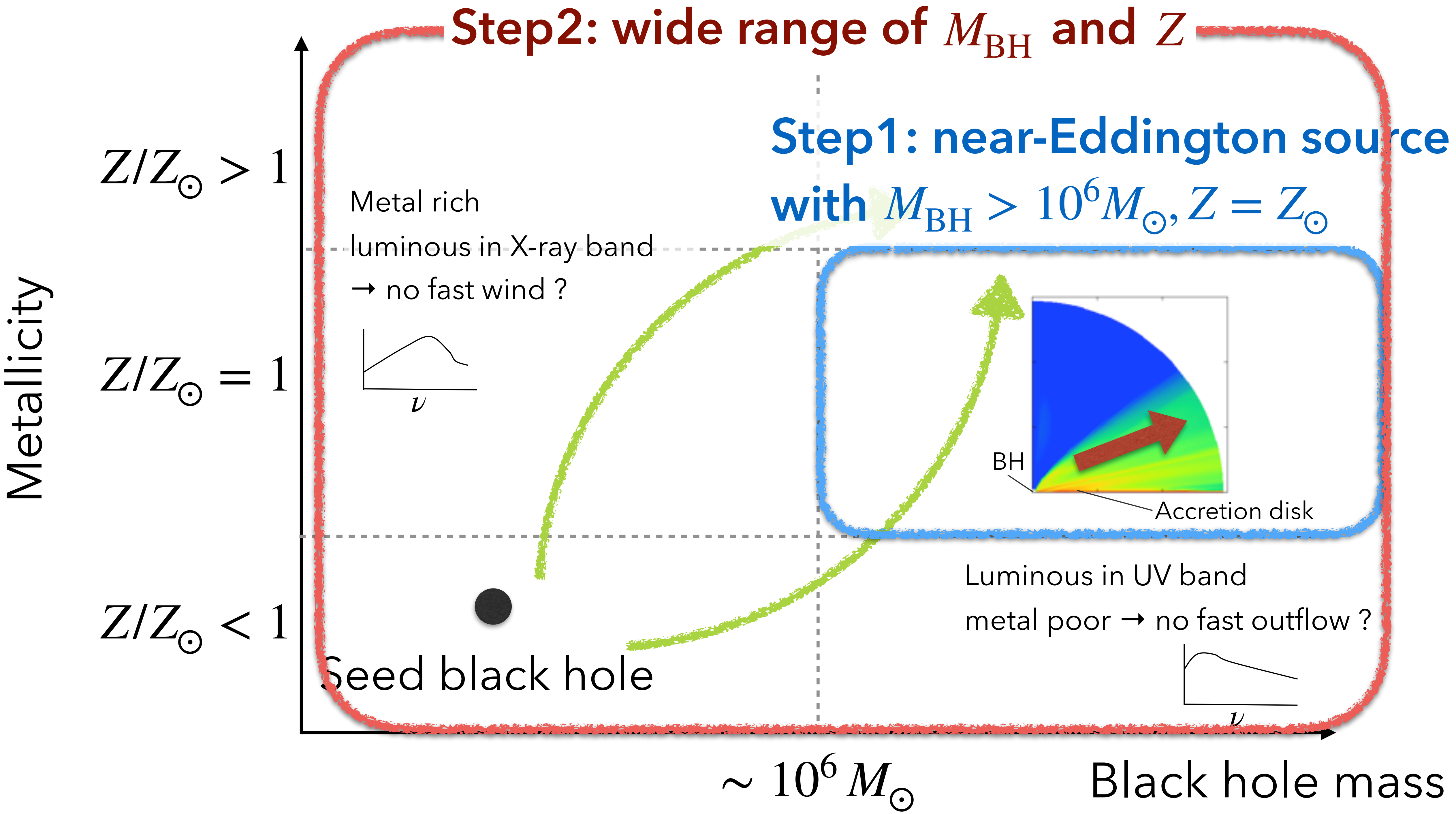
Nomura et al. (2017)

Line-driven wind model reproduces luminosity-dependence of mass loss rate.

We assume **large BH mass, sub-Eddington accretion rate, and solar metallicity**.

SMBH-galaxy evolution and outflows

- We investigate **mass loss rate and kinetic energy** transferred by the disk wind at each stage of the evolution. → explore **the role of the line-driven disk wind in SMBH-galaxy co-evolution**



Step2: wide range of $M_{\rm BH}$ and Z

Step1: near-Eddington source with $M_{\rm BH} > 10^6 M_\odot, Z = Z_\odot$

Metal rich
luminous in X-ray band
→ no fast wind ?

Luminous in UV band
metal poor → no fast outflow ?

Seed black hole

Method

- Mass conservation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$
- Equation of motion $$\frac{\partial (\rho v_r)}{\partial t} + \nabla \cdot (\rho v_r \mathbf{v}) = -\frac{\partial p}{\partial r} + \rho \left[\frac{v_\theta^2}{r} + \frac{v_\varphi^2}{r} + g_r + \underline{f_{\mathrm{rad},\, r}} \right]$$

  $$\frac{\partial (\rho v_\theta)}{\partial t} + \nabla \cdot (\rho v_\theta \mathbf{v}) = -\frac{1}{r}\frac{\partial p}{\partial \theta} + \rho \left[-\frac{v_r v_\theta}{r} + \frac{v_\varphi^2}{r} \cot\theta + g_\theta + \underline{f_{\mathrm{rad},\, \theta}} \right]$$

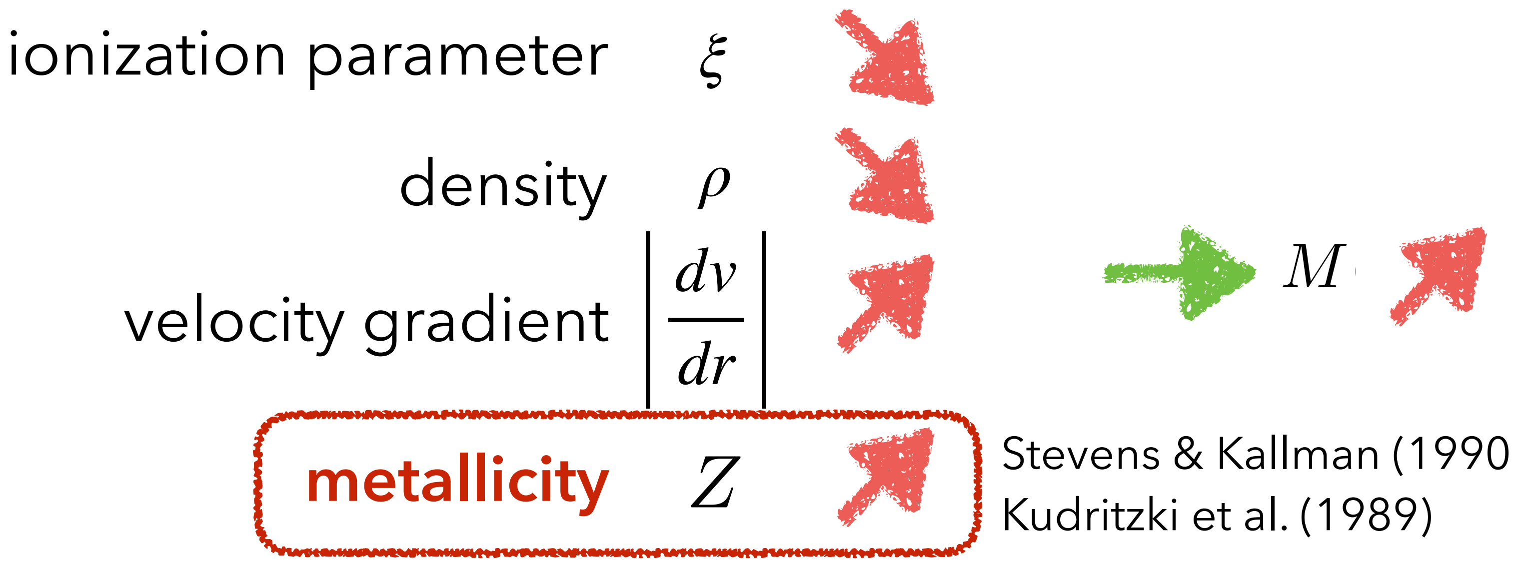
  Radiation force

  $$\frac{\partial (\rho v_\varphi)}{\partial t} + \nabla \cdot (\rho v_\varphi \mathbf{v}) = -\rho \left[\frac{v_\varphi v_r}{r} + \frac{v_\varphi v_\theta}{r} \cot\theta \right]$$
- Energy equation $$\frac{\partial}{\partial t}\left[\rho \left(\frac{1}{2} v^2 + e \right) \right] + \nabla \cdot \left[\rho \mathbf{v} \left(\frac{1}{2} v^2 + e + \frac{p}{\rho} \right) \right] = \rho \mathbf{v} \cdot \mathbf{g} + \underline{\rho \mathscr{L}}$$

  Radiative heating/cooling

Radiation force

$$f_{\mathrm{rad}} = \overbrace{\frac{\sigma_{\mathrm{e}} F_{\mathrm{UV}}}{c}}^{\text{Radiation force due to Thomson scattering}} + \overbrace{\frac{\sigma_{\mathrm{e}} F_{\mathrm{UV}}}{c} \underbrace{M}_{\text{force multiplier}}}^{\text{Line force}}$$



ionization parameter ξ ↘

density ρ ↘

velocity gradient $\left| \frac{dv}{dr} \right|$ ↗

metallicity Z ↗

→ M ↗

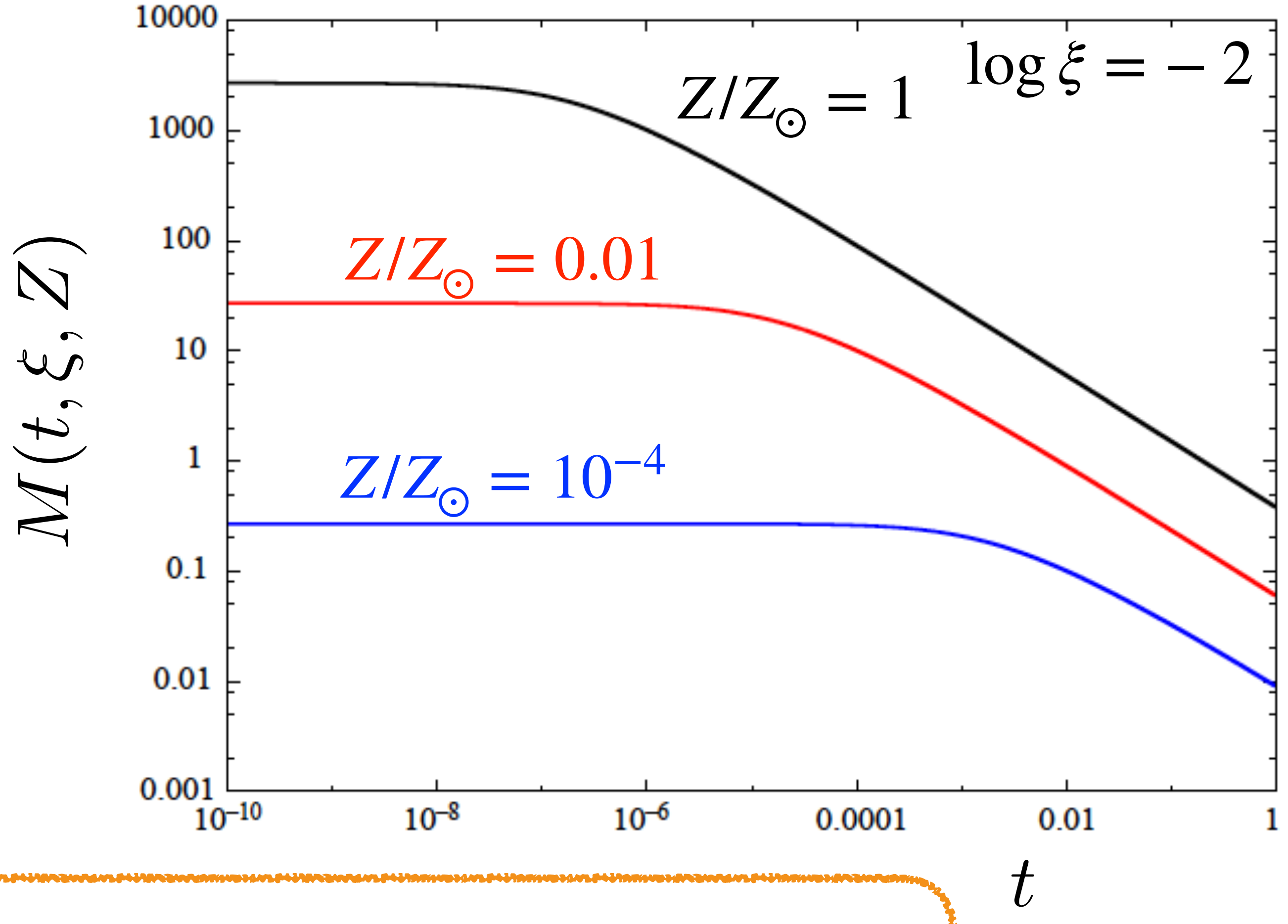
Stevens & Kallman (1990)
Kudritzki et al. (1989)

Metallicity dependence of force multiplier

Line strength is proportional to metallicity, $k_i = k_i^{\odot}(Z/Z_{\odot})$.

→ $$M_{\rm max} \propto \frac{Z}{Z_{\odot}} \text{ for } \rho\left|\frac{dv}{ds}\right|^{-1} \ll 1 \qquad M \propto \left(\frac{Z}{Z_{\odot}}\right)^{0.4}$$

Kudritzki et al. (1989)



$$\xi = 4\pi F_{\rm X}/n$$

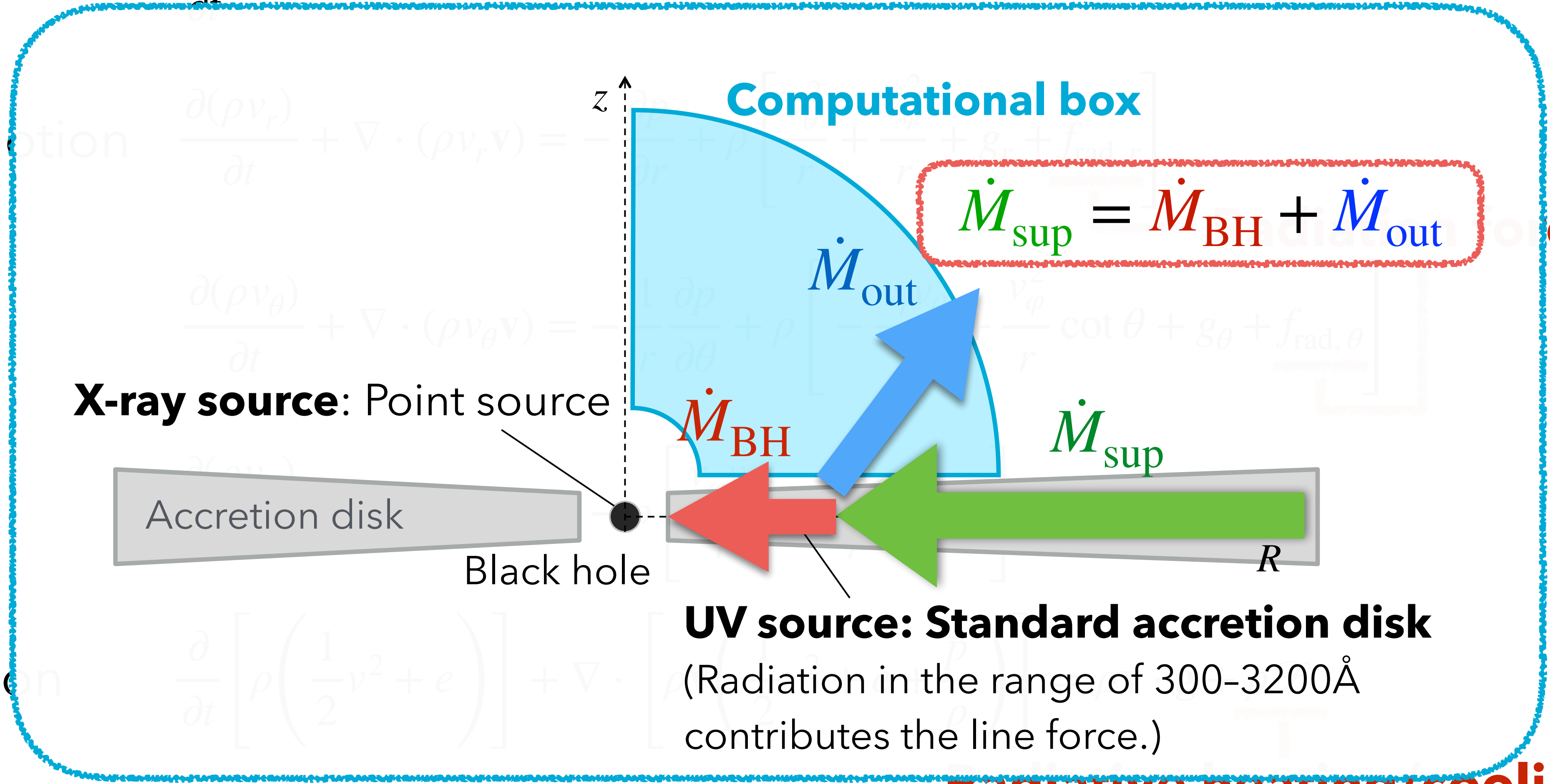
$$t \propto \rho\left|\frac{dv}{ds}\right|^{-1}$$

$$\mathbf{f}_{\rm rad} = \overbrace{\frac{\sigma_{\rm e}\mathbf{F}_{\rm UV}}{c}}^{\text{Radiation force due to Thomson scattering}} + \overbrace{\frac{\sigma_{\rm e}\mathbf{F}_{\rm UV}}{c}M(t,\xi,Z)}^{\text{Line force}}$$

force multiplier

Method

- Mass conservation $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$
- Equation of motion
- Energy equation



Computational box

$\dot{M}_{\rm sup} = \dot{M}_{\rm BH} + \dot{M}_{\rm out}$

X-ray source: Point source

Accretion disk

Black hole

UV source: Standard accretion disk
(Radiation in the range of 300–3200Å
contributes the line force.)

ce

Radiative heating/cooling

Radiation force

$$f_{\rm rad} = \overbrace{\frac{\sigma_{\rm e} F_{\rm UV}}{c}}^{\text{Radiation force due to Thomson scattering}} + \overbrace{\frac{\sigma_{\rm e} F_{\rm UV}}{c} \underbrace{M}_{\text{force multiplier}}}^{\text{Line force}}$$

ionization parameter ξ ↘

density ρ ↘

velocity gradient $\left|\frac{dv}{dr}\right|$ ↗

metallicity Z ↗

→ M ↗

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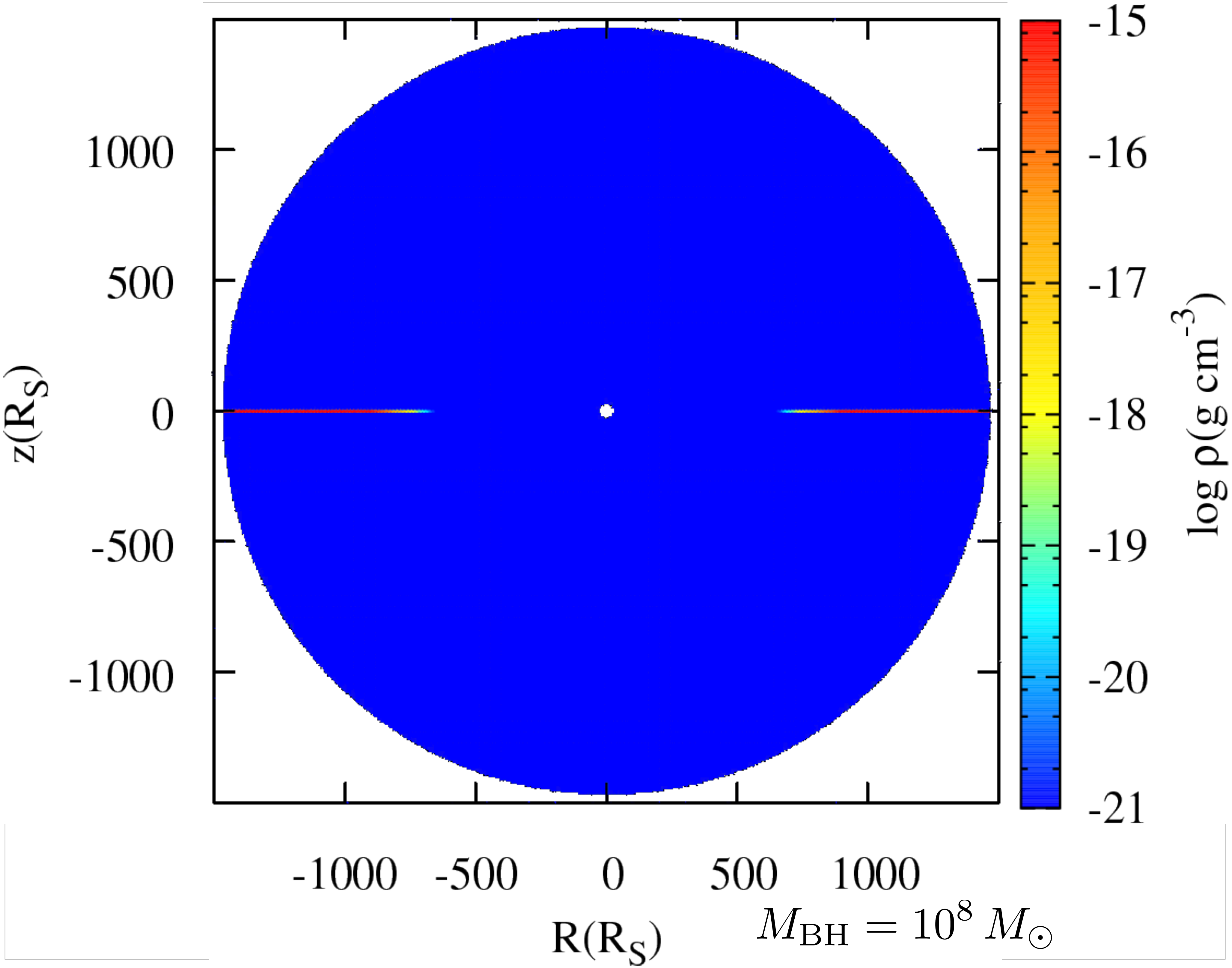
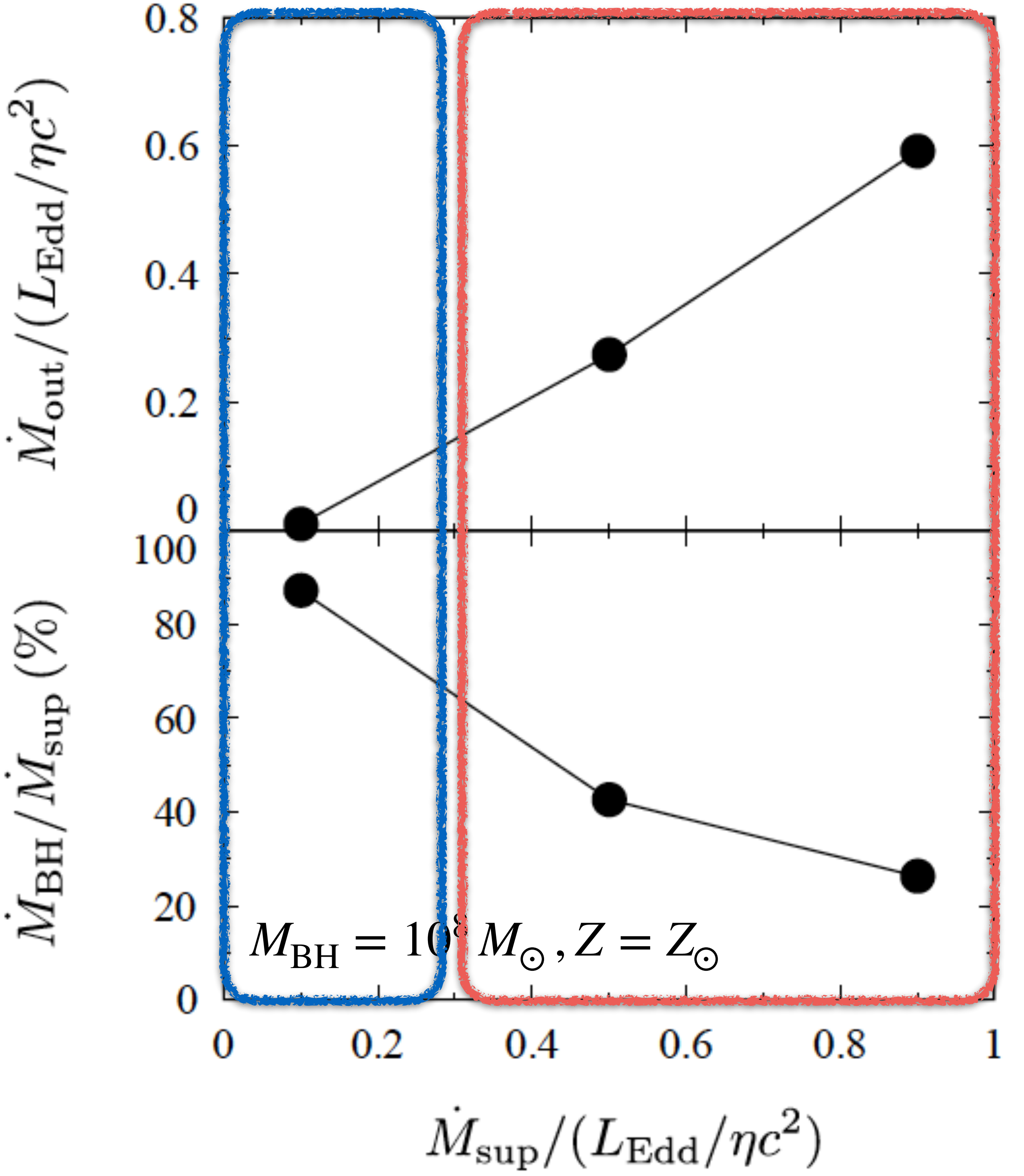
Results



$M_{\rm BH} = 10^8\,M_\odot$

$\dot{m}_{\rm sup} = \dot{M}_{\rm sup}/(L_{\rm Edd}/\eta c^2) = 0.5$

Mass supply rate dependence



Nomura et al. in submitted

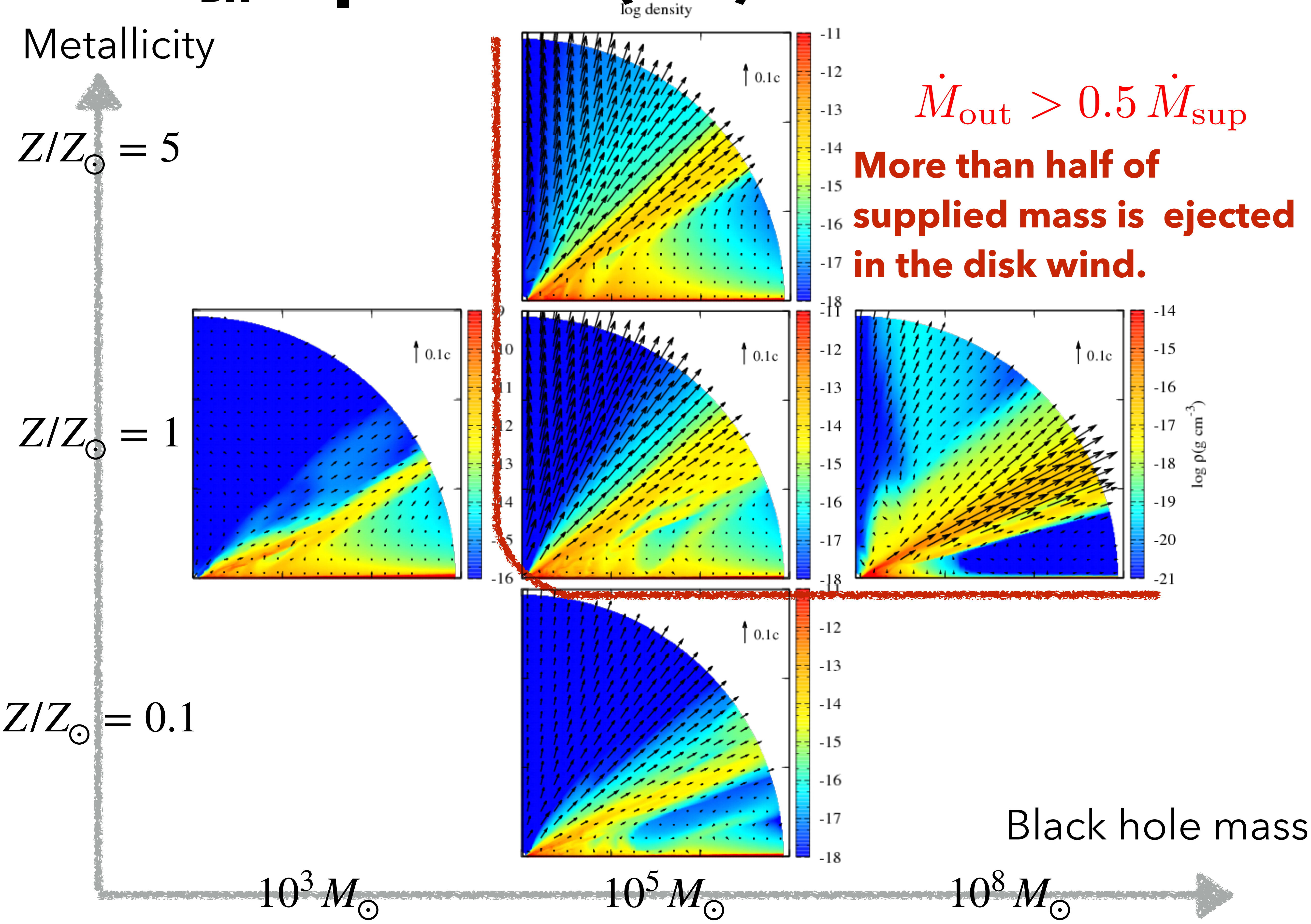
- For small $\dot{M}_{\rm sup}$
  - small mass loss rate
  - Mass accretion rate onto BH is ~90% of mass supply rate onto disk.

- For large $\dot{M}_{\rm sup}$
  - large mass outflow rate
  - Mass accretion rate onto BH is less than ~50% of the mass supply rate.

→ **The line-driven winds decrease the mass accretion onto SMBHs in near-Eddington sources.**

Z & *M*$_{\rm BH}$ dependence (1/3)

$\dot{m}_{\rm sup} = \dot{M}_{\rm sup}/(L_{\rm Edd}/\eta c^2) = 0.5$

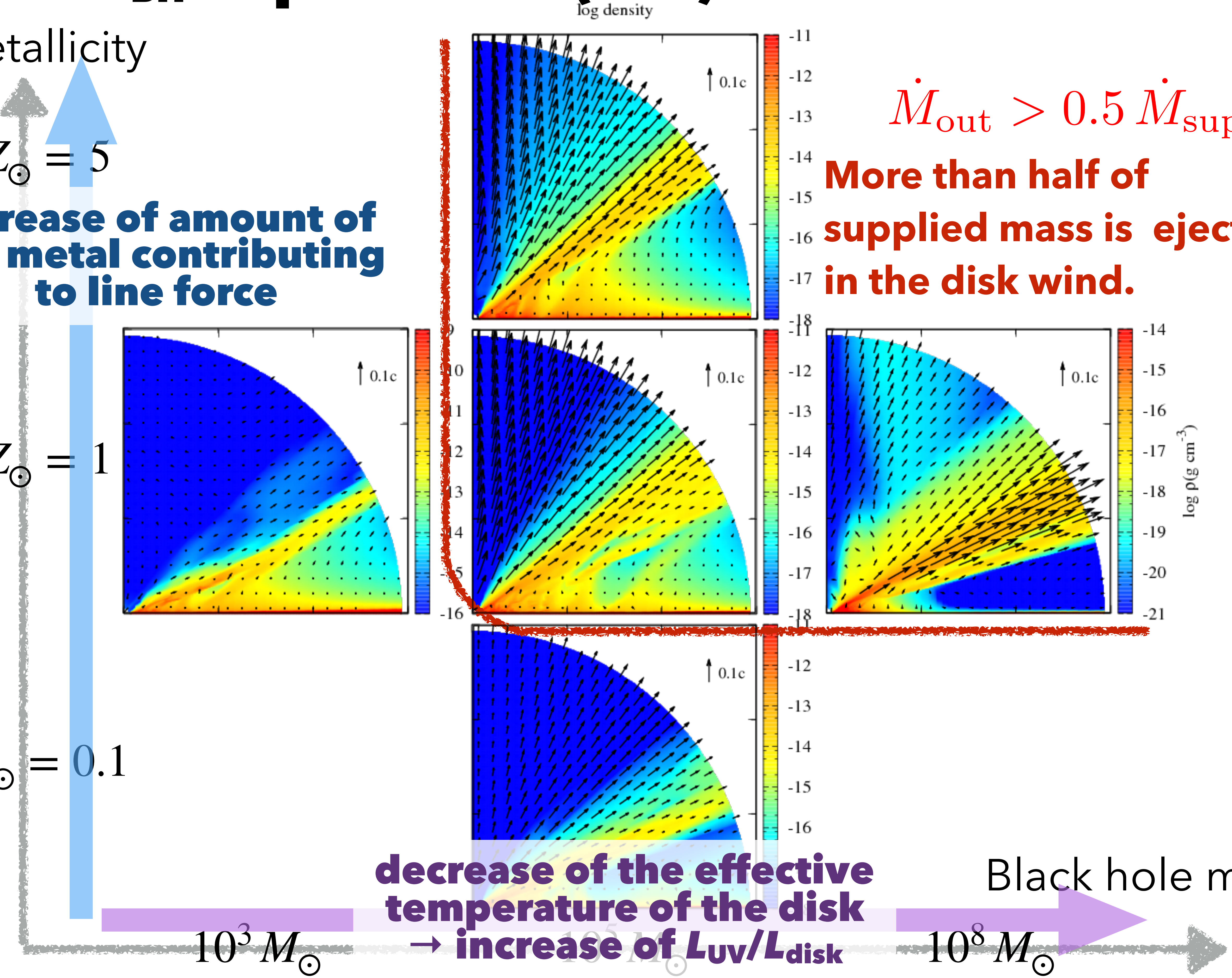


$\dot{M}_{\rm out} > 0.5\,\dot{M}_{\rm sup}$

More than half of supplied mass is ejected in the disk wind.

Z & $M_{\rm BH}$ dependence (1/3)

$$\dot m_{\rm sup} = \dot M_{\rm sup}/(L_{\rm Edd}/\eta c^2) = 0.5$$



Metallicity

$Z/Z_\odot = 5$

increase of amount of the metal contributing to line force

$Z/Z_\odot = 1$

$Z/Z_\odot = 0.1$

$$\dot M_{\rm out} > 0.5\,\dot M_{\rm sup}$$

More than half of supplied mass is ejected in the disk wind.

decrease of the effective temperature of the disk → increase of $L_{\rm UV}/L_{\rm disk}$

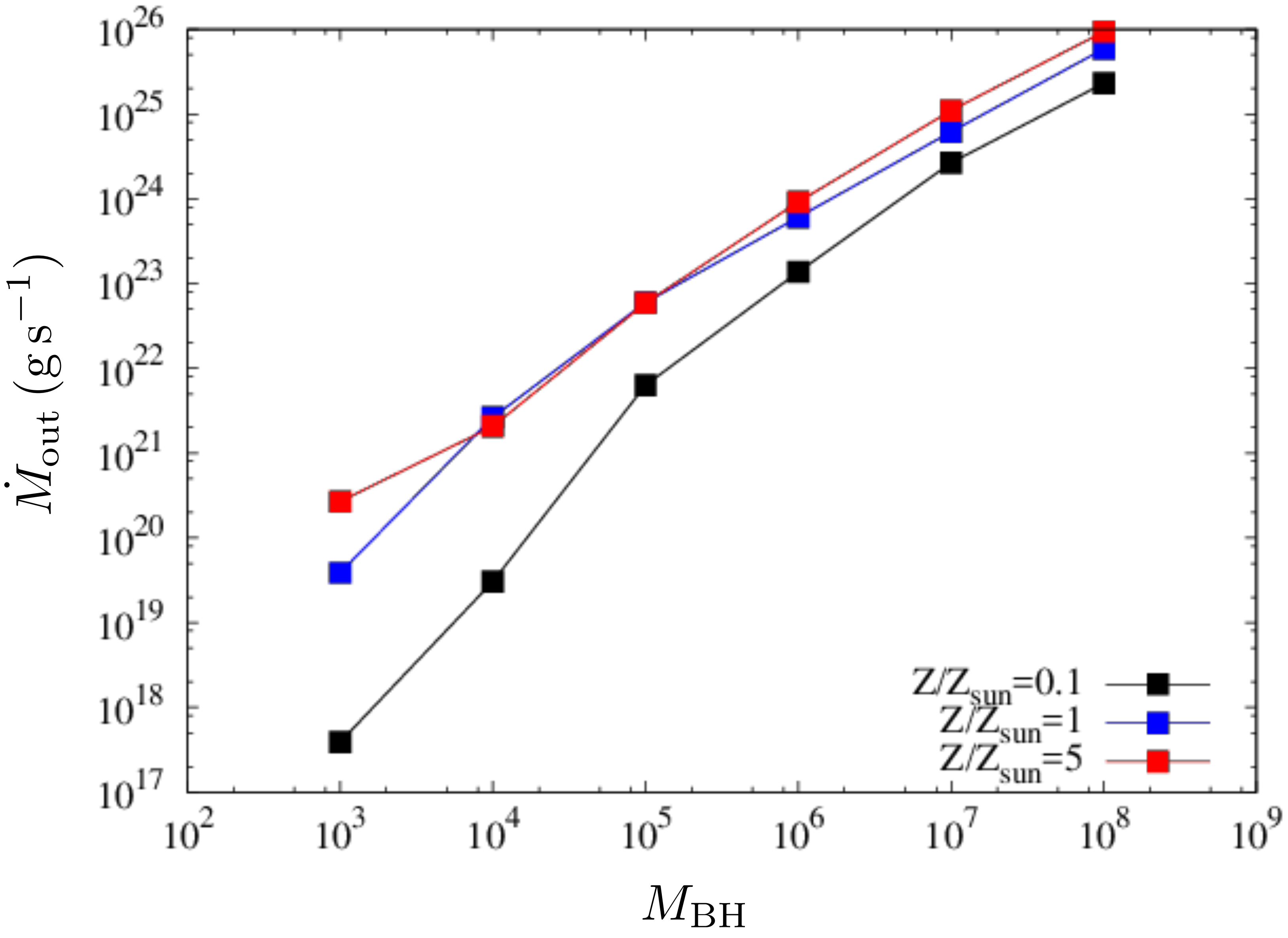
Black hole mass

$10^3 M_\odot$

$10^8 M_\odot$

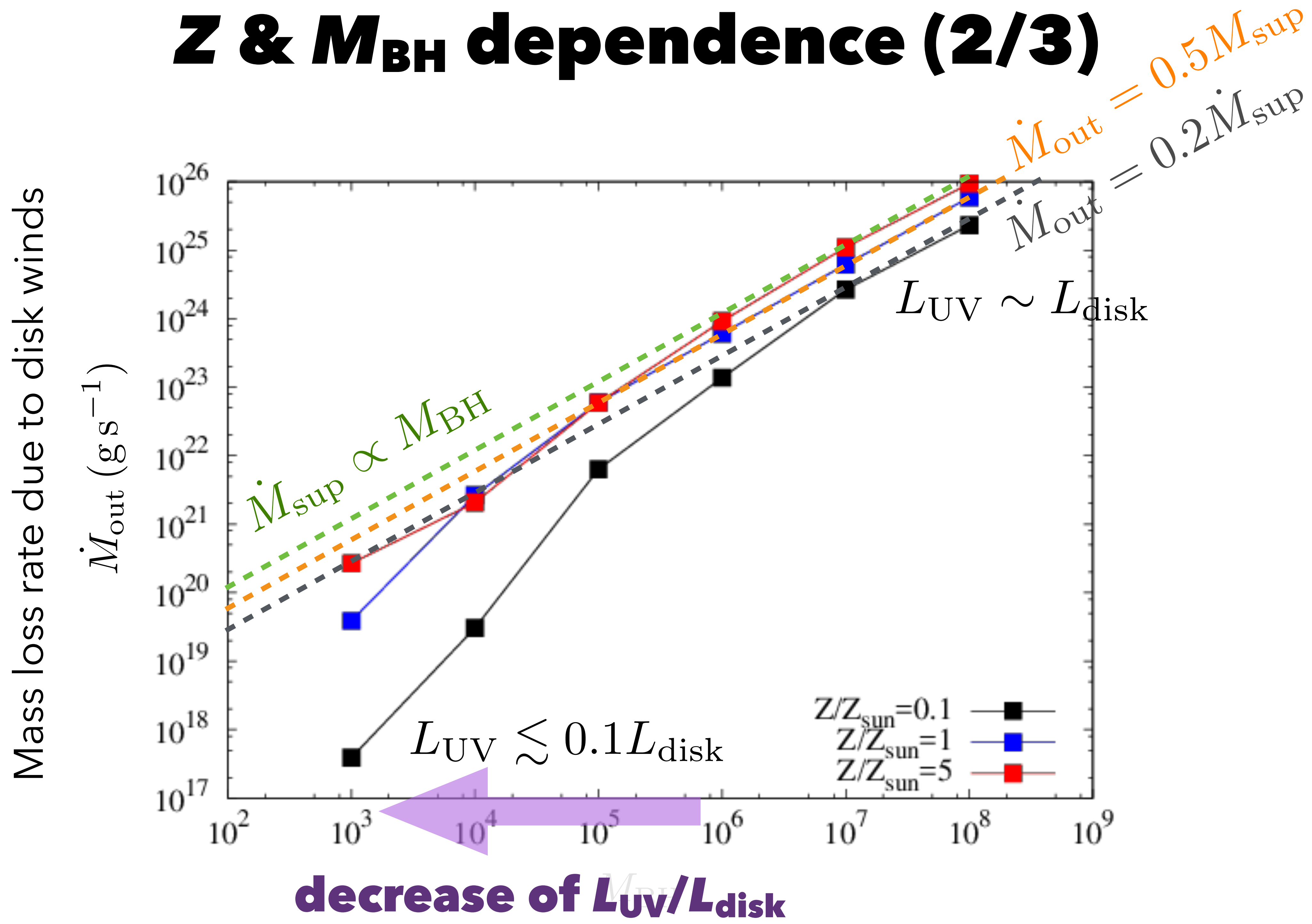
Z & $M_{\rm BH}$ dependence (2/3)

Mass loss rate due to disk winds



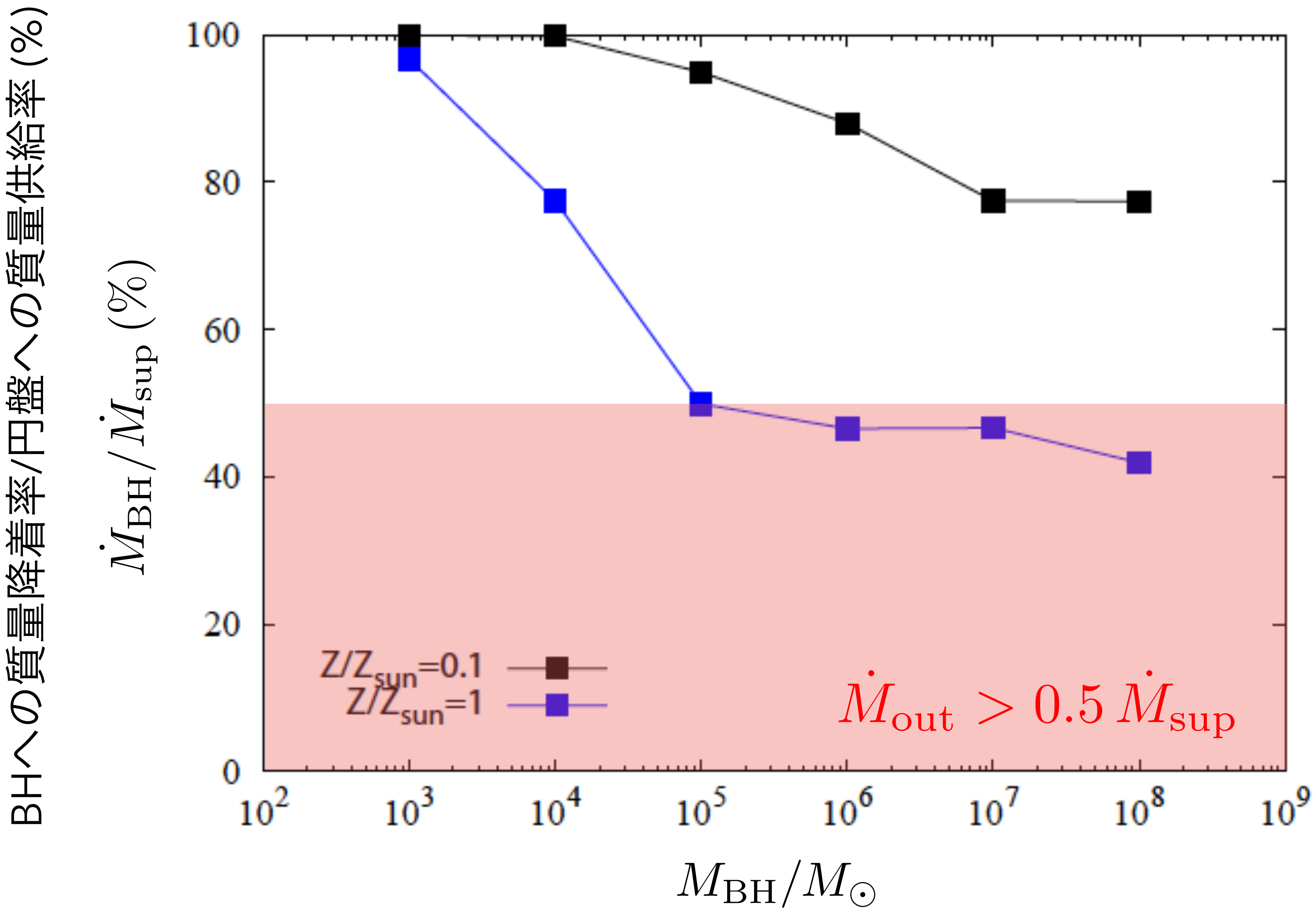
- Mass loss rate becomes large with the increase of BH mass and metallicity.
- Mass loss rate sharply increases at $M_{\rm BH} \sim 10^5 M_\odot$ and $Z \sim Z_\odot$.

Z & $M_{\rm BH}$ dependence (2/3)



- Mass loss rate becomes large with the increase of BH mass and metallicity.
- Mass loss rate sharply increases at $M_{\rm BH}\sim 10^5 M_{\odot}$ and $Z\sim Z_{\odot}$.

Z & $M_{\rm BH}$ dependence (3/3)



- For the small BH mass and the low metallicity, mass accretion rate is smaller than ~80% of mass supply rate.
- Mass accretion rate becomes smaller than ~50% of mass supply rate for $M_{\rm BH} \gtrsim 10^5 M_\odot$ and $Z \gtrsim Z_\odot$.

Discussions

- When the BH mass is small ($M_{\rm BH} \lesssim 10^4 M_\odot$) or metallicity is low ($Z \lesssim 0.1 Z_\odot$), ~80% of the supplied mass accretes onto the BH.

  → **Outflows do not suppress the SMBHs growth at the early stage of their evolution.**

- For large BH mass ($M_{\rm BH} \gtrsim 10^{5-6}\, M_\odot$) and large metallicity ($Z \gtrsim Z_\odot$), the mass accretion rate is reduced to ~50% of the mass supply rate.

  → **Outflows suppress the growth of SMBHs at the final stage of SMBH-galaxy co-evolution and provide feedback onto the host galaxies.**

Summary

- We performed the RHD simulations of the line-driven wind considering the metallicity dependence of the line force.
- Mass loss rate due to the disk wind becomes large with the increase of the BH mass and the metallicity.
- For $M_{\rm BH} \gtrsim 10^{5-6}\,M_\odot$ and $Z \gtrsim Z_\odot$, the mass accretion rate onto the BH is reduced to less than 50% of mass supply rate.
- **Line-driven disk winds do not suppress the growth at the early stage of BH evolution and reduce the growth rate of SMBH and provide feedback at the final stage of the evolution.**