Radiation hydrodynamics simulations of line-driven disk winds: metallicity dependence and SMBH growth

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Collaborators:

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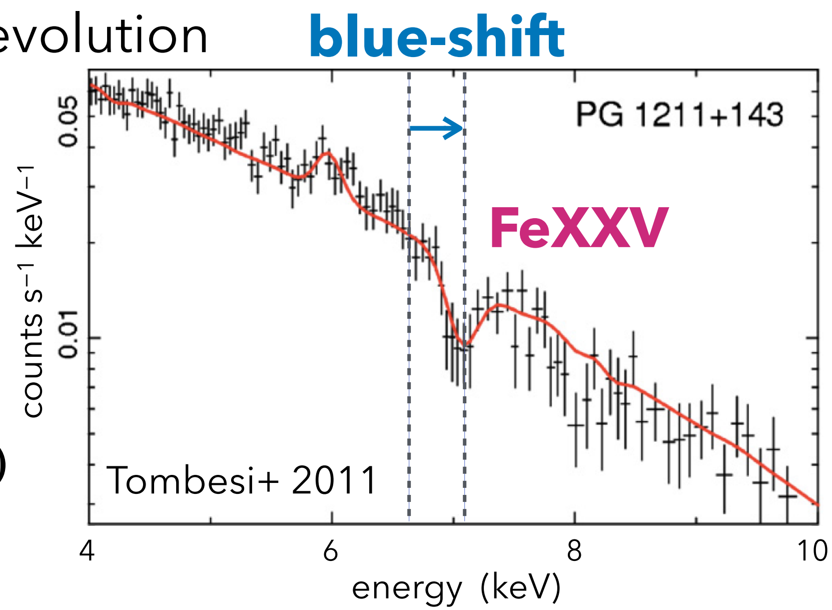
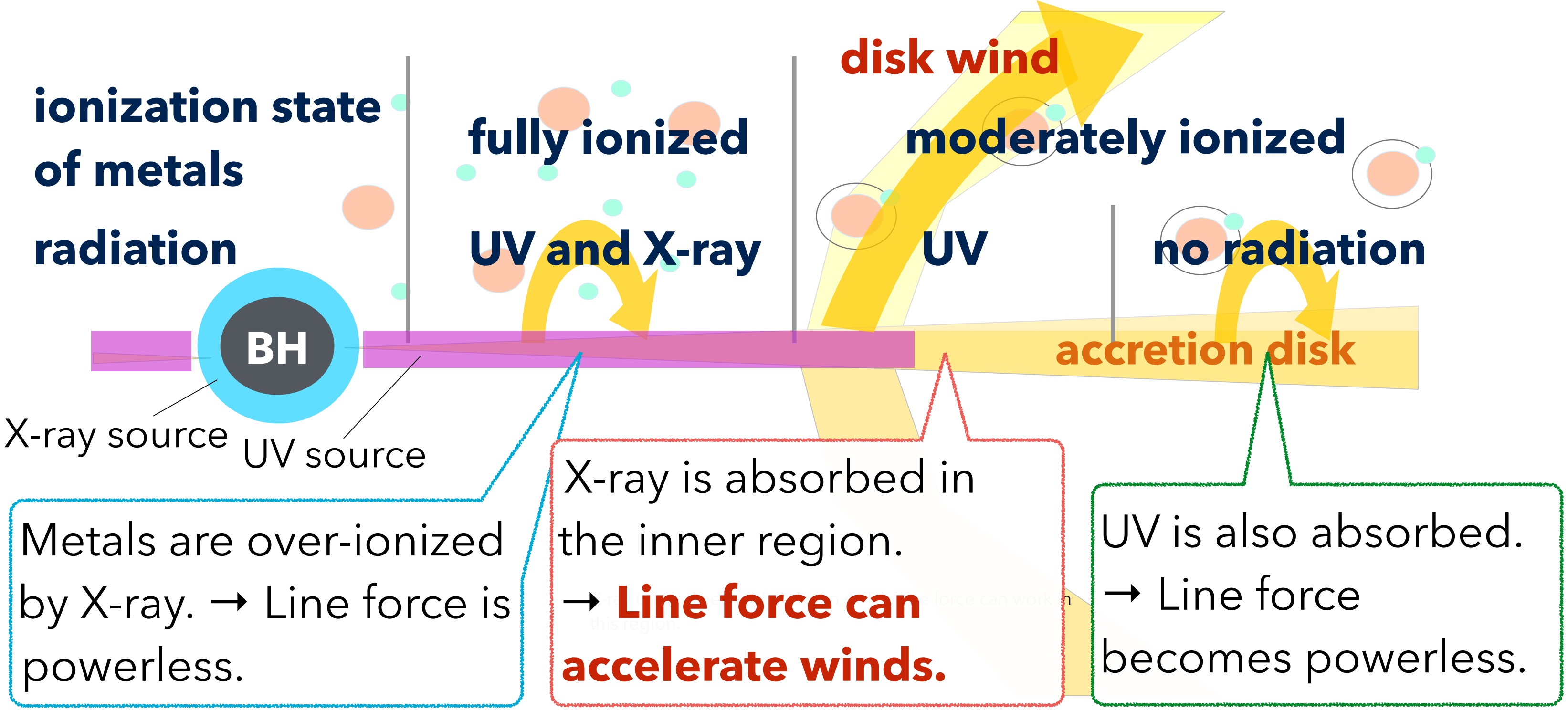
Motivation: SMBH growth and outflows

- ✦ Evolution process from seed BHs to SMBHs is still unknown, but **mass accretion process must be important.**
- ✦ In AGNs, outflows are ubiquitous and must affect on the accretion processes.
  - **decrease mass accretion rate → suppress SMBH growth**
  - feedback onto host galaxy → SMBH-galaxy co-evolution
- ✦ Ultrafast Outflows
  - outflow speed ~0.1-0.3c
  - detected in ~40% AGN samples
  - large mass loss rate and kinetic energy
    $(\dot{M}_{\rm wind}/\dot{M}_{\rm Edd} \sim 0.01-1,\ L_{\rm wind}/L_{\rm Edd} \sim 0.1-10\%)$



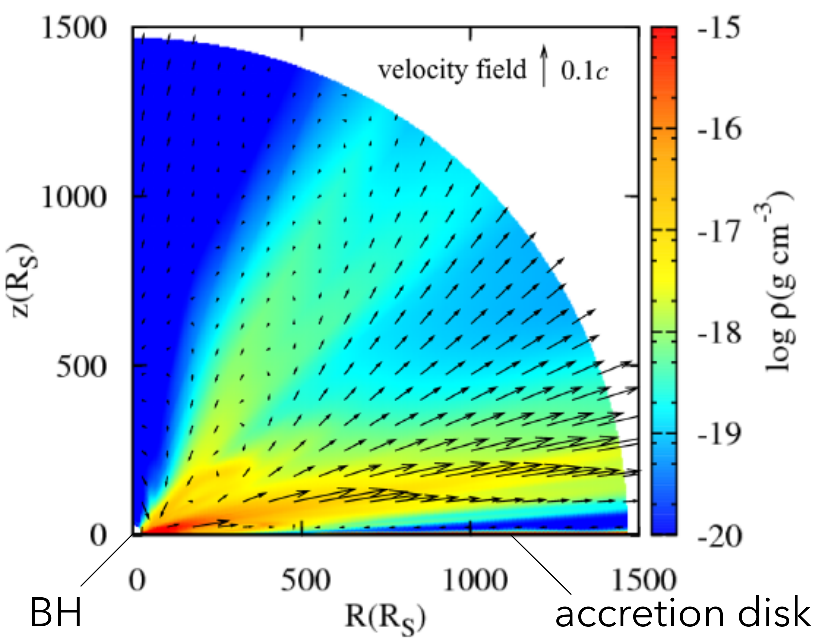
Plausible model for UFOs: line-driven winds

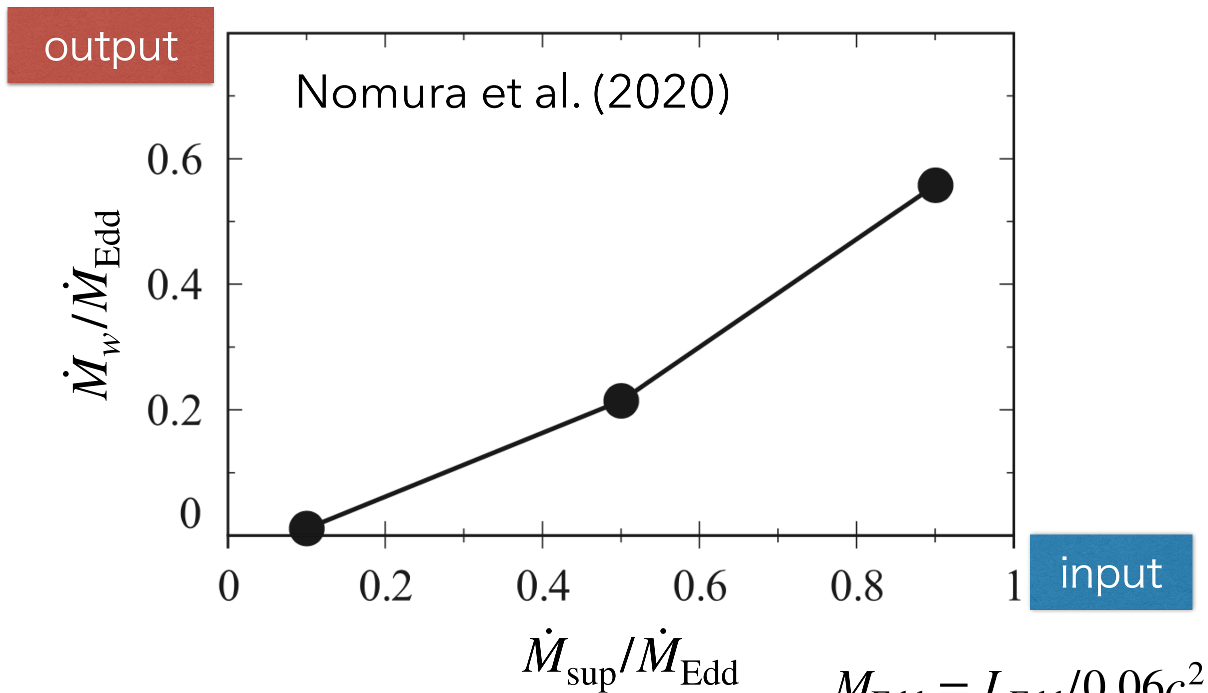
- ✦ accelerated by radiation force due to absorbing UV radiation through the bound–bound transition of metals (**line force**)
- ✦ Line force can accelerate the moderately ionized matter effectively.



Mass loss rate of line-driven winds

- ✦ Line-driven winds reproduce the mass-loss rate of UFOs.
- ✦ Line-driven winds suppress the mass accretion on to BH especially in the luminous AGNs ($\dot{M}_{\rm sup}/\dot{M}_{\rm Edd} \gtrsim 0.5$).

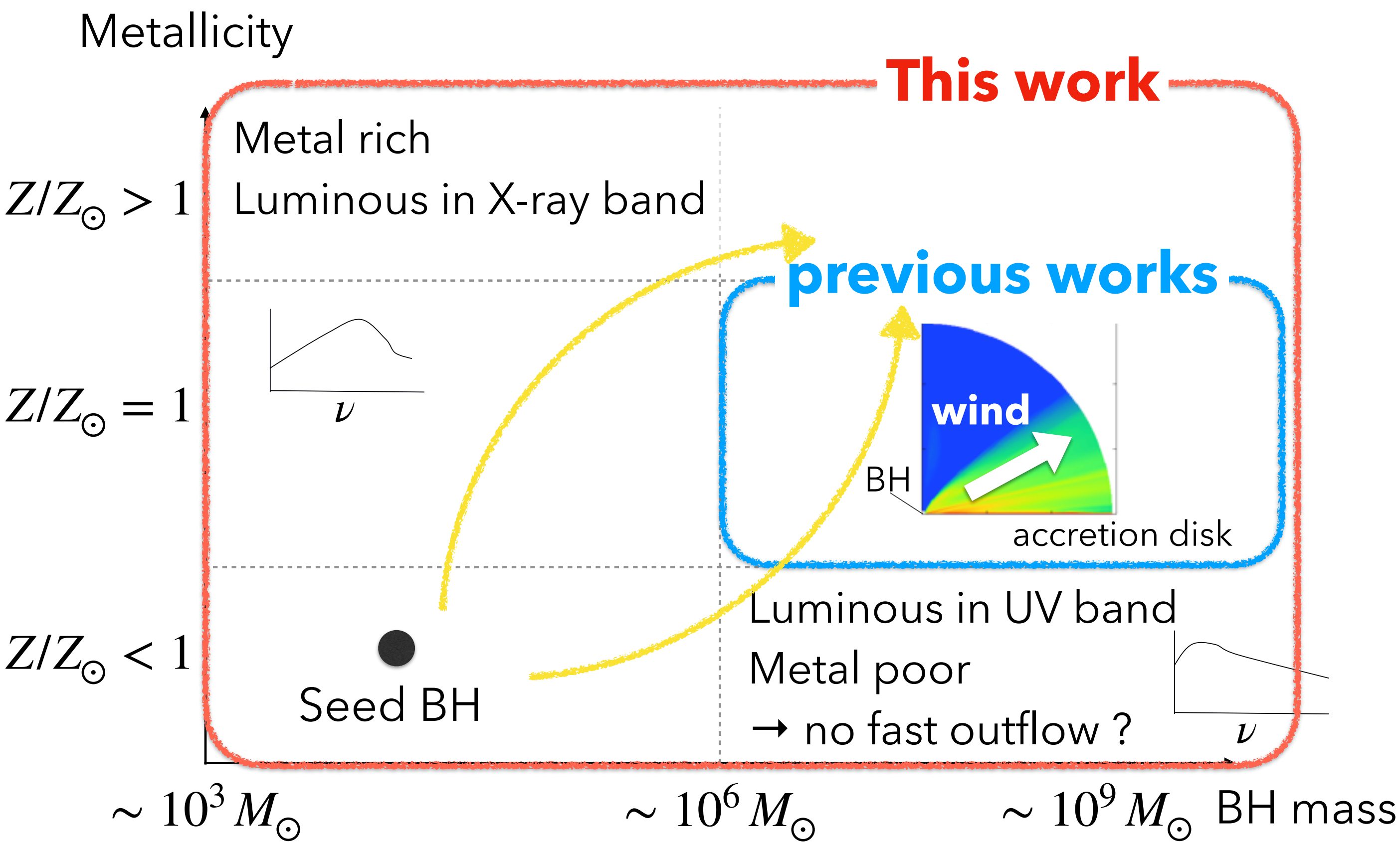




$M_{\rm Edd} = L_{\rm Edd}/0.06c^2$

Outflows in SMBH evolution

- Question: Do the line driven winds suppress the mass accretion on the evolutional pass from seeds to SMBHs?
- This work explores **the role of line-driven winds in a wide range of BH mass and metallicity**.



Method: basic equations

- Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

- Equations of motion

Radiation force

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

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

$$\frac{\partial(\rho v_\varphi)}{\partial t} + \nabla \cdot (\rho v_\varphi \mathbf{v}) = -\rho \left[\frac{v_\varphi v_r}{r} + \frac{v_\varphi v_\theta}{r} \cot\theta \right]$$

- Energy equation

Radiative heating/cooling

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + e\right)\right] + \nabla \cdot \left[\rho \mathbf{v}\left(\frac{1}{2}v^2 + e + \frac{p}{\rho}\right)\right] = \rho \mathbf{v} \cdot \mathbf{g} + \rho \mathscr{L}$$

radiation force due to Thomson scattering — **line force**

$$f_{\mathrm{rad}} = \frac{\sigma_e \boldsymbol{F}_{\mathrm{UV}}}{c} + \frac{\sigma_e \boldsymbol{F}_{\mathrm{UV}}}{c} M$$

force multiplier

ionization parameter $\xi = 4\pi F_X / n$ ↘

density ρ ↘

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

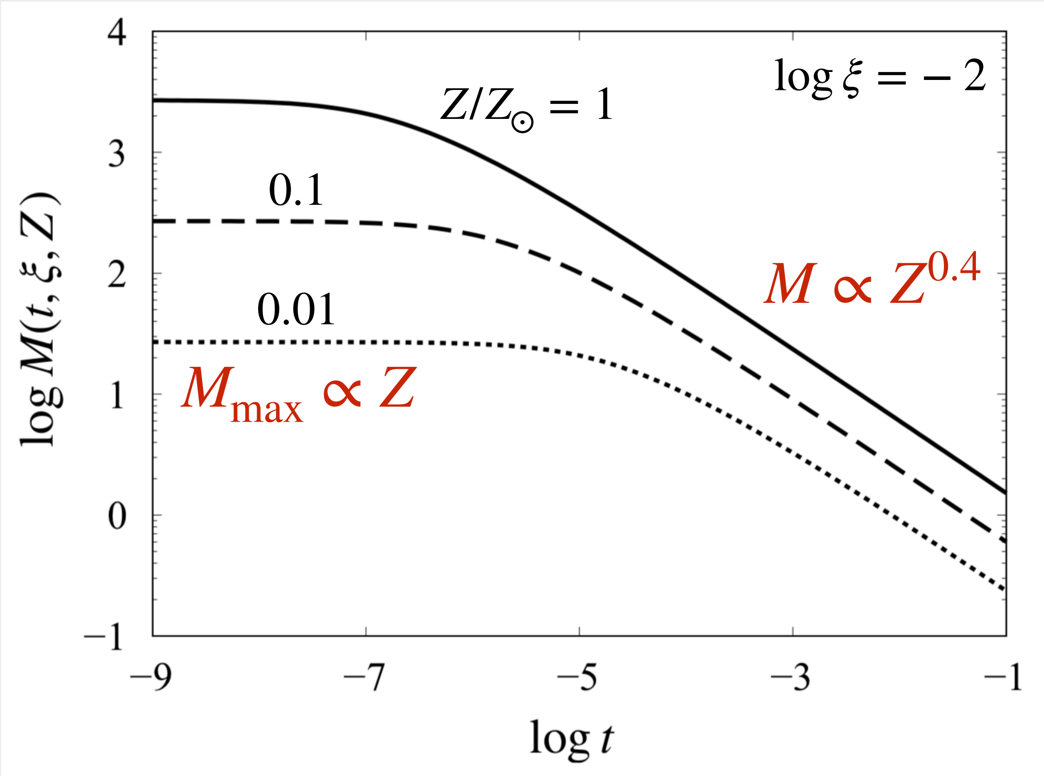
metallicity Z ↗

$\Rightarrow M$ ↗

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

Method: basic equations

Z-dependence of force multiplier



local optical depth parameter: $t \propto \rho \left| \frac{dv}{ds} \right|^{-1}$

radiation force due to Thomson scattering — **line force**

$$f_{\rm rad} = \frac{\sigma_{\rm e} F_{\rm UV}}{c} + \frac{\sigma_{\rm e} F_{\rm UV}}{c} M$$

force multiplier

ionization parameter	$\xi = 4\pi F_{\rm X}/n$	↘
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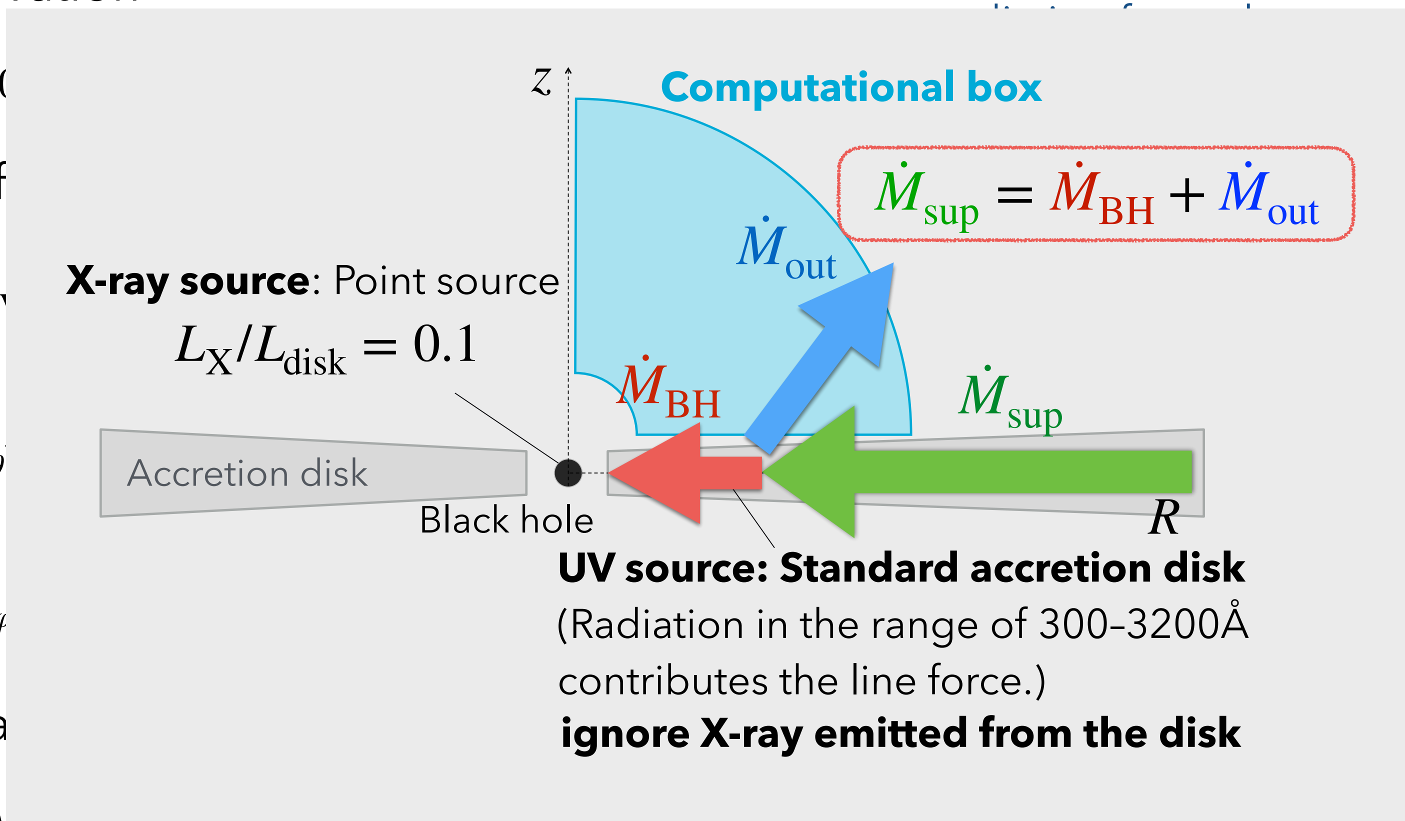
$$\frac{\partial (\rho v_\varphi)}{\partial t} + \nabla \cdot (\rho v_\varphi$$

✦ Energy equa

$$\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + e\right)\right] + \nabla \cdot \left[\rho \mathbf{v}\left(\frac{1}{2}v^2 + e + \frac{p}{\rho}\right)\right] = \rho \mathbf{v} \cdot \mathbf{g} + \rho \mathscr{L}$$



e force

$\frac{F_{\rm UV}}{c} M$

e multiplier

$\Rightarrow M$

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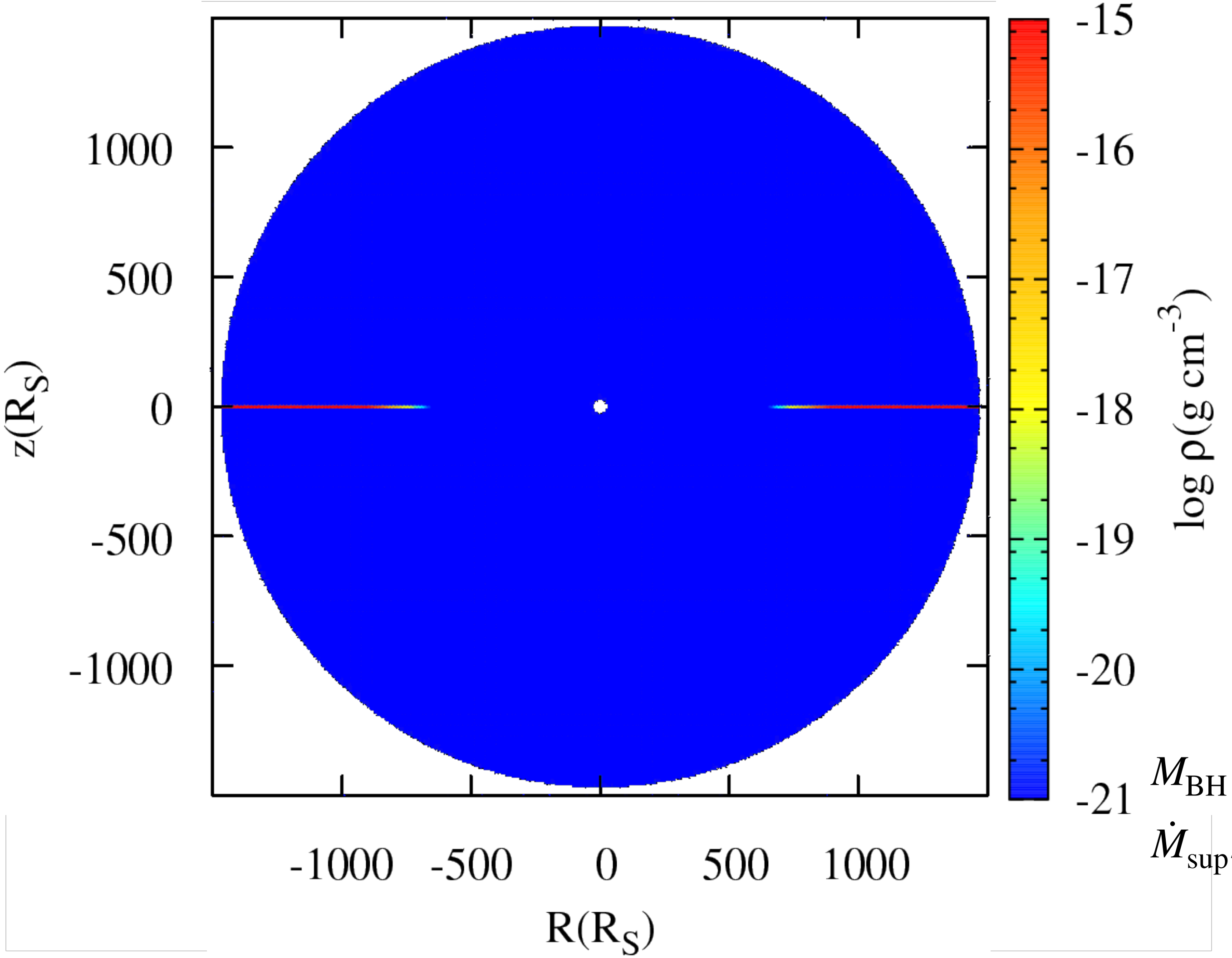
Results

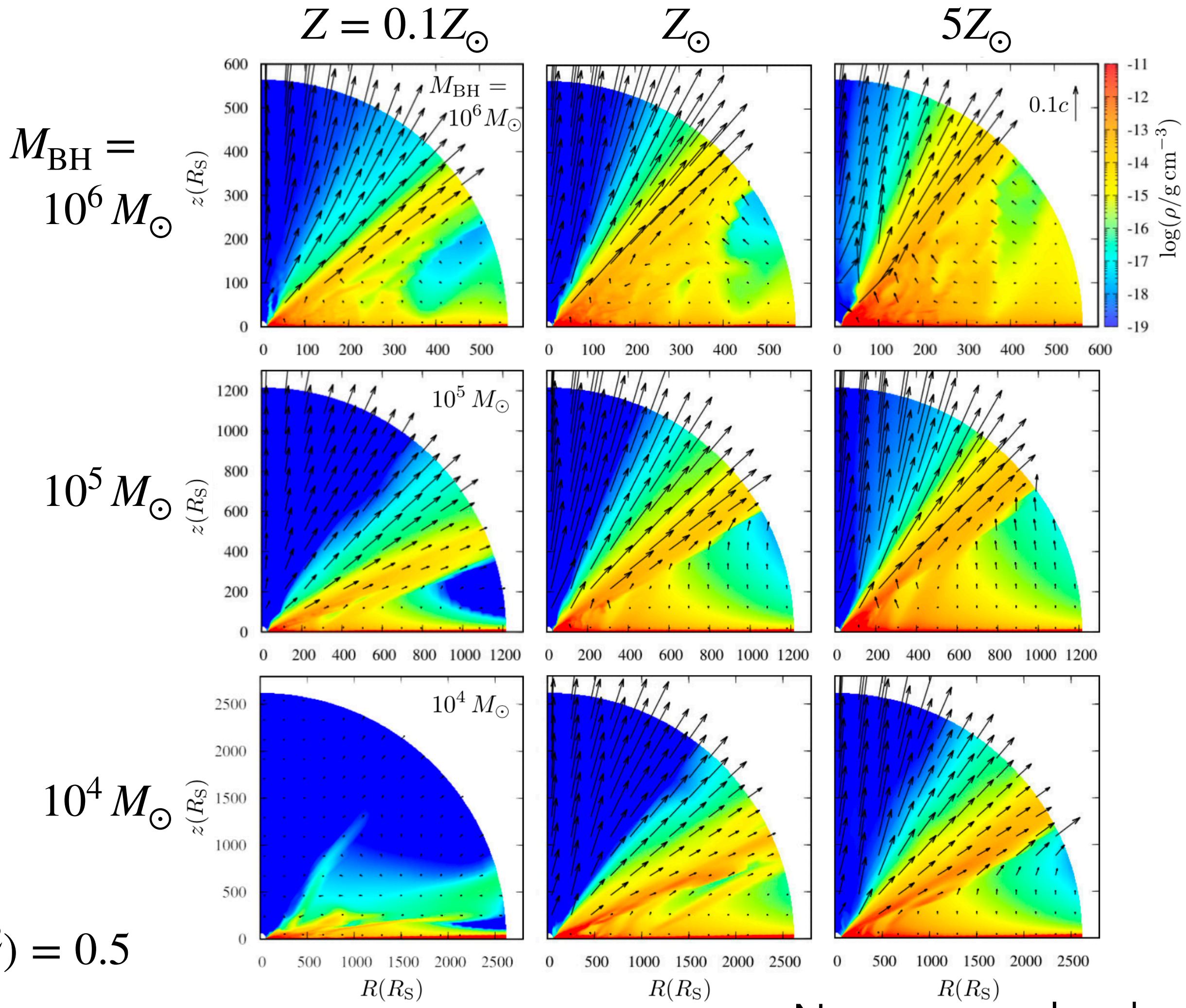


$M_{\rm BH} = 10^8\, M_\odot$

$\dot{M}_{\rm sup}/(L_{\rm Edd}/0.06c^2) = 0.5$

Metallicity and BH mass dependencies

- Denser and faster winds appear for higher metallicity and larger BH mass.



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Nomura et al. submitted

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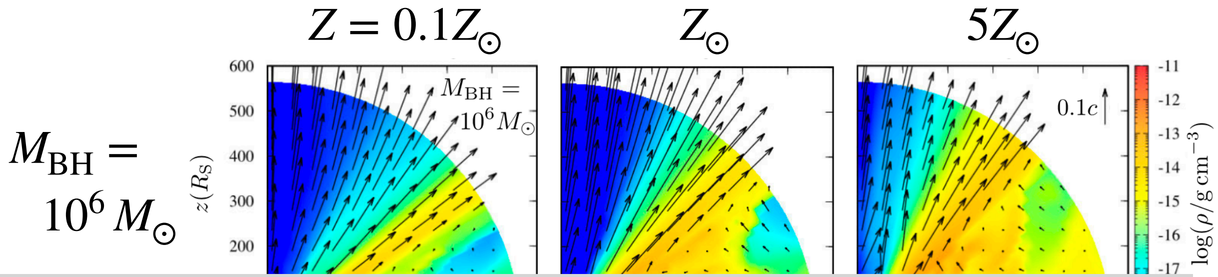

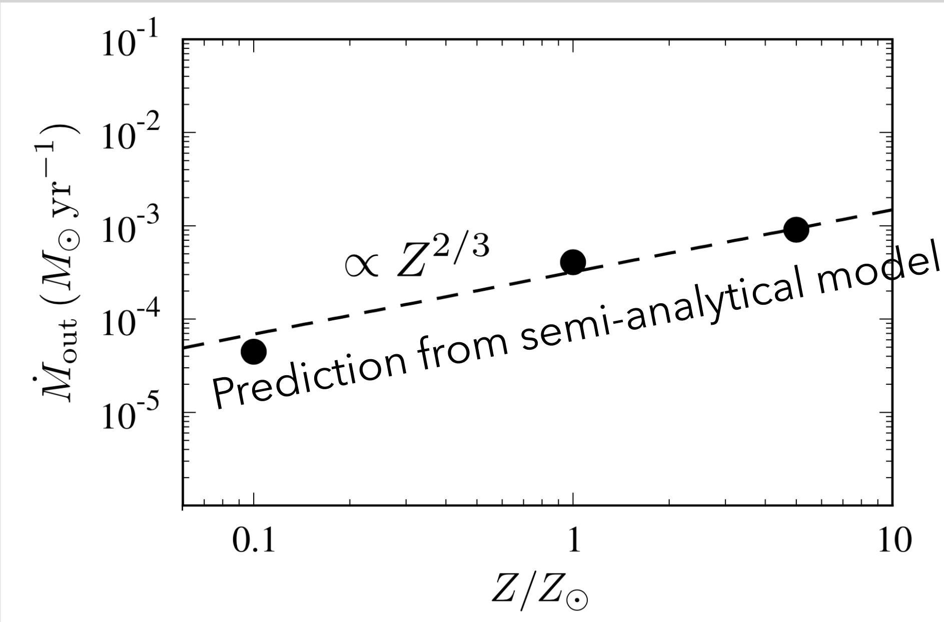

- Z-dependence comes from the Z-dependence of the force multiplier in the low ionized launching region region $M \propto Z^{0.4}$.

Nomura et al. submitted

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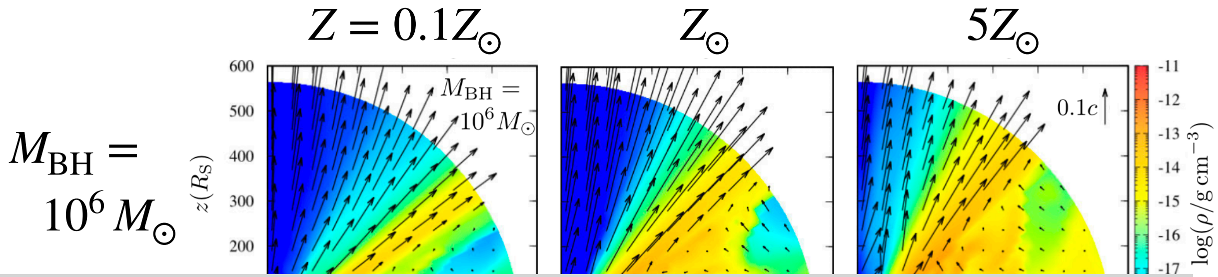
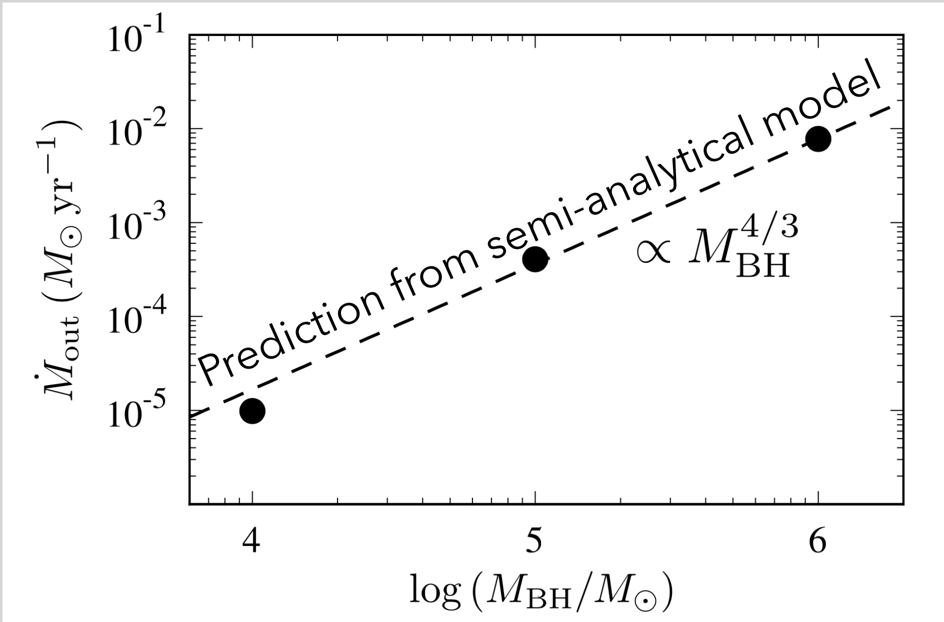




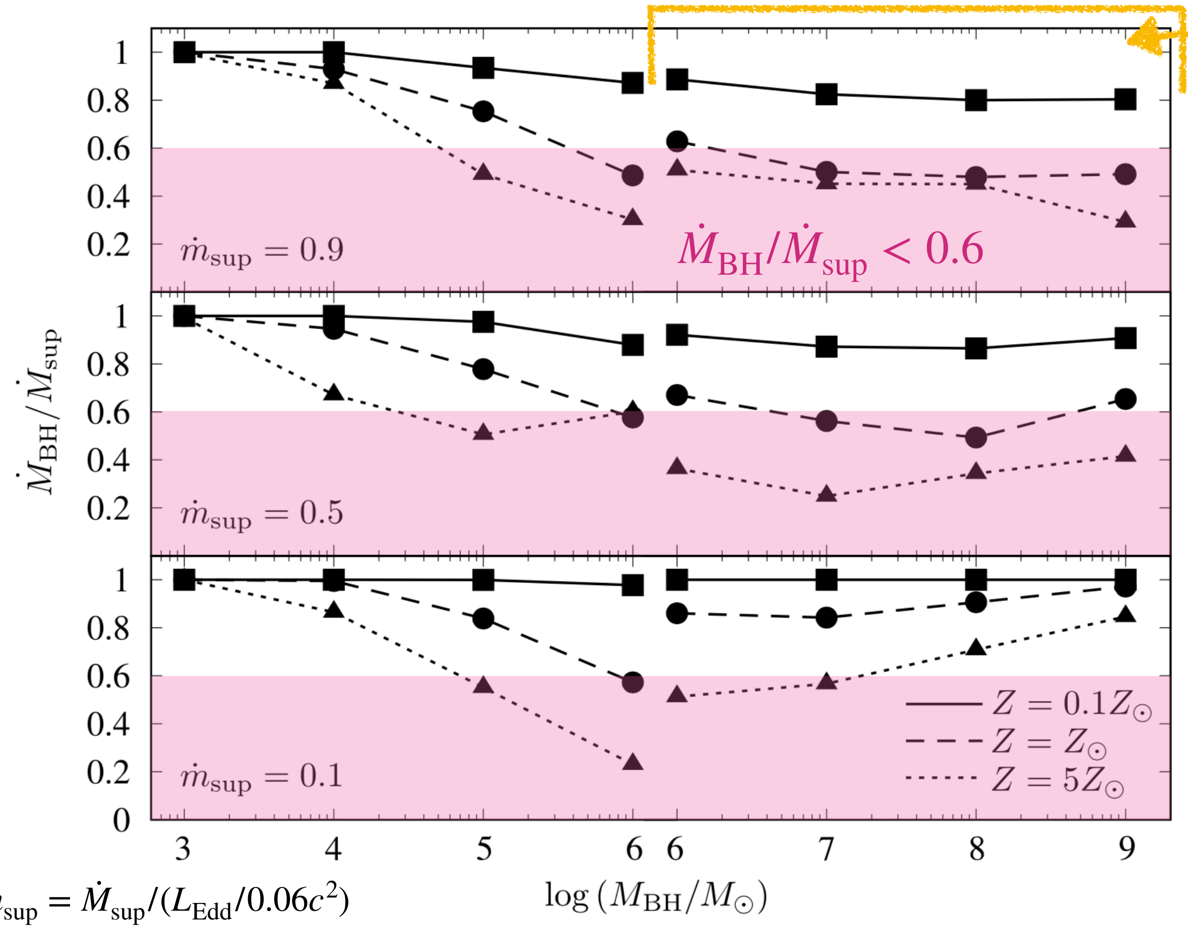
- $M_{\rm BH}$-dependence is explained by $M_{\rm BH}$-dependence of the surface area of the UV-bright launching region $S \propto R(T_{\rm eff} \sim 10^5\,{\rm K})^2 \propto M_{\rm BH}^{4/3}$.

$R(R_{\rm S})$ $R(R_{\rm S})$ $R(R_{\rm S})$

Nomura et al. submitted

Mass accretion rate

Mass accretion rate onto the BH/mass supply rate onto the disk



$\dot{m}_{\rm sup} = \dot{M}_{\rm sup}/(L_{\rm Edd}/0.06c^2)$

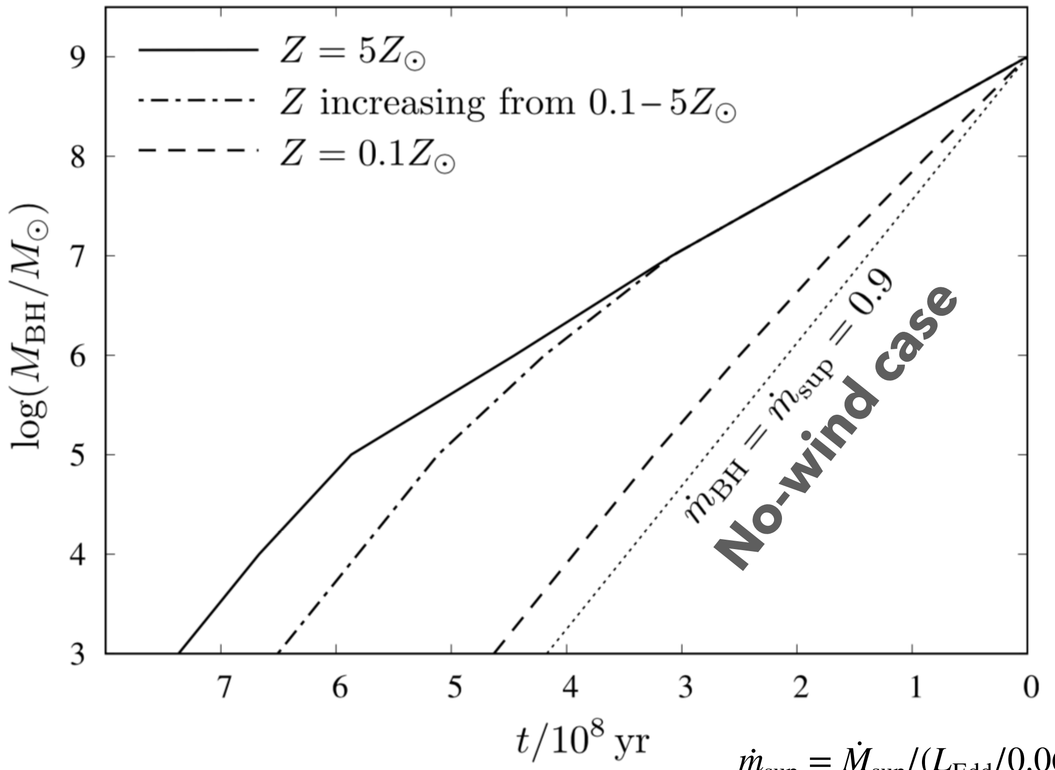
We apply the model assuming that the AGNs have highly-ionized region around the SMBHs ($r < 30R_{\rm S}$).

✦ The line-driven winds may **suppress the mass accretion for $M_{\rm BH} \gtrsim 10^5\,M_\odot$ in high-metallicity environments**.

Effects on the growth time of BHs

- In metal poor environment ($Z = 0.1Z_\odot$), the growth time is not different from that for the no-wind case, relatively fast evolution is possible.
- Growth times for $Z = 5Z_\odot$ at all the time or for Z increasing from $0.1-5Z_\odot$ are 1.6 and 1.8 times larger than that for no-wind case respectively.

  → Metal enrichment has an impact on the evolution of SMBHs.



$\dot{m}_{\rm sup} = \dot{M}_{\rm sup}/(L_{\rm Edd}/0.06c^2)$

Summary

- ✦ **Denser and faster disc winds appear for higher metallicity and larger BH mass.**
- ✦ The line-driven winds may **suppress the mass accretion for $M_{\rm BH} \gtrsim 10^5\, M_\odot$ in high-metallicity environments**.
- ✦ Z-dependence and $M_{\rm BH}$-dependence of the mass loss rate are explained by the Z-dependence of the force multiplier in the low ionized launching region and $M_{\rm BH}$-dependence of the surface area of the UV-bright launching region and effective temperature at the launching radius.
- ✦ **The BH growth slows down when the metallicity is high at all the time or increases with the growth of BH mass.**