A Novel Model for Line-driven Disk Winds: Origin of UFOs and Self-regulation of SMBH Growth

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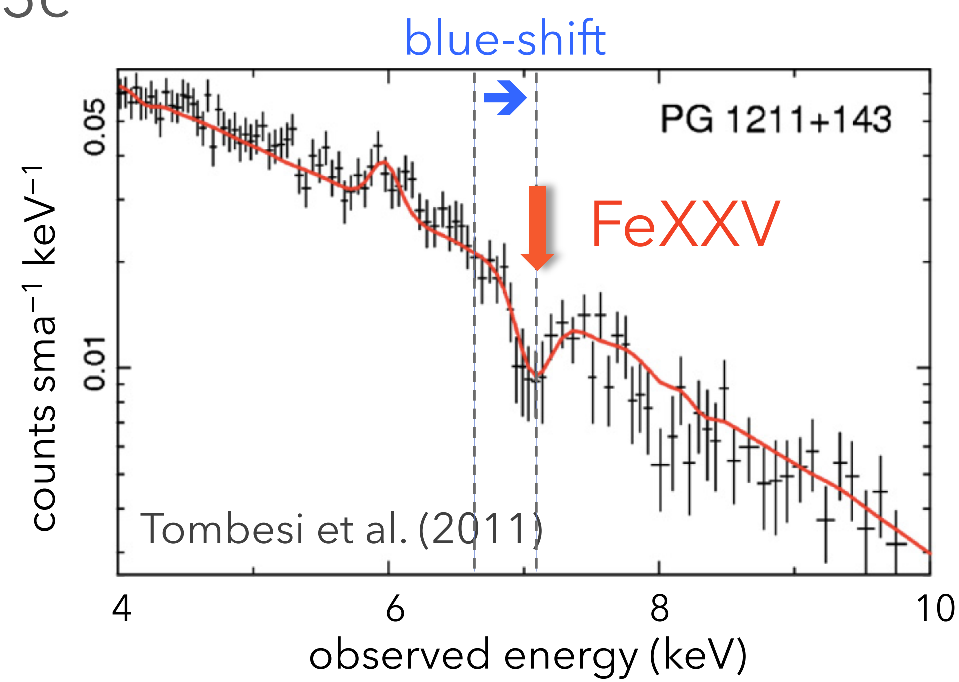
Ultra-fast outflows

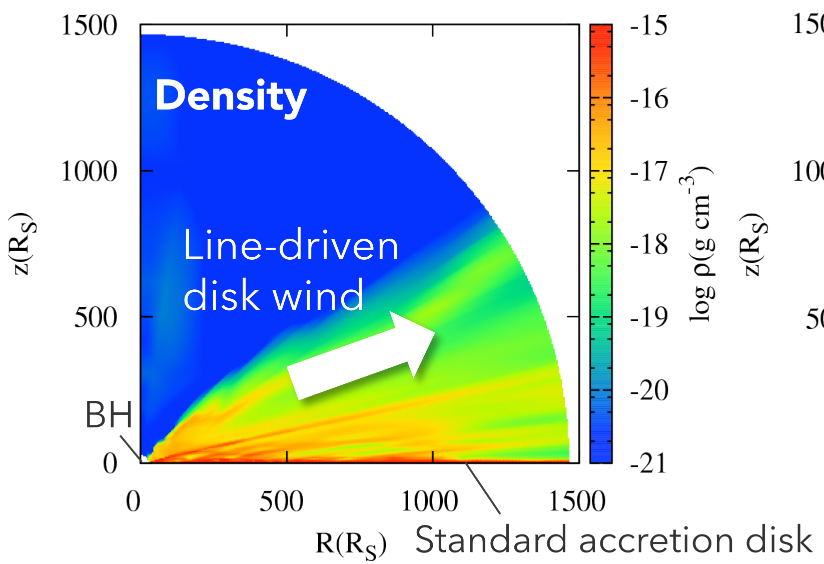
- suggested by absorption lines of FeXXV and/or FeXXVI in X-ray spectra
- outflow speed ~0.1c–0.3c
- detected in ~40% of AGNs

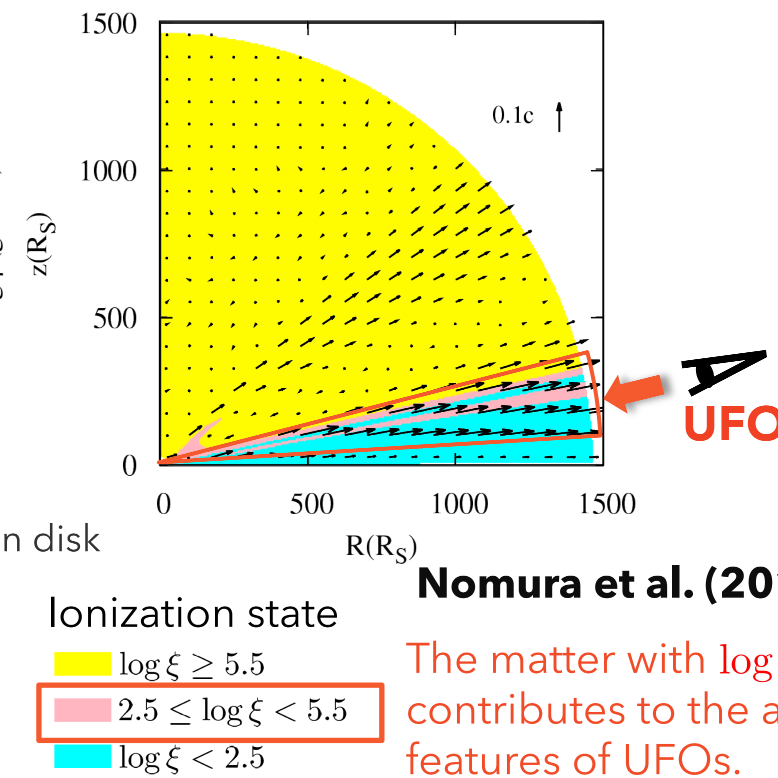


UFOs may have an important role in the co-evolution of SMBHs and their host galaxies because the mass outflow rate and energy outflow rate are large.

Line-driven disk winds

- accelerated by the radiation force due to spectral lines (line force)
- The line force accelerates moderately ionized metals.
- **reproduce the observational features of UFOs**





Nomura et al. (2016, 2017)

The matter with $\log \xi \sim 2.5$–5.5 contributes to the absorption features of UFOs.

Aim of this work

- Previous model:
  - ignore decrease of the accretion rate due to the disk wind
  - When the Eddington ratio $\gtrsim 0.5$, the outflow rate is larger than the accretion rate.

    ➔ **violate the mass conservation**
- This work:
  - **construct a new model in which the outflow rate, the accretion rate and the wind structure are calculated self-consistently**
  - **research a role of the outflow in the context of the SMBH growth**

Method

Basic equations [polar coordinate (r, θ, ϕ)]

Radiation force including the line force

(1) Mass conservation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

(2) Equation of motion
$$\begin{cases} \dfrac{\partial(\rho v_r)}{\partial t} + \nabla \cdot (\rho v_r \boldsymbol{v}) = -\dfrac{\partial p}{\partial r} + \rho\left[\dfrac{v_\theta^2}{r} + \dfrac{v_\varphi^2}{r} + g_r + f_{\mathrm{rad},\,r}\right] \\ \dfrac{\partial(\rho v_\theta)}{\partial t} + \nabla \cdot (\rho v_\theta \boldsymbol{v}) = -\dfrac{1}{r}\dfrac{\partial p}{\partial \theta} + \rho\left[-\dfrac{v_r v_\theta}{r} + \dfrac{v_\varphi^2}{r}\cot\theta + g_\theta + f_{\mathrm{rad},\,\theta}\right] \\ \dfrac{\partial(\rho v_\varphi)}{\partial t} + \nabla \cdot (\rho v_\varphi \boldsymbol{v}) = -\rho\left[\dfrac{v_\varphi v_r}{r} + \dfrac{v_\varphi v_\theta}{r}\cot\theta\right] \end{cases}$$

(3) Energy equation $$\frac{\partial}{\partial t}\left[\rho\left(\frac{1}{2}v^2 + e\right)\right] + \nabla \cdot \left[\rho \boldsymbol{v}\left(\frac{1}{2}v^2 + e + \frac{p}{\rho}\right)\right] = \rho \boldsymbol{v} \cdot \boldsymbol{g} + \rho \mathcal{L}$$

Radiative heating/cooling

Radiation force including the line force

$$\mathbf{f}^{\mathrm{rad}} = \frac{\sigma_e \mathbf{F}_{\mathrm{UV}}}{c} + \frac{\sigma_e \mathbf{F}_{\mathrm{UV}}}{c} M$$

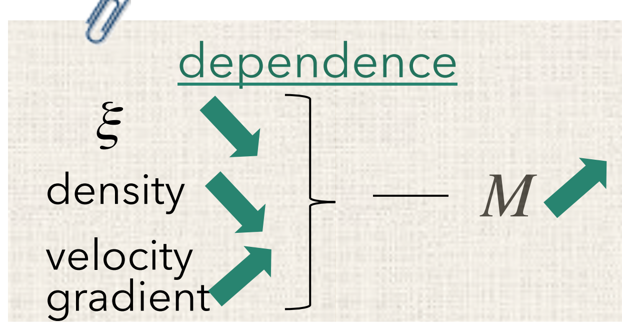
Radiation force due to electron scattering

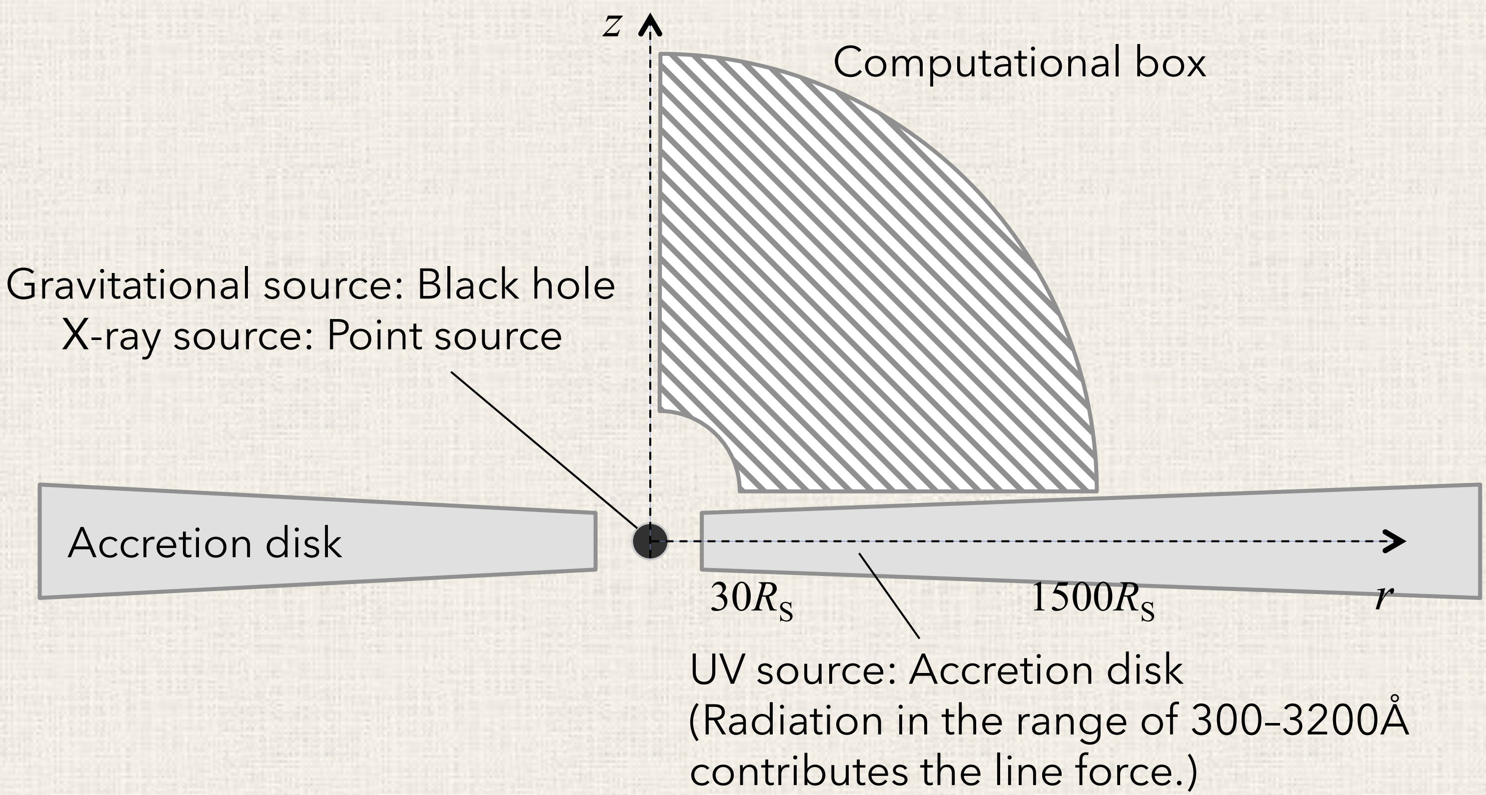
Line force

Force multiplier: function of density, ionization parameter ξ , and velocity gradient (Stevens & Kallman 1990)

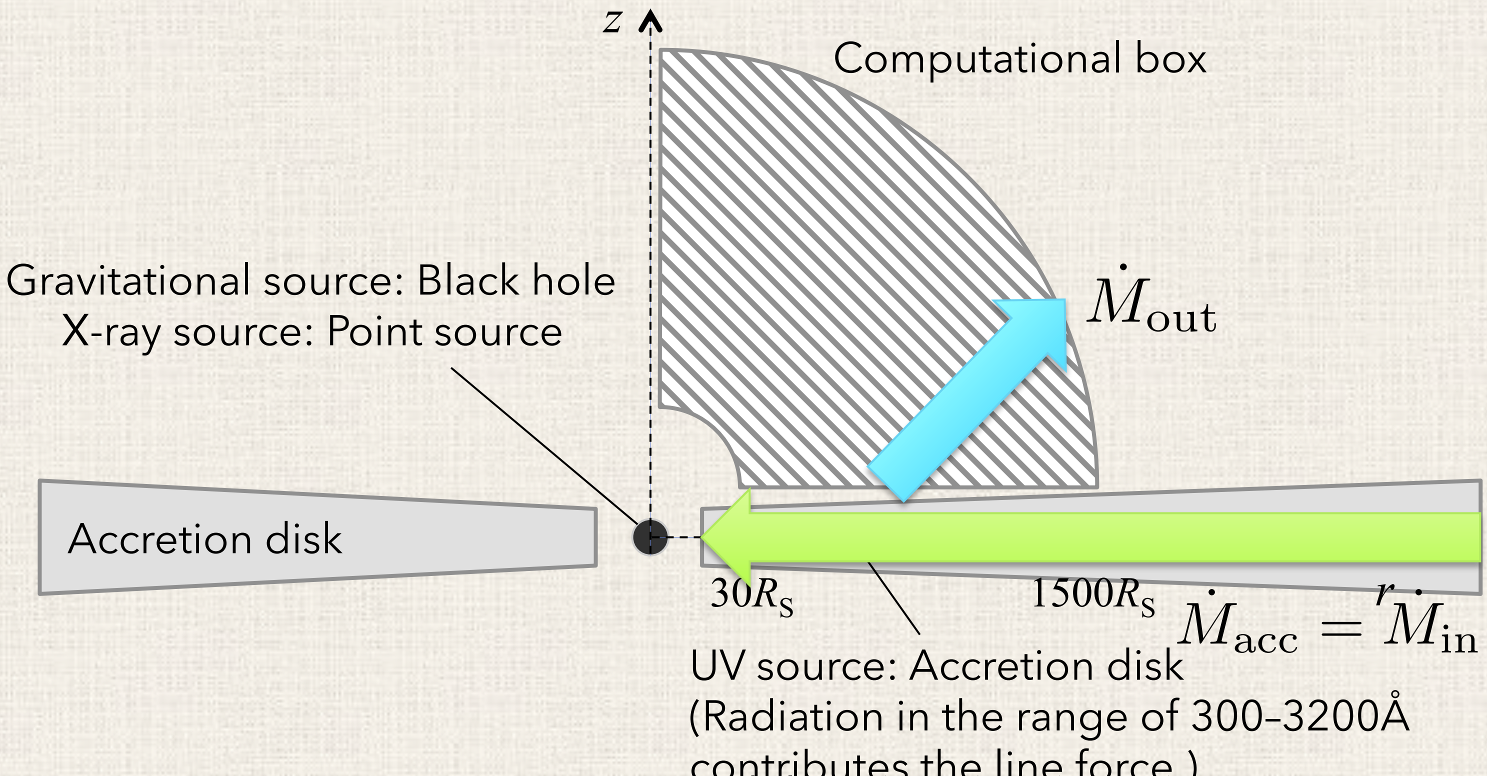
ionization parameter: $\xi = \dfrac{4\pi F_{\mathrm{X}}}{n}$

F_{X}: X-ray flux
n: number density





- Radiation is divided into two colors, X-ray & UV.
- Accretion disk surface is the boundary.
- Radiation source is located outside the simulation box.



Previous model: Mass accretion rate is constant.

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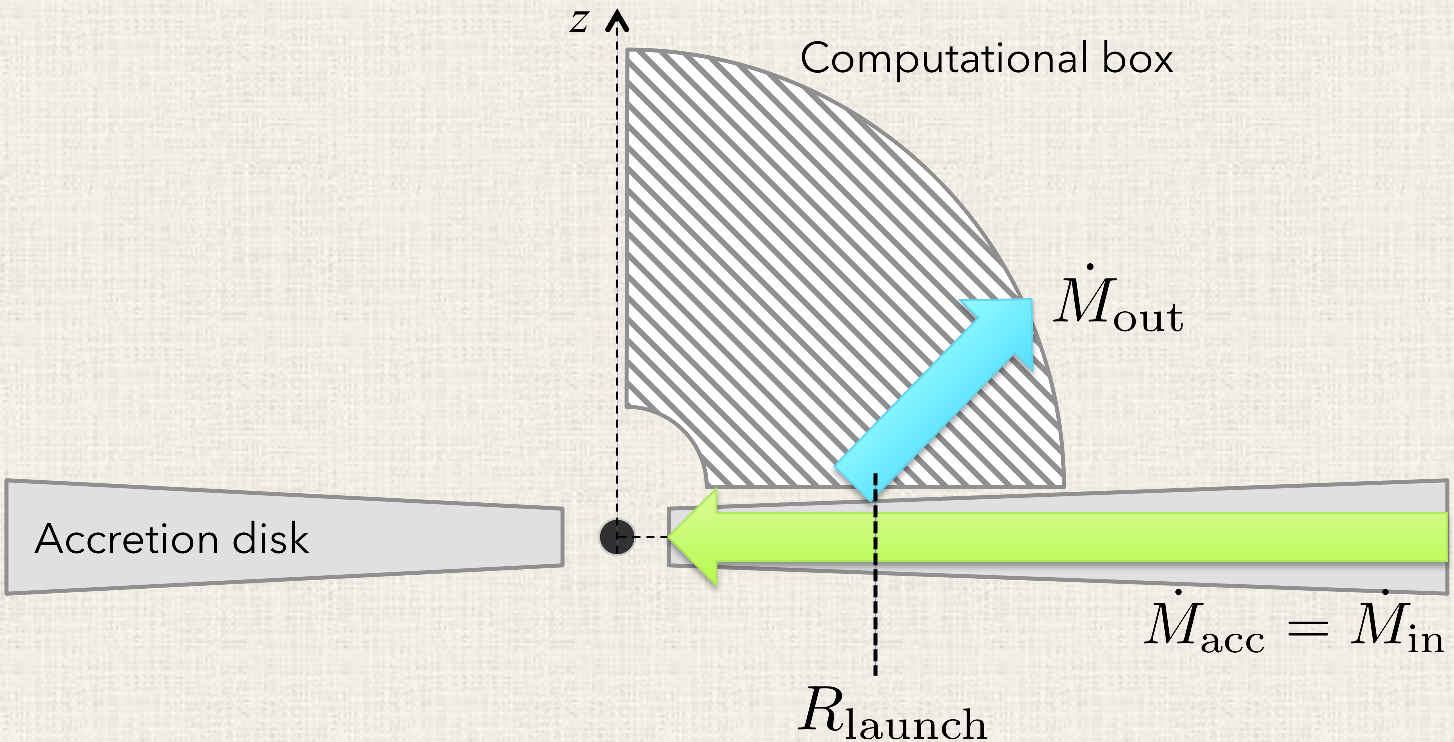

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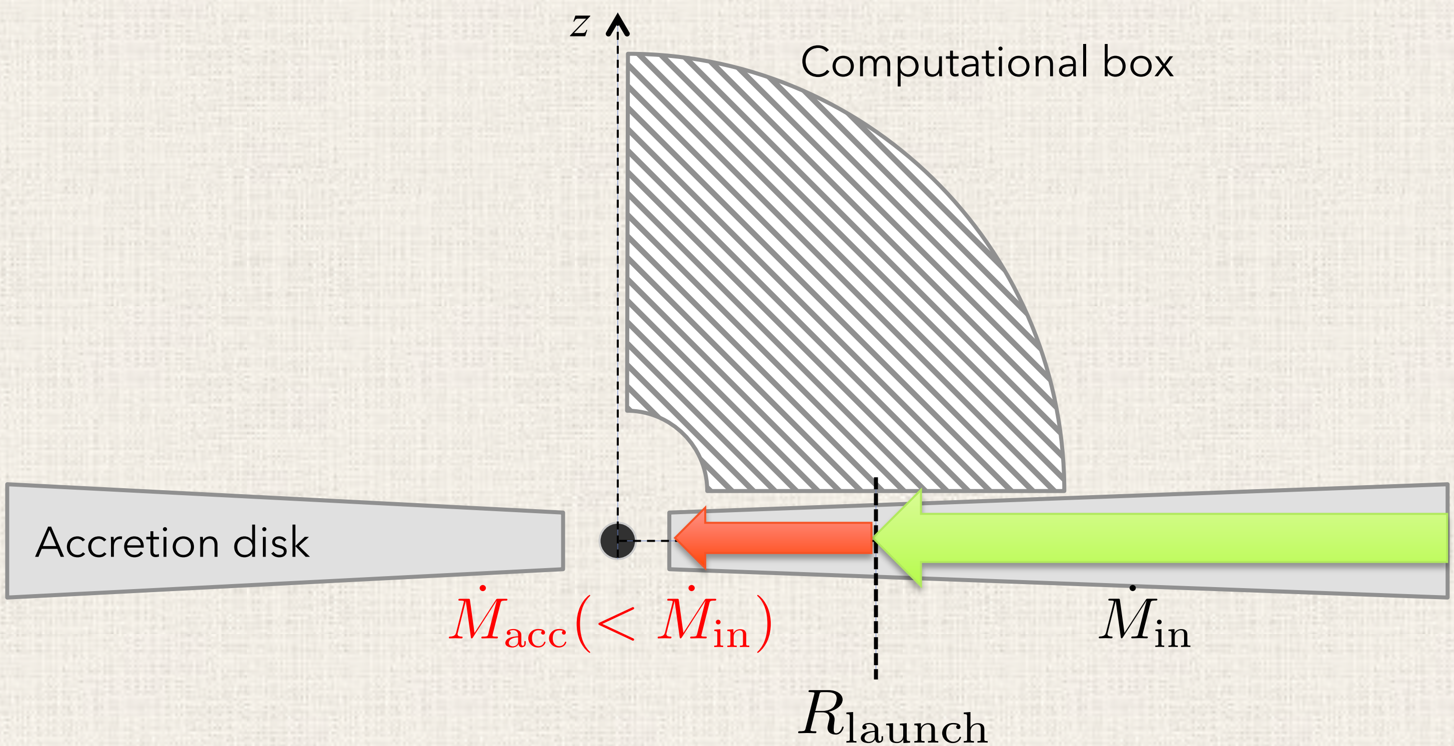
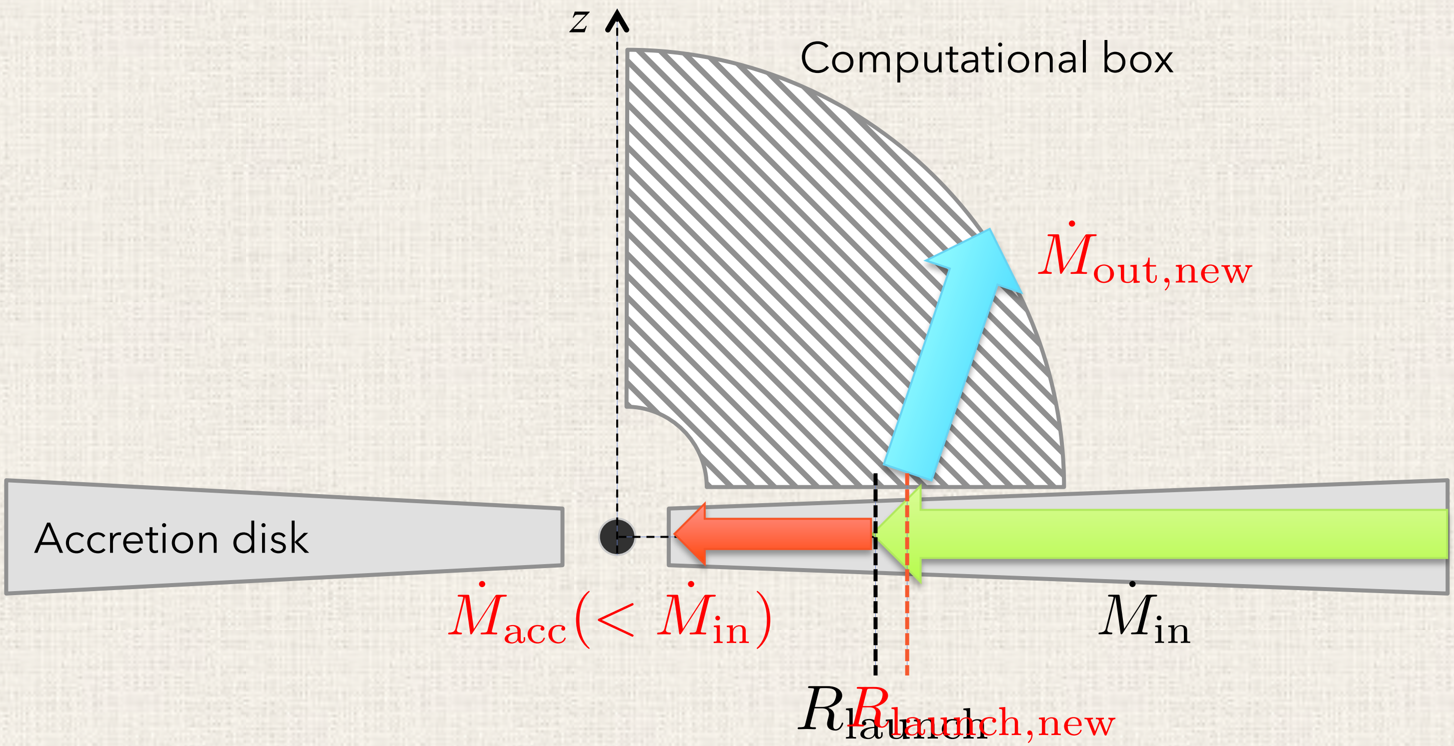


Previous model: Mass accretion rate is constant.

New model: Mass accretion rate decreases in response to the outflow rate.

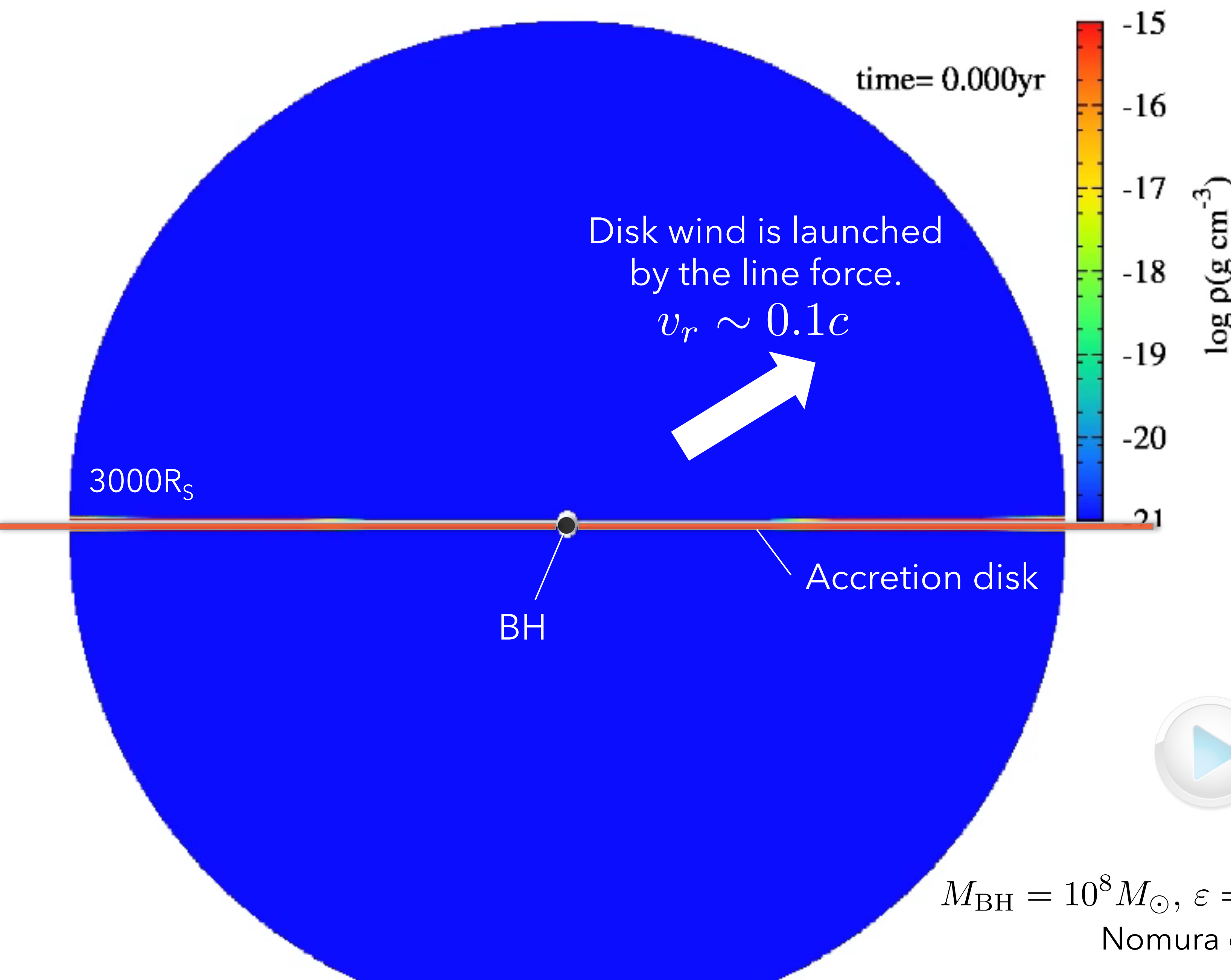


Previous model: Mass accretion rate is constant.

New model: Mass accretion rate decreases in response to the outflow rate.

For $M_{\rm BH}$ and $\dot{M}_{\rm in}$, we iterate the calculation until $\dot{M}_{\rm acc}$, $\dot{M}_{\rm out}$, and $R_{\rm launch}$ are converged.

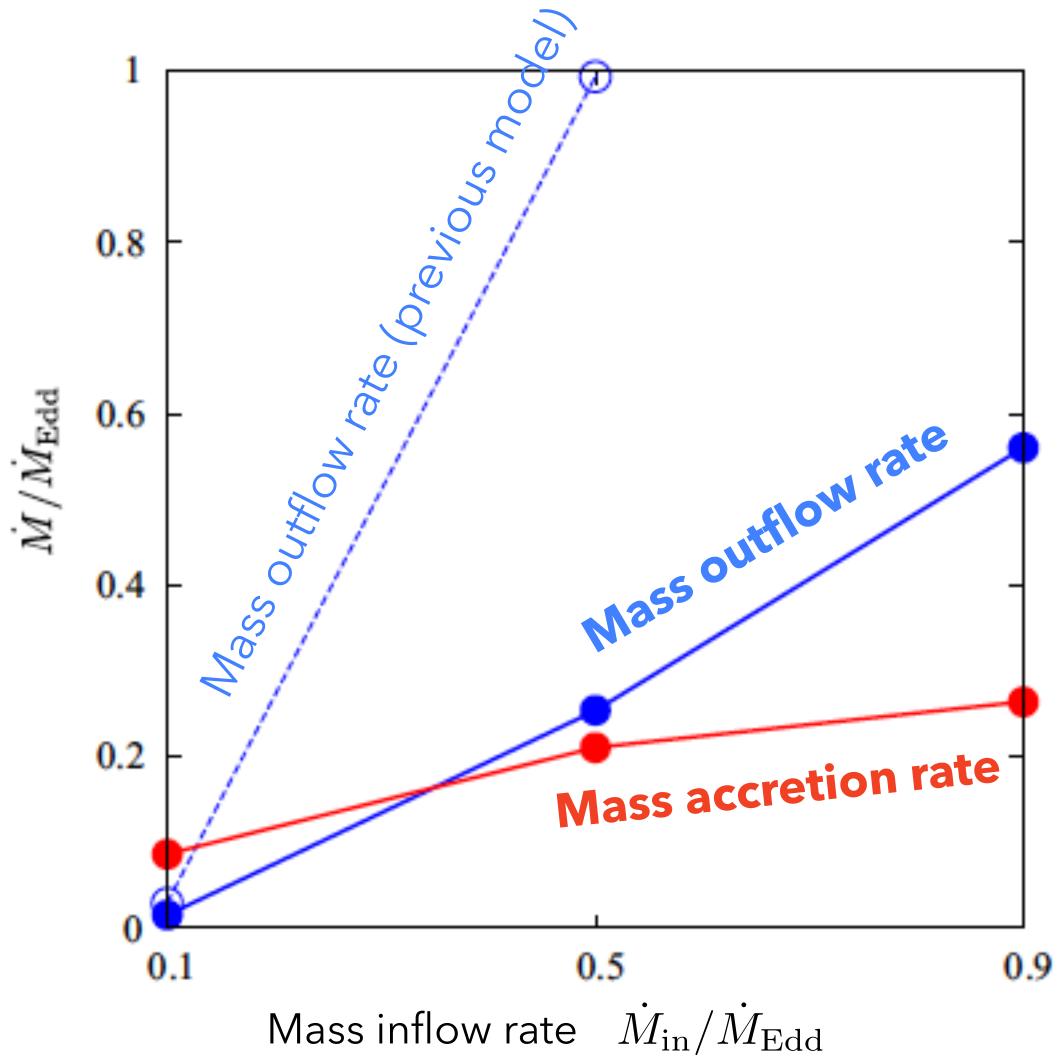
Results



$M_{\rm BH} = 10^8 M_\odot,\ \varepsilon = 0.5$

Nomura et al. (2016)

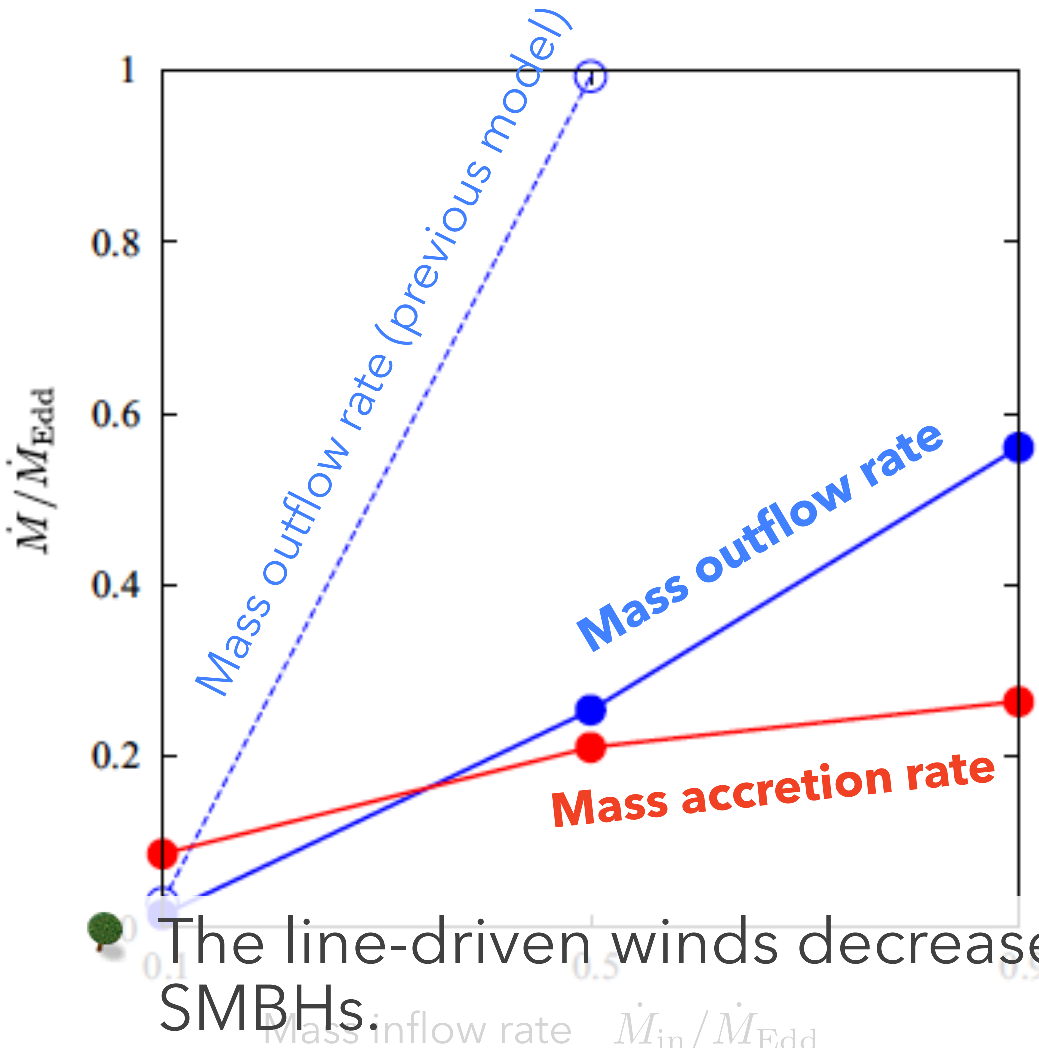
Mass outflow rate and accretion rate



For small inflow rate
the mass outflow rate is small
and $\dot{M}_{\rm acc} \sim \dot{M}_{\rm in}$.

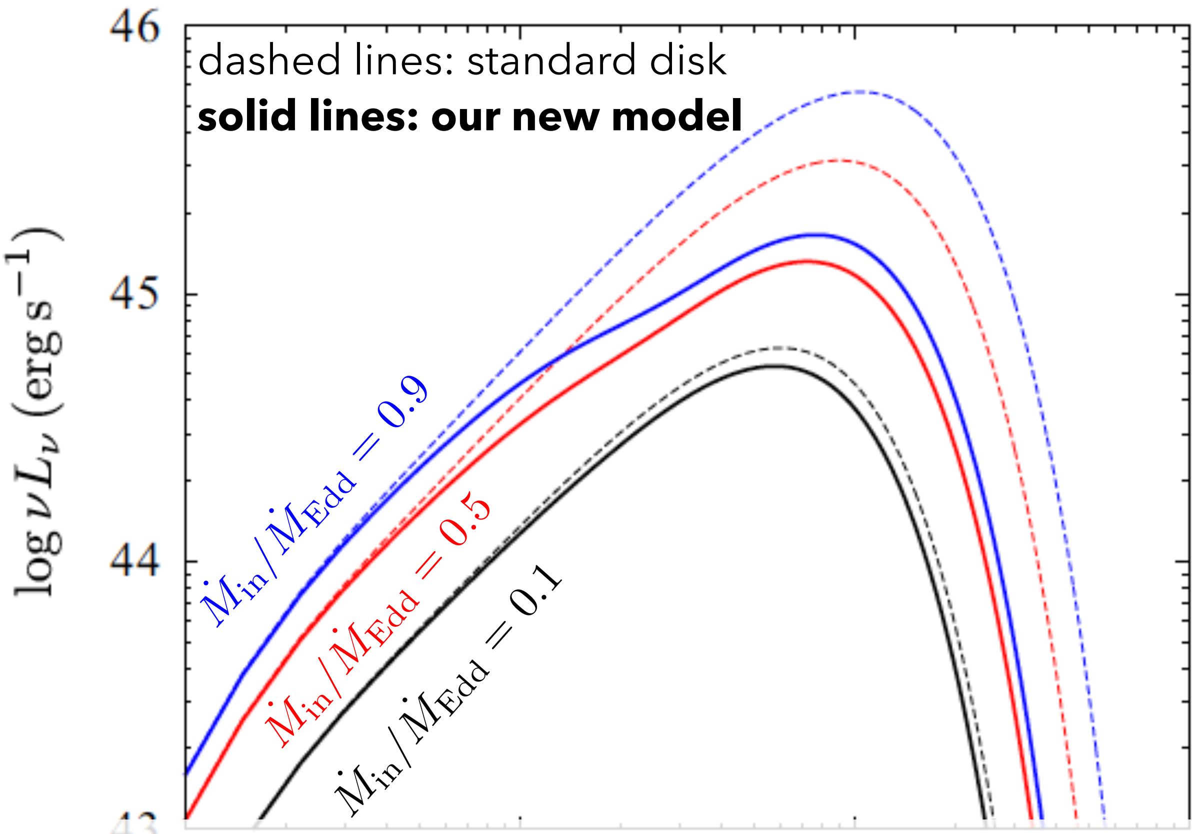
For large inflow rate,
the mass accretion rate is less
than a half of the inflow rate.

Mass outflow rate and accretion rate



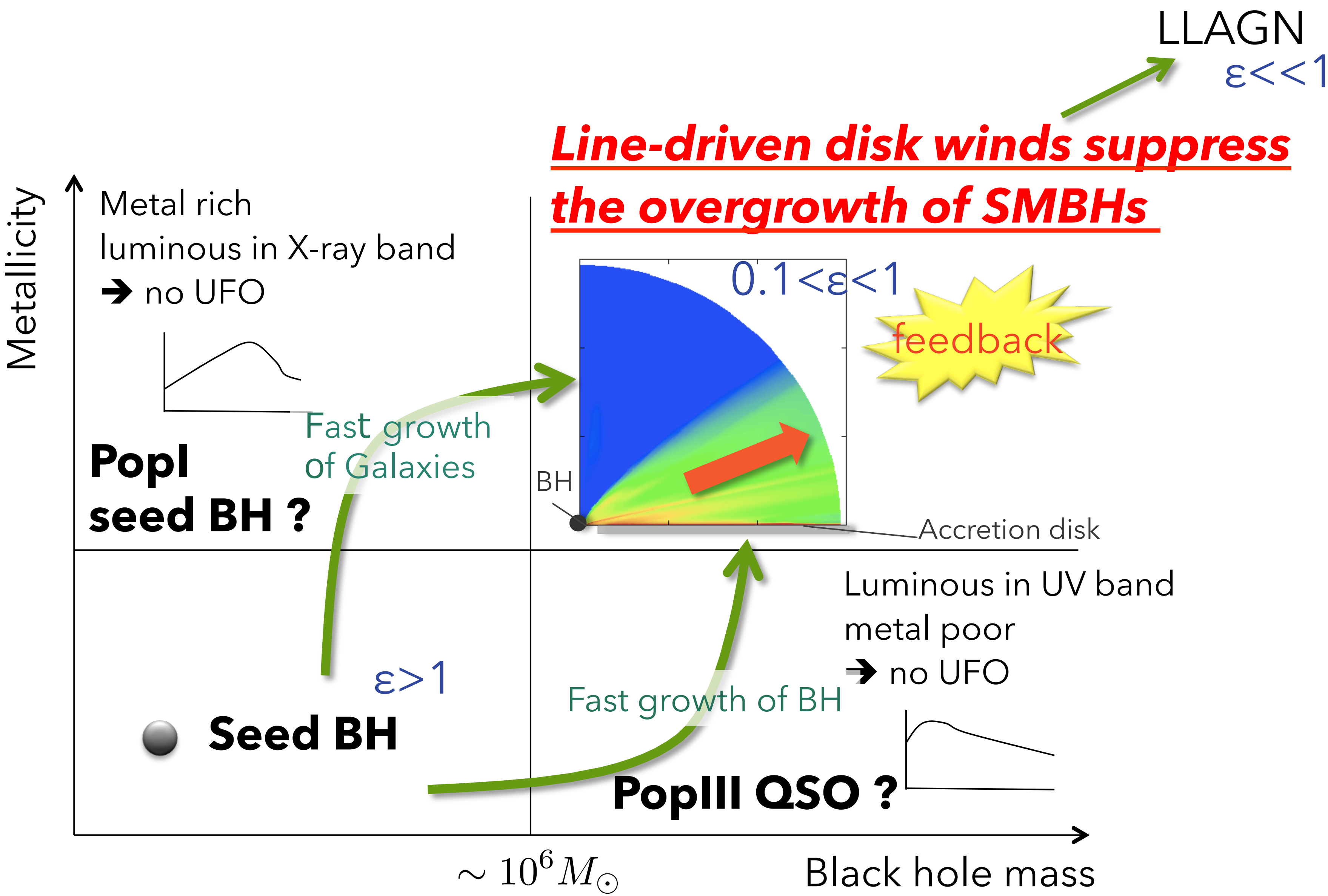
- The line-driven winds decrease the mass accretion onto SMBHs.
- These results are consistent with that almost all quasars are sub-Eddington.

Spectral Energy Distributions



- decease of the accretion rate in the inner region of the disk
  - ➔ low effective temperature
  - ➔ reduced flux in the large-frequency range
- We could find the outflows from continuum spectra.

Role of line-driven winds



Summary

- We constructed the self-consistent model of the line-driven disk winds.
- The line-driven winds decrease the mass accretion rates onto SMBHs.
- The line-driven winds suppress the overgrowth of SMBHs in the final stage of their evolution.

  ➔ **Self-regulation of SMBH Growth**