超巨大ブラックホールの超エディントン降着成長における熱伝導の影響

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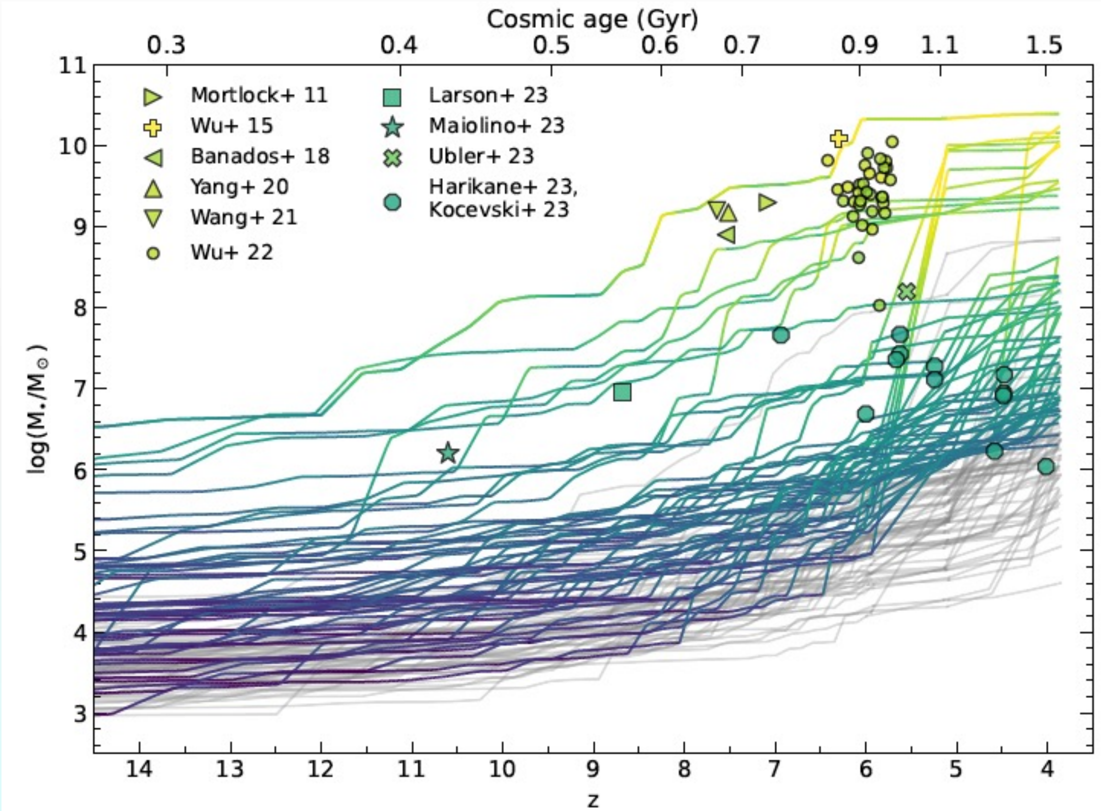
References: NK & Kohri 2023, ApJ, **955**, 67

ブラックホール大研究会〜星質量から超巨大ブラックホールまで〜 2024.2.28 - 3.2

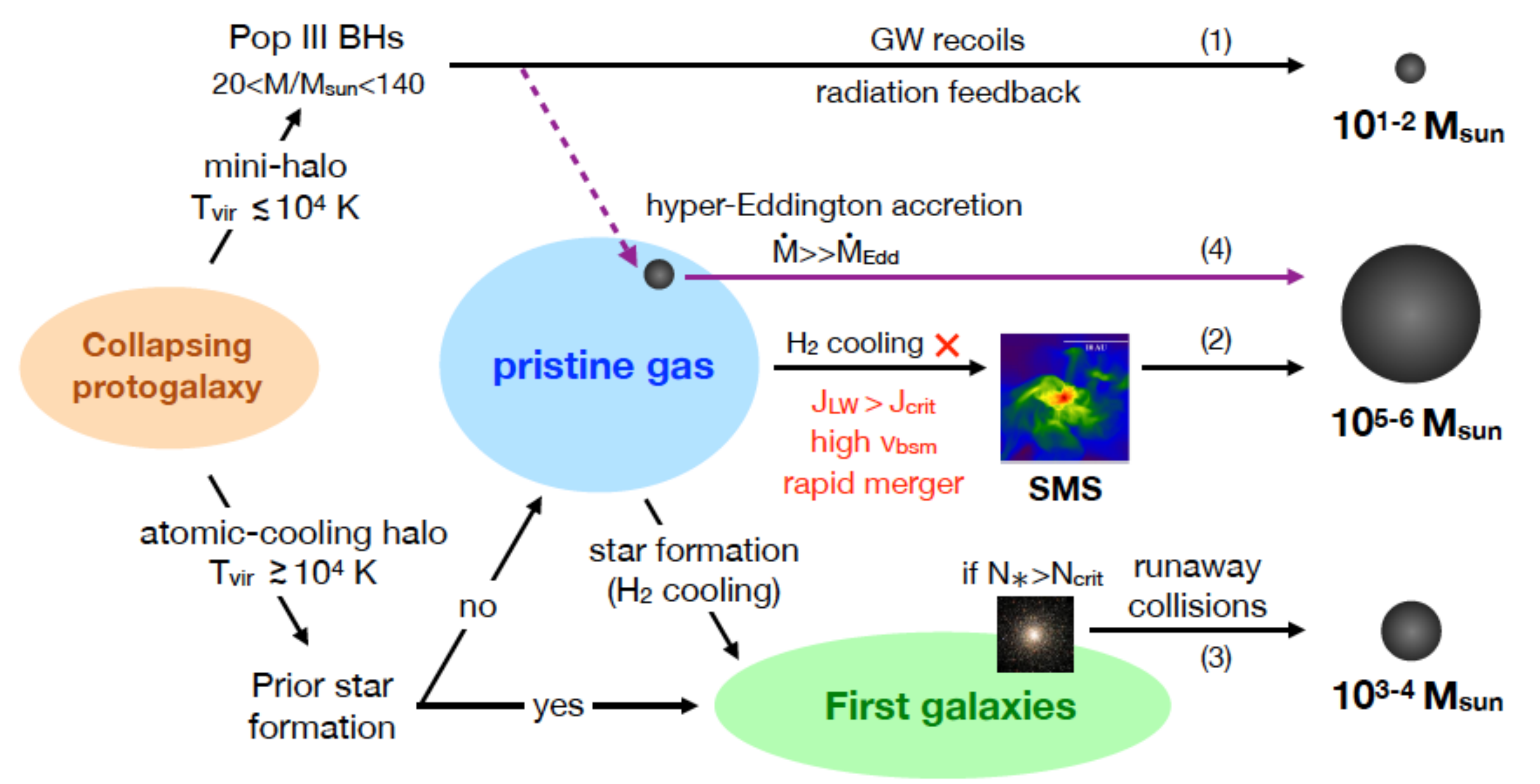
SMBHs at high redshifts



Li, Inayoshi, Onoue et al. 2023

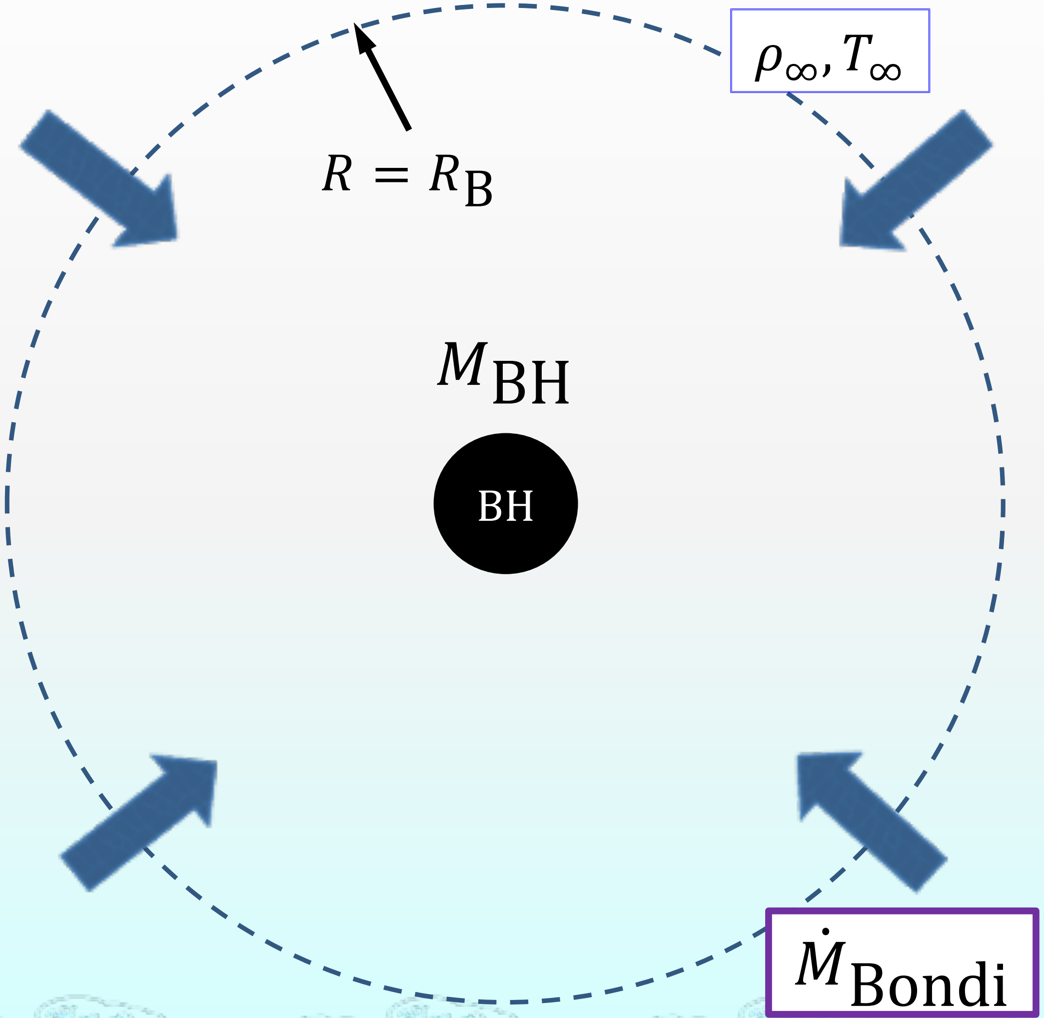
- The observations of high redshift quasars poses a challenge to the theoretical models of SMBH growth
- Uninterrupted (super-) Eddington accretion onto seed BHs ($M_{\mathrm{BH}} \backsim 10 - 10^5 M_{\odot}$?) is needed
- They should be “rare”.

SMBH formation processes



Inayoshi, Visbal & Haiman 2019

Bondi accretion



spherically symmetric accretion of ambient medium:

$$\dot{M}_{\mathrm{Bondi}} \approx 4\pi R_{\mathrm{B}}^2 \rho_\infty c_s$$

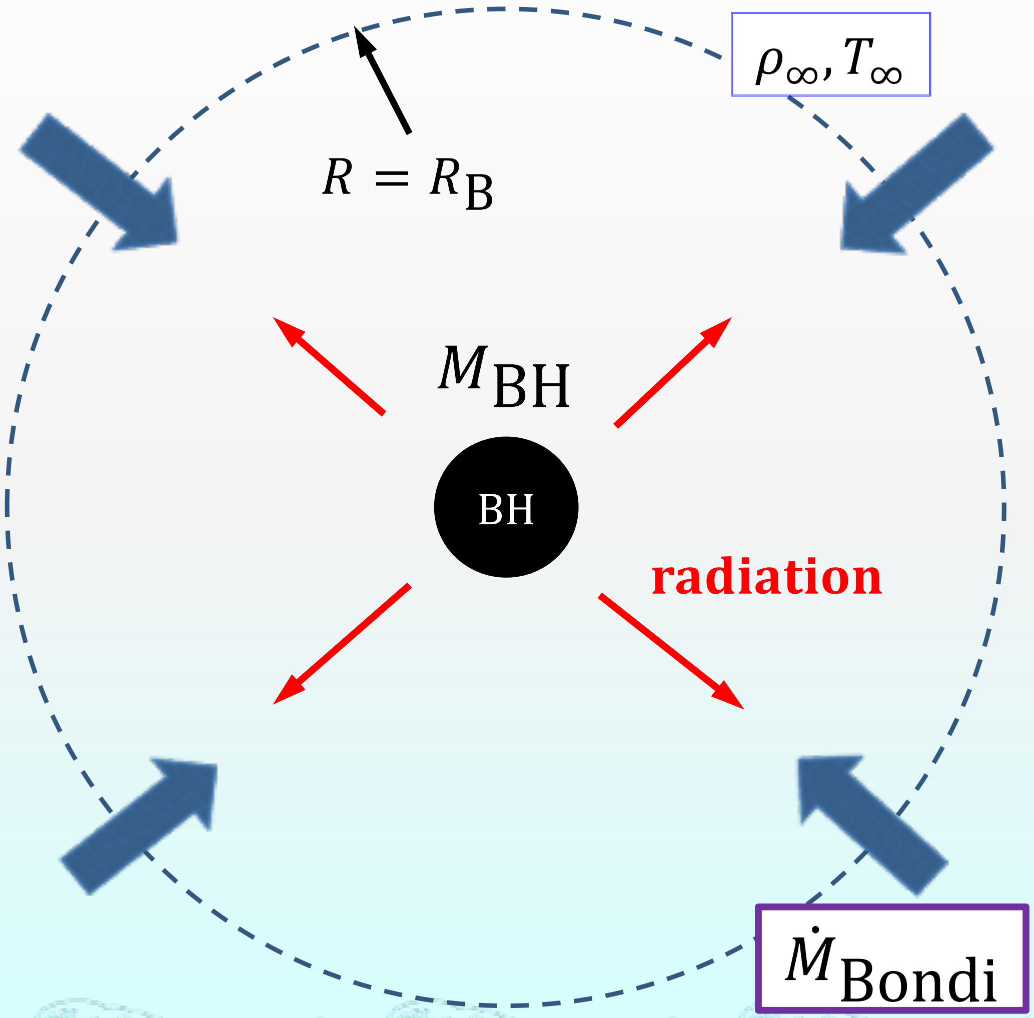
where

$$R_{\mathrm{B}} = \frac{G M_{\mathrm{BH}}}{c_s^2} \sim 1.97 \times 10^{18} \mathrm{cm}\, M_{\mathrm{BH},4}\, T_{\infty,4}^{-1}$$

... Bondi radius

$$\dot{M}_{\mathrm{Bondi}} / \dot{M}_{\mathrm{Edd}} = 22 M_{\mathrm{BH},4}\, n_{\infty,4}\, T_{\infty,4}^{-3/2}$$

radiation feedback



Intense mass accretion is always associated with intense radiation.

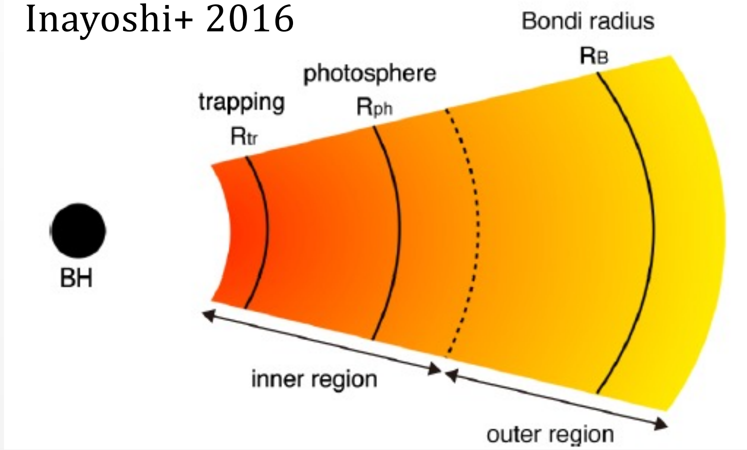
- radiation pressure (∵ super-Eddington)
- radiative heating (ionization, Compton scattering)

→ suppression of $\dot{M}_{Bondi} \propto T_\infty^{-3/2}$

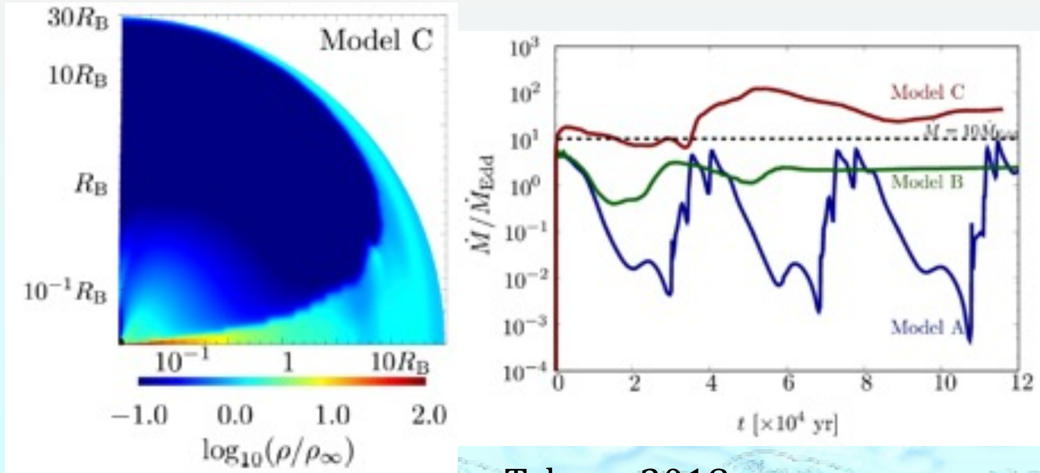
How to avoid feedback effects

- In the spherically symmetric case, the feedback due to radiation pressure and heating can be ineffective because of photon trapping only when $\dot{M}_{\rm Bondi} \gg 1$ (Inayoshi et al. 2016).

Inayoshi+ 2016

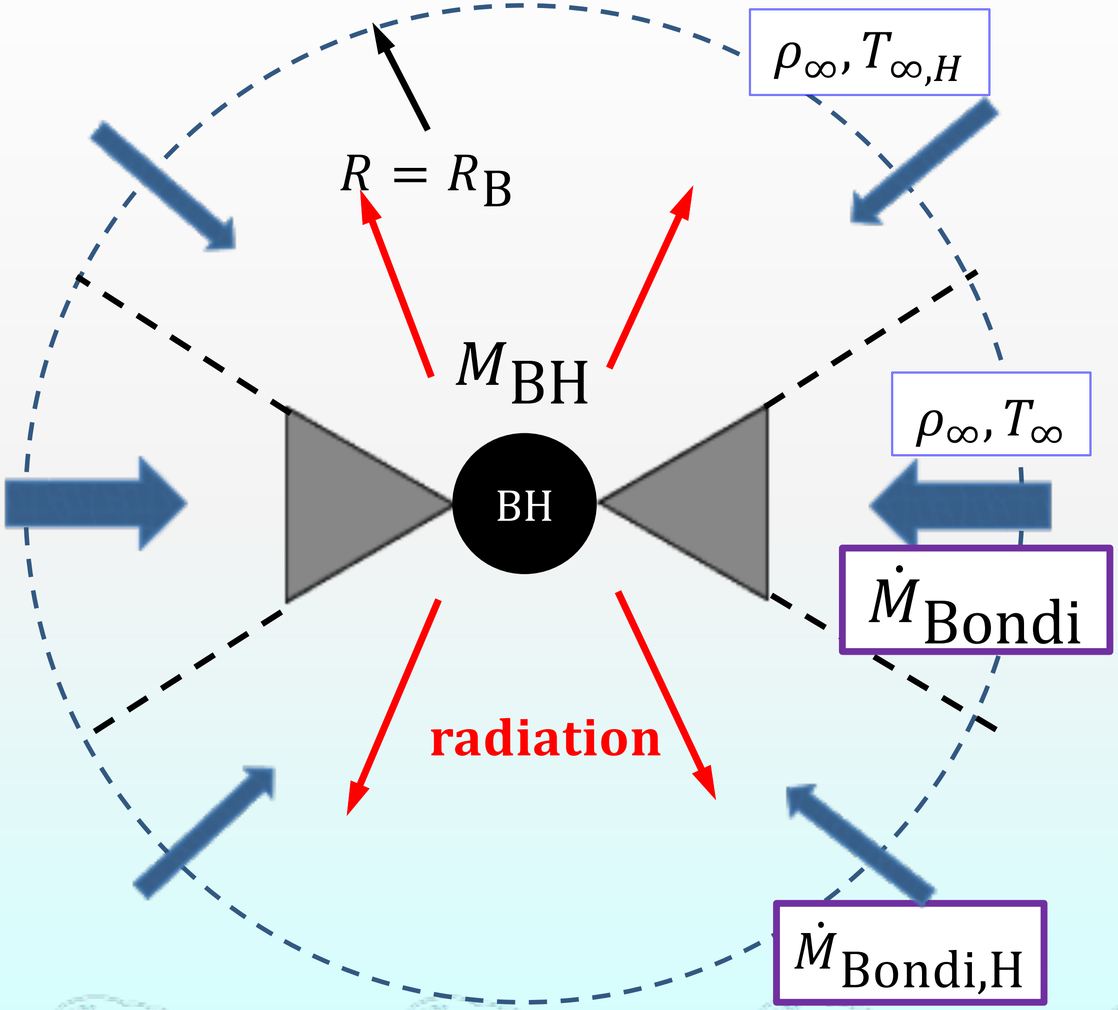


- Due to the formation of an accretion disk, the radiation would be anisotropic and super-Eddington accretion through the equatorial plane is expected (Sugimura et al. 2017; Takeo, Inayoshi et al. 2018).



Takeo+ 2018

Mass accretion under anisotropic radiation



- super-Eddington accretion → formation of a geometrically thick disk (slim disk)
- The region around the equatorial plane do not suffer from radiative heating

→ $\dot{M}_{\rm Bondi}$ would not be suppressed within a certain solid angle around the equatorial plane and remains super-Eddington.

Motivation of this work

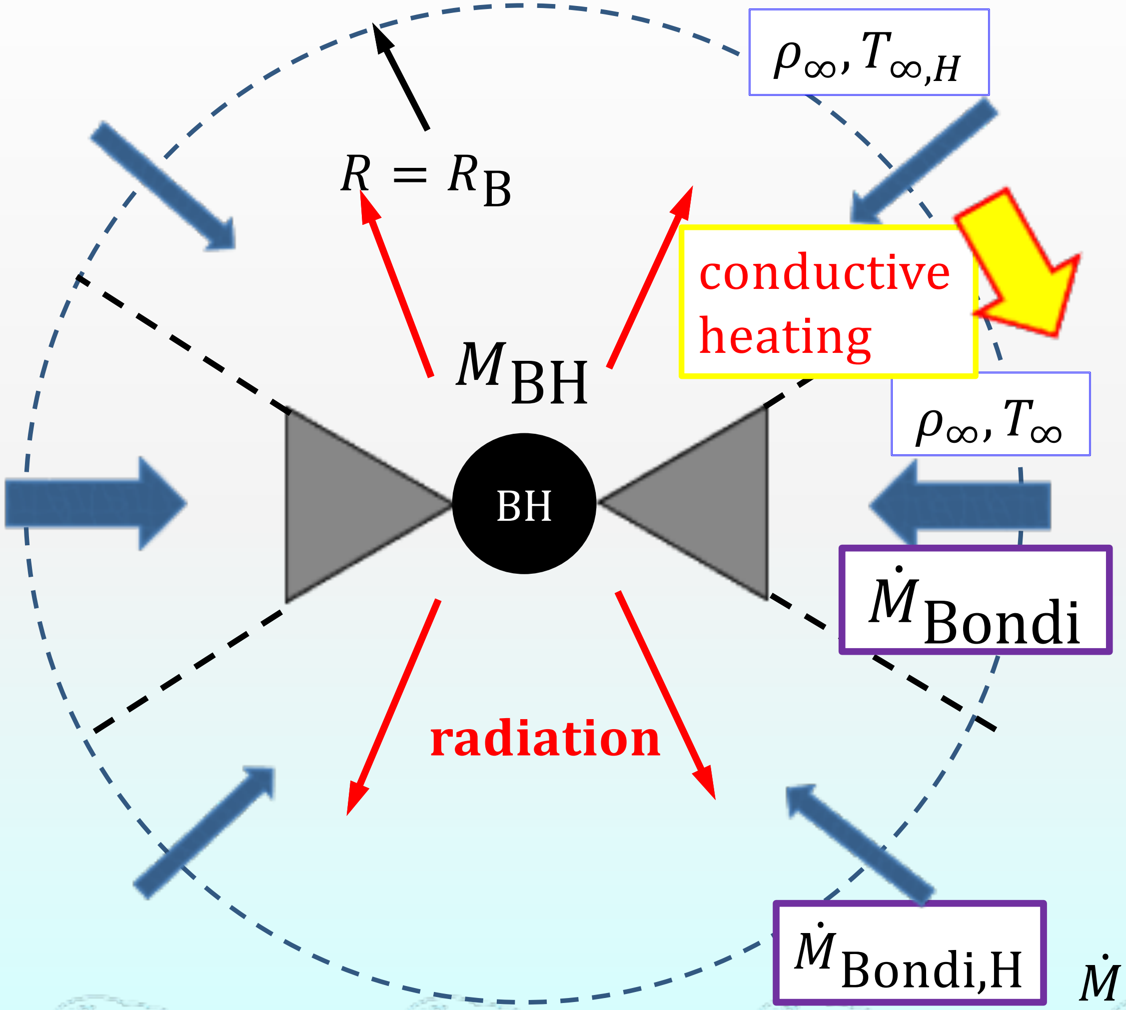
- Mass accretion onto a black hole is not in general isotropic but is disk-like, and so radiation from an accretion disk would be shielded by the disk itself

→ Gas within the shielded angle would not be heated and Bondi accretion rate would not be suppressed (Sugimura+ 2016; Takeo+ 2018 etc.)

- Can the gas behind the disk really avoid heating?
  - Non-radial radiation flux produced by electron scattering

  → unlikely, because the ionized gas is optically thin
  - Heat conduction ← this work
  - Convection

Our picture



- $T_{\infty,H} \gg T_\infty$
  → heat conduction from the radiatively-heated region to the adjacent cold region can be significant
  → If the conduction is faster than the accretion, the surrounding medium would be isotropically heated → whole suppression of $\dot{M}_{Bondi}$

$$\dot{M}_{Bondi,H}/\dot{M}_{Edd} = 7\times10^{-4} M_{BH,4} n_{\infty,4} T_{\infty,H,7}^{-3/2}$$

About radiative heating

Bondi radius

$$R_{\rm B} \equiv \frac{GM_{\rm BH}}{c_\infty^2} \simeq 1.97 \times 10^{18} M_{\rm BH,4} T_{\infty,4}^{-1}\ {\rm cm},$$

ionization radius (i.e., the gas is fully ionized inside this radius)

$$R_{\rm H\,II} = \left(\frac{3Q_{\rm ion}}{4\pi\alpha_{\rm rec,B} n_\infty^2}\right)^{1/3}$$

Compton sphere (i.e., the gas inside is heated by Compton scattering)

$$R_{\rm Comp}^{\Xi} = \left(\frac{L}{4\pi c \Xi_c nkT}\right)^{1/2} = 2.8 \times 10^8 R_G L_{40}^{1/2} n_4^{-1/2} T_4^{-1/2} m_3^{-1},$$

Krolik+ 1981; Wang, Chen & Hu 2006

$R_{\rm B} < R_{\rm HII}$ or $R_{\rm Comp}^{\Xi}$ → necessary for the suppression of $\dot{M}_{\rm Bondi}$ (otherwise the gas in between $R_{\rm HII}$ ($R_{\rm Comp}^{\Xi}$) and $R_{\rm B}$ would accumulate and crush the bubble; Inayoshi+ 2016; Sugimura+ 2017)

Compton heating

Compton heating rate:

$$\Gamma_C = \frac{\sigma_T n_e}{m_e c^2} \int_{\nu_{min}}^{\nu_{max}} d\nu F_\nu (h\nu - 4k_B T),$$

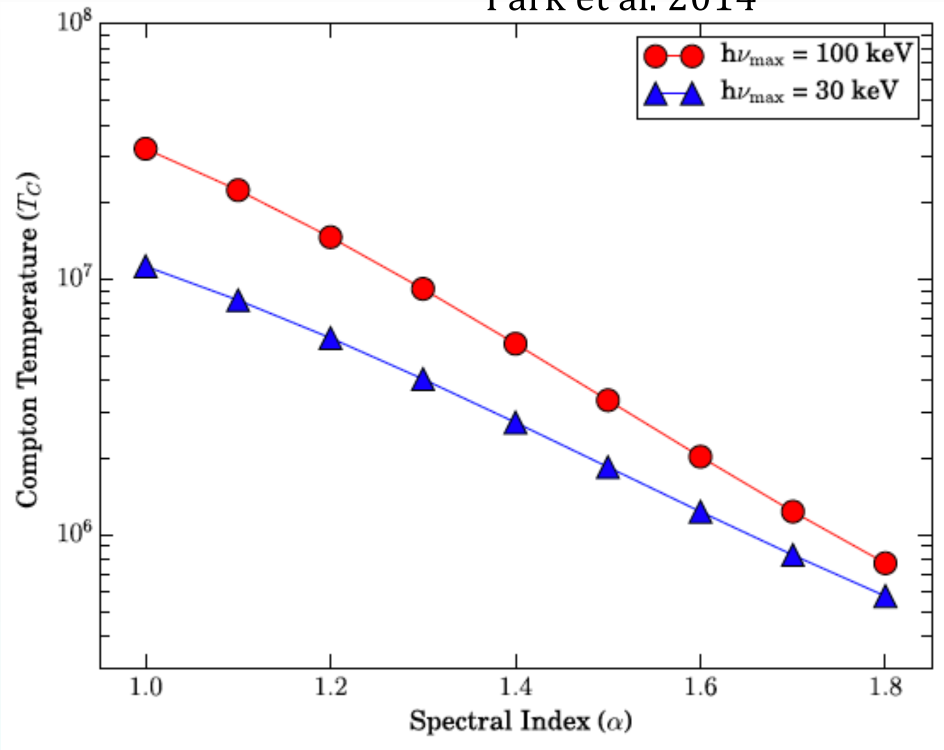
F_ν: radiation flux per frequency bin
T: ambient temperature
n_e: ambient electron density

$$\int_{\nu_{min}}^{\nu_{max}} d\nu\, F_\nu \equiv F$$

$$\Rightarrow \Gamma_C = F \frac{\sigma_T n_e}{m_e c^2} \left(\frac{h\nu_{max}}{\Lambda_C} - 4k_B T \right)$$

where $\Lambda_C = \left(\frac{2-\alpha}{\alpha-1} \right) \frac{\nu_{max}^{2-\alpha} - \nu_{min}^{2-\alpha}(\nu_{max}/\nu_{min})}{\nu_{max}^{2-\alpha} - \nu_{min}^{2-\alpha}}$ (1<α<2)

Park et al. 2014



Independent of n_e !

$\therefore$ the radiation field and the gas are in equilibrium when $T = \frac{h\nu_{max}}{4k_B \Lambda_C} \equiv T_C$

Condition for suppression of Bondi accretion

1. The surrounding material outside of the Bondi radius is Compton-heated. → $R_{\rm Comp} \gtrsim R_{\rm B}$

2. The conduction timescale at the Bondi radius is shorter than the accretion timescale → $t_{\rm acc} \gtrsim t_{\rm cond}$

1. $R_{\rm Comp} \gtrsim R_{\rm B}$

Two kinds of the Compton radius:

(1) $$R^{\Xi}_{\rm Comp} = \left(\frac{L}{4\pi c \Xi_c n_\infty k T_\infty}\right)^{1/2}$$

$$\simeq 8.5\times10^{16}{\rm cm}\, M_{\rm BH,2}^{1/2}\left(\frac{L}{L_{Edd}}\right)^{1/2} T_{\rm C,7}^{3/4} n_{\infty,5}^{-1/2} T_{\infty,4}^{-1/2}$$

(2) $$t_C = \frac{6\pi m_e c^2 R^2}{\sigma_T L},\ t_{\rm infall} = \frac{R}{v_R} = \frac{R^{3/2}}{\sqrt{2GM_{BH}}}$$

$$t_C = t_{\rm infall}$$

$$\Rightarrow R^{\rm infall}_{\rm Comp} = \frac{1}{2GM_{BH}}\left(\frac{\sigma_T L}{6\pi m_e c^2}\right)^2 \simeq 1.17\times10^{17}{\rm cm} M_{\rm BH,2}\left(\frac{L}{L_{Edd}}\right)^2$$

→ Compare them with $R_{\rm B} \simeq 1.97\times10^{16}{\rm cm}\, M_{\rm BH,2} T_{\infty,4}^{-1}$

2. $t_{\rm acc} \gtrsim t_{\rm cond}$ at $R = R_{\rm B}$

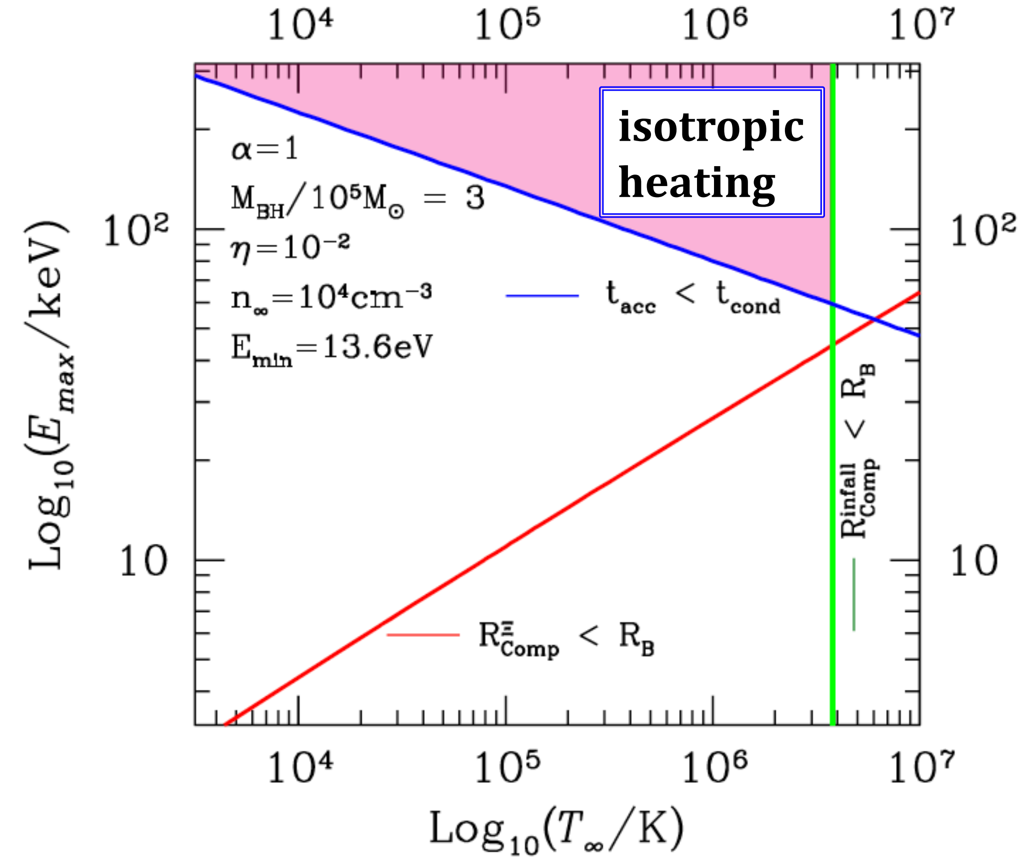
$$t_{\rm acc} \sim \sqrt{\frac{r^3}{GM_{\rm BH}}} \approx 8.66\times10^9\ {\rm s}\ M_{\rm BH,2}^{-1/2}\, r_{16}^{3/2}$$

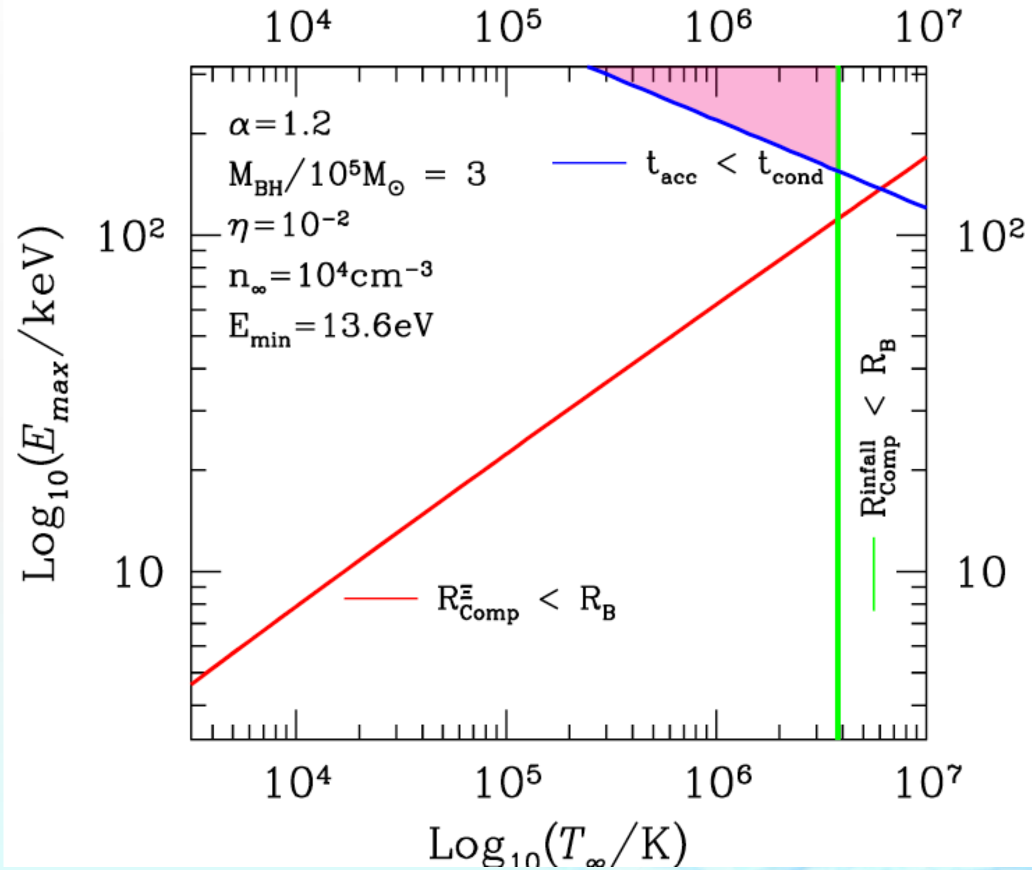
$$t_{\rm cond} \sim \frac{n_\infty k_{\rm B} T_{\rm C} \cdot r}{\kappa_{\rm sp} T_{\rm C}/r} \approx 2.4\times10^9\ {\rm s}\ n_{\infty,5} T_{\rm C,7}^{-5/2} r_{16}^{2}$$

where $\kappa_{\rm sp} \backsimeq 5.82\times10^{11}\ T_{\rm C,7}^{5/2}$ (erg K^{-1} cm^{-1} s^{-1}) is the Spitzer's heat conductivity

$$t_{\rm acc} \gtrsim t_{\rm cond} \text{ at } R = R_{\rm B} \iff M_{\rm BH,5} n_{\infty,4} T_{\infty,4}^{-1/2} T_{\rm C,7}^{-5/2} \lesssim 2.57\times10^{-2}$$

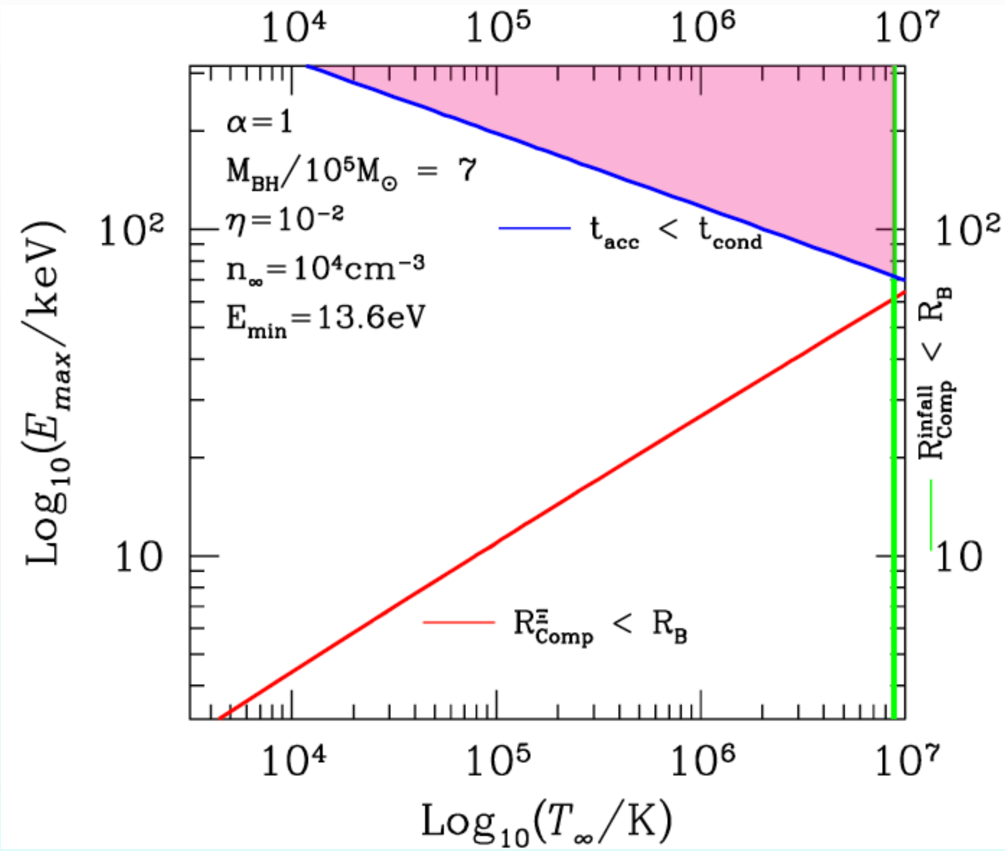
Results: condition of $\dot{M}$ suppression

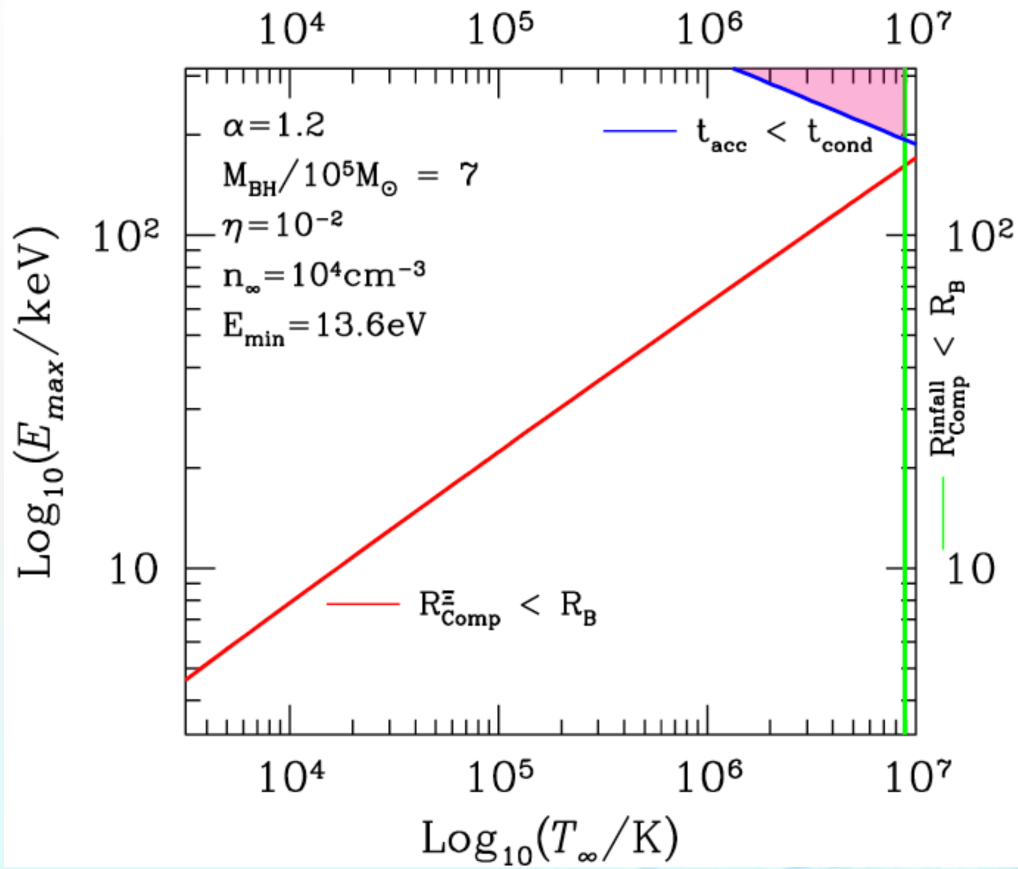




high $E_{\rm max}$, flatter spectrum of irradiation → high $T_{\rm C}$
→ efficient conductive heating

Results: condition of $\dot{M}$ suppression

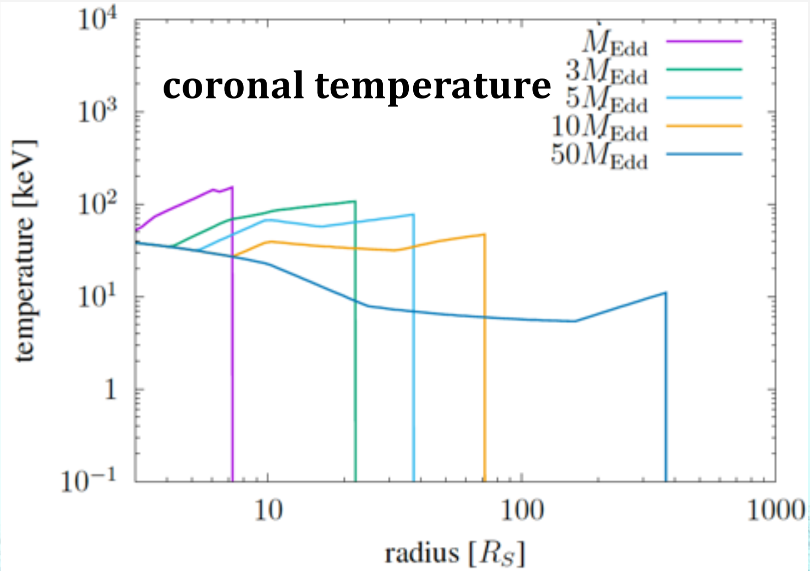




high E_{max}, flatter spectrum of irradiation → high T_{C}
→ efficient conductive heating

Discussion

- What values of E_{max} and α are relevant?
  - Comptonizing plasma (corona) in a super-Eddington accretion flow has lower temperature ($T \backsim$ a few keV) and larger Thomson optical depth ($\tau_e \gtrsim 10$) compared to that in a sub-Eddington accretion flow (NK & Mineshige 2021 etc.)
  - E_{max} may be significantly lower than $\backsim$ 100 keV and the X-ray spectrum may be steeper than typical AGNs (i.e., $\alpha \gtrsim 1$).



Can we apply this results to the seed BH growth at high redshift?

NK & Mineshige 2021

Summary

- **We investigate how the heat conduction affects the growth of a seed of a supermassive black hole.**
- When a geometrically thick accretion disk is formed and the radiation is anisotropic, it has been considered that super-Eddington accretion from the equatorial plane is possible. However, that region may be heated up through conduction from the adjacent heated region.
- We evaluate the condition of $\dot{M}$ suppression due to conduction. If the irradiation spectrum is flat ($\alpha \backsim 1$) and has a high E_{max} ($\gtrsim 100$ keV), the medium surrounding a BH is isotropically heated and $\dot{M}$ would be sub-Eddington.