超巨大ブラックホールへのdusty gasの超臨界降着

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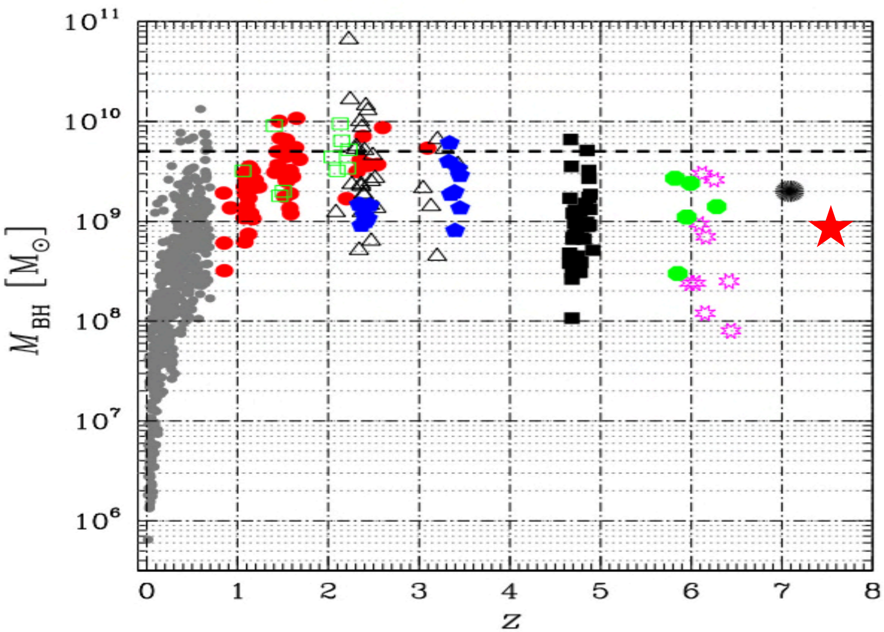
初代星・初代銀河研究会2018＠呉　2018/2/10

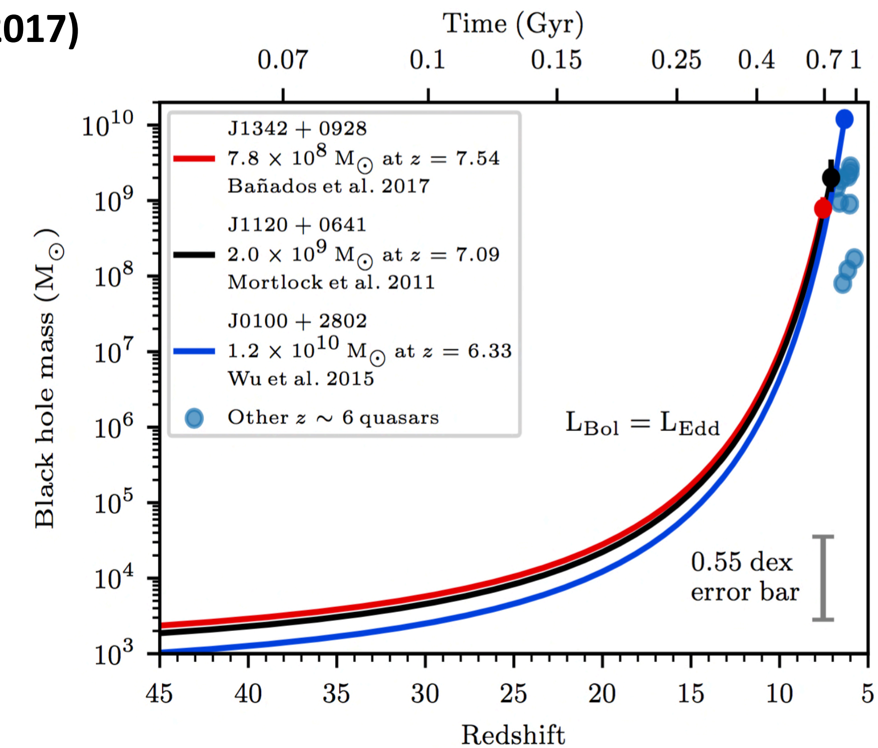
SMBHs in the early universe

最遠方SMBH

✓ **z ~ 7.5, M_{BH} ~ 8.8 x 10^8 M_{sun} (Banados et al. 2017)**



Marziani et al. (2012)



Banados et al. (2017)

$M_{BH,seed}$ > 10^4 M_{sun} ? or super-Eddington accretion ?

Effect of radiation feedback

- **Bondi accretion rate**

$$\dot{M}_{\rm acc} \simeq 4\pi\rho_\infty R_{\rm B}^2 c_{\rm s}$$
$$\propto \rho_\infty T_\infty^{-3/2} M_{\rm BH}^2$$

- **Photoionization heating**

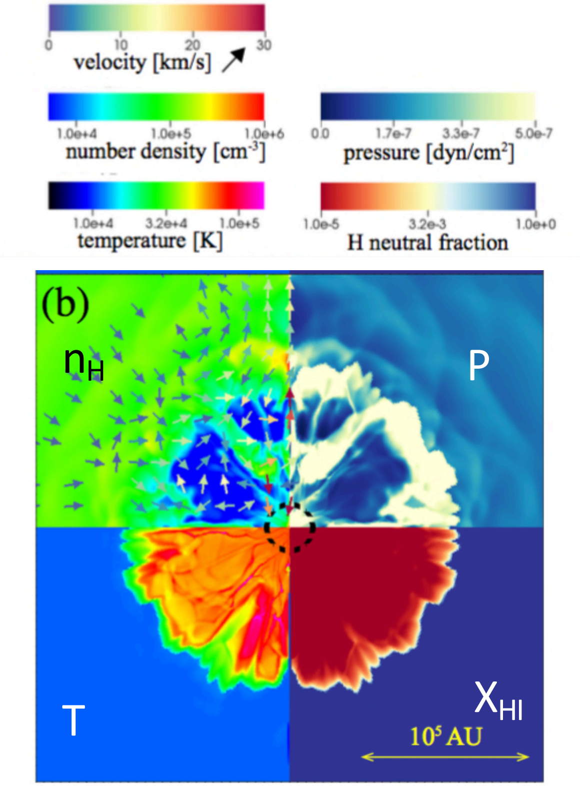
✓ T ↑↑

✓ $\dot{M}_{\rm acc}$ ↓↓

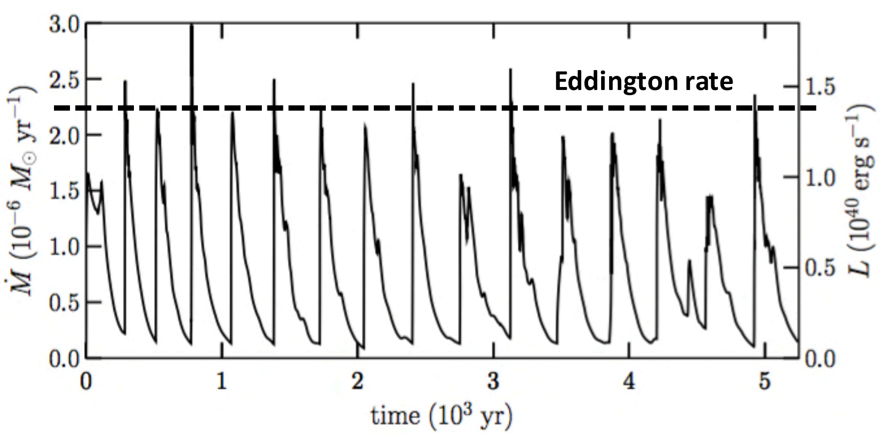
⇨ $\left\langle \dot{M}_{\rm acc} \right\rangle << \dot{M}_{\rm Edd}$

熱圧のせいでエディントン降着すら維持できない

熱圧、輻射圧の影響を免れて
Edd. or super-Edd. を実現するメカニズムが必要



Sugimura et al. (2017)



Milosavljec et al. (2009)

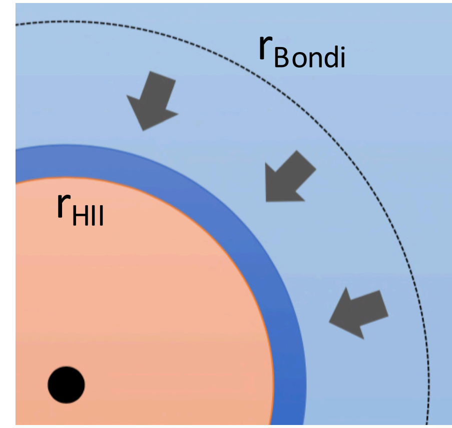
Super–Eddington accretions onto MBHs

- **Condition for the super-Edington accretion ($r_{Bondi} > r_{HII}$)**

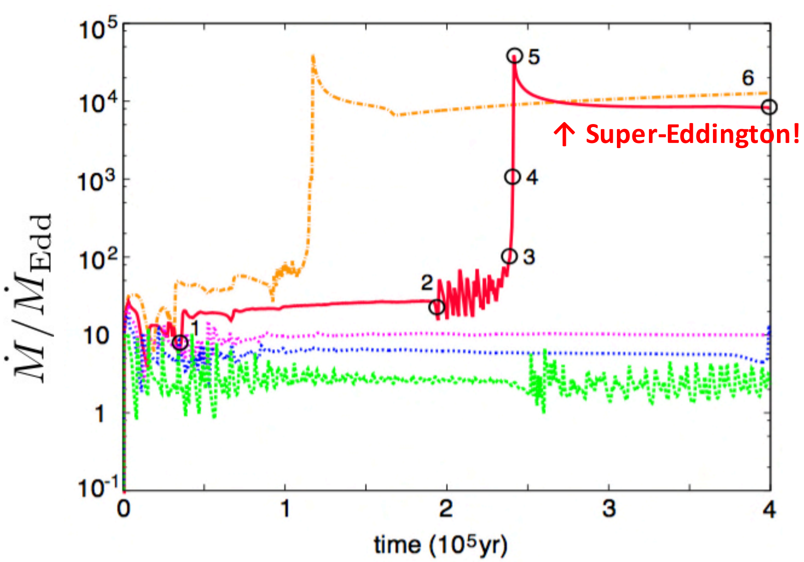
$$r_{\rm Bondi} \equiv \frac{GM_{\rm BH}}{c_{\rm s,\infty}^2} \propto M_{\rm BH}\, T_\infty^{-1} \qquad r_{\rm HII} \sim \frac{3L_{\rm Edd}}{4\pi\alpha_{\rm rec}h\nu_{\rm pi}n_\infty} \propto M_{\rm BH}^{1/3}\, n_\infty^{-2/3}\, T_{\rm HII}^{0.28}$$

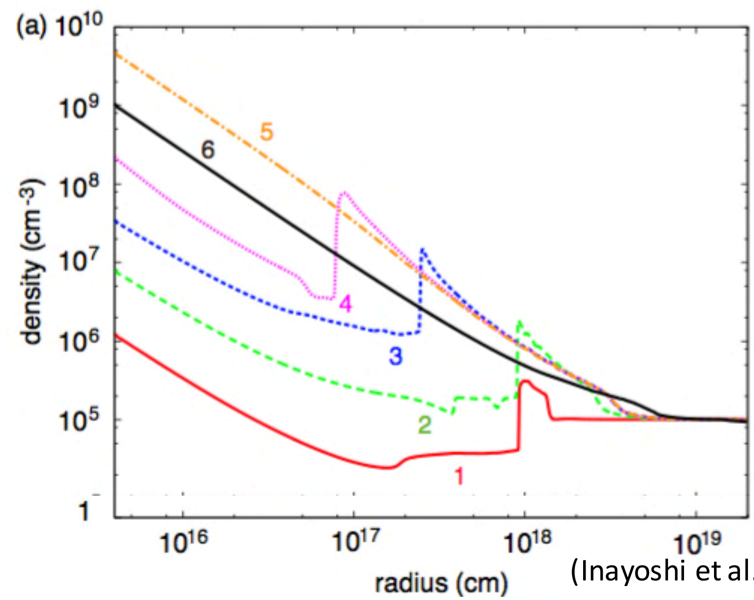
$$M_{\rm BH,4}\, n_{\infty,5} \gtrsim 0.64\, T_{\infty,4}^{2/3}\, T_{\rm HII,4}^{0.42}$$

(Inayoshi et al. 2016)



Gas within r_{bondi} can accrete onto the edge of the HII region





(Inayoshi et al. 2016)

Existence of dust in high-z QSOs

ex)

- Weis et al. (2007)
  - CO lines and dust continuum from lensed QSO at z = 3.9
  - n_{H2} ~ 10^5 cm^{-3}, M_{mol} ~ 5 × 10^9 M_{sun}, M_{dust} ~ 3.3 × 10^7 M_{sun}

- Venemans et al. (2012)
  - [CII] line and dust continuum from QSO (M_{BH} = 2 × 10^9 M_{sun}) at z = 7.08
  - M_{dust} ~ (0.7-5.7) × 10^8 M_{sun}

- Venemans et al. (2017)
  - [CII] line and dust continuum from QSO (M_{BH} = 8 × 10^8 M_{sun}) at z = 7.54
  - M_{dust} ~ (0.6-4.3) × 10^8 M_{sun}、M_{dyn} < 1.5 × 10^{11} M_{sun}

⇒ ダストを含んだガスでも超臨界降着が実現するか？

Radiation pressure to dust particles

✓ **radiation pressure from UV photons ($F_{d,UV}$)**

$$a_{\rm d,UV} = \frac{\kappa_{\rm UV}}{4\pi R^2}\frac{L}{c}$$

$$L_{\rm Edd,d,UV} = 1.4\times 10^{-3}\left(\frac{Z}{Z_\odot}\right)^{-1} L_{\rm Edd}$$

$Z > 10^{-3}$ Zsun でメインの輻射圧源

$$= 4.6\times 10^4 L_\odot \left(\frac{M_{\rm BH}}{10^3 M_\odot}\right)\left(\frac{Z}{Z_\odot}\right)^{-1}$$

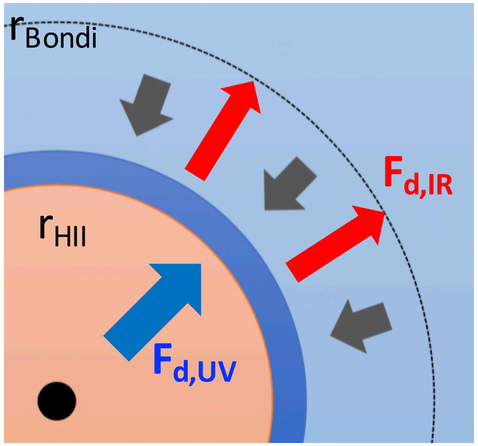
Yajima et al. (2017)

✓ **radiation pressure from dust thermal emission（$F_{d,IR}$）**

- UV photons absorbed by dust are reemitted as IR photons
- Radiation pressure from IR photons pushes gas outside of HII region

$$a_{\rm d,IR} = \frac{\kappa_{\rm IR}}{4\pi R^2}\frac{L}{c}$$

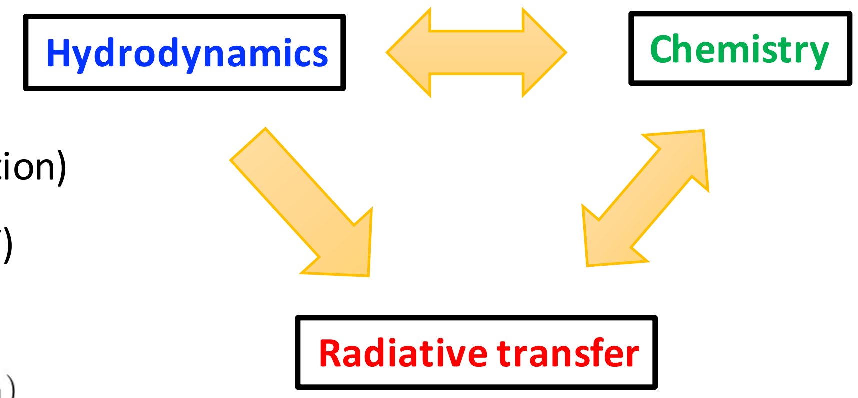
$$L_{\rm Edd,d,IR} = 5\times 10^5 L_\odot \left(\frac{M_{\rm BH}}{10^3 M_\odot}\right)\left(\frac{Z}{Z_\odot}\right)^{-1} > L_{\rm Edd,d,UV}$$



Methods

- **HD simulation (public code "PLUTO", 1D-spherical coordinate)**

- **Radiative transfer**
  - ✓ photoionization (EUV)
  - ✓ dust attenuation (FUV, EUV)
  - ✓ dust thermal emission (IR; FLD approximation)
  - ✓ mass accretion rate → radiation (FUV, EUV)



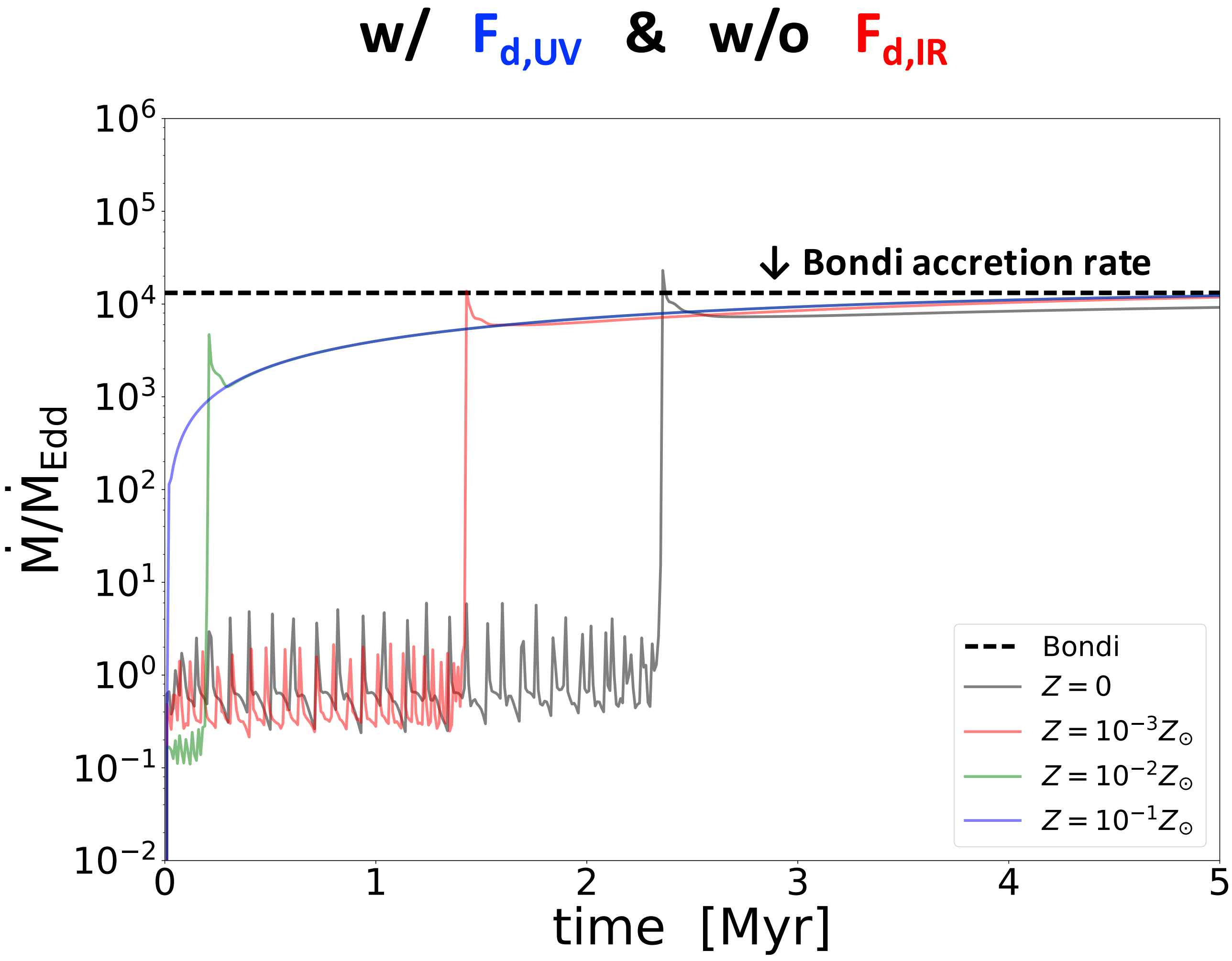
slim disk (Watarai+2000)

$$L = \begin{cases} 2L_{\rm Edd}\left[1+\ln\left(\frac{\dot{M}}{2\dot{M}_{\rm Edd}}\right)\right] & (\dot{M} > 2\dot{M}_{\rm Edd}) \\ L_{\rm Edd}\left(\frac{\dot{M}}{\dot{M}_{\rm Edd}}\right) & (\dot{M} < 2\dot{M}_{\rm Edd}) \end{cases}$$

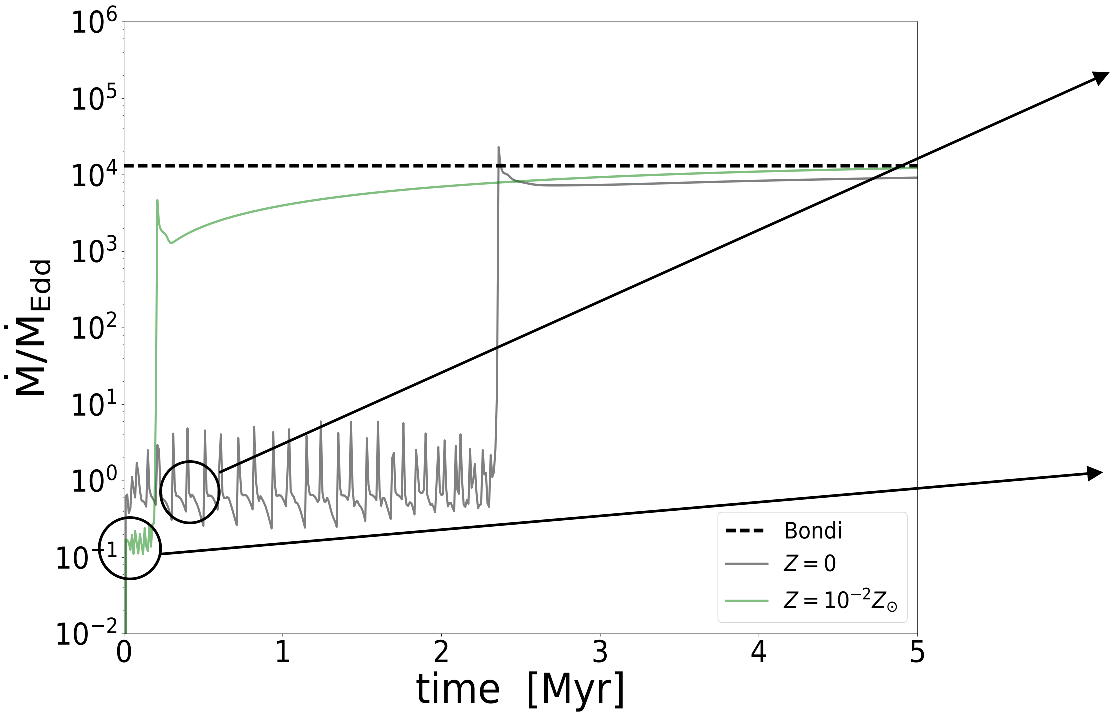
- **Non-equilibrium Chemistry**
  - ✓ six species: HI, HII, HeI, HeII, HeIII, e-
  - ✓ photoionization, recombination, collisional excitation & ionization, free-free emission etc.

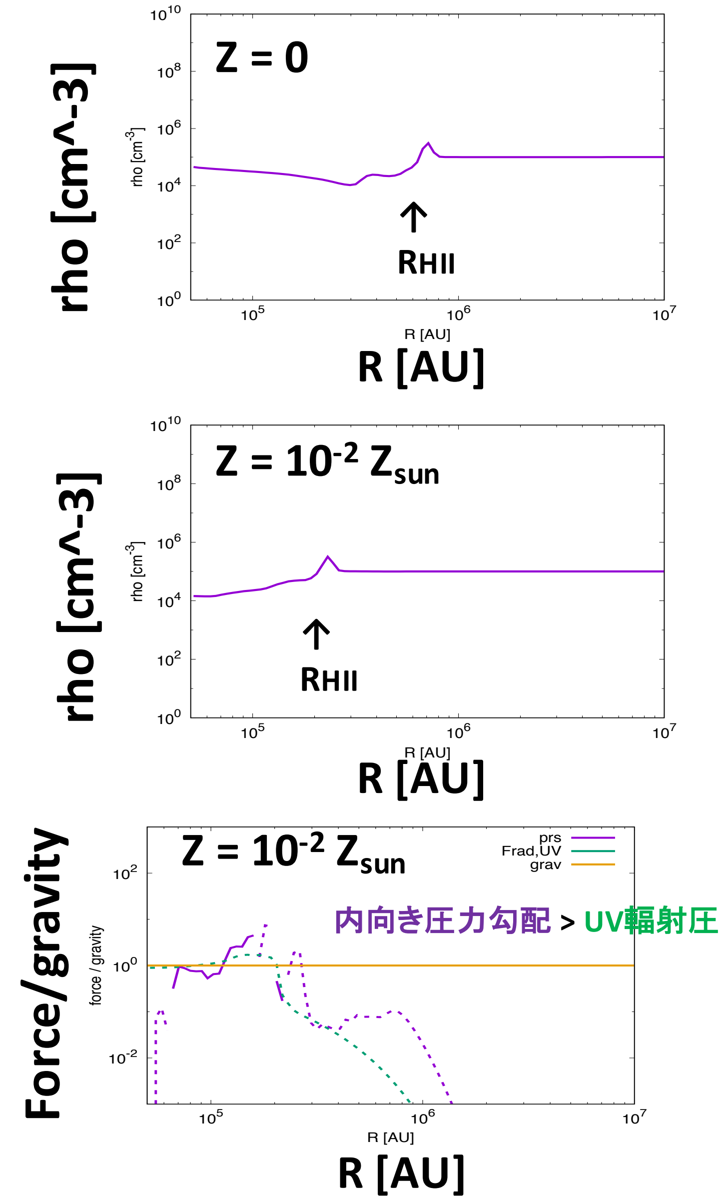
- **Initial condition**: $M_{BH} = 10^5$ Msun、$n_{gas} = 10^5$ cm^{-3}、$T_{gas} = 10^4$ K 、dust-to-gas mass ratio, D = 0.01 (Z/Zsun)

Effects of dust attenuation & UV radiative force



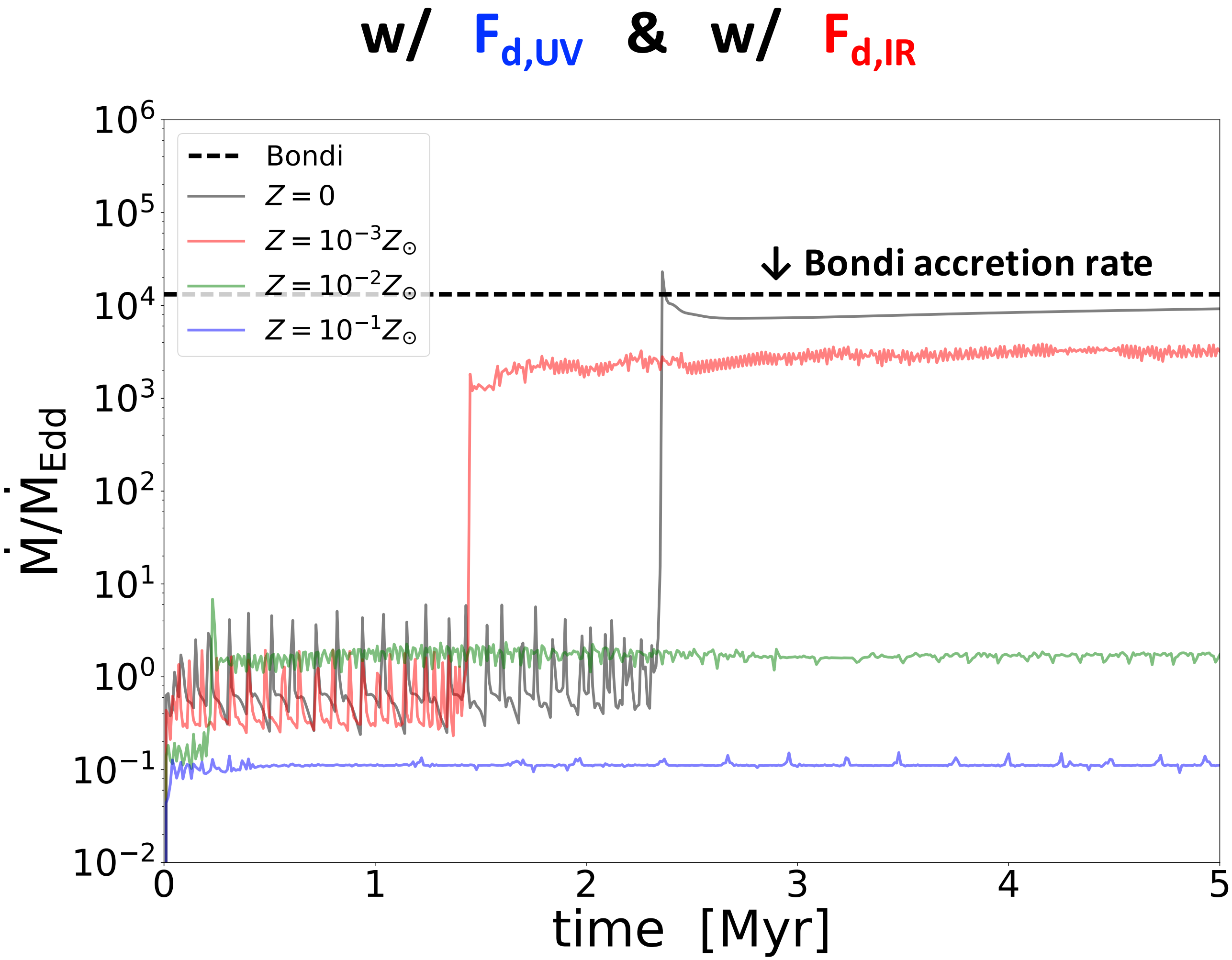
Effects of dust attenuation & UV radiative force





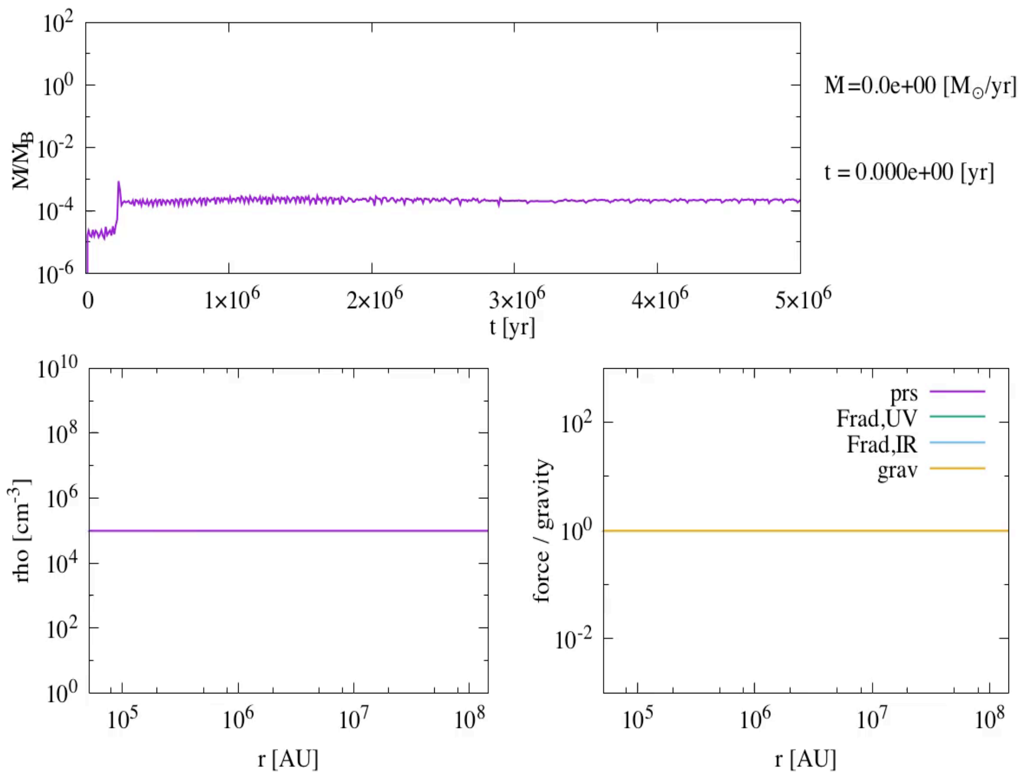
- ✓ dust attenuation → R_{HII} ↓↓ → quicker transition to super-Edd.
- ✓ UV radiative force on dust cannot stop super-Edd. flow

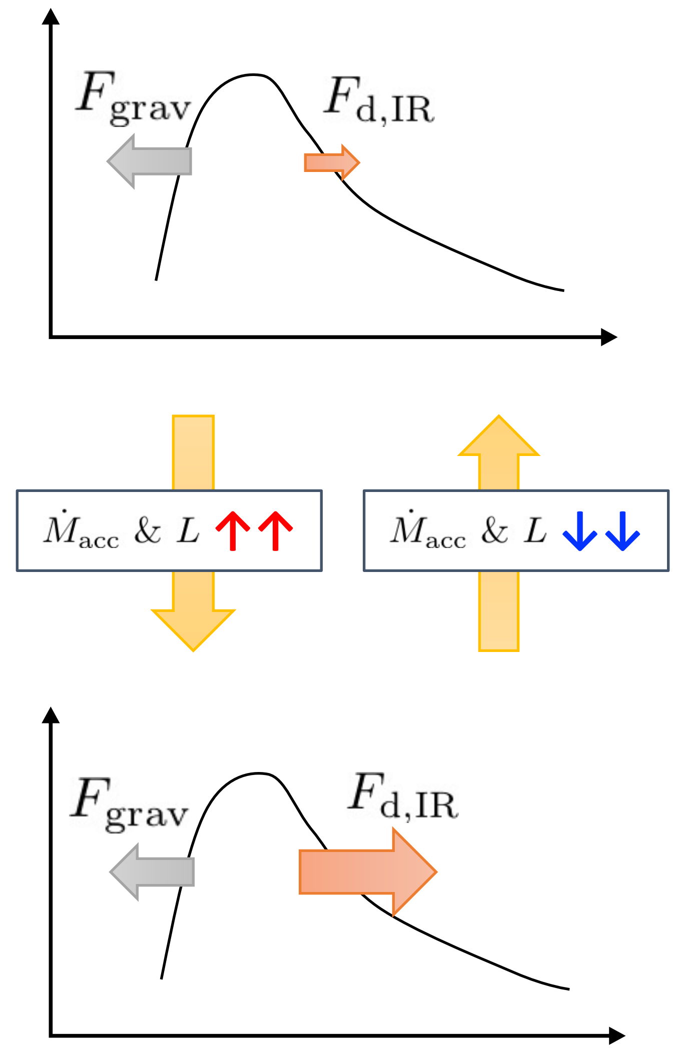
Effects of IR radiative force



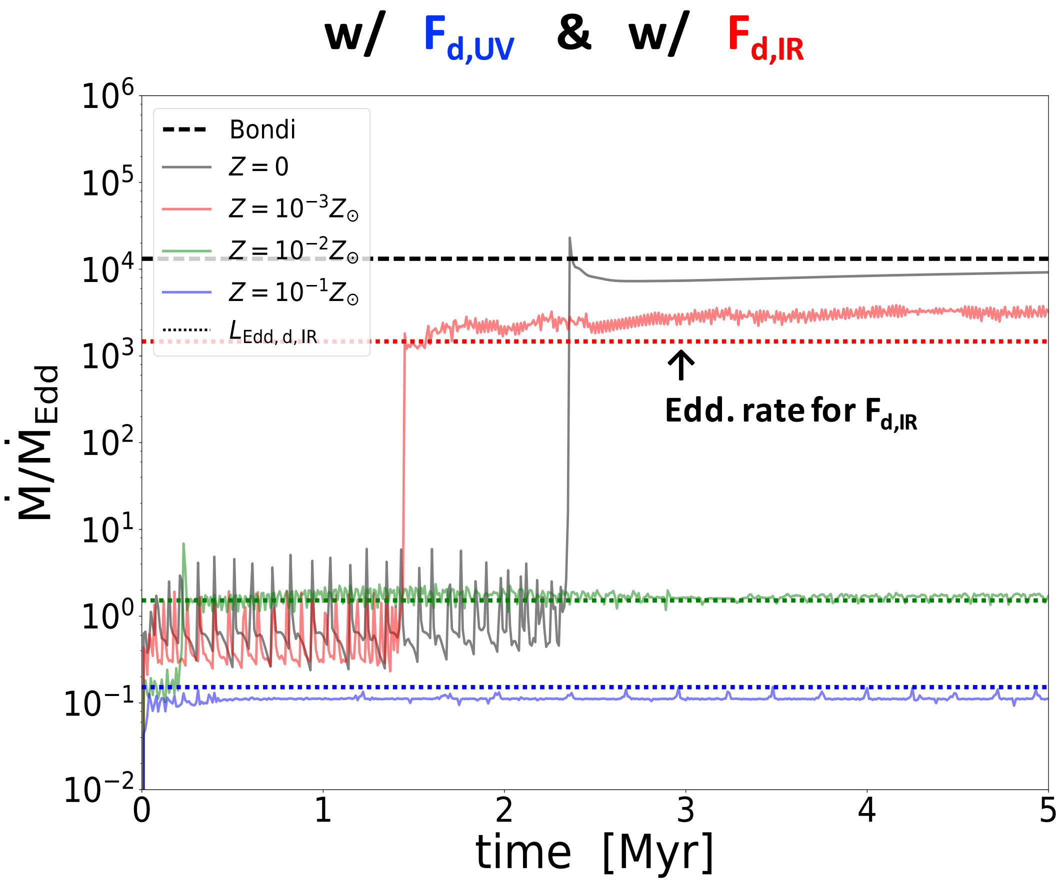
Effects of IR radiative force

Z = 10^{-2} Zsun





Effects of IR radiative force



Condition for super-Edd. accretion

$$\dot{M}_{\rm Edd,d,IR} > \dot{M}_{\rm Edd} \Rightarrow Z < 1.5 \times 10^{-2} Z_\odot$$

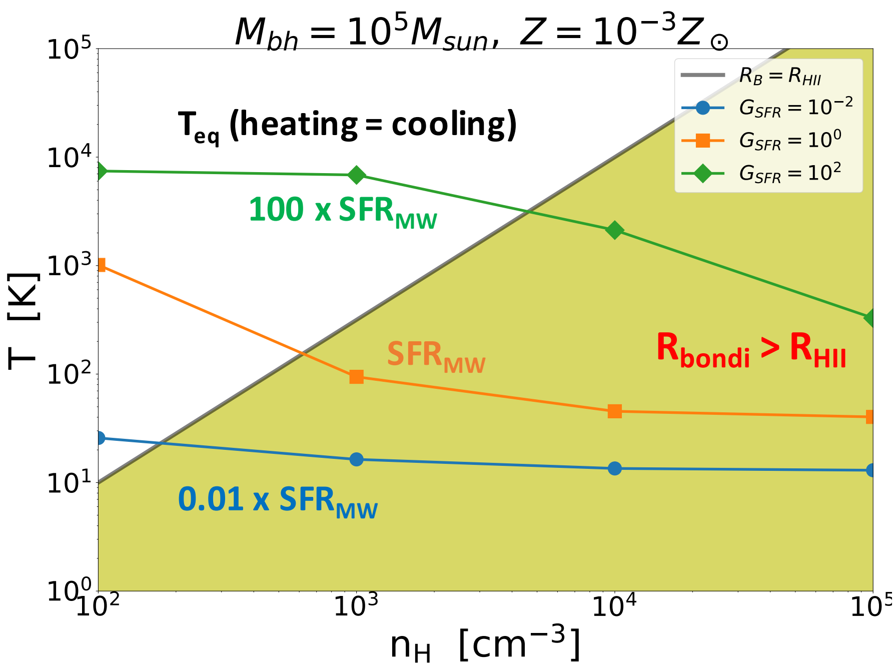
Metal cooling

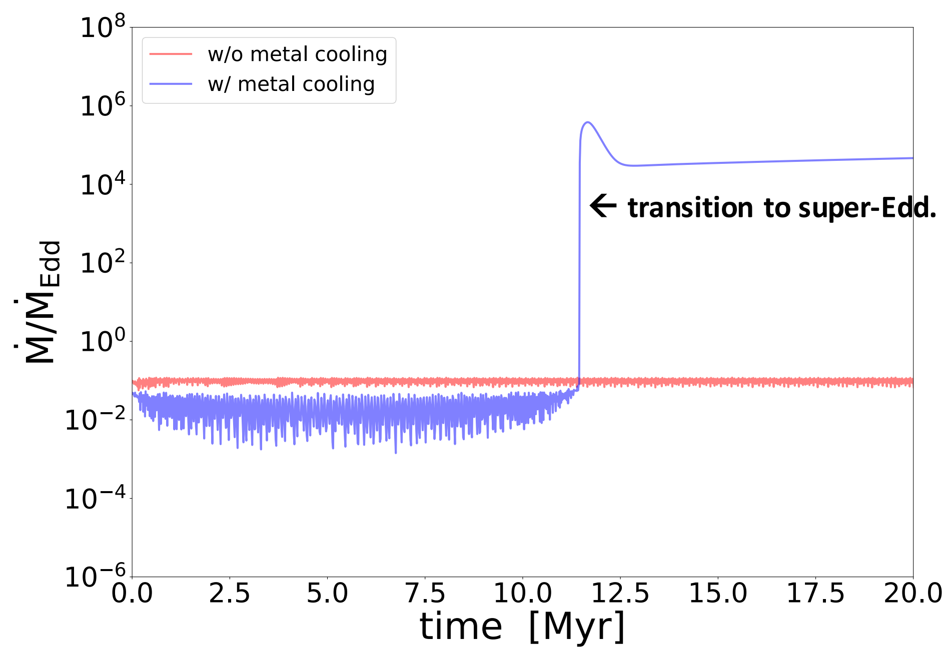
✓ **Important cooling sources ➔ CII, OI, dust-gas collisional cooling**

$$M_{\rm BH,4}\, n_{\infty,5} \gtrsim 0.64\, \boxed{T_{\infty,4}^{2/3}}\, T_{\rm HII,4}^{0.42}$$

Inayoshi et al. (2016)

T_{HI} ↓↓ ➔ R_{bondi} ↑↑ ➔ metal cooling があると降着率が上がりやすい





Summary & Conclusion

R_{bondi} > R_{HII}

$$M_{\mathrm{BH},4}\, n_{\infty,5} \gtrsim 0.64\, \boxed{T_{\infty,4}^{2/3}}\, T_{\mathrm{HII},4}^{0.42}$$

+ dust attenuation

metal cooling

+

$$\dot{M}_{\mathrm{Edd,d,IR}} > \dot{M}_{\mathrm{Edd}}$$

→

$$Z < 1.5 \times 10^{-2} Z_{\odot}$$

⇨

- ✓ 金属量が高すぎる($Z > 10^{-2} Z_{sun}$) とIR輻射圧が強くなるのでダメだが、$Z \sim 10^{-3} Z_{sun}$ (?) くらいならむしろ超臨界降着を引き起こしやすい
- ✓ z ~ 7 のSMBHs はまだ化学進化が十分進んでいない時期に一気に成長？

ただし･･･
あくまで1次元球対称の結果。多次元効果（密度分布、非等方輻射、角運動量）の検証は重要