Hyper-Eddington accretion flows onto massive black holes

Kohei Inayoshi

Simons Society of Fellows
Columbia University

collaborators : Z. Haiman & J. P. Ostriker

(arXiv:1511.02116)

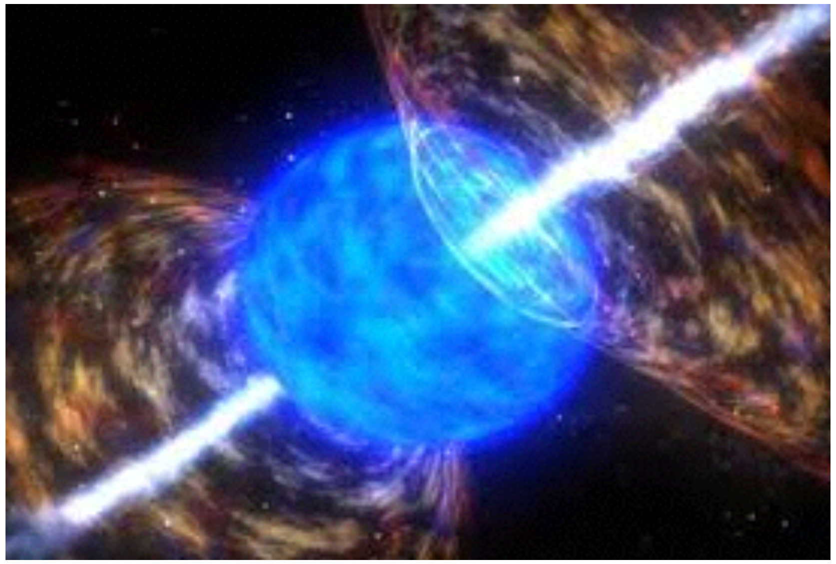
BH + accretion flow

- supermassive BHs ($>10^6 M_{sun}$)

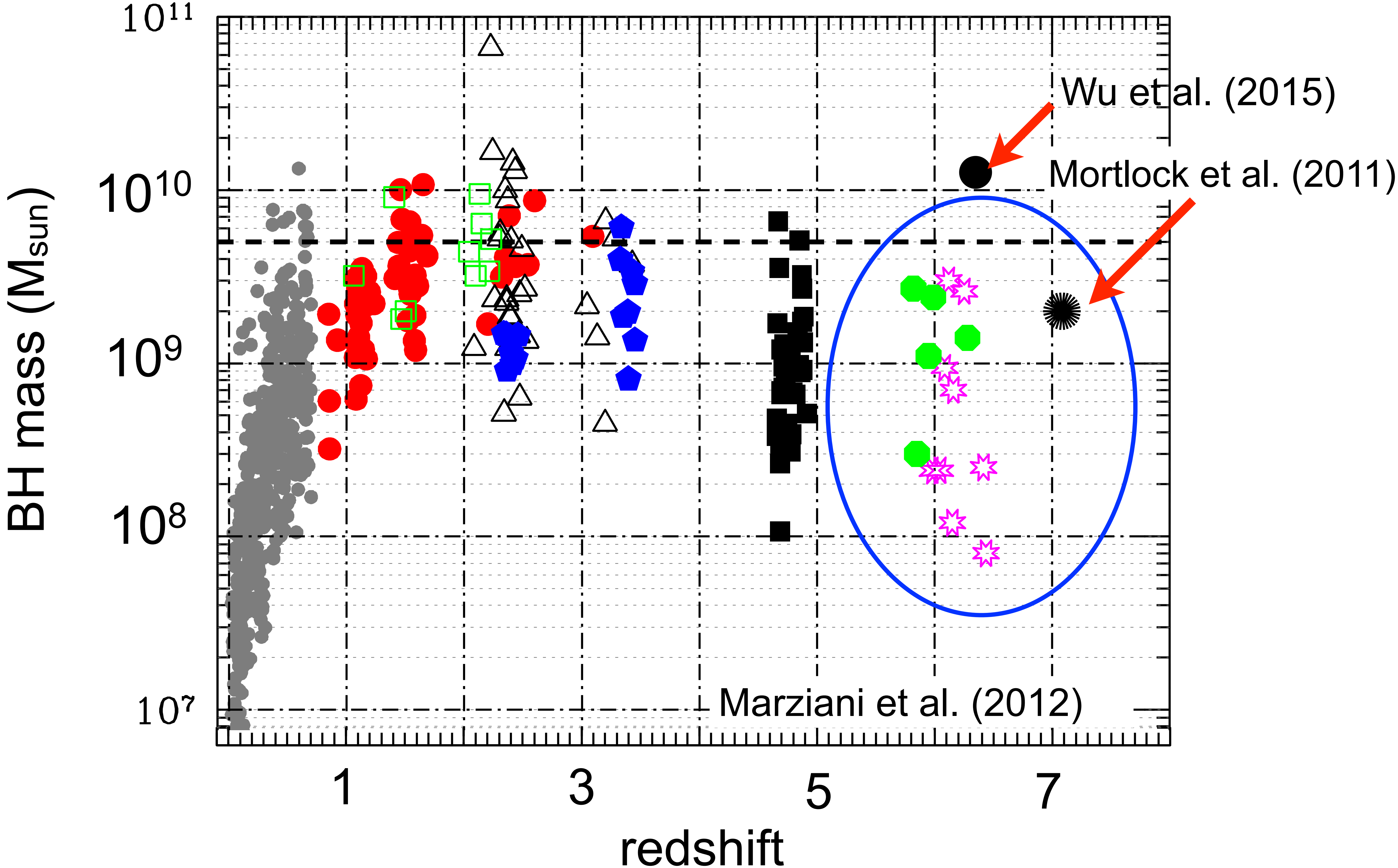
  — quasars, AGN, (ultra) luminous IR galaxie etc…

- massive BHs ($1\text{-}10 M_{sun}$)

  — X-ray binaries, SNe, GRBs, etc…



High-redshift SMBHs

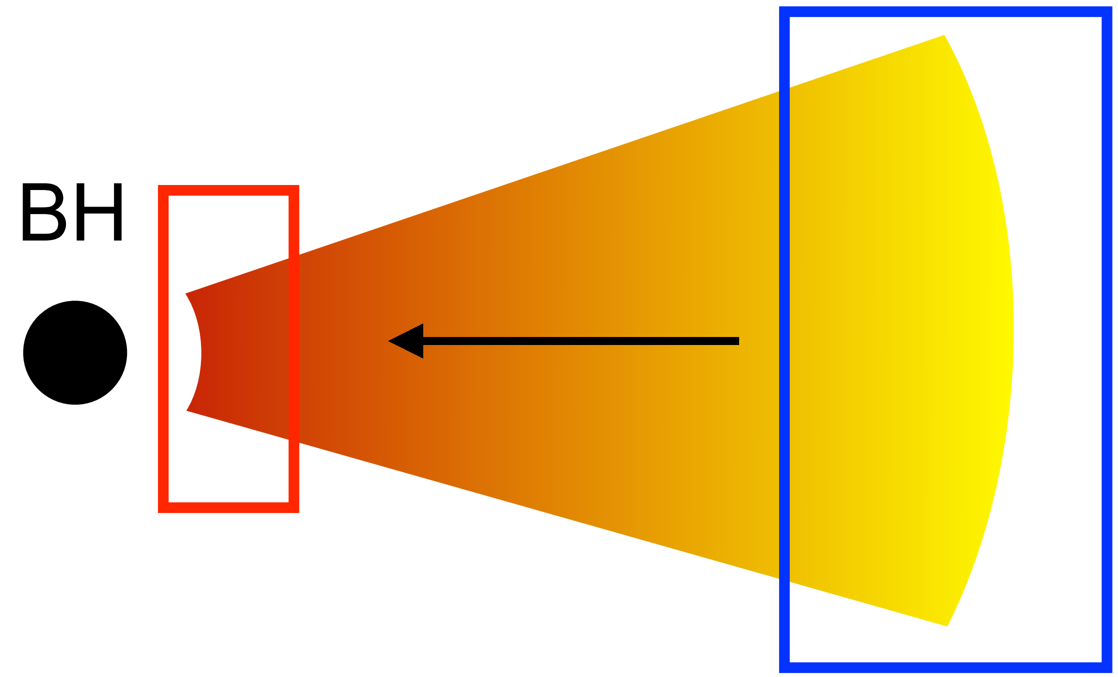


Two limits of BH growth

1. radiation pressure

$$L \sim \dot{M}c^2 \leq L_{\rm Edd}$$

$$\Rightarrow \quad \dot{M} \leq \frac{L_{\rm Edd}}{\eta c^2} = \frac{\dot{M}_{\rm Edd}}{\eta}$$



2. radiation heating / ionization

$$R_{\rm B} \sim \frac{GM_{\rm BH}}{c_s^2}$$

(Bondi radius)

$$\dot{M} \lesssim \rho c_s R_{\rm B}^2 \propto \rho \, M_{\rm BH}^2 \, T^{-3/2}$$

episodic accretion: $\dot{M}$ ↗ T ↗ $\dot{M}$ ↘

Super-Eddington accretion

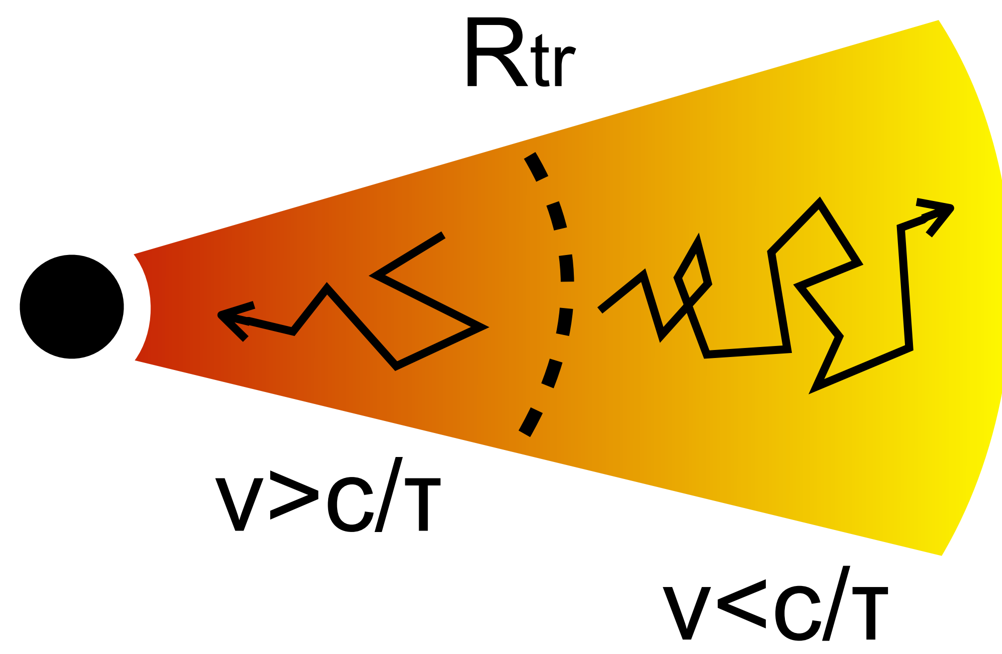
- photon trapping within flows

$$v > \frac{c}{\tau} \qquad (\tau \gg 1)$$

(advection > diffusion)

$$R < R_{\rm tr} \sim \frac{\dot{M}}{\dot{M}_{\rm Edd}} R_{\rm g}$$

Begelman (1978)
Abramowicz et al. (1988)



Super-Eddington accretion

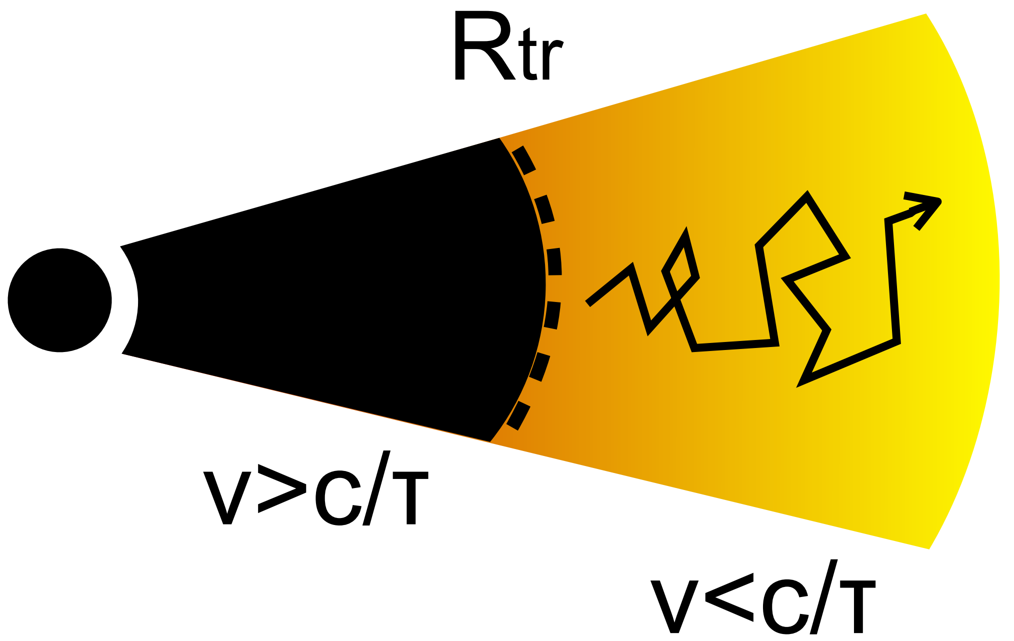
- photon trapping within flows

$$v > \frac{c}{\tau} \qquad (\tau \gg 1)$$

(advection > diffusion)

⇨ $$R < R_{\rm tr} \sim \frac{\dot{M}}{\dot{M}_{\rm Edd}} R_{\rm g}$$

Begelman (1978)
Abramowicz et al. (1988)



Super-Eddington accretion

- photon trapping within flows

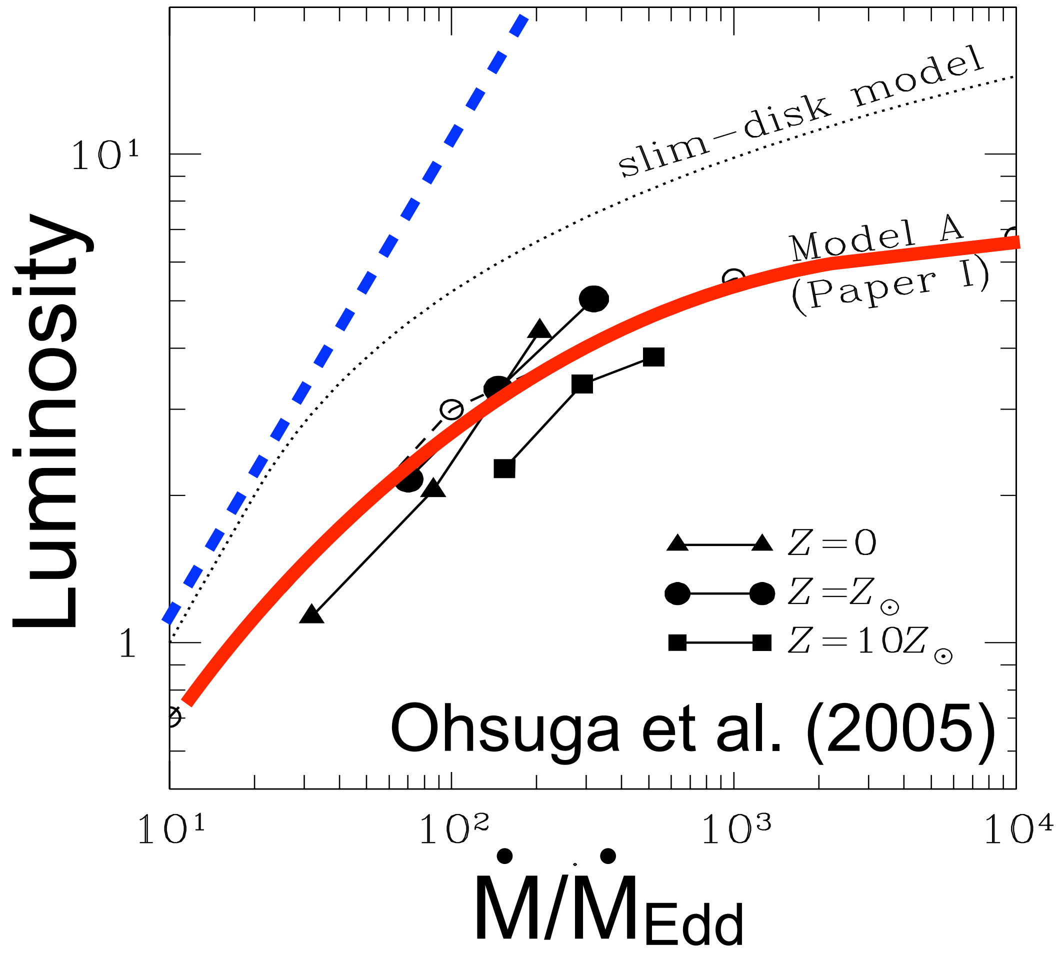
$$v > \frac{c}{\tau} \qquad (\tau \gg 1)$$

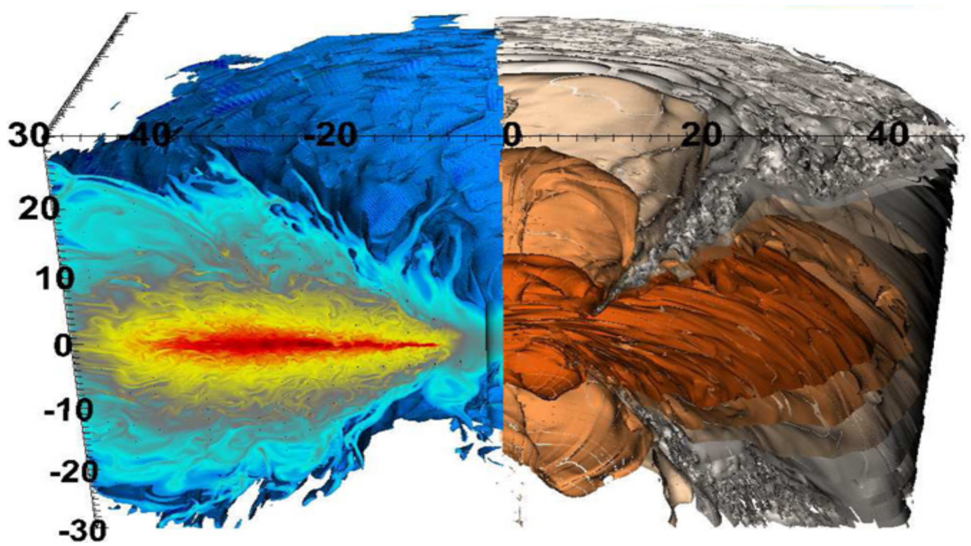
(advection > diffusion)

$$\Rightarrow \quad R < R_{\rm tr} \sim \frac{\dot{M}}{\dot{M}_{\rm Edd}} R_{\rm g}$$

$$\dot{M} \gg \dot{M}_{\rm Edd} \quad (L \sim L_{\rm Edd})$$

because of photon trapping





Jiang et al. (2014)

This work

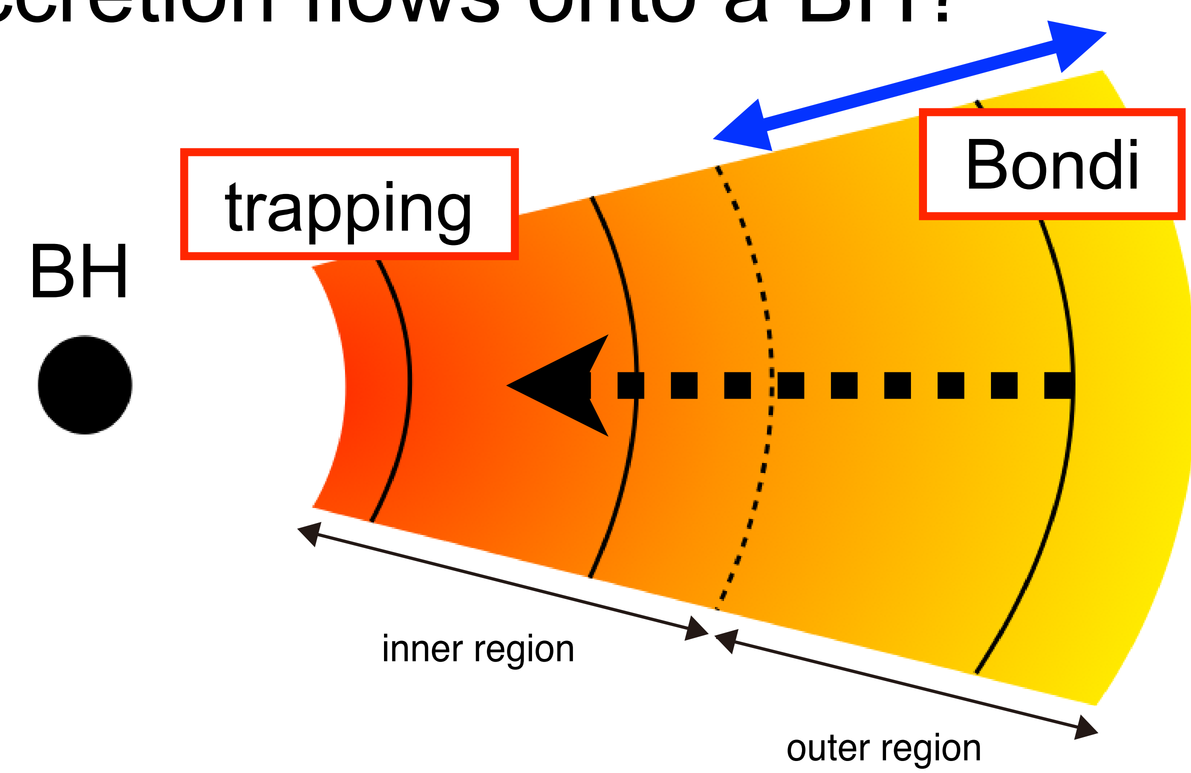
Question

$$\dot{M} \gg \dot{M}_{\rm Edd}$$

What is a global solution of accretion flows onto a BH?

Methods

1D radiation hydro simulation



ZEUS + multi-frequency non-eq chemistry

Stone & Norman (1992)

Goals

Find *self-consistent solutions* of *hyper-Eddington accretion* from the Bondi radius

$$L = \eta \dot{M} c^2$$

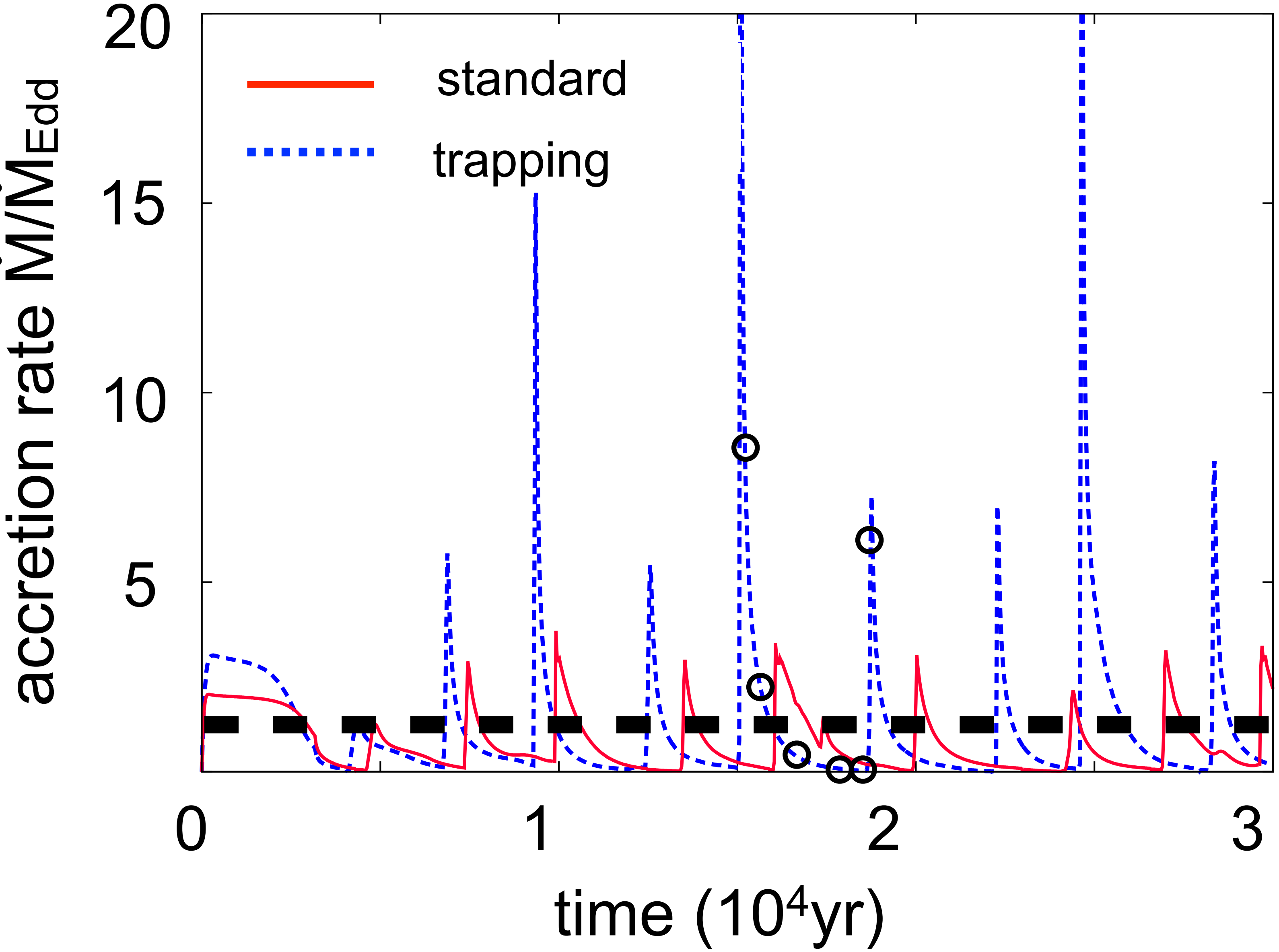
$$\eta = 0.3 \quad \text{(standard)}$$

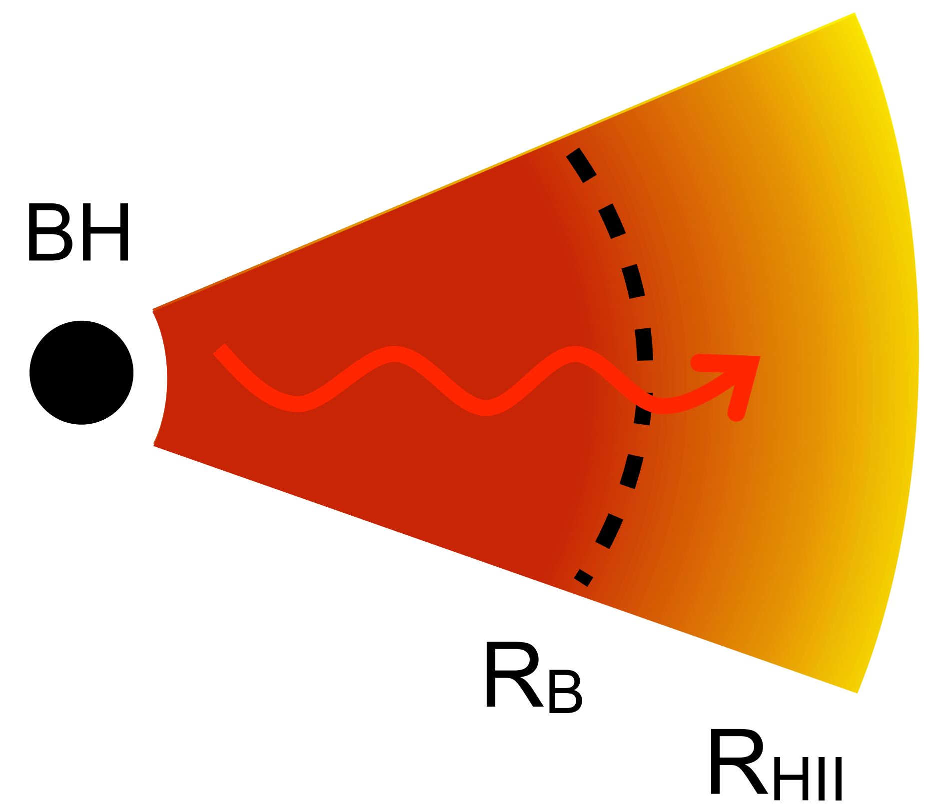
$$\eta = \frac{3}{10 + 3\dot{m}} \quad \text{(trapping)}$$

Stella-mass BH case

M_{BH}=100 M_{sun}

n_∞=10^5 cm^{-3}





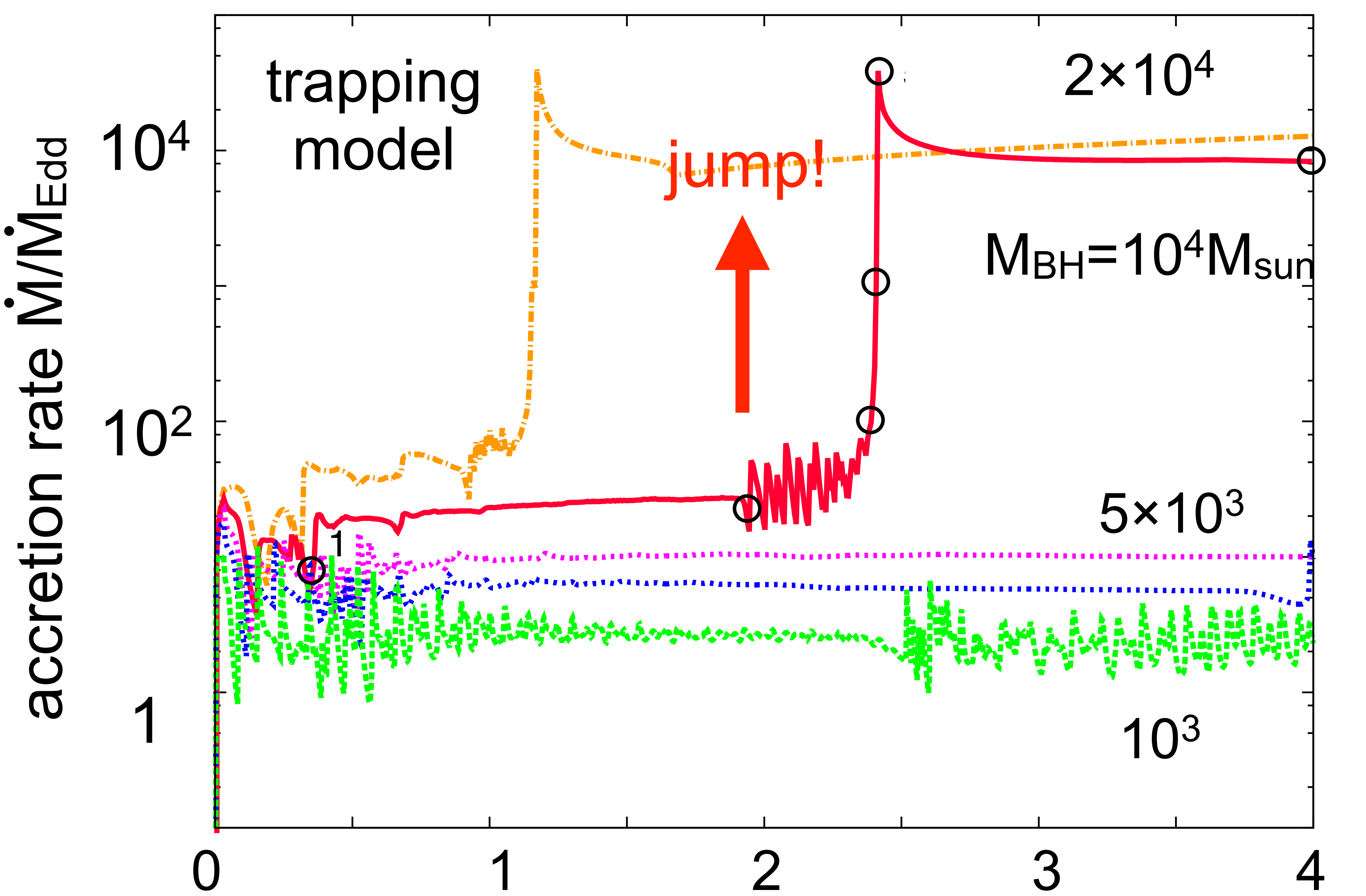
episodic accretion by
radiation heating **(R_B < R_{HII})**

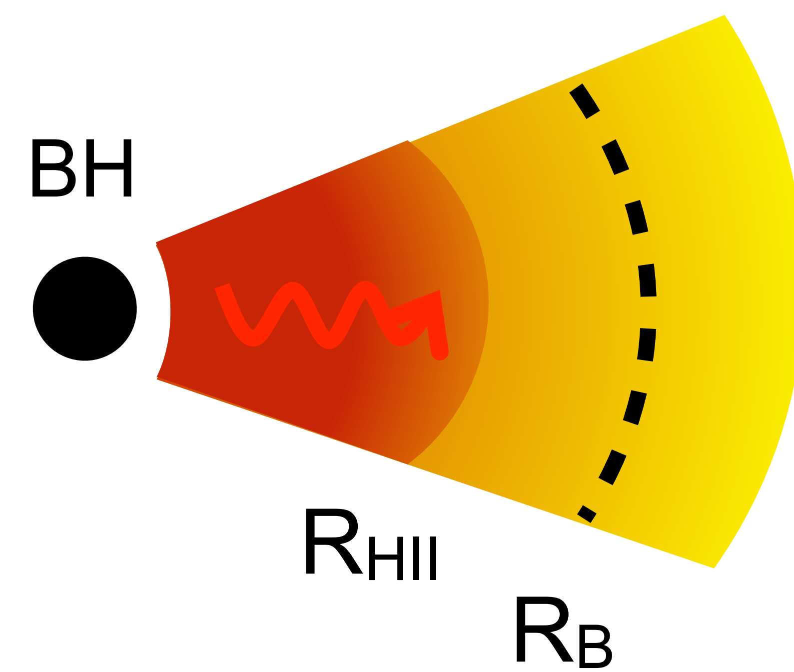
$\langle \dot{M} \rangle \lesssim \dot{M}_{\rm Edd}$

Higher BH mass cases

$n_\infty = 10^5$ cm^{-3}

$M_{BH} >= 10^3 M_{sun}$





hyper-Eddington for higher M_{BH} ⇨ isothermal Bondi $\dot{M} \simeq \dot{M}_B$

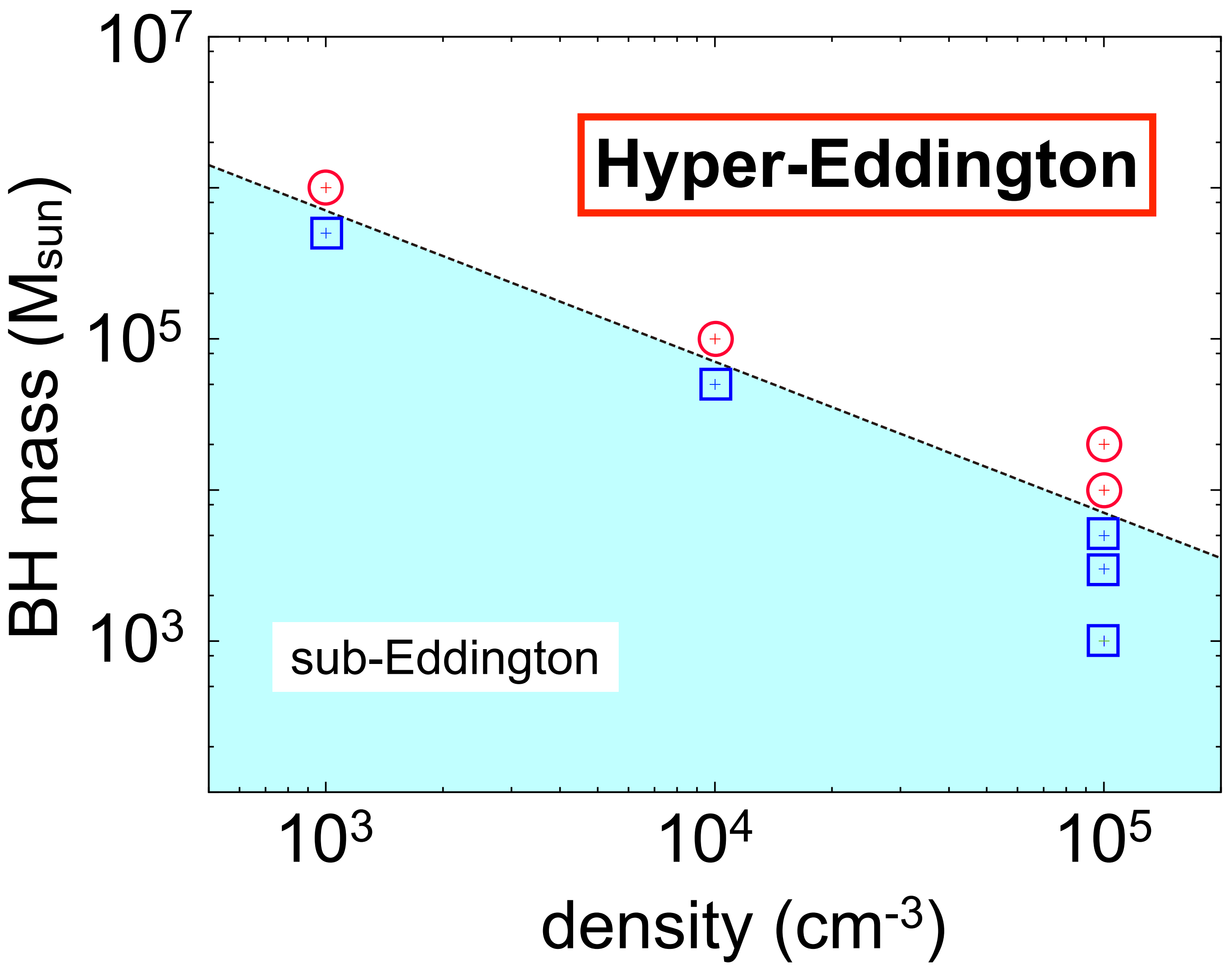
Physical interpretation

- analytical argument

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

$$\propto L^{1/3} n_\infty^{-2/3} \leq \underline{M_{\rm BH}^{1/3}} n_\infty^{-2/3}$$

$$R_{\rm B} = \frac{GM_{\rm BH}}{c_\infty^2} \propto \underline{M_{\rm BH}} T_\infty^{-1}$$



Hyper-Eddington conditions (**$R_{\rm HII}$<$R_{\rm B}$**)

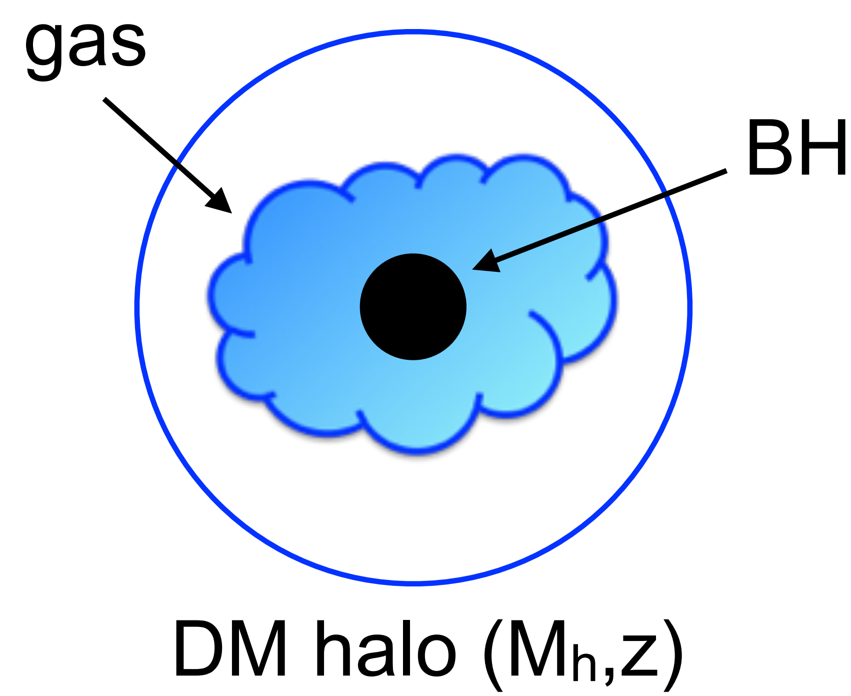
$$M_{\rm BH,4} n_{\infty,5} \gtrsim T_{\infty,4}^{3/2} \quad \Leftrightarrow \quad \dot{m} = \frac{\dot{M}}{\dot{M}_{\rm Edd}} \geq 5000$$

BH growth in the early Universe

- gas density in a DM halo

$$T_{\rm vir} \simeq 1.9 \times 10^4 \ M_{\rm h,8}^{2/3} \ {\rm K} \left(\frac{1+z}{21} \right)$$

$$n(r) \simeq 10^3 \ T_{\rm vir,4} \ {\rm cm}^{-3} \left(\frac{r}{10 \ {\rm pc}} \right)^{-2}$$



- hyper-Eddington conditions $(\dot{m} > 5000)$

$$\frac{\dot{M}}{\dot{M}_{\rm Edd}} \propto n(R_{\rm B}) M_{\rm BH} T_\infty^{-3/2} \simeq 5 \times 10^4 \ M_{\rm BH}^{-1} \ T_{\infty,4}^{1/2} \ T_{\rm vir,4} \ {\rm M}_\odot$$

$$\Rightarrow \quad M_{\rm BH} \leq 2 \times 10^5 \ T_{\infty,4}^{1/2} \ T_{\rm vir,4} \ {\rm M}_\odot$$

independent of seed BHs

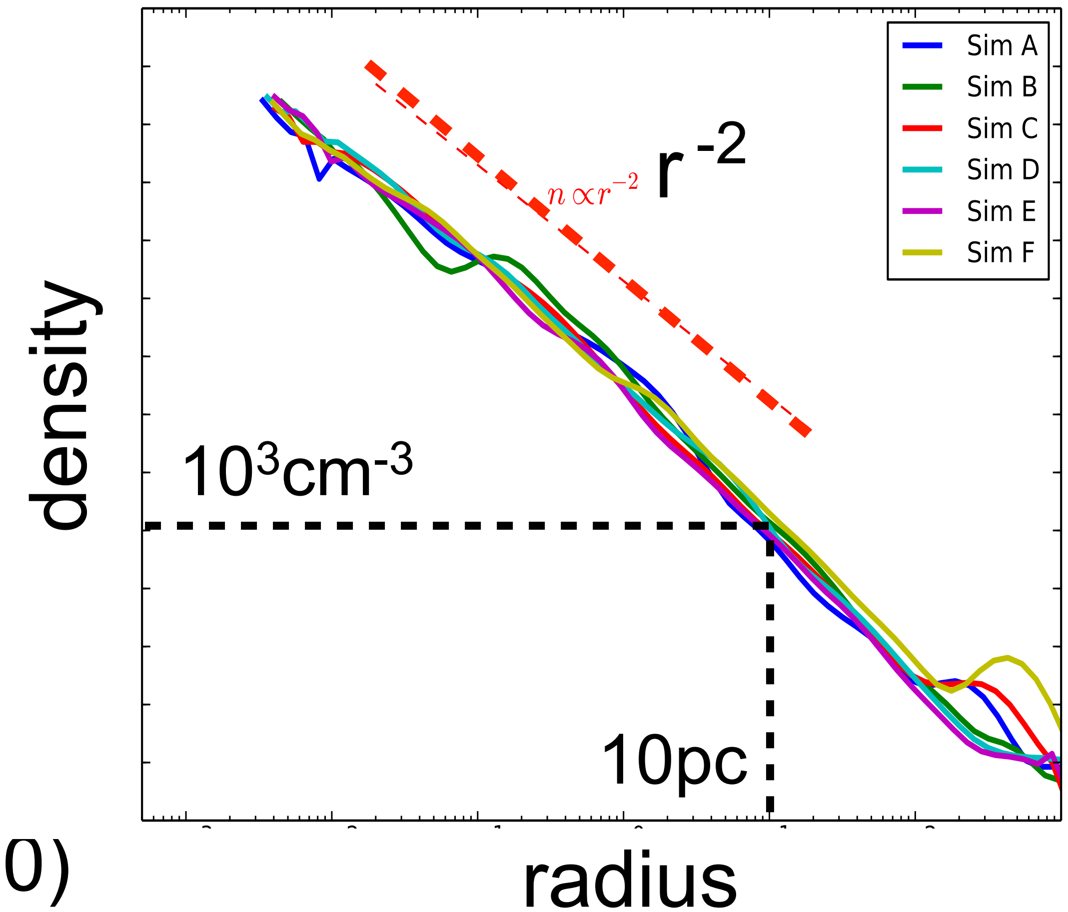
BH growth in the early Universe

- gas density in a DM halo

$$T_{\rm vir} \simeq 1.9 \times 10^4 \ M_{\rm h,8}^{2/3} \ {\rm K} \left(\frac{1+z}{21} \right)$$

$$n(r) \simeq 10^3 \ T_{\rm vir,4} \ {\rm cm}^{-3} \left(\frac{r}{10 \ {\rm pc}} \right)^{-2}$$

Regan et al. (2014) $T_{\rm vir} \sim 10^4$K



- hyper-Eddington conditions ($\dot{m}$ > 5000)

$$\frac{\dot{M}}{\dot{M}_{\rm Edd}} \propto n(R_{\rm B}) M_{\rm BH} T_\infty^{-3/2} \simeq 5 \times 10^4 \ M_{\rm BH}^{-1} \ T_{\infty,4}^{1/2} \ T_{\rm vir,4} \ {\rm M}_\odot$$

$$\Rightarrow \quad \boxed{M_{\rm BH} \leq 2 \times 10^5 \ T_{\infty,4}^{1/2} \ T_{\rm vir,4} \ {\rm M}_\odot}$$

independent of seed BHs

Summary

- A steady hyper-Eddington accretion solution with $\dot{m} \geq 5000$ is found (from the Bondi radius to the BH accretion disk)

- Necessary conditions required for hyper-Eddington accretion is

$$M_{\rm BH,4} n_{\infty,5} \gtrsim T_{\infty,4}^{3/2} \quad \Leftrightarrow \quad \dot{m} = \frac{\dot{M}}{\dot{M}_{\rm Edd}} \geq 5000$$

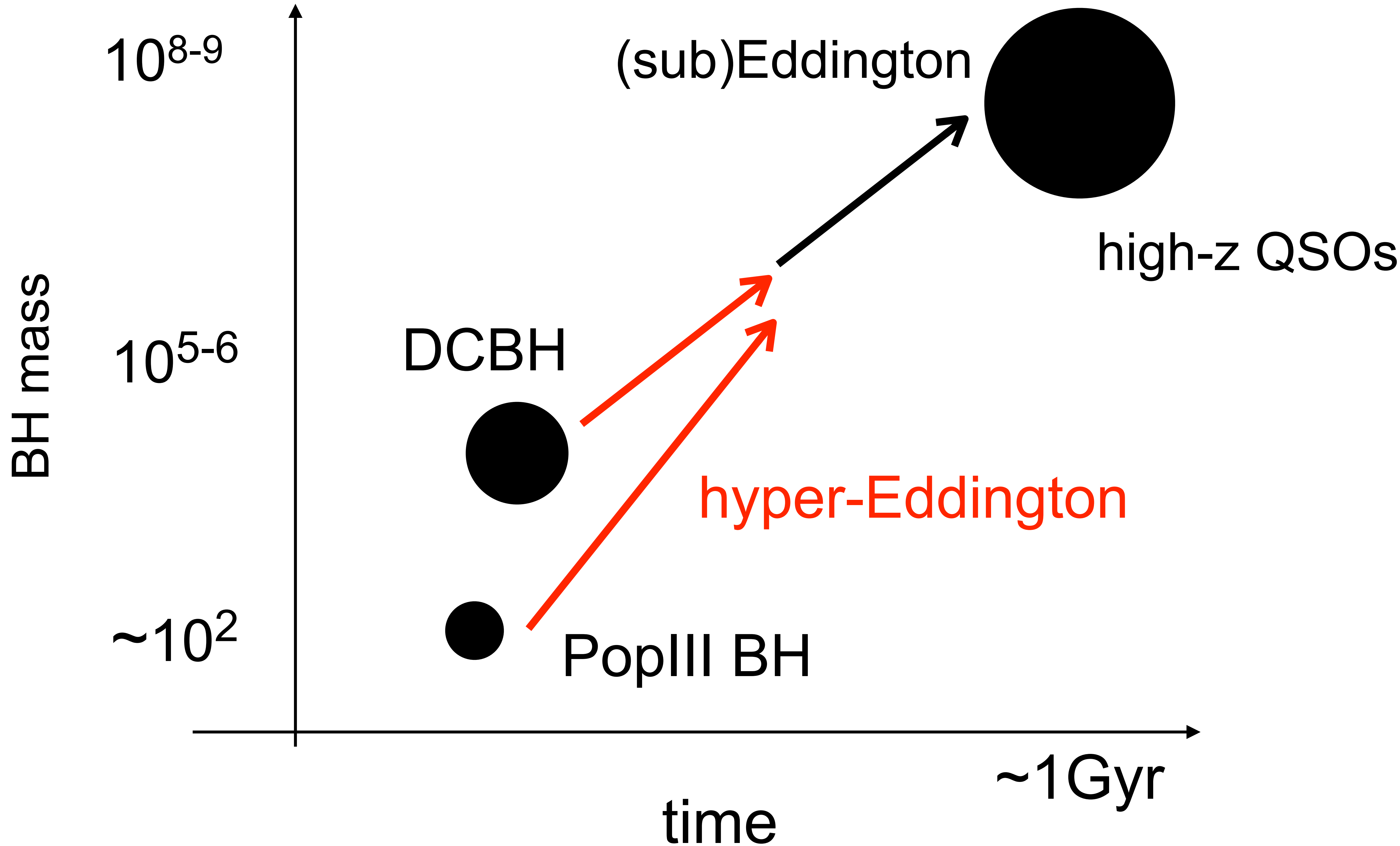
- The result is applied to

  BH growth in the early Universe → rapid growth up to $M_{\rm BH} \sim 10^{5-6}\ M_{\odot}$

  Lya emitters & ultra-luminous IR galaxies

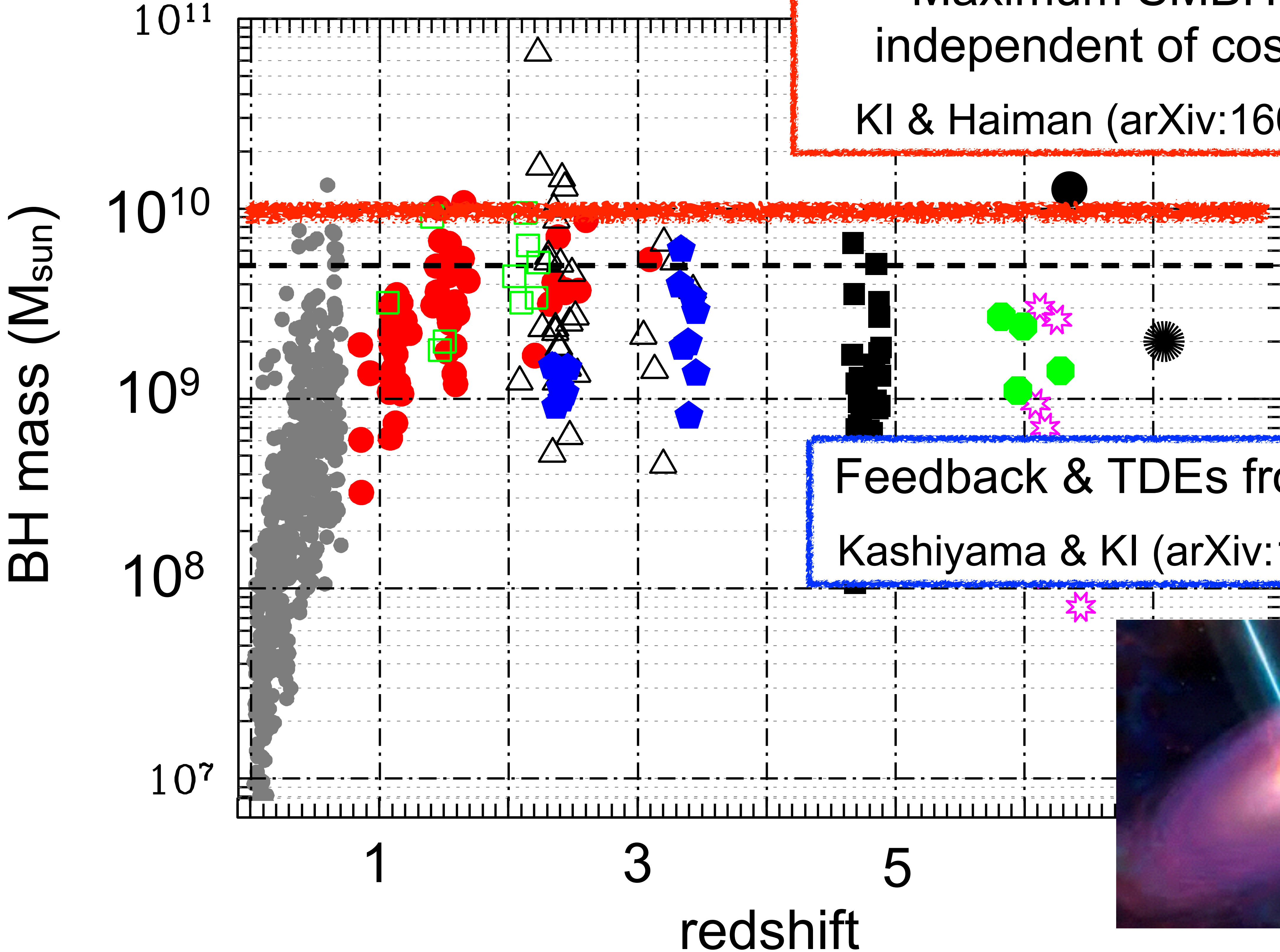
Inayoshi, Haiman & Ostriker (arXiv:1511.02116)

Summary



(sub)Eddington
10^{8-9}
high-z QSOs
10^{5-6}
DCBH
BH mass
hyper-Eddington
$\sim 10^2$
PopIII BH
~1Gyr
time

Recent/Future works



Maximum SMBH mass
independent of cosmology

KI & Haiman (arXiv:1601.02611)

Feedback & TDEs from DCBHs

Kashiyama & KI (arXiv:1602.04293)