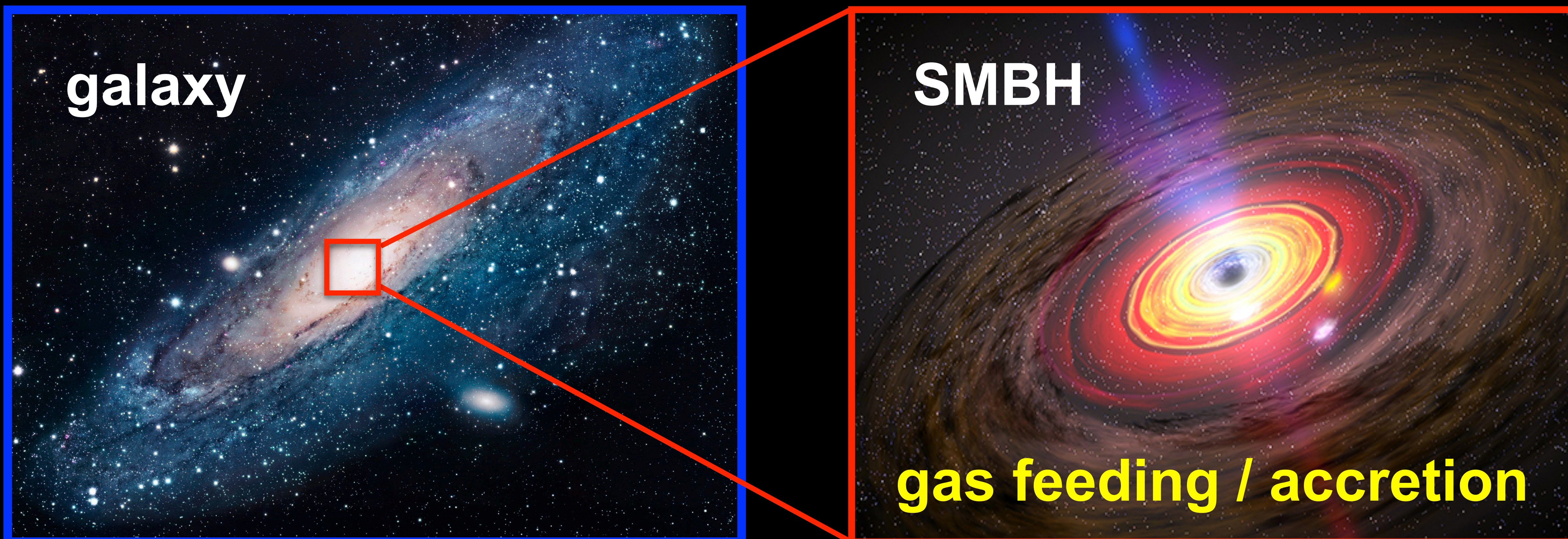
Supermassive black holes (SMBH)

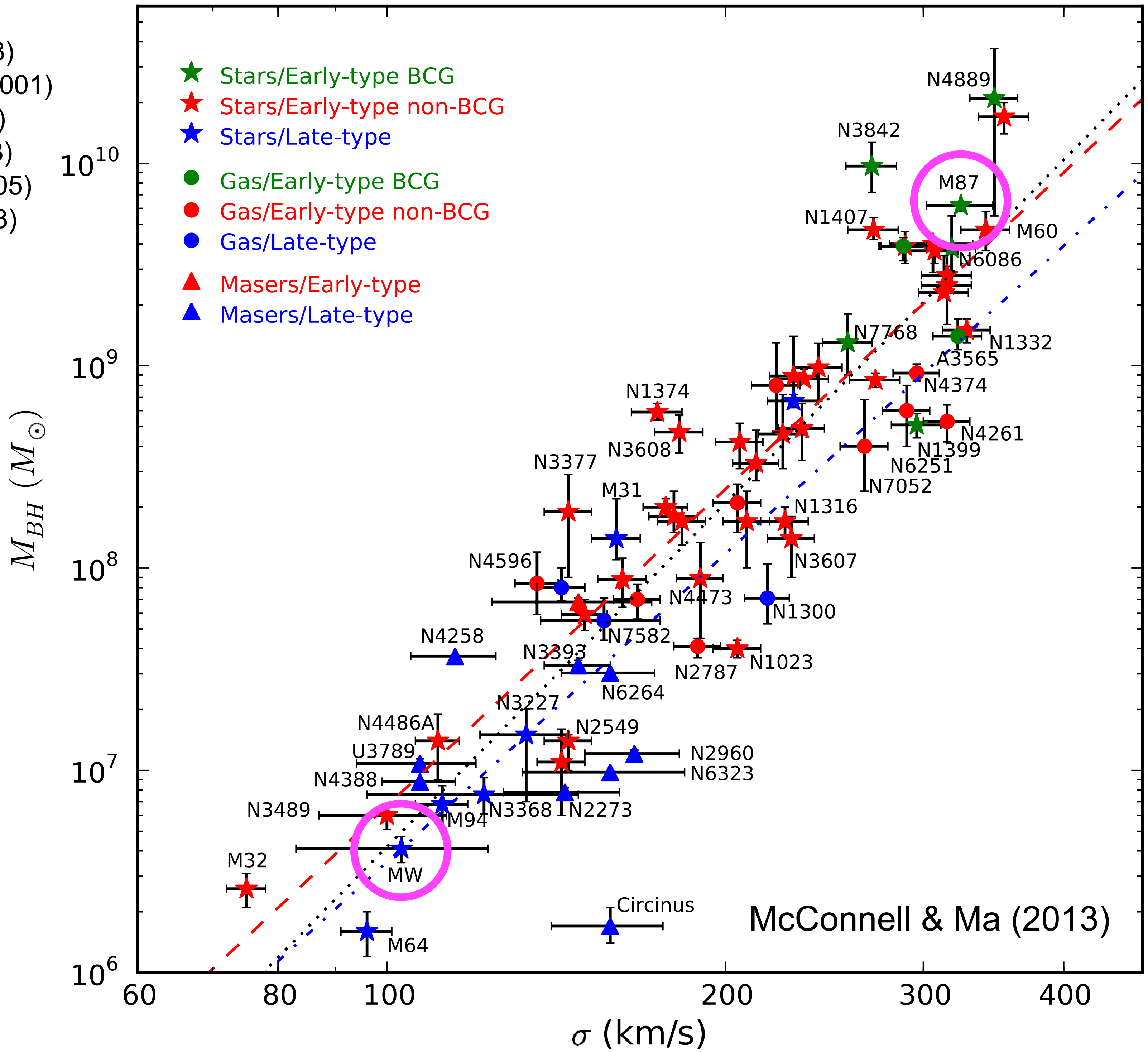


- very massive objects: $M_{BH} \sim 10^{6} - 10^{10}\, M_{sun}$
- universal existence at the galaxy centers
- very powerful engines of radiation & outflows

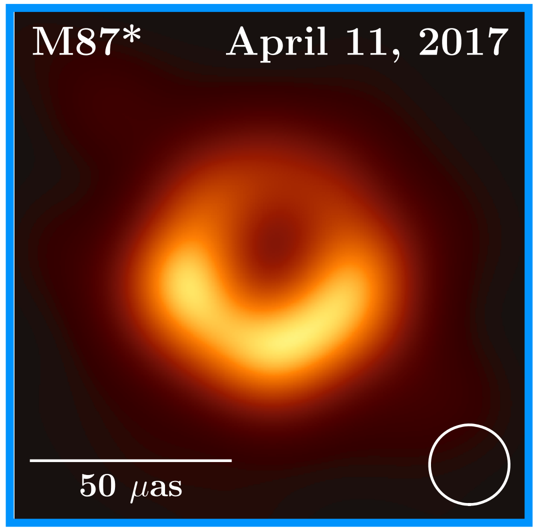
BH-galaxy coevolution

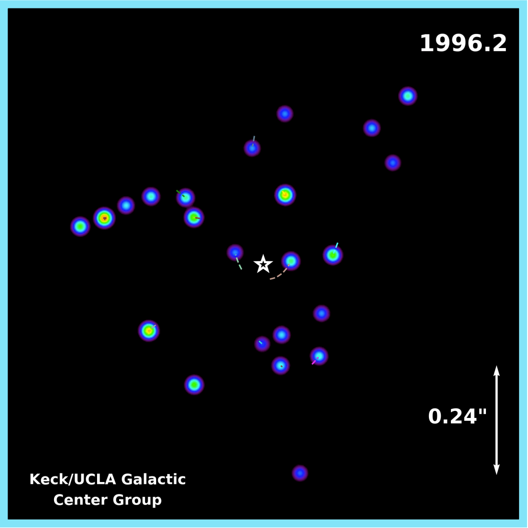
see also…
Magorrian et al. (1998)
Merritt & Ferrarese (2001)
Tremaine et al. (2002)
Marconi & Hunt (2003)
Ferrarese & Ford (2005)
Kormendy & Ho (2013)

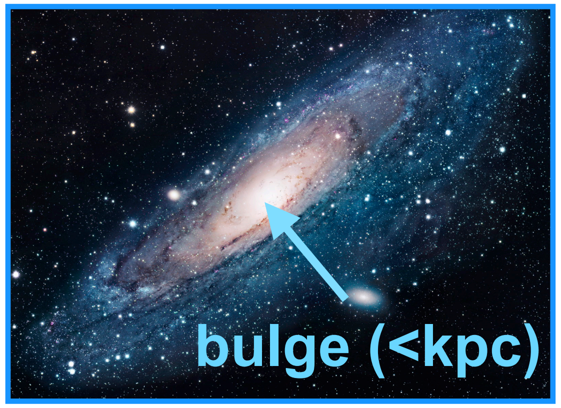
BH mass



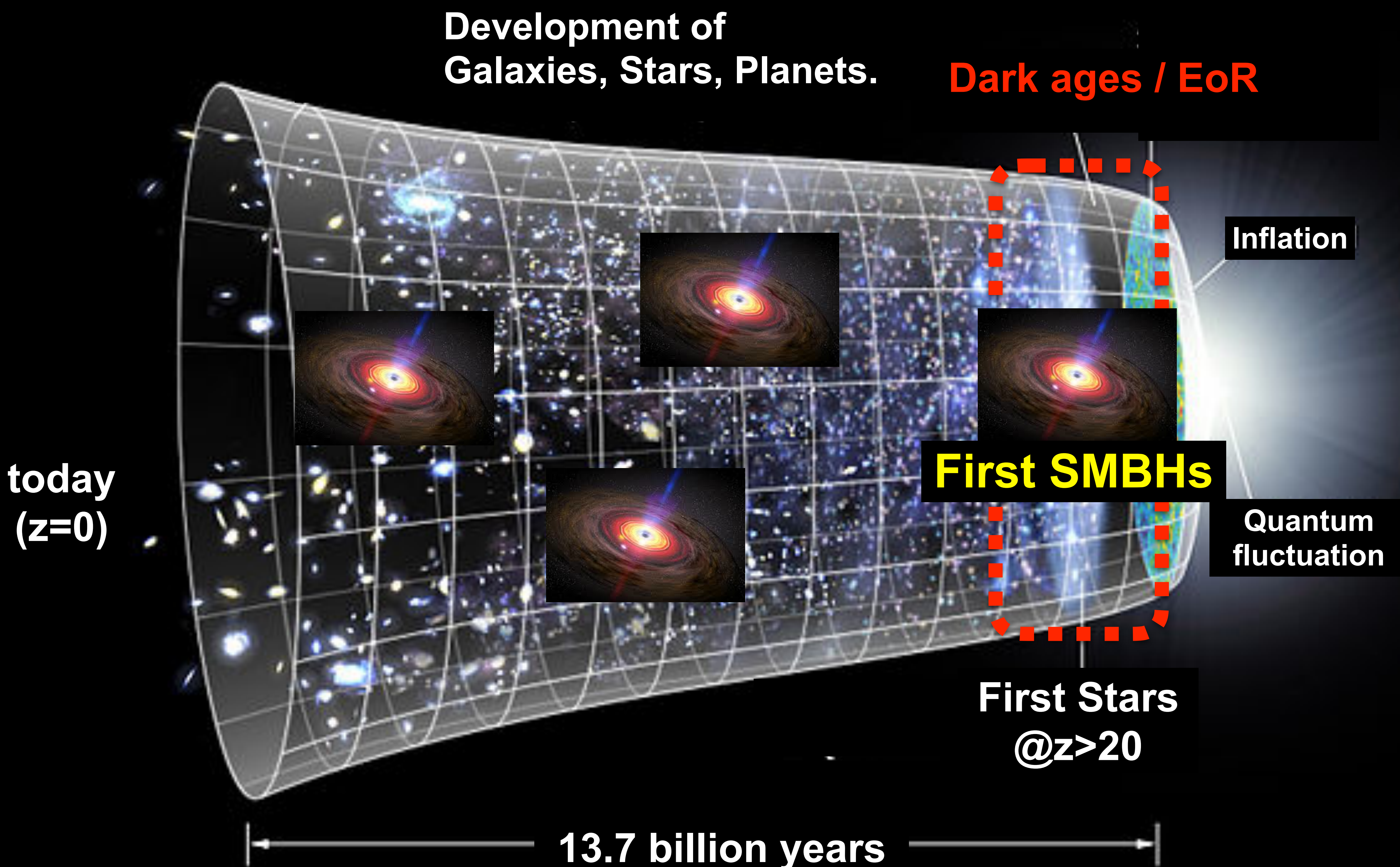
velocity dispersion of bulge stars







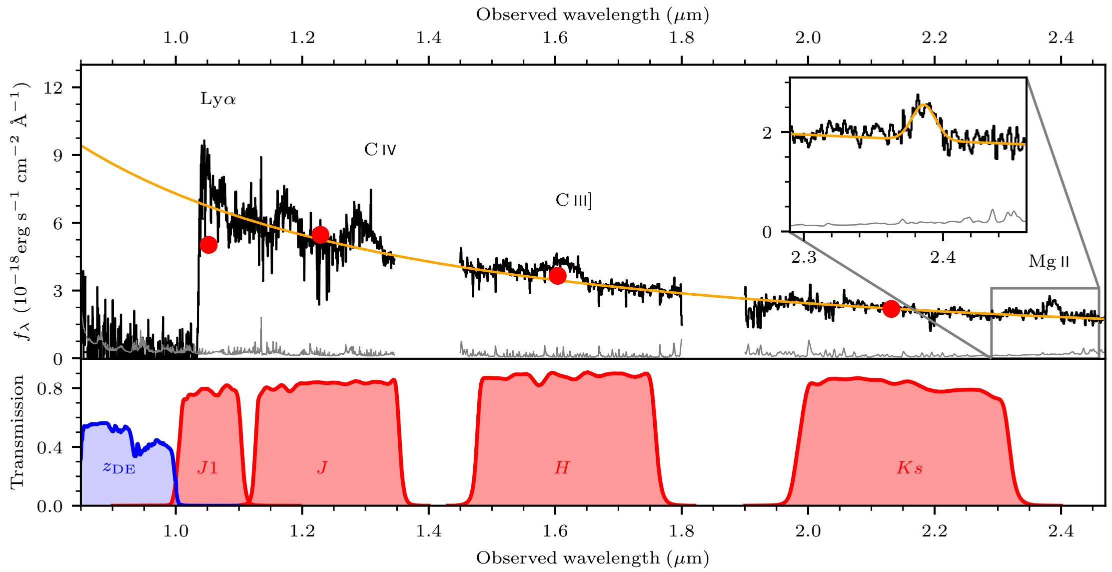
Cosmological QSO population



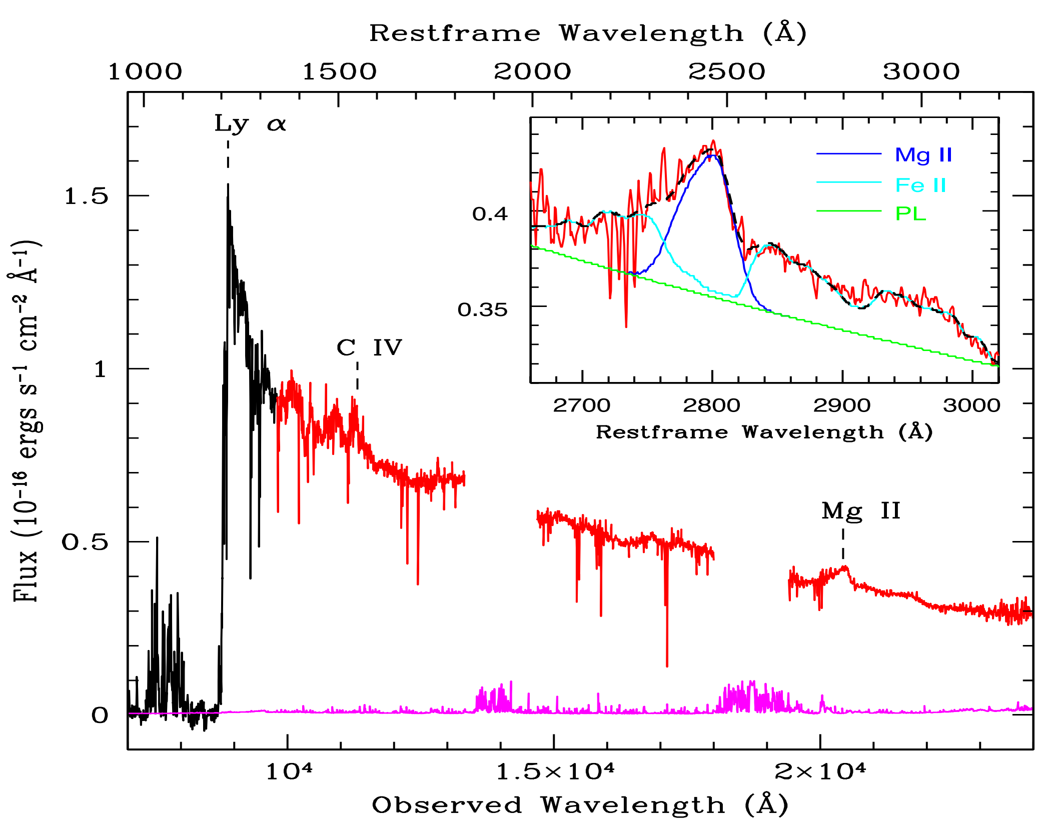
High-z monsters

See also
Willott+10, Mortlock+11,
Onoue+19, Yang+20

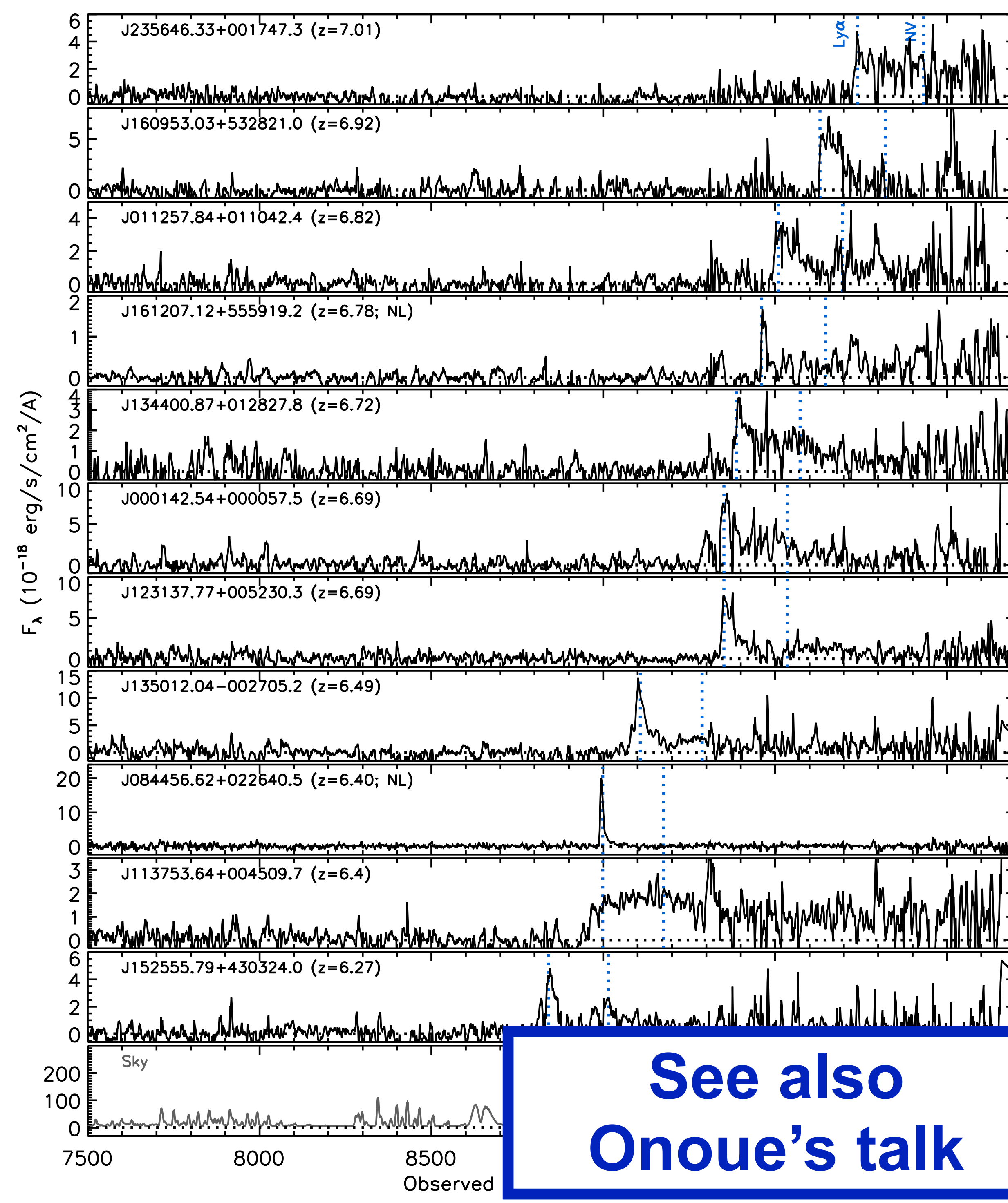
Most distant z=7.54 Banados et al. (2017)



Most massive M=10^{10}M$_{sun}$ Wu et al. (2015)



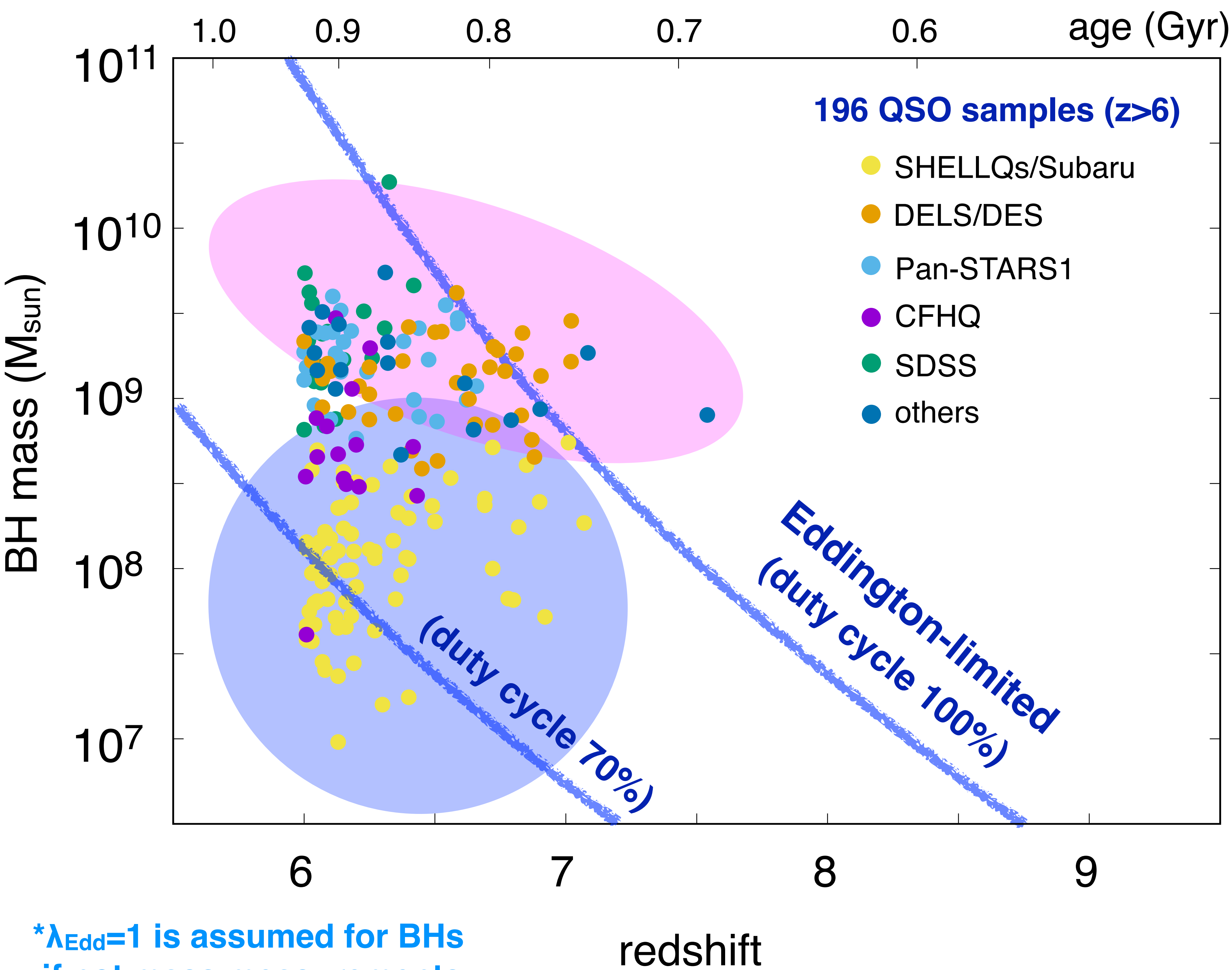
Subaru HSC, SHELLQs (Matsuoka et al. 2019)



See also Onoue's talk

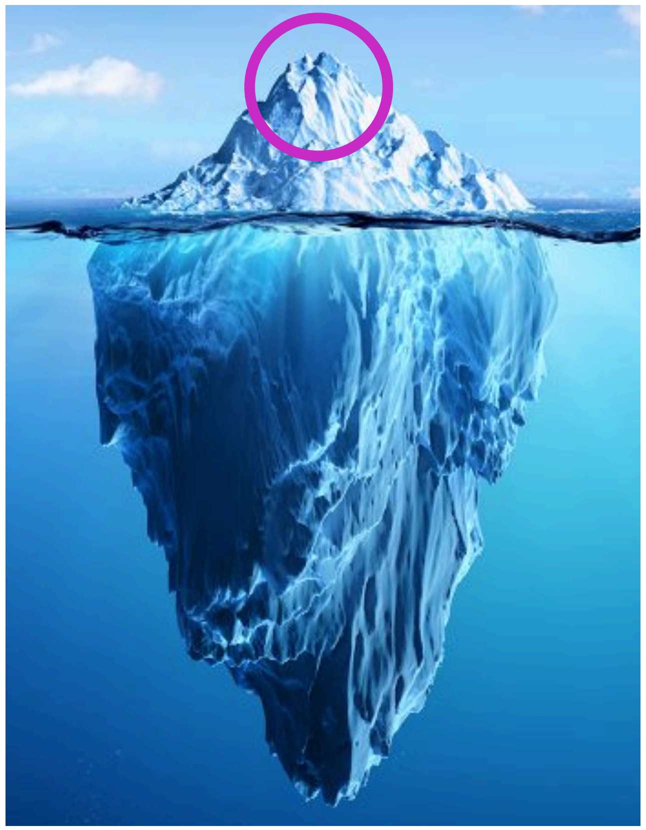
High-redshift monster BHs

Compilation from KI, Visbal & Haiman (2020), ARA&A



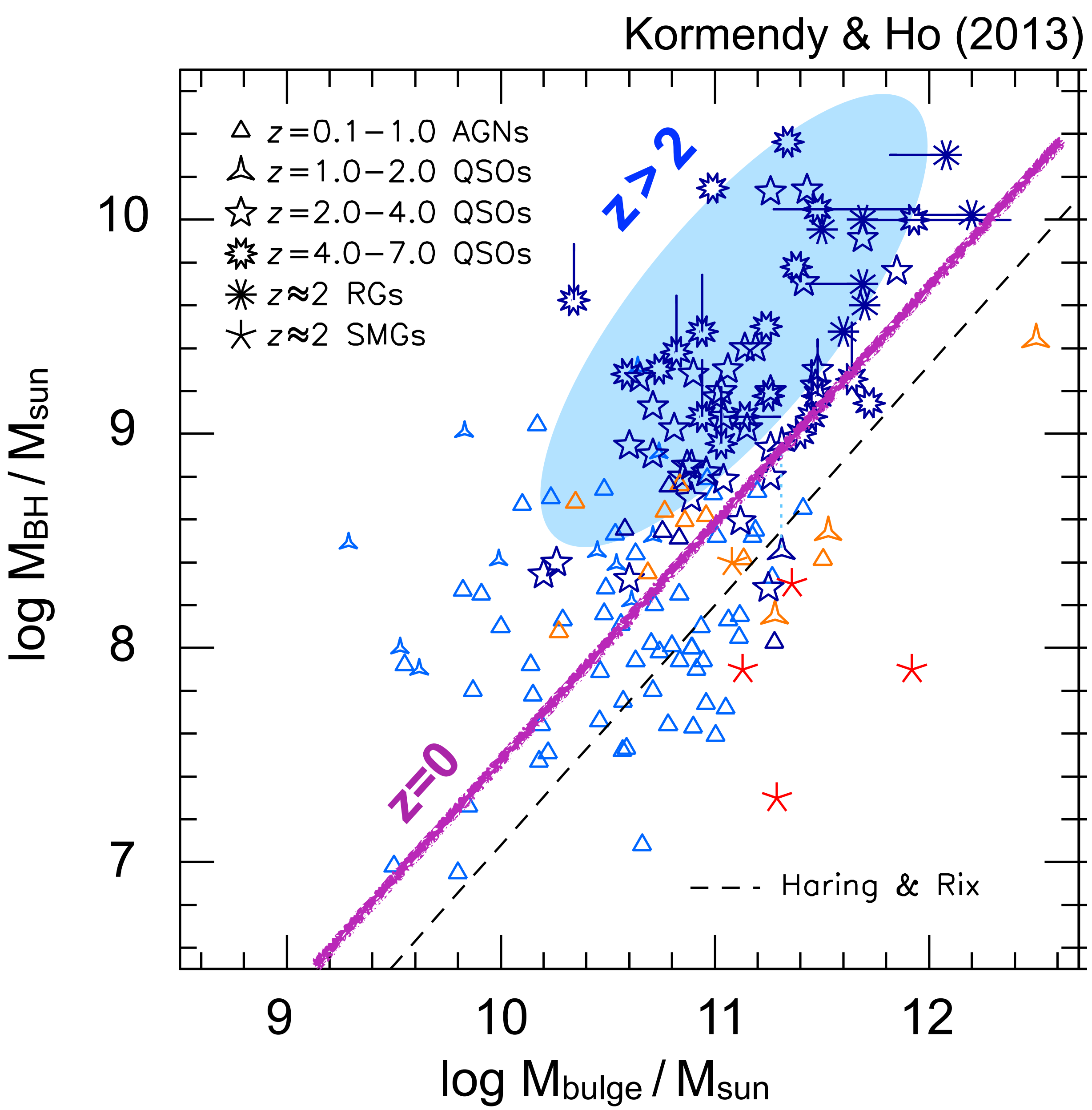
*λ_{Edd}=1 is assumed for BHs if not mass measurements

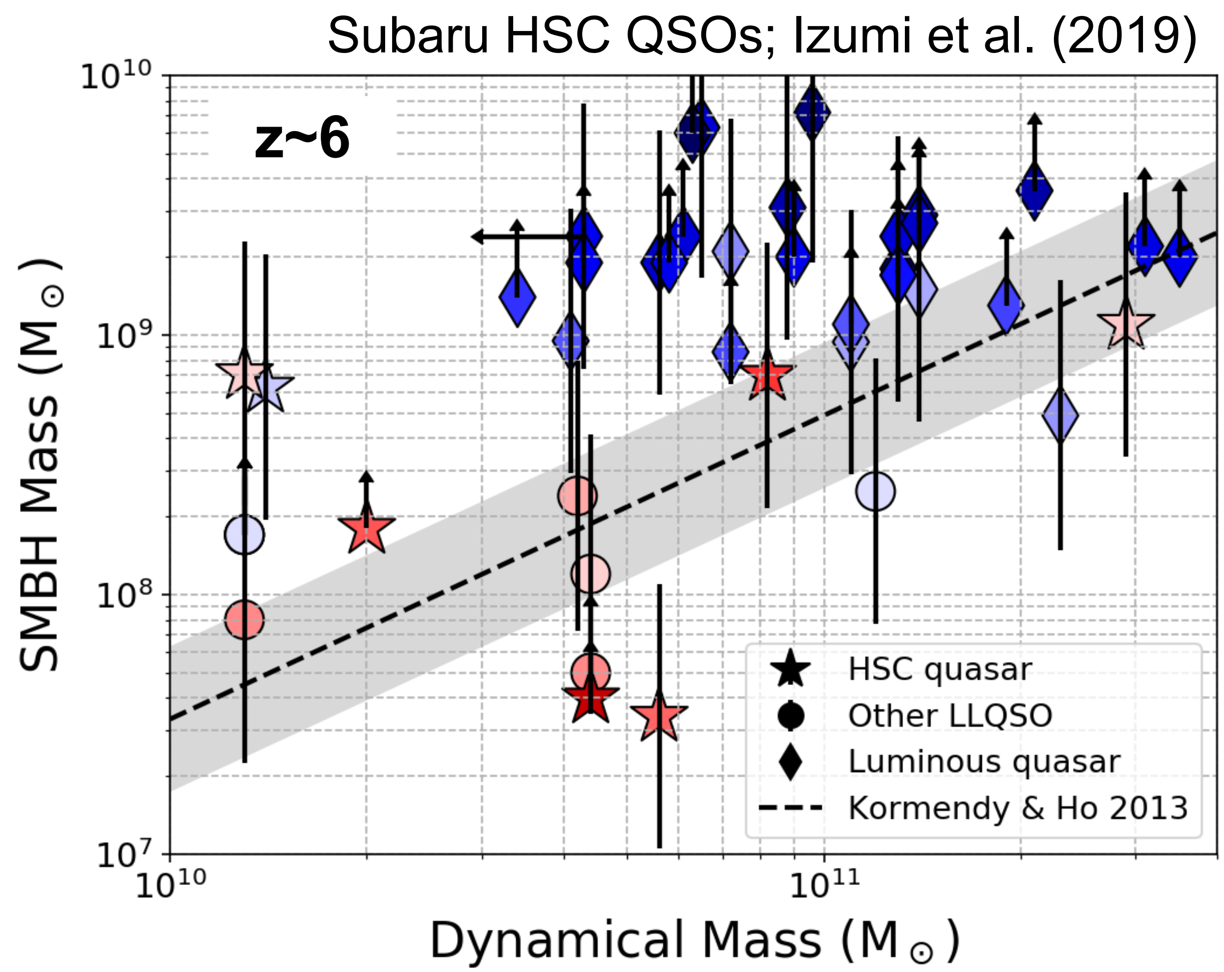
Tips of iceberg



Underlying / dominant BH population

BH-galaxy coevolution from high-z





(measured by radio emission withALMA)

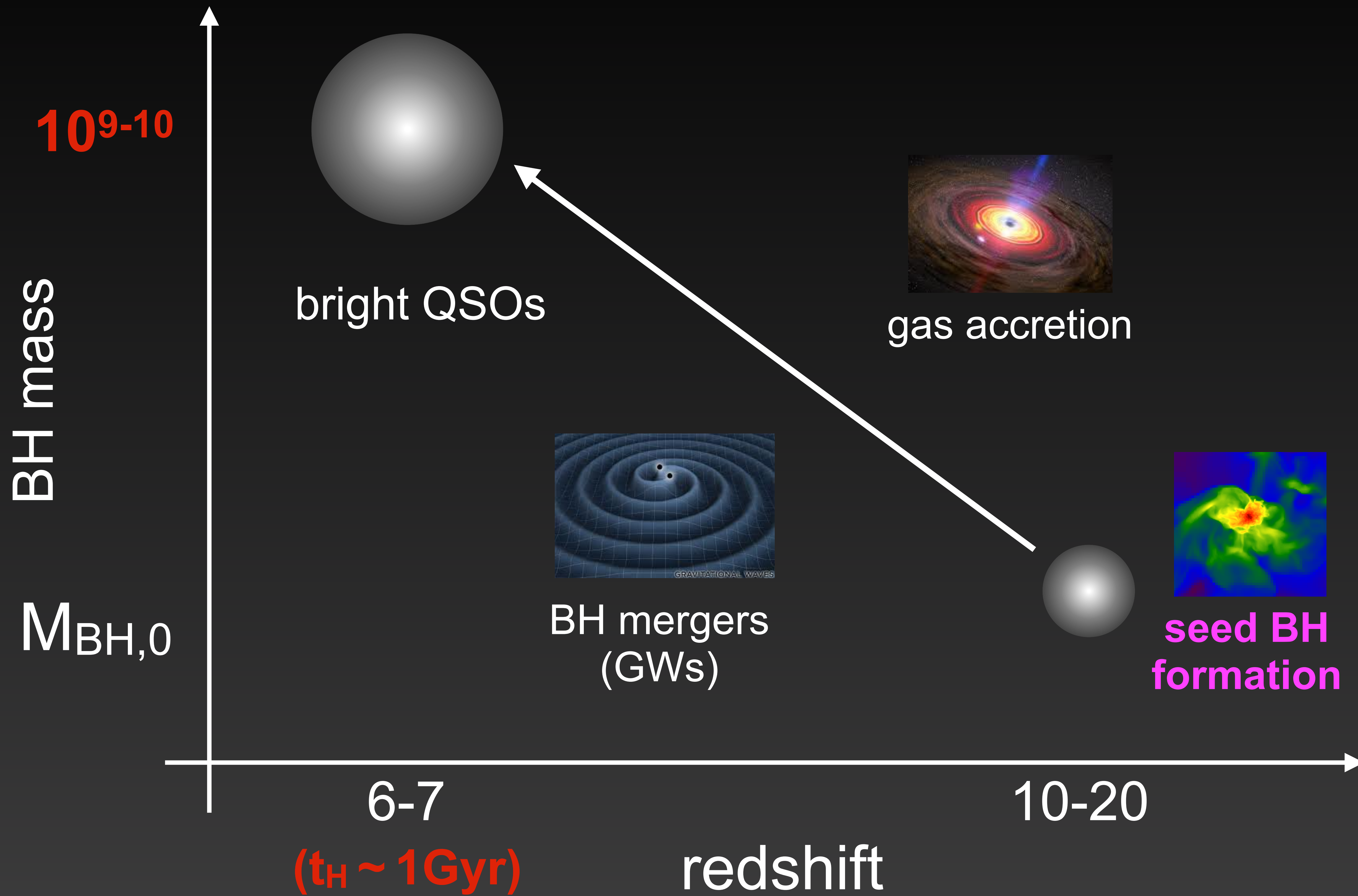
Overmassive BHs from the BH-gal relation

but possibly true for the brighter end (?)

The Assembly of the First Massive Black Holes

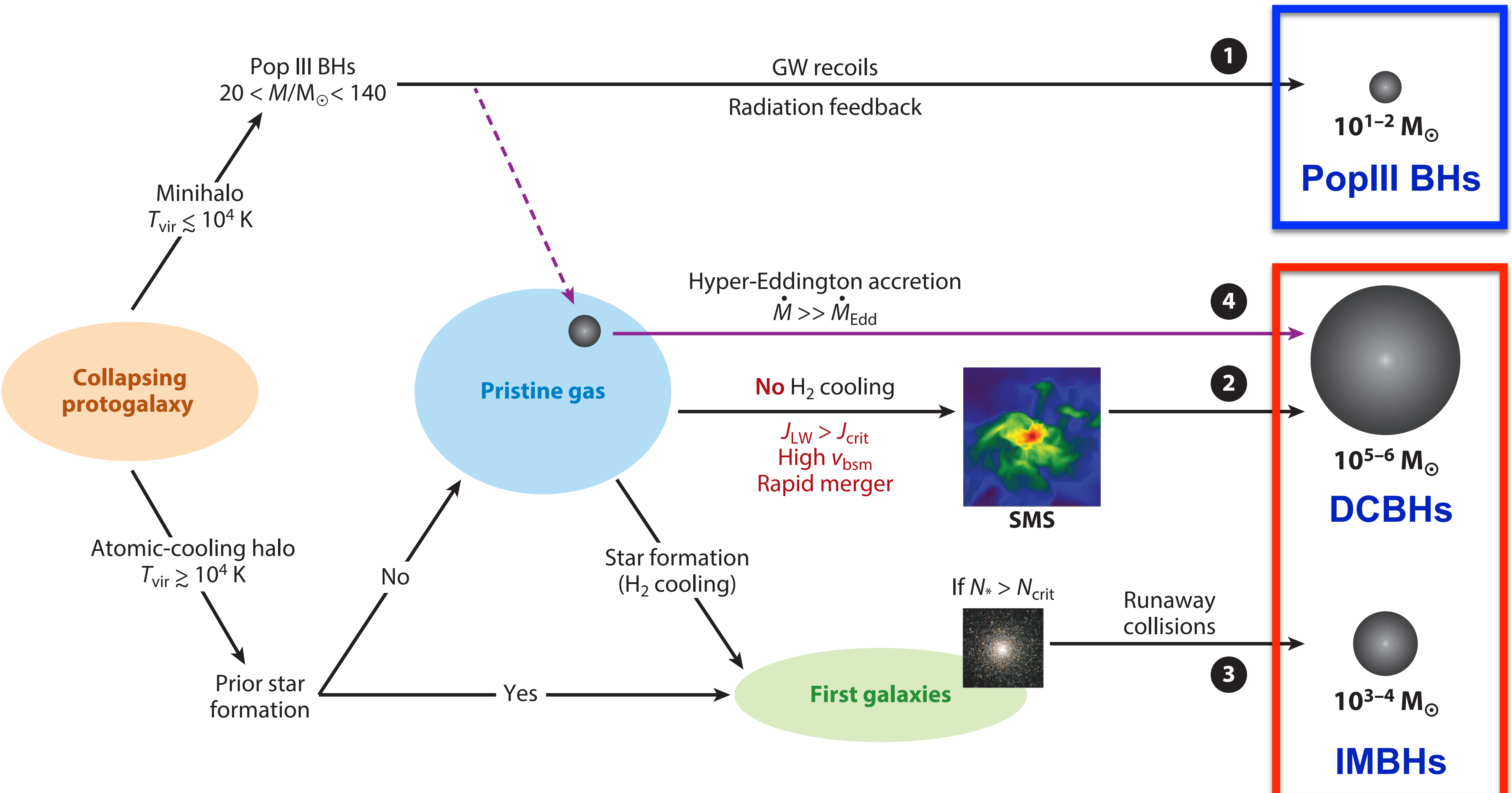
1. *Massive Seed Formation*
2. *Rapid Growth of BHs*
3. *Toward Future Observations*

Early SMBH assembly



Formation channels of early BHs

The mass of seed BHs would depend on the environments



KI, Visbal & Haiman (2020) ARA&A

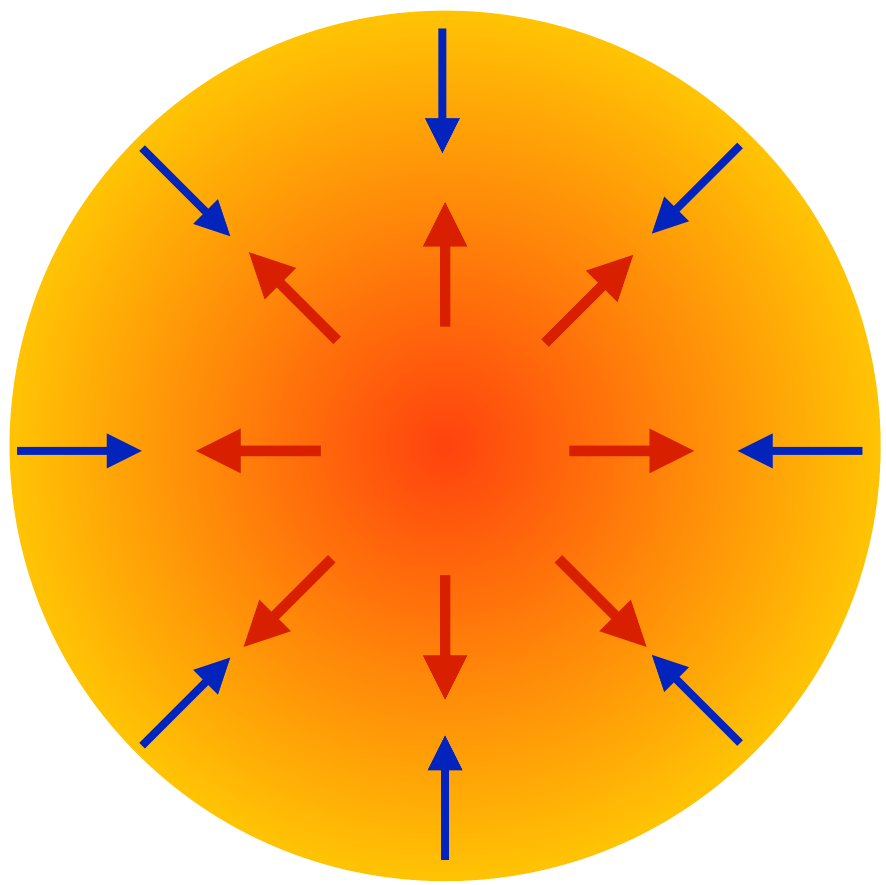
Basics of star formation

- suppose a spherically symmetric system

gas self-gravity

$$g_{\rm grav} = \frac{GM_r}{r^2}$$

$$\sim G\rho r$$



pressure-grad. force

$$g_{\rm gas} = \frac{1}{\rho}\frac{dp}{dr}$$

$$\sim c_{\rm s}^2 r^{-1}$$

Cloud collapse conditions $g_{\rm grav} \gtrsim g_{\rm gas}$

$$r \gtrsim \lambda_{\rm J} \sim \frac{c_{\rm s}}{(G\rho)^{1/2}} \propto T^{1/2}\rho^{-1/2}$$ “Jeans length”

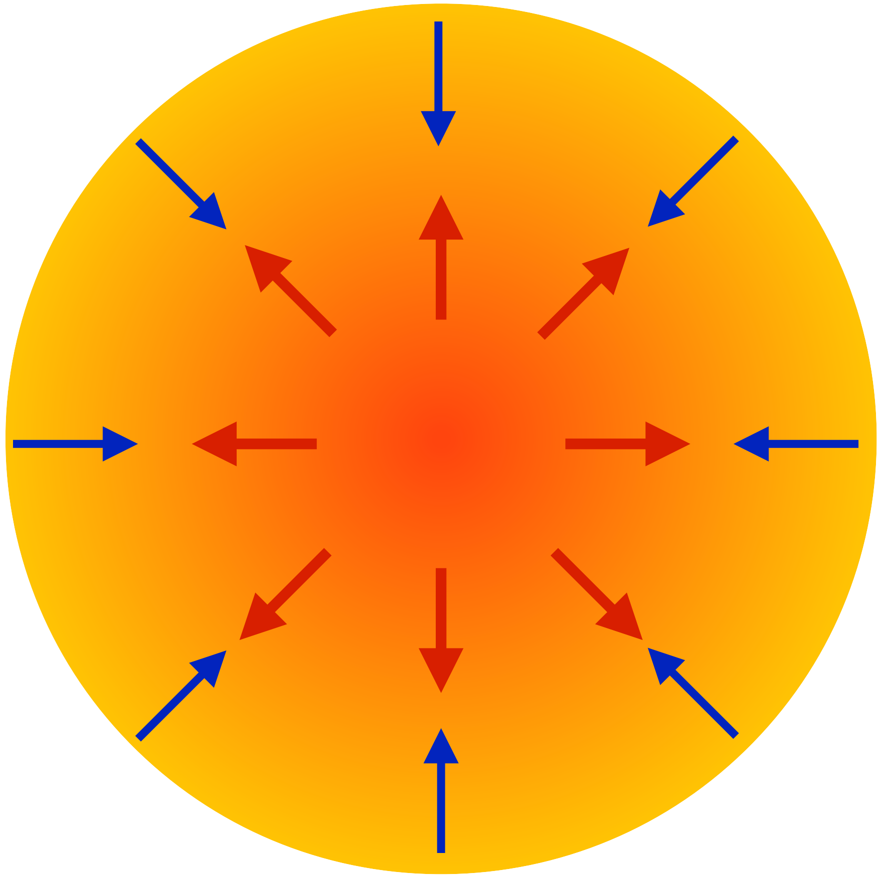
Basics of star formation

- suppose a spherically symmetric system

gas self-gravity

$$g_{\rm grav} = \frac{GM_r}{r^2}$$

$$\sim G\rho r$$



pressure-grad. force

$$g_{\rm gas} = \frac{1}{\rho}\frac{dp}{dr}$$

$$\sim c_{\rm s}^2 r^{-1}$$

Cloud collapse conditions $g_{\rm grav} \gtrsim g_{\rm gas}$

$$M \gtrsim M_{\rm J} \equiv \rho\lambda_{\rm J}^3 \propto T^{3/2}\rho^{-1/2}$$ "Jeans mass"

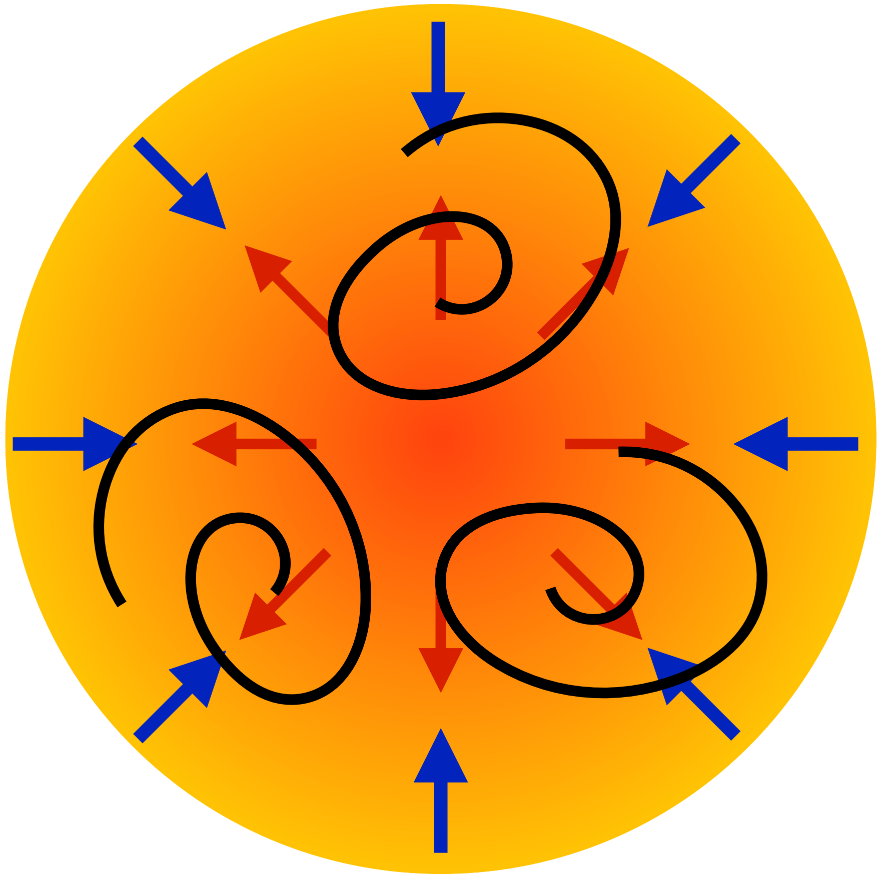
Basics of star formation

- mass inflow rate in collapsing gas

$$\dot{M} \sim \frac{M_{\rm J}}{t_{\rm ff}} \simeq \frac{c_{\rm s}^3}{G} \quad \propto T^{3/2}$$

if highly turbulent…

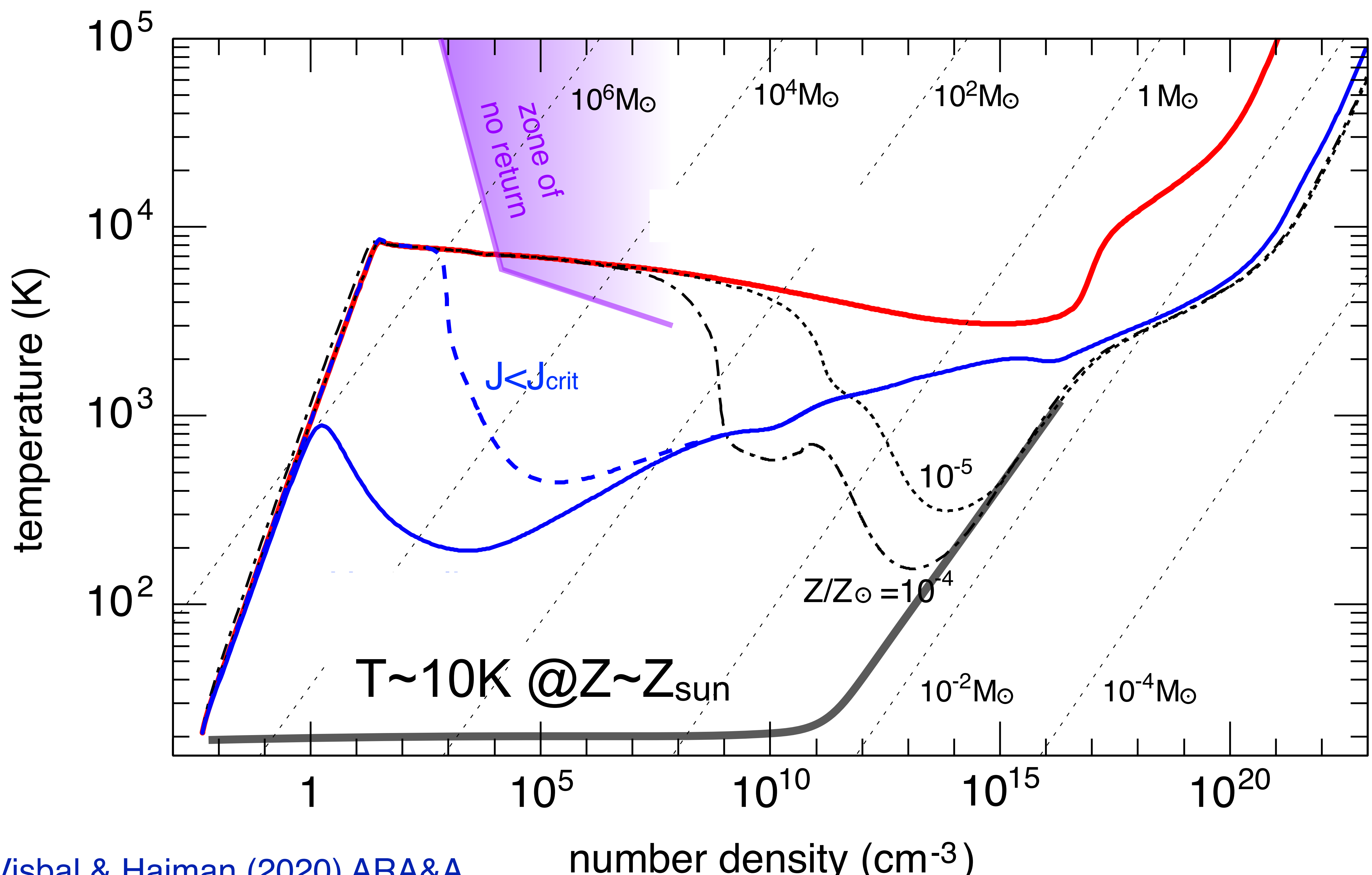
$$c_{\rm eff} = (c_{\rm s}^2 + v_{\rm tur}^2)^{1/2} \gg c_{\rm s}$$



$$t_{\rm ff} \sim (G\rho)^{-1/2}$$

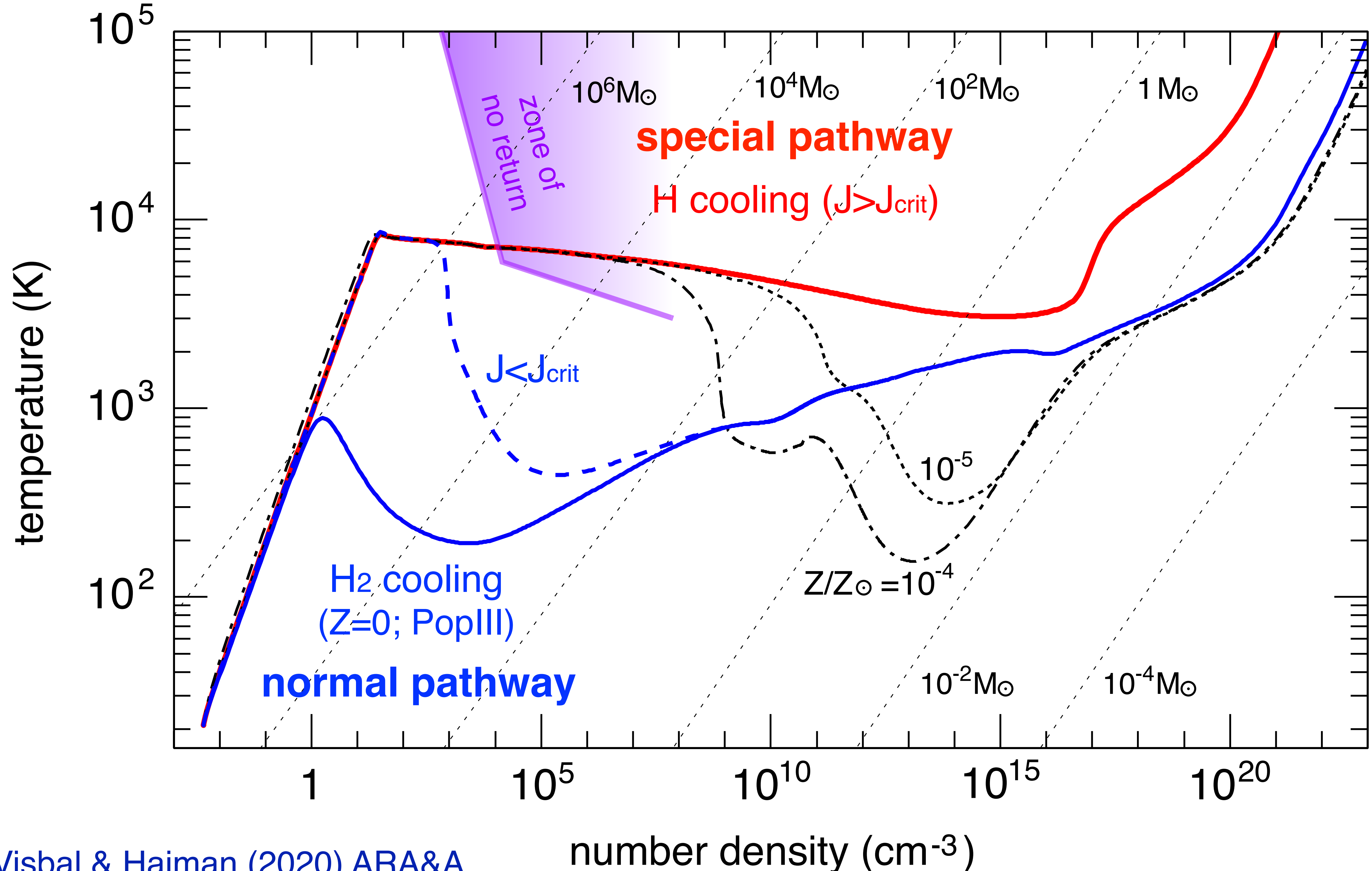
"**Warmer**" gas hardly collapses by its self-gravity,
but once it happens, the inflow rate becomes **higher**

High-z star formation



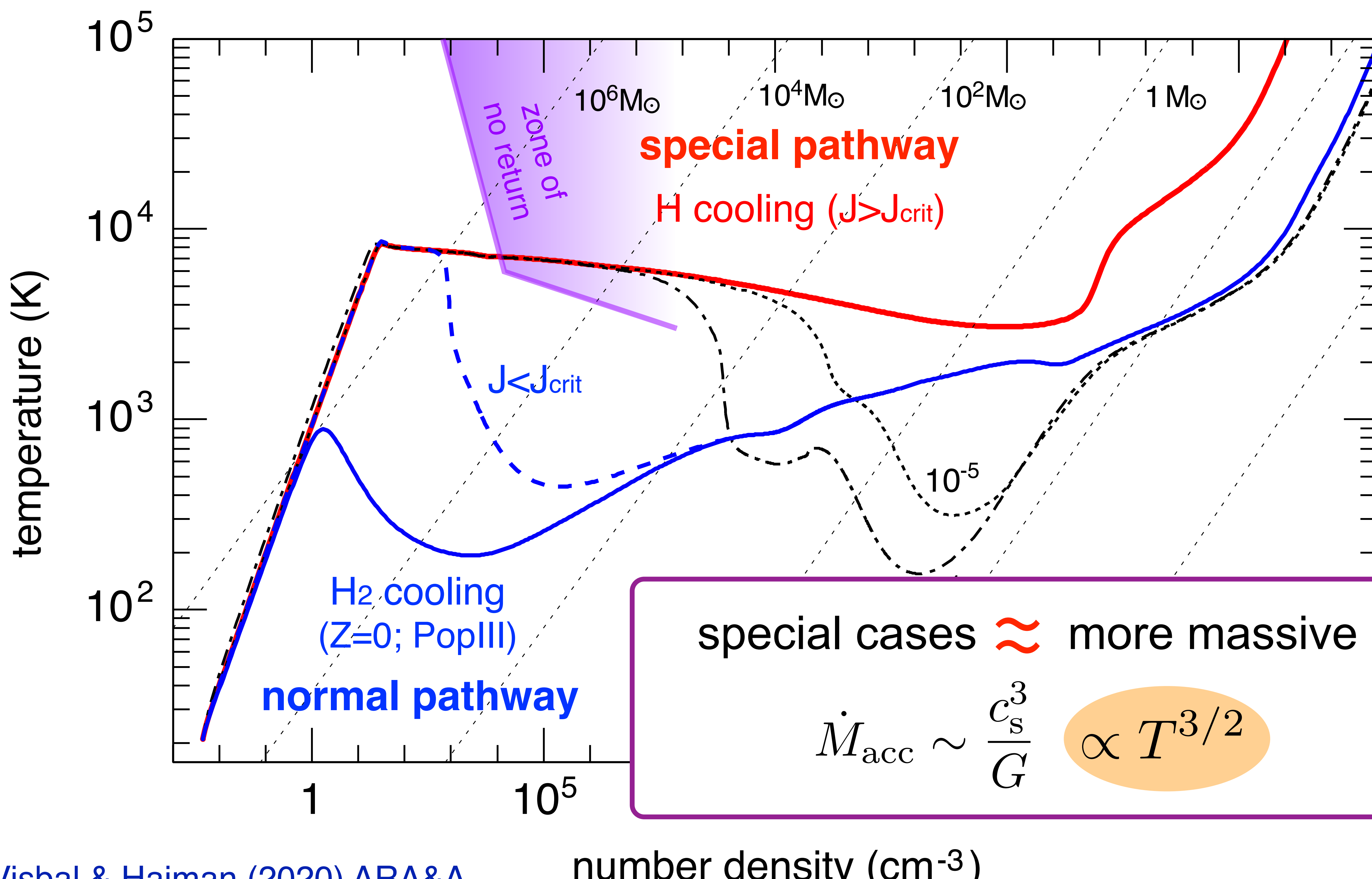
KI, Visbal & Haiman (2020) ARA&A
data from Omukai et al. (2008)

High-z star formation



KI, Visbal & Haiman (2020) ARA&A
data from Omukai et al. (2008)

High-z star formation

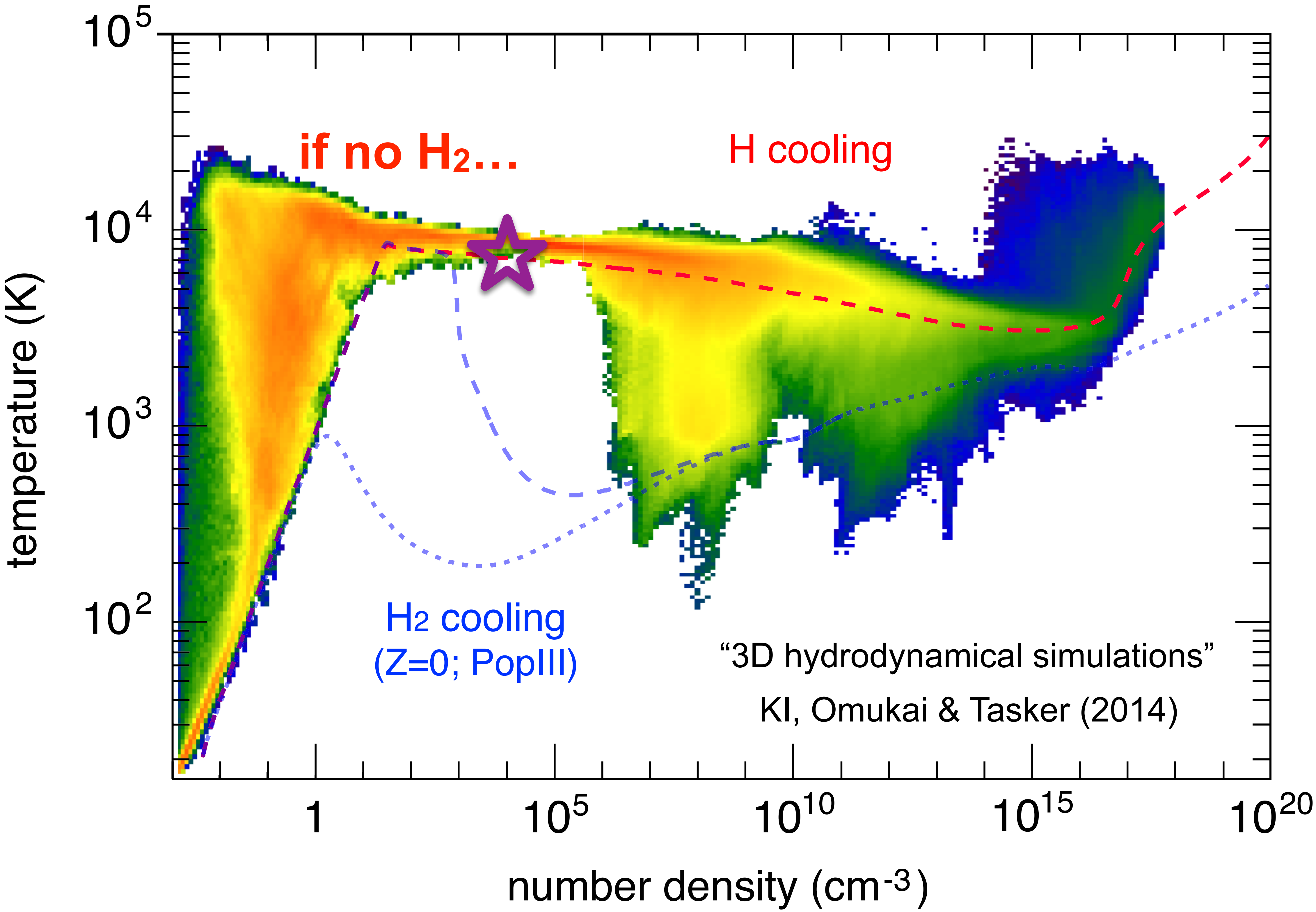


special cases ≈ more massive

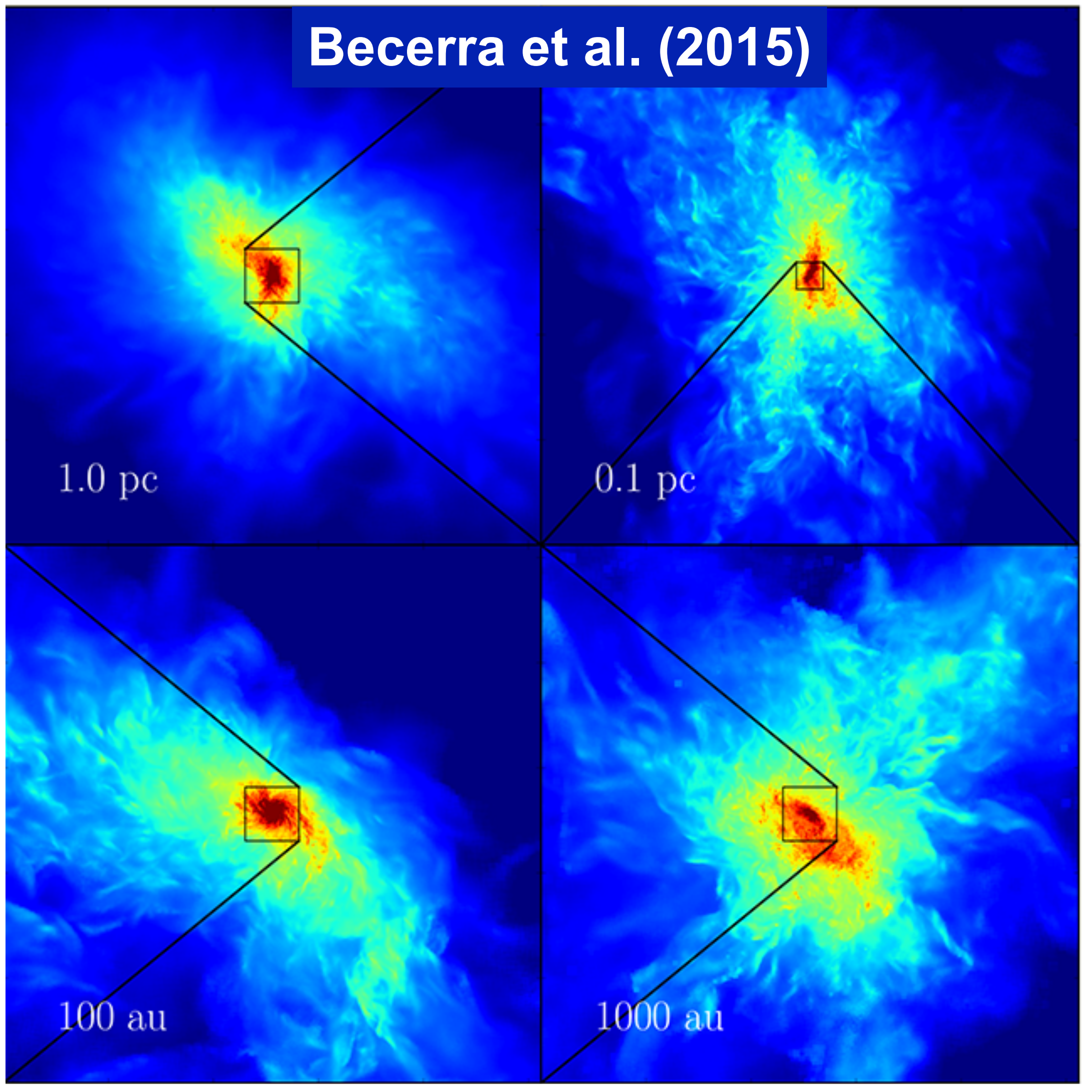
$$\dot{M}_{\rm acc} \sim \frac{c_{\rm s}^3}{G} \propto T^{3/2}$$

KI, Visbal & Haiman (2020) ARA&A
data from Omukai et al. (2008)

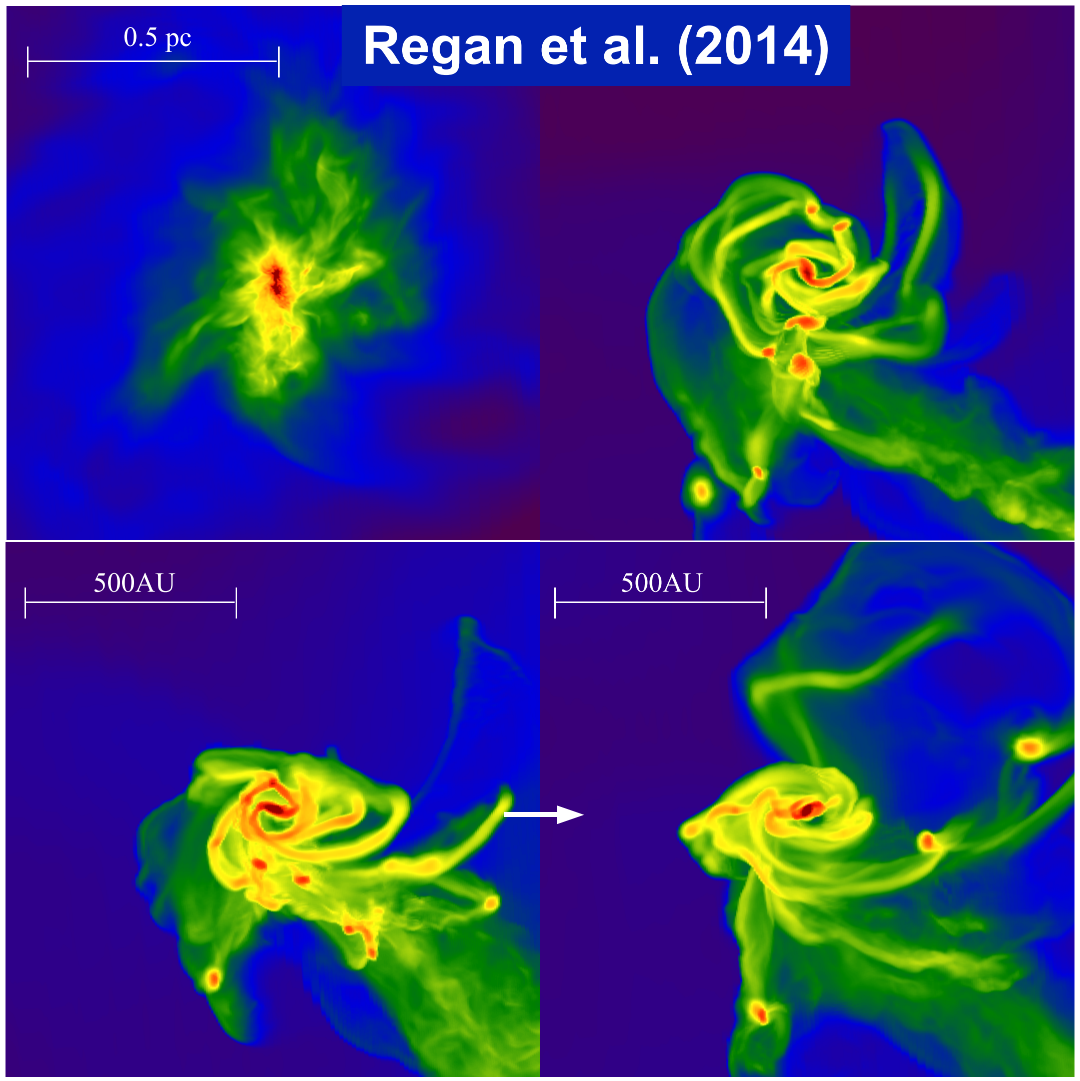
High-z star formation



No fragments / high Mdot!



gravitational collapse

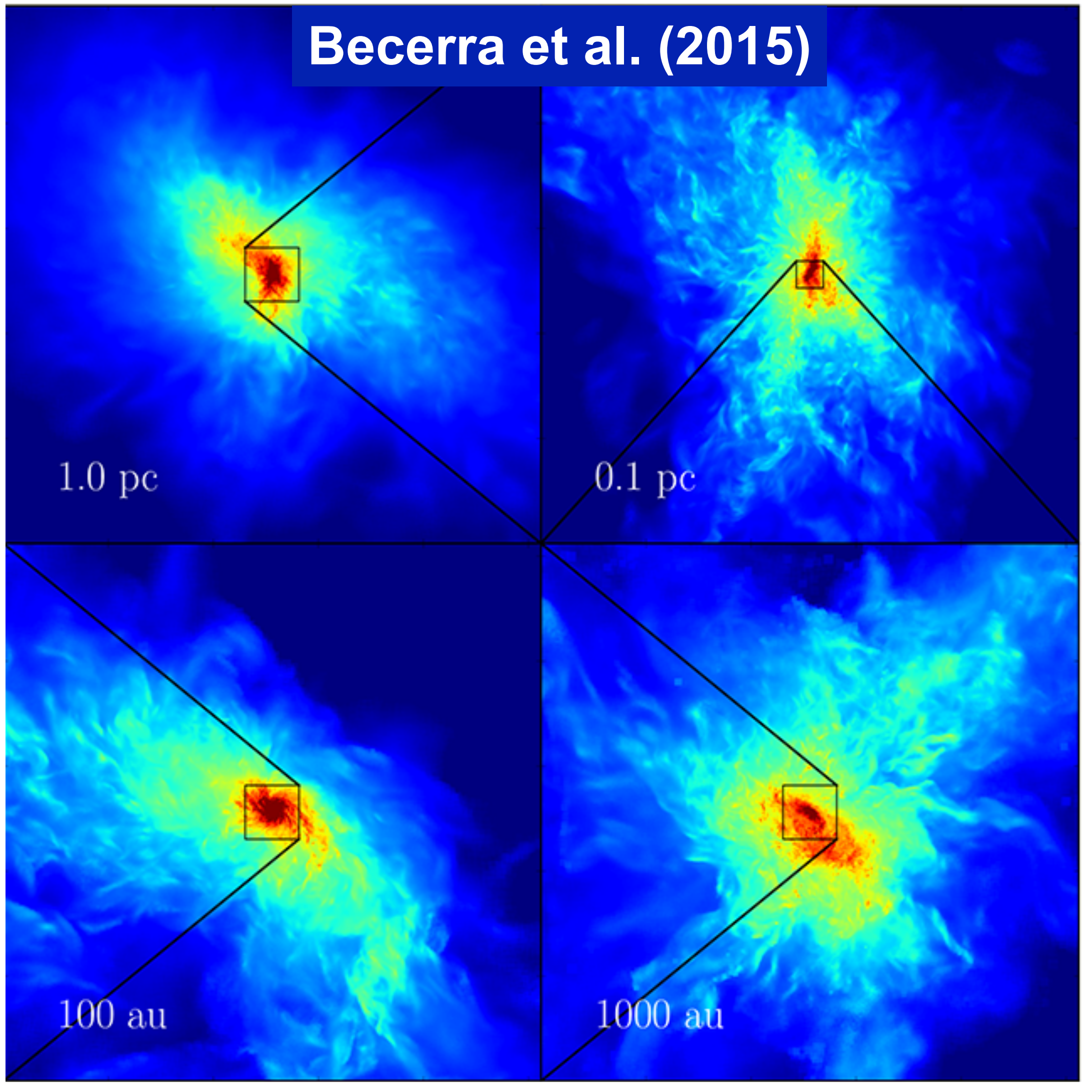


accretion disk

- **no/weak fragmentation**
- **high accretion rate**

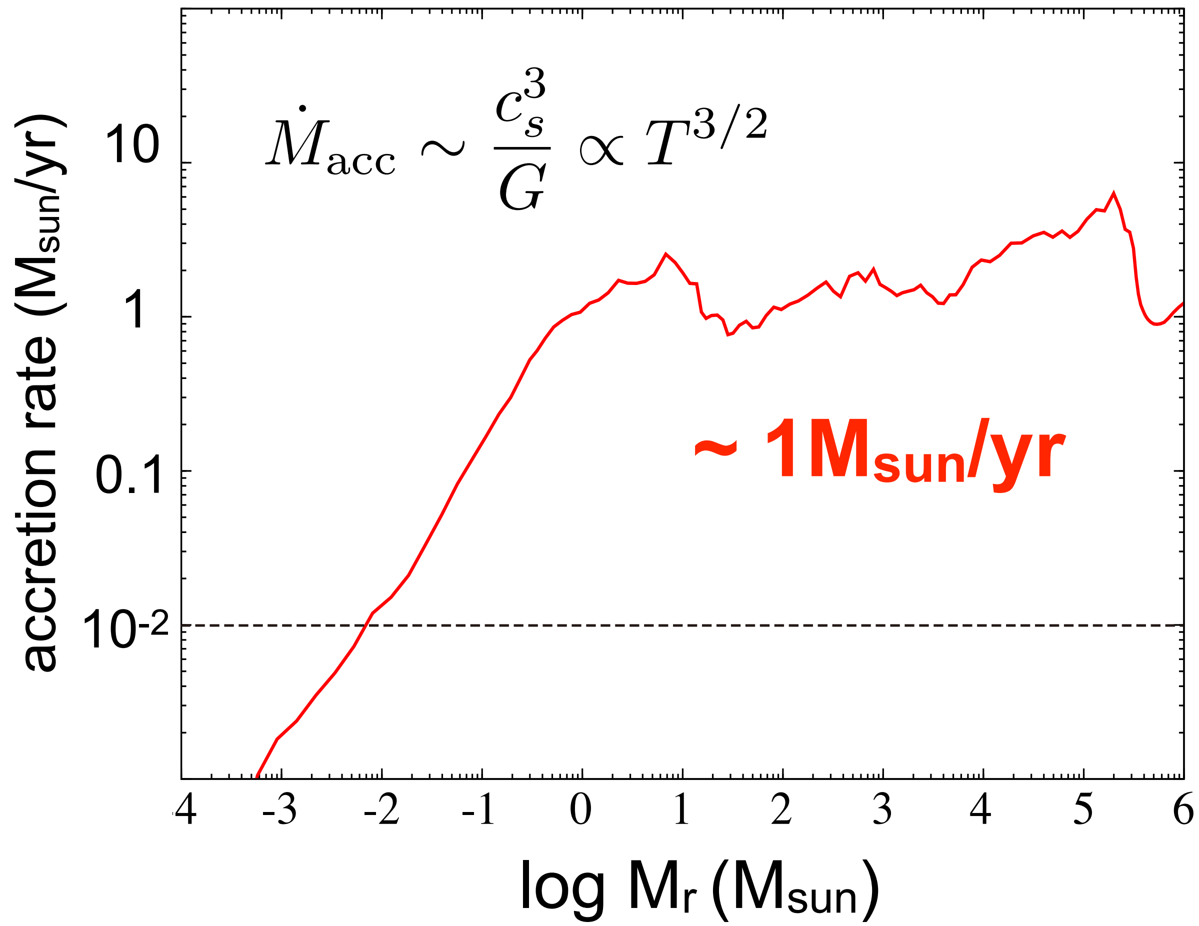
➡ **massive seed BHs**

No fragments / high Mdot!



gravitational collapse

KI, Omukai & Tasker (2014)



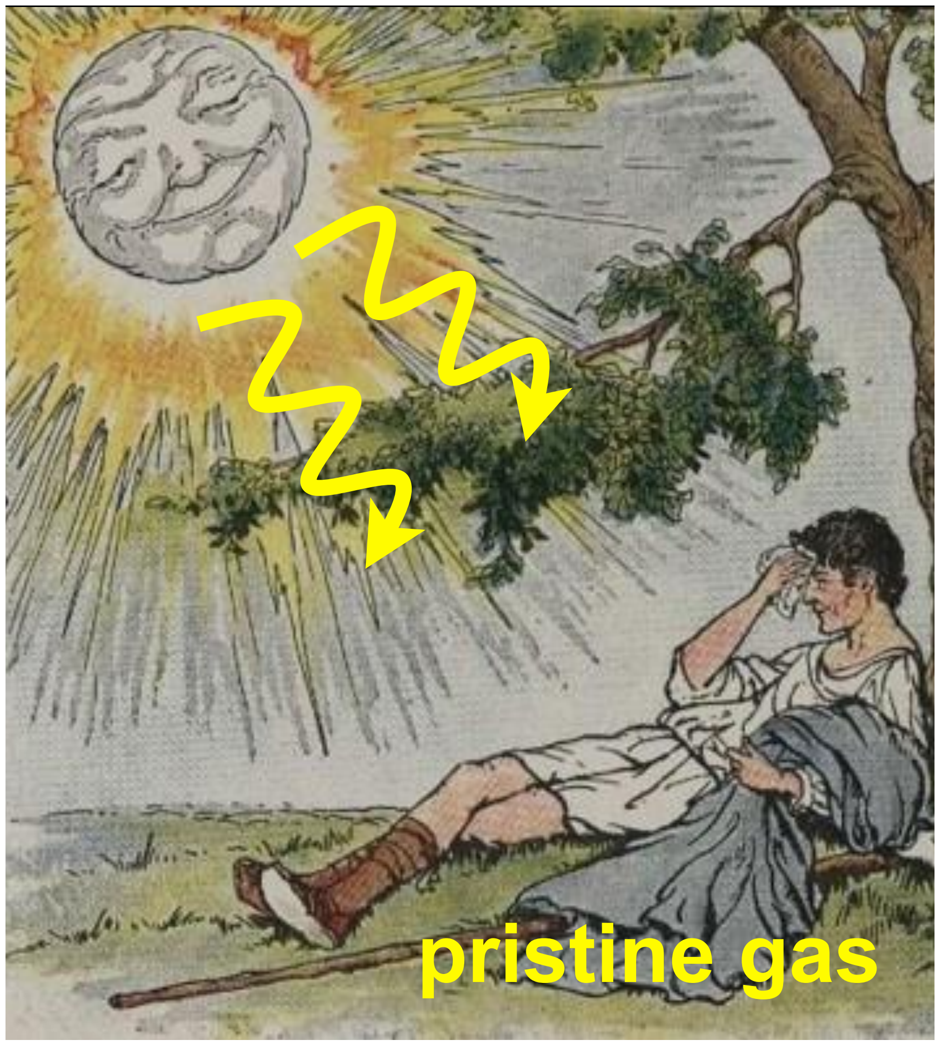
$$M_\star \approx \dot{M}_{\rm acc} \times t_{\rm life} \sim O(10^5)\ M_\odot$$

- **no/weak fragmentation**
- **high accretion rate**

➡ **massive seed BHs**

Seed formation ≈ H_2 suppression

Lyman-Werner irradiation



$$H_2 + \gamma_{LW} \rightarrow 2\ H$$

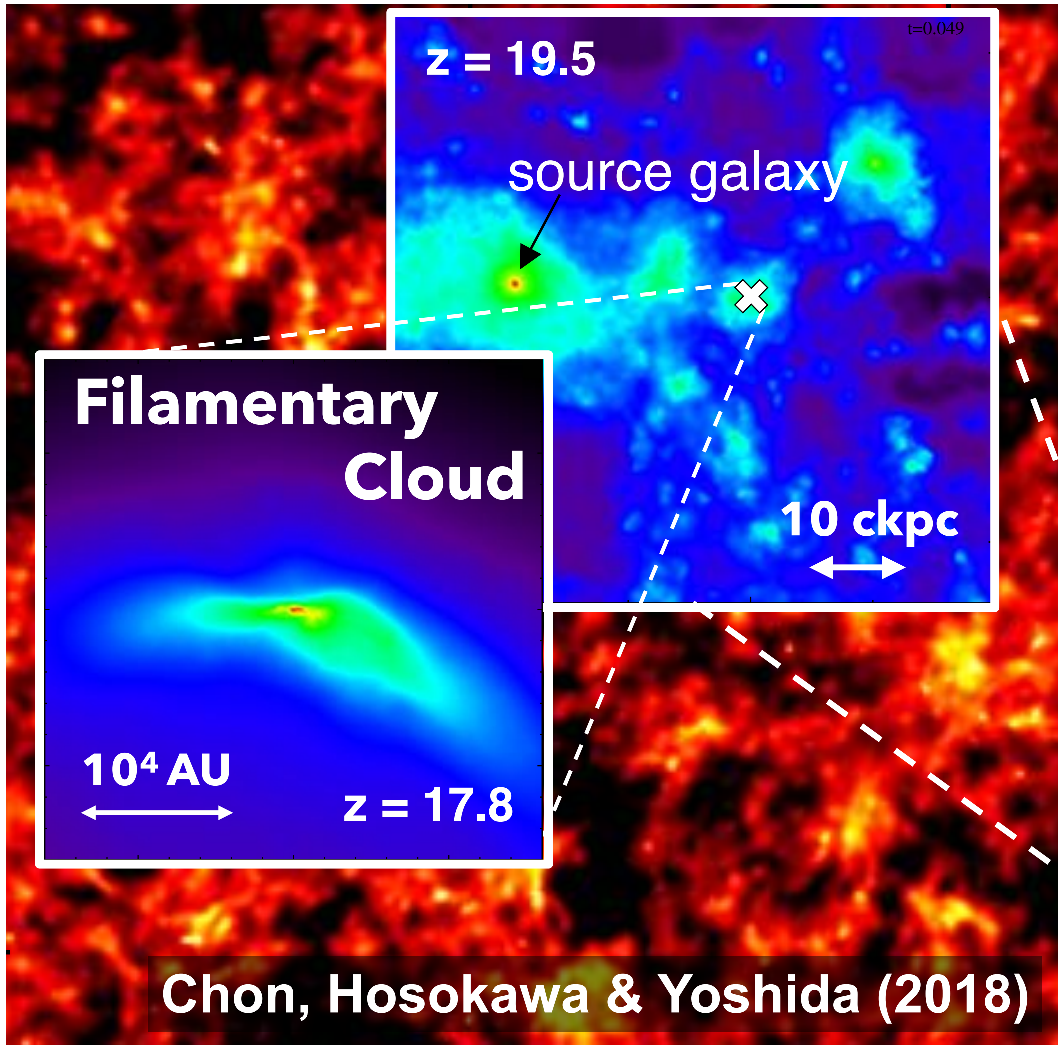
baryonic streaming motion

$$c_{\rm eff}^2 = c_{\rm s}^2 + v_{\rm bsm}^2$$

Bromm & Loeb 2003; Shang +2010; Latif +2013; Johnson +(2013); Regan +2014; Inayoshi +2014; Sugimura + 2014; Visbal +2015; Latif +2016; Chon+2016; Hirano+2018; Inayoshi+2018; Wise +2019; Luo+2019 etc…

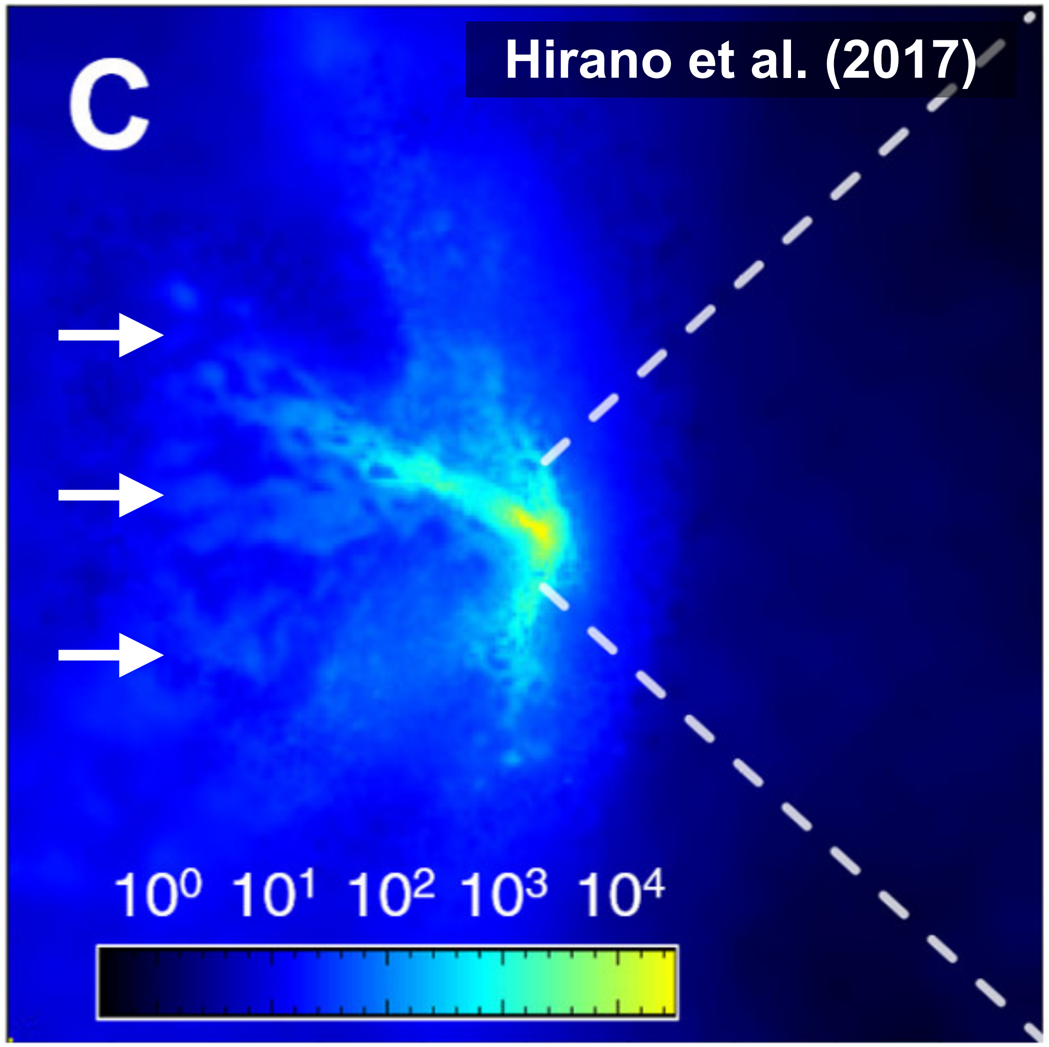
Seed formation ≈ H_2 suppression

Lyman-Werner irradiation



$$\mathrm{H_2} + \gamma_{\mathrm{LW}} \rightarrow 2\ \mathrm{H}$$

baryonic streaming motion



$$c_{\mathrm{eff}}^2 = c_s^2 + \boxed{v_{\mathrm{bsm}}^2}$$

Bromm & Loeb 2003; Shang +2010; Latif +2013; Johnson +(2013); Regan +2014; Inayoshi +2014; Sugimura + 2014; Visbal +2015; Latif +2016; Chon+2016; Hirano+2018; Inayoshi+2018; Wise +2019; Luo+2019 etc…

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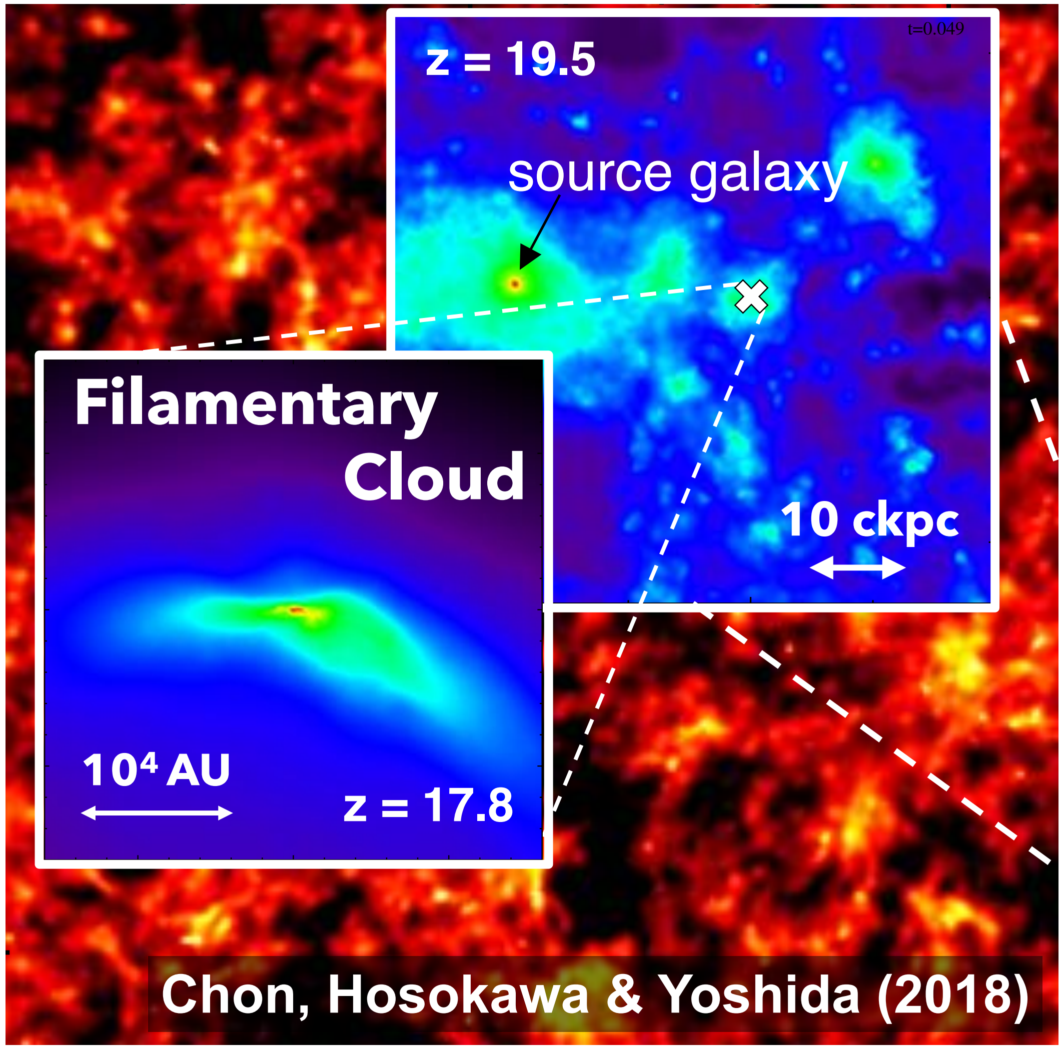

$$H_2 + \gamma_{LW} \rightarrow 2\ H$$

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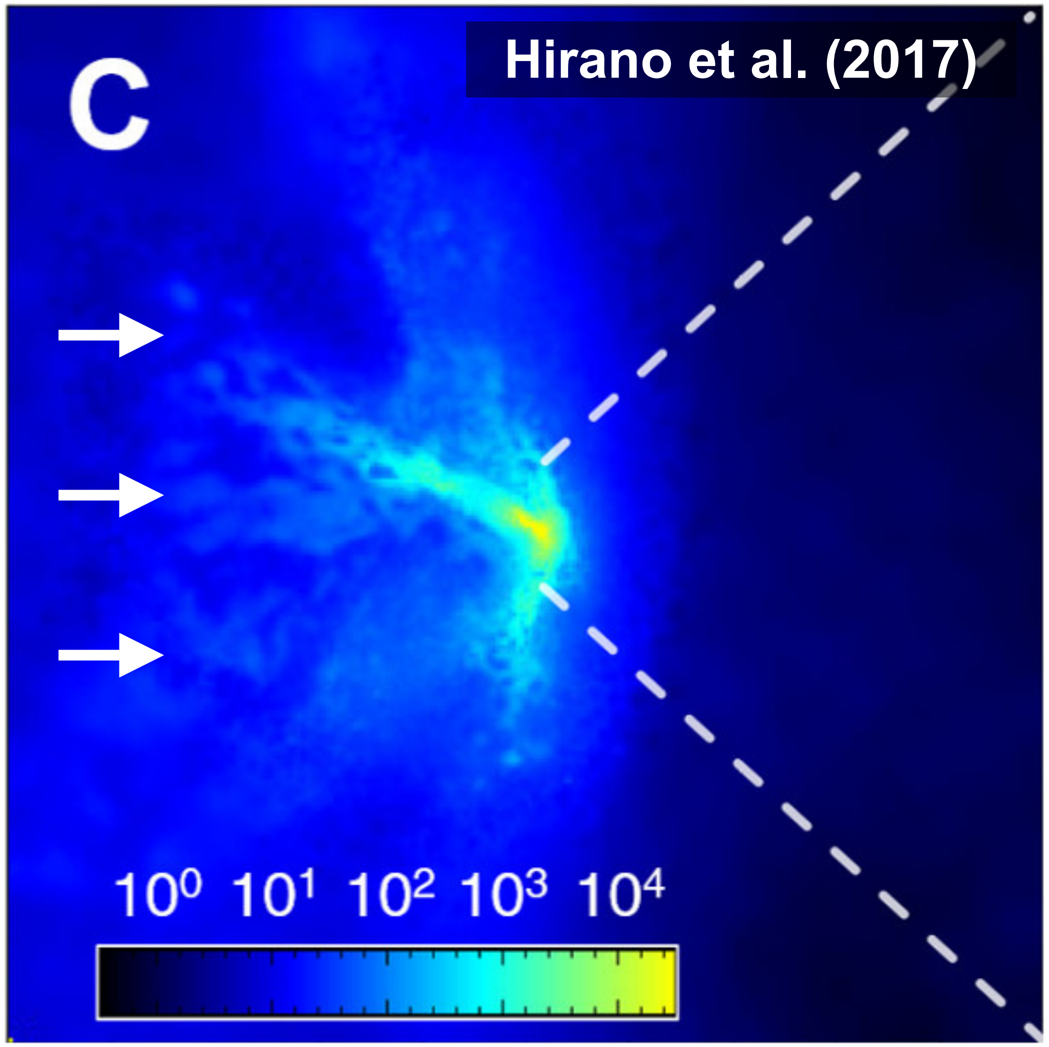
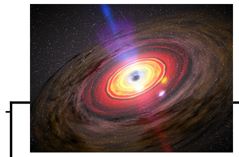


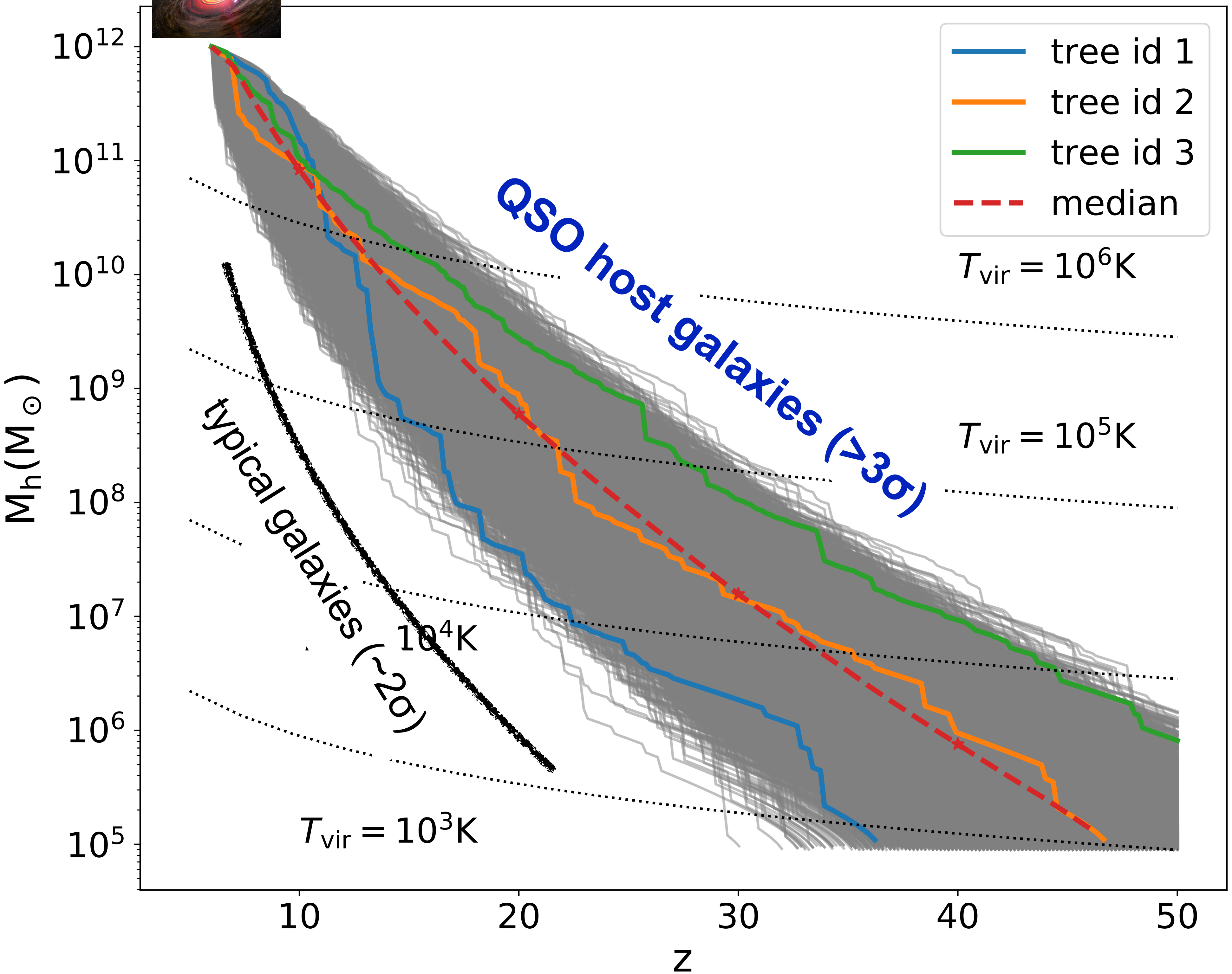
$$c_{\rm eff}^2 = c_s^2 + \boxed{v_{\rm bsm}^2}$$

… leaving behind **massive seed BHs** (10^3-$10^6 M_{sun}$)

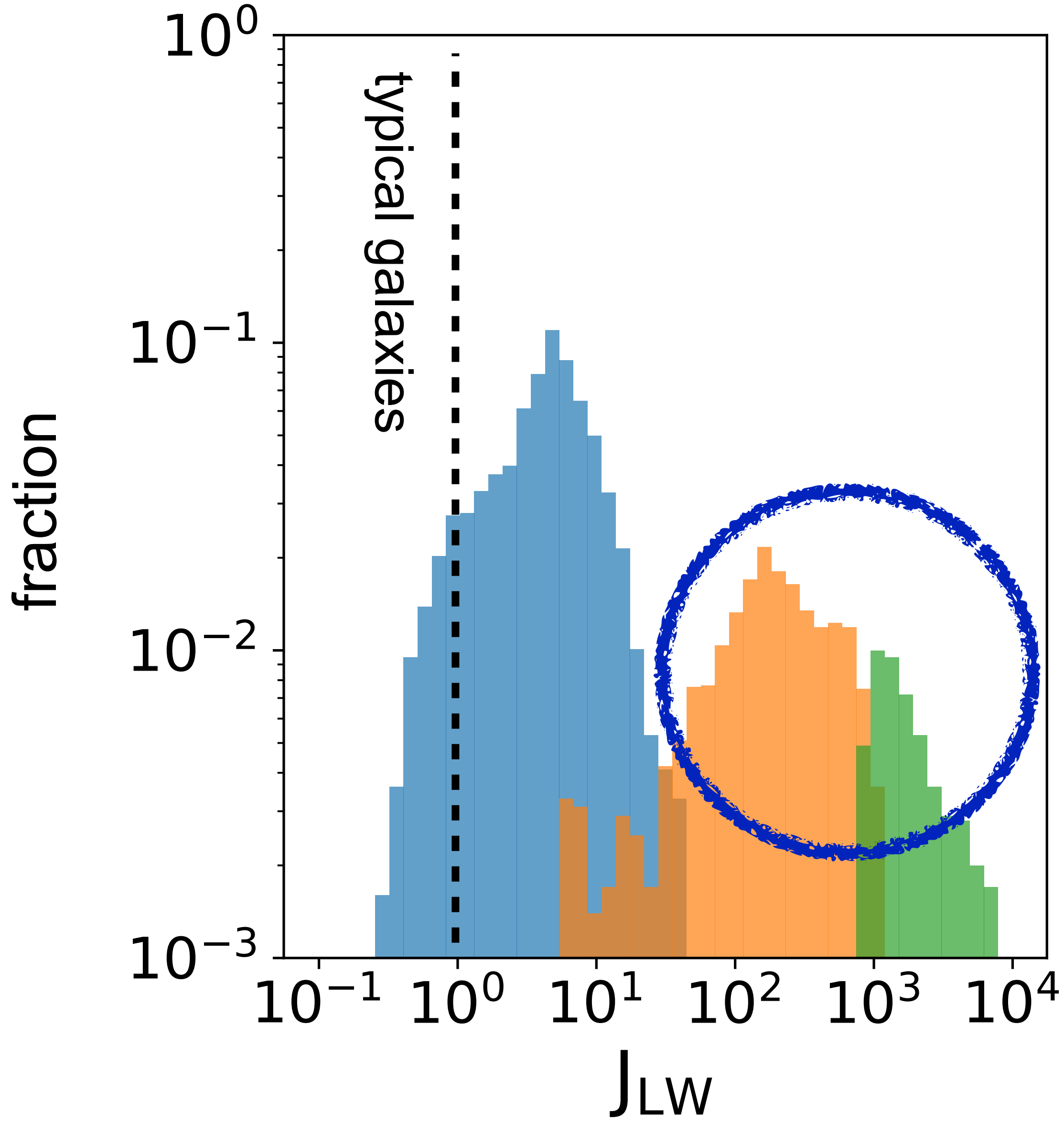
see also Hirano's talk

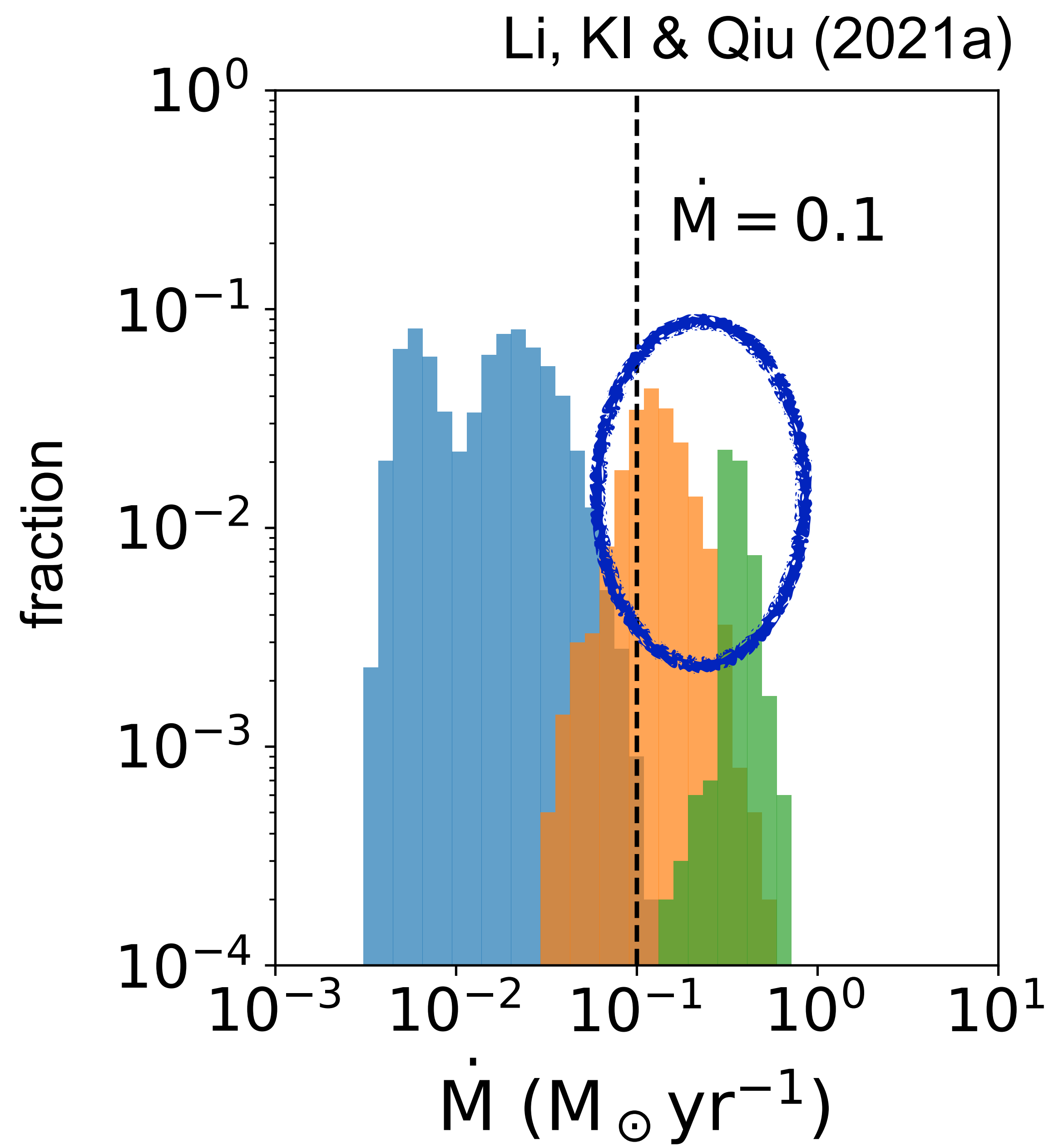
Seed formation in QSO hosts





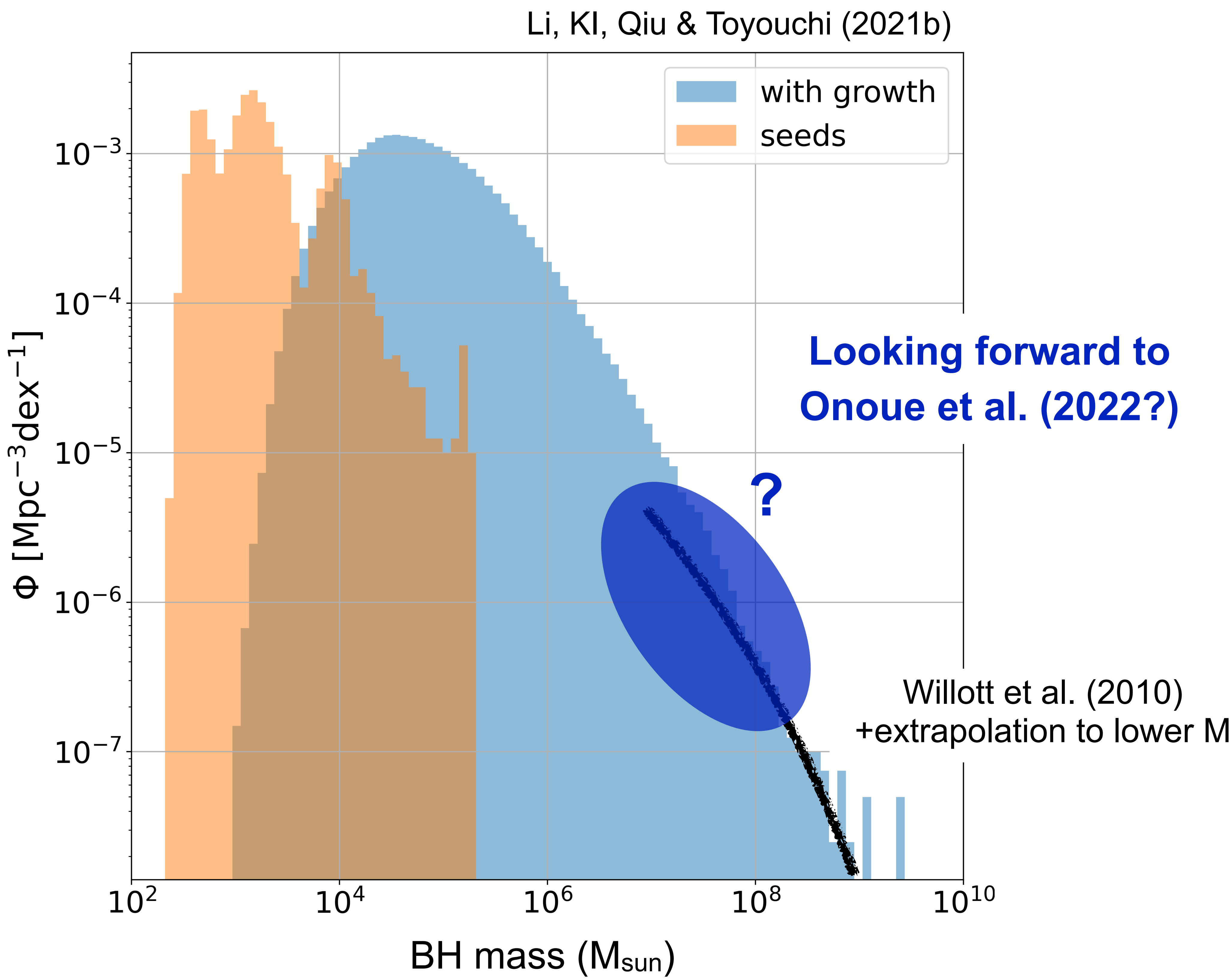
Seed formation in QSO hosts





Strong LW irradiation & merger heating lead to high accretion rates (>0.1M_{sun}/yr) in QSO hosts

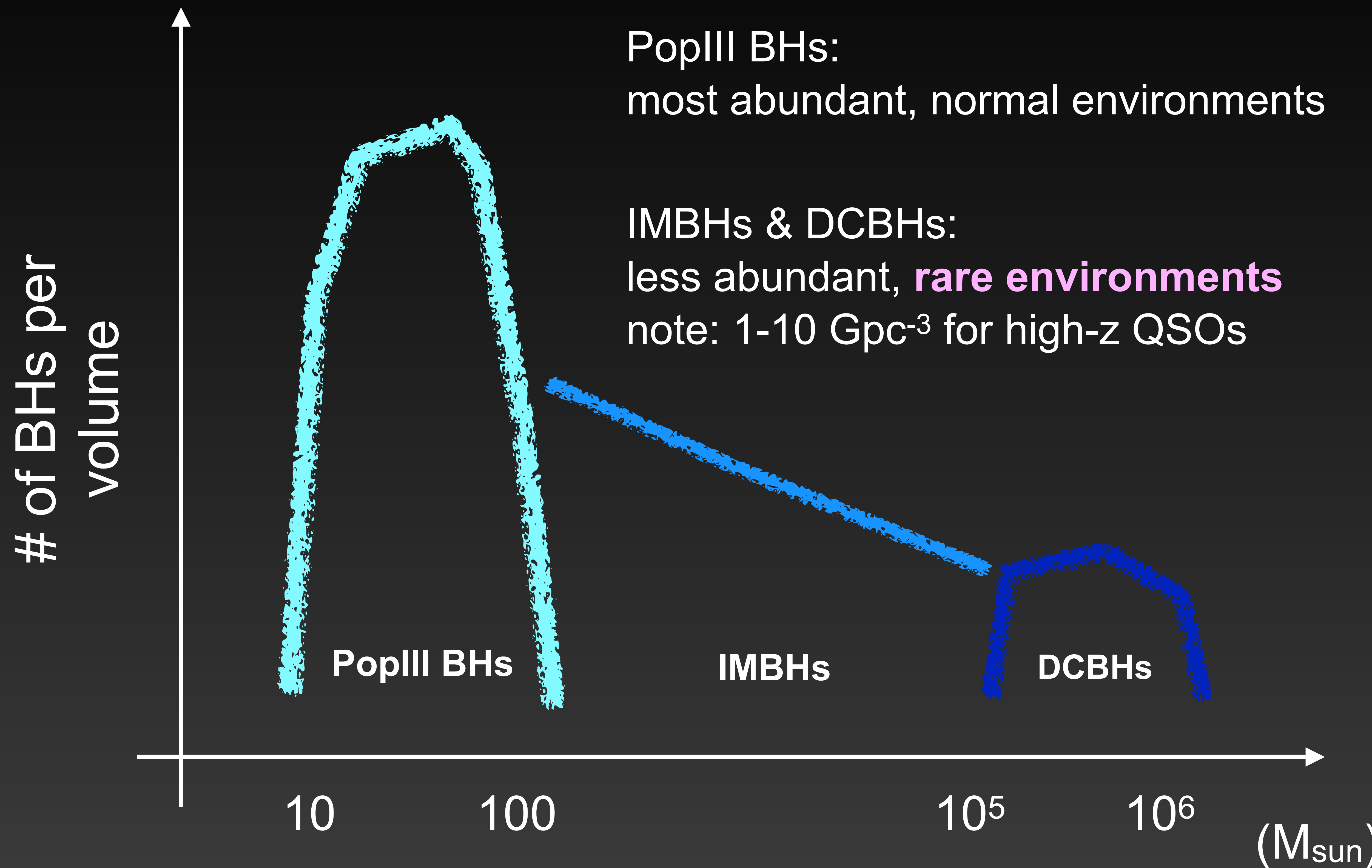
Seed formation in QSO hosts



(Seed) BH mass function

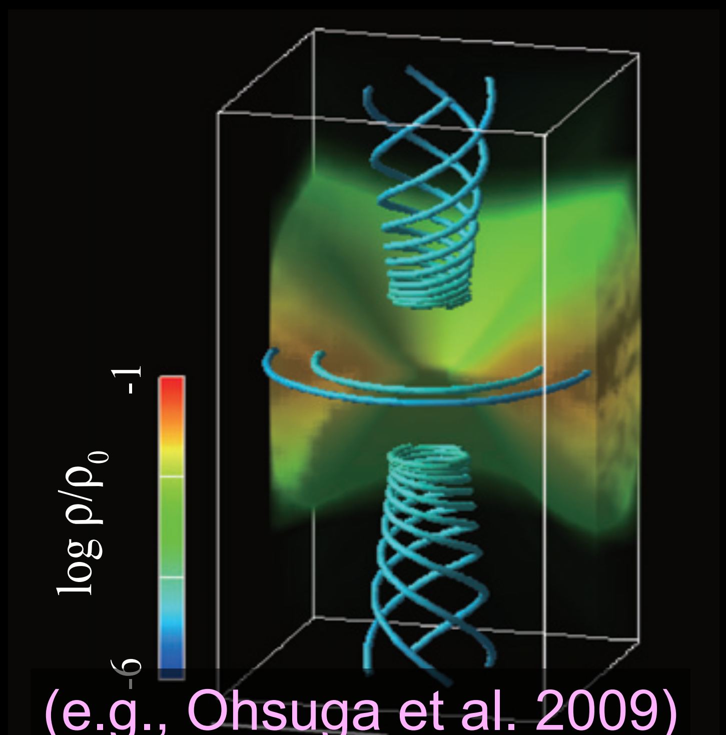
PopIII BHs:
most abundant, normal environments

IMBHs & DCBHs:
less abundant, **rare environments**
note: 1-10 Gpc^{-3} for high-z QSOs



BH accretion in multi-scales

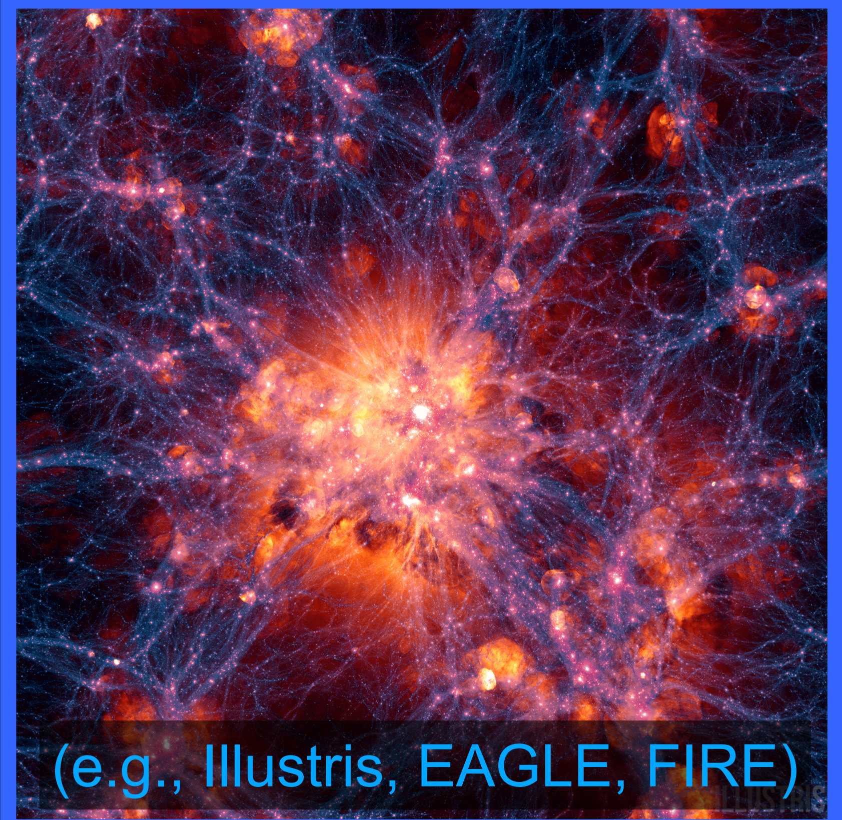
Nuclear disk: ~ 1 mpc



(e.g., Ohsuga et al. 2009)

?

Galaxy scale: ~kpc


(e.g., Illustris, EAGLE, FIRE)

Q. How can we connect the two different scales?

A. Construct the global accretion solution including the BH influence radii (1-100pc) !

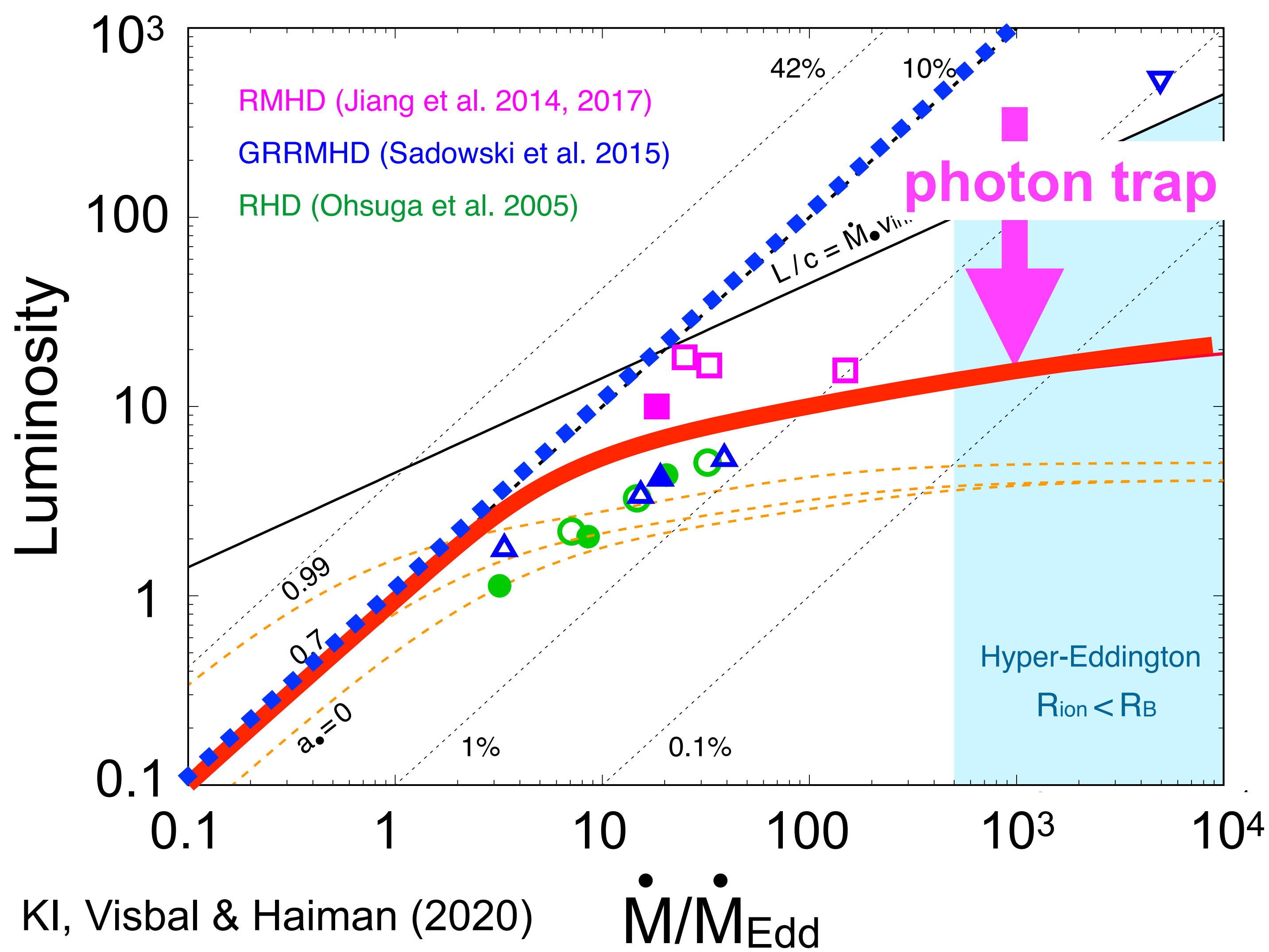
Super-Eddington accretion

- GR/Radiation/MHD simulations
  - **photon trapping** in a disk
  - radiative flux to the poles

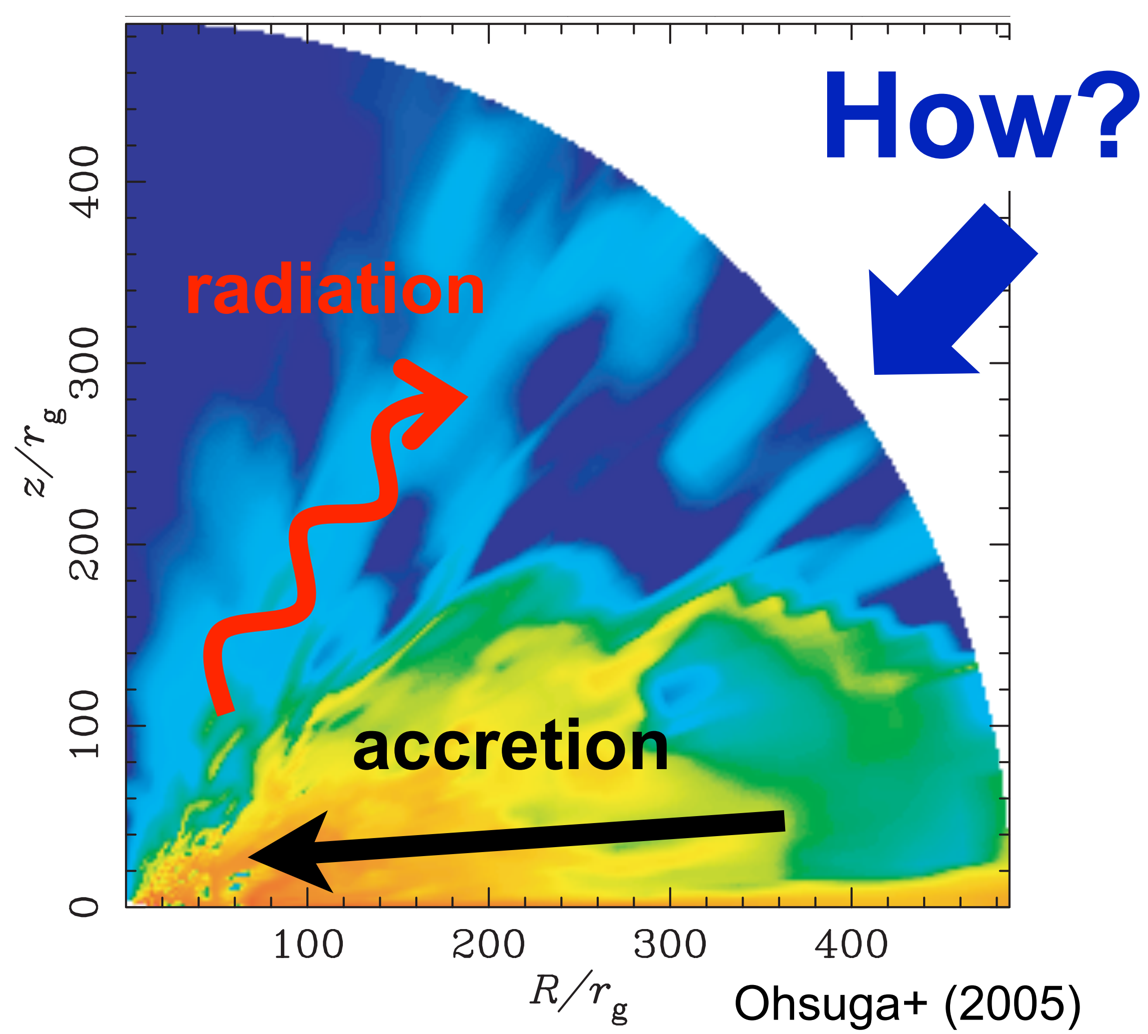
Ohsuga+2009; Jiang+2014, 2017; Sadowski+2015; Takahashi+2015

$\dot{M} \gg \dot{M}_{\rm Edd}$ is possible!

at small scales



KI, Visbal & Haiman (2020)



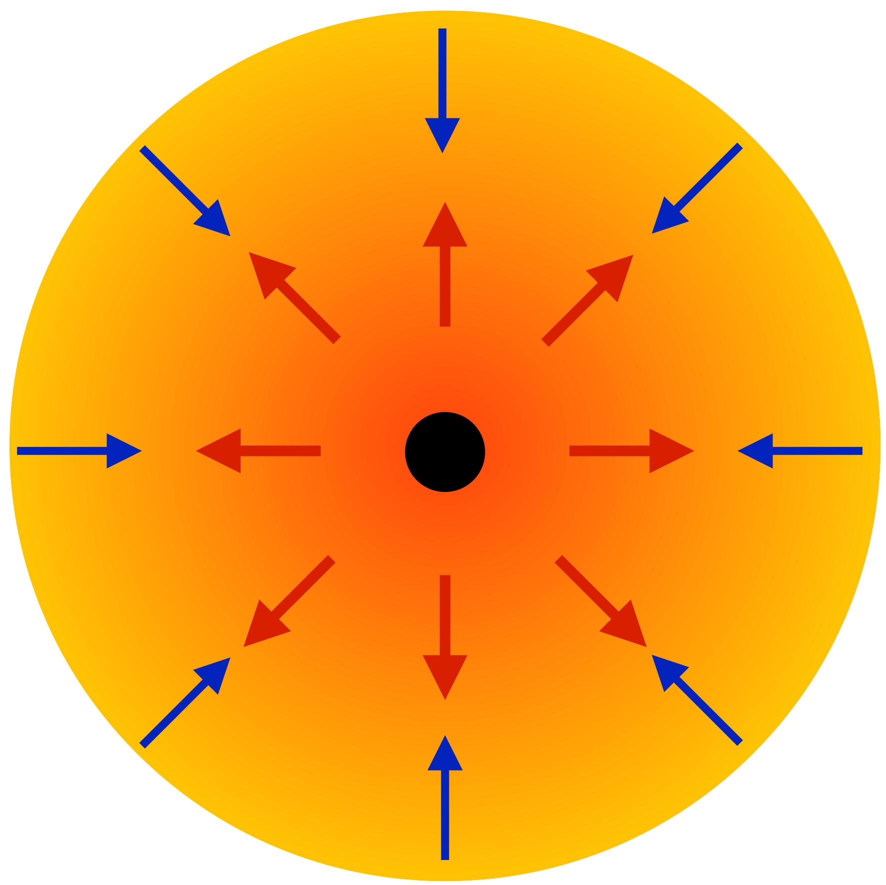
Ohsuga+ (2005)

Bondi accretion

- suppose a spherically symmetric system

gas self-gravity

$$g_{\rm grav} = \frac{GM_r}{r^2} \simeq \frac{GM_{\rm BH}}{r^2}$$



pressure-grad. force

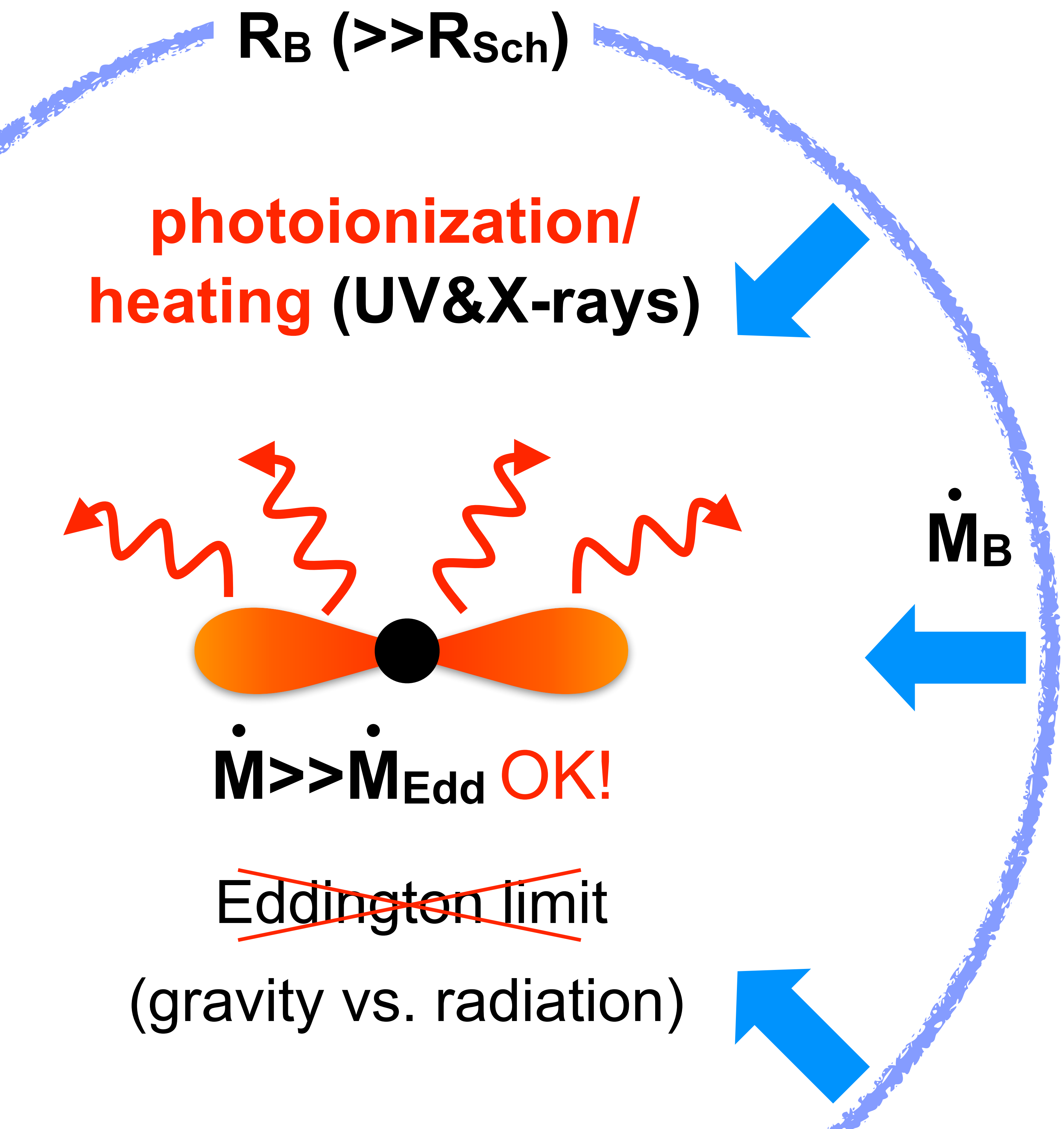
$$g_{\rm gas} = \frac{1}{\rho}\frac{dp}{dr} \sim \frac{c_{\rm s}^2}{r}$$

Cloud collapse conditions $\quad g_{\rm grav} \gtrsim g_{\rm gas}$

$$r \lesssim R_{\rm B} \equiv \frac{GM_{\rm BH}}{c_{\rm s}^2} \propto M_{\rm BH} T^{-1}$$

"Bondi radius"

Bondi accretion limit



Mass inflows within R_B

(gravity > thermal / kinetic)

$$\dot{M}_{\rm B} \sim 4\pi\rho R_{\rm B} c_{\rm s}$$

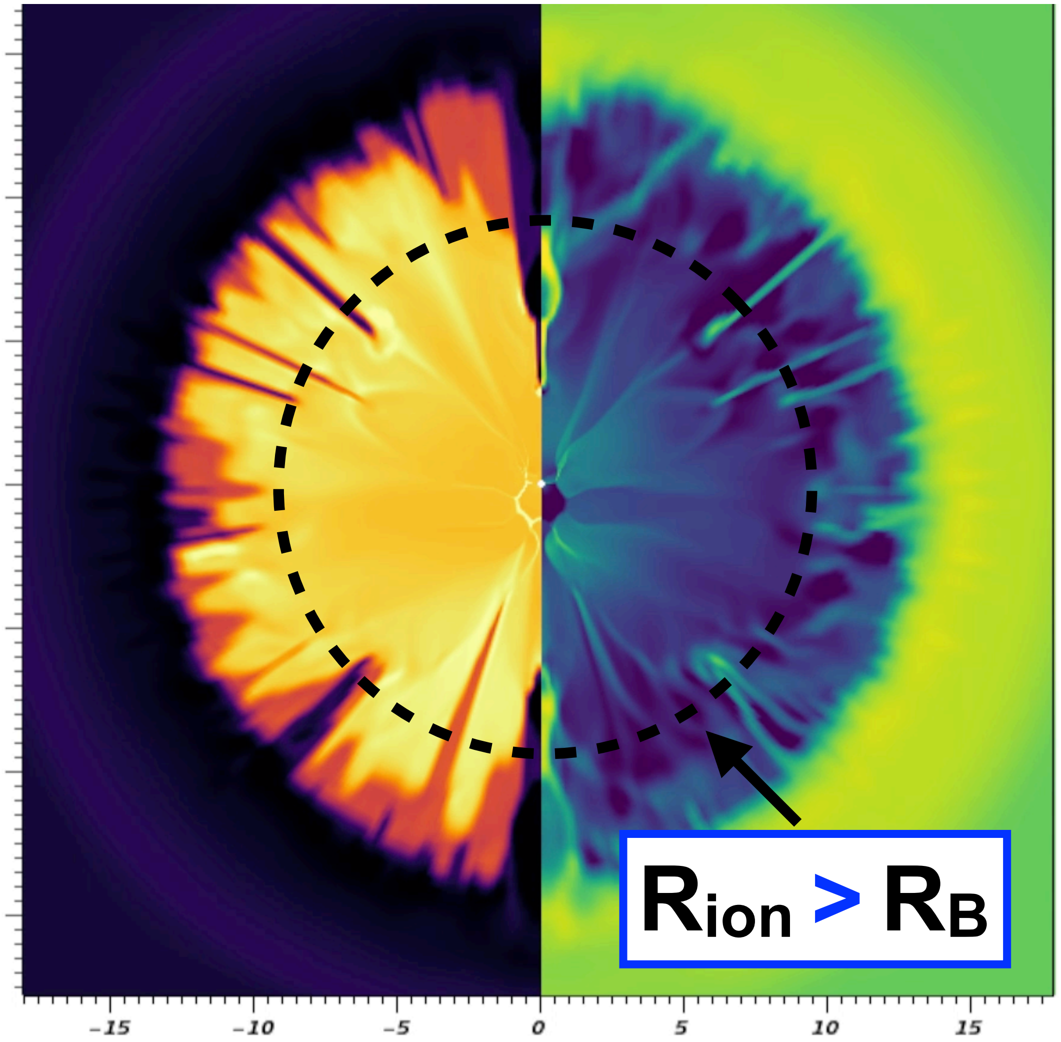
$$\propto \rho M_{\rm BH}^{2} \boxed{T^{-3/2}}$$

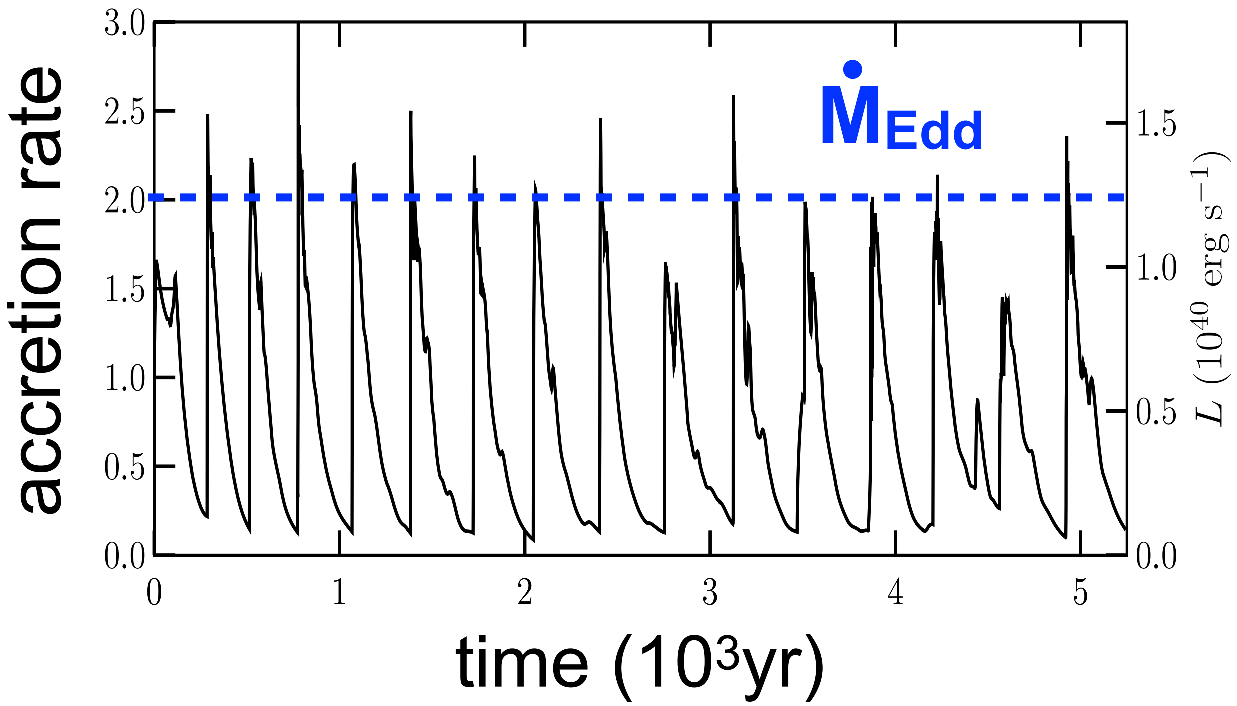
photo-heating by UV/X-rays
reduces the mass supply

BH accretion in typical first galaxies

- **low density** case ($\dot{M}_{\rm B,ini} \sim 10\dot{M}_{\rm Edd}$)

Ciotti & Ostriker (2001)
Milosavljevic+ (2009)
Park & Ricotti (2011, 2012)





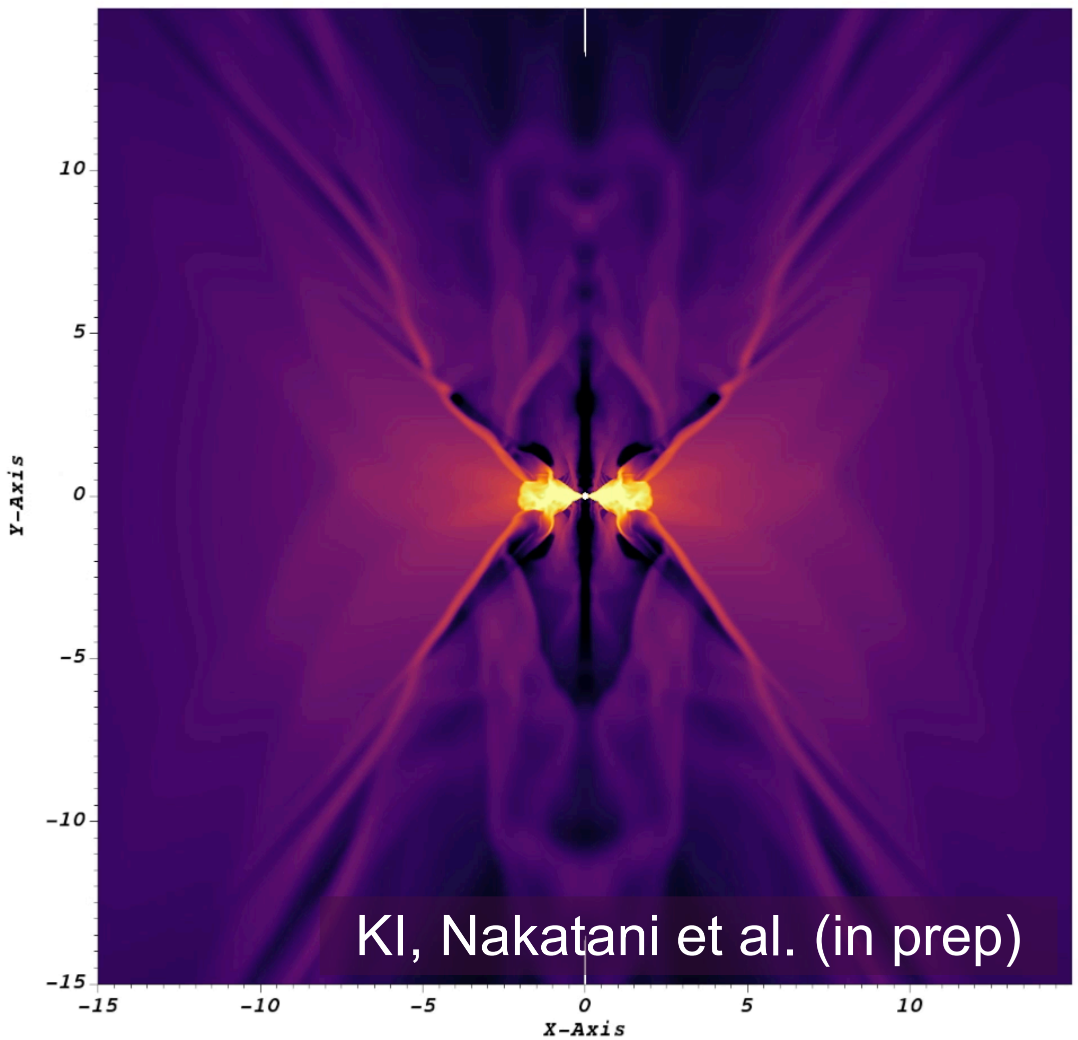
$$\dot{M}_{\rm B} \propto \rho M_{\rm BH}^2 T^{-3/2}$$

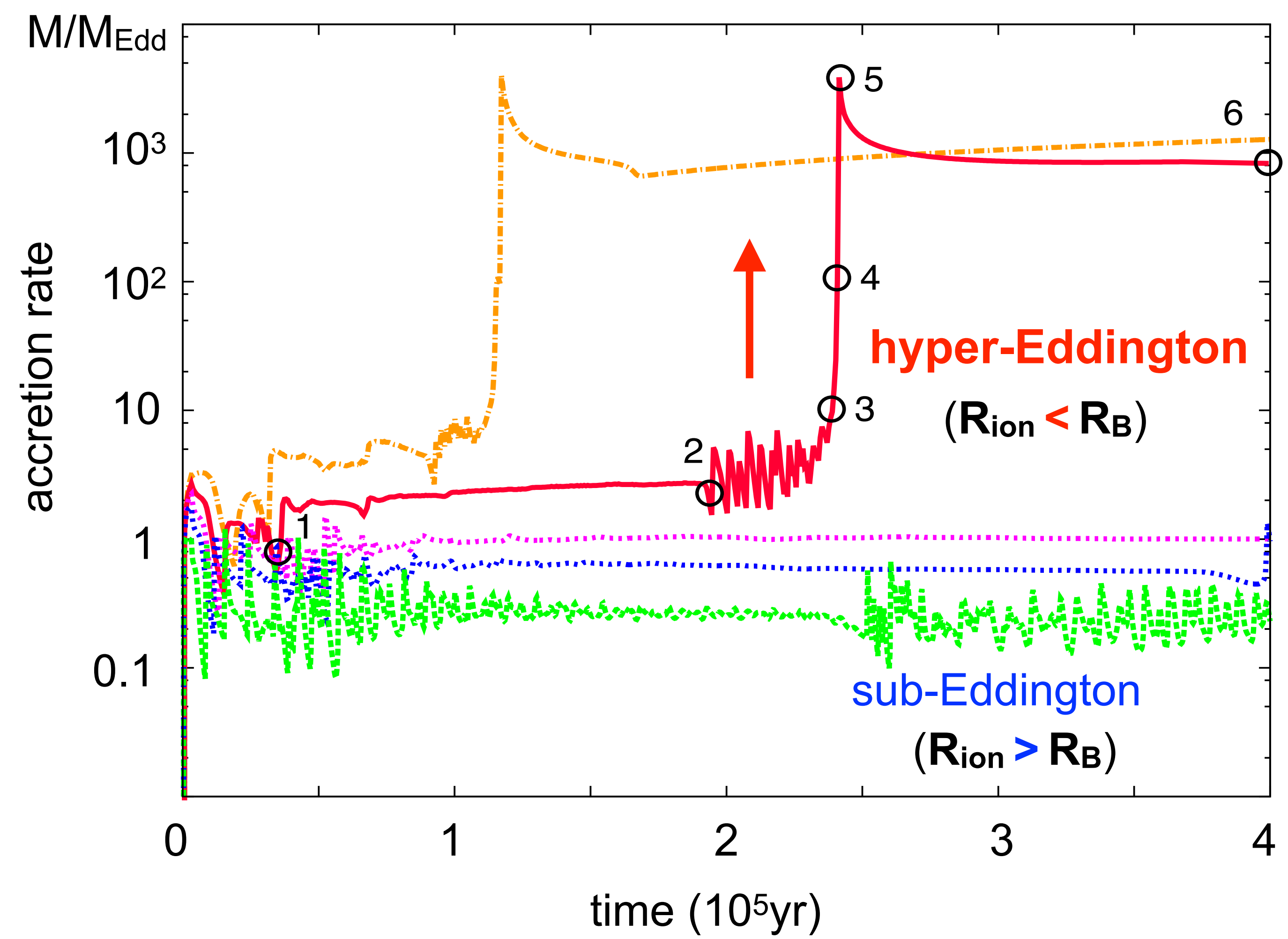
episodic accretion (radiation heating) ➡ $\langle \dot{M} \rangle << \dot{M}_{\rm Edd}$

BH accretion in massive first galaxies

- **high density** case ($\dot{M}_{\rm B,ini} \sim 500\ \dot{M}_{\rm Edd}$)

KI, Haiman & Ostriker (2016)
Takeo, KI et al. (2018,2019,2020)
Toyouchi, KI et al. (2021)





ionized bubble collapses ($R_{\rm ion} < R_{\rm B}$) → hyper-Eddington acc. $\langle \dot{M} \rangle \gg \dot{M}_{\rm Edd}$

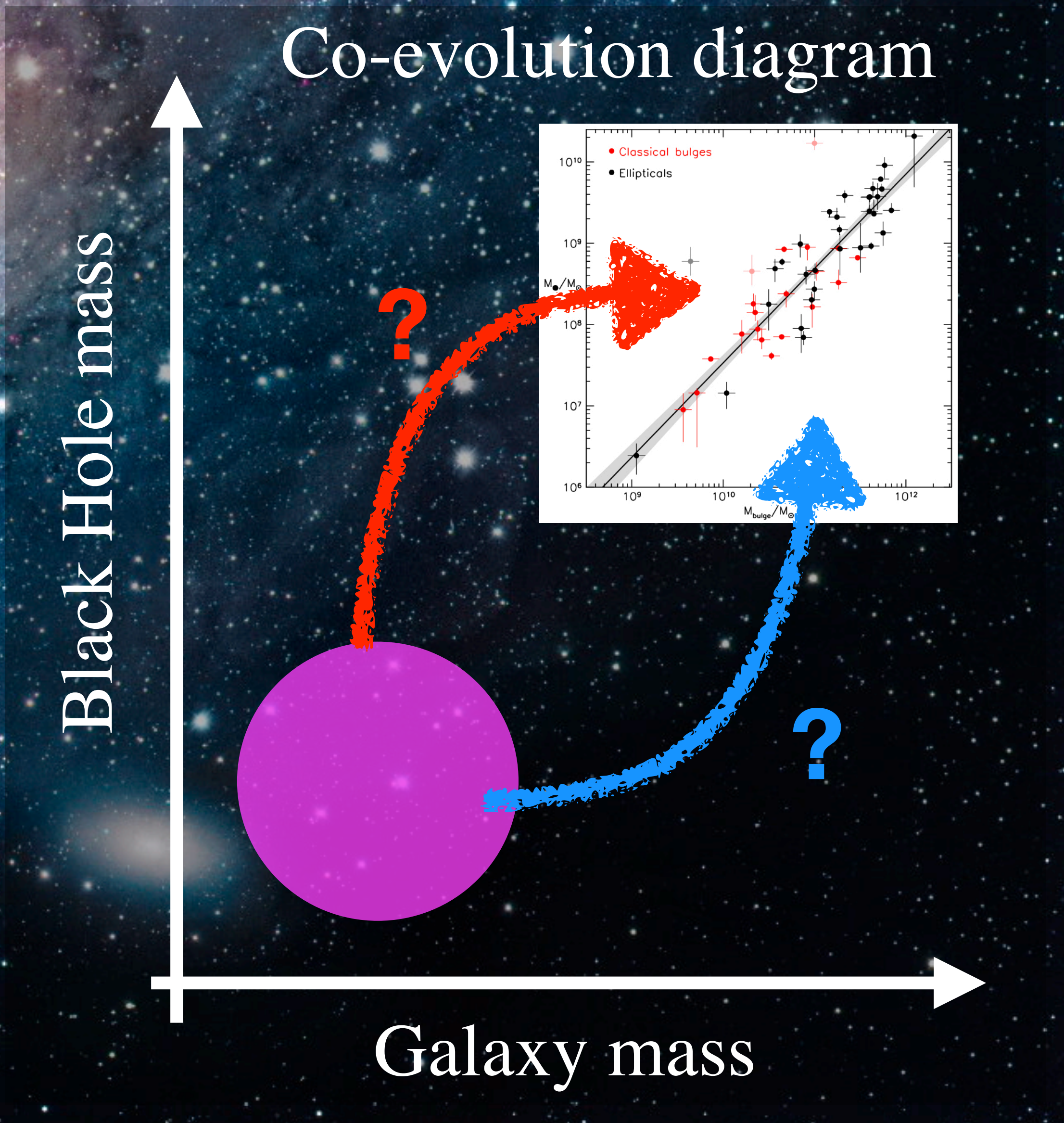
Early BH-galaxy coevolution

Effects by bulge stars

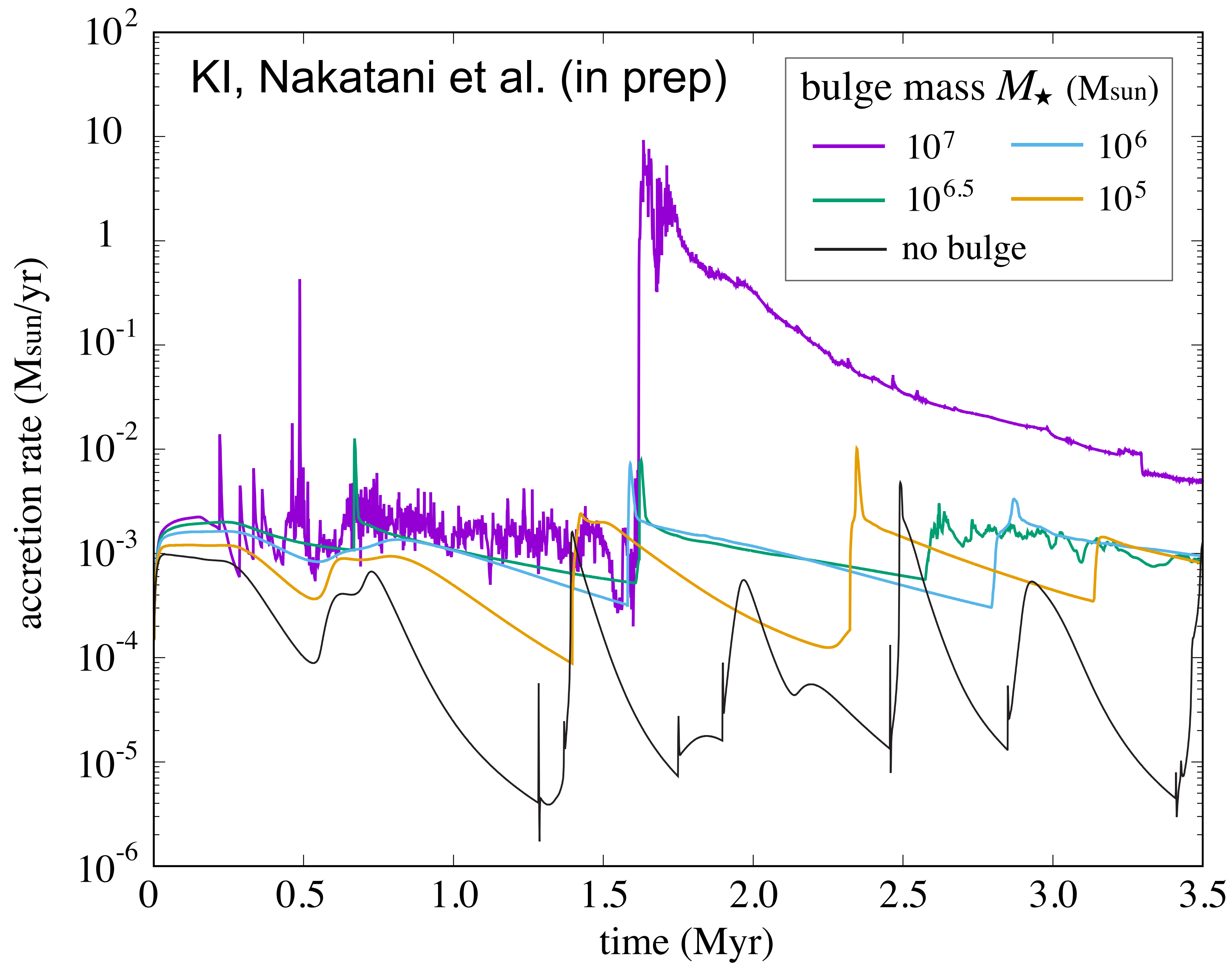
- gravitational potential
- stellar irradiation

BH feeding & feedback

- resolving the BH inf. radius

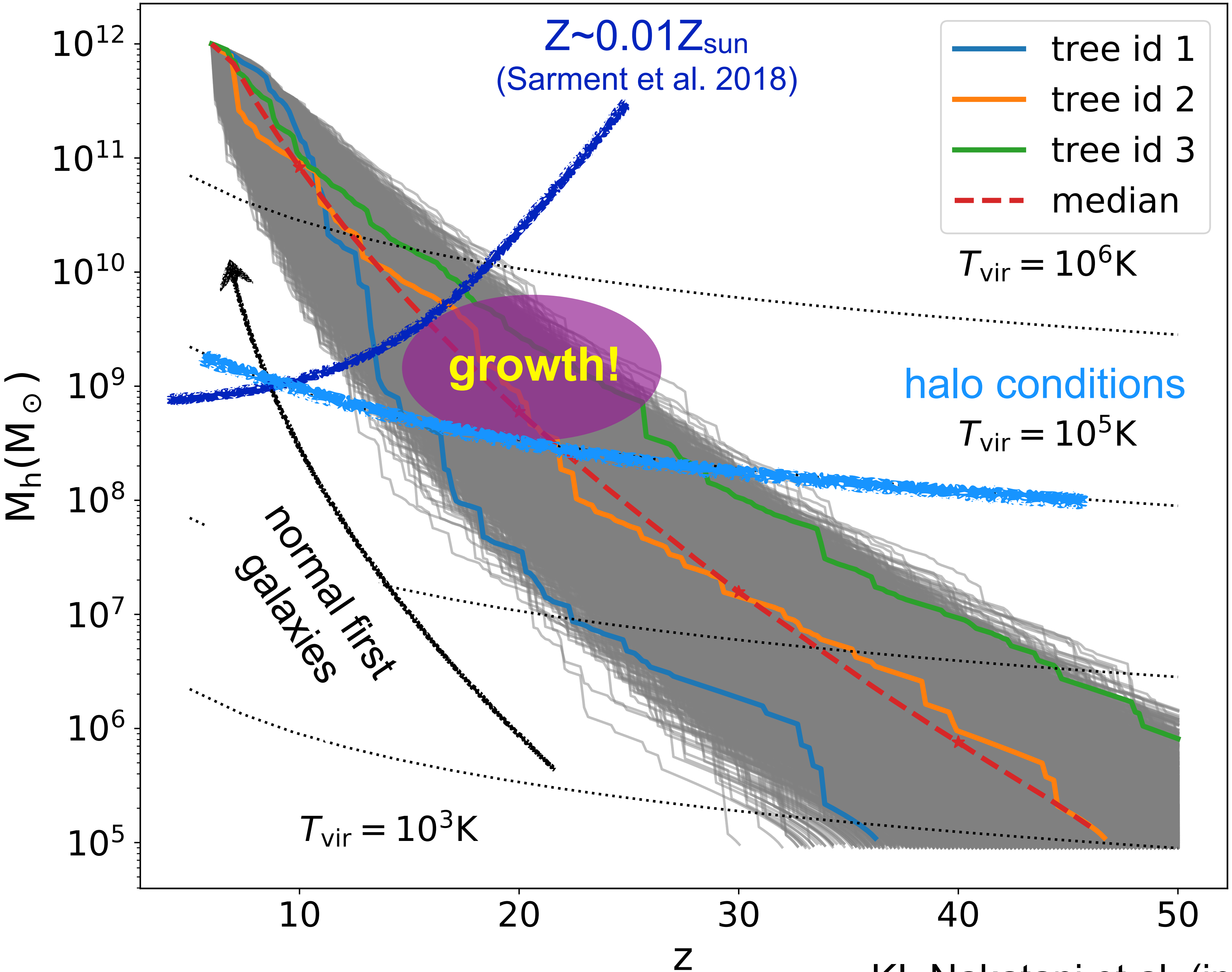


Early BH-galaxy coevolution



Rapid BH growth is triggered in a massive halo ($T_{vir} \sim 10^5$ K) with a bulge heavier than $>100 M_{BH}$

Seed formation in QSO hosts

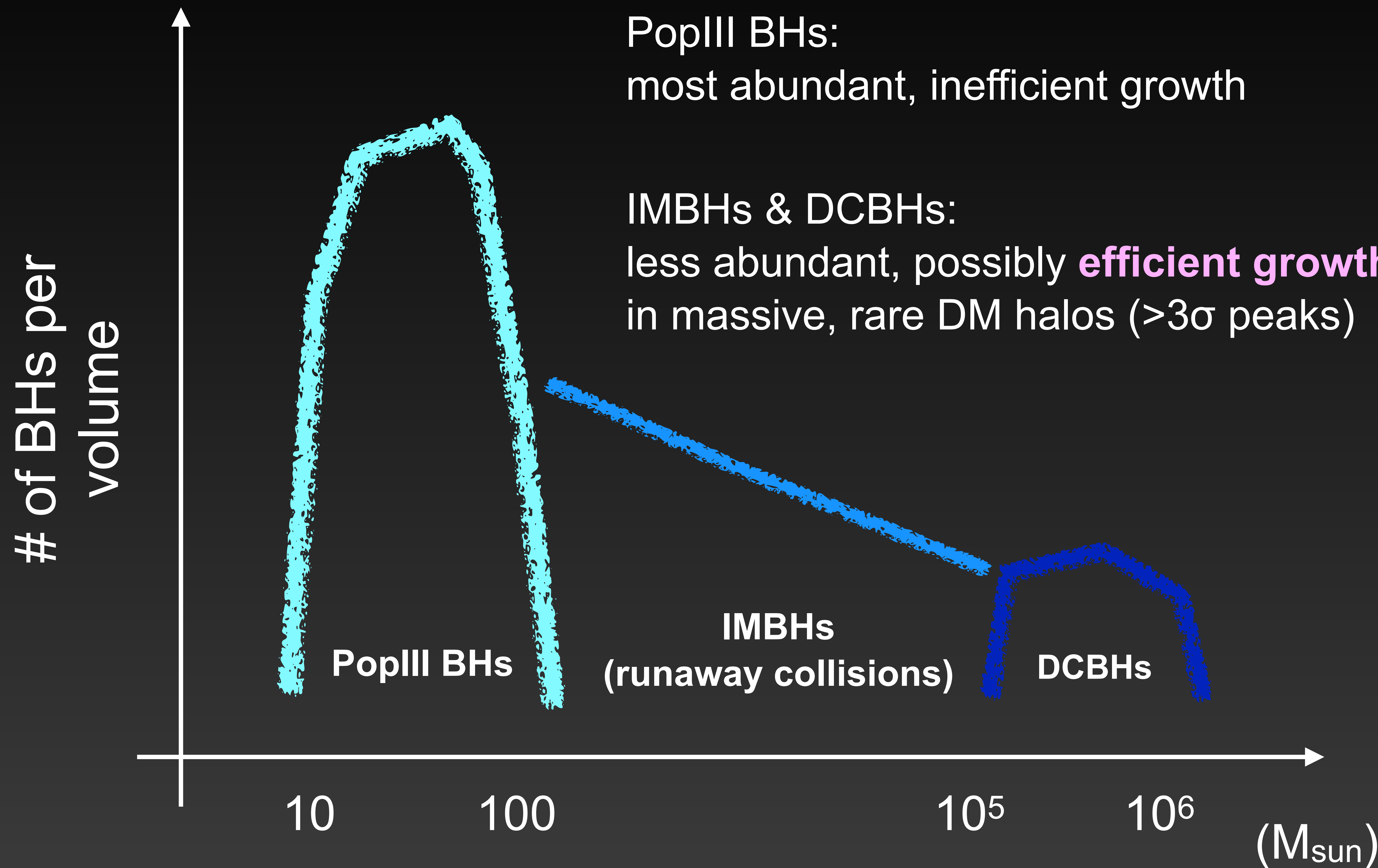


KI, Nakatani et al. (in prep)

(Seed) BH mass function

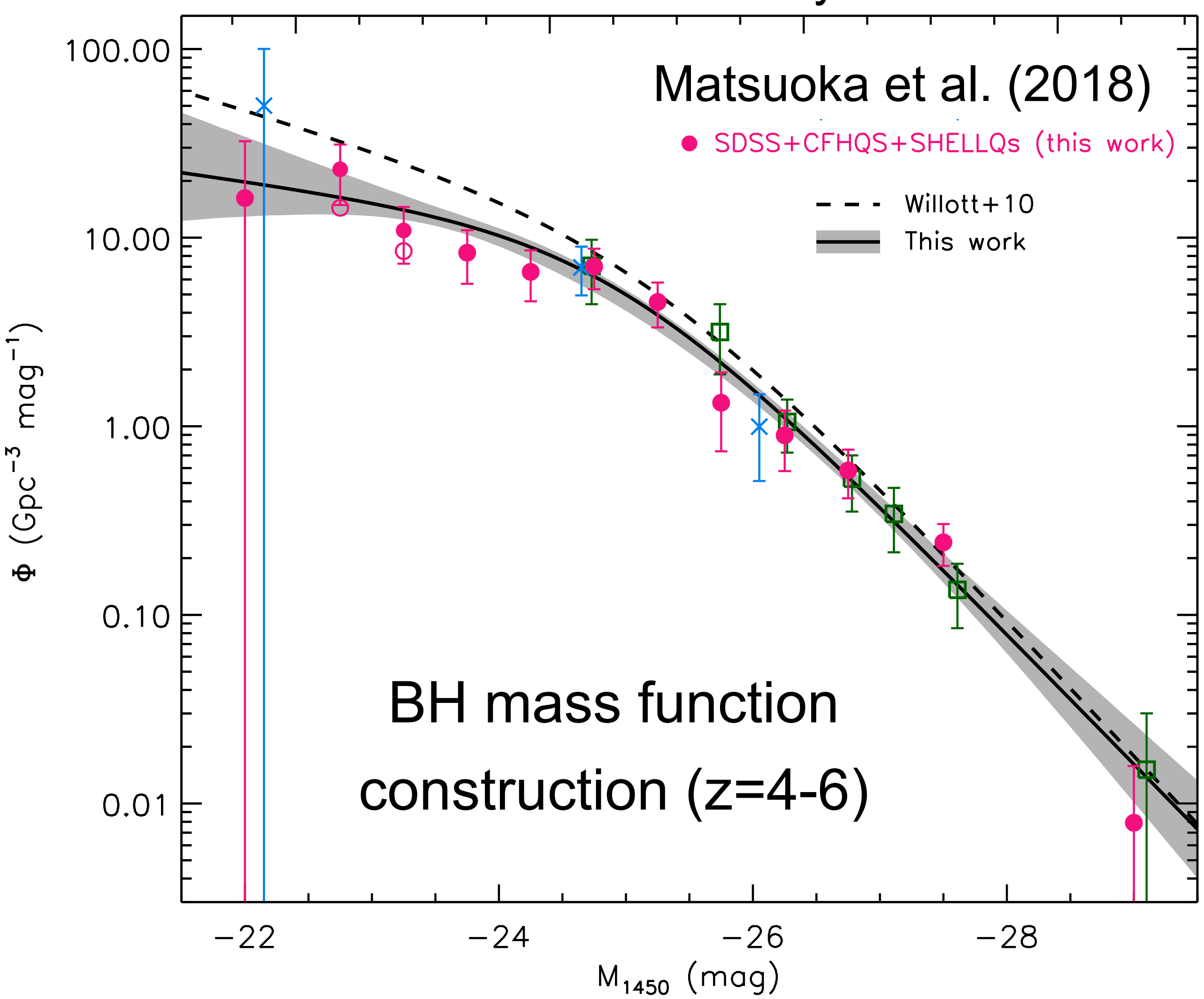
PopIII BHs:
most abundant, inefficient growth

IMBHs & DCBHs:
less abundant, possibly **efficient growth**
in massive, rare DM halos (>3σ peaks)



High-redshift universe

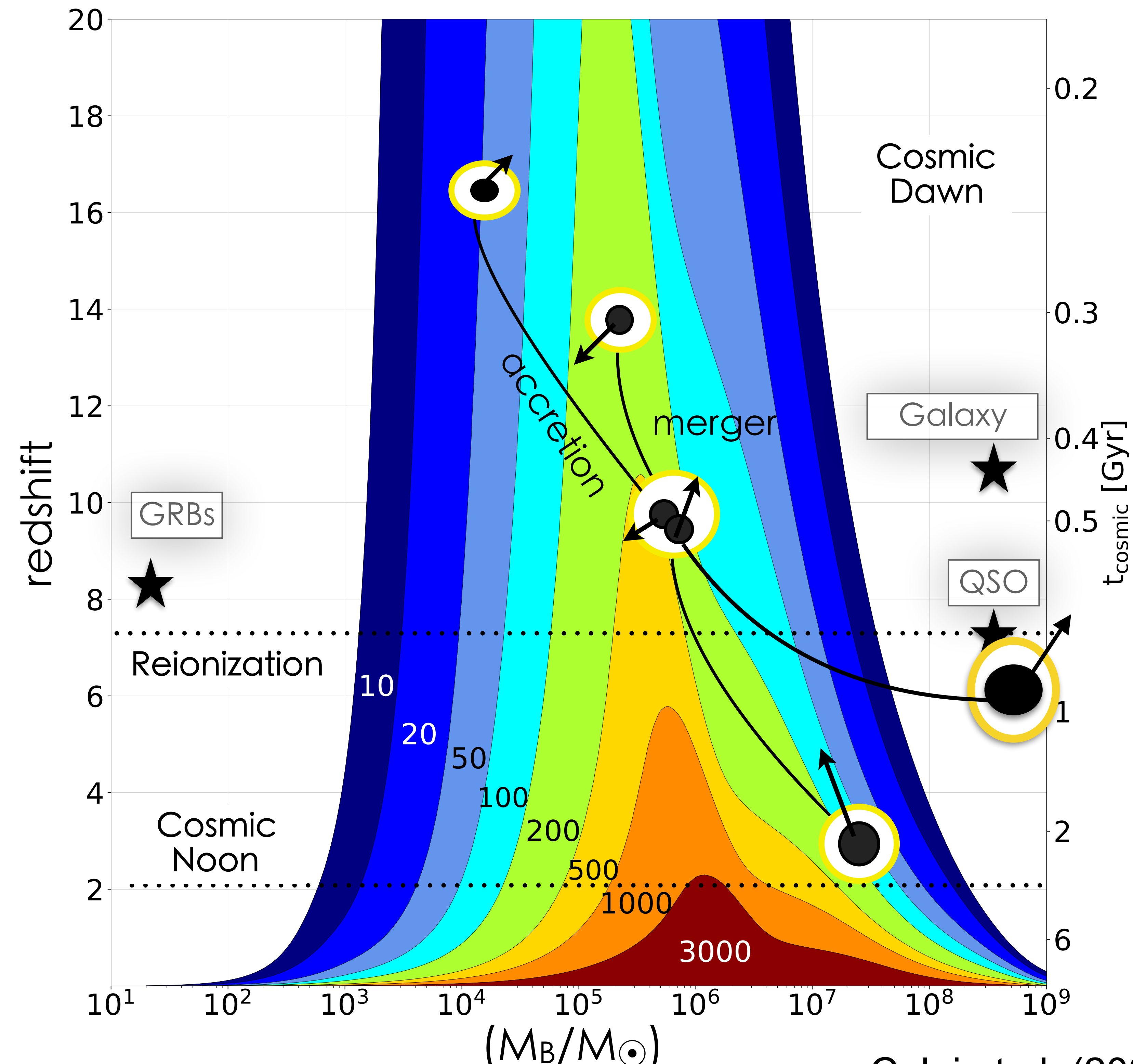
z~6 QSO luminosity function



ongoing/future multi-wavelength observations

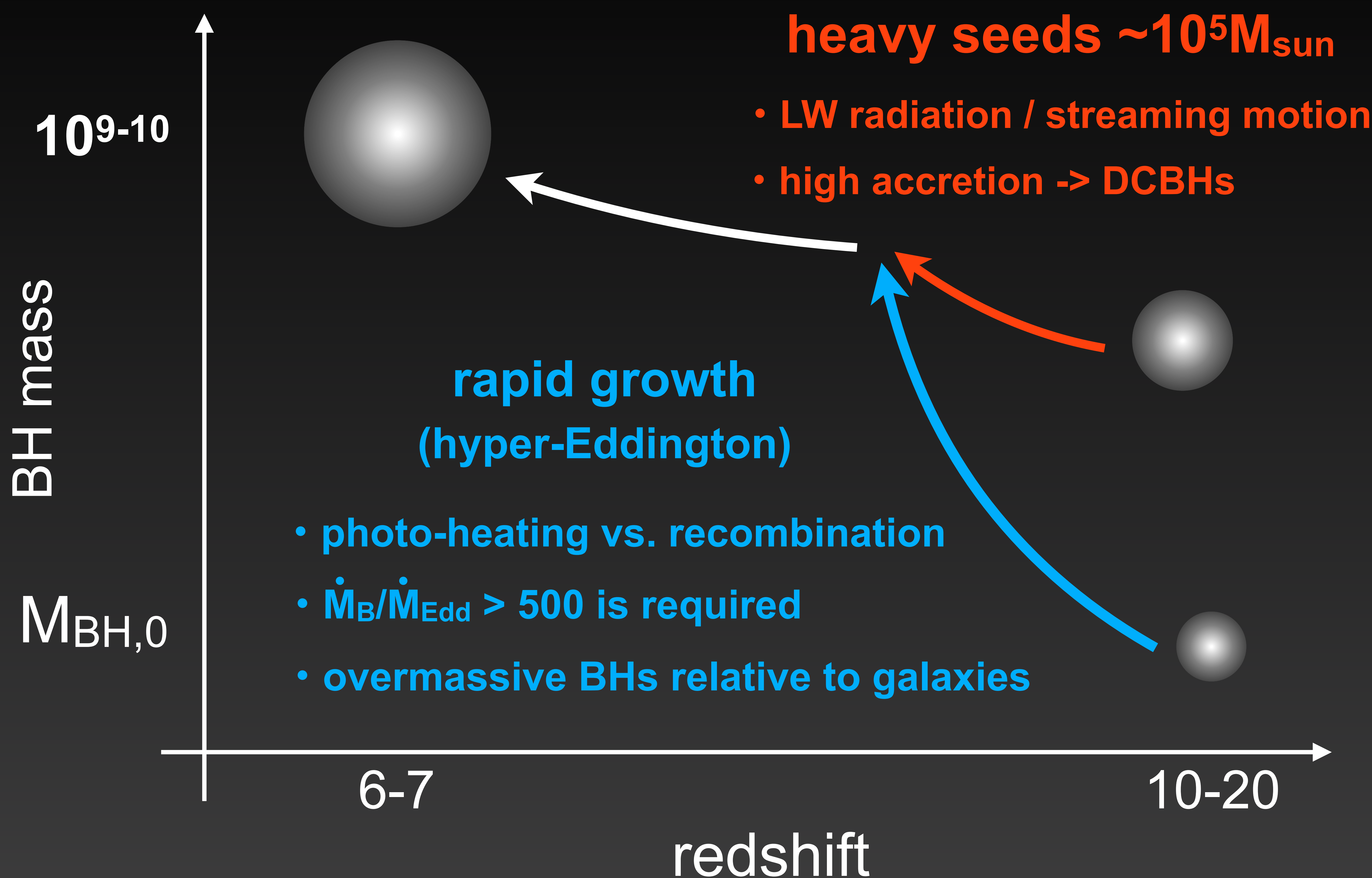
- construction of LF/MF for low-mass / less luminous BHs
- direct probes of the host galaxy properties (radio - IR) and SMBHs / seeds themselves (X-ray, GWs)

Synergy btw EM & GW observations



Colpi et al. (2021), Astro2020

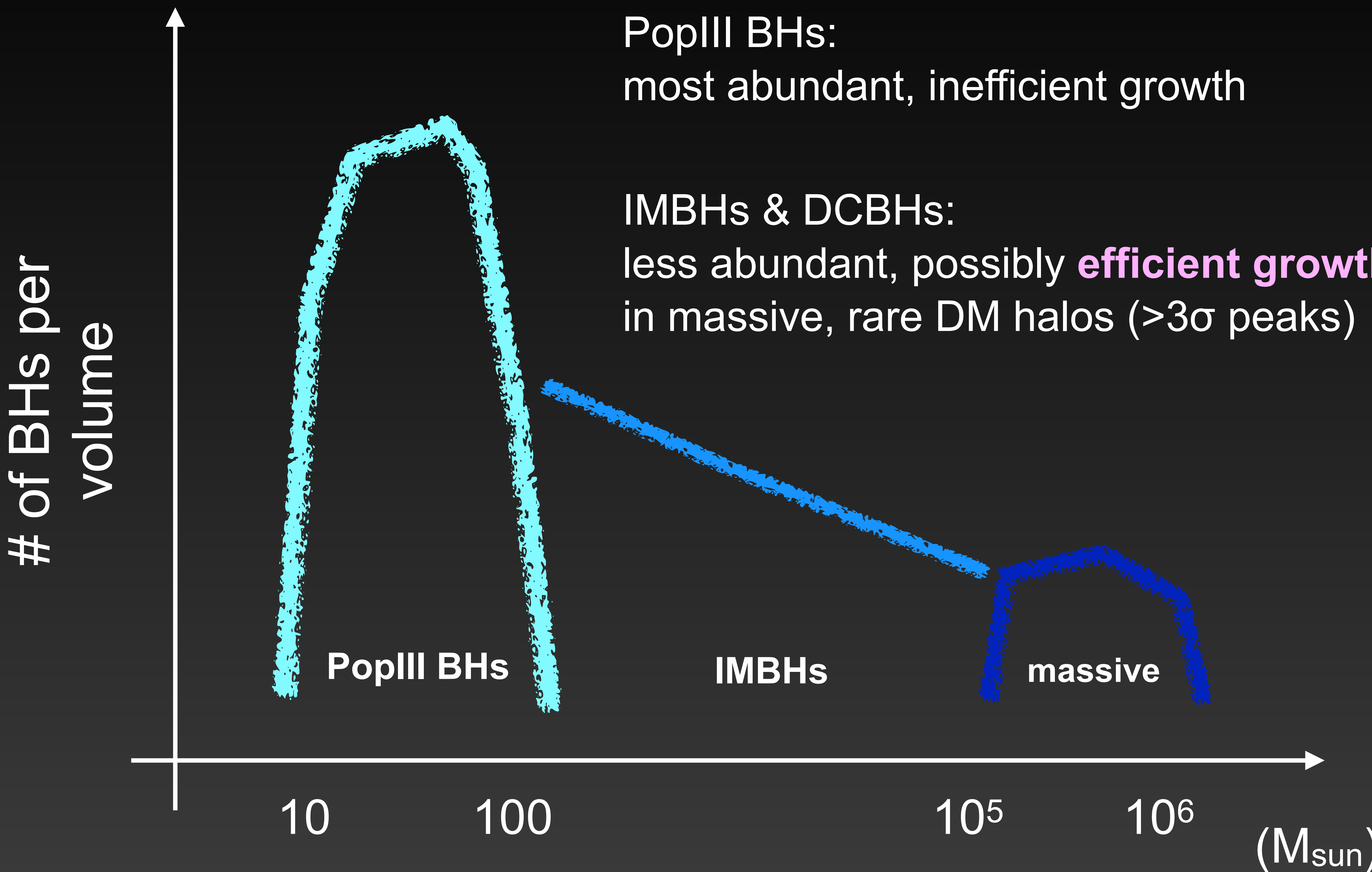
Summary (I)


heavy seeds ~$10^5 M_{sun}$
• LW radiation / streaming motion
• high accretion -> DCBHs
10^{9-10}
BH mass
$M_{BH,0}$
rapid growth
(hyper-Eddington)
• photo-heating vs. recombination
• $\dot{M}_B/\dot{M}_{Edd}$ > 500 is required
• overmassive BHs relative to galaxies
6-7
10-20
redshift

Summary (II)

PopIII BHs:
most abundant, inefficient growth

IMBHs & DCBHs:
less abundant, possibly **efficient growth**
in massive, rare DM halos (>3σ peaks)



Thank you!