The Assembly of the First Massive BHs and the Detections with Upcoming Observations

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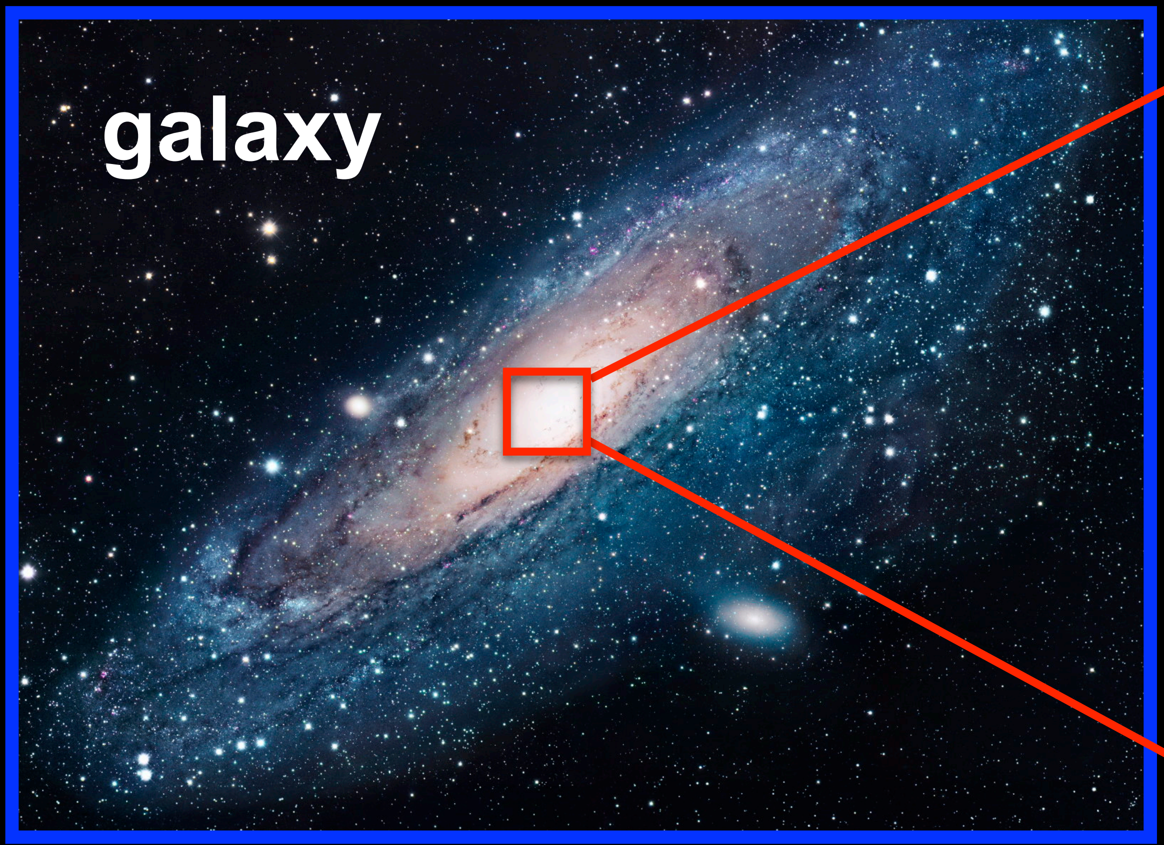
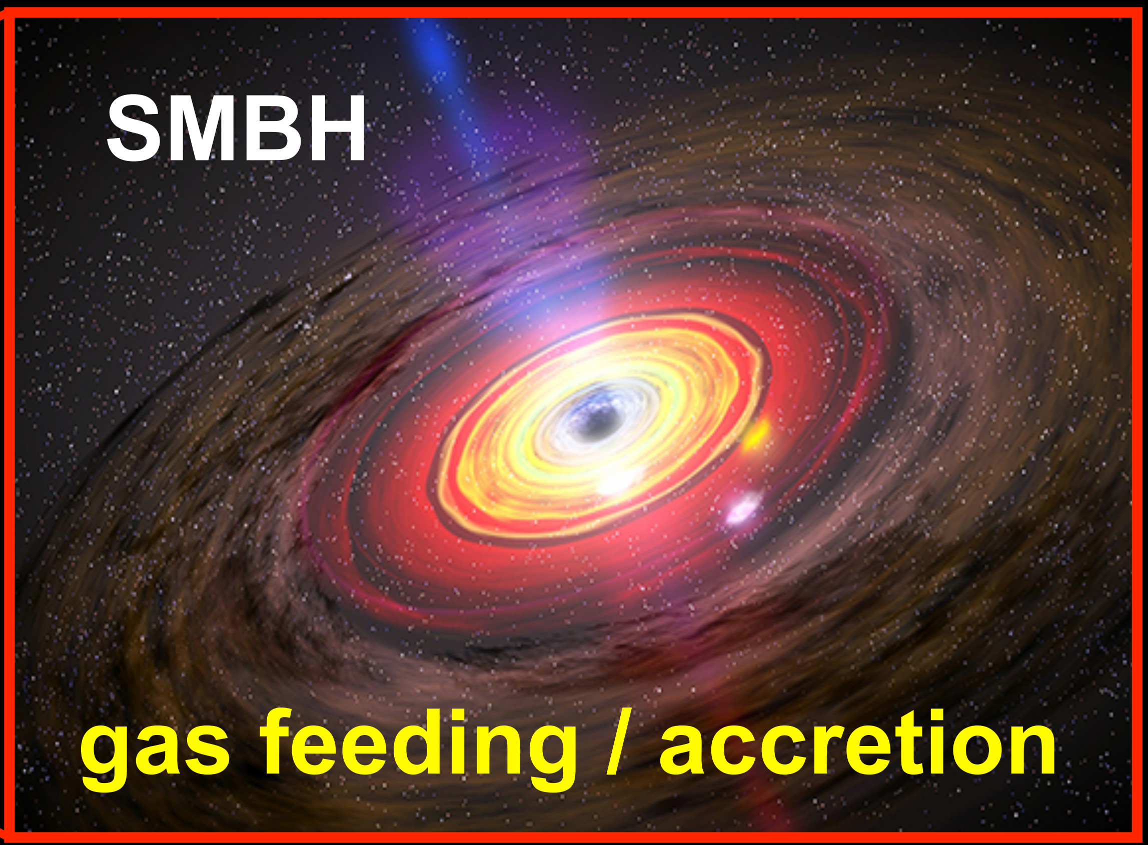
第10回観測的宇宙論ワークショップ

Supermassive black holes (SMBH)



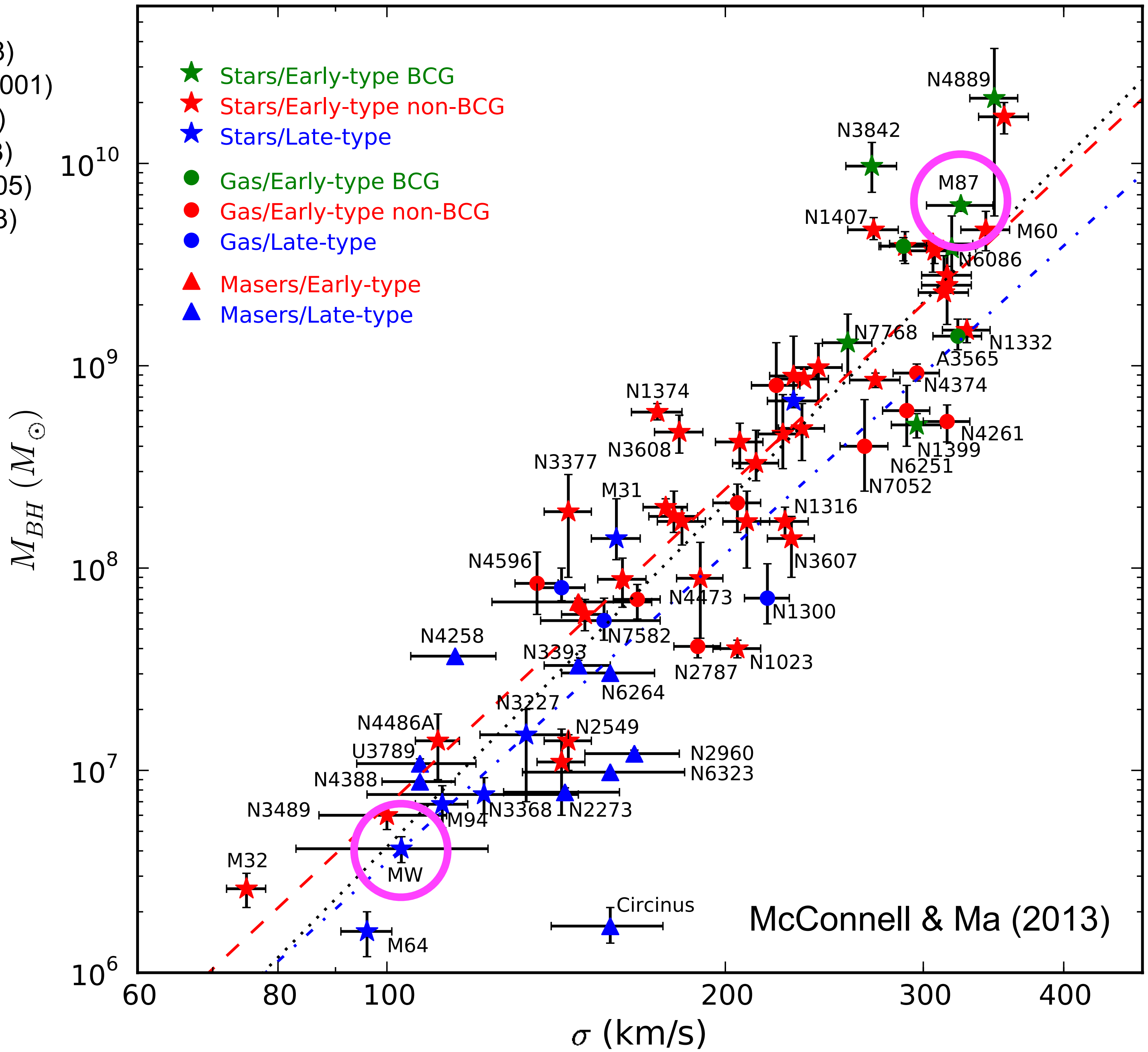


- very massive objects: $M_{BH} \sim 10^6 - 10^{10} M_{sun}$
- universal existence at the galaxy centers
- very powerful engines of radiation & outflows

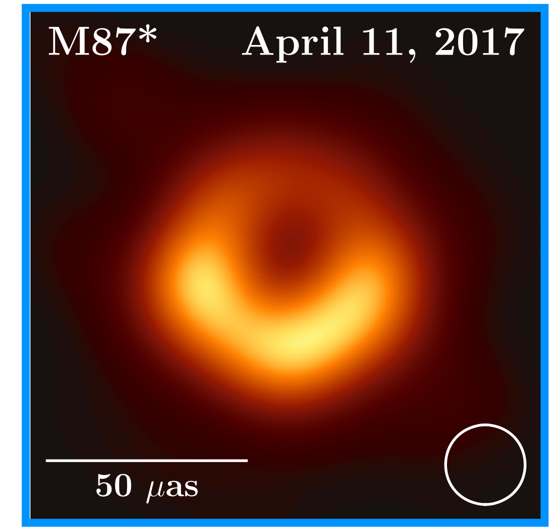
BH-galaxy coevolution

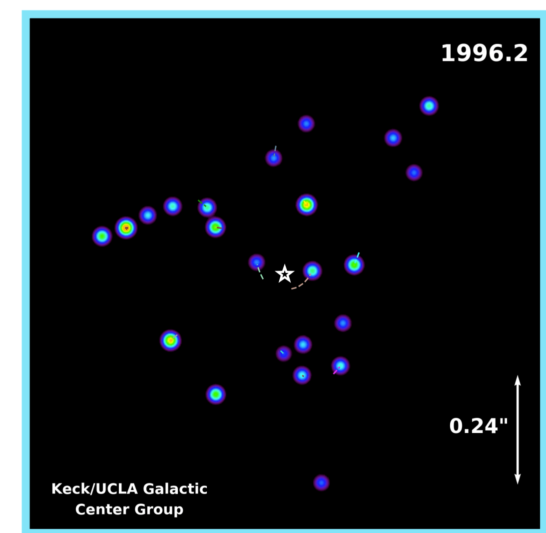
see also…
Magorrian et al. (1998)
Merritt & Ferrarese (2001)
Tremaine et al. (2002)
Marconi & Hunt (2003)
Ferrarese & Ford (2005)
Kormendy & Ho (2013)

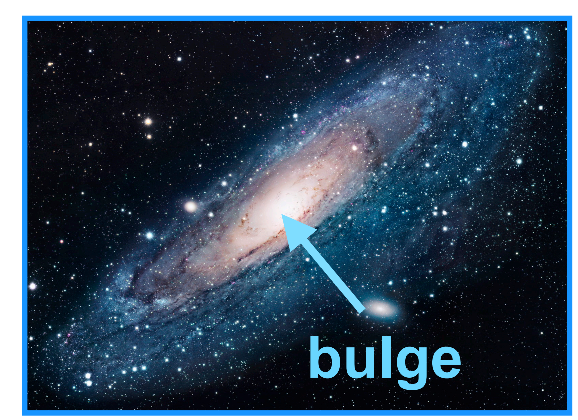
BH mass



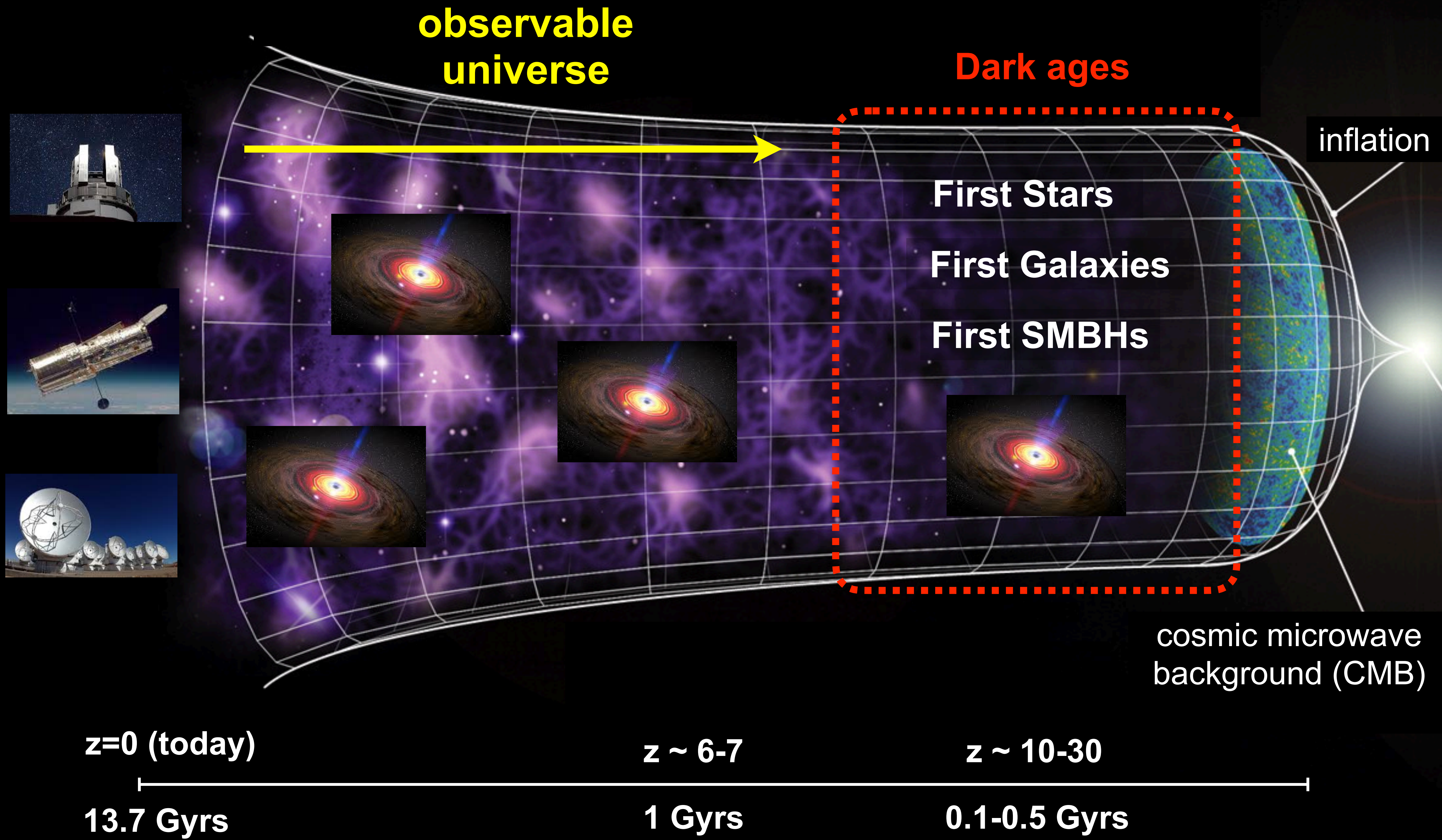
velocity dispersion of bulge stars







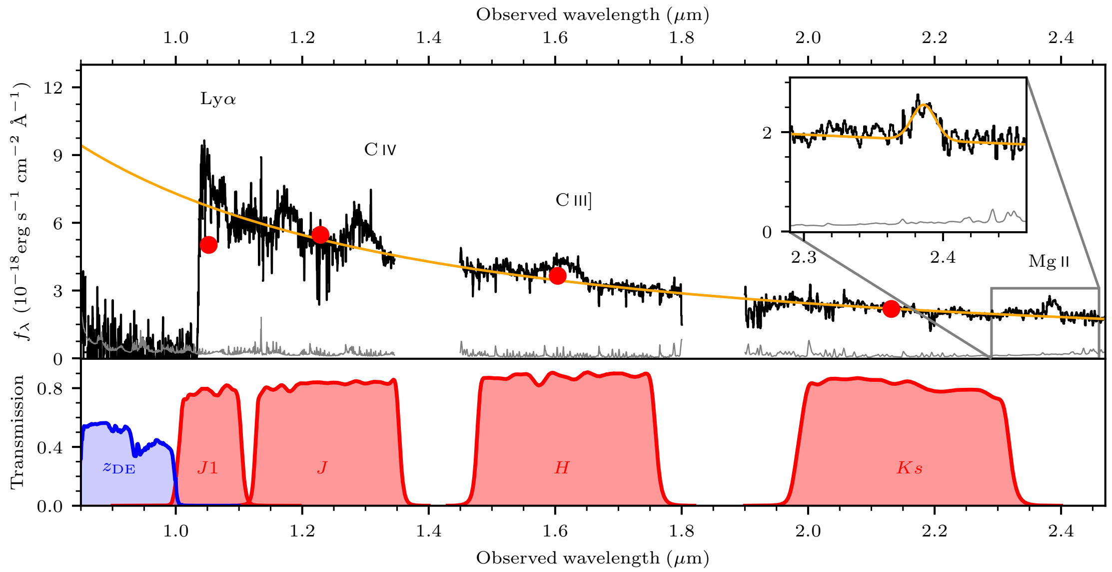
History of the universe



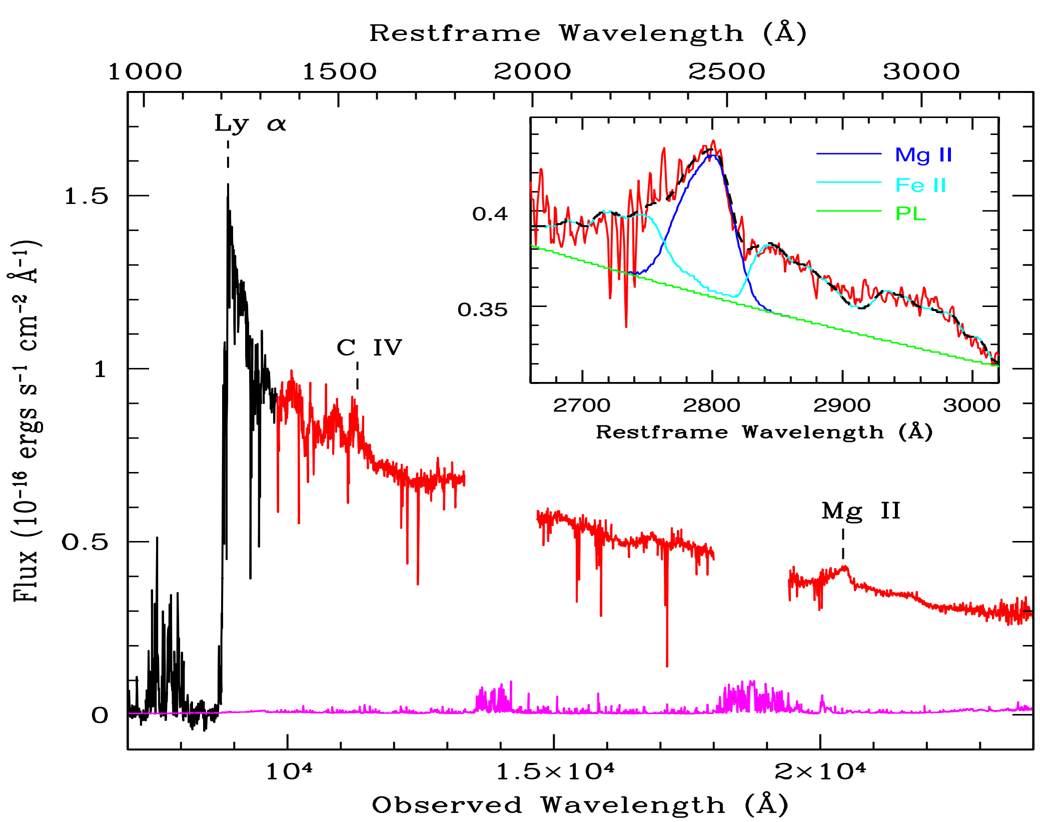
High-z monsters

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

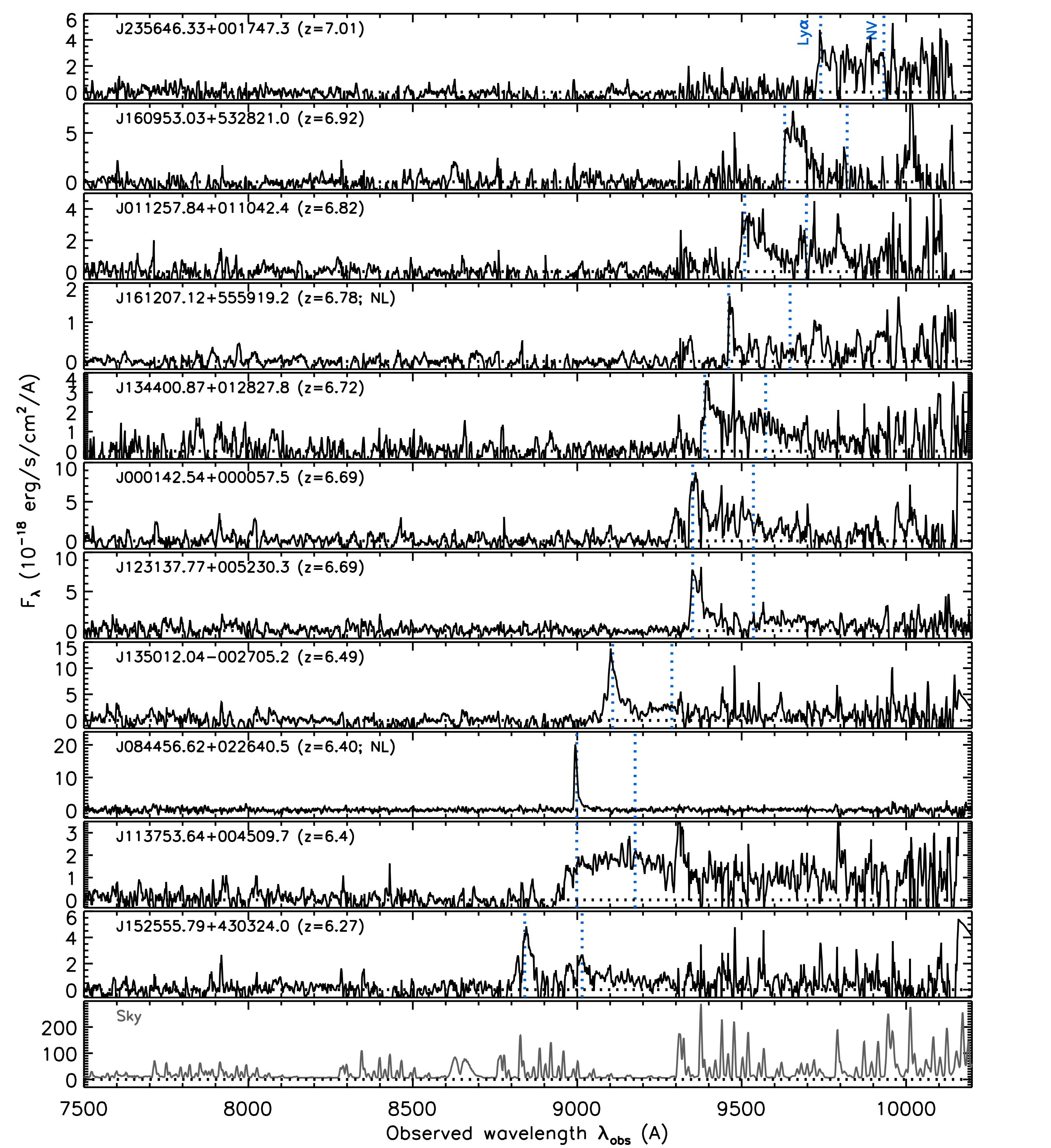
Most distant z=7.54 Banados et al. (2017)



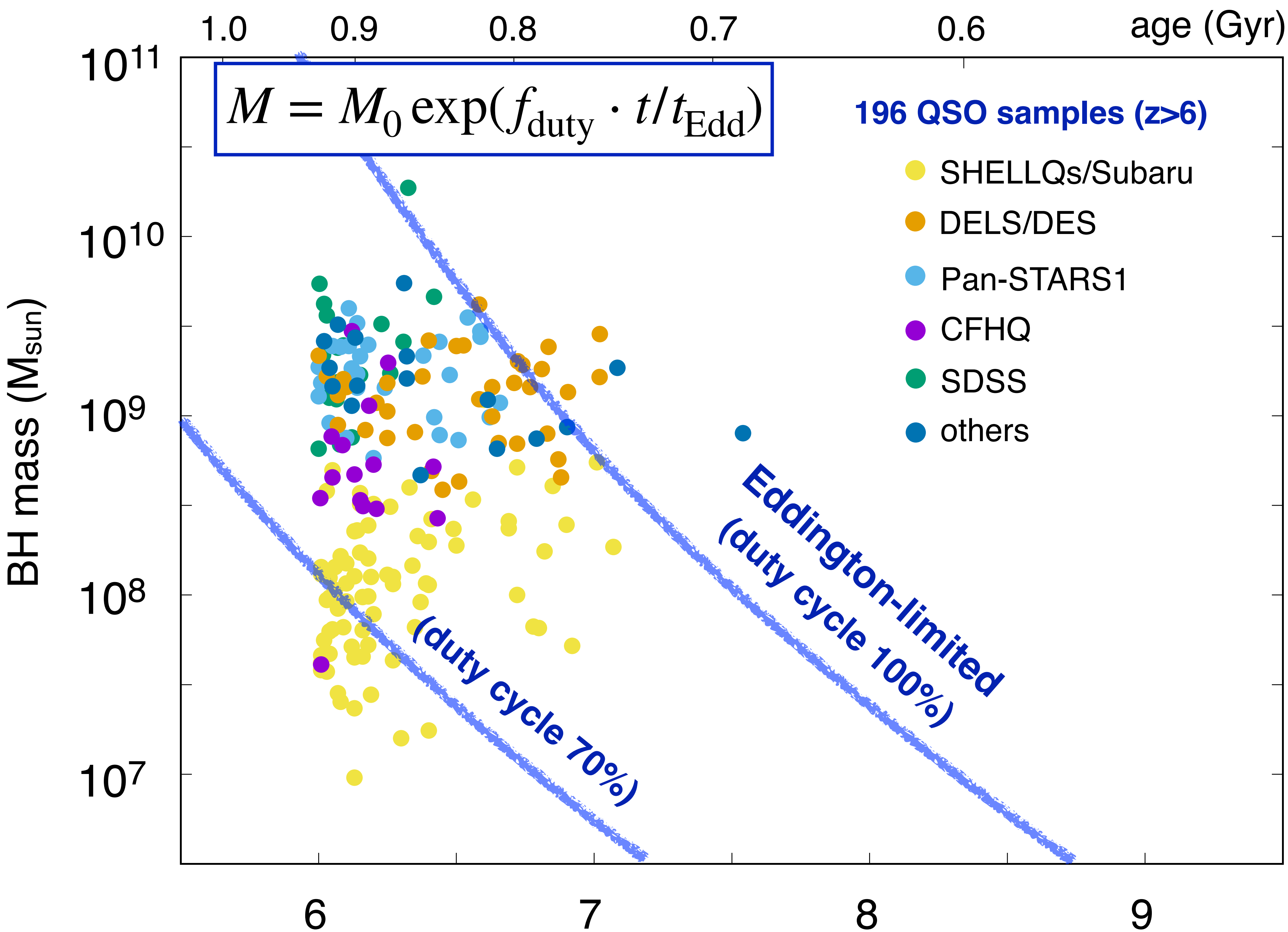
Most massive $M=10^{10}M_{sun}$ Wu et al. (2015)



Subaru HSC, SHELLQs (Matsuoka et al. 2019)



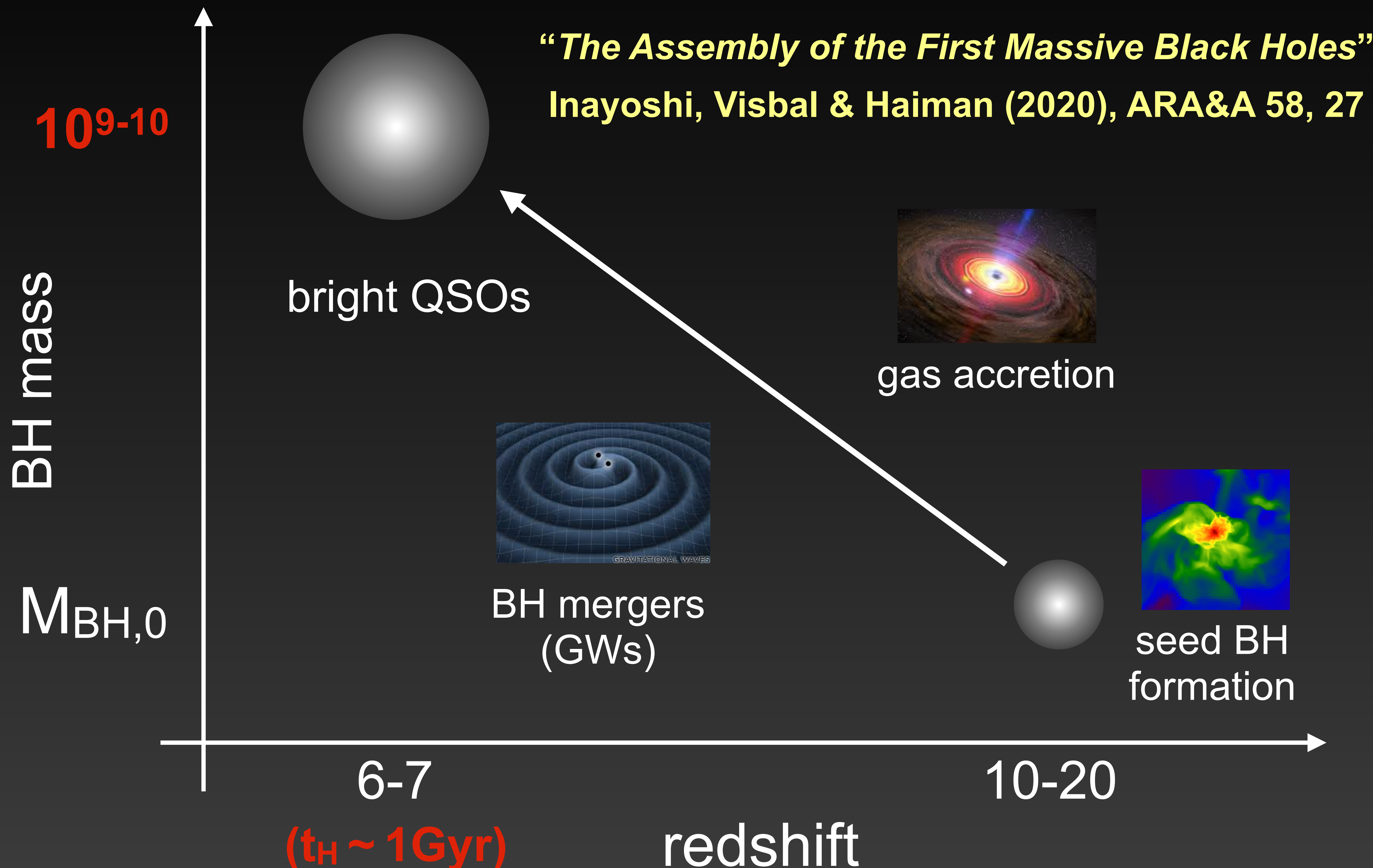
High-z SMBH population



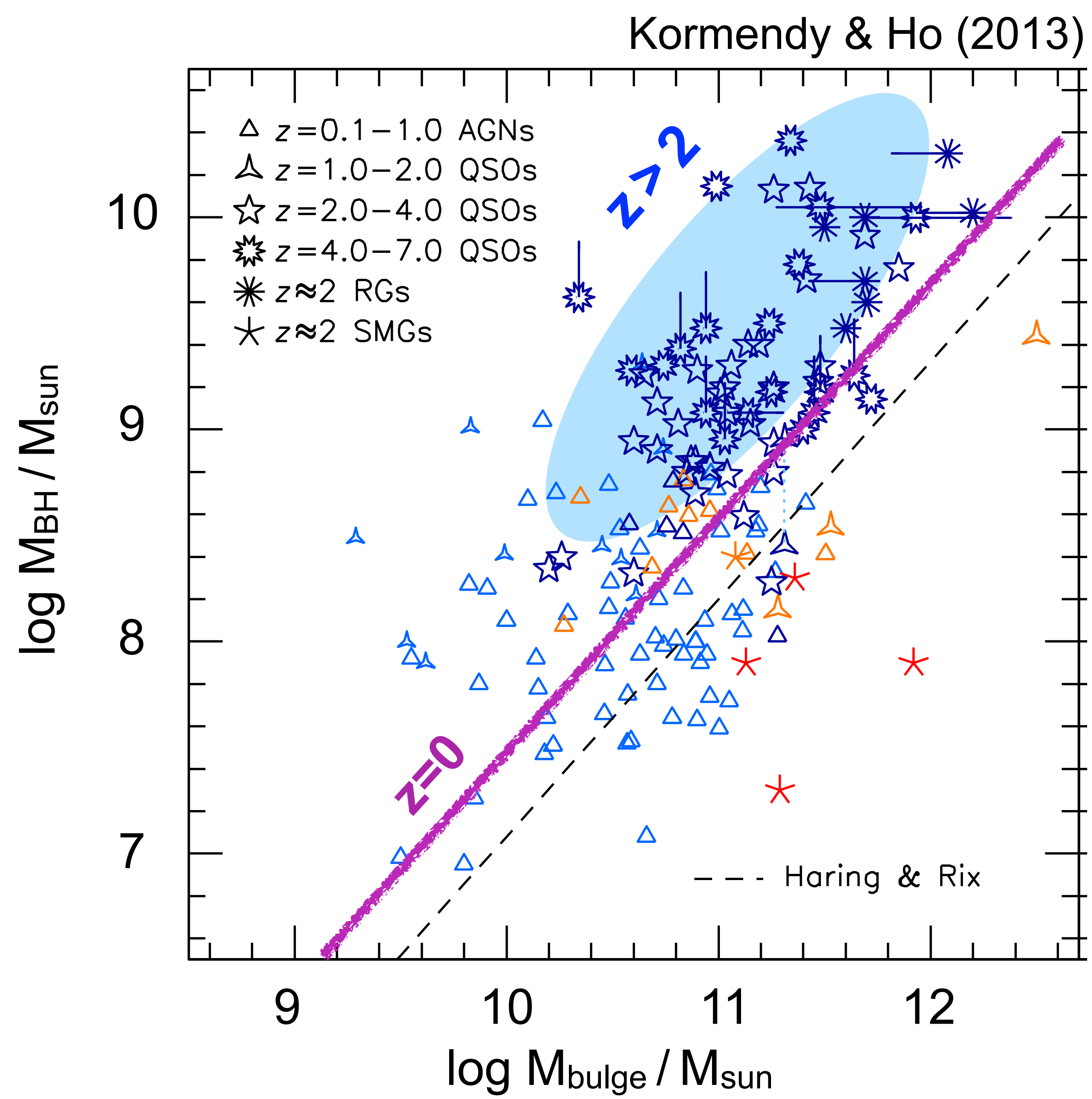
*λ_{Edd}=1 is assumed for BHs if not mass measurements

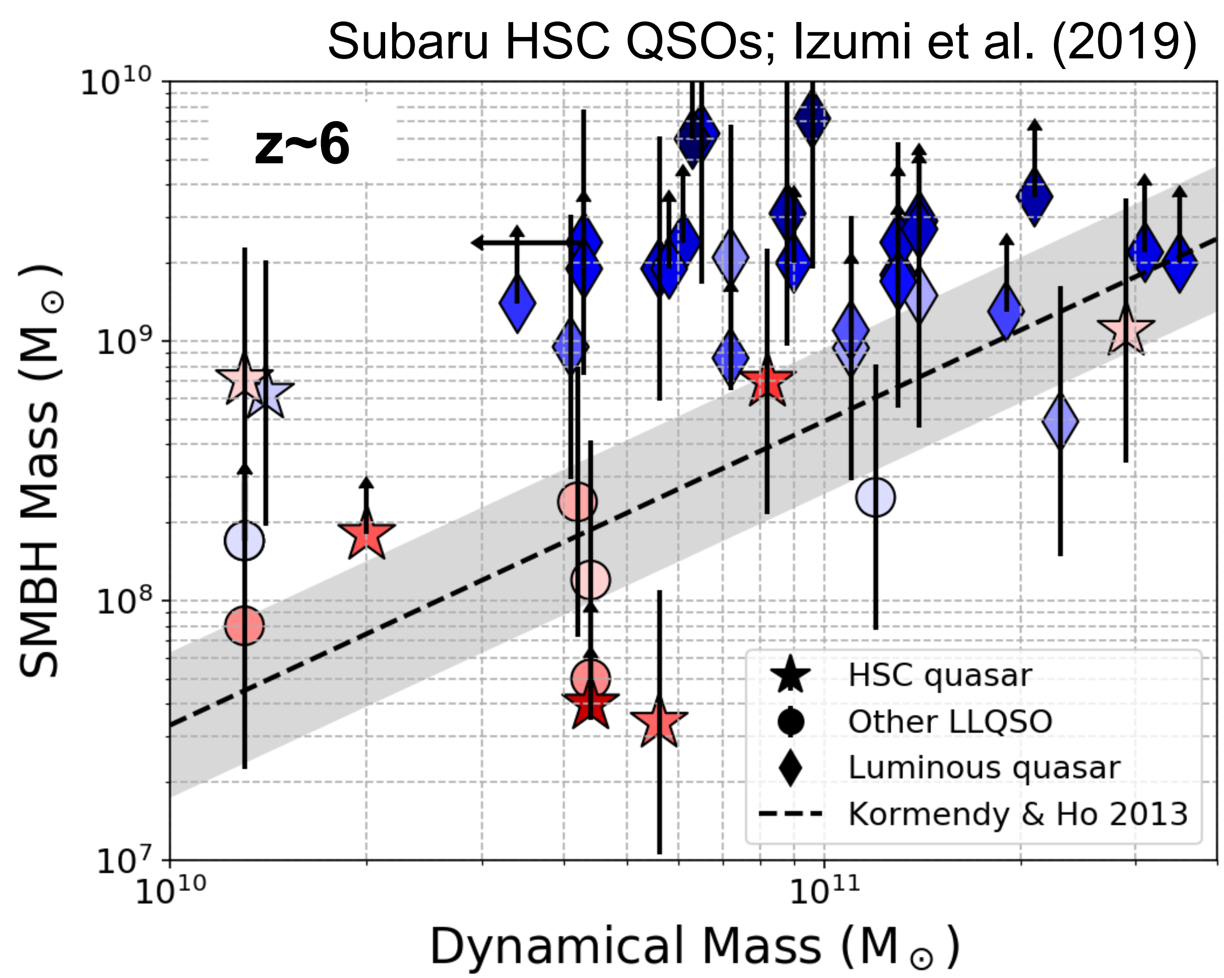
KI, Visbal & Haiman (2020)

Rapid SMBH assembly



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

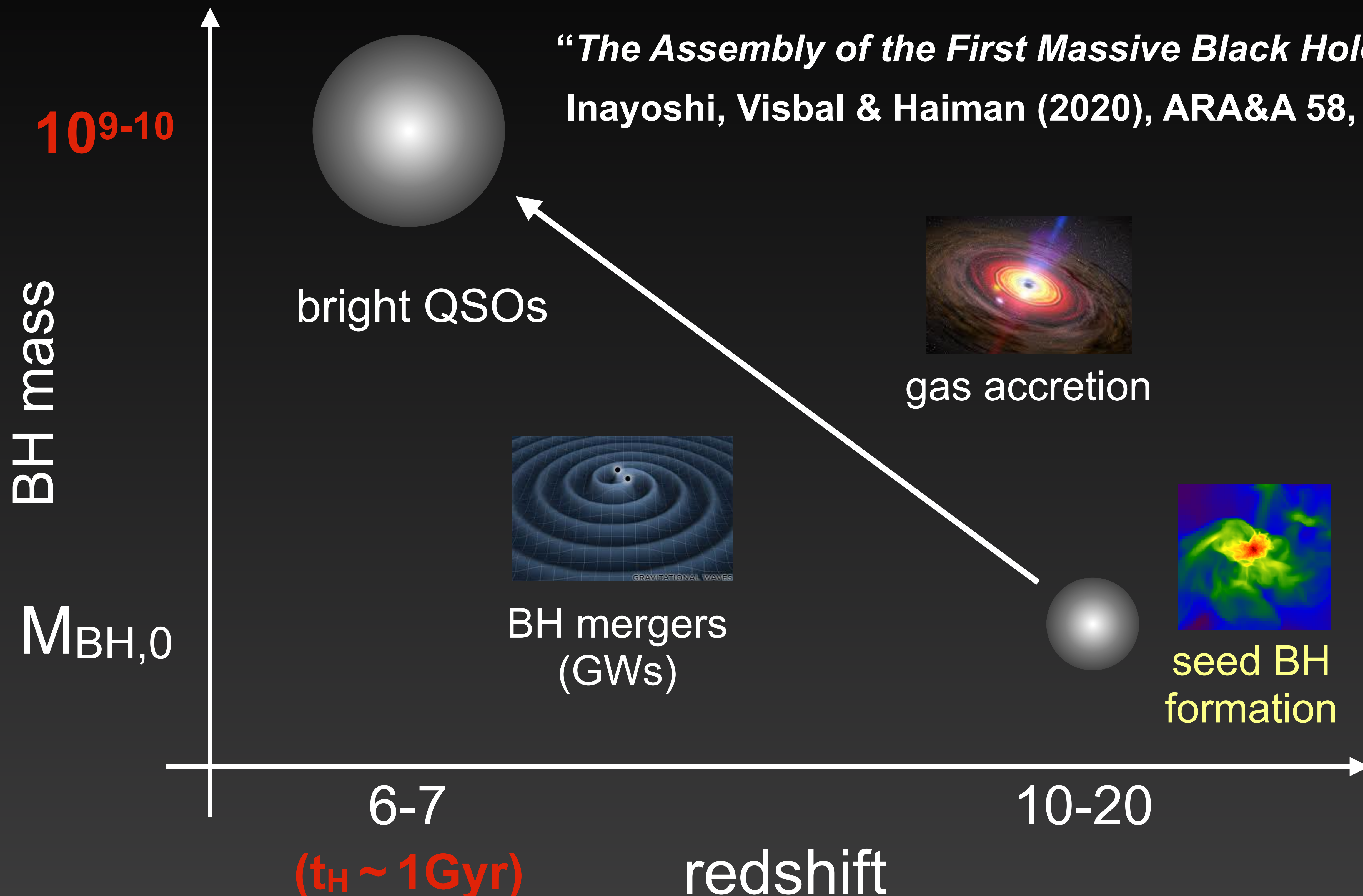
1. Massive Seed Formation
2. Rapid Growth of BHs
3. Toward Future Observations

BH seed formation

Rapid SMBH assembly

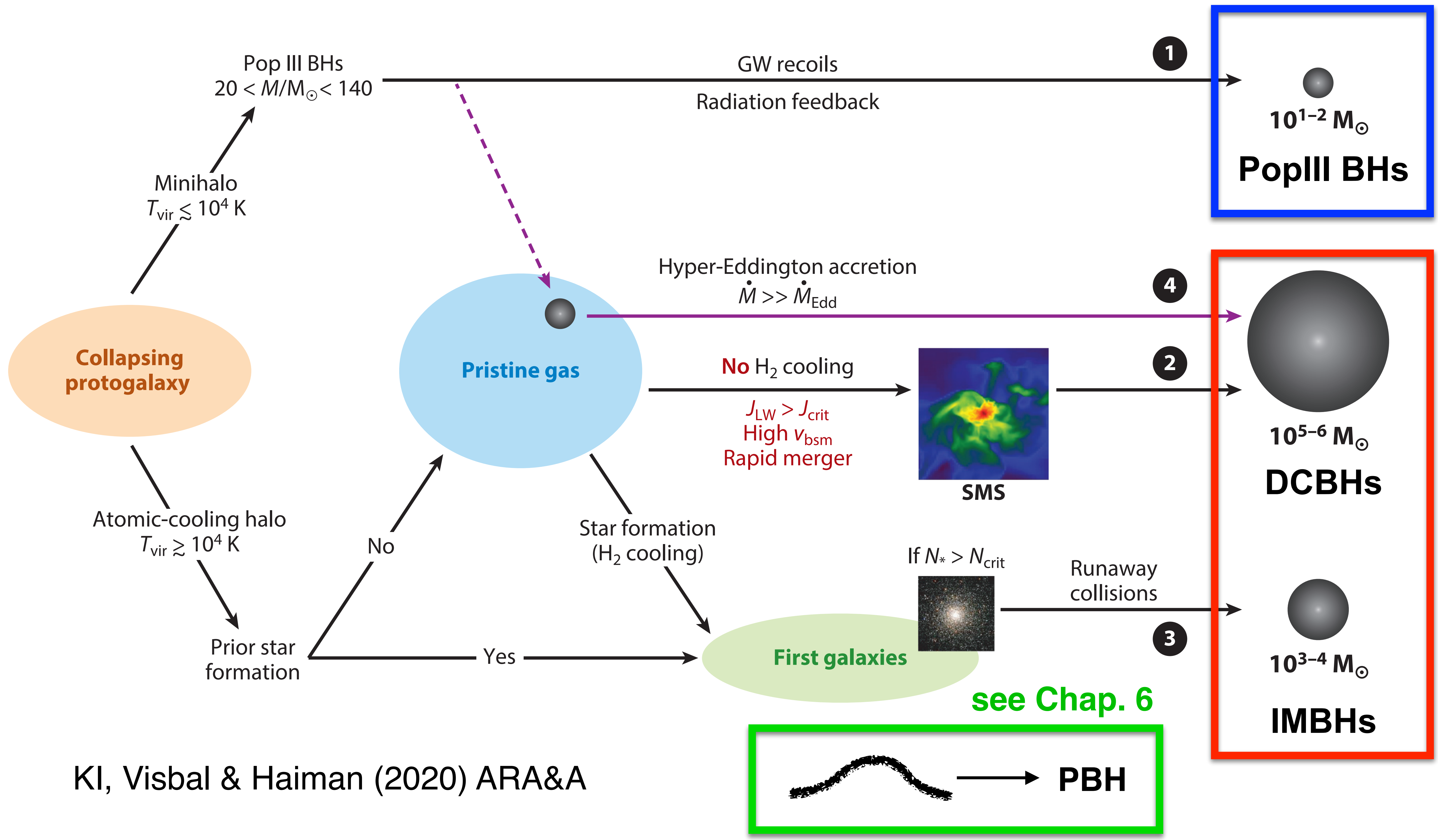
"*The Assembly of the First Massive Black Holes*"

Inayoshi, Visbal & Haiman (2020), ARA&A 58, 27



Formation channels of early BHs

The mass of seed BHs would depend on the environments

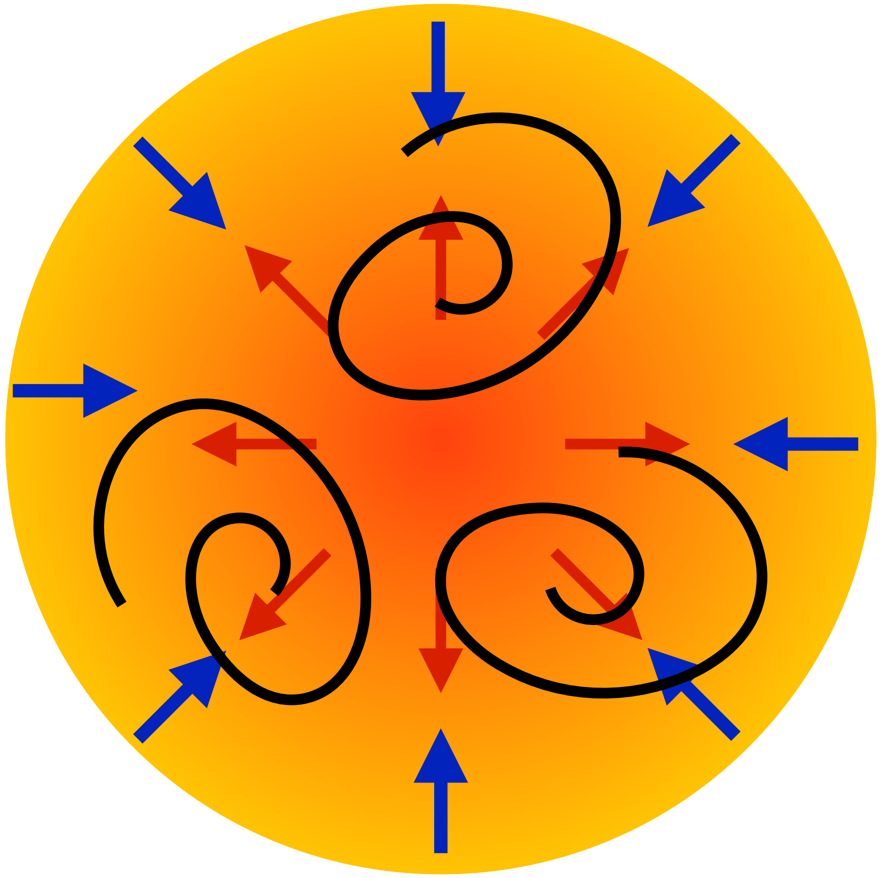


KI, Visbal & Haiman (2020) ARA&A

Basics of star formation

- mass inflow rate in collapsing gas

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



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

if highly turbulent…

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

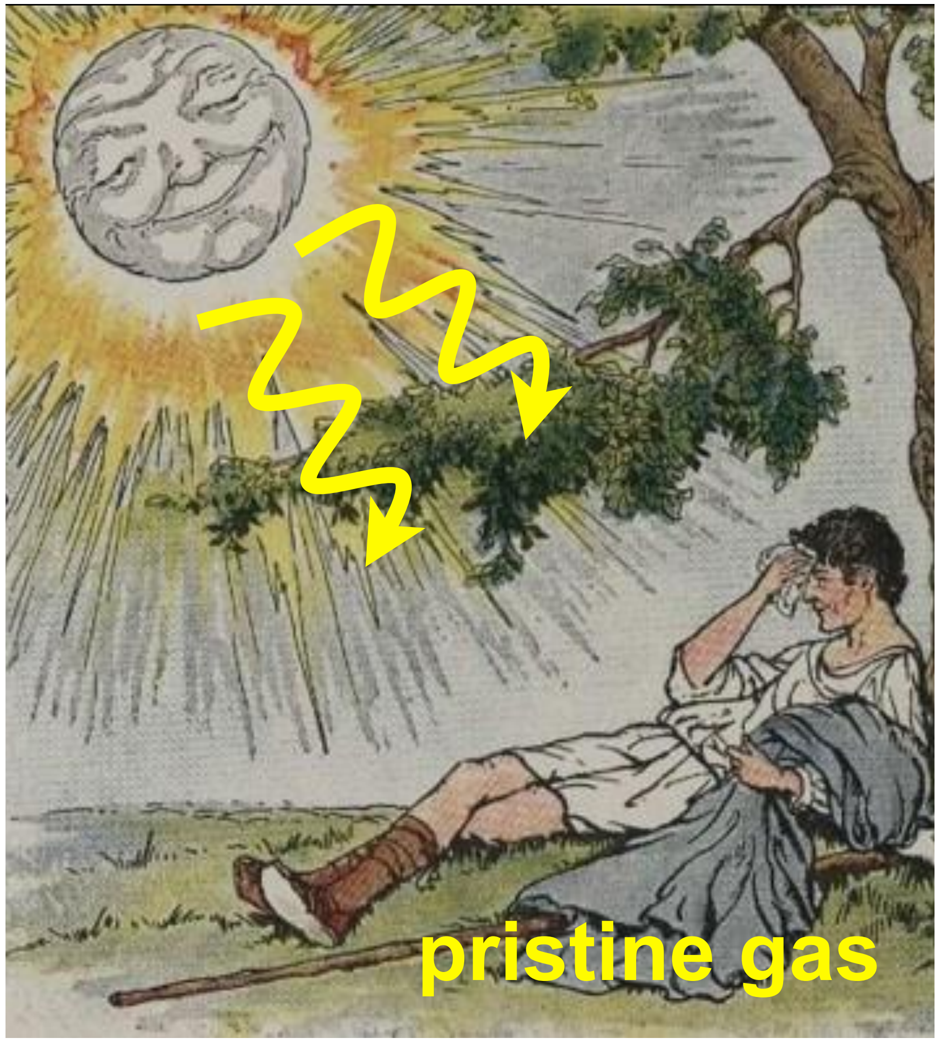
in the radiation-dom. era (PBHs)

$$c_\mathrm{eff} = c/\sqrt{3}$$

Warmer collapsing gas yields **higher** inflow rates

Seed formation ≈ H_2 suppression

Lyman-Werner irradiation



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

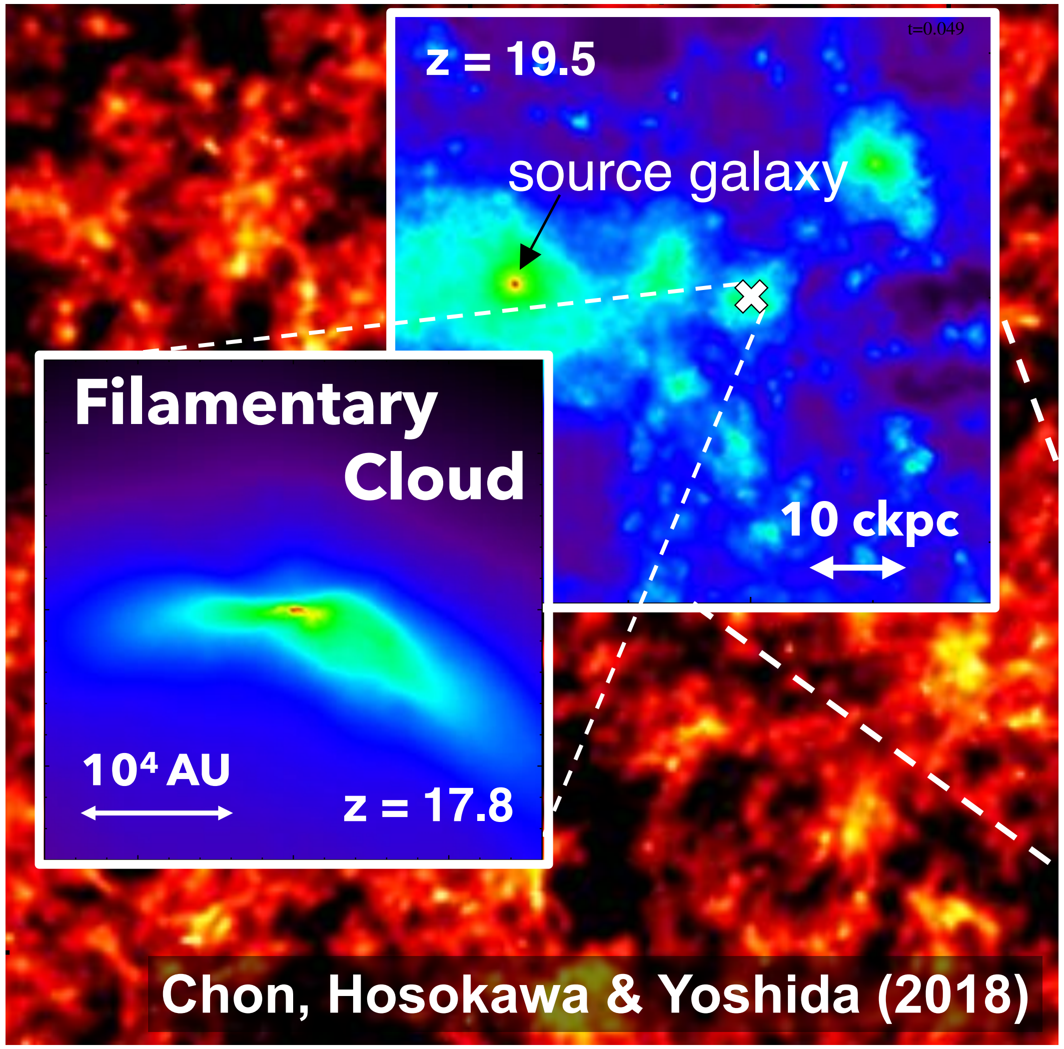
Dynamical heating

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

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…

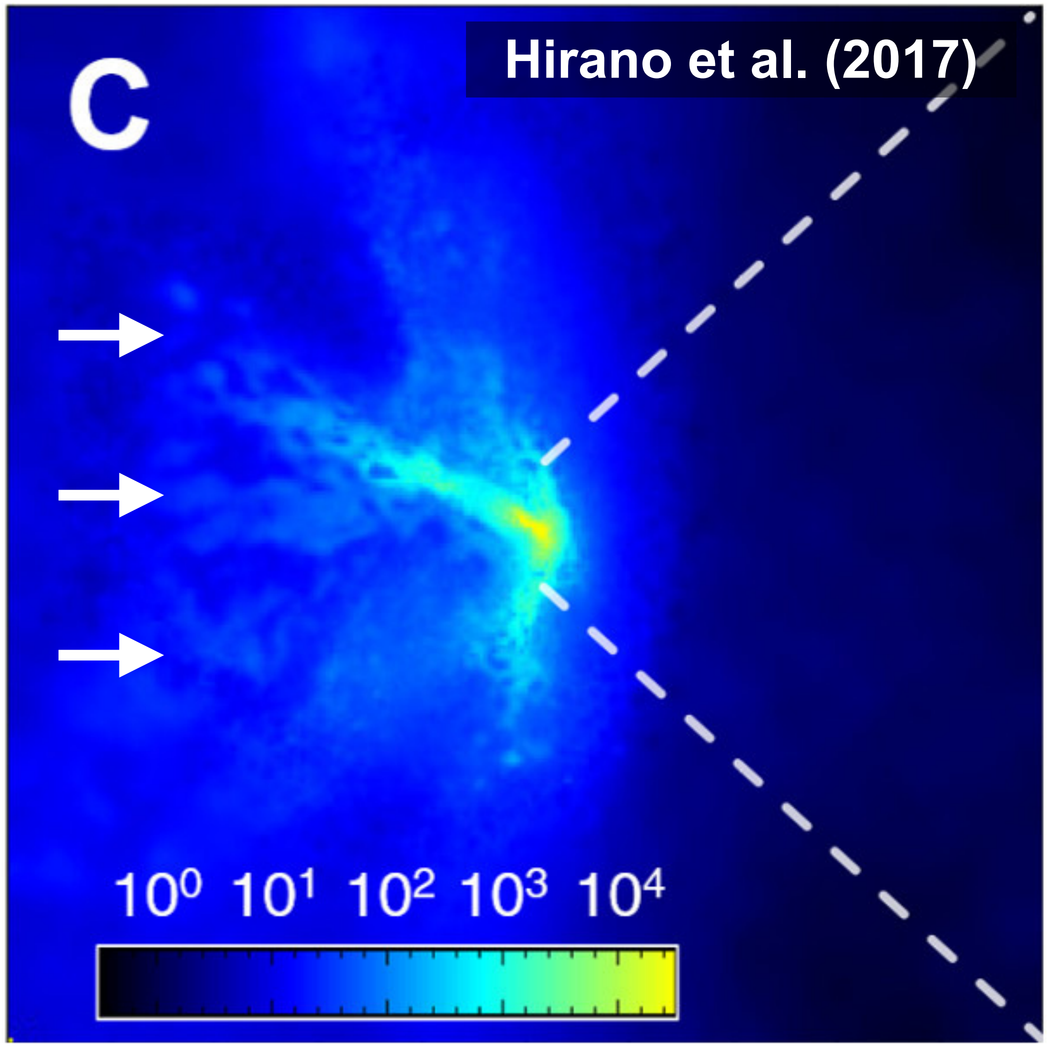
Seed formation ≈ H_2 suppression

Lyman-Werner irradiation



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

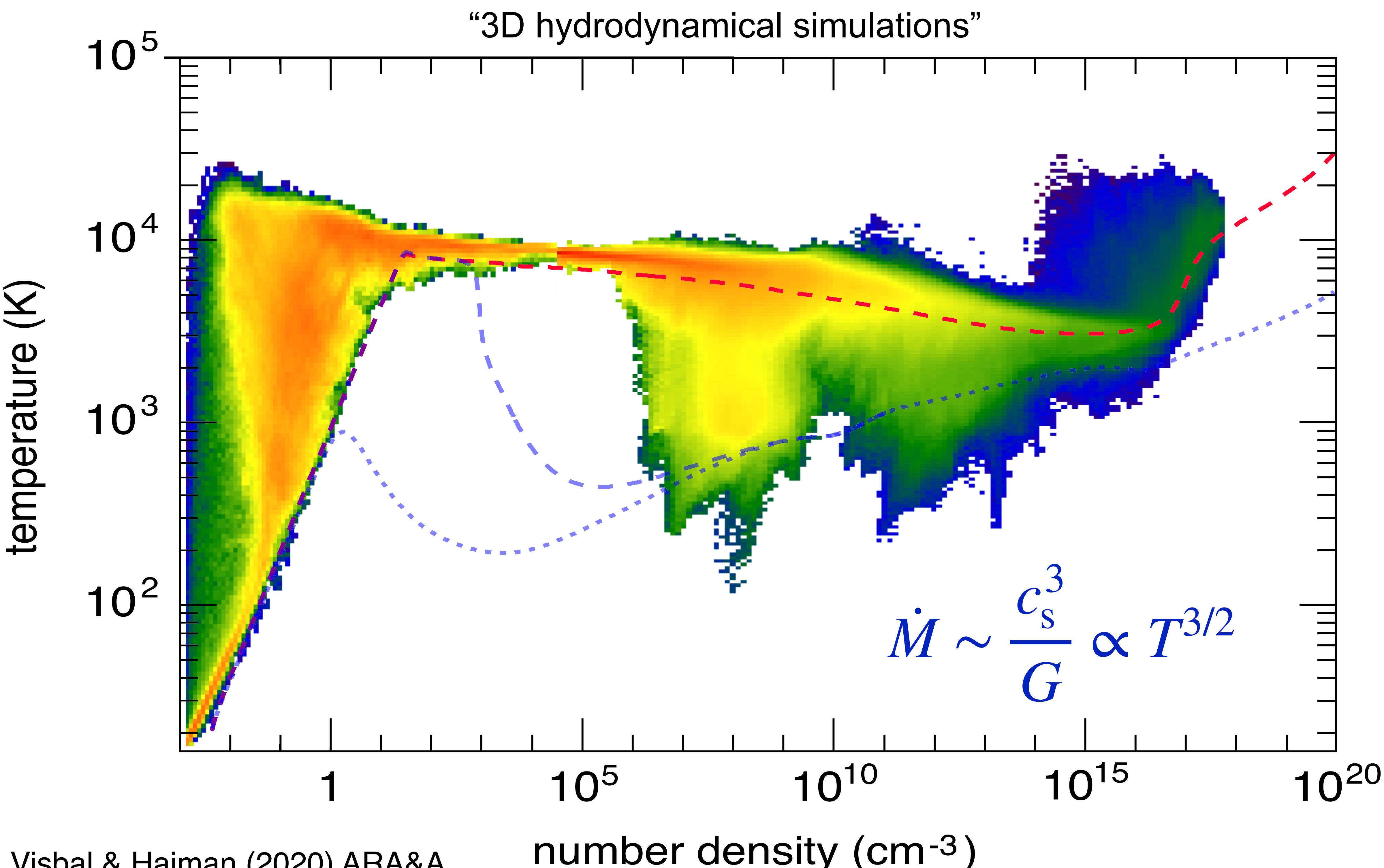
Dynamical heating



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

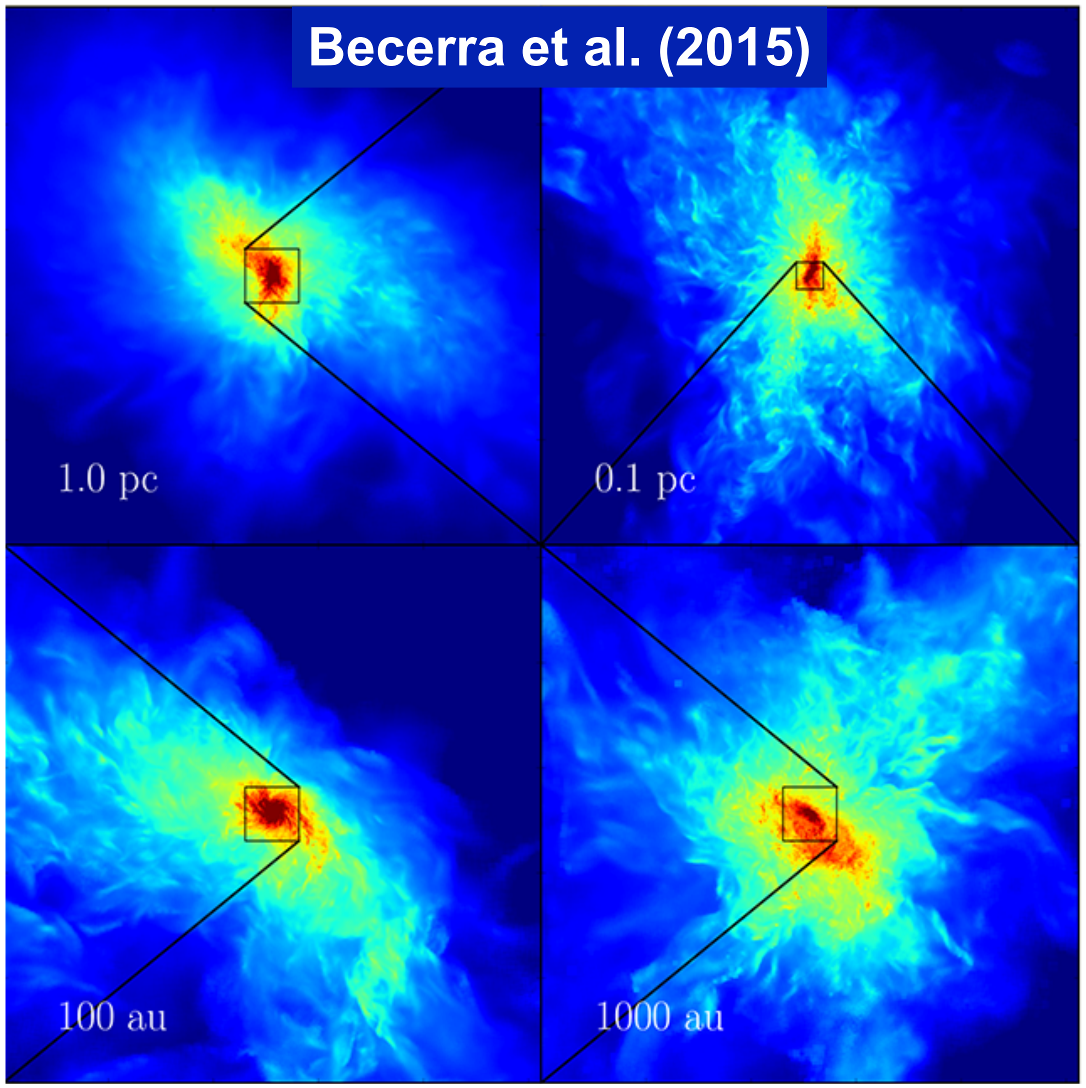
… leaving behind **massive seed BHs** (10^3-$10^6 M_{sun}$)

High-z star formation

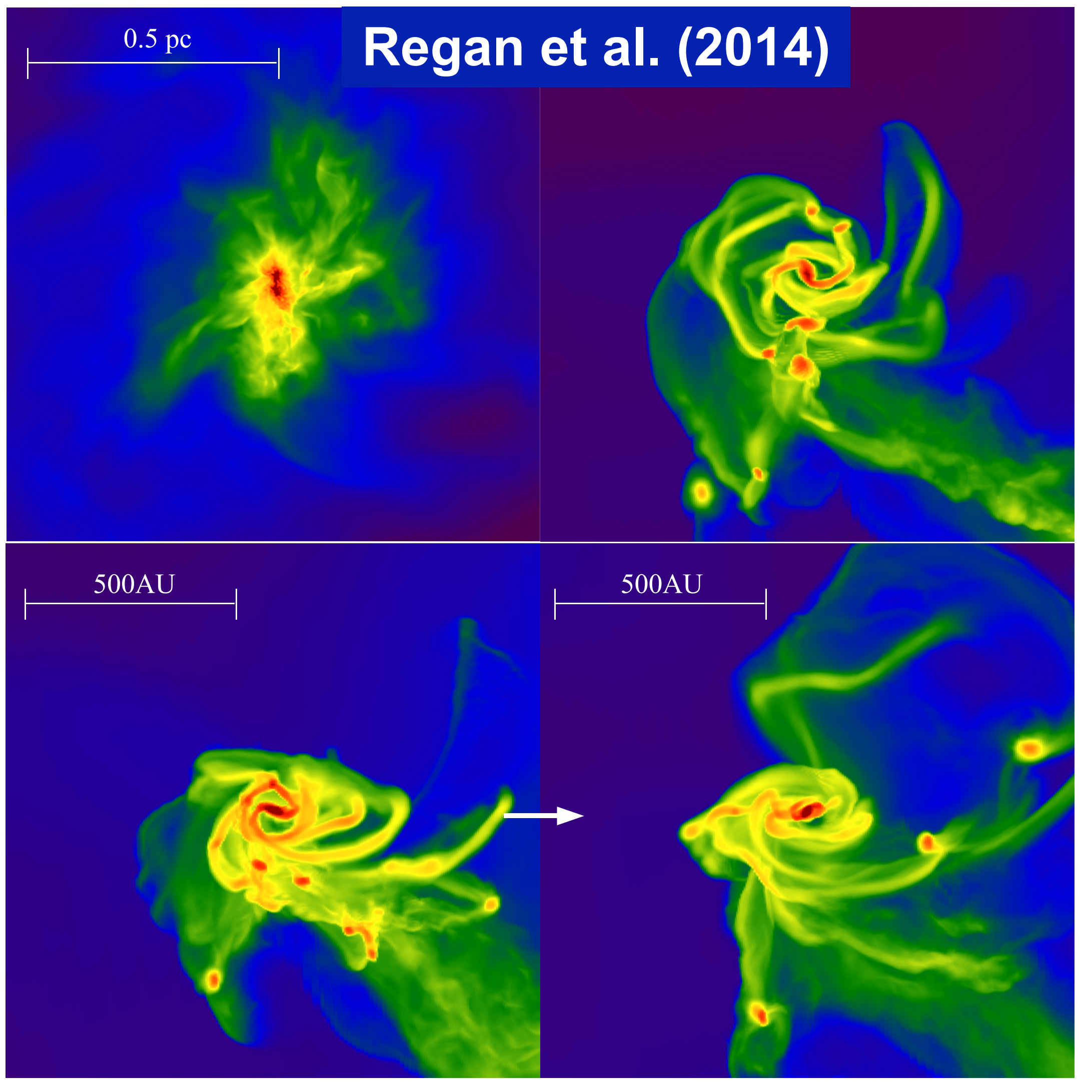


KI, Visbal & Haiman (2020) ARA&A
data from KI, Omukai & Tasker (2014)

High acc. Rate & Massive star



gravitational collapse

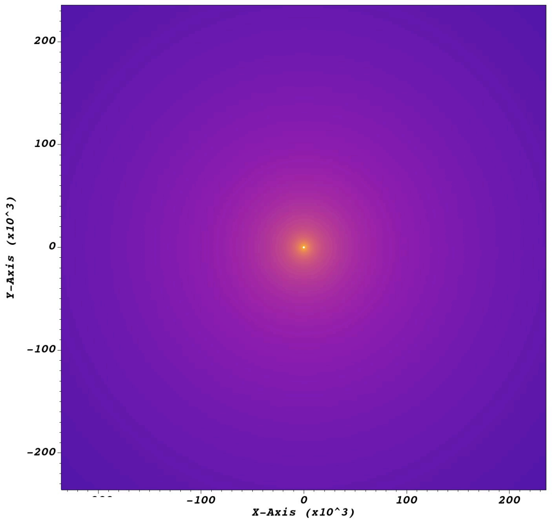


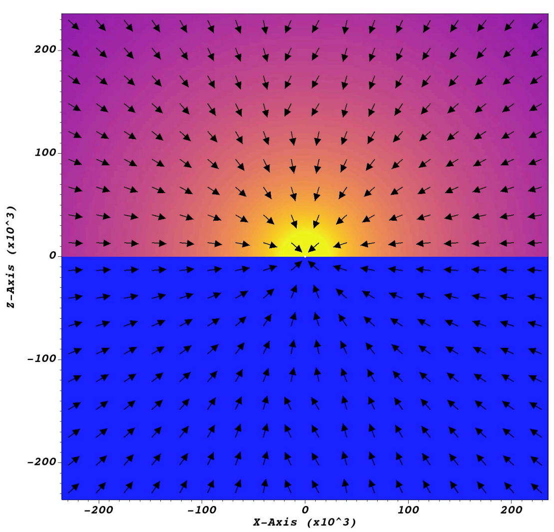
accretion disk

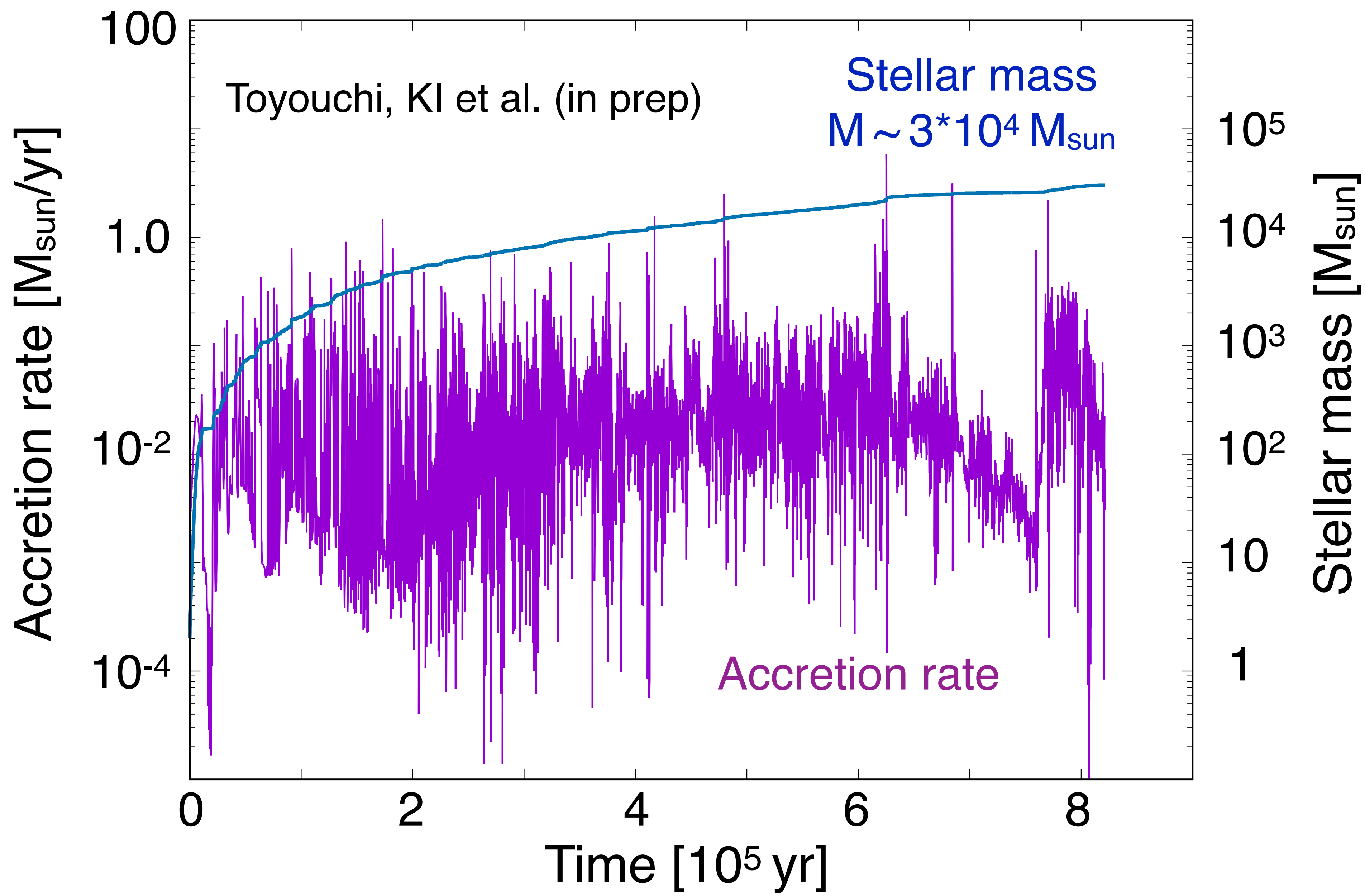
- no/weak fragmentation
- high accretion rate

massive seed BHs

High acc. Rate & Massive star



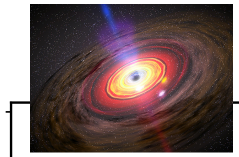




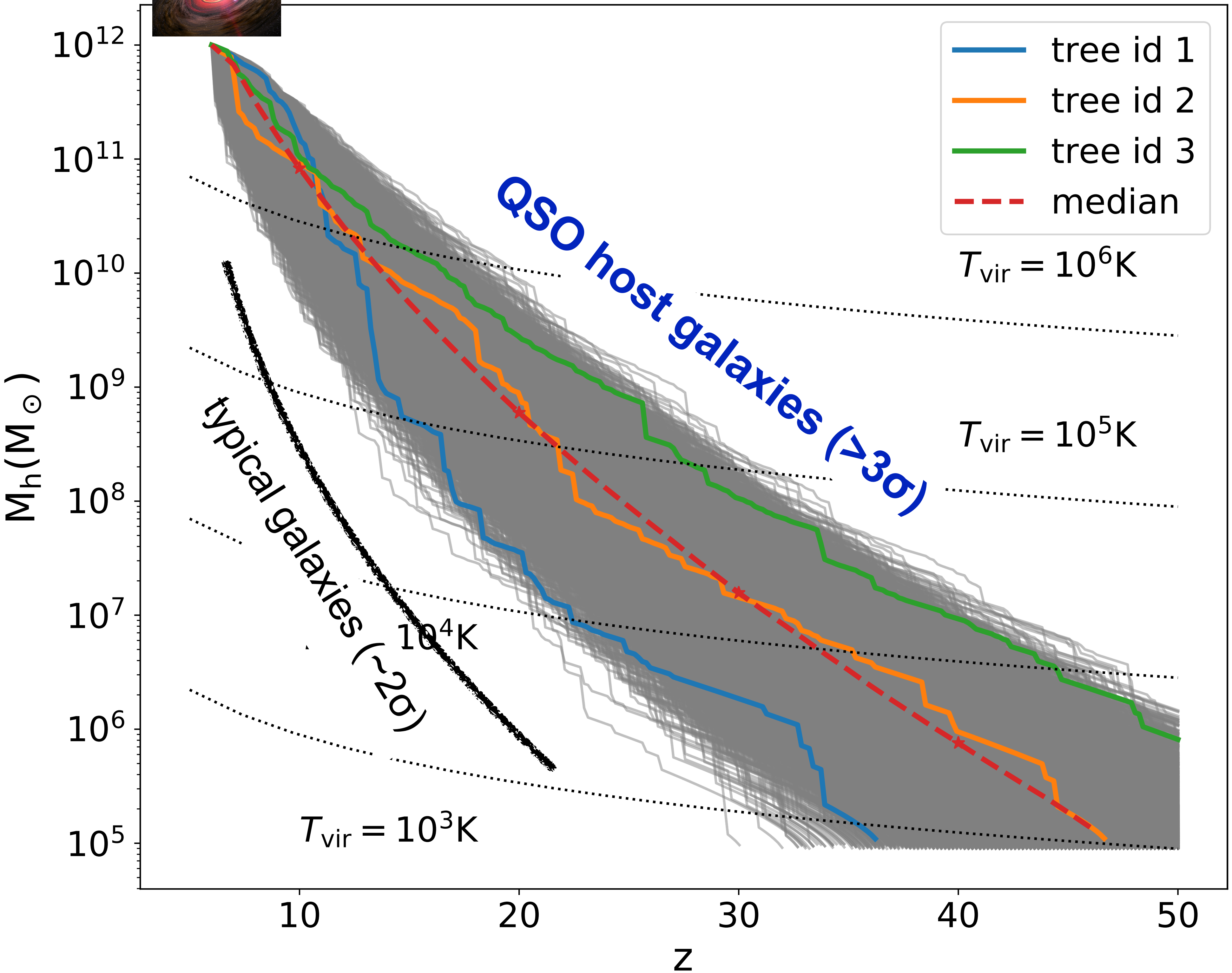
- no/weak fragmentation
- high accretion rate

➡ massive seed BHs

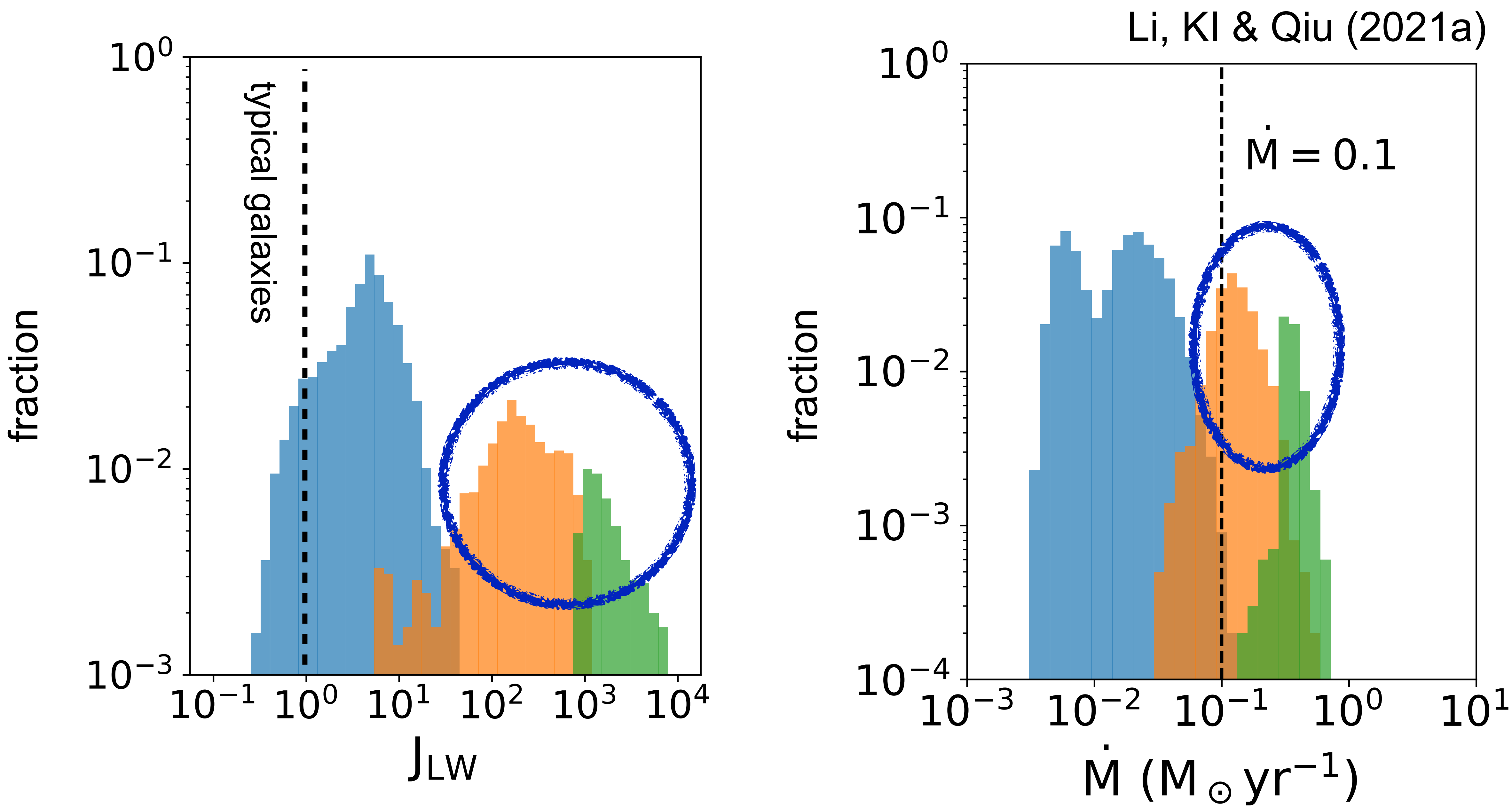
Seed formation in QSO hosts



Li, KI & Qiu (2021a)

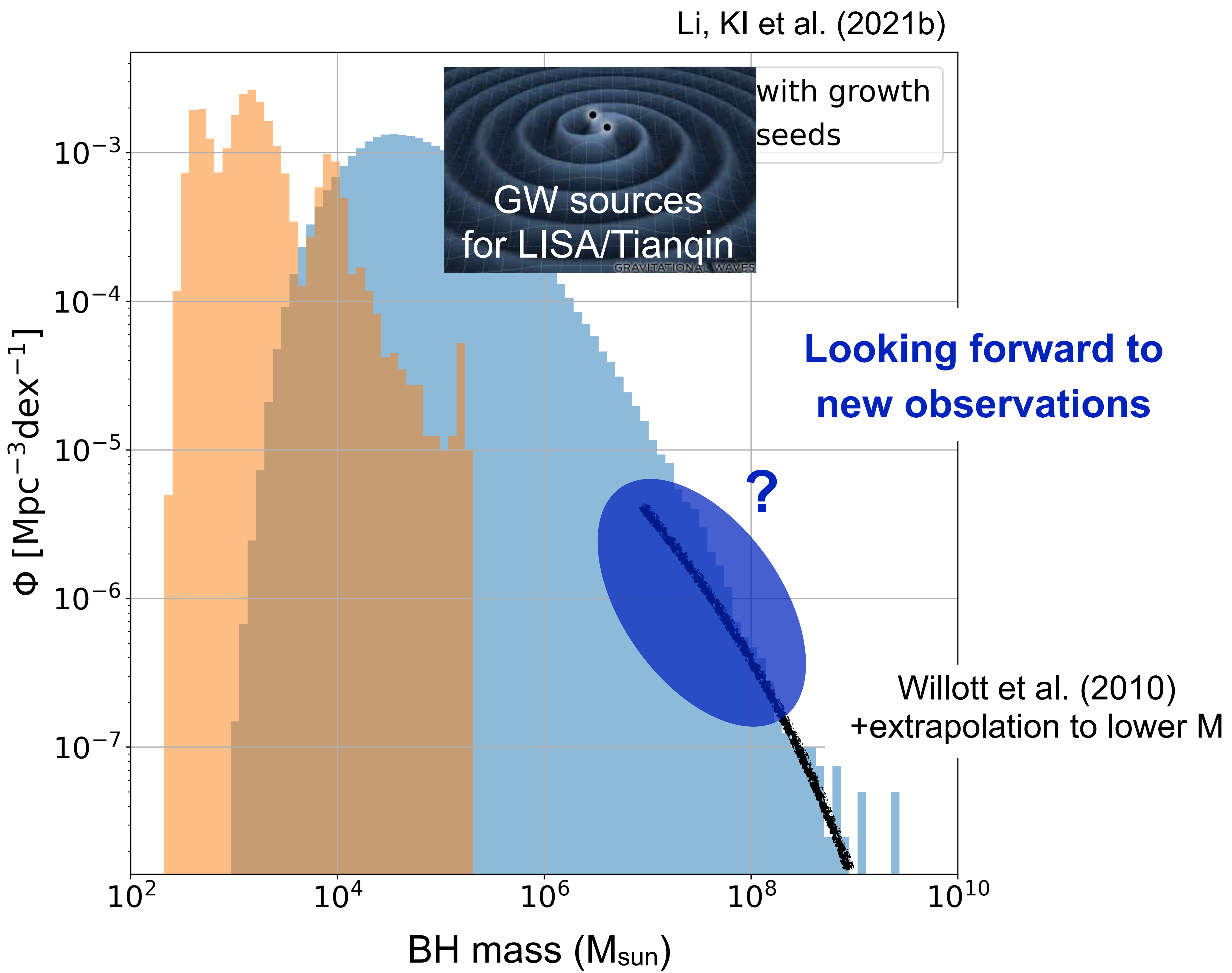


Seed formation in QSO hosts

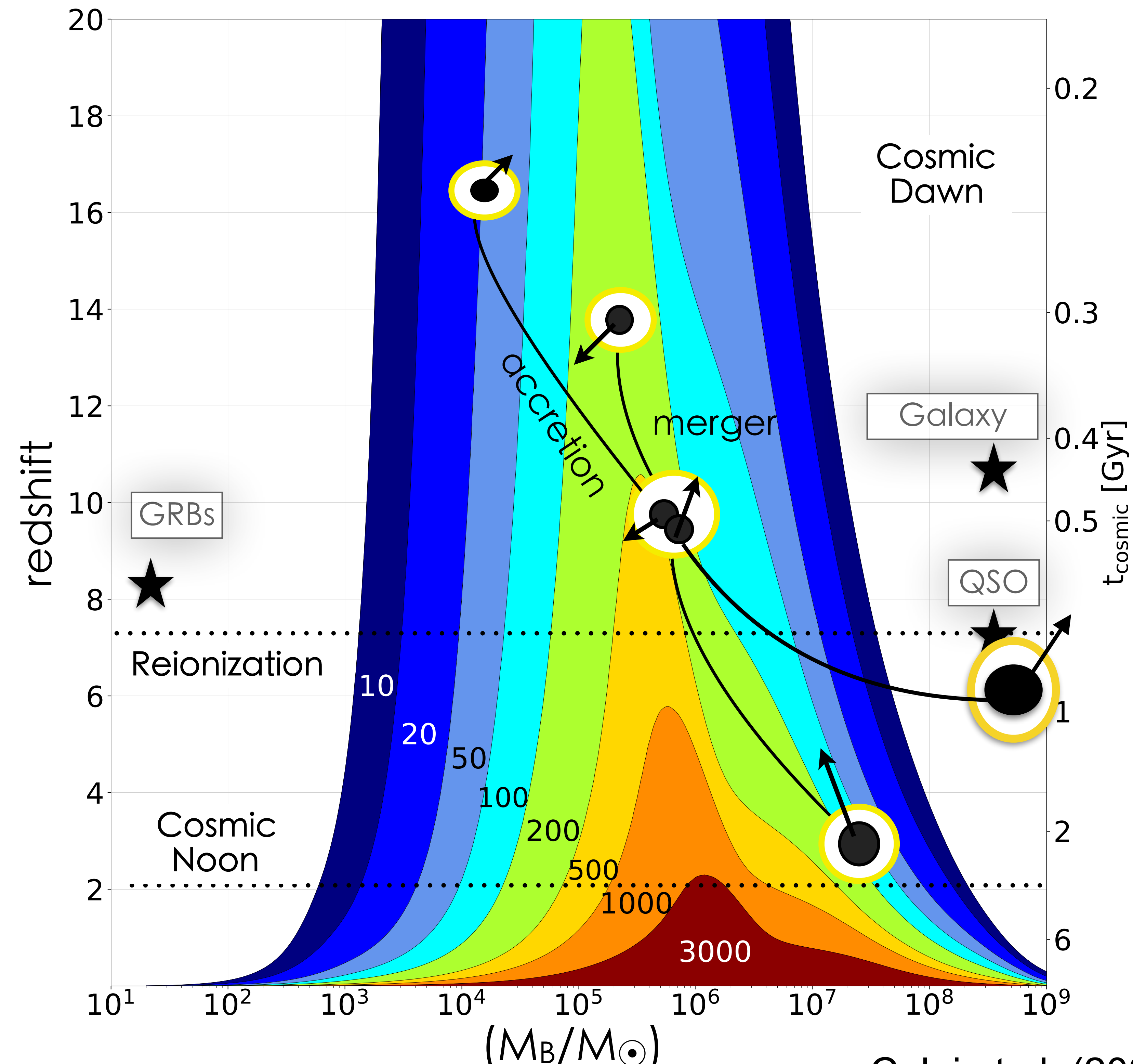


Strong LW irradiation & merger heating lead to high accretion rates (>0.1M_{sun}/yr) in QSO hosts

Seed formation in QSO hosts



Synergy btw EM & GW observations

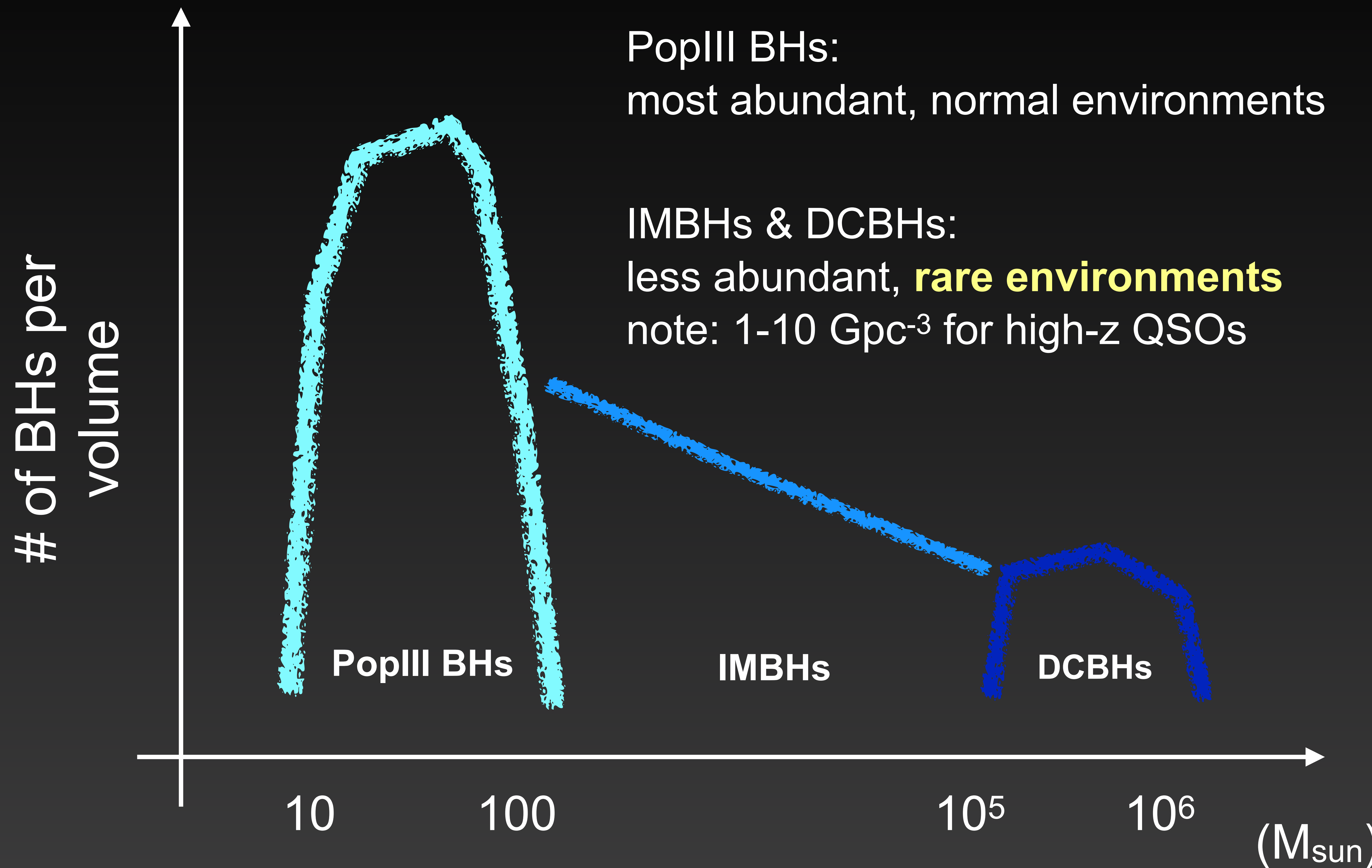


Colpi et al. (2021), Astro2020

(Seed) BH mass function

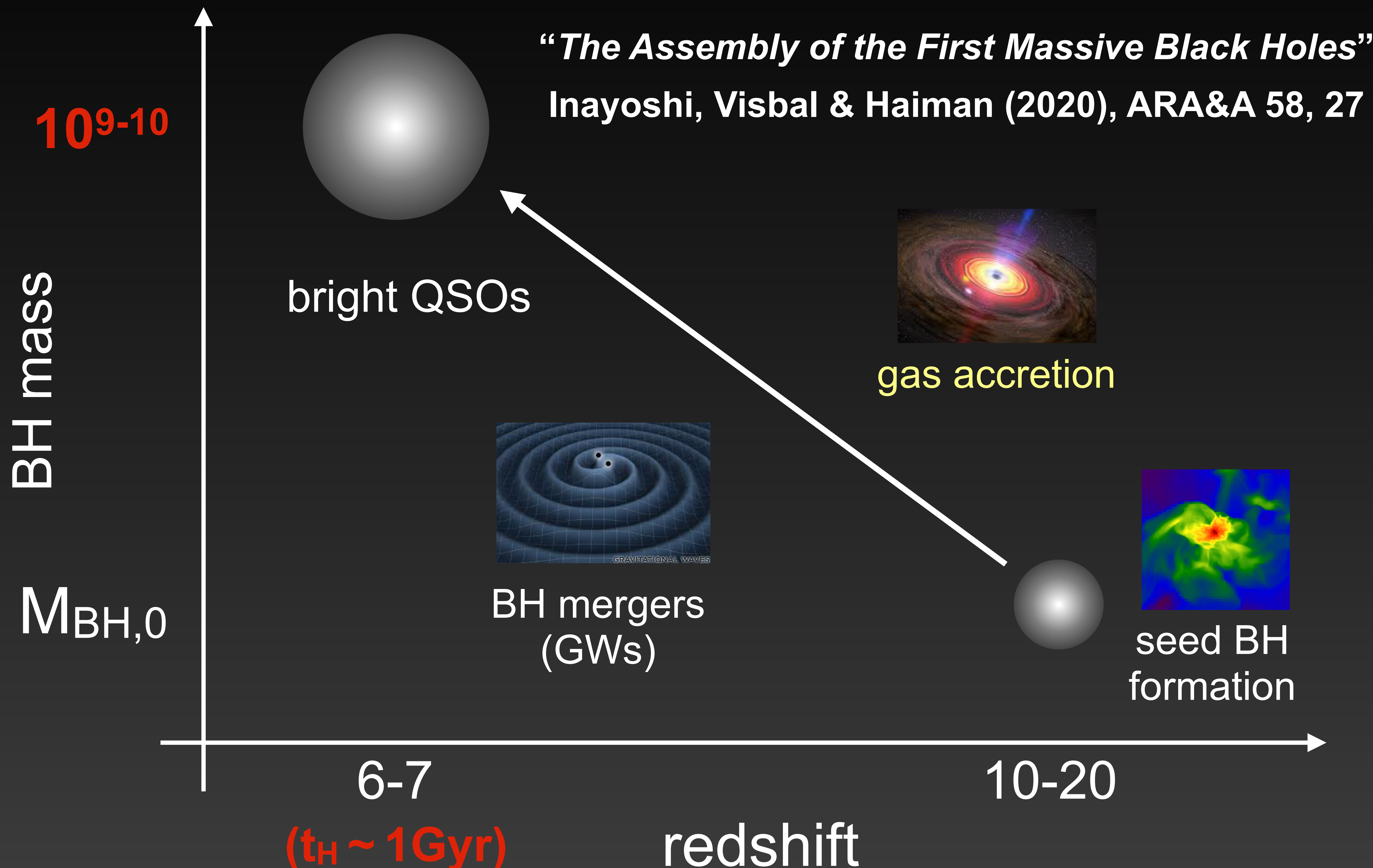
PopIII BHs:
most abundant, normal environments

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



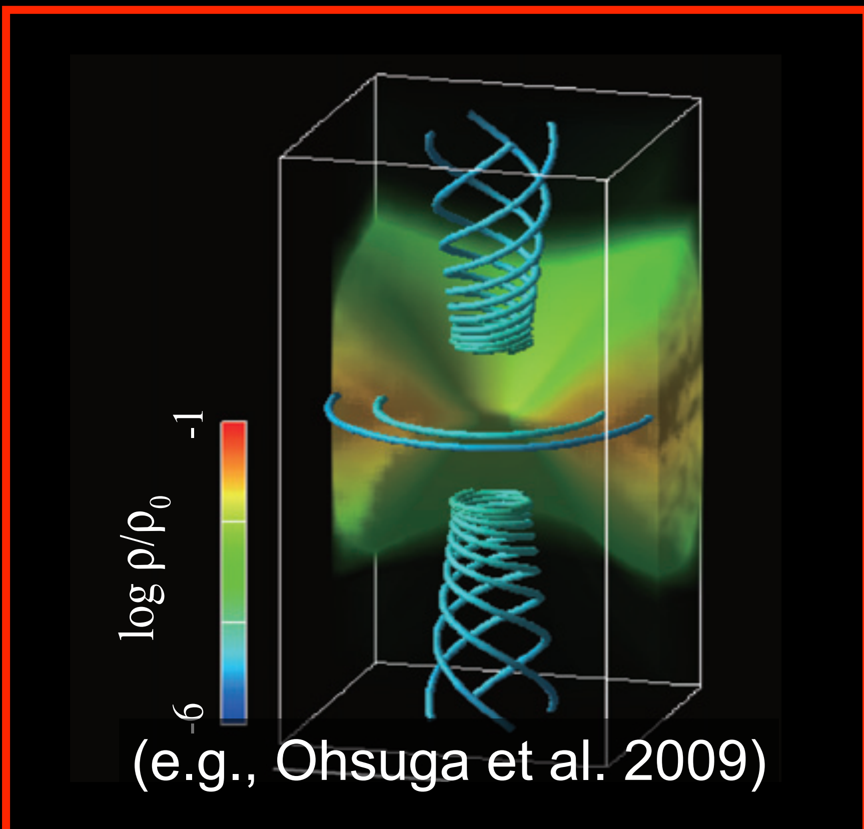
Rapid growth of BHs via accretion

Rapid SMBH assembly



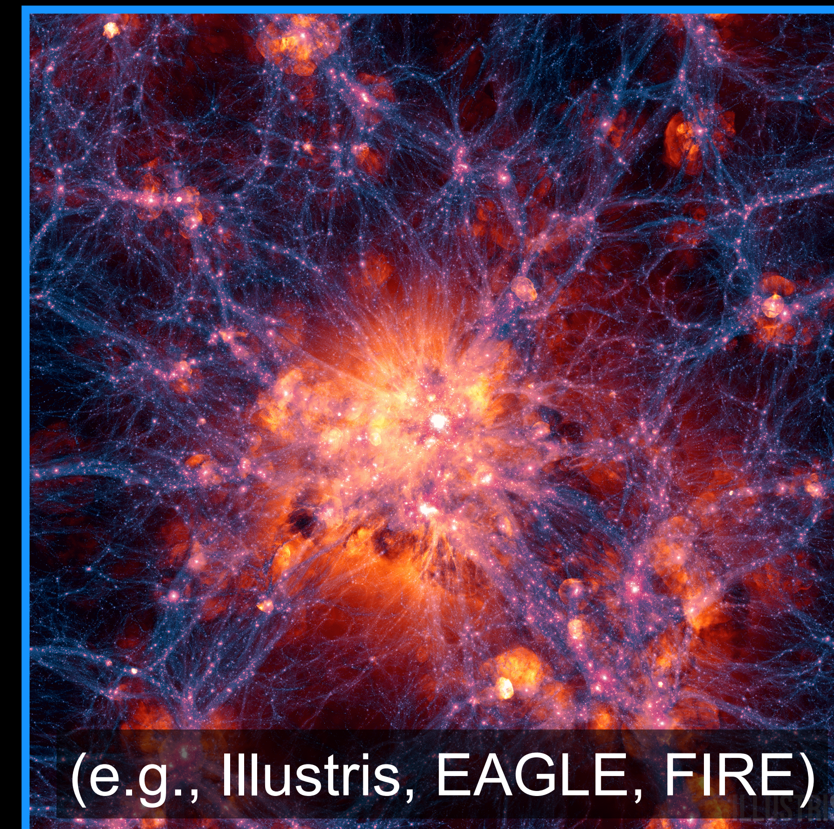
BH accretion in multi-scales

Nuclear disk: ~ 1 mpc



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

Galaxy scale: ~kpc



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

?

$$\dot{M} > \dot{M}_{\mathrm{Edd}}$$

$$\dot{M} < \dot{M}_{\mathrm{Edd}}$$

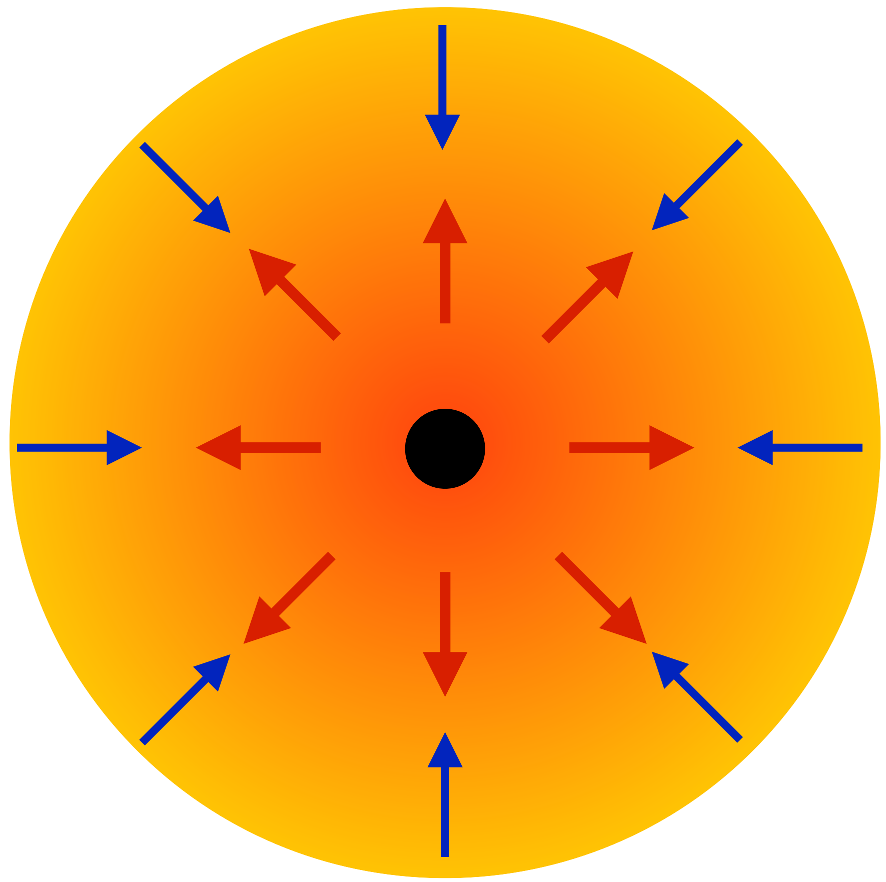
Construction of the global structure of the accretion flow including the BH influence radii (1-100pc) is essential !

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

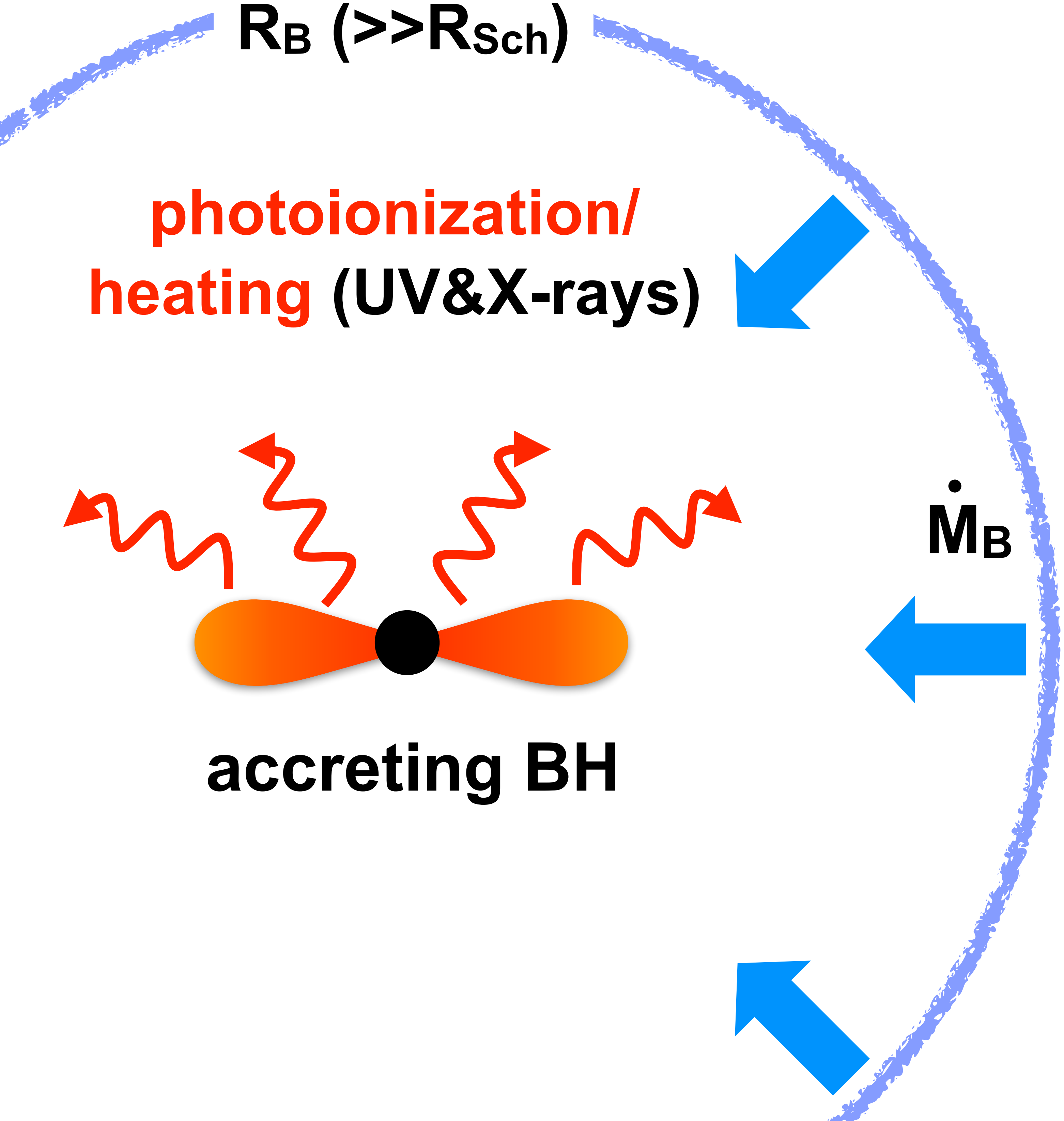
$$g_{\rm gas} = \frac{1}{\rho}\frac{dp}{dr} \sim \frac{c_{\rm s}^2}{r}$$

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

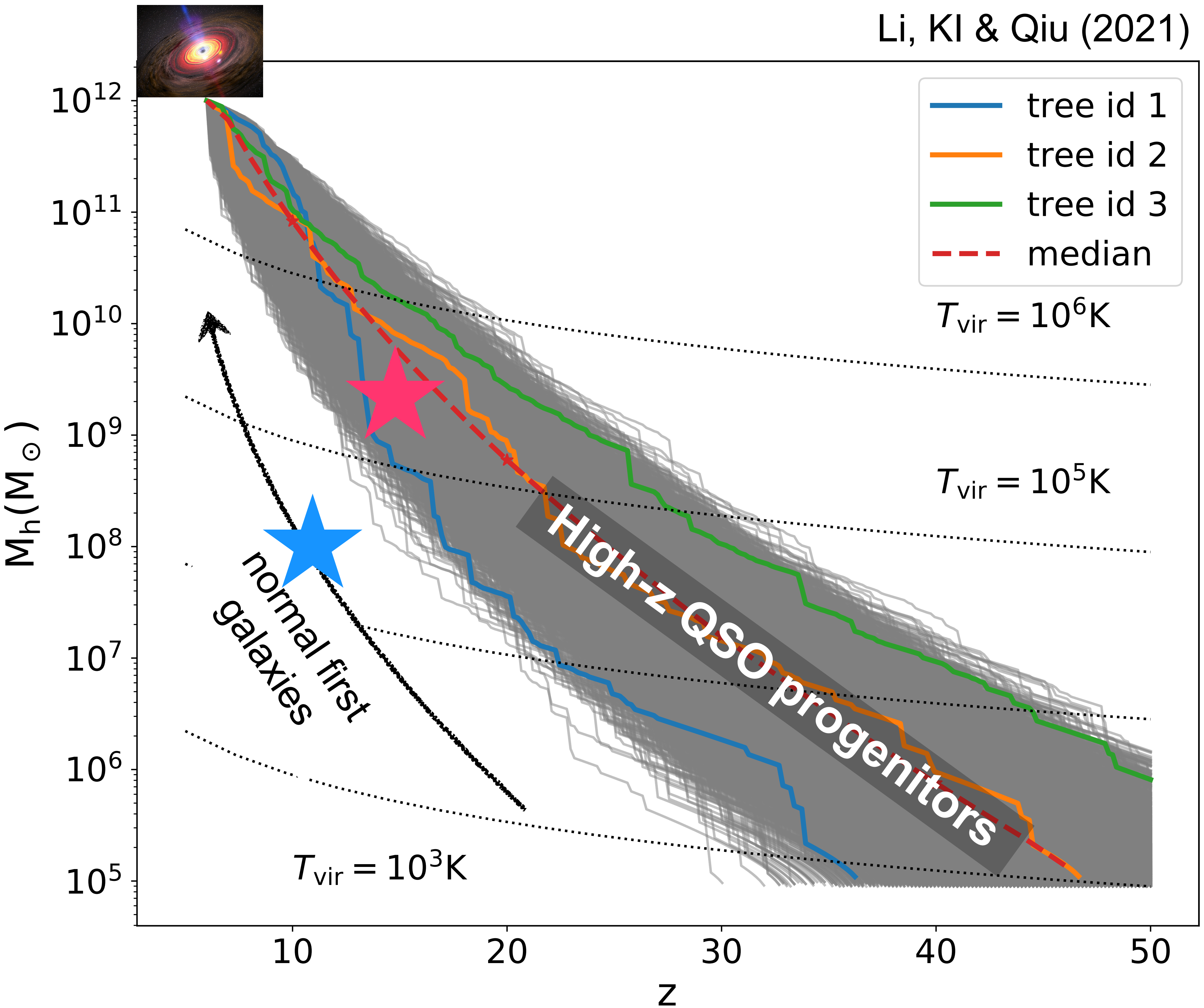
(gravity > thermal / kinetic)

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

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

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

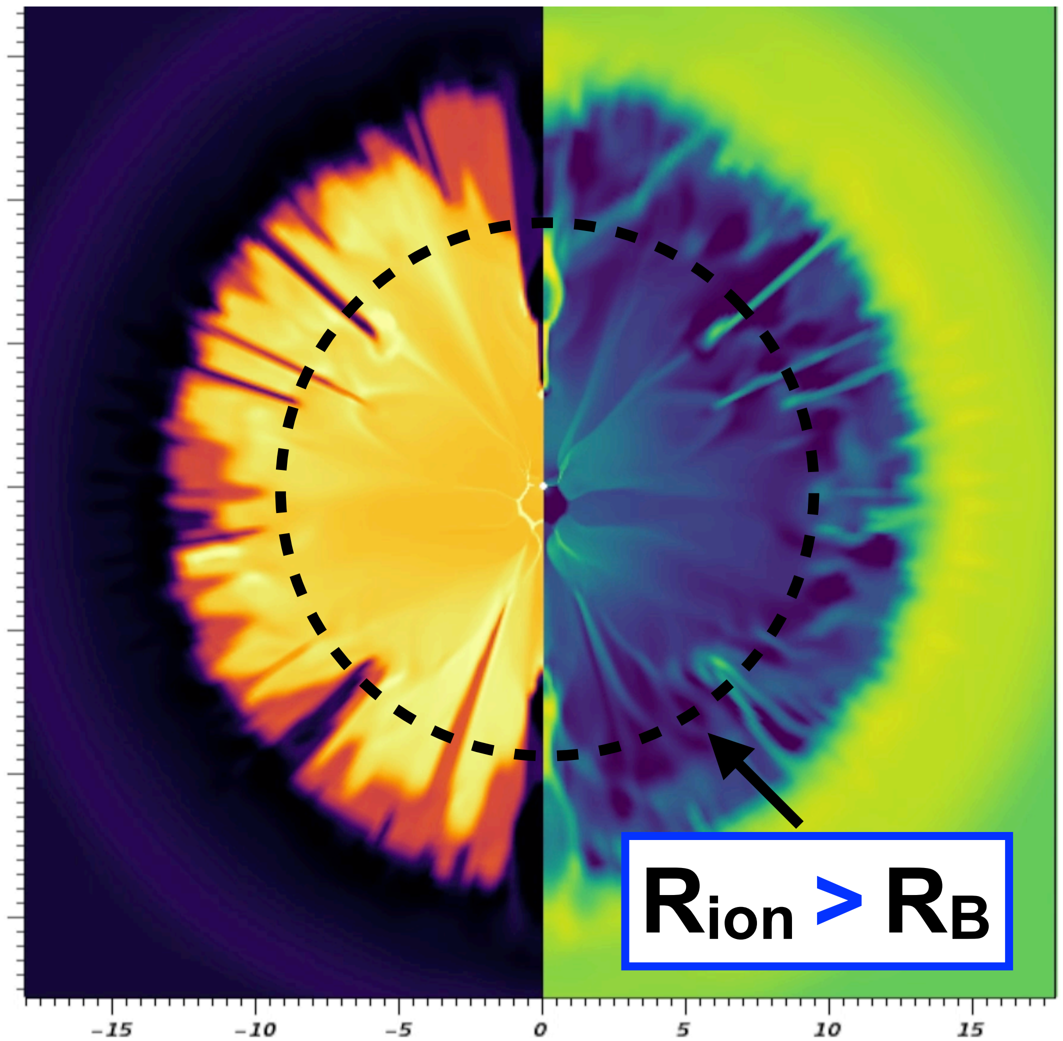
Seed formation in QSO hosts

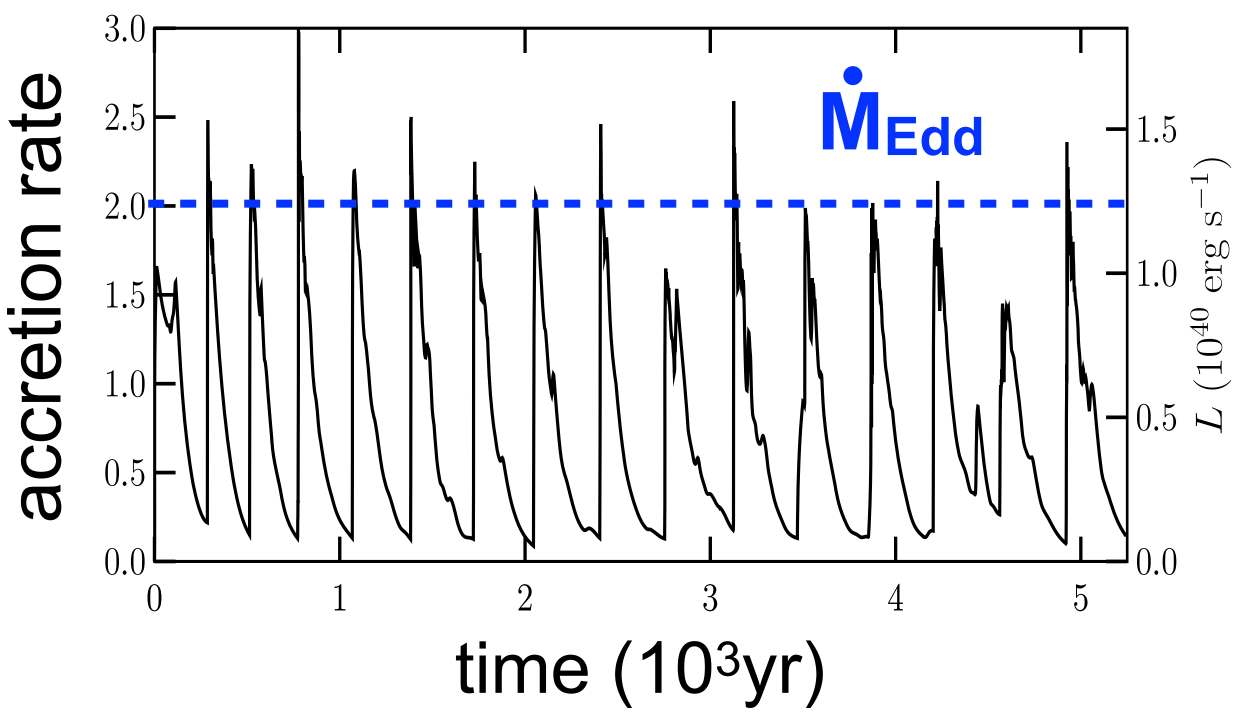


BH accretion in typical first galaxies

- Feedback regulated case

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





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

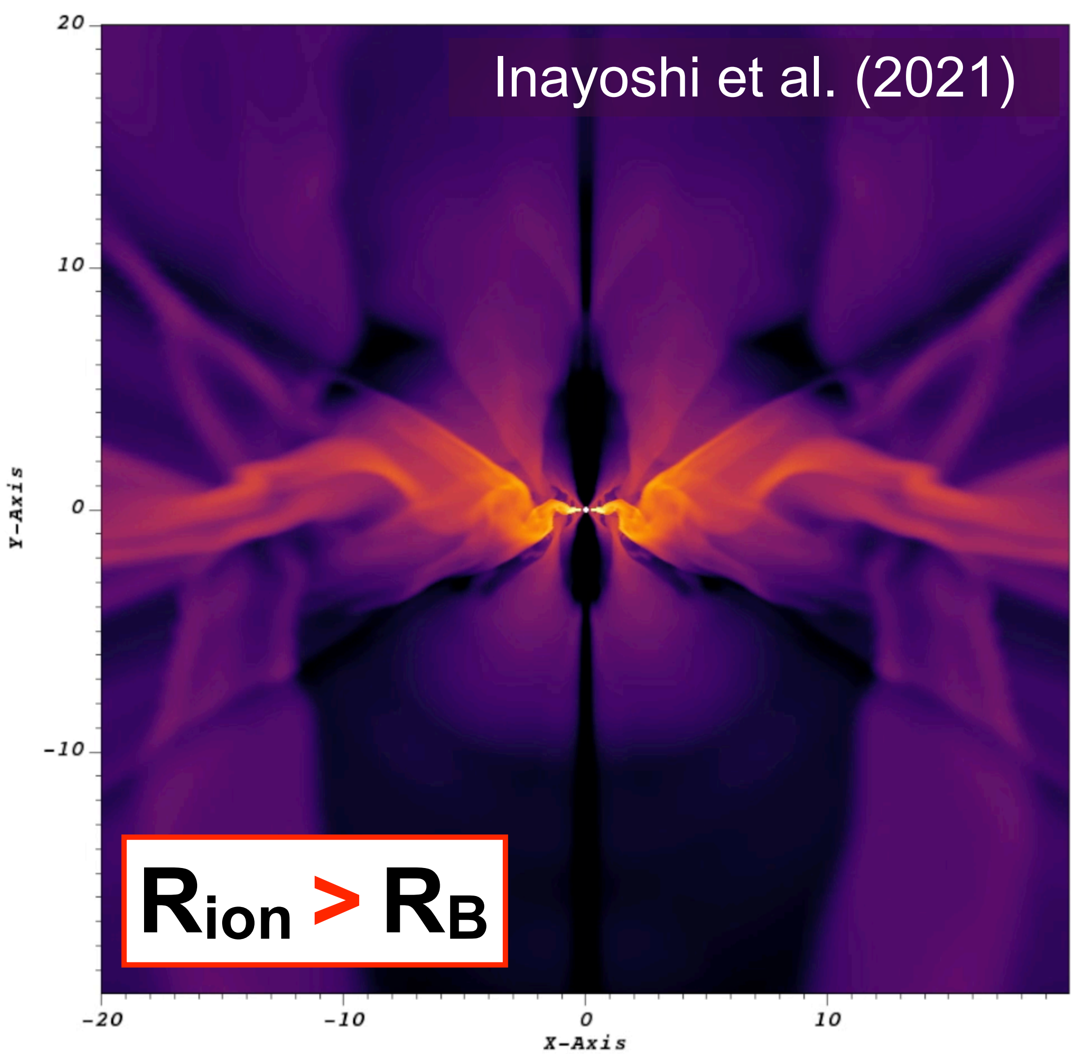
episodic accretion
(radiation heating)

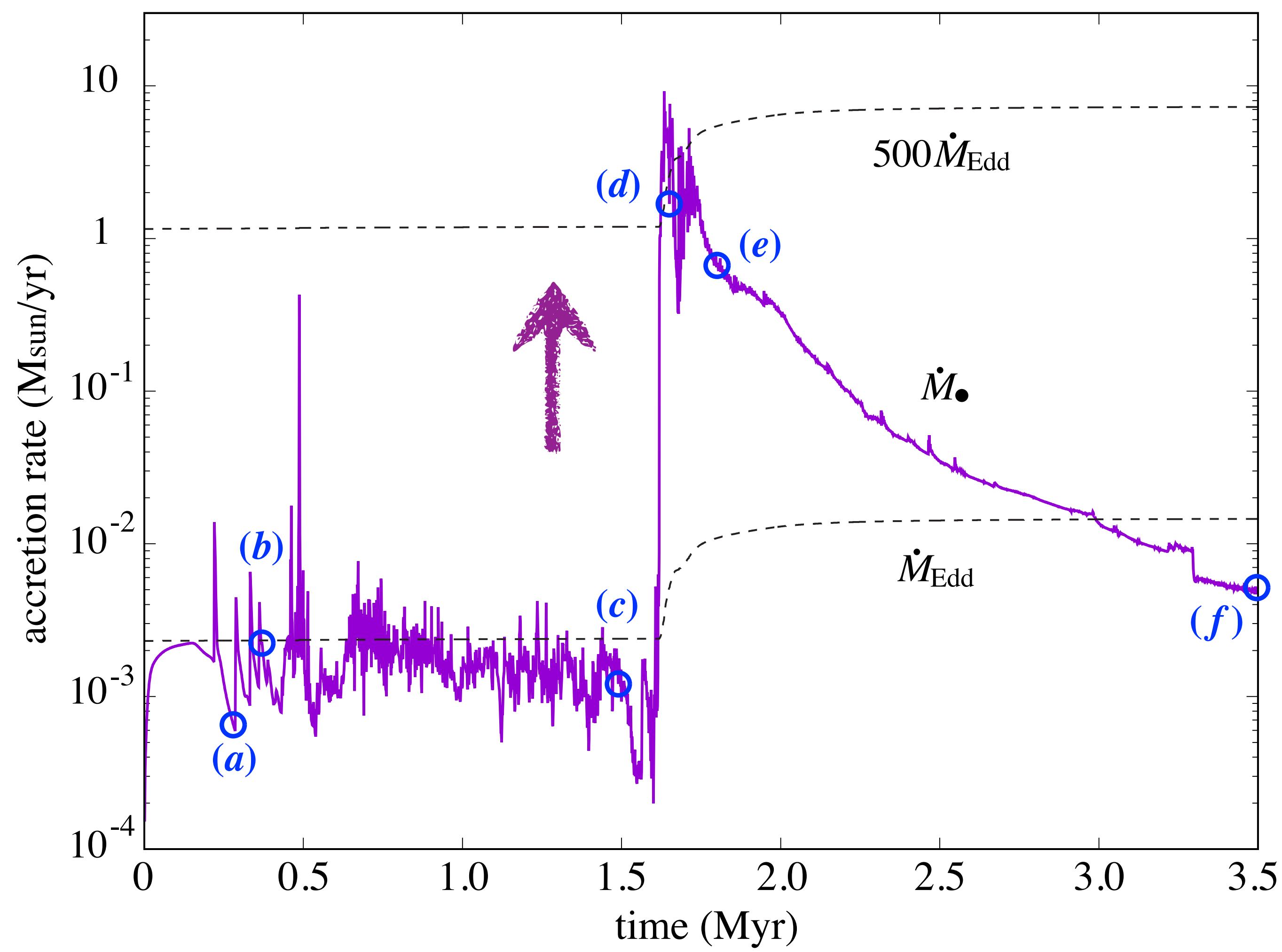
$$\langle \dot{M} \rangle << \dot{M}_{\rm Edd}$$

BH accretion in **massive** first galaxies

- Rapidly growing case

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



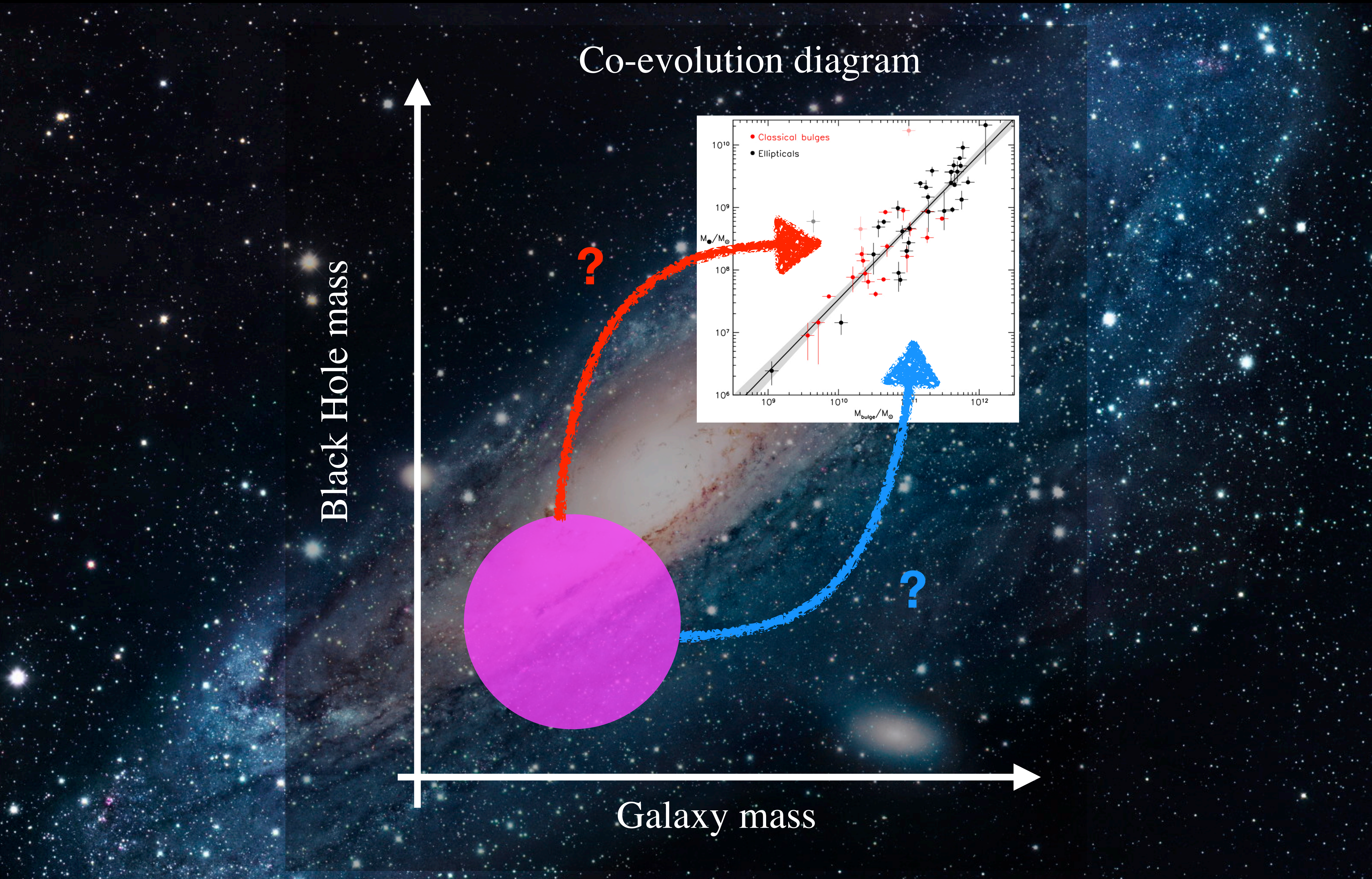


ionized bubble
collapses (**R_{ion} < R_B**)

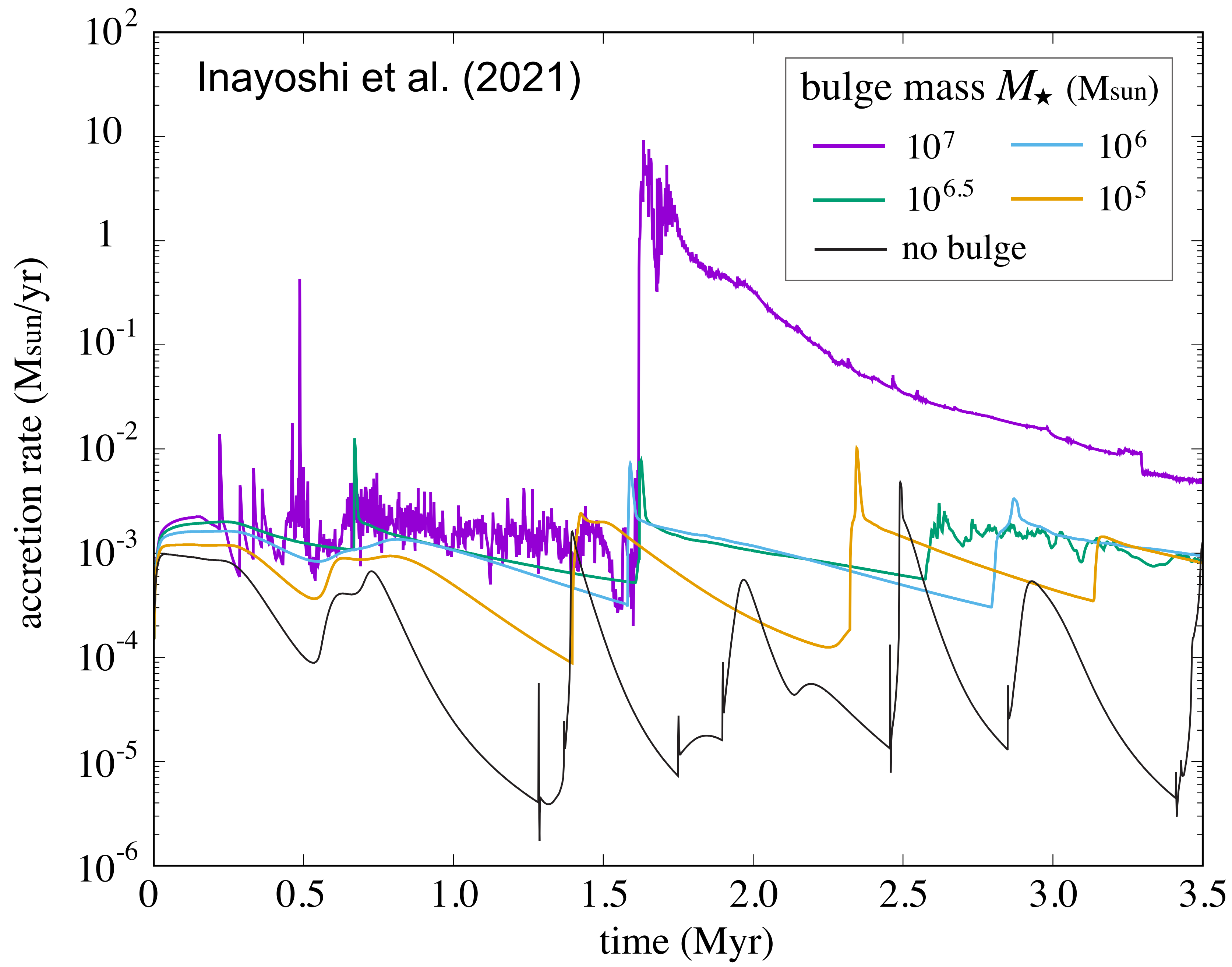
→

hyper-Eddington acc.
$\langle \dot{M} \rangle \gg \dot{M}_{\rm Edd}$

Early BH-galaxy coevolution

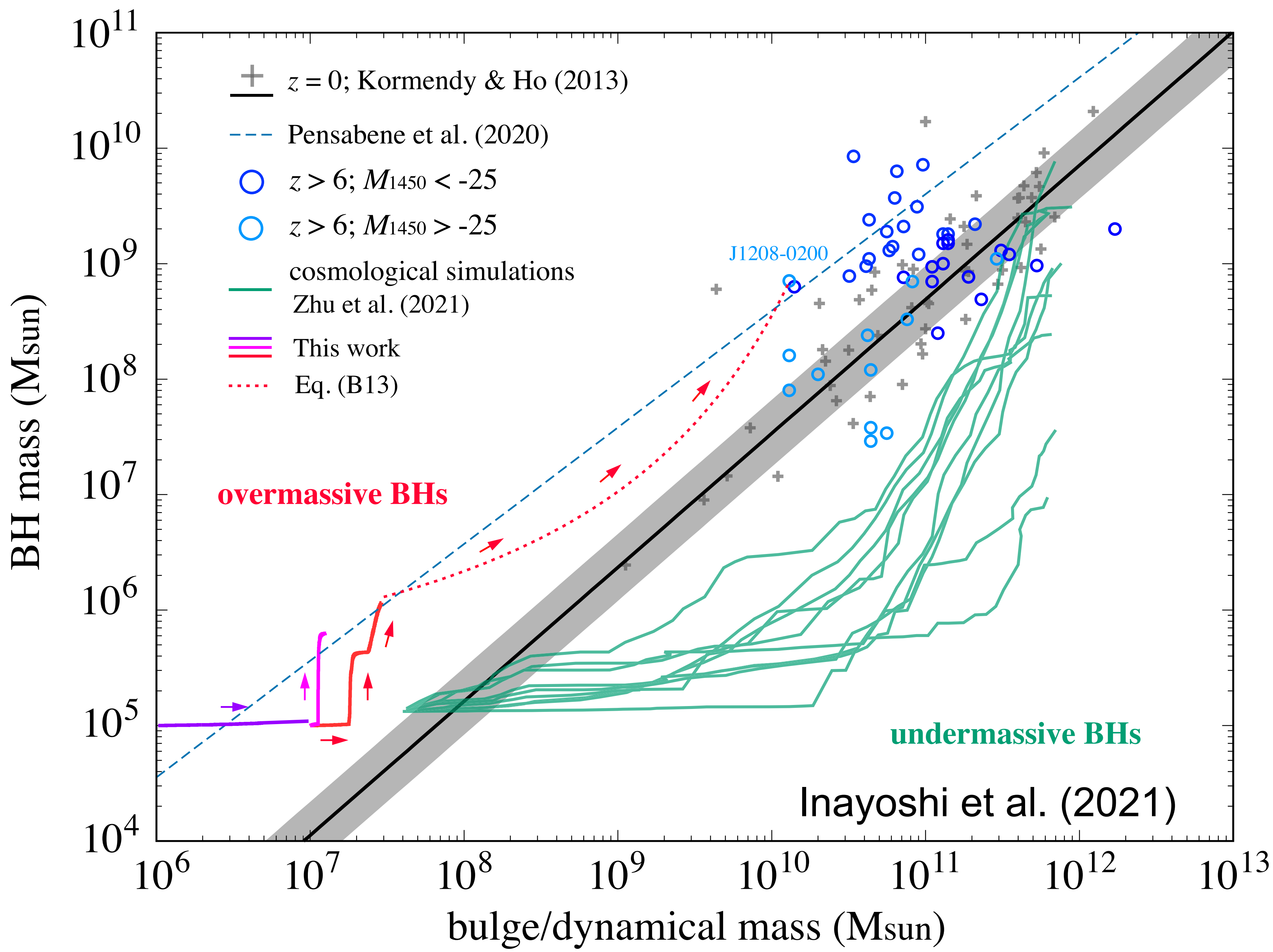


Early BH-galaxy coevolution



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

Early BH-galaxy coevolution

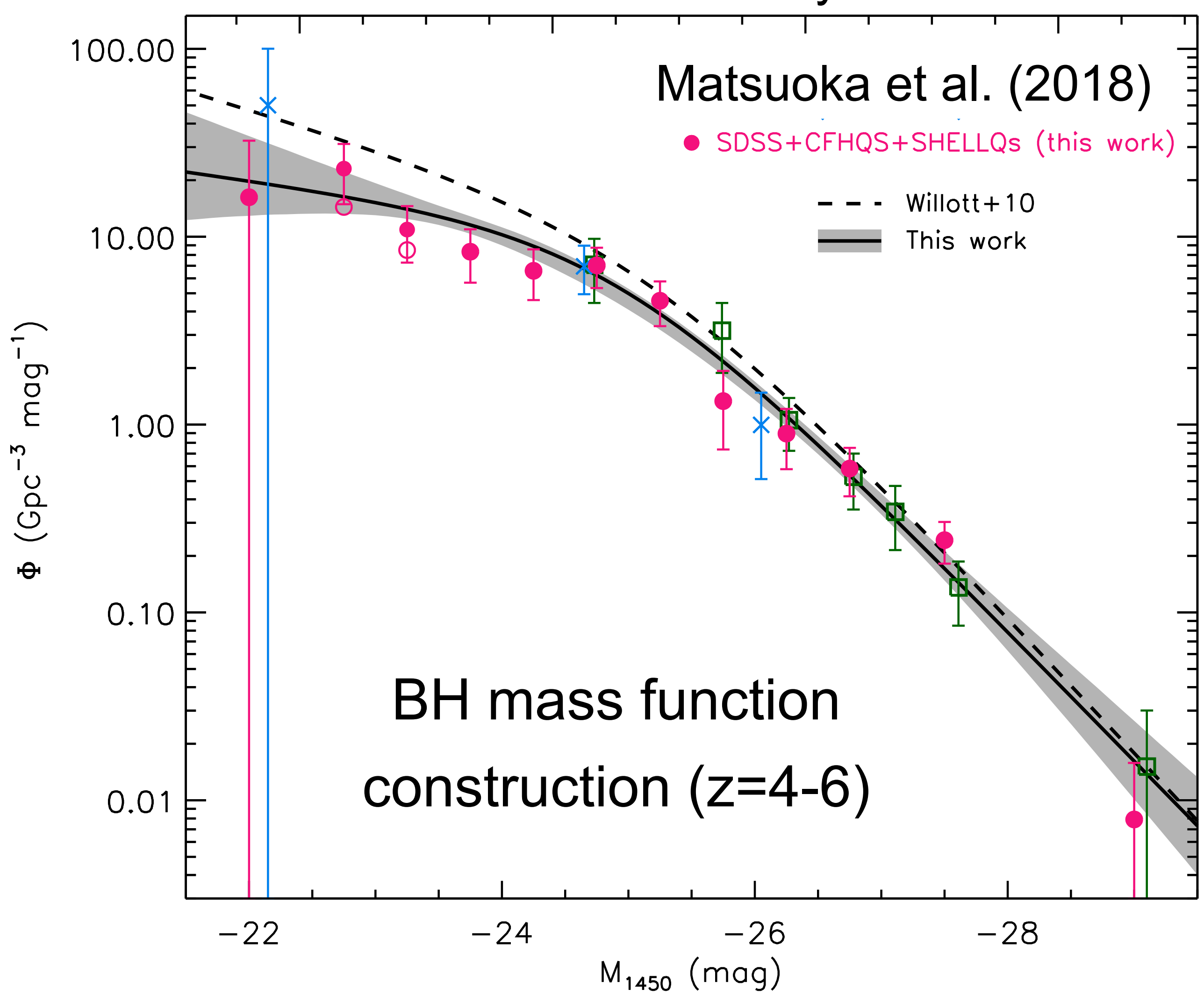


Rapid BH accretion makes them “overmassive”
(very unique locations on the diagram)

Future observations of seed BHs coevolving with galaxies

Ongoing/future high-z observations

z~6 QSO luminosity function



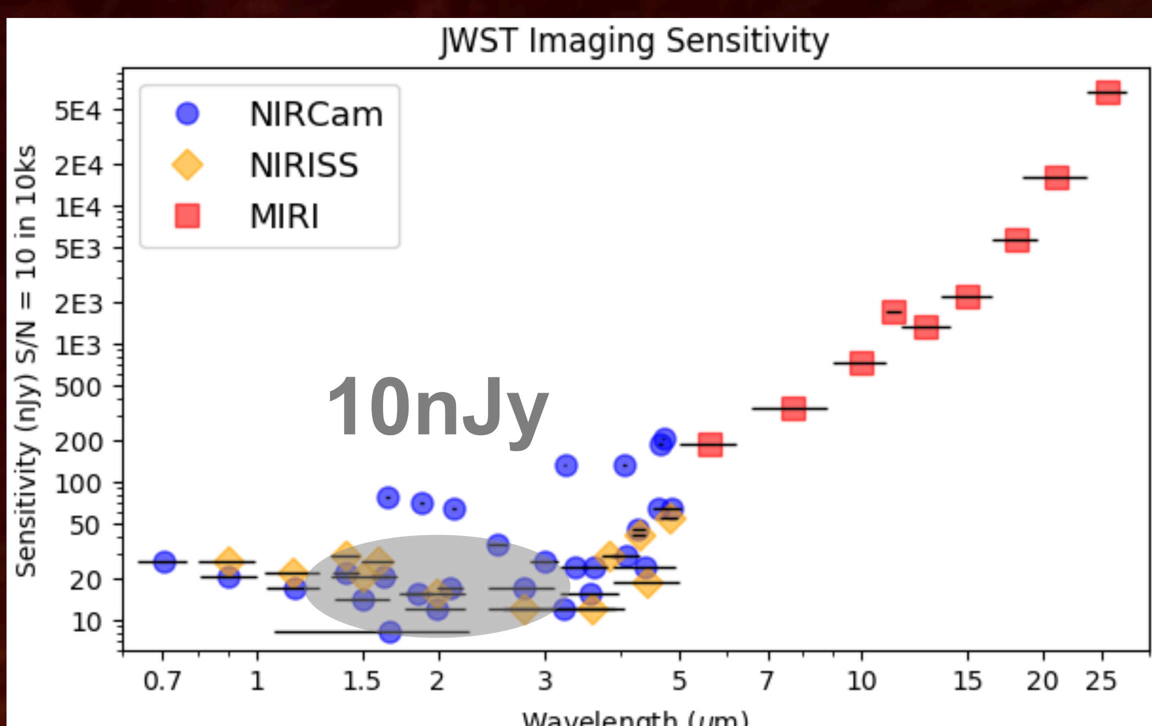
ongoing/future multi-wavelength observations

- 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)

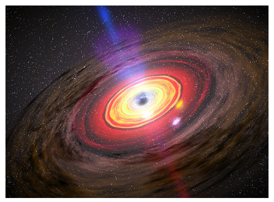
JWST & Roman for hunting seed BHs

Observed wavelength **1.98μm** [(1+z)/16]

Rest-frame ~ 10eV (0.124μm)

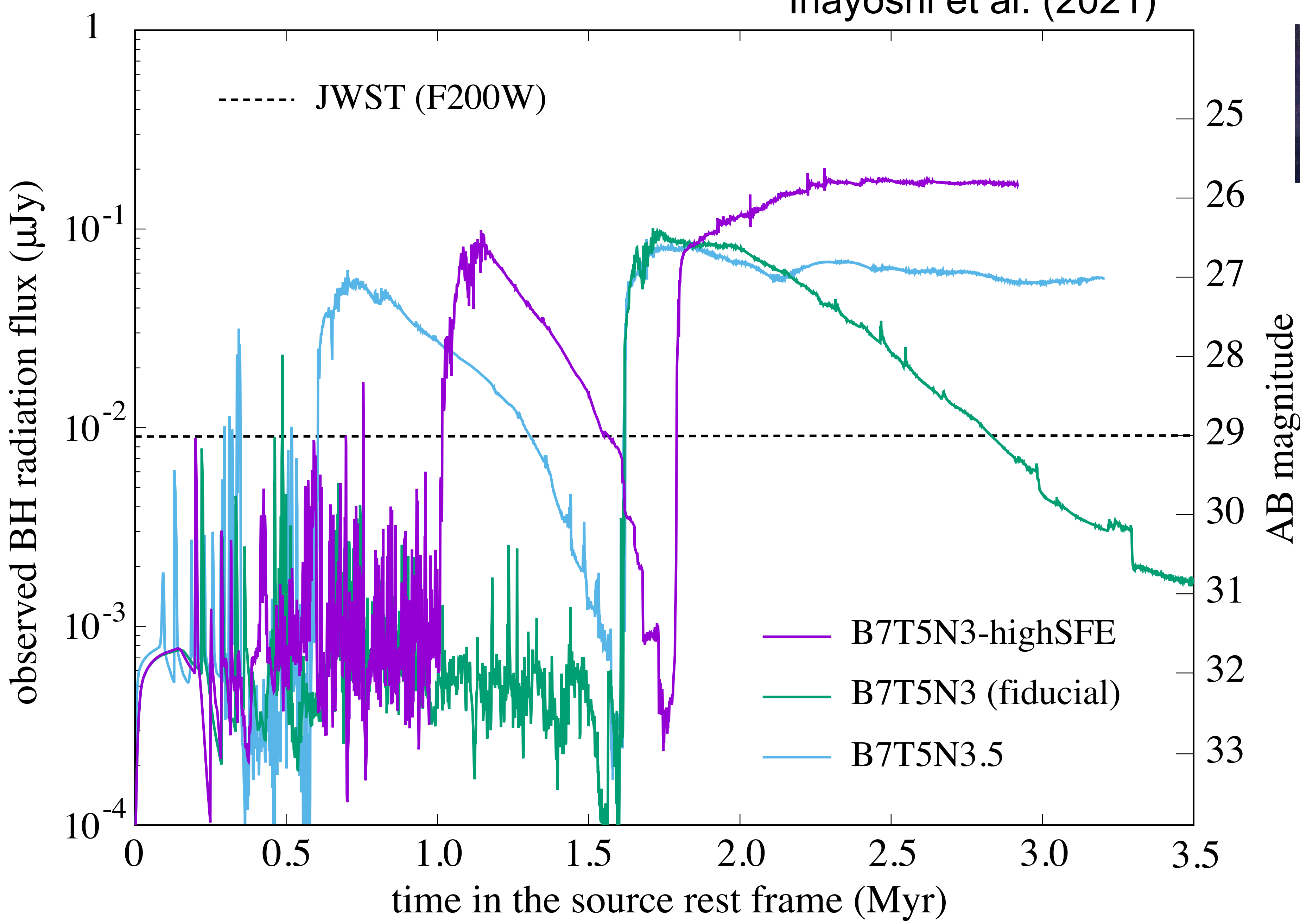


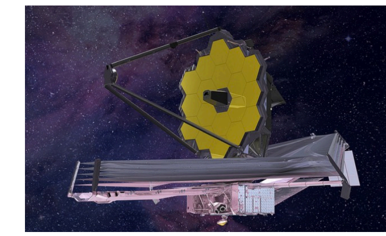
Light curves of growing seed BHs



source
@z~15

Inayoshi et al. (2021)





10ks exposure
time, S/N=10

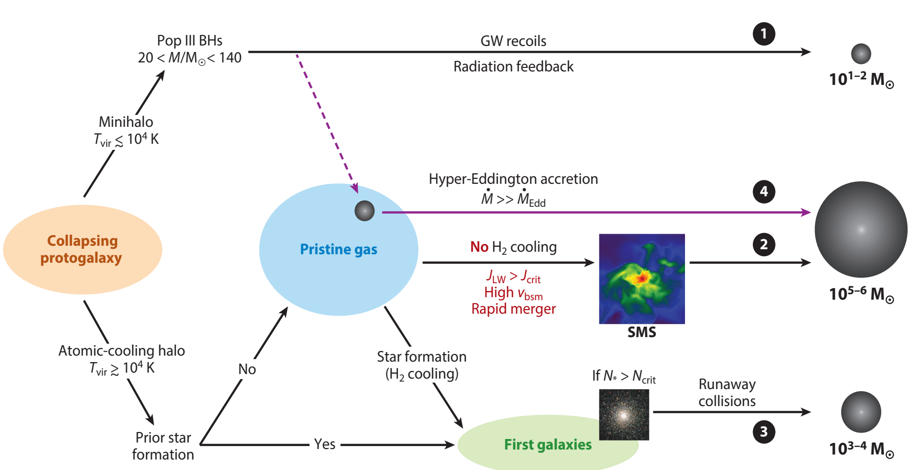
Transient accretion bursts can be detected with JWST even at the source redshift z~15 (m_{AB}~ 26 - 29)

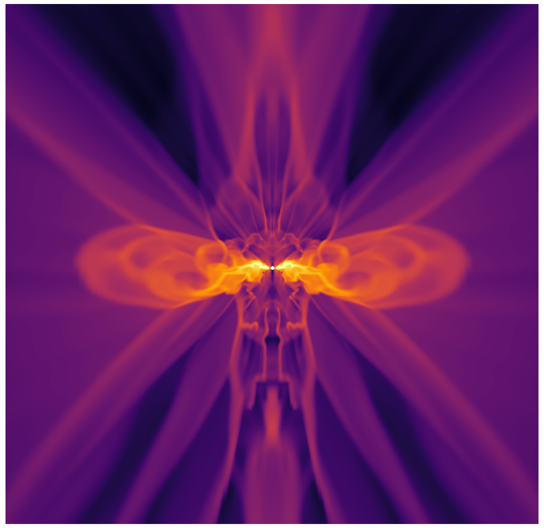
Summary

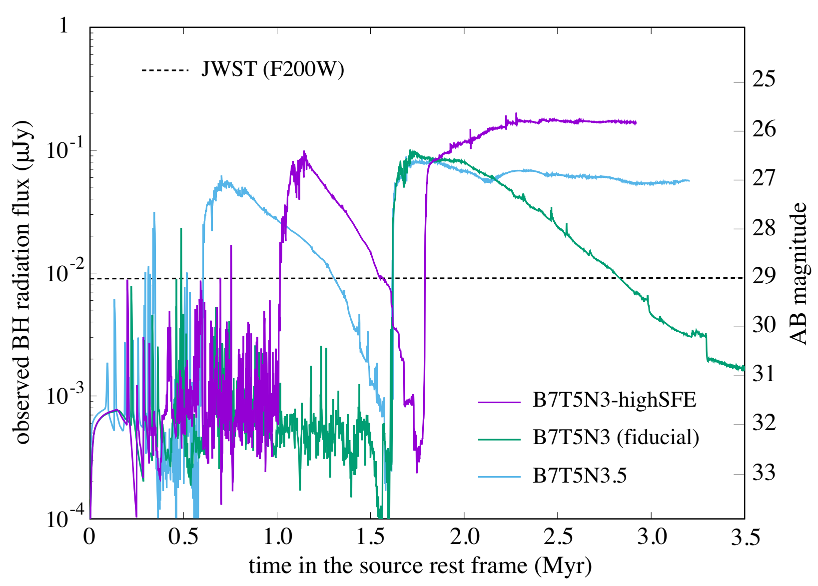
- The existence of high-z SMBHs requires their quick assembly mechanisms (massive seed formation, rapid accretion)

- Rapid accretion onto seed BHs in massive DM halos naturally explains the existence of "overmassive" BHs

- Future observations by JWST and RST will enable us to detect transient bursts (the first cry) of seed BHs







Thank you!