Full Census of Supermassive Black Holes at z>6 Probed by Subaru and JWST

Masafusa Onoue (KIAA / Kavli IPMU joint fellow)

On behalf of the SHELLQs collaboration

High-z quasars - Unique probe of the early Universe

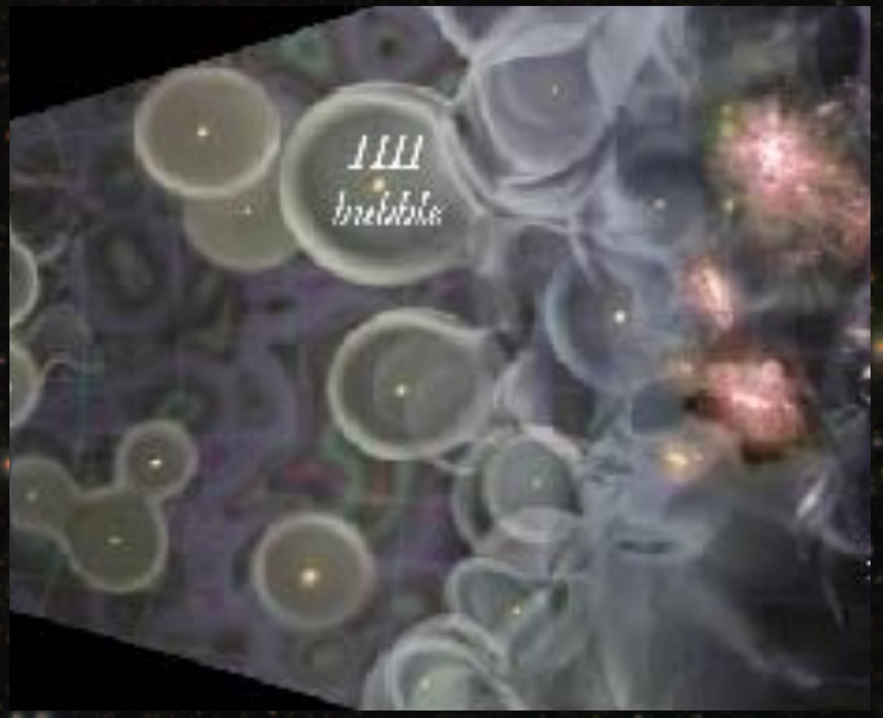
Fundamental questions we aim to answer:

Why do supermassive black holes (SMBHs) exist?

✶ When were they born?
✶ What were their seeds?
✶ How did they grow in the early and late epochs of the cosmic history?

How did the host galaxies form and (co-)evolve?

✶ When and how did the first stellar-mass assembly happen?
✶ Did SMBHs impact the host galaxy evolution? If so, how?
✶ Do they mark the highest density peaks of the DM distribution?



When and how was the Universe re-ionized?

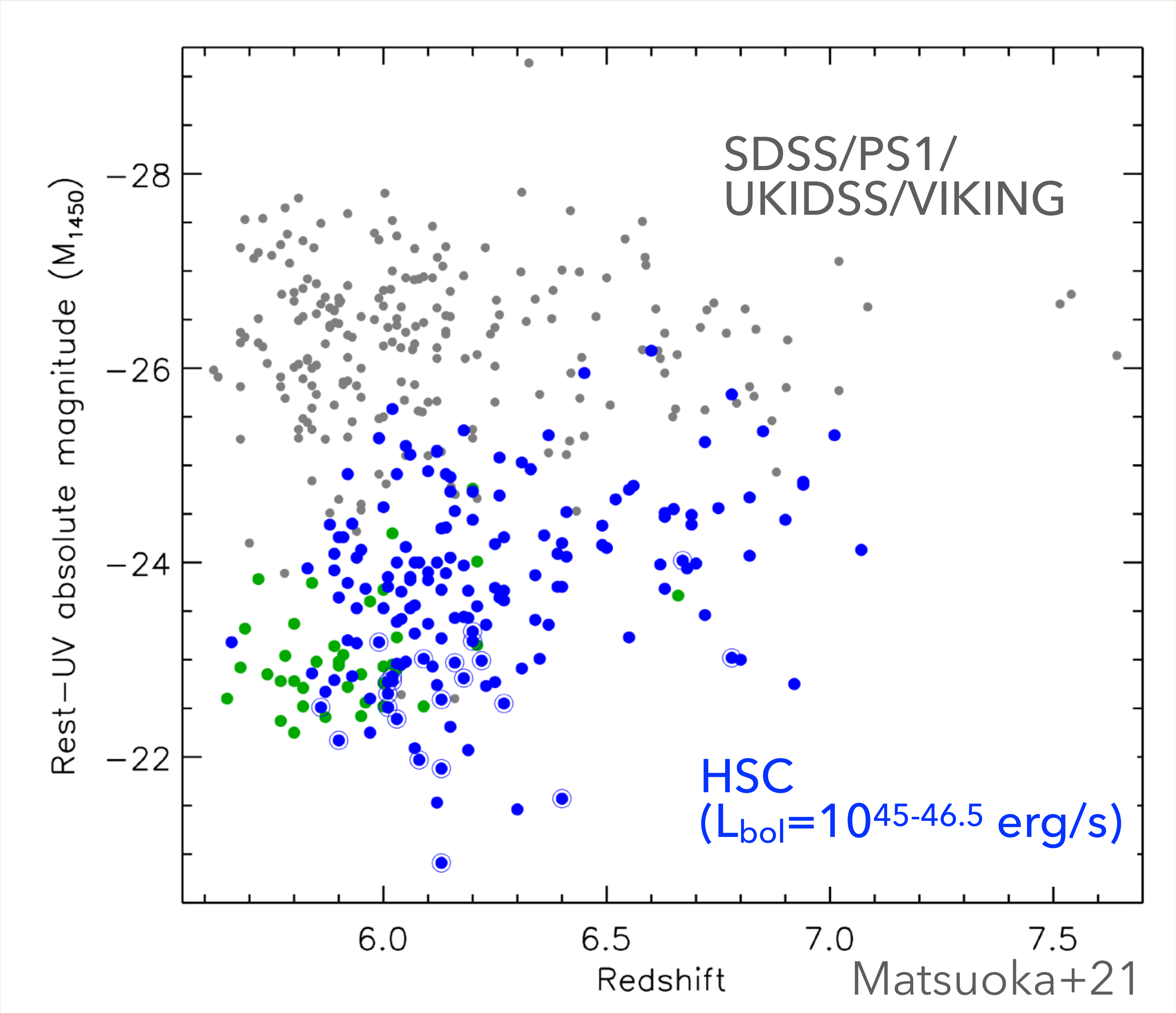
✶ When did re-ionization start and complete?
✶ How did it proceed, as a function of space and time?
✶ What provided the ionizing photons?

and many more!

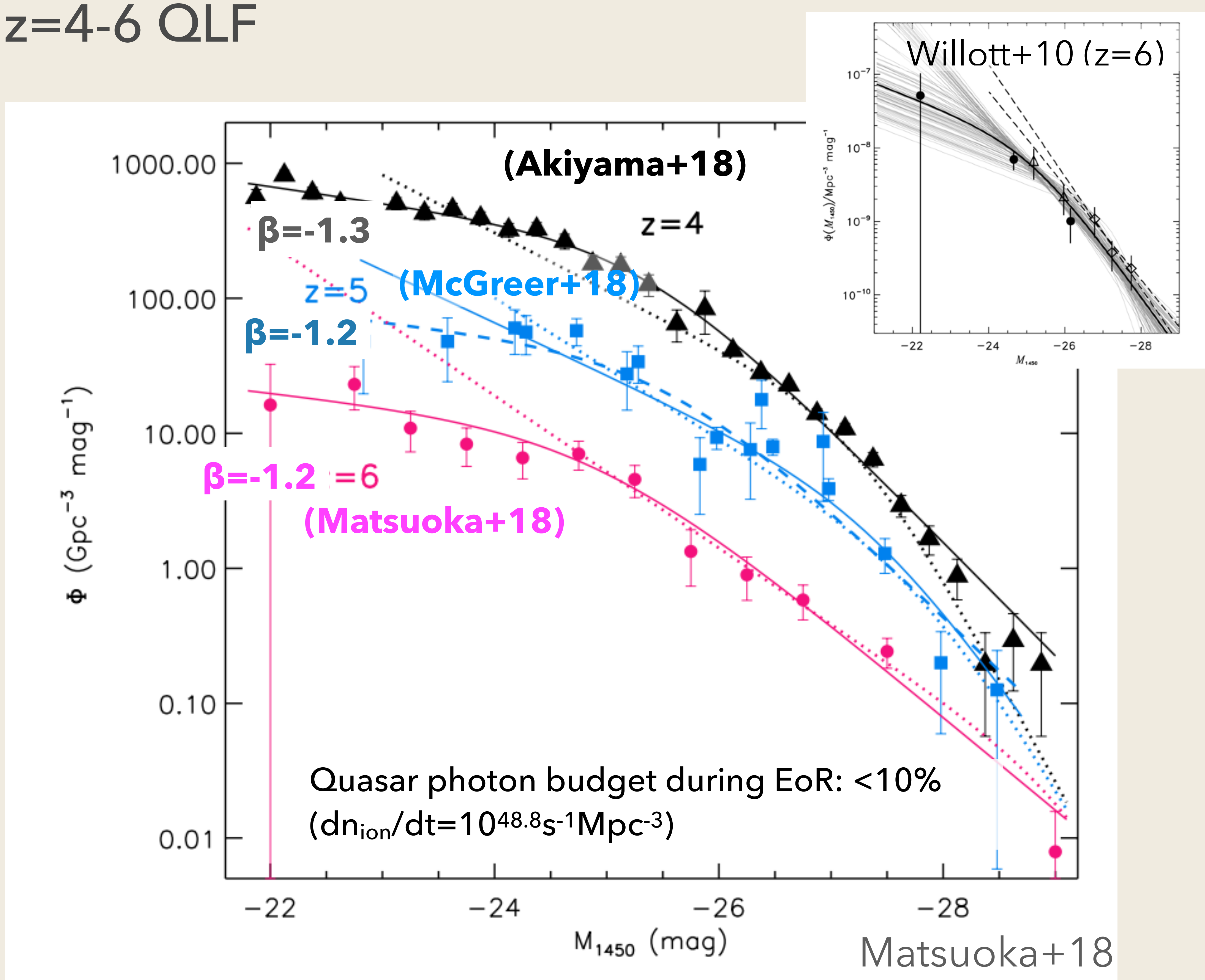
From Matsuoka-san's slide on Tuesday

z>6 Low-luminosity Quasars

- Known z>6 quasars



- z=4-6 QLF

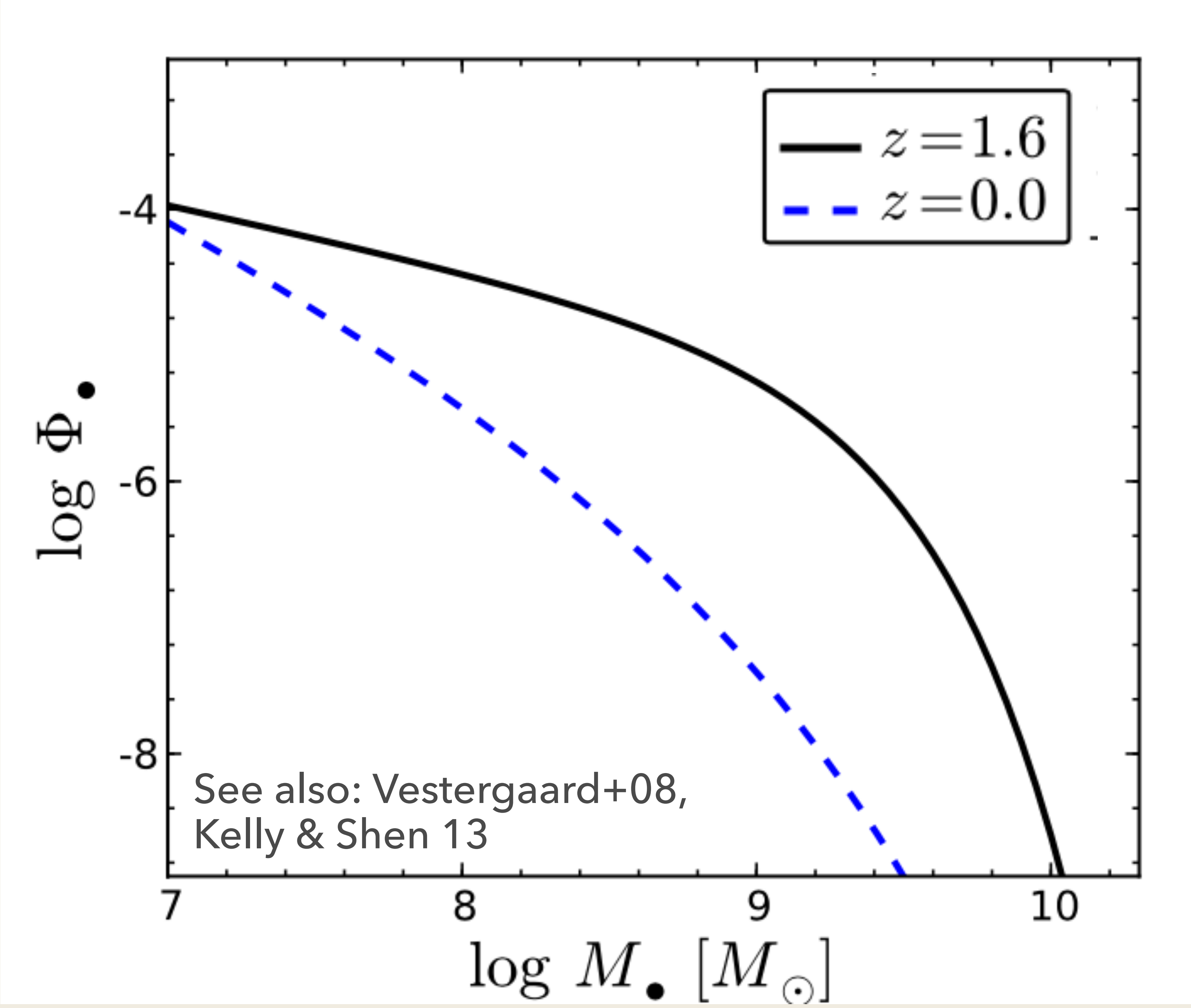


HSC probes the faint-end of quasar population
–> sensitive to general SMBH population at z=4-7

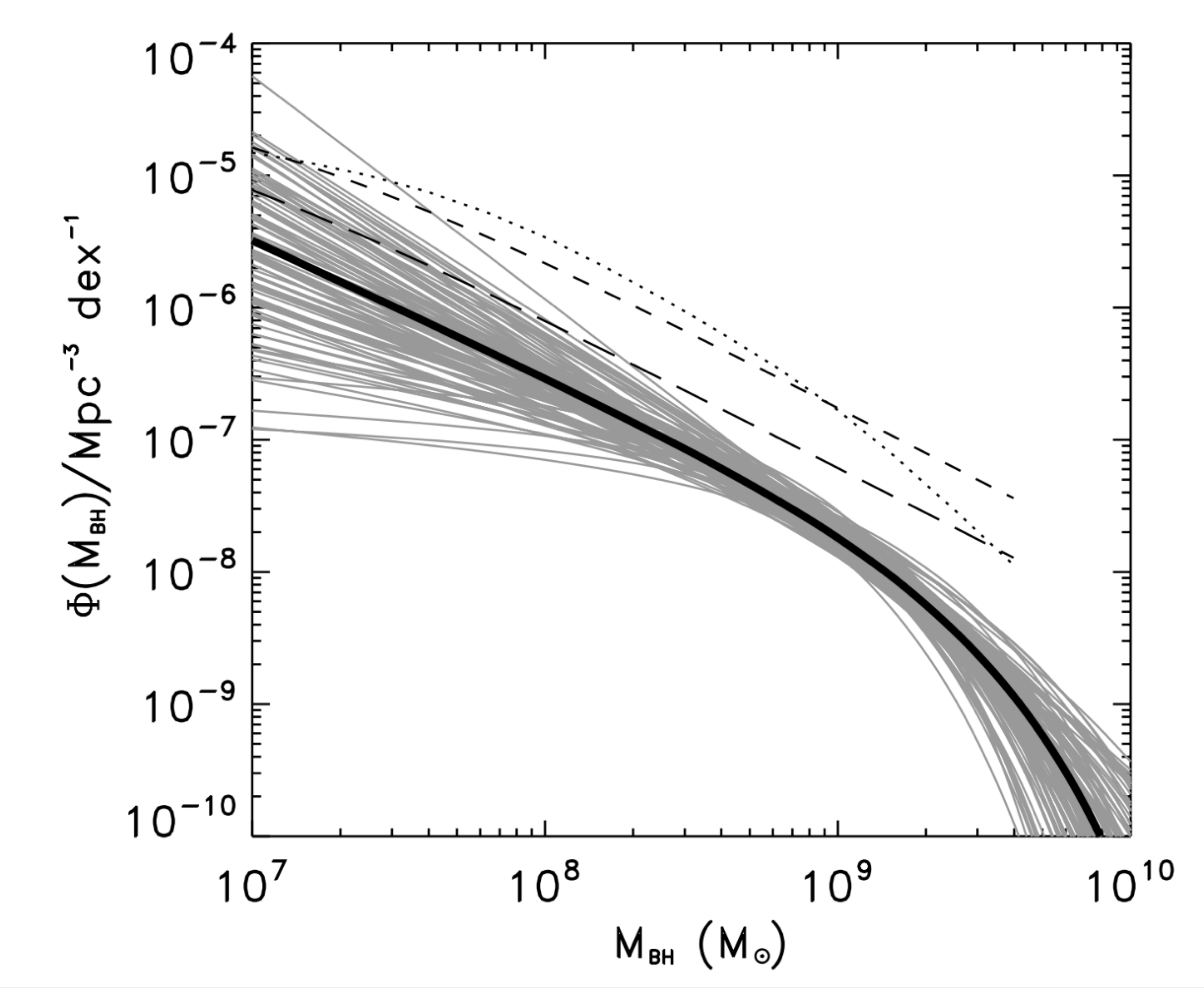
How about Mass Function?

quasar UV luminosity = BH mass x acc. rate

- Schulze et al. (2015; z=1-2)



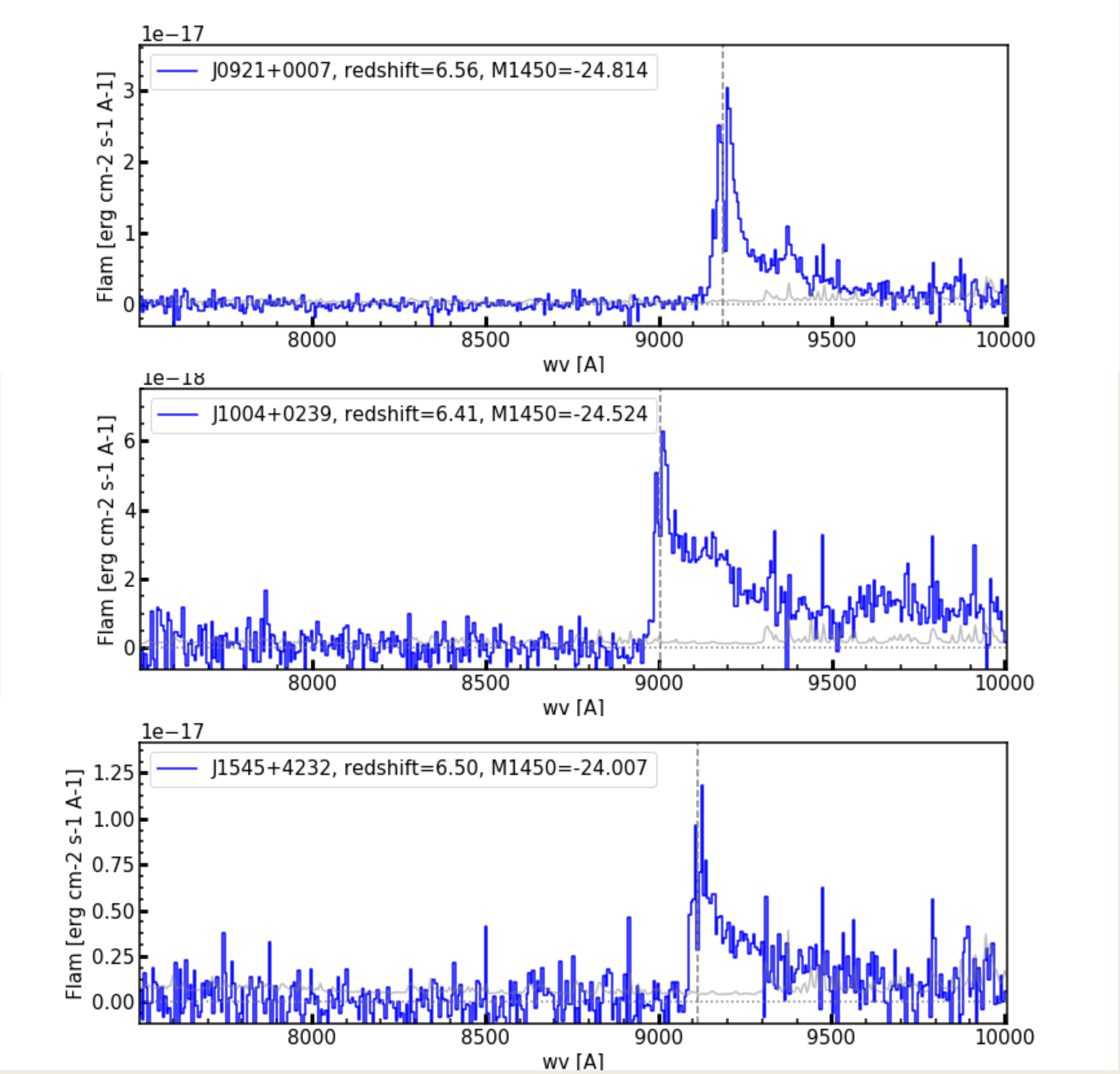
- Willott et al. (2010; z=6)



BH mass / Edd ratio distribution is poorly constrained at z>2
(observationally expensive & affected by luminosity bias)

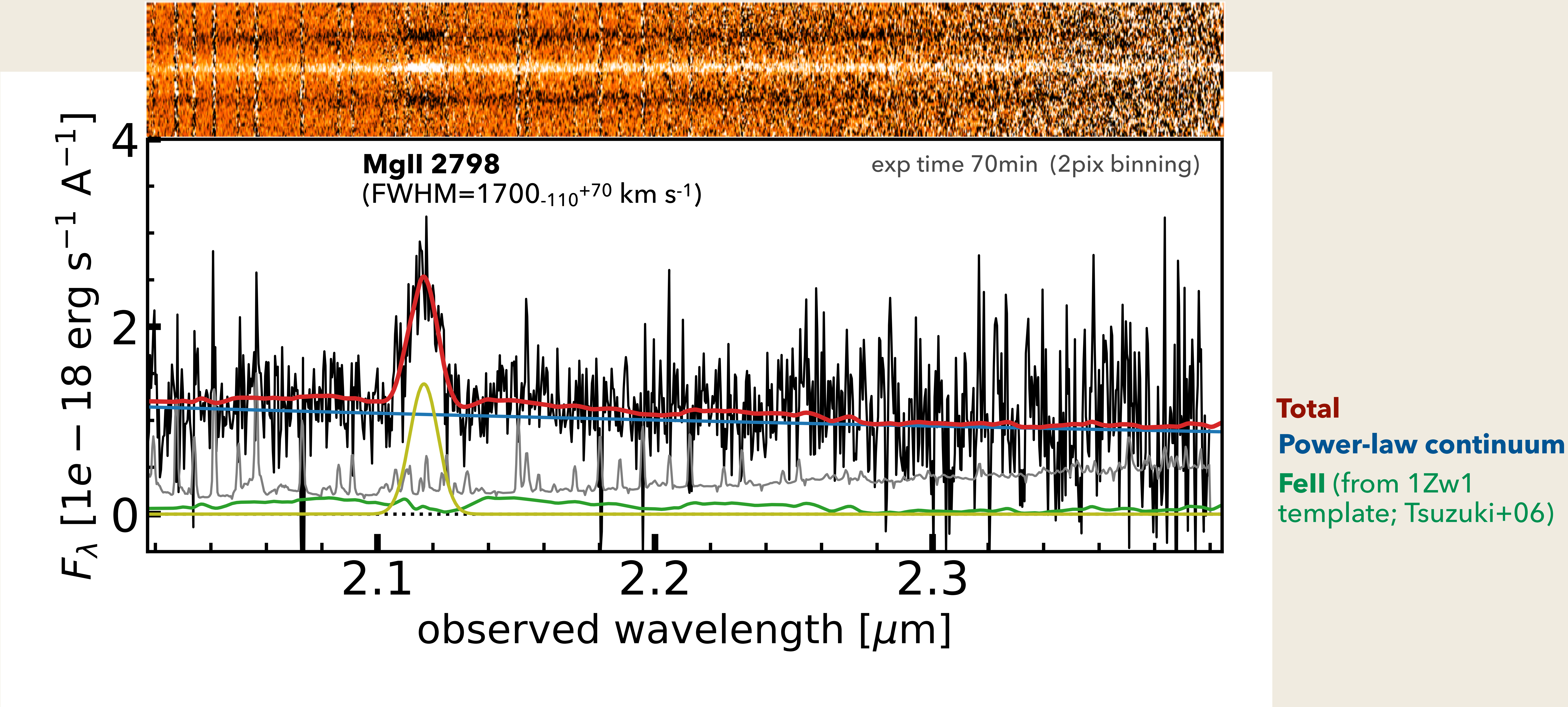
Subaru/MOIRCS follow-up

- S18A-061, S19A-015, S20B-114 (PI: M.Onoue)
  - Continued work from Onoue+19 (N=6)
  - MOIRCS VPH-K spectroscopy (0``.8 slit, R=1680)
  - Target: 9 HSC quasars at 6.2<z<6.9
    - 1450A absolute mag: $-26 < M_{1450} < -24$ (a few mag fainter than other z>6 studies, e.g., Shen+19; Schindler+20; Yang+21)
    - Most z~6 targets from the z=6 HSC QLF sample (complete at $6.18<z<6.4$ & $M_{1450}<-24$; N=21 incl. literature)
  - Exp. time: 1-4 hours on source
  - Ks-band imaging for flux calib. (20.7<Ks<22.6 AB mag)



MOIRCS K-band Spectra of z>6 QSOs

- J0921+0007 (z_{MgII}=6.56, M_{1450}=-26.2, Ks=20.7)



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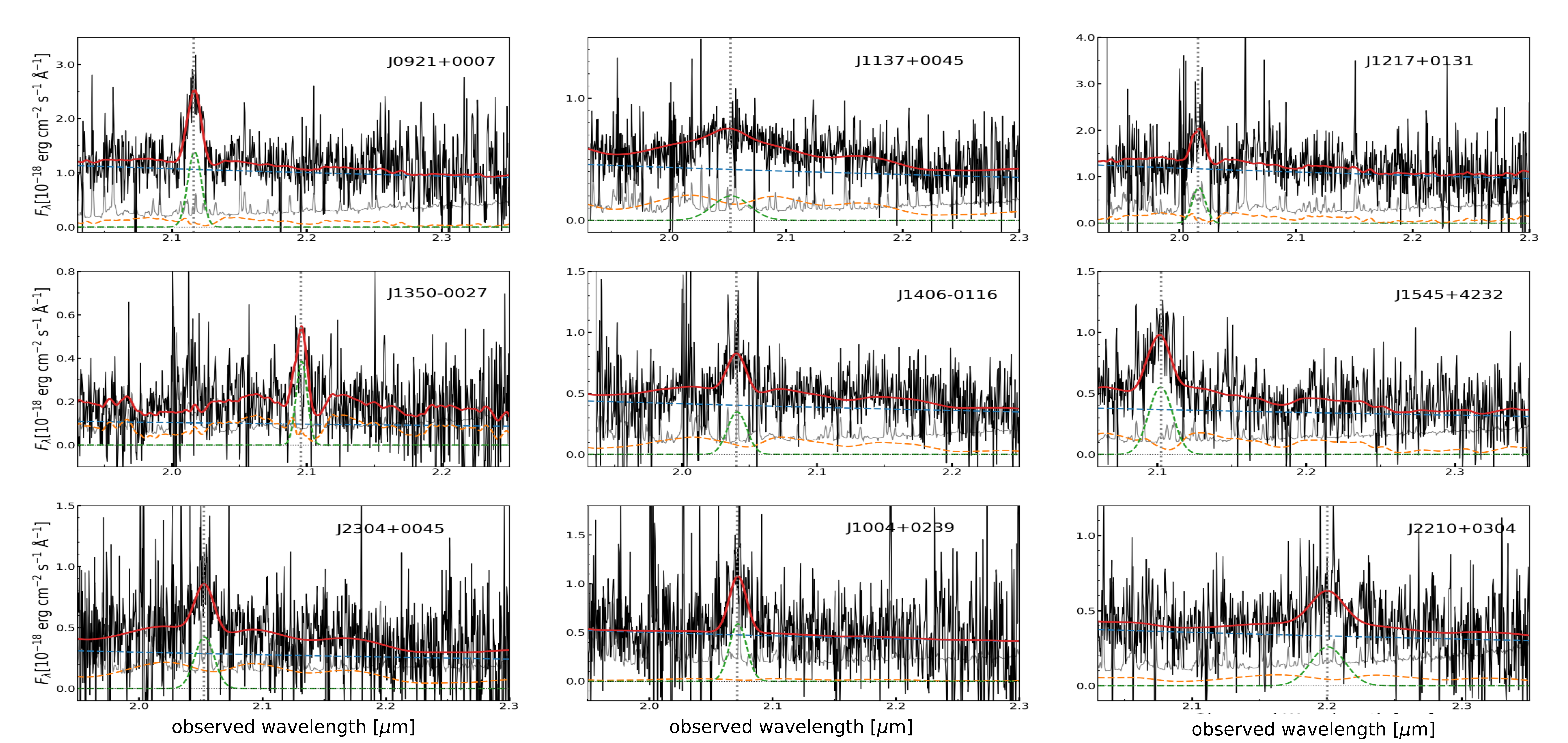
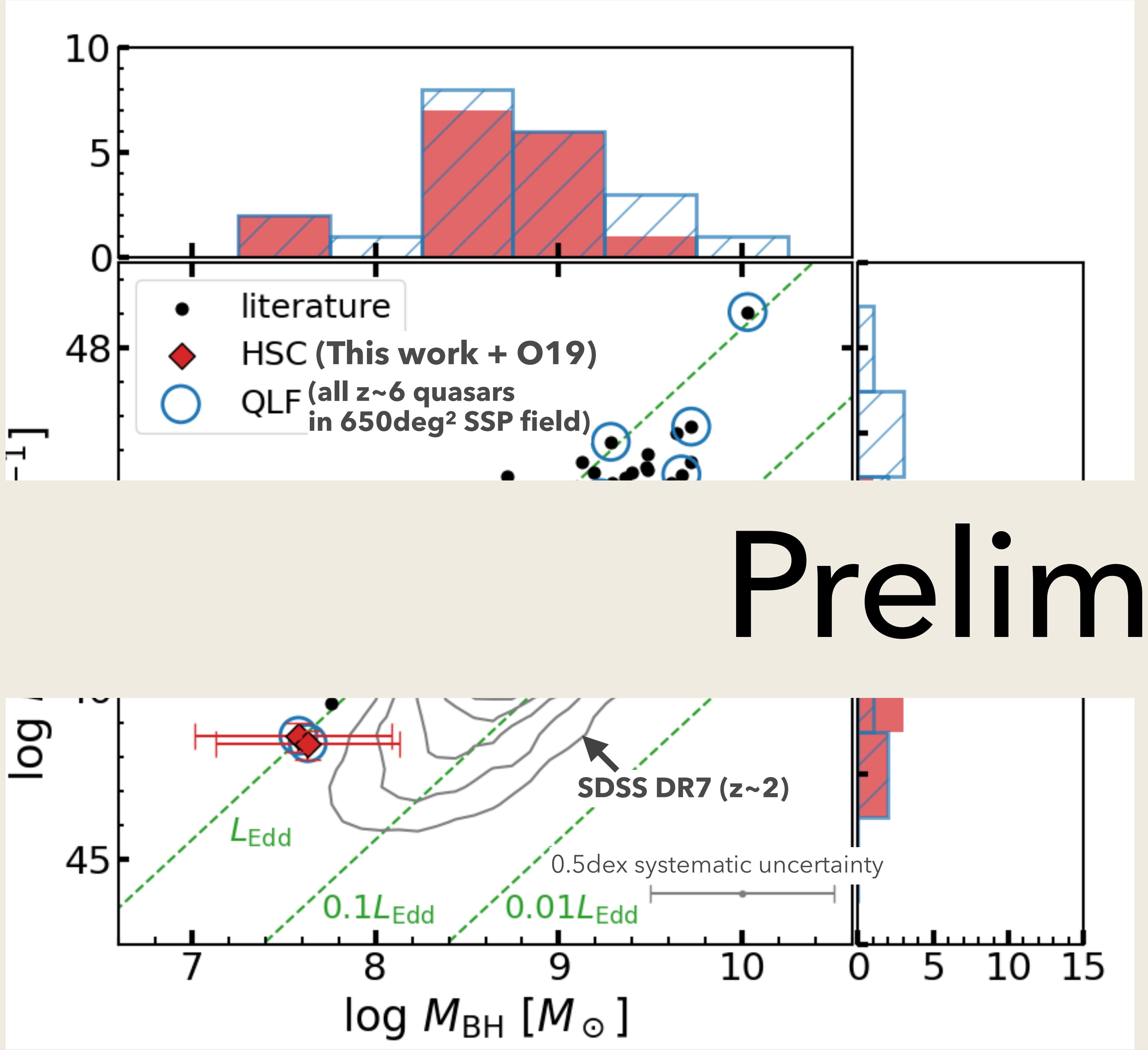
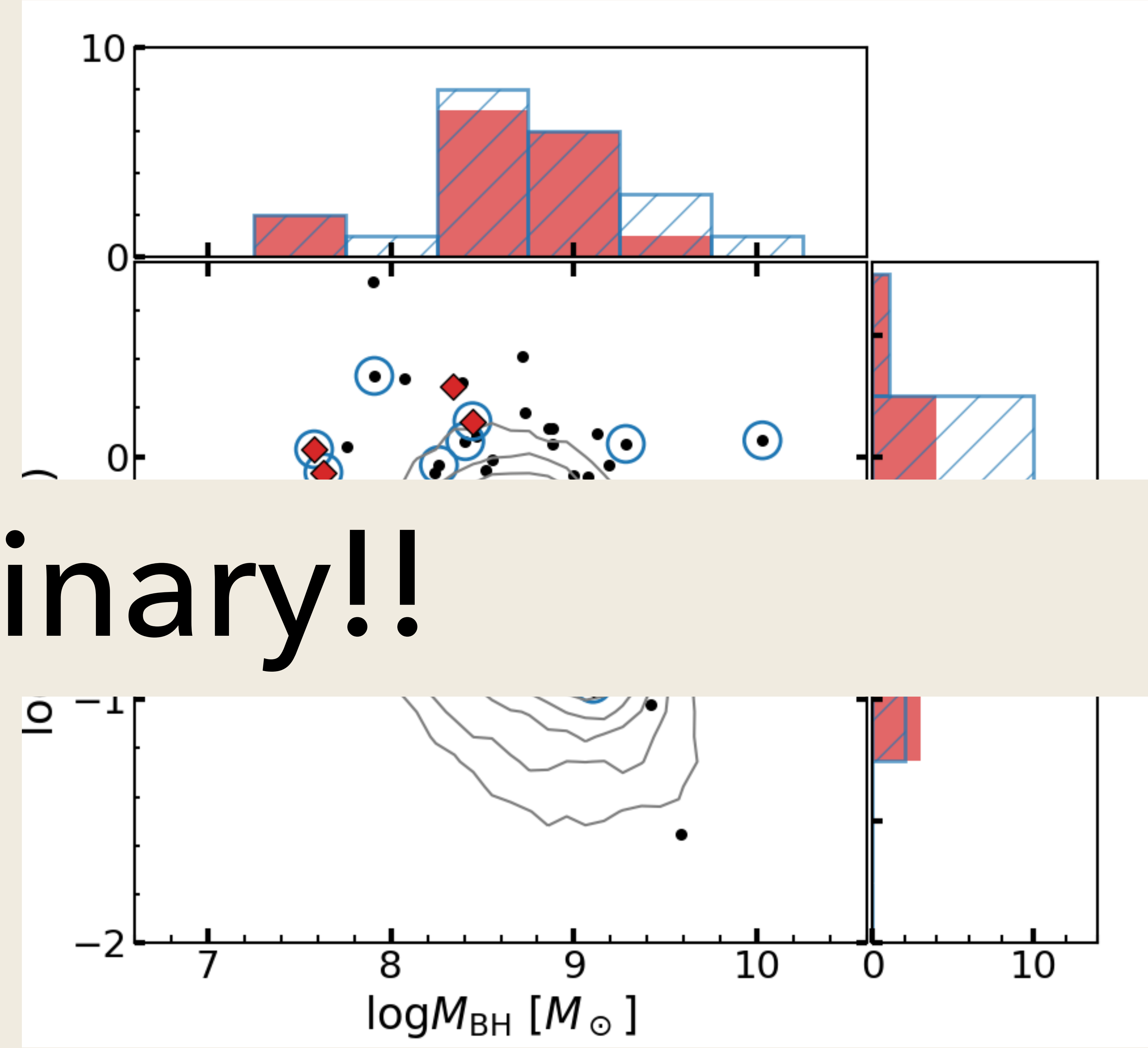


FWHM (MgII) =1300-5400 km s^{-1}

z>6 SMBH mass - L_{bol} / Edd Ratio distribution





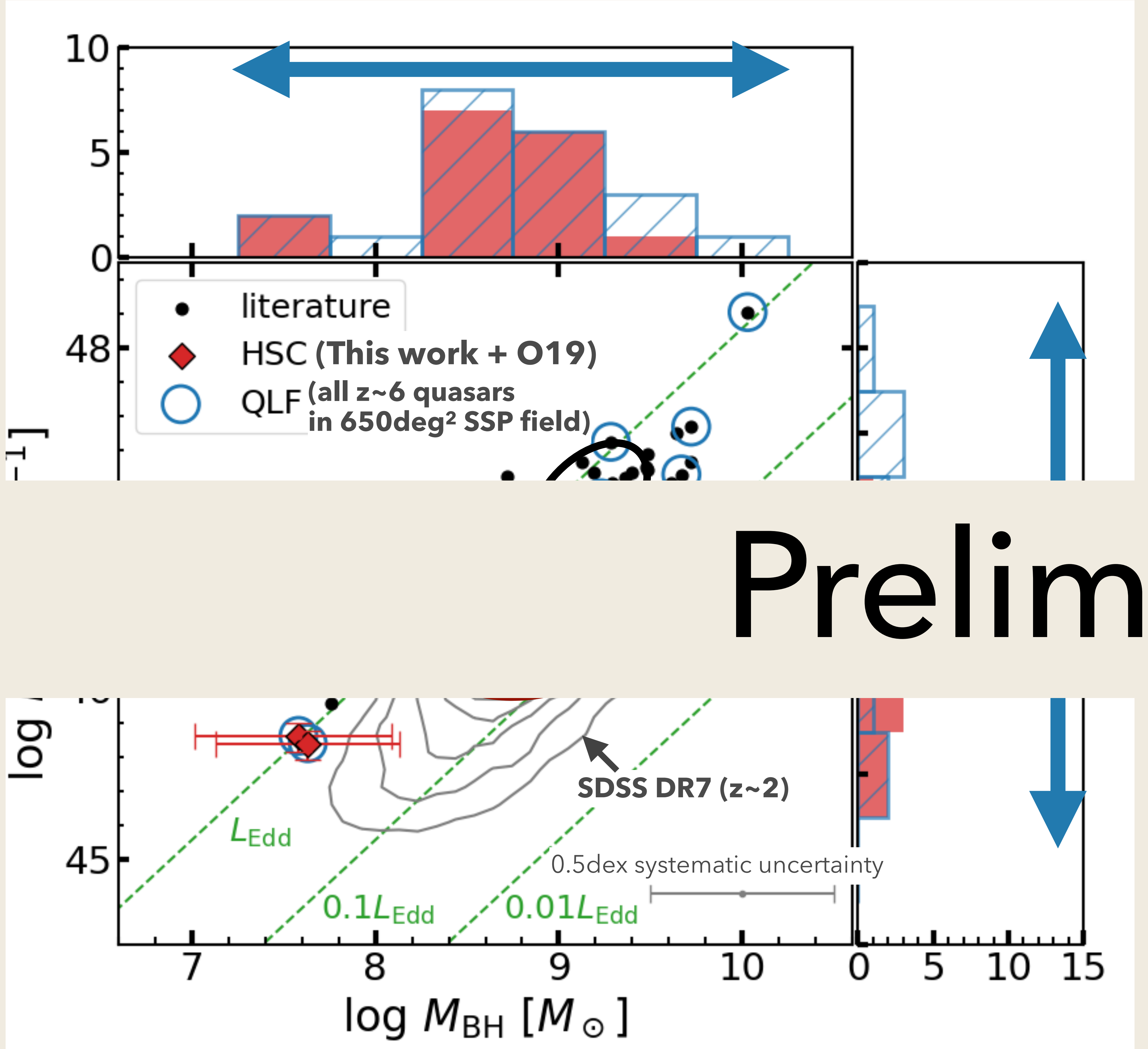
Preliminary!!

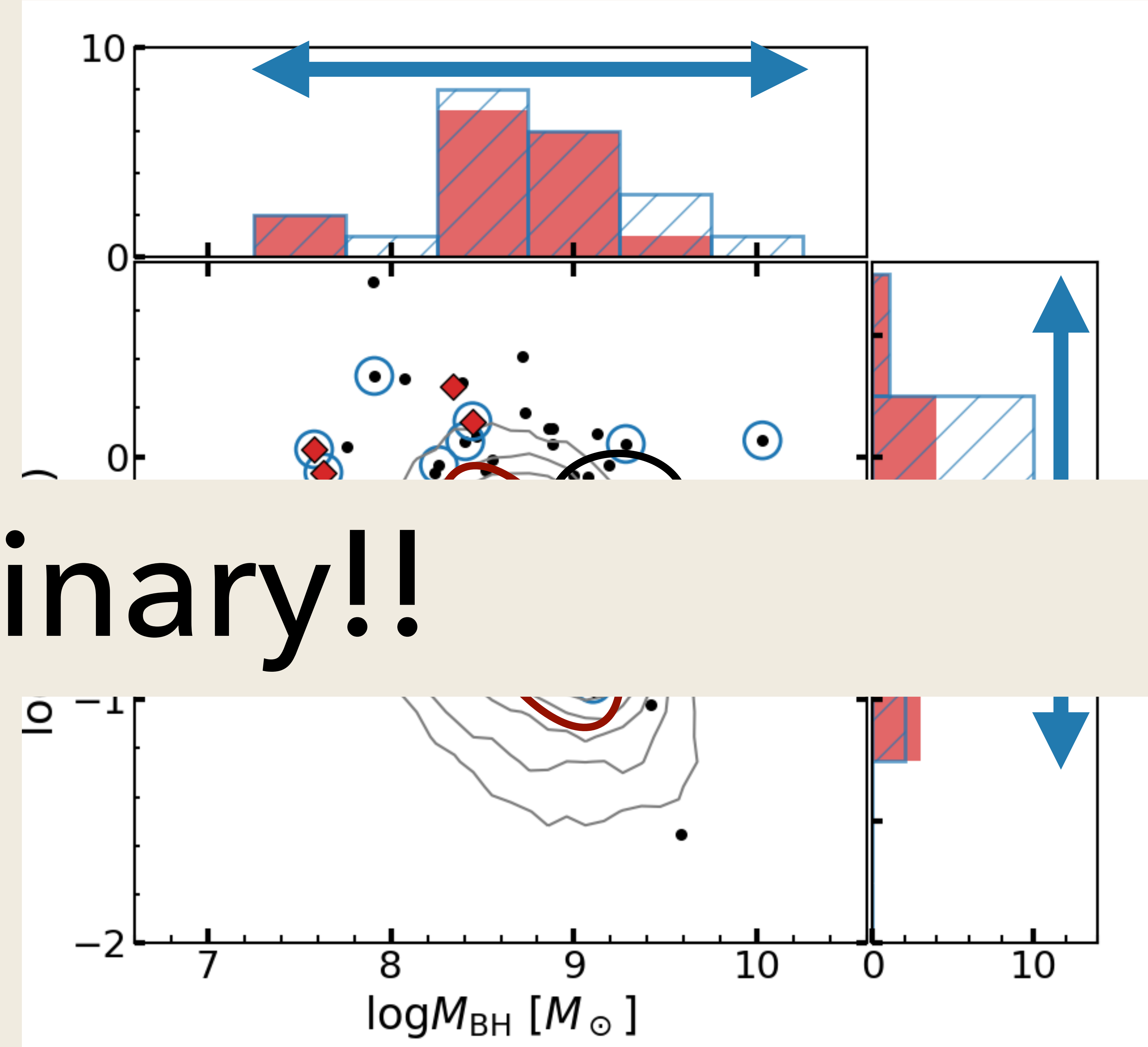
- MgII-based single-epoch MBH measurement (Vestergaard & Wilkes 2006)

$$M_{BH} = 10^{6.86}\left(\frac{\mathrm{FWHM(Mg\ II)}}{10^3\ \mathrm{km\ s^{-1}}}\right)^2\left(\frac{\lambda L_\lambda\ (3000\ \text{Å})}{10^{44}\ \mathrm{erg\ s^{-1}}}\right)^{0.5} M_\odot,$$

BLR Velocity   BLR Radius (+ R - L relation)

z>6 SMBH mass - L_{bol} / Edd Ratio distribution





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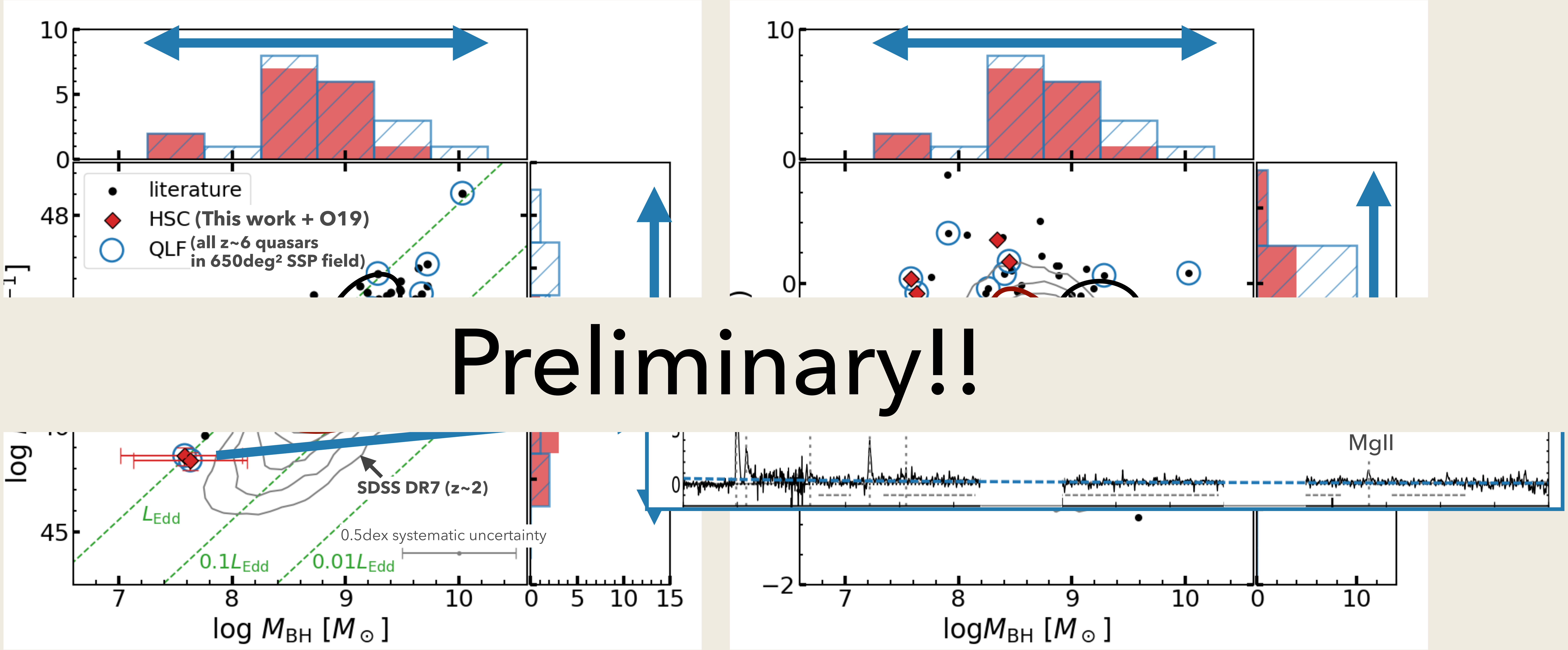

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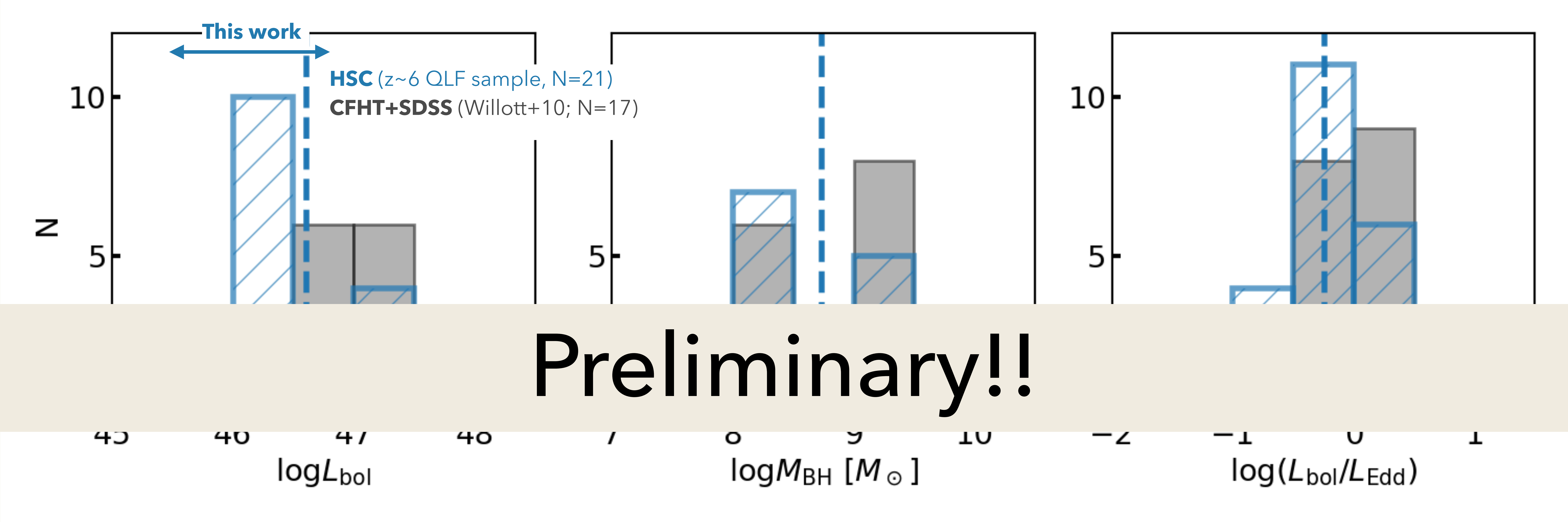
Diversity of z~6 SMBHs



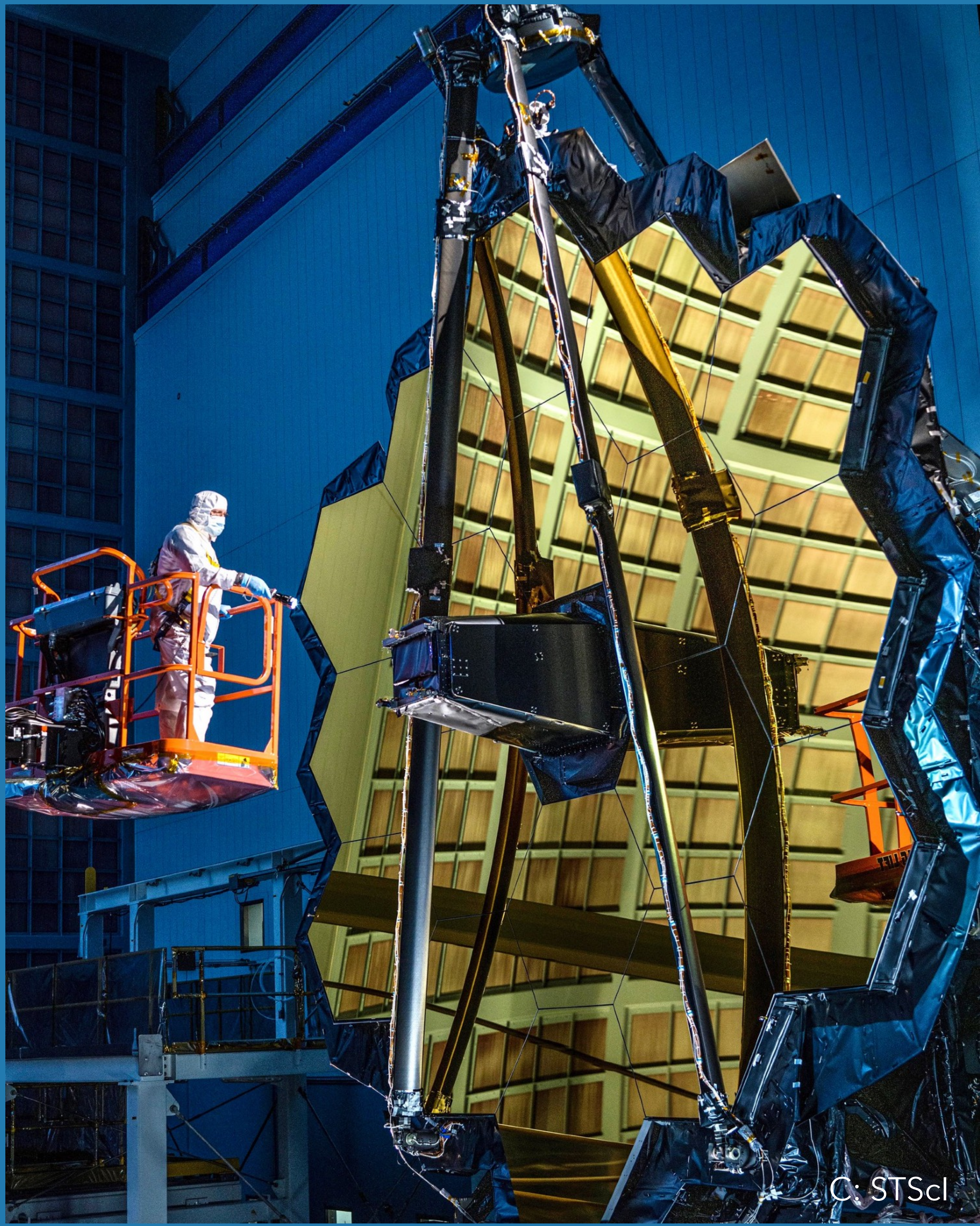
Ongoing & near future projects: :

(i) estimate intrinsic mass/Edd ratio distributions (to be compared with z=4 works by W.He+)
(ii) combine with a large luminous quasar sample (Wu+ in prep.)
(iii) reproduce z=4-6 LF & MF from BH seed models (with W.Li & K.Inayoshi at KIAA)
(iv) z=7 (SWIMS spectra taken for 7 z>6.5 quasars in S21A)

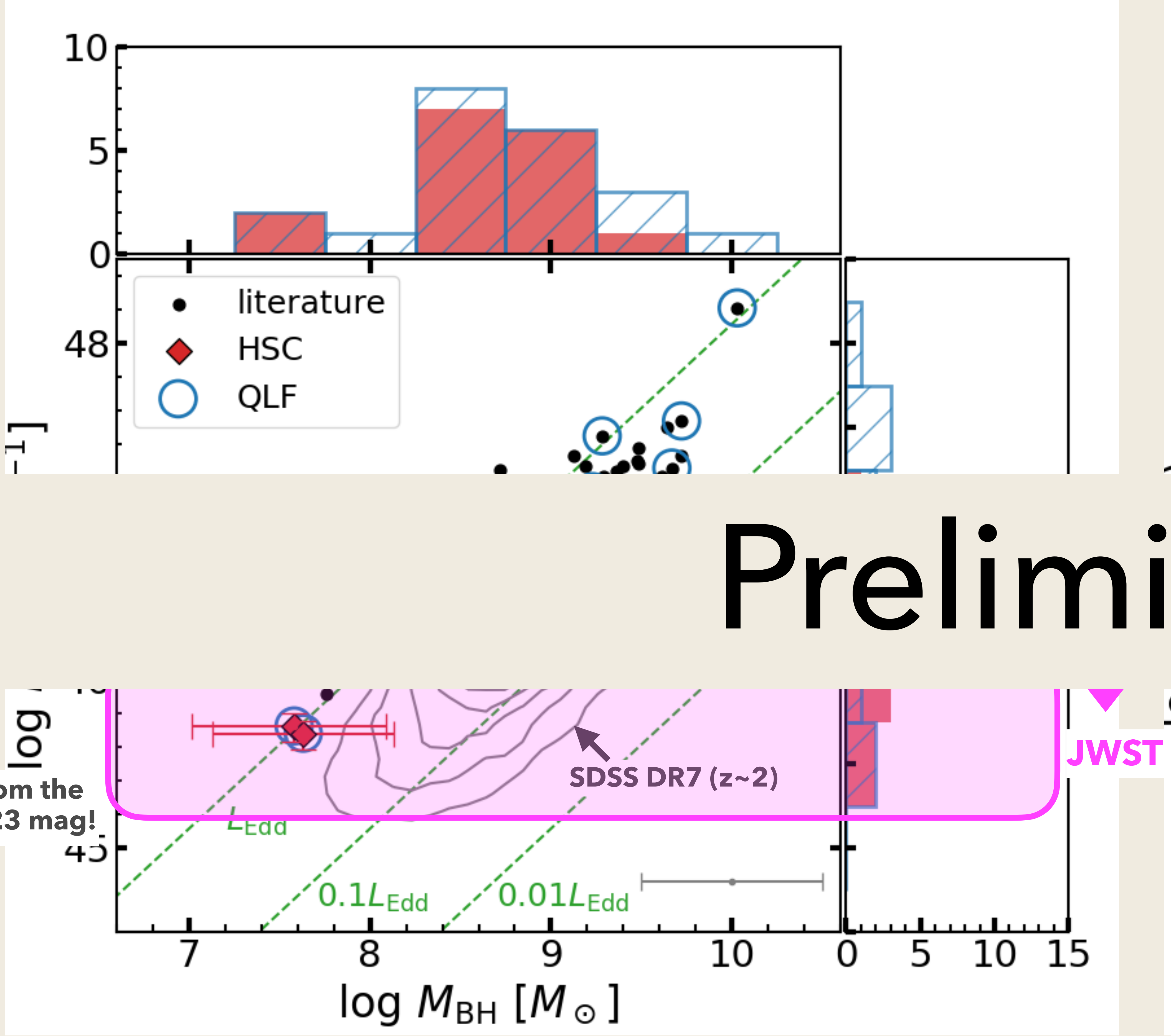
Cy1 JWST GO project:

Full Census of SMBHs and Host Galaxies at z=6

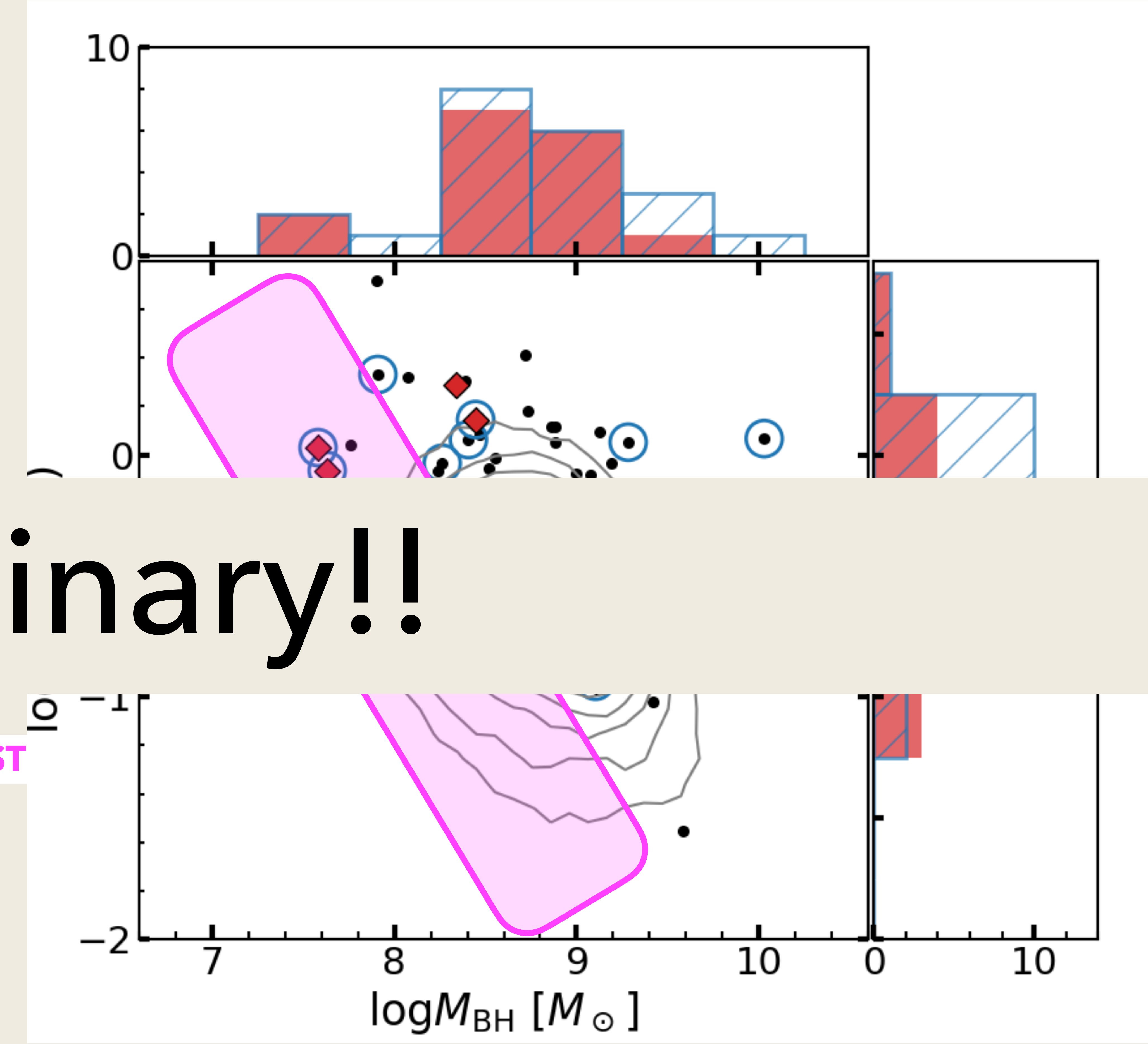
(50hr, PI: M.Onoue, Co-PI: Y.Matsuoka, X.Ding, J.Silverman, T.Izumi + 40 Co-Is)



JWST targets: faintest z~6 quasars from HSC



NIR spectroscopy from the ground below y_{AB}~23 mag!



Preliminary!!

12 faintest quasars from the QLF sample –> fair comparison with low-z quasars

- NIRCam Imaging (FoV: 2.2x2.2 amin^2)
  - Filter: F150W + F356W (straddling 4000A break)
- Quasar- Host decomposition -> host stellar light detection!
  - $\mathbf{M_*}$, age, companions, environment, etc.

+

- NIRSpec Fixed-Slit spectroscopy
  - Grism: G395M (R=1000), 2.87-5.27μm (rest 4000-7300Å, incl. many Balmer lines)
- Rest-optical emission line measurements
  - Hβ-based $\mathbf{M_{BH}}$, (-> mass function), [OIII] gas outflow, etc.

- Mean (and scatter of) $\mathbf{M_{BH}}$ **/** $\mathbf{M_*}$ ratio at z=6
  -> Do BHs and galaxies grow together, or one went faster than the other?
  -> ALMA dynamical mass measurements suggest $M_{BH}/M_{*/dyn}$ has little redshift evolution up to z=6 (e.g., Izumi+19)

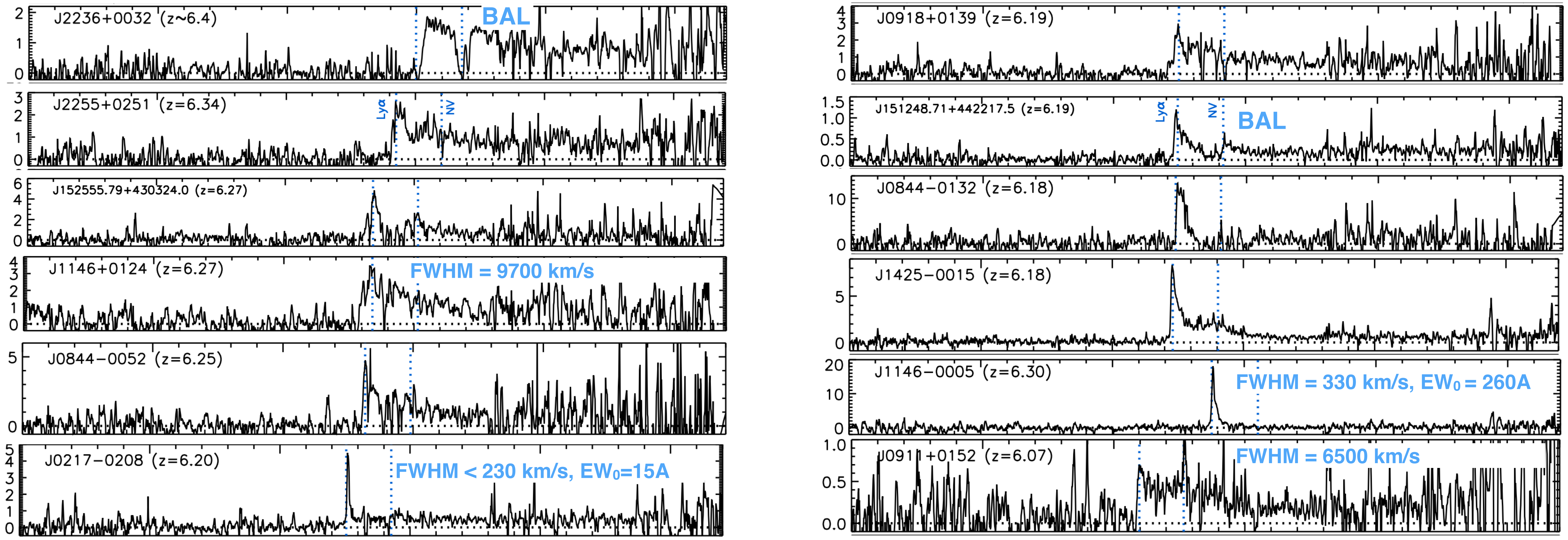
Summary

- SMBH cosmic evolution has been discussed mostly with luminosity functions, whereas observational constraints on the BH mass and Eddington ratio distributions are poor at z>2
- Deep MOIRCS spectroscopy of z>6 low-luminosity quasars reveals a wide diversity of SMBH masses (log M_{BH}/M_{sun} > 7.6) and Eddington ratios (log L_{bol}/L_{Edd} >-1). The majority are well matured SMBHs (log M_{BH}=8.5 M_{sun}, log L_{bol}/L_{Edd} = -0.5) in the fist billion years of the universe. SWIMS data for our z>6.5 sample is under analysis.
- JWST provides a unique opportunity to probe the least-biased SMBH sample at high redshift. With 12 lowest-luminosity (L_{bol}~10^{45} erg s^{-1}) quasars at z=6, we will derive the comprehensive picture of SMBHs, host galaxies, and their relative growth within the first billion years of the universe

Backup Slides

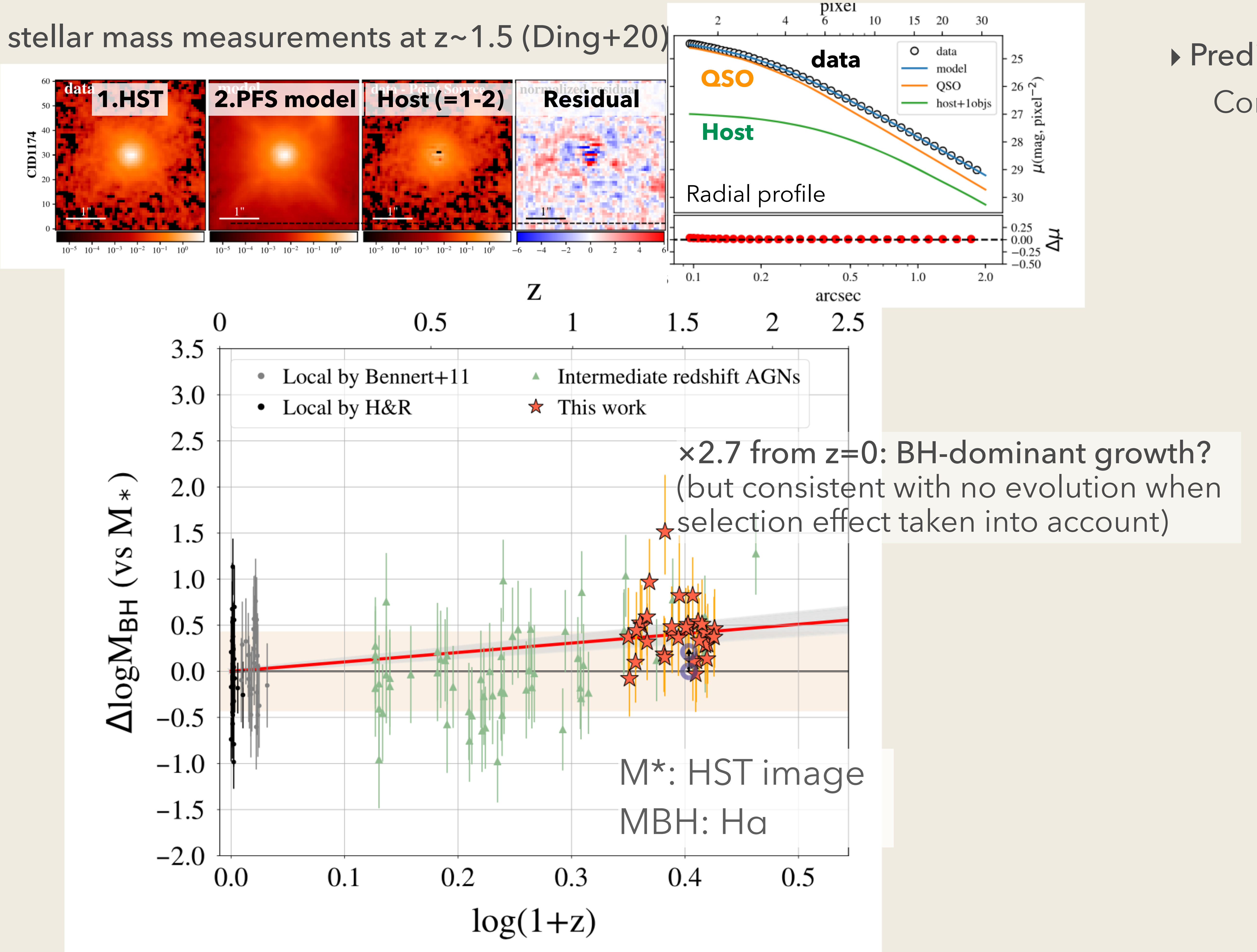
Characterizing Lowest-luminosity Quasars at z=6

- Discovery spectra of 12 JWST targets (y_{HSC}=23.0-24.8 AB mag, from Matsuoka+18's QLF sample) -> least-biased SMBH sample!



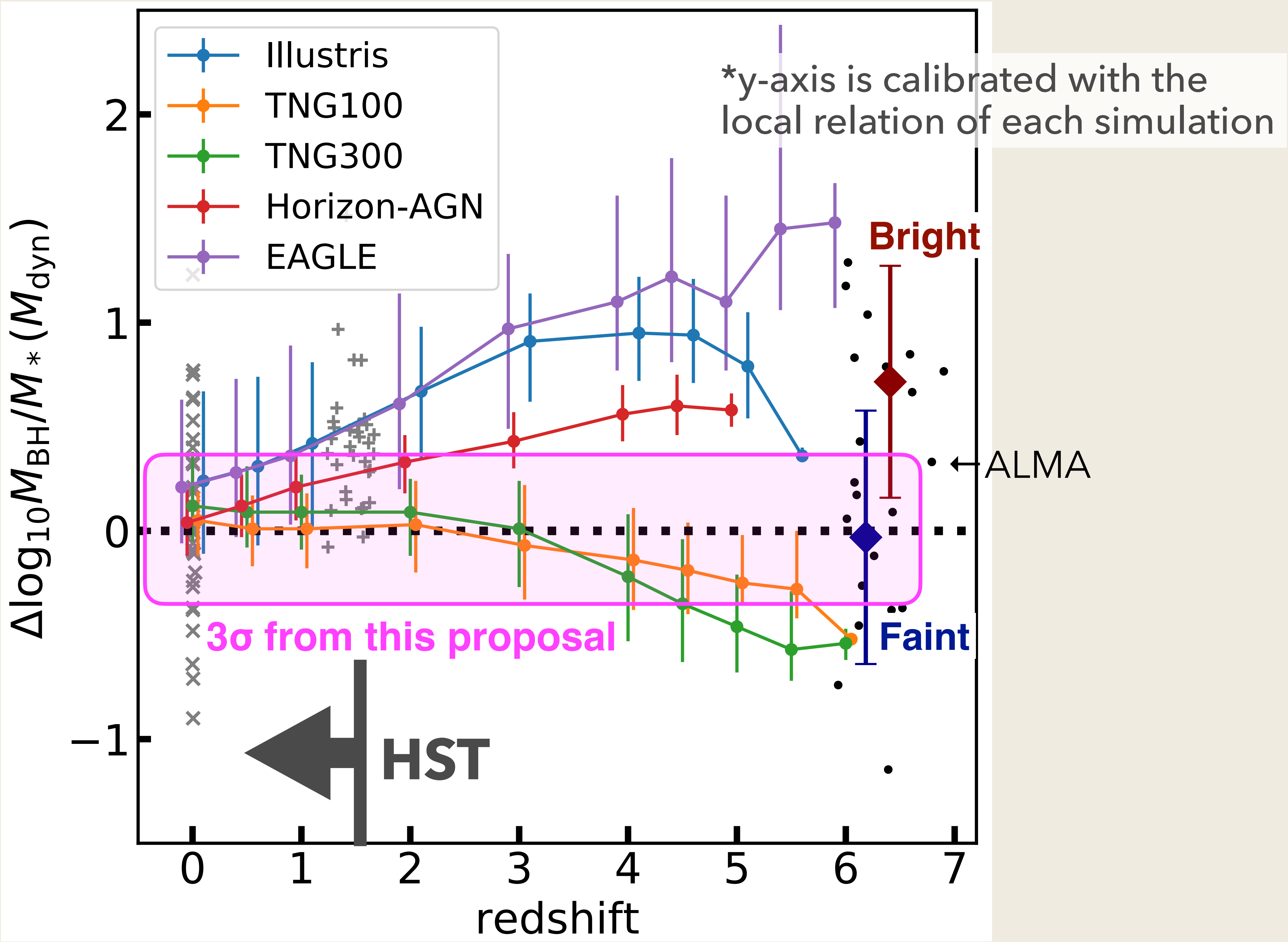
Redshift Evolution of M_{BH}/M_* Ratio

- Host stellar mass measurements at z~1.5 (Ding+20)



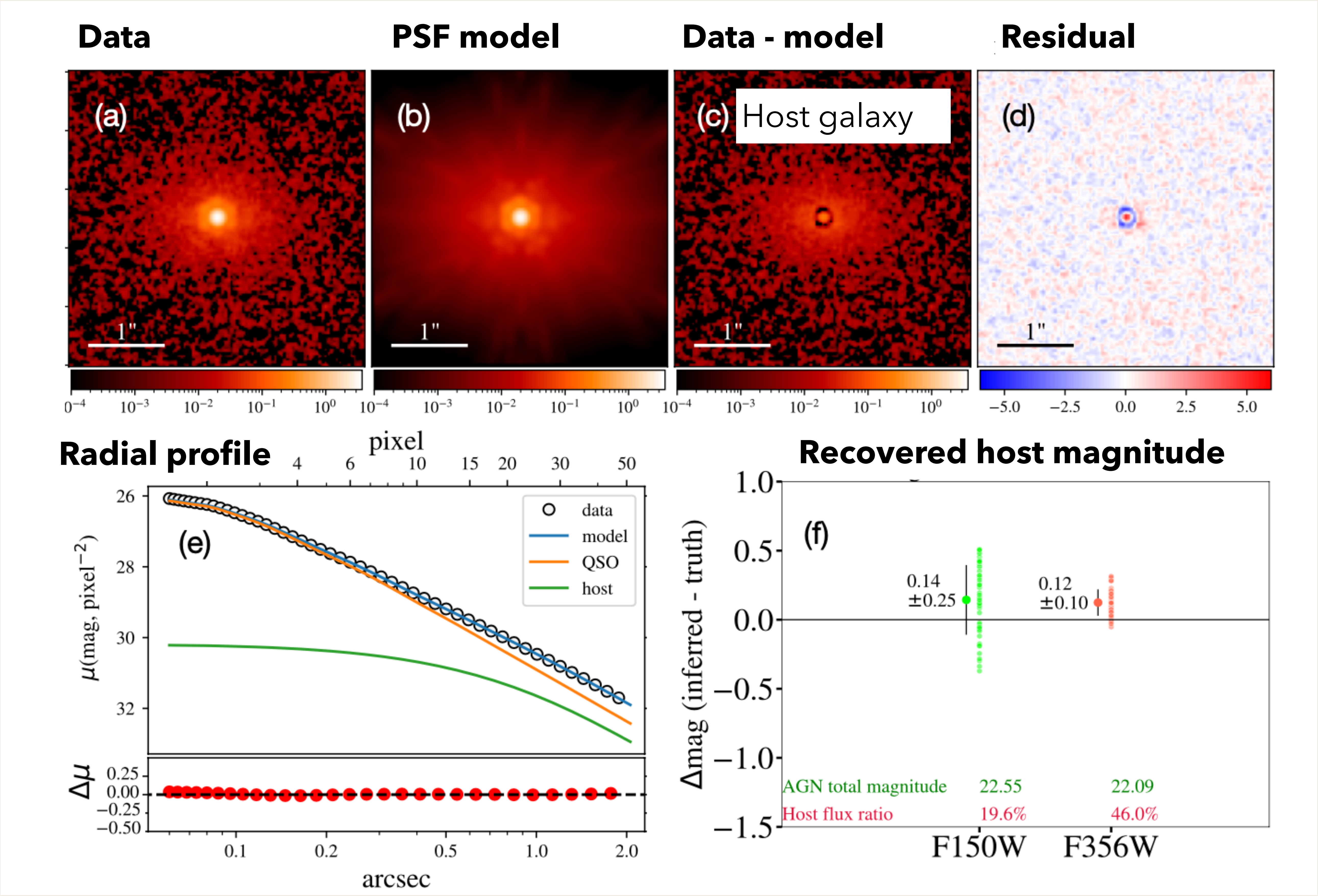
- Prediction from six cosmological simulations (Habouzit+ in prep.):

  Completely different predictions due to different modeling of AGN feedback

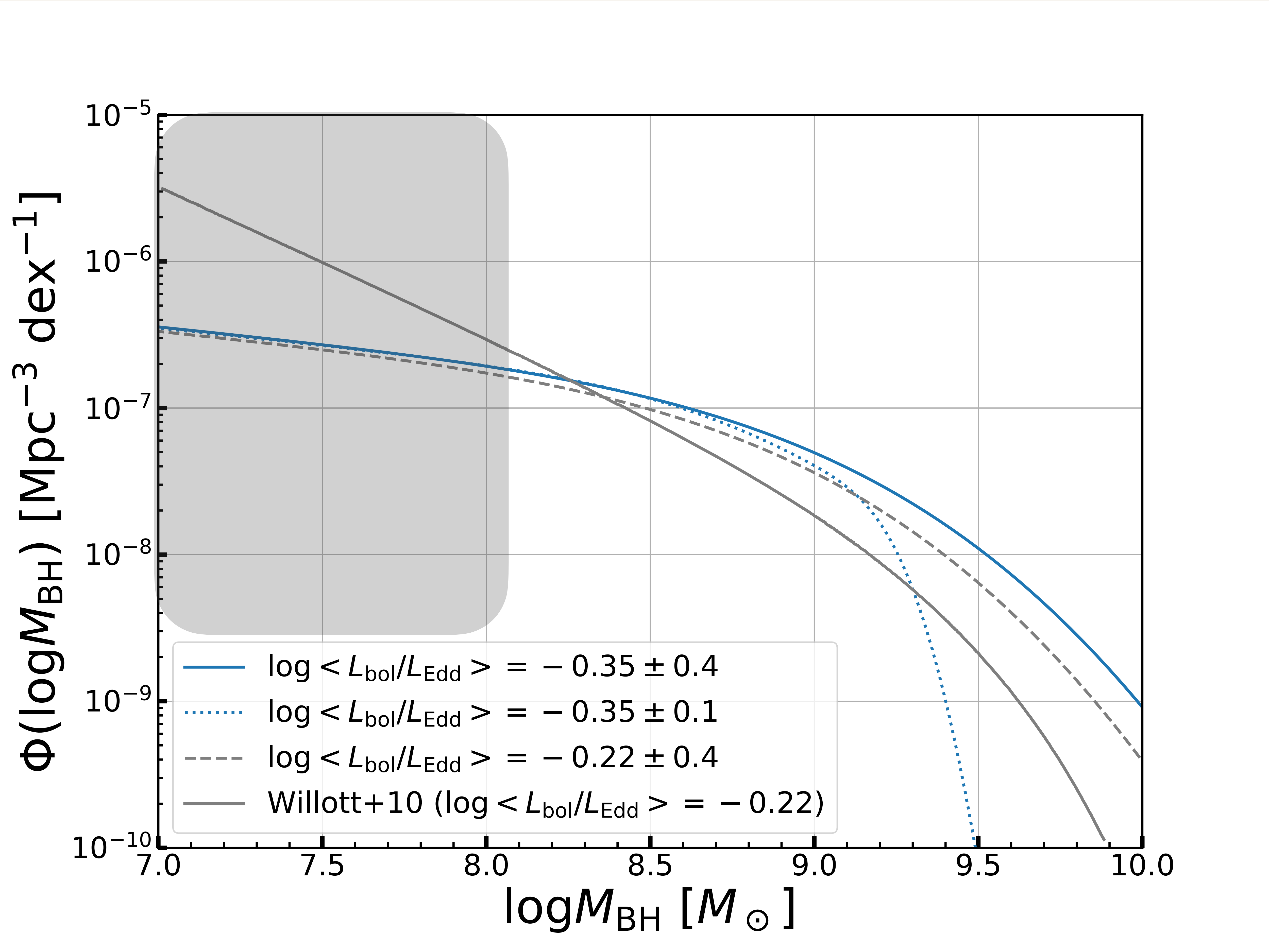


- NIRCam Imaging (FoV: 2.2x2.2 amin^2)
  - Filter: F150W + F356W (straddling 4000A break)
- Quasar- Host decomposition -> host stellar light detection!
  - **M***, age, companions, environment, etc.

- NIRCam simulation: J0859 ($M_{BH}=10^{7.6}M_{sun}$, $M_*=10^{10.7}M_{sun}$), Courtesy of X.Ding



The first trial of z=6 BHMF measurement



Assumption:

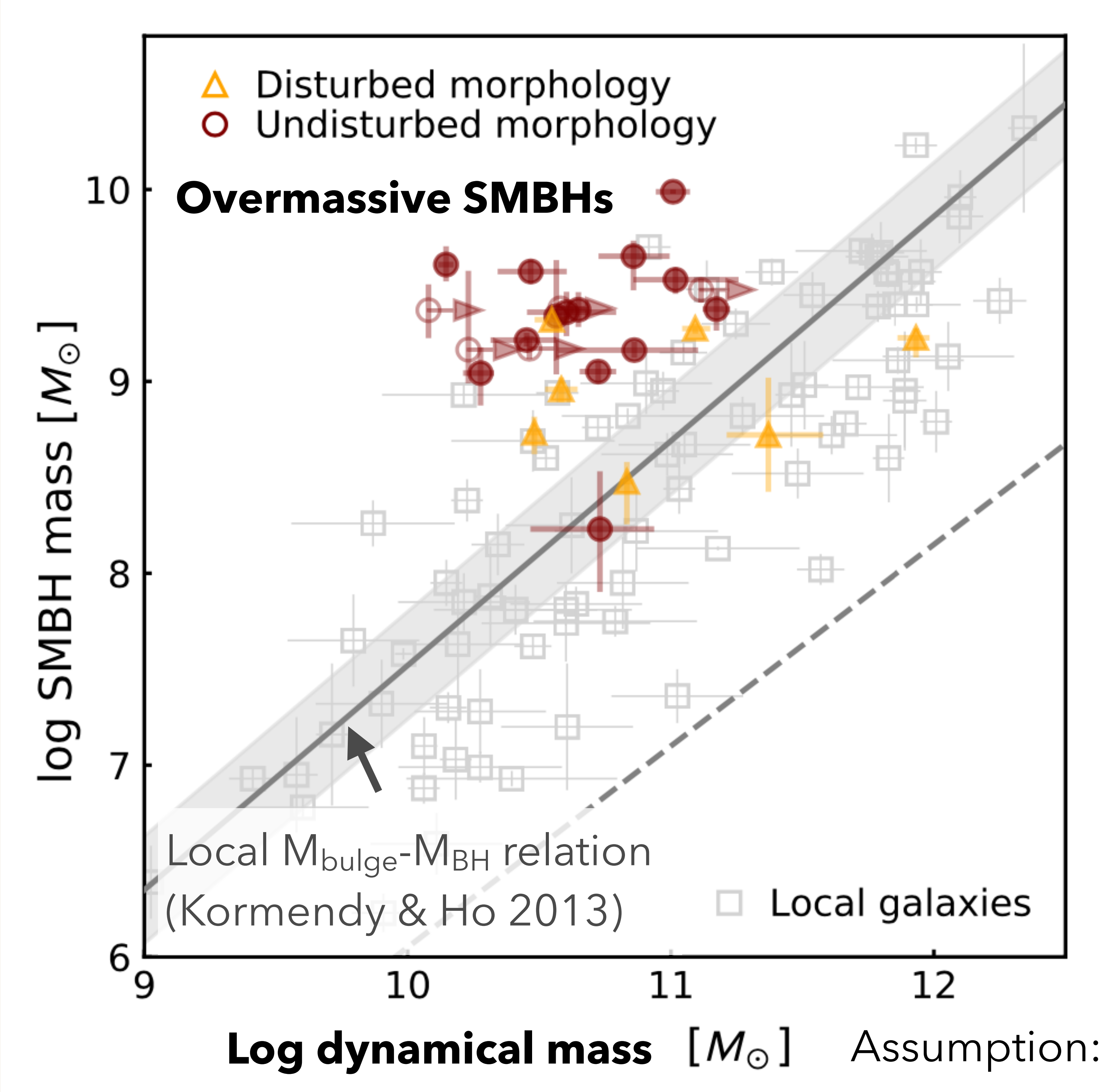
- z=6 type-I QLF of Matusoka+18c
- Obscuration correction: 80% (Vito+18)
- ERDF: Gaussian shape
- No MBH dependence on Edd ratio distribution, no completeness correction

Todo:

- implement sample incompleteness
- deal with MBH's systematic uncertainty (0.5 dex; Shen13)
- try Schechter function?
- compare with low-z measurements (for samples whose luminosity ranges are comparable)

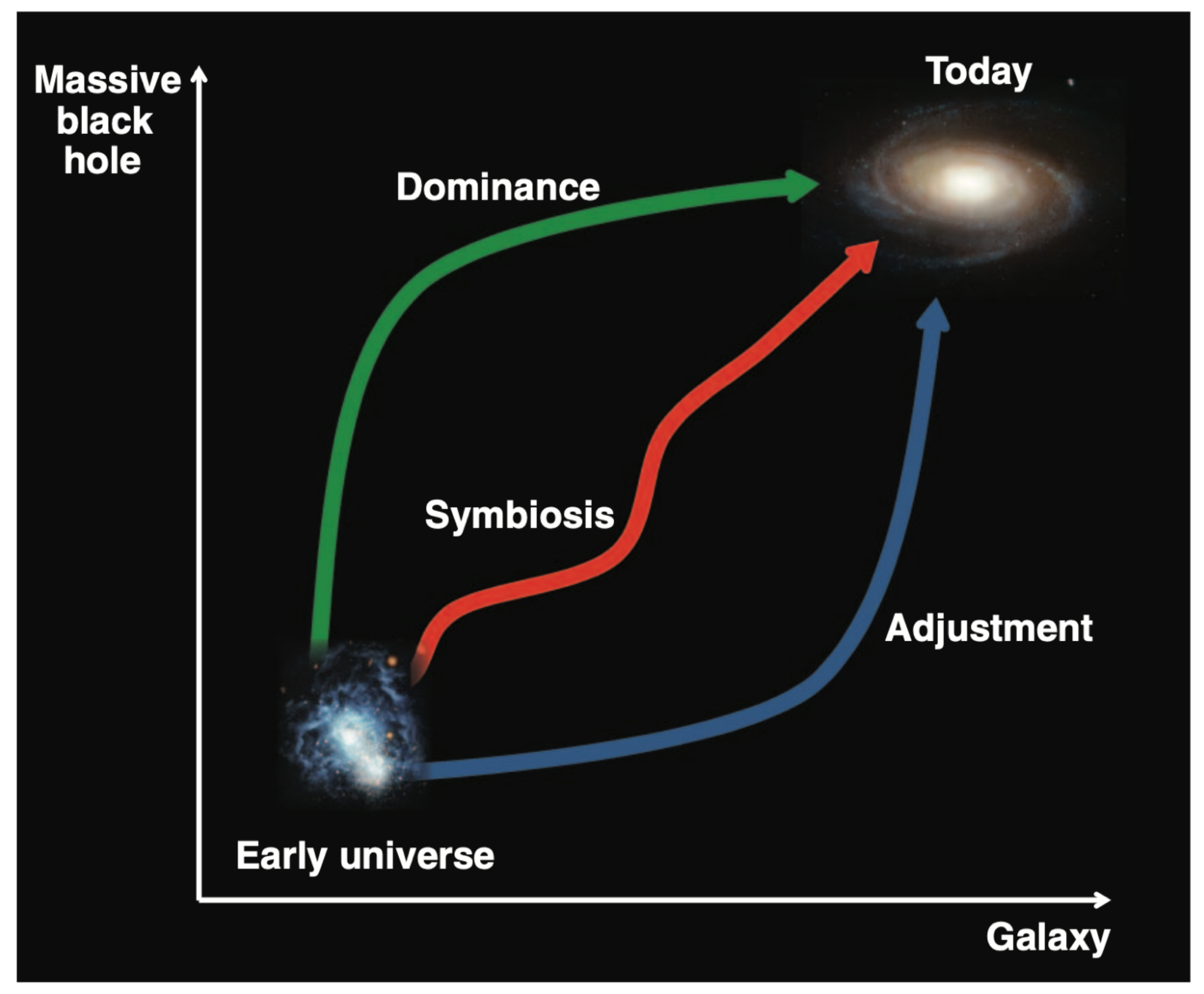
SMBH vs Host Dynamical Mass

- Dynamical mass vs SMBH mass at z=6 (Neeleman+21)



Assumption: $M_{dyn} \sim M_{bulge}$

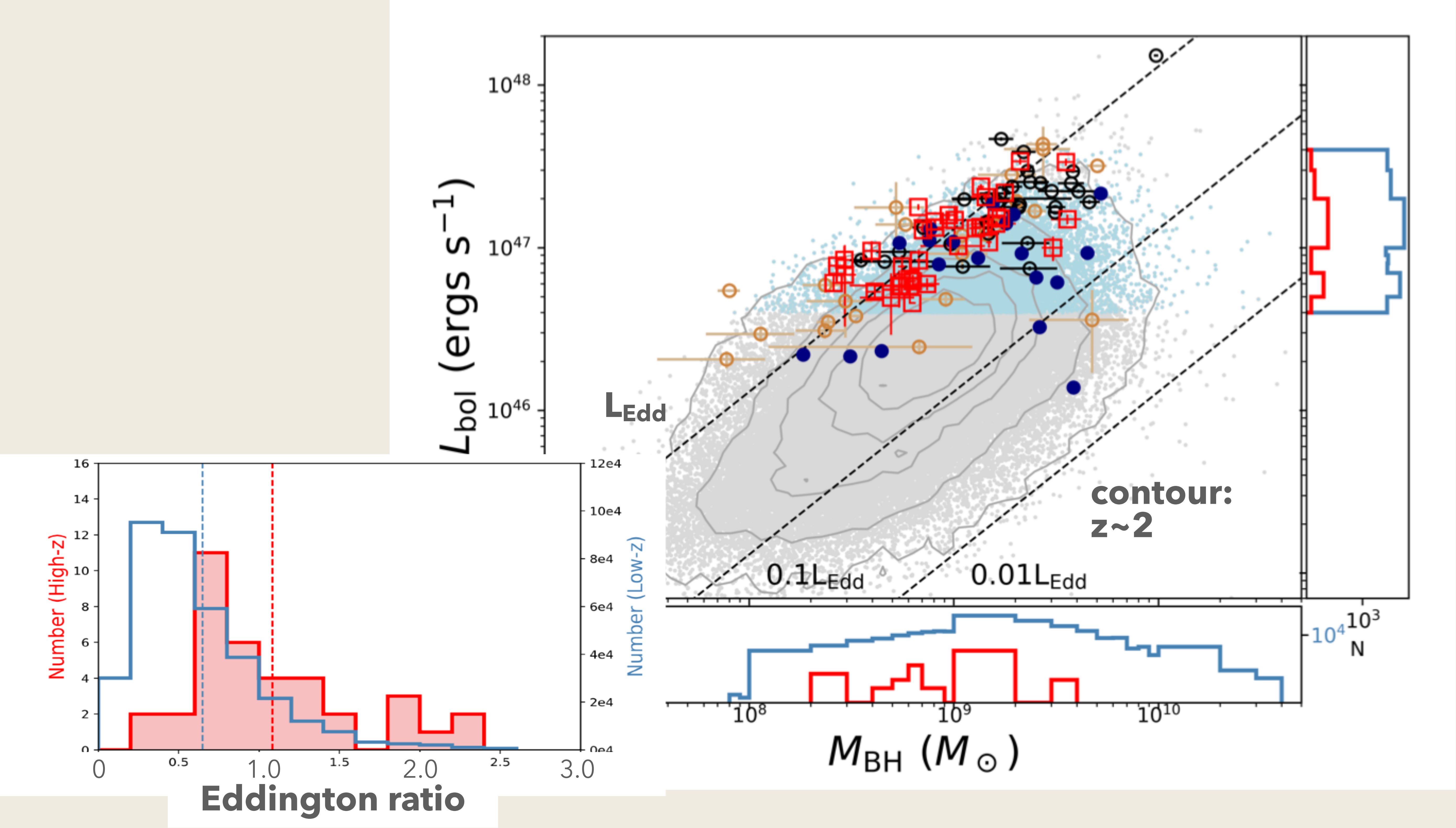
- Schematic diagram of SMBH-galaxy co-evolution (Volonteri12)

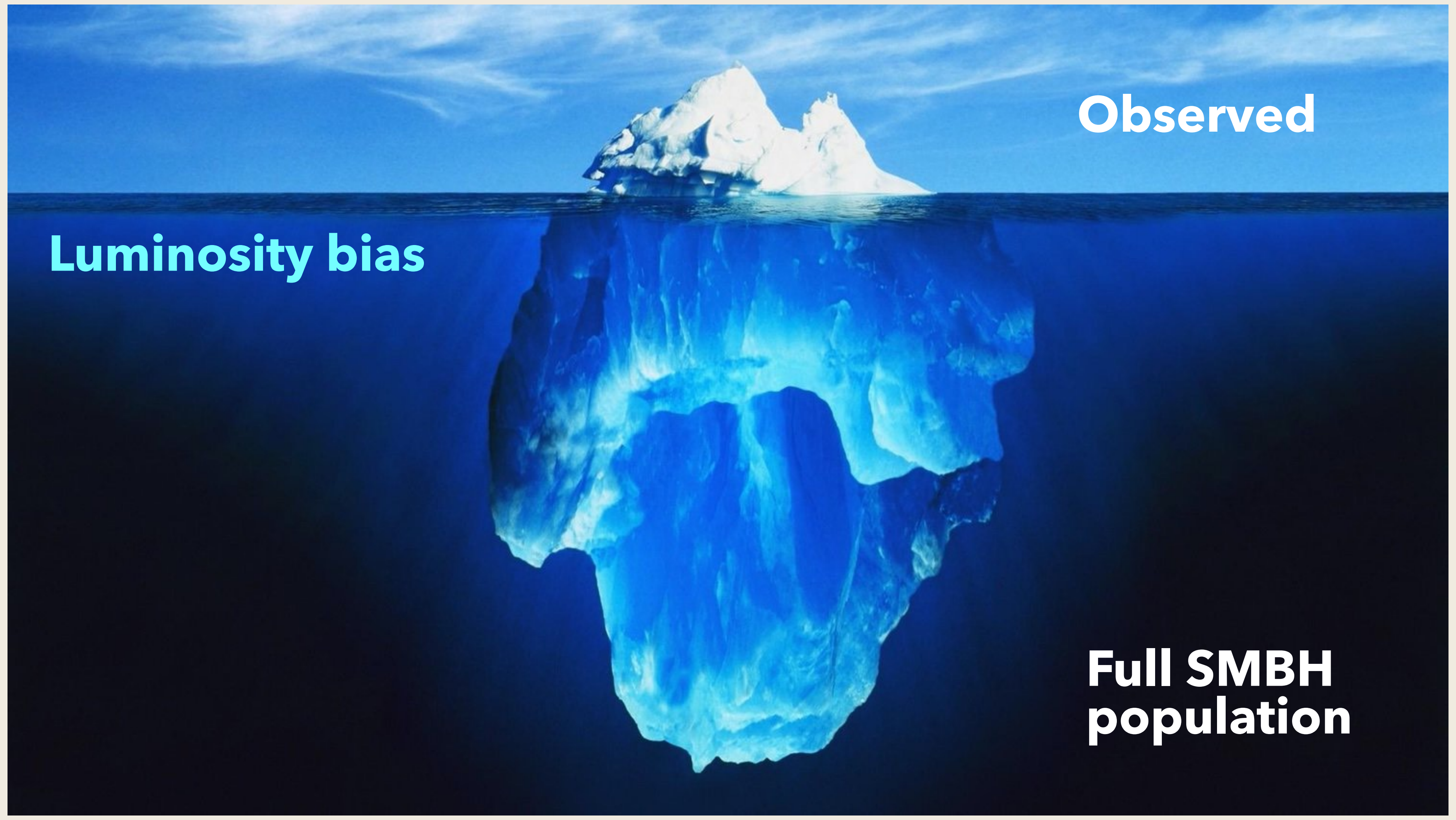


BH growth first and host stellar mass growth next?

Looking behind the Tip of the Iceberg

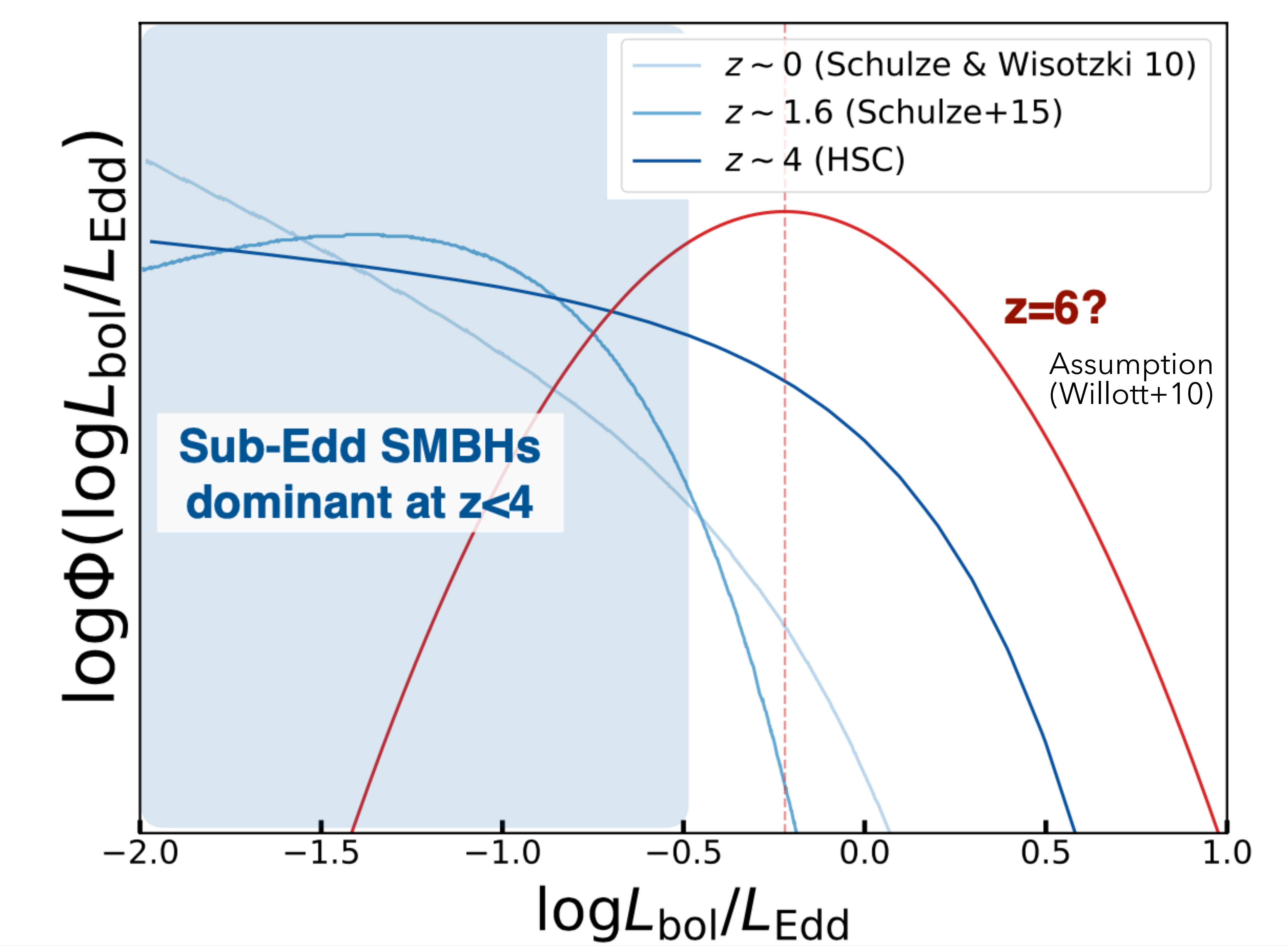
- BH mass vs bolometric luminosity plane of z>6.5 QSOs (Yang+21)





➡ It is essential to probe *lower-luminosity quasars* to understand the demographics of high-z SMBHs (The most luminous QSOs could just be the outliers among the whole SMBH population)

Eddington Ratio Distribution

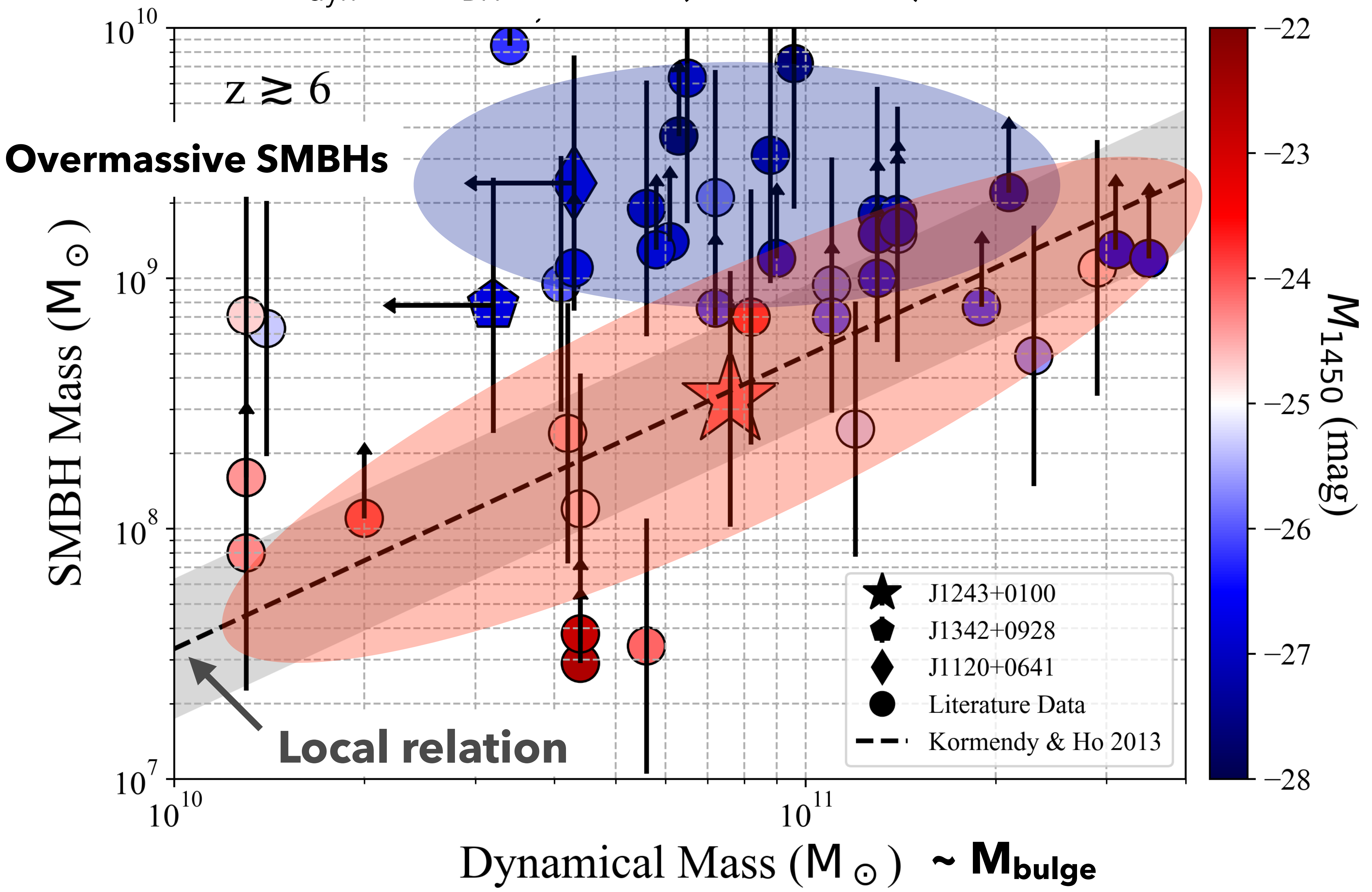


cf. Jin Wu's talk yesterday

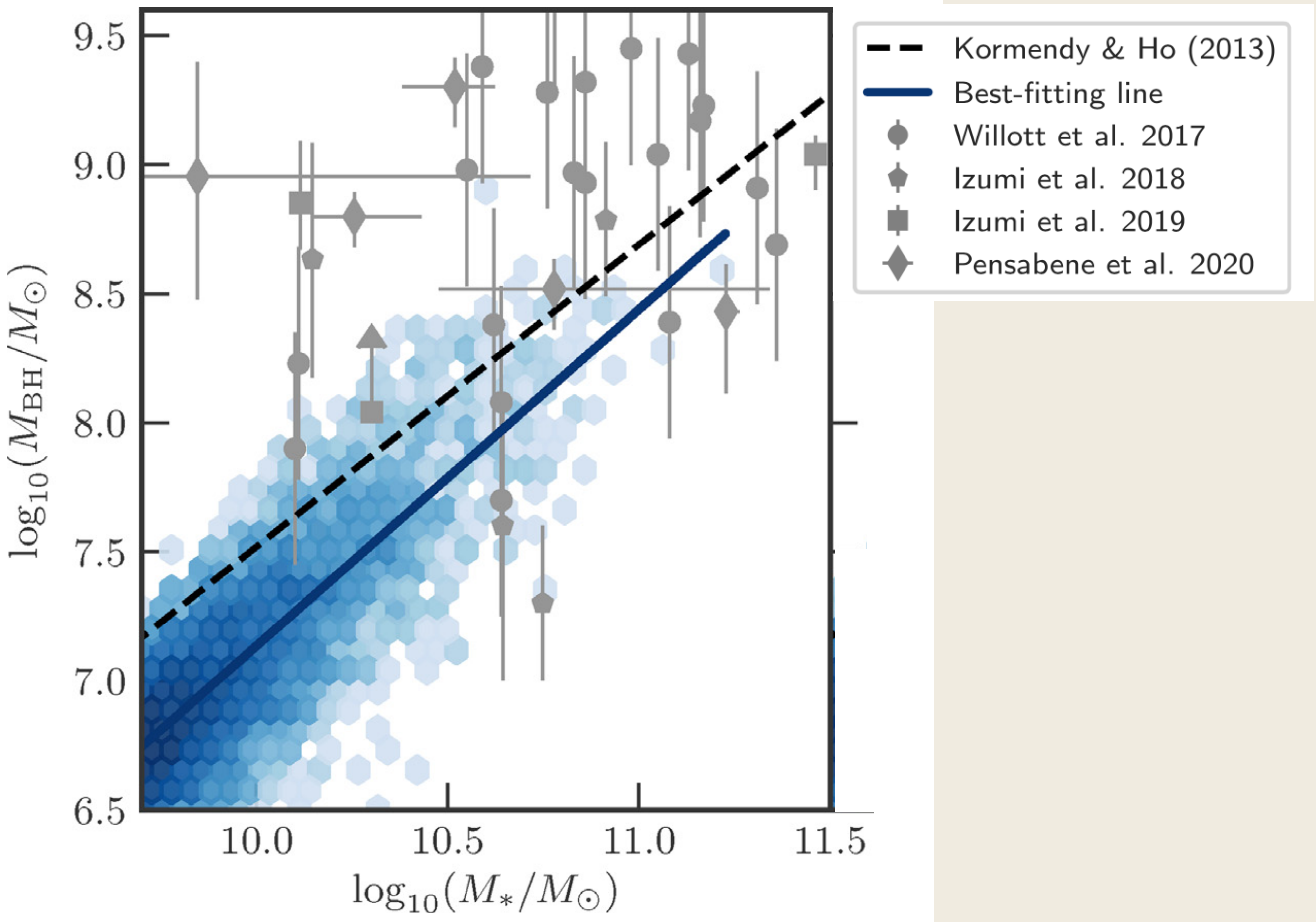
Do All z>6 SMBHs have extreme accretion rates?

ALMA Views of Co-evolution at z>6

z>6 M_{dyn} vs M_{BH} relation (Izumi+21b)



▸ BLUETIDES prediction (Marshall+20b)



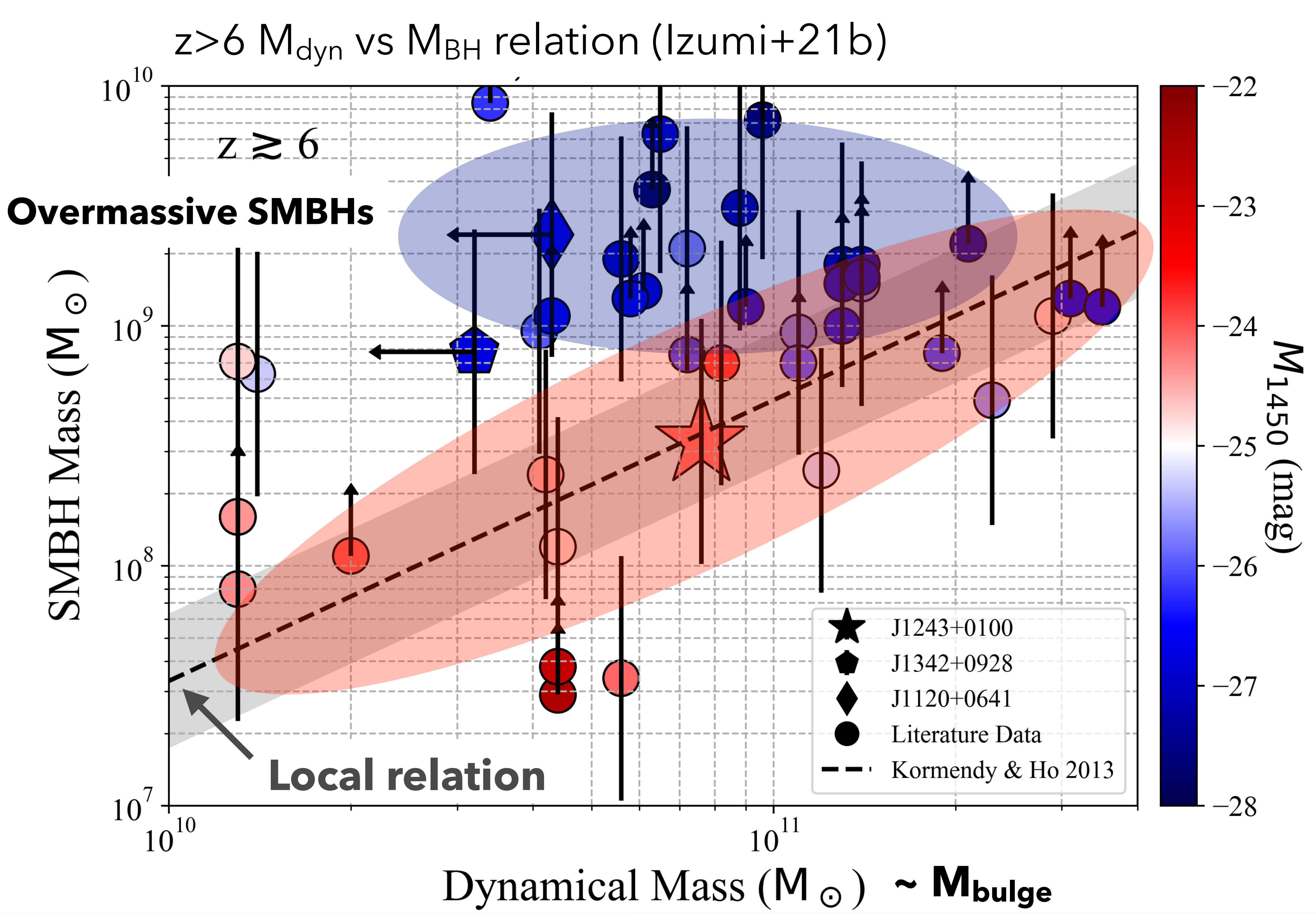
✦Co-evolution relation established already at z=6-7?

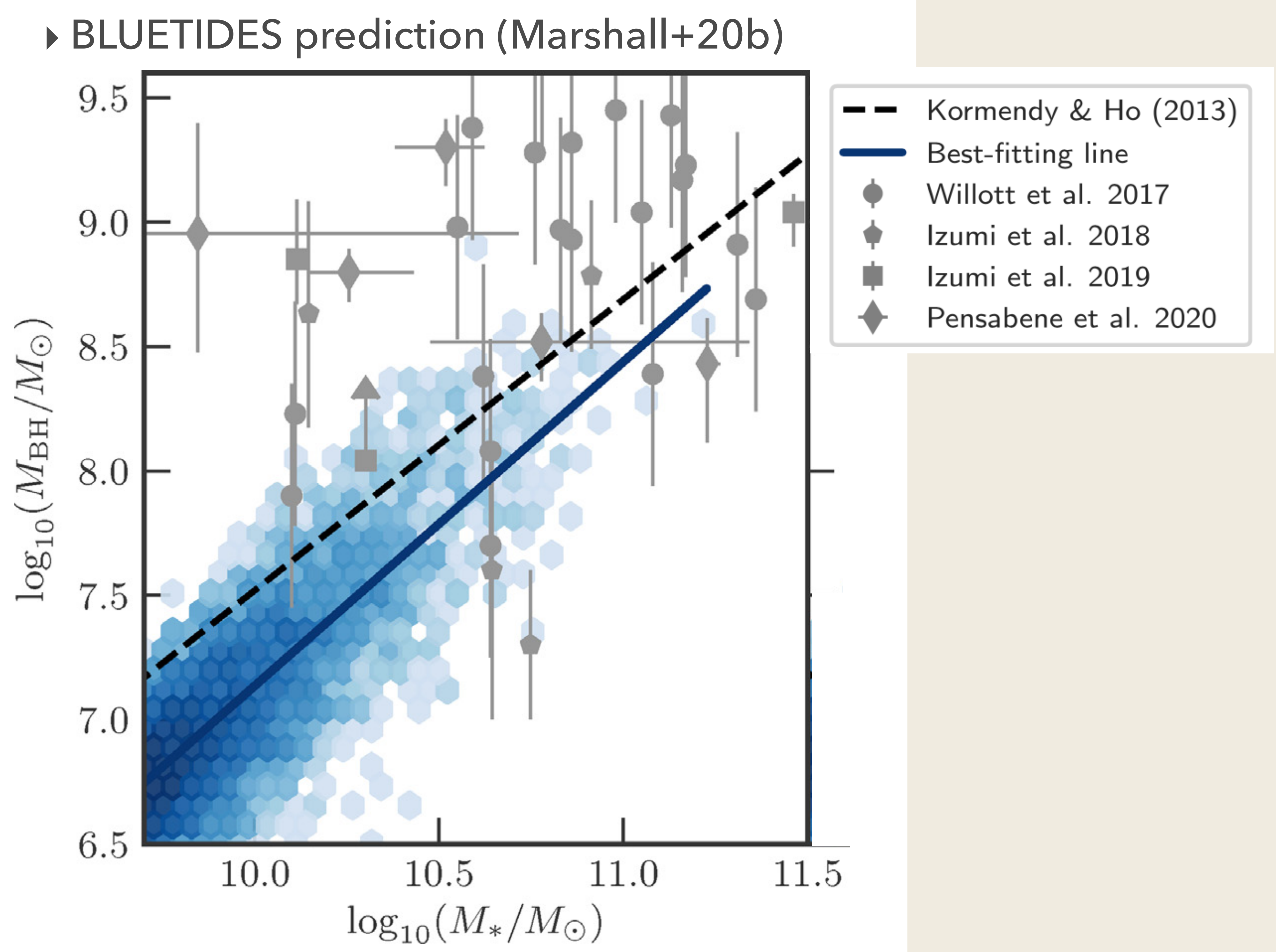
✦Less-biased low-luminosity quasars essential to trace the general SMBH trend

✦Consistent with a recent hydrodynamical model prediction

See also Wang+15; Izumi+18; Pensabene+20; Marshall+20ab; Neeleman+21

ALMA Views of Co-evolution at z>6



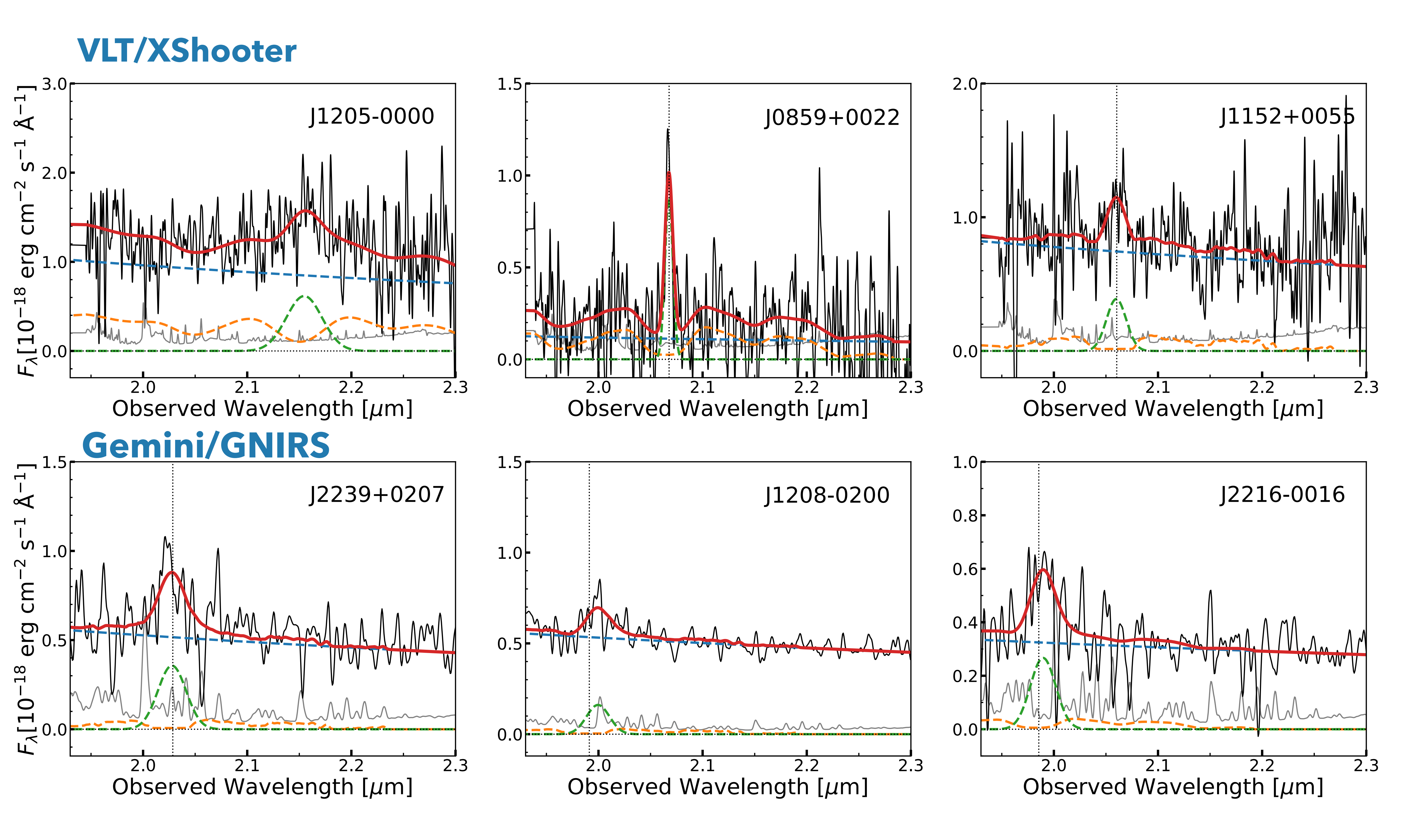


Is M_{dyn} really a good estimator of M_{bulge}? (gas,DM,disk inclination, etc.)

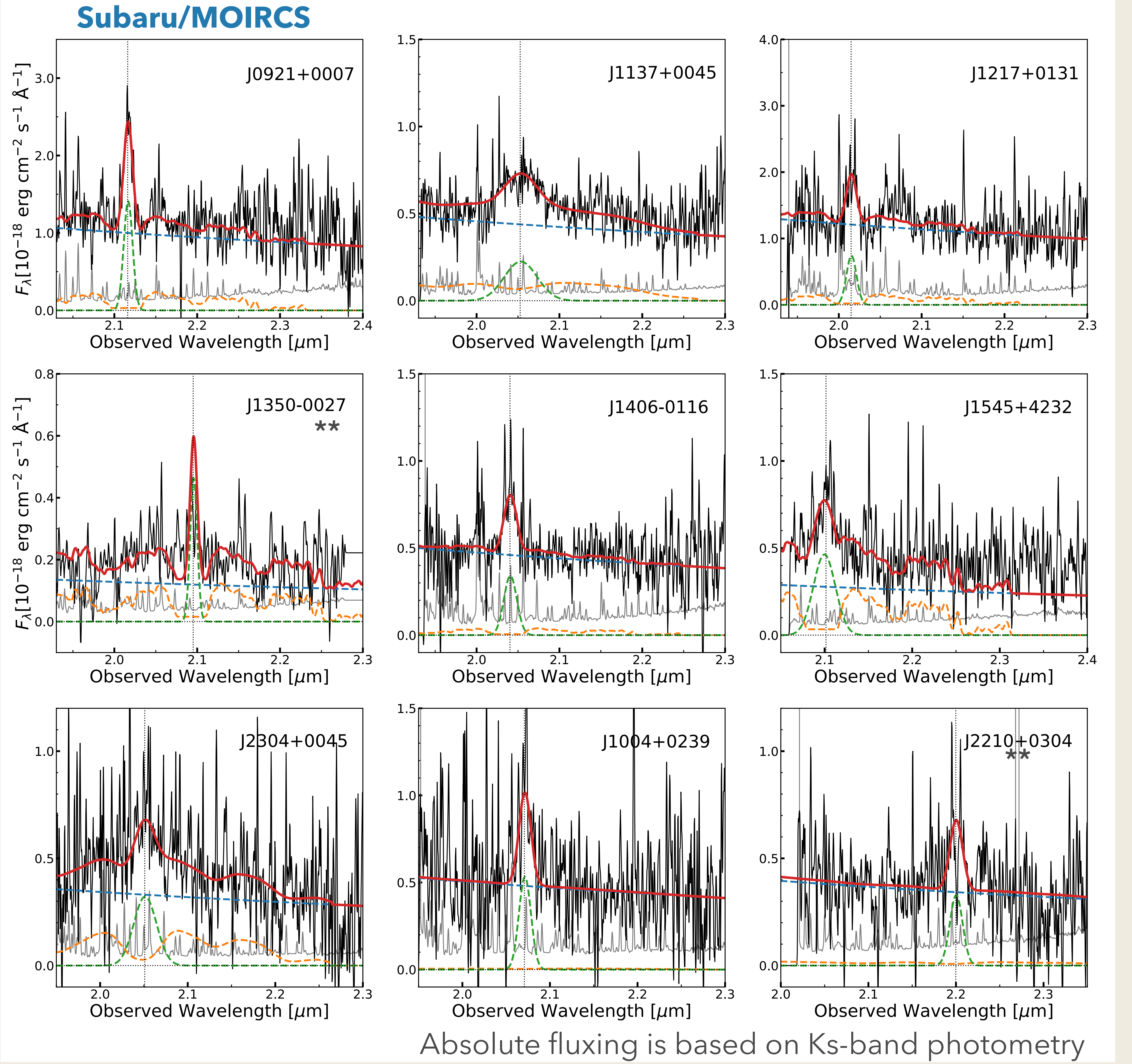
Do we miss undermassive BH population?

-18;
20ab;

MgII emission line detection from z>6 low-luminosity quasars



Published in Onoue+19



Onoue+ in prep. (Very preliminary!!)