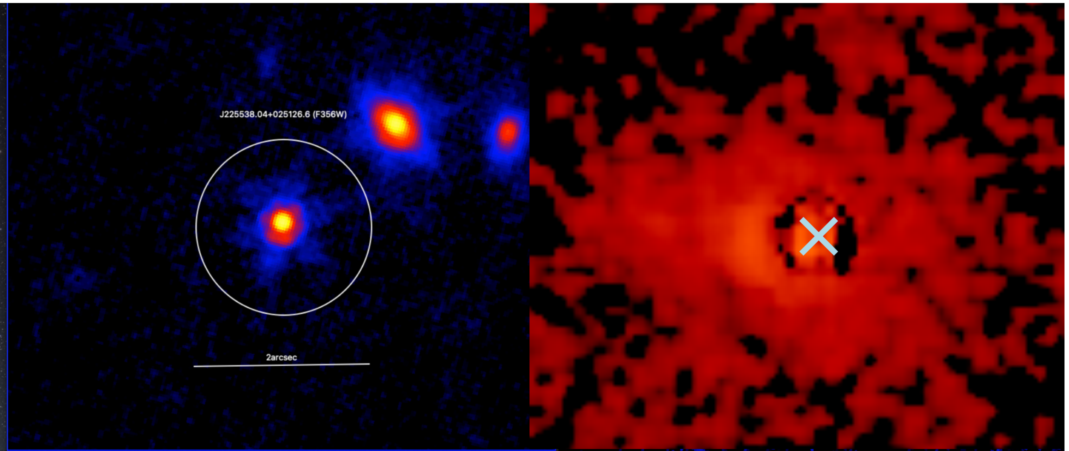


NIRCam + NIRSpec FS Observations of z=6 Subaru/HSC quasars

Masafusa Onoue (Kavli astrophysics fellow, Kavli IPMU / KIAA)

Main collaborators: Xuheng Ding (Wuhan U), John Silverman (Kavli IPMU), Yoshiki Matsuoka (Ehime U), Kohei Inayoshi (KIAA), Dale Kocevski (Colby College), Takuma Izumi (NAOJ), Michael A. Strauss (Princeton), Junya Arita (U Tokyo) and the project members of JWST GO #1967, #3859

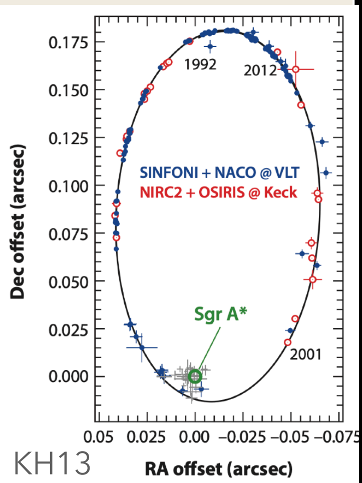
HSC

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

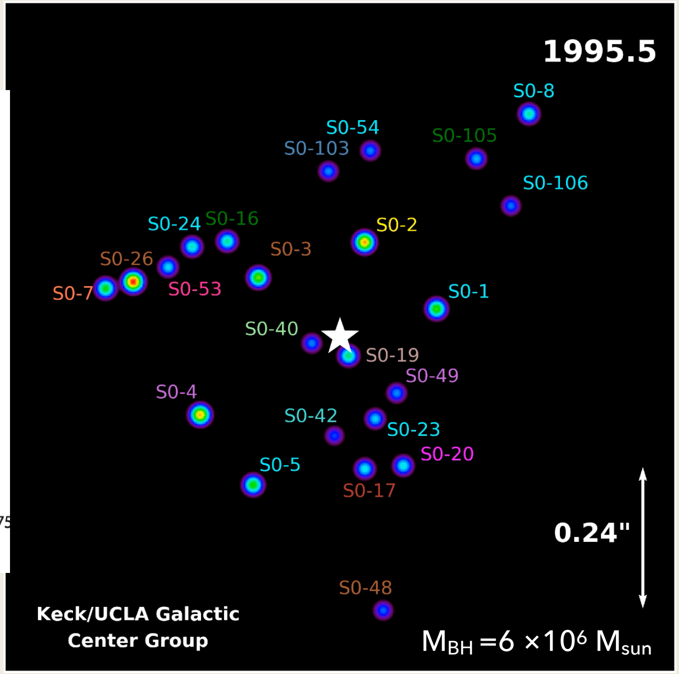
KIAA-PKU

Super Massive Black Hole (SMBH)

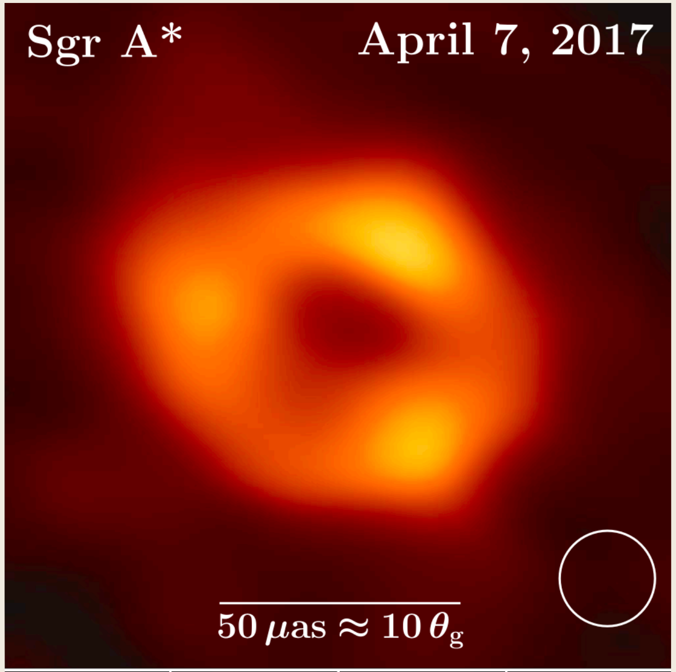
- Stellar orbit around Galactic center



KH13



- EHT image of BH shadow

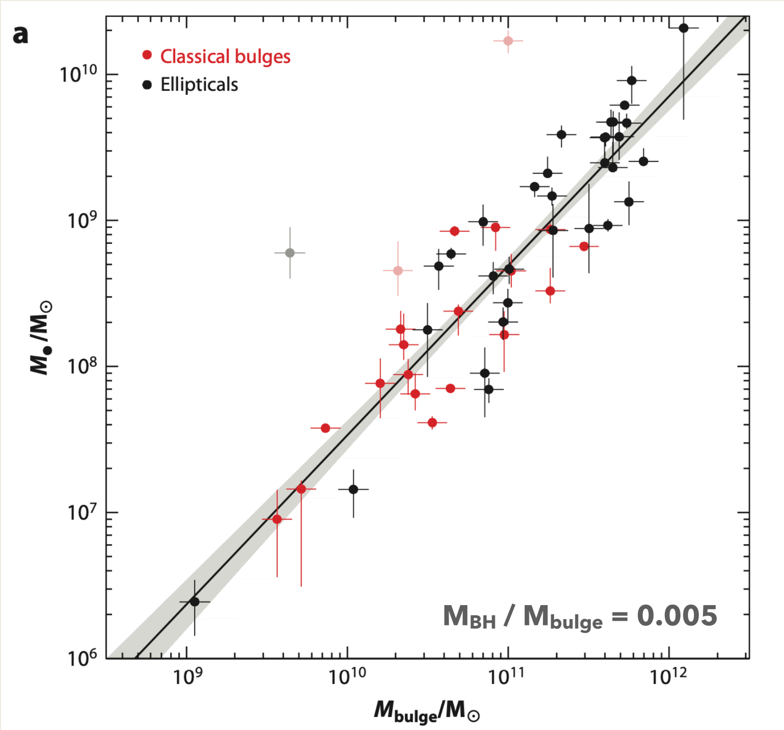


EHT collab. 2022

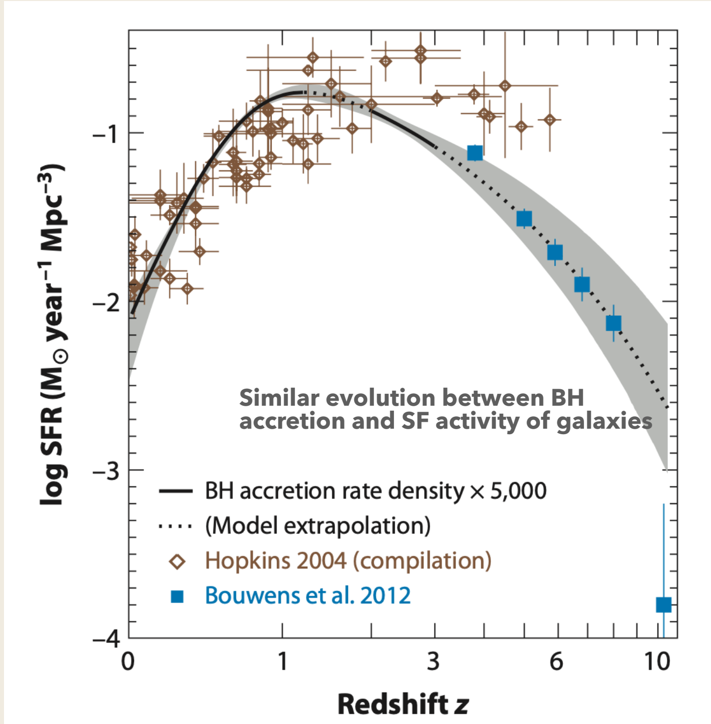
What is their origin? –> high-redshift AGN

SMBH - Galaxy Co-evolution

- BH - bulge mass relation



- Evolution of BH accretion density

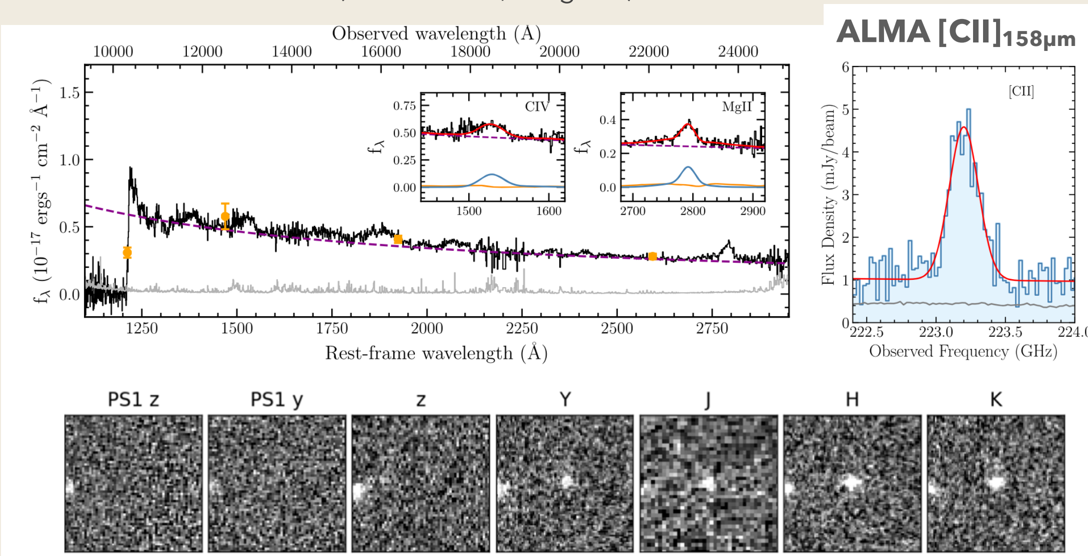


Kormendy & Ho (2013)

Cosmic ``chicken-or-egg" problem

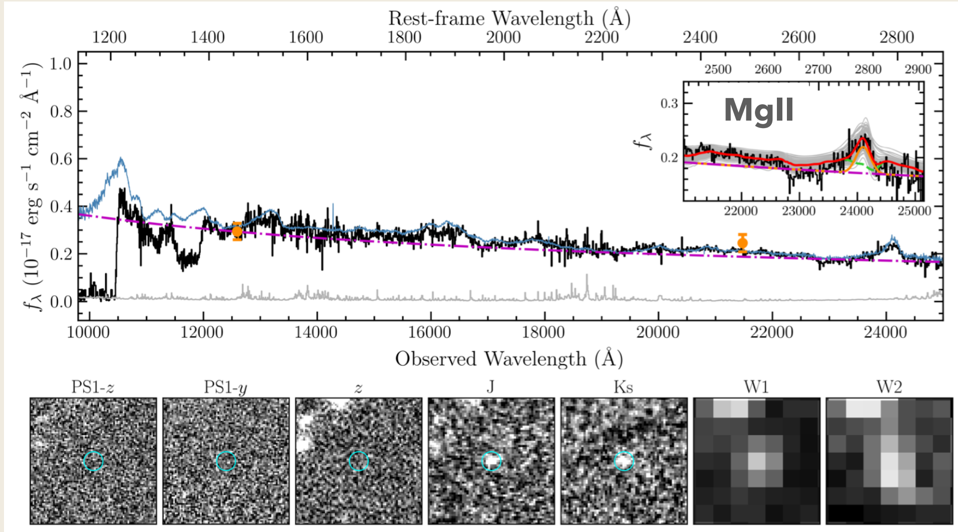
Most Distant Quasars

- J1007+2115 at z=7.515 ("Pōniuā'ena"; Yang+20)



- Selection: J & WISE detection + color cuts
- J_{AB}=20.20, M_{UV}=-26.66
- M_{BH} =1.5 x 10^9 M_{sun}, L_{bol}/L_{Edd}=1.06

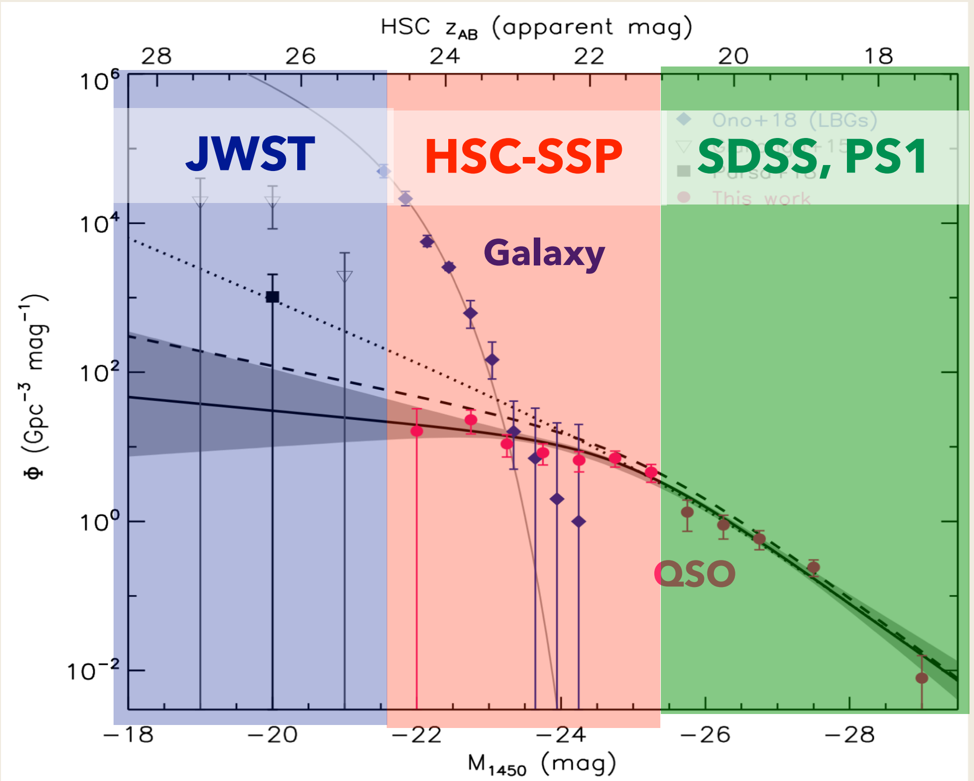
- J0313-1806 at z=7.642 (Wang+21)

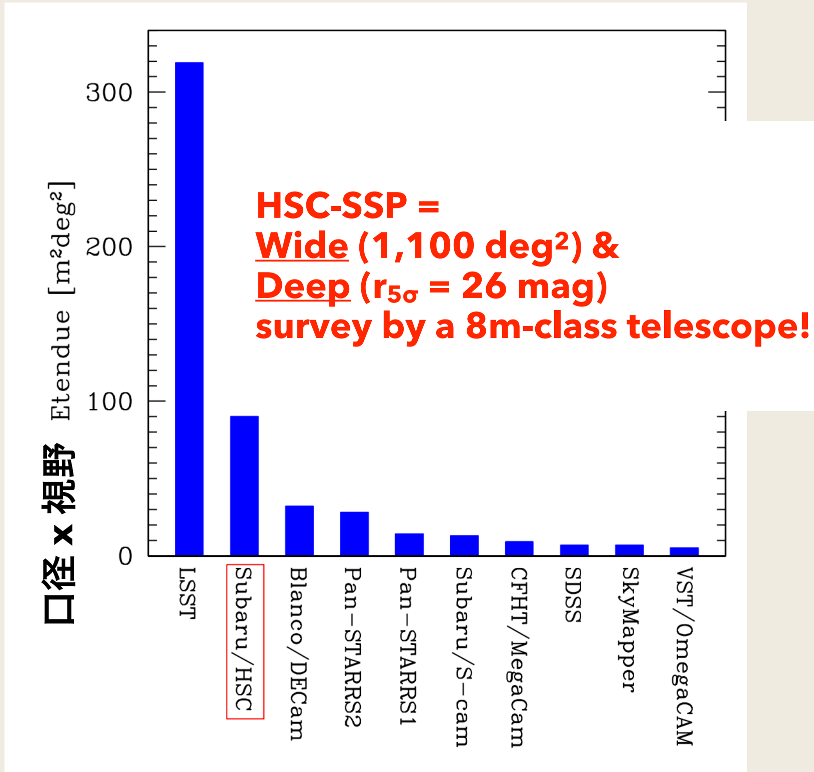


- Selection: J & WISE detection + color cuts
- J_{AB}=20.92, M_{UV}=-26.13
- M_{BH} =1.6 x 10^9 M_{sun}, L_{bol}/L_{Edd}=0.67
- Strong BAL feature in CIV & SiIV (+ MgII?)

Quasar Discovery & Wide-Field Survey

- z=6 Quasar Luminosity Function (Matsuoka+18c)

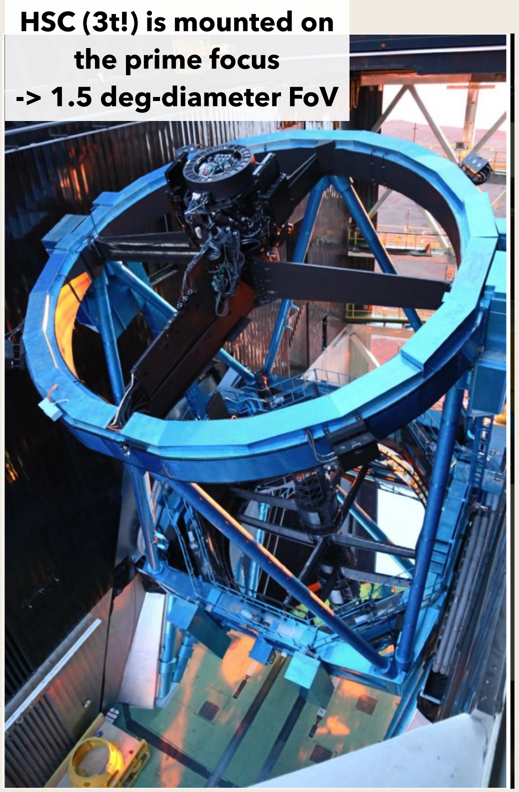


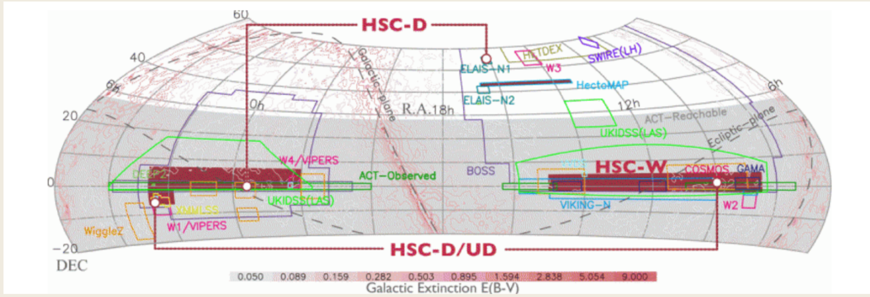


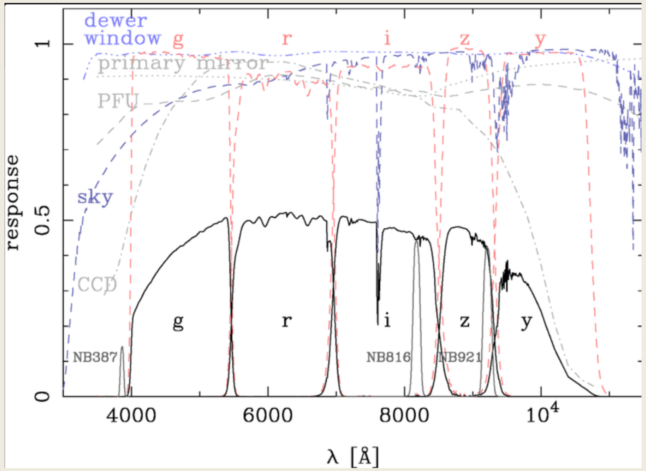
HSC-SSP white paper

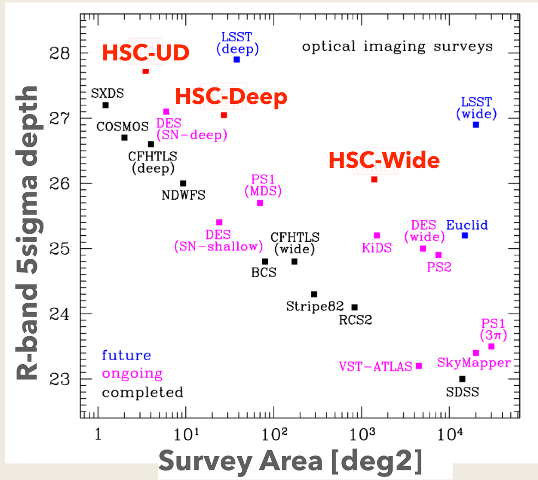
Most massive BHs -> Wide surveys, Representative BHs -> Deep surveys

HSC Subaru Strategic Program (HSC-SSP)



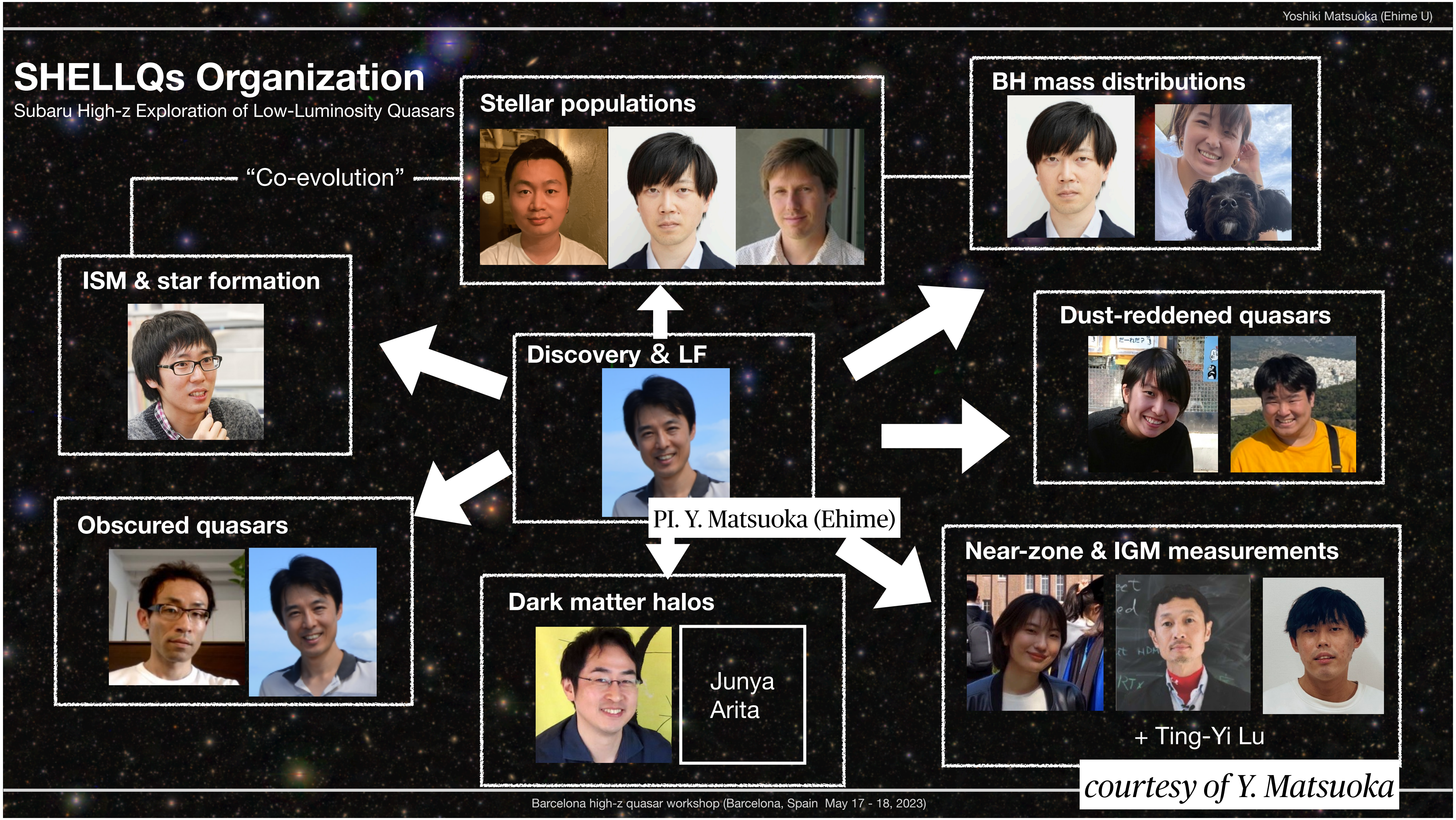




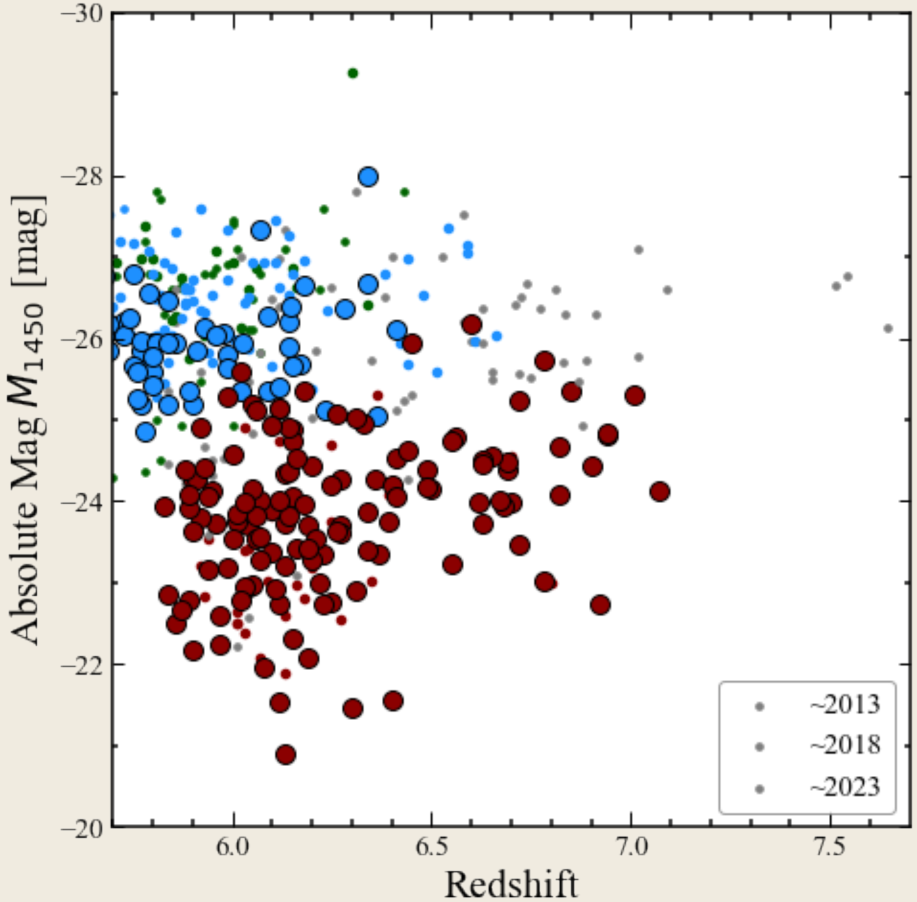


1,100 deg²-class optical survey with a 8.2m telescope ($r_{5\sigma}$~26mag)

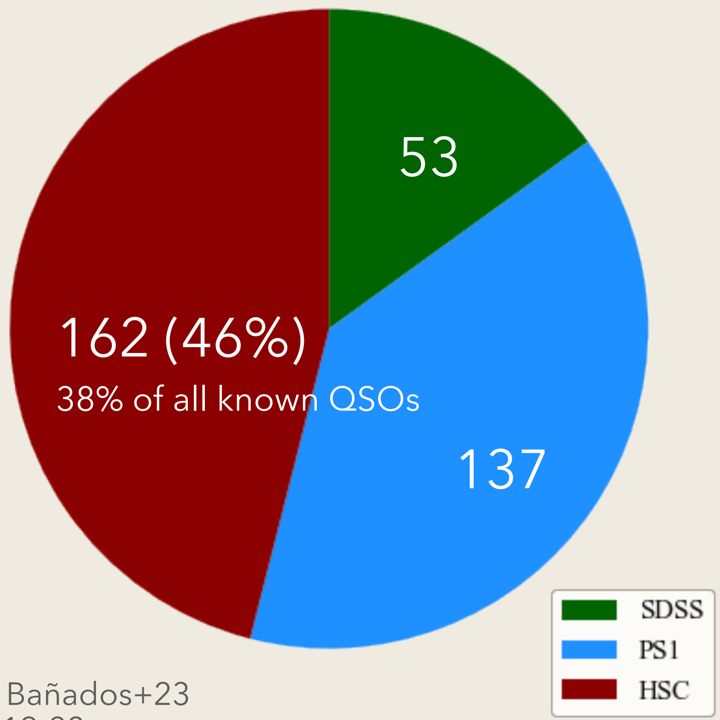
300 nights observations have completed (final public DR in prep.)


Yoshiki Matsuoka (Ehime U)
SHELLQs Organization
Subaru High-z Exploration of Low-Luminosity Quasars
"Co-evolution"
Stellar populations
BH mass distributions
ISM & star formation
Discovery & LF
Dust-reddened quasars
PI. Y. Matsuoka (Ehime)
Obscured quasars
Near-zone & IGM measurements
Dark matter halos
Junya Arita
+ Ting-Yi Lu
courtesy of Y. Matsuoka
Barcelona high-z quasar workshop (Barcelona, Spain May 17 - 18, 2023)

QSO Discovery (now)



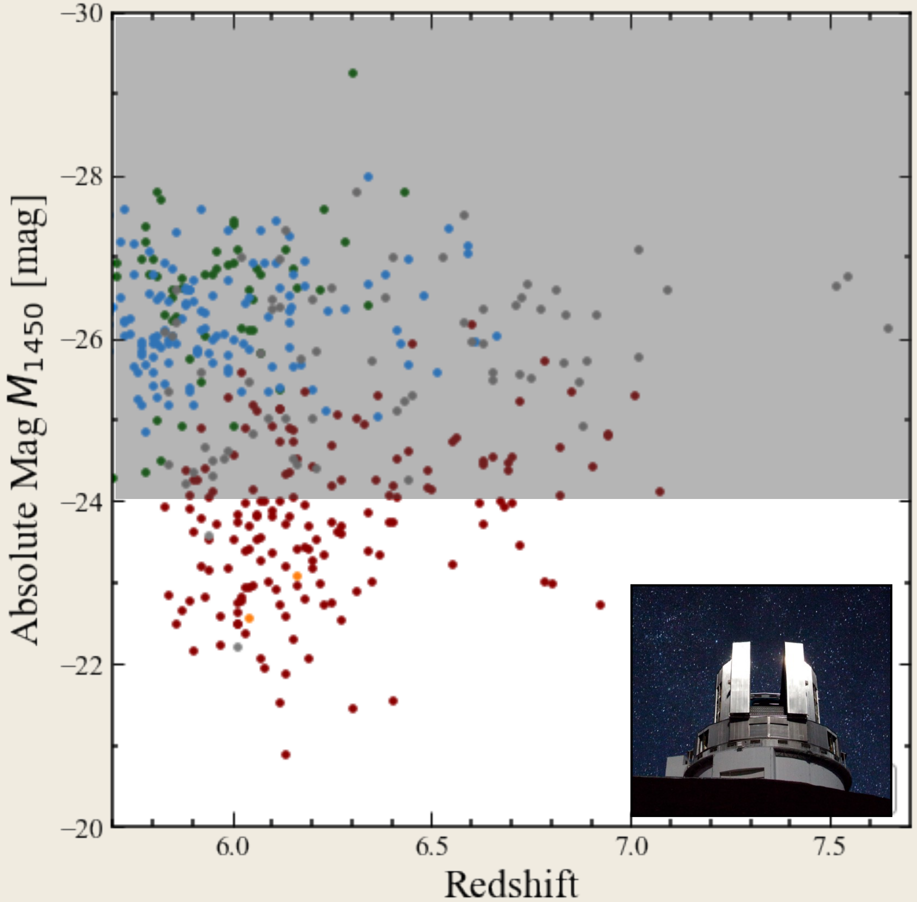
DESI not included (sorry!)



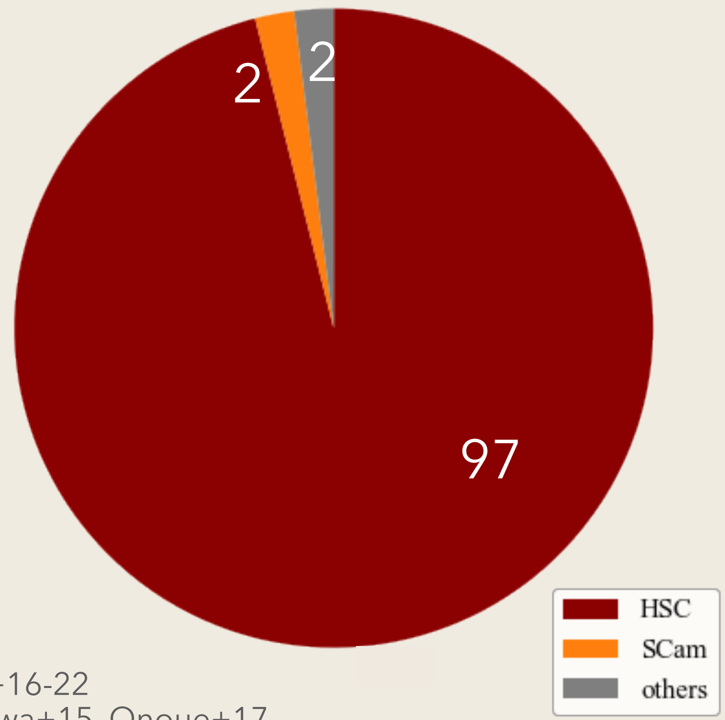
PS1: Andika+20, Bañados+23
HSC: Matsuoka+19-22
Others: e.g., Reed+19, Yang+19-20, Wang+21, Yang+23

* w/o JWST AGN (e.g., Kocevski, MO+23; Harikane+23, Matthee+23, Maiolino+23, Greene+23)

QSO Discovery (M_{1450}>-24)



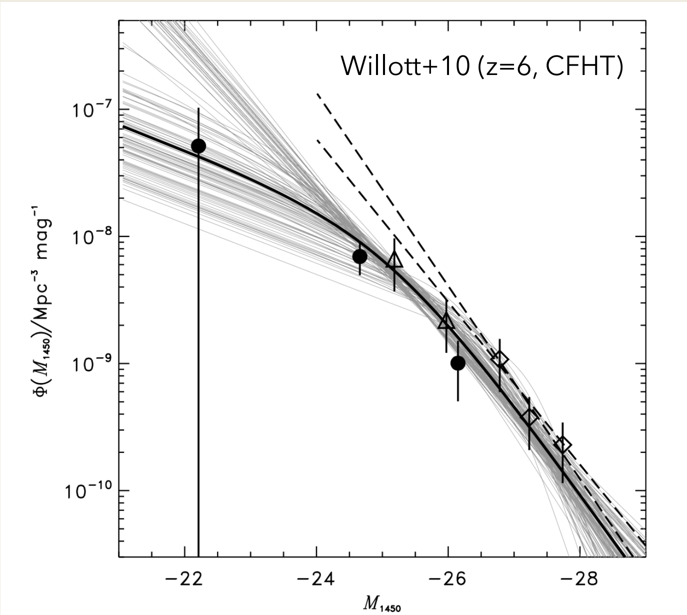
Subaru has a dominant position in high-z ``faint" quasar discovery!

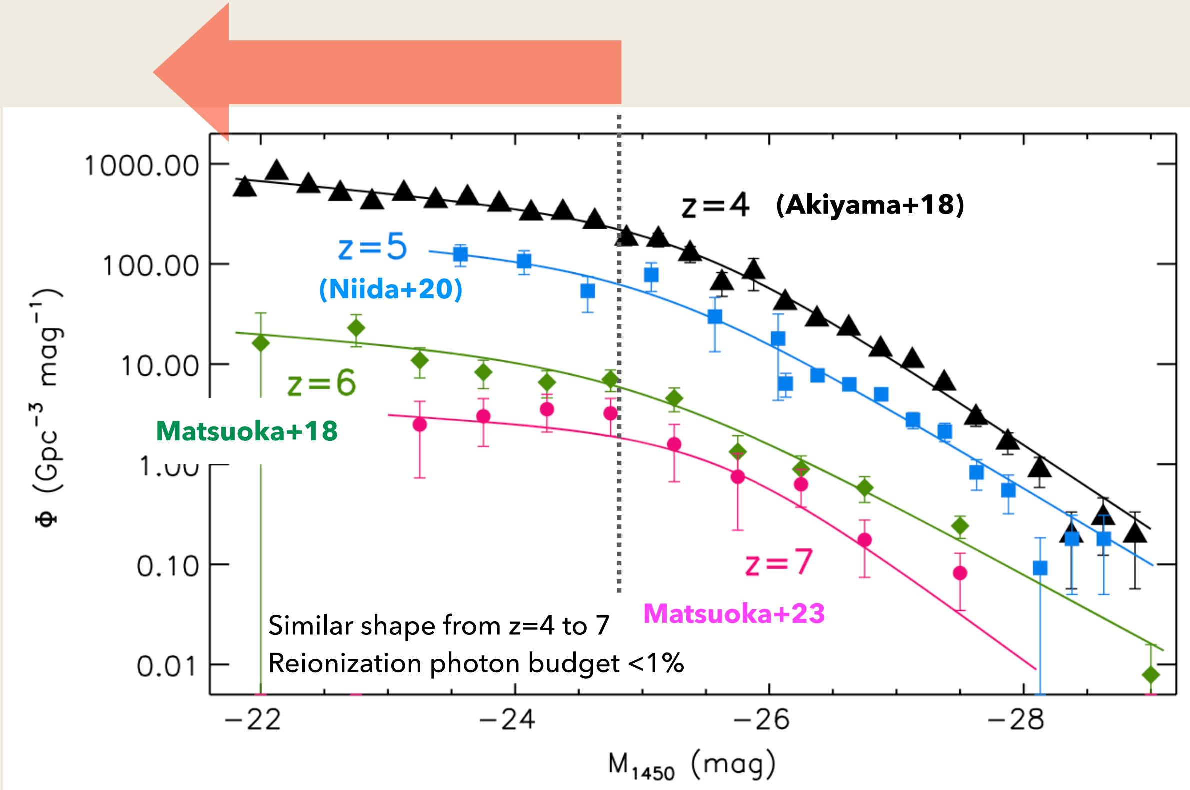


HSC: Matsuoka+16-22
Subaru: Kashikawa+15, Onoue+17
Others: Willott+09, Kim+15

* w/o JWST AGN (e.g., Kocevski, MO+23; Harikane+23, Matthee+23, Maiolino+23, Greene+23)

z=6-7 Quasar Luminosity Function (Paper V & XIX)





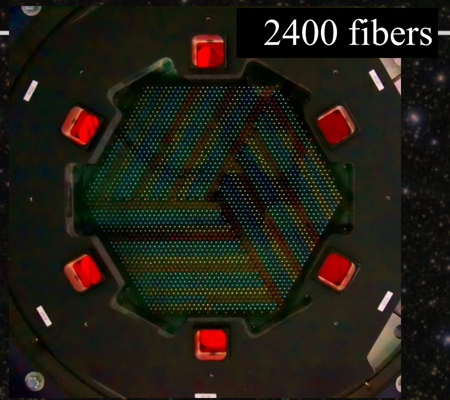
See also: e.g., Venemans+13, Jiang+16, Wang+19, Kulkarni+19, Schindler+22, and recent JWST red AGN works (e.g., Kocevski+23, Harikane+23, Matthee+23, Maiolino+23, Greene+23)

HSC-r

AGN observations in PFS-SSP (Prime Focus Spectrograph)

- ✶ ~11,000 fibers (tbc) in the GE field
  … Discussion ongoing in the GE-AGN sub-WG, led by Yoshiki Toba
- ✶ ~36,000 fibers (tbc) in the CO field
  … Will be proposed as ancillary science targets (with internal priorities?)

Targets being finalized based on HSC-SSP catalog

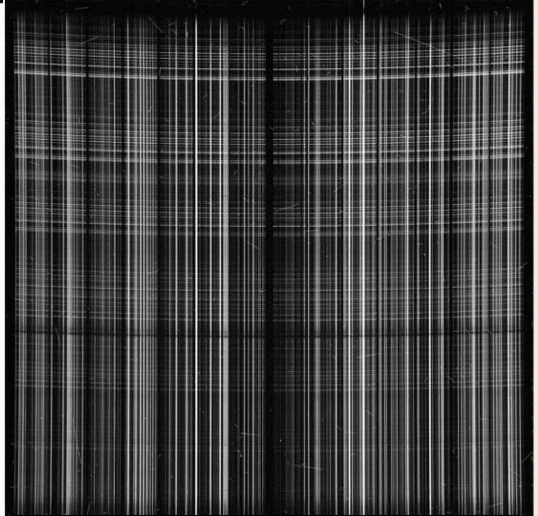


PFS public-facing document (arXiv:2206.14908 Greene et al.)

Table 4
Target selection and observing strategy

Targets (1)	Selection (2)	$N_{\rm AGN}^{\rm total}$ (3)	$N_{\rm AGN}$ (4)	$N_{\rm fiber}$ (5)	$T_{\rm exp}$ (6)	$N_{\rm fiber}T_{\rm exp}$ (7)
GE field						
BL candidates ($z < 4$)	CFHT u – *Spitzer* colors	5,700	3,000	6,000 (0.5)	1 – 4	15,000
BL candidates ($z > 4$)	HSC – *Spitzer* colors	500	500	1,000 (0.5)	4 – 5	4,500
X-ray sources	*Chandra*, *XMM-Newton*	10,000	2,000	2,000 (1.0)	4 – 5	9,000
Sub-mm galaxies	SCUBA-2 w/ ALMA counterparts	300	300	1,000 (0.3)	5	5,000
Radio galaxies	FIRST	200	200	300 (0.7)	3	900
IMBH candidates	HSC flux variability	30	30	300 (0.1)	2	600
Total			6,030	10,600		35,000
CO field						
BL candidates ($z > 4$)	HSC colors	15,000	15,000	30,000 (0.5)	0.5	15,000
X-ray sources	*eROSITA*	1,700	1,700	1,700 (1.0)	0.5	850
Mid-IR sources	WISE 22 μm	1,000	1,000	1,500 (0.7)	0.5	750
Radio galaxies	FIRST	20,000	1,500	1,700 (0.9)	0.5	850
Lensed quasar candidates	HSC shapes	100	100	1,100 (0.1)	0.5	550
Total			19,300	36,000		18,000

Note. — Columns (1) target; (2) selection method; (3) total number of AGNs expected over the entire survey field; (4) number of AGNs we aim to observe; (5) number of requested fibers (the number in parenthesis represents the expected success rate of AGN identification, i.e., $N_{\rm AGN}/N_{\rm fiber}$); (6) exposure time (hr); (7) fiber hours.



from engineering run (NGC 1980)

courtesy of Y. Matsuoka

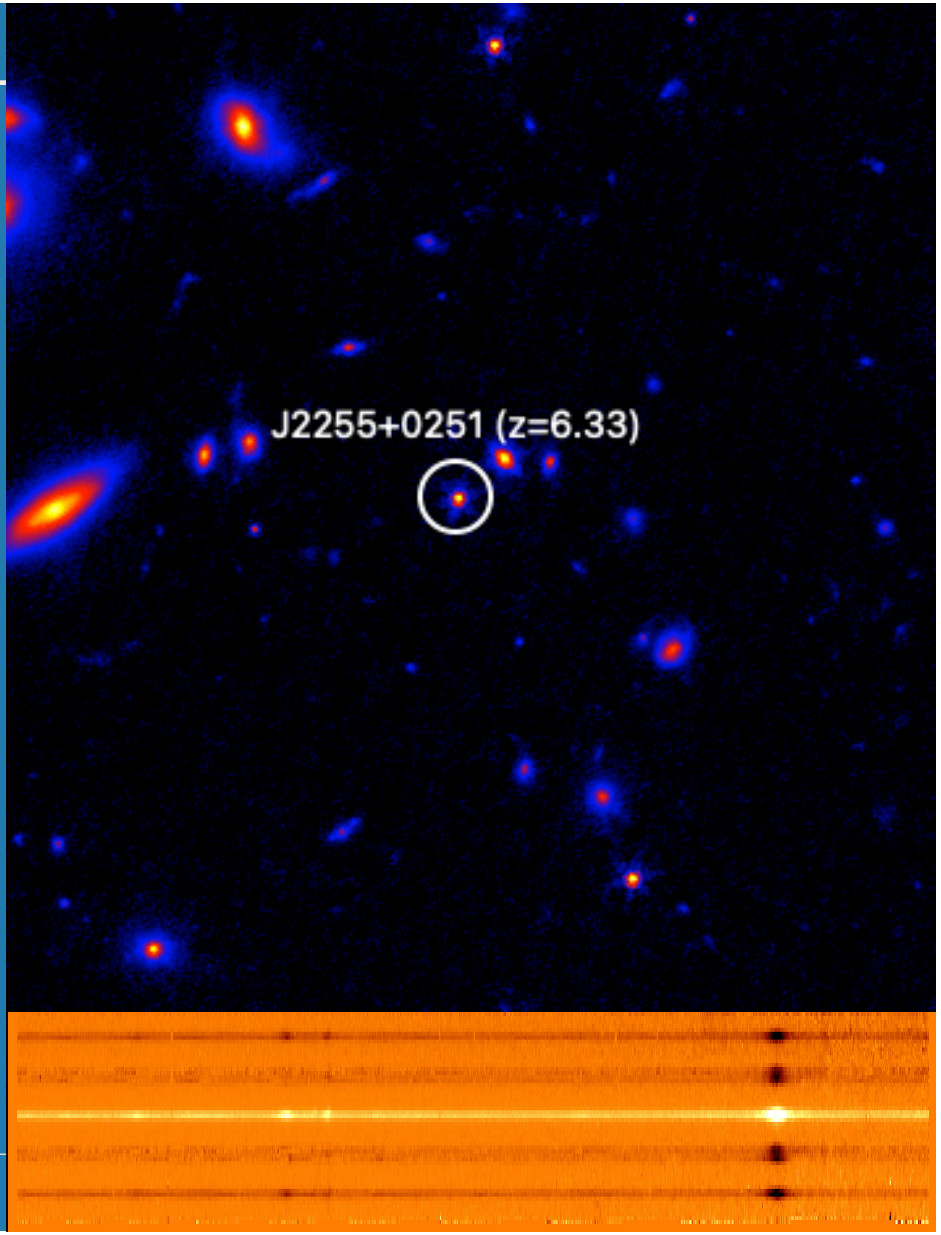
JWST follow-up of z~6 HSC quasars

Cy1 JWST #1967 (50hr)

``Full Census of SMBHs and Host galaxies at z=6"

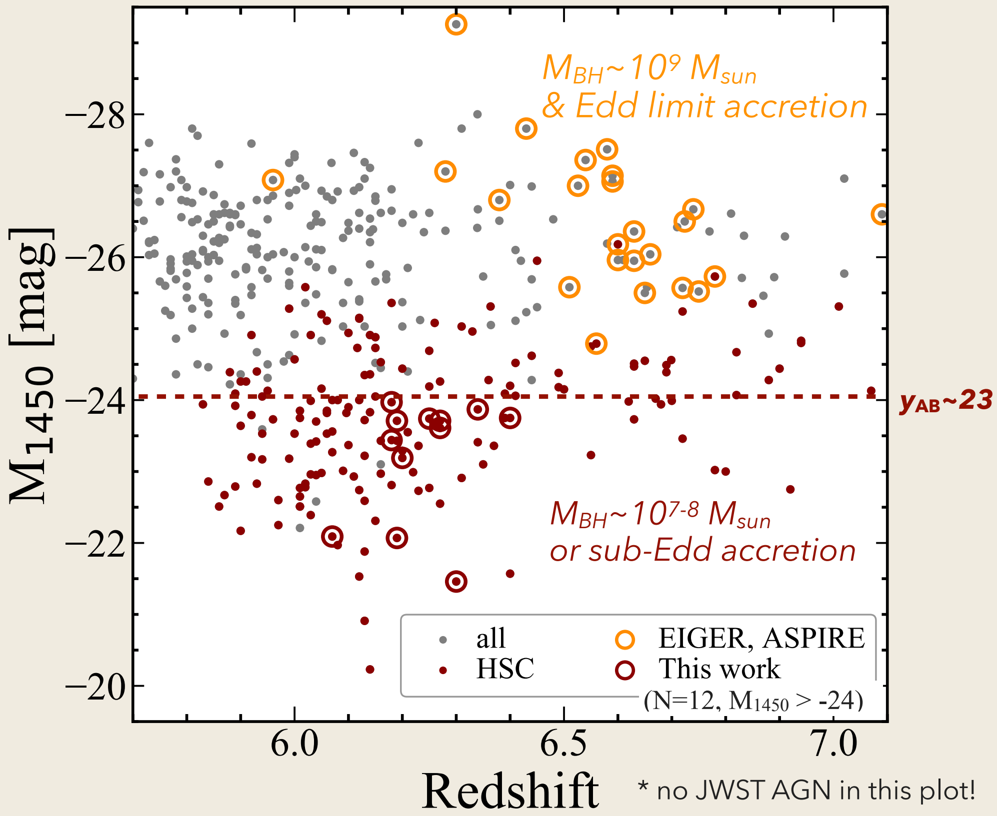
PI: M.Onoue (KIAA/IPMU)

Co-PIs: X.Ding, J.Silverman (IPMU), T.Izumi (NAOJ), Y.Matsuoka (Ehime)

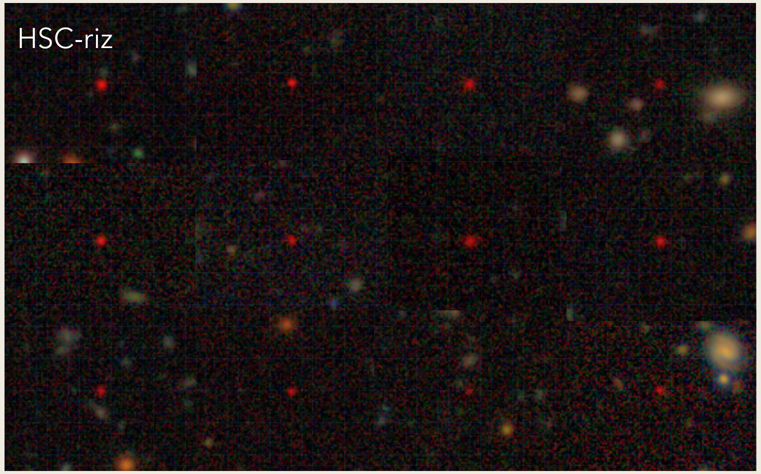


GO 1967: Full Census of SMBHs and Host Galaxies at z=6 (50hr)

PI: M.Onoue (IPMU / KIAA)
Co-PIs: X.Ding, J.Silverman (IPMU), Y.Matsuoka (Ehime), T.Izumi (NAOJ)
Co-Is: M.Strauss (Princeton), K.Jahnke (MPIA) + 38 collaborators



* no JWST AGN in this plot!



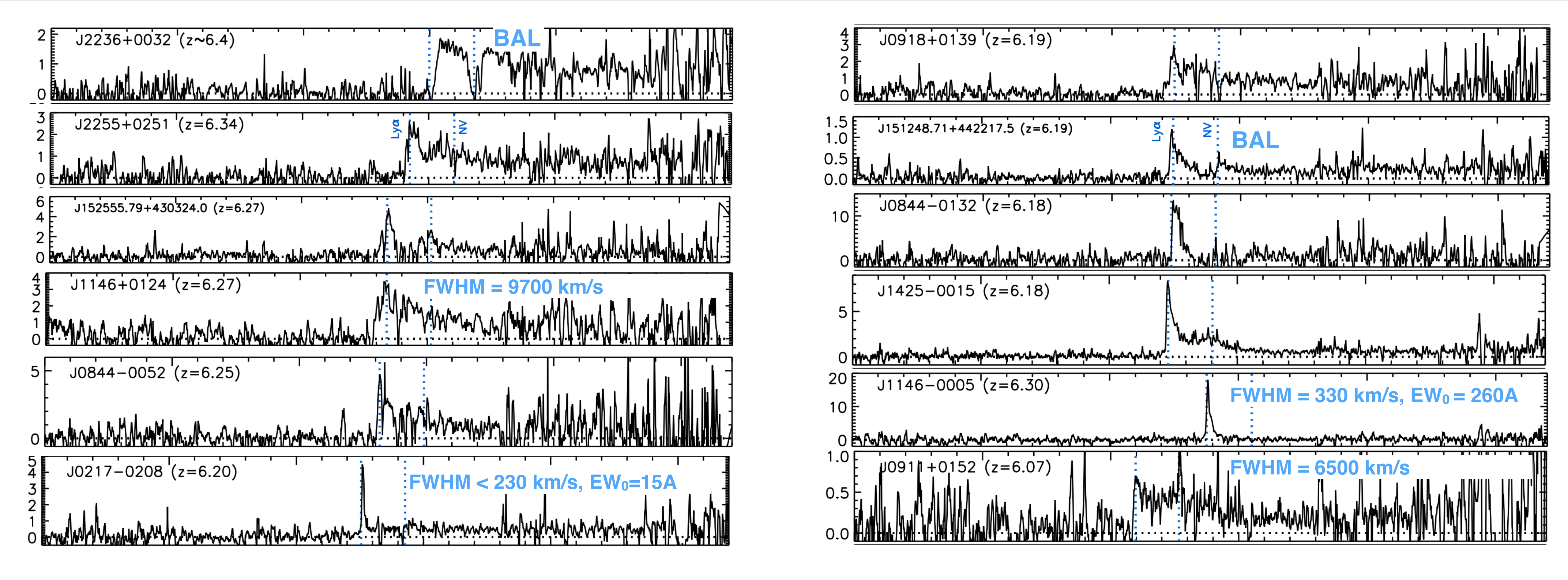
Matsuoka+16-22

✦Targets: 12 moderate-luminosity AGN discovered by the HSC-SSP (1,100 deg^2, $r_{5\sigma}$~26)

- $6.18 < z < 6.40$
- $M_{1450} > -24$ (ground-based limit for NIR spectroscopy)

Cy1 Targets: Faintest z=6 Quasars

- Optical spectra (y_{HSC}=23.0-24.8 AB mag, M_{1450} > –24); Targets extracted from Matsuoka+18's QLF sample



- NIRCam Imaging
  - Filter: F150W + F356W (straddling 4000Å break)

➡ Host detection

  - **M_***, size, age, companions

\+

- NIRSpec Fixed-Slit spectroscopy
  - Grism: G395M (R=1000), 2.87-5.27μm (rest 4000-7300Å, incl. Balmer lines)

➡ Rest-optical emission line measurements

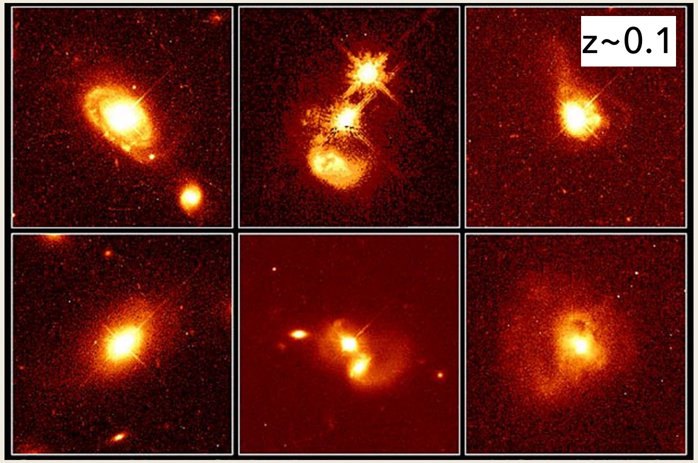
  - Hβ-based **M_{BH}**, BLR/NLR, [OIII] outflow

✦ Mean (and scatter of) **M_{BH} / M_*** ratio at z=6

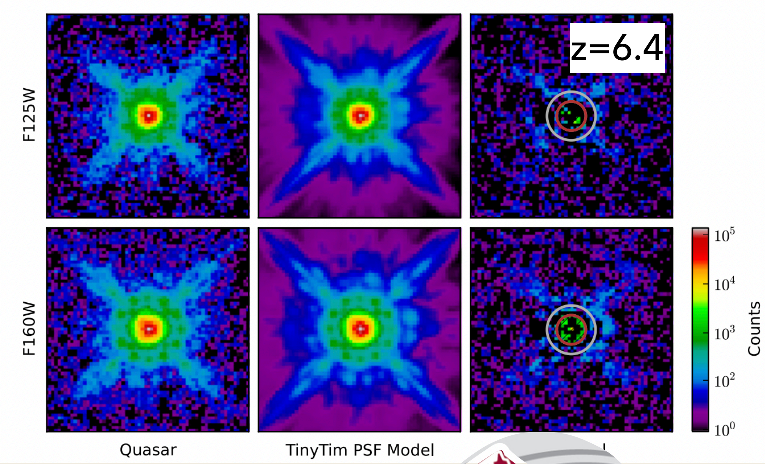
✦ BH mass function, Eddington ratio distribution

✦ M_* vs M_{dyn}, nuclear & host-scale gas outflow (with Cy9 ALMA; PI: T.Izumi)

Challenge in Resolving Host Stellar Emission

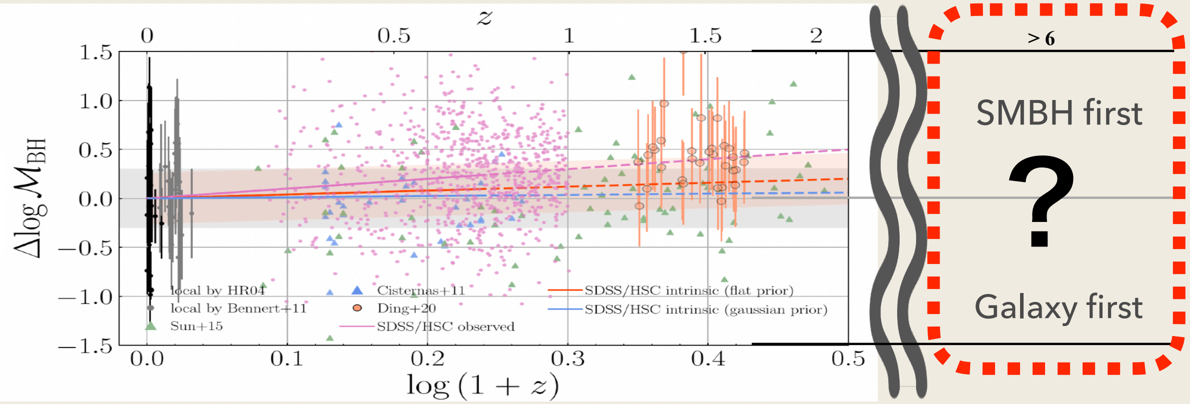


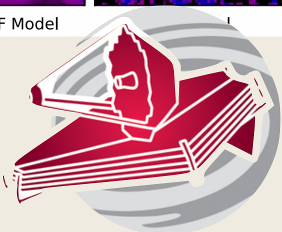
Credit: John Bahcall/Mike Disney/NASA/ESA



Mechtley+12

offset from local Mbh-M* relation





HST and ground-based studies are limited up to z~1.5

JWST!

Decomposition tool ***Galight***:

1. Determine a suitable cutout size for the image frame.

2. Search PSFs in the FOV.

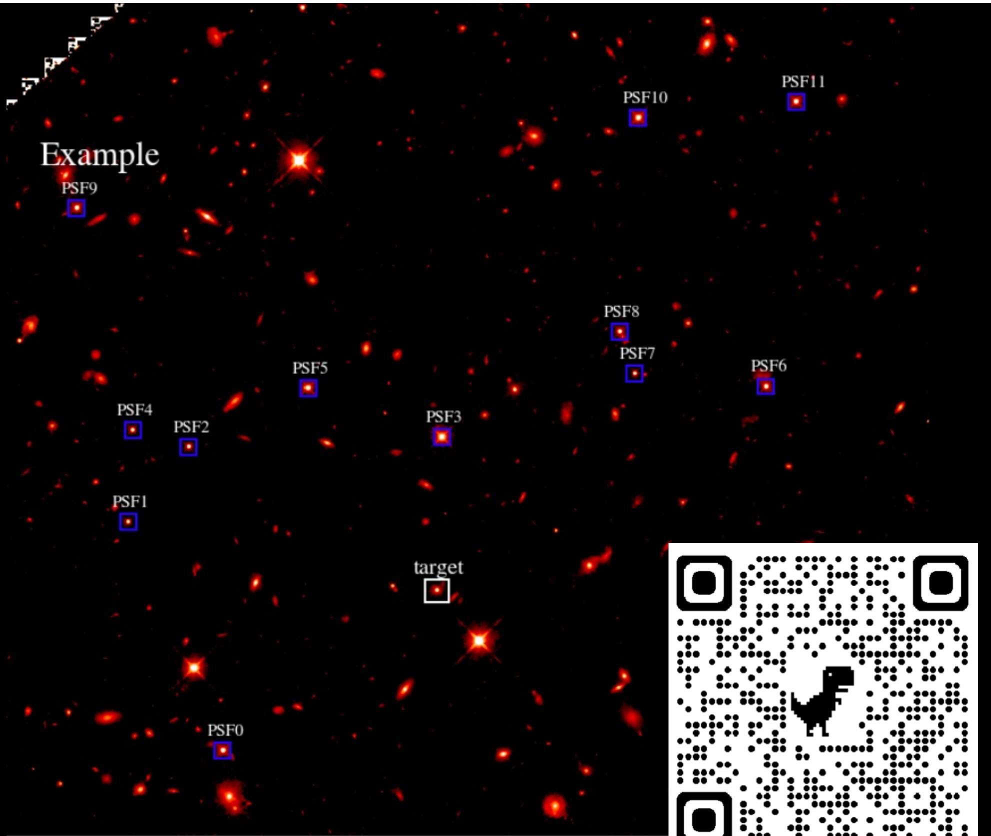
3. If needed, a noise map can be generated using the exposure time and the background noise level from empty regions.

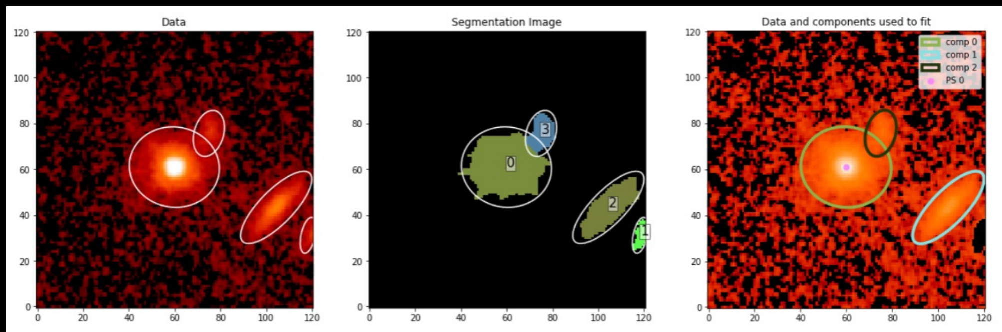
4. Neighboring sources can be masked or simultaneously modeled.

5. By default, the parameter settings for all the fitting sources will be assigned automatically.

6. Output data products are generated for full assessment of the goodness-of-fit with the ability to share across different platforms.

7. Perform galaxy morphology measure, non-parameters including asymmetry, concentration, smoothing, Gini, M20.

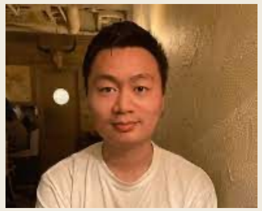




Galight:

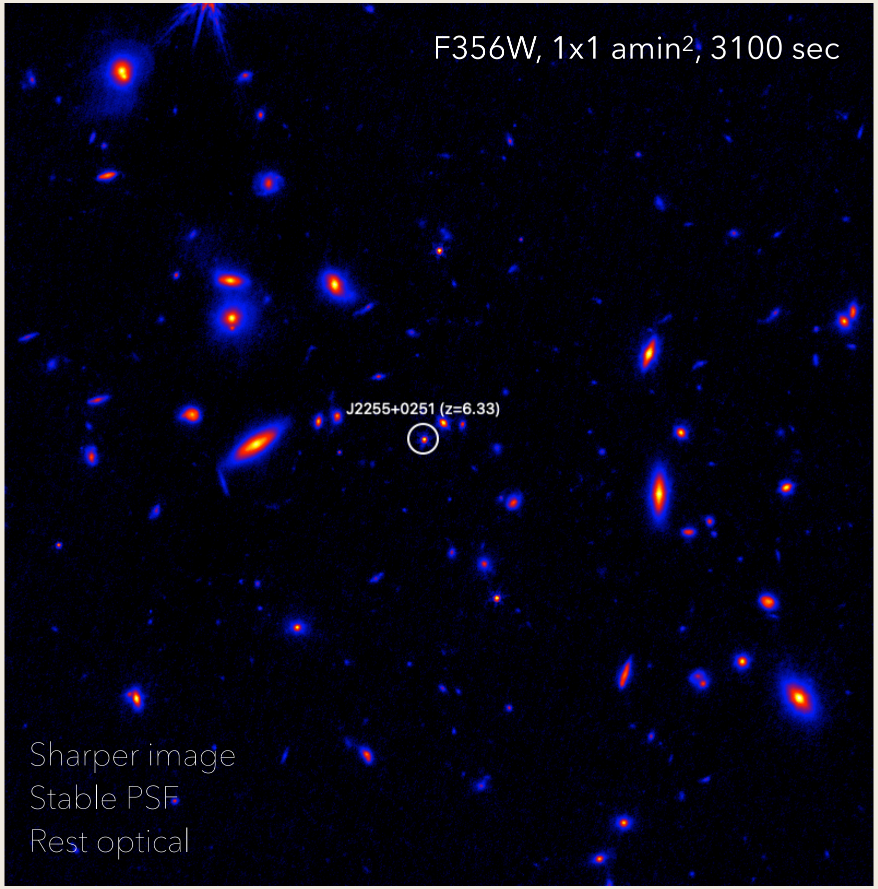
a 2D image modeling tool based on LENSTRONOMY (originally developed for modeling gravitational lens systems)

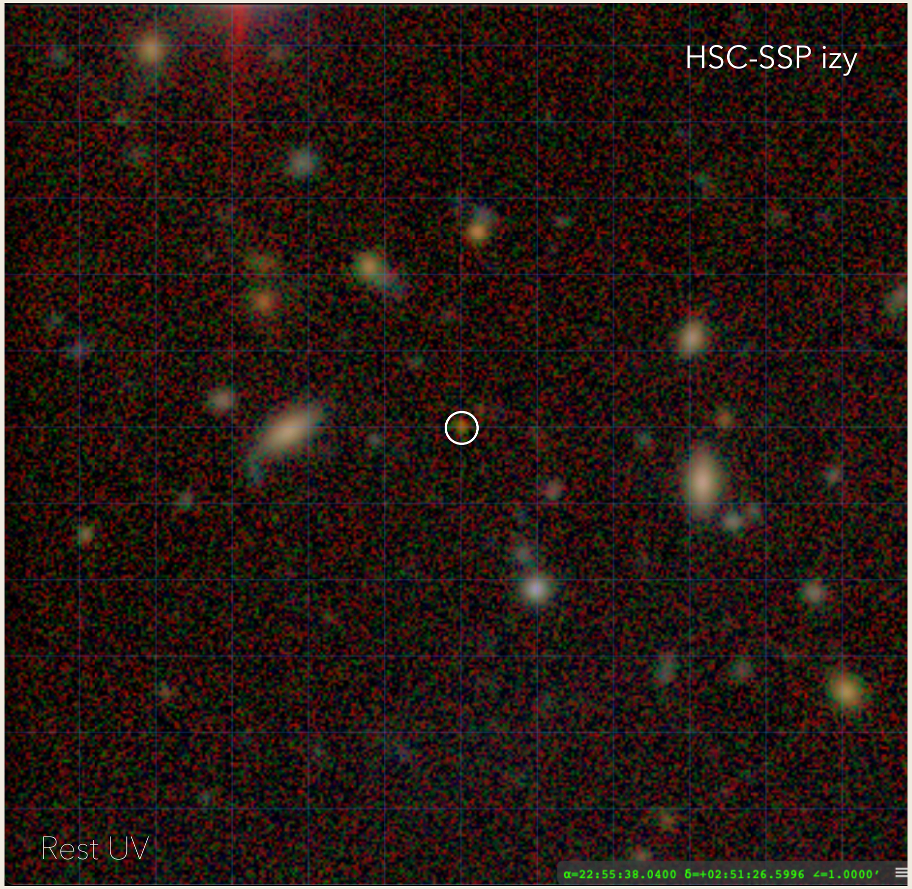
Tested in HST images of 1<z<2 QSOs (Ding+20a) and JWST images of 2<z<4 QSOs (Ding+22, +23)



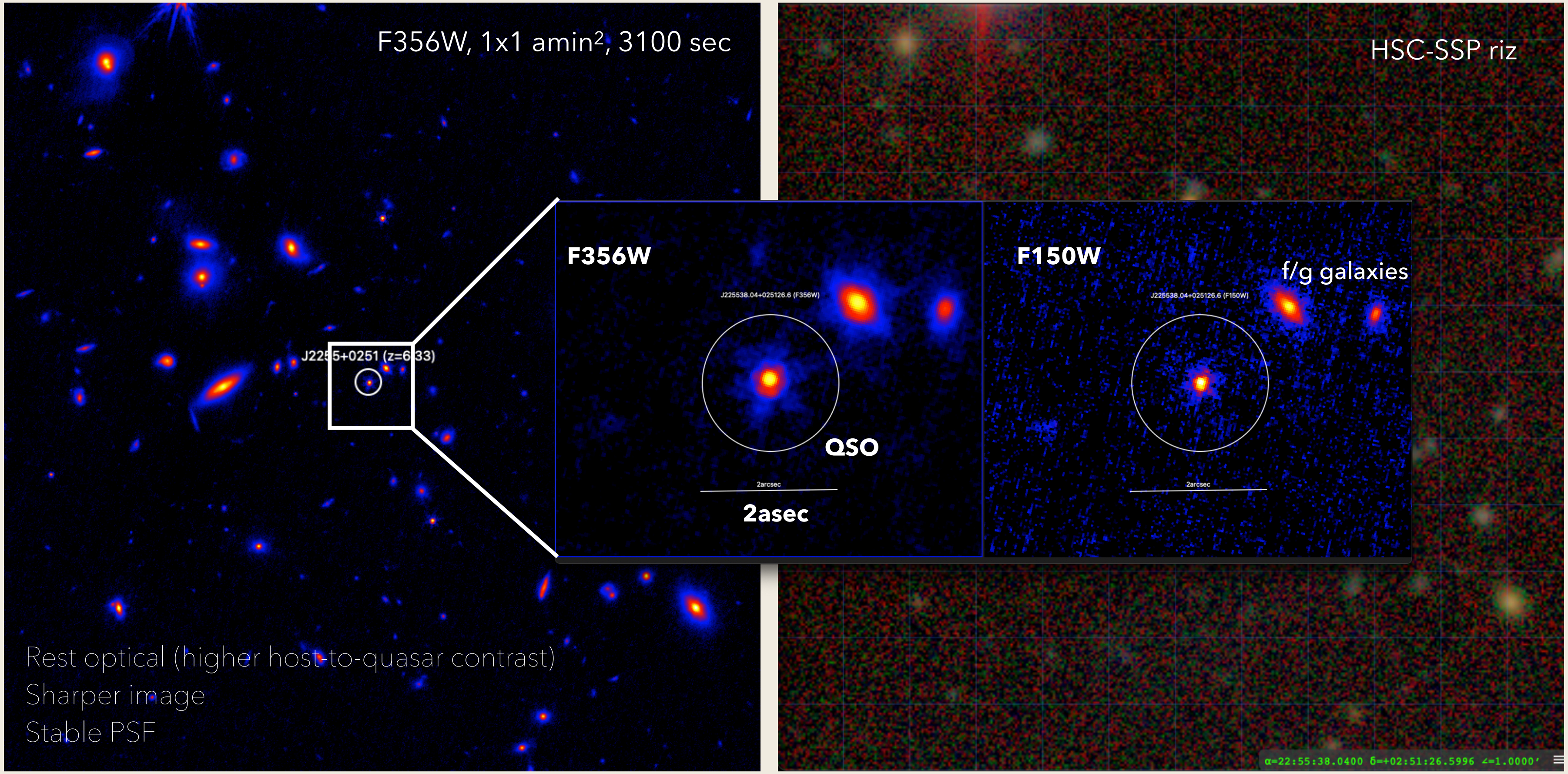
Developed by X.Ding (IPMU -> Wuhan U.)

NIRCam: HSC J2255+0251 (z=6.33)





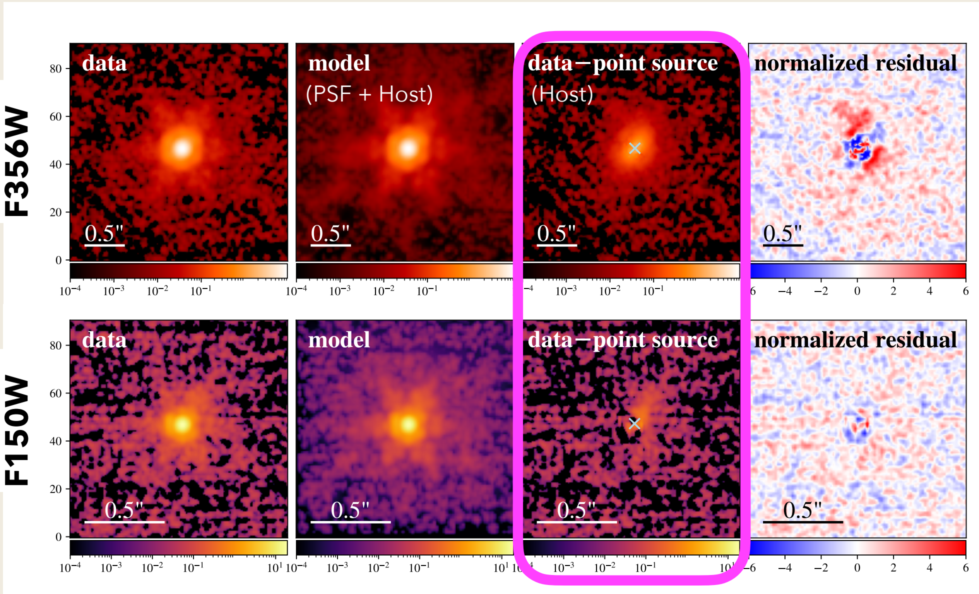
NIRCam: HSC J2255+0251 (z=6.33)

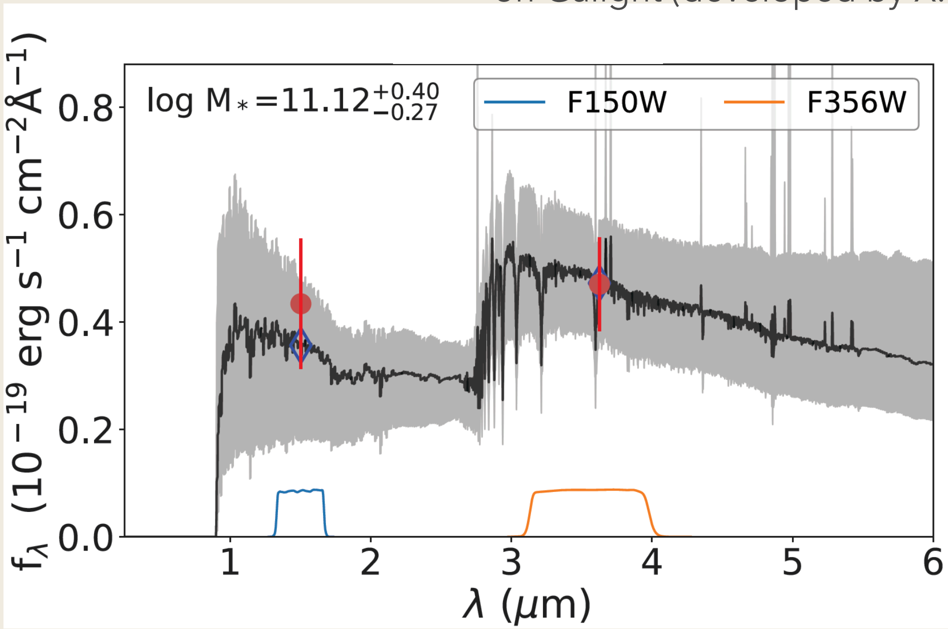


Host Starlight Detection at z>6:

J2236+0032 (z=6.40, y_{AB}=23.2, M_{1450}=-23.8)

2D image decomposition based on Galight (developed by X.Ding)



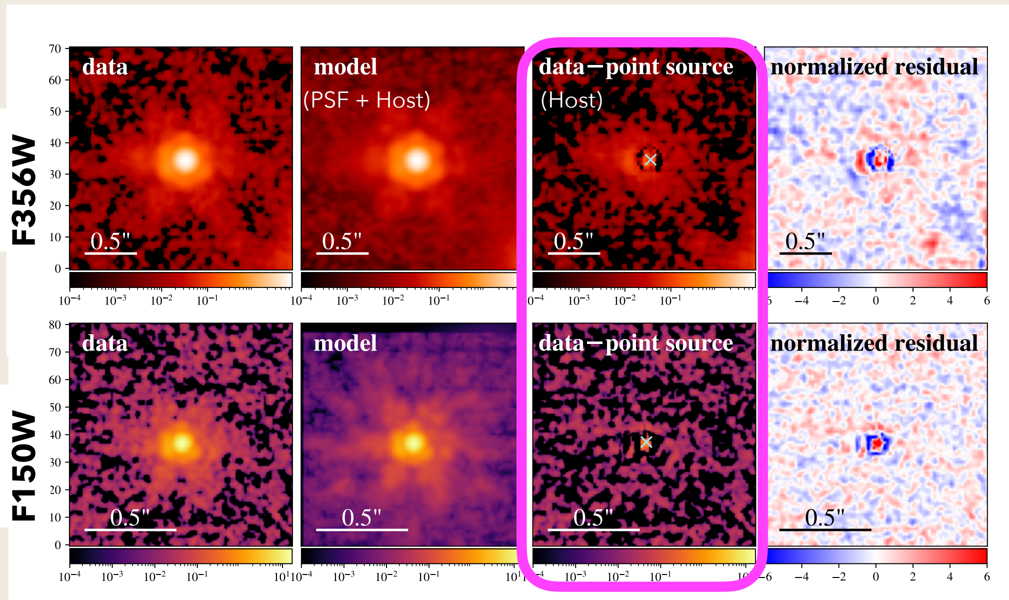


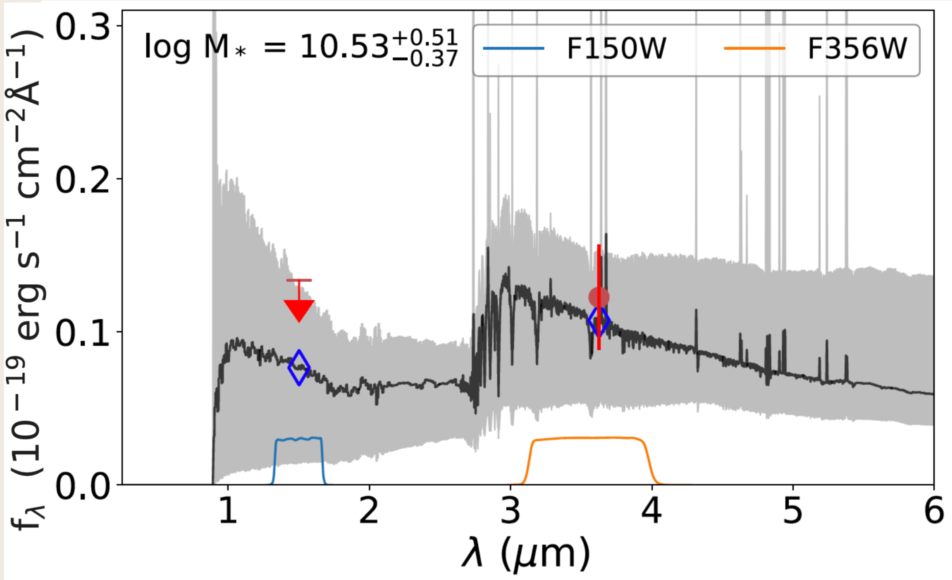
Host fraction		Host mag		Stellar mass
F356W	F150W	F356W	F150W	[log M*/M☉]
25.5%	10.2%	23.12 (0.20)	25.12 (0.29)	$11.12^{+0.40}_{-0.27}$

Ding, Onoue, Silverman et al. (2023)

Host Starlight Detection at z>6:

J2255+0251 (z=6.34, y_{AB}=23.0, M_{1450}=-23.9)





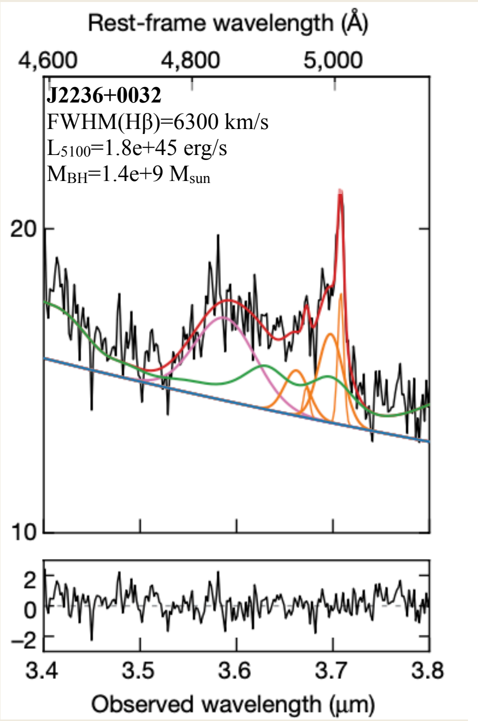
Host fraction		Host mag		Stellar mass
F356W	F150W	F356W	F150W	[log M*/M☉]
9.8%	< 3.8%	24.58 (0.30)	> 26.3	$10.53^{+0.51}_{-0.37}$

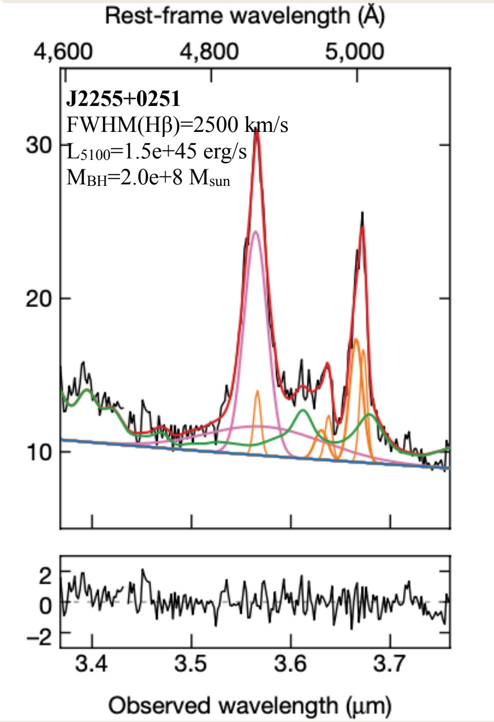
Ding, Onoue, Silverman et al. (2023)

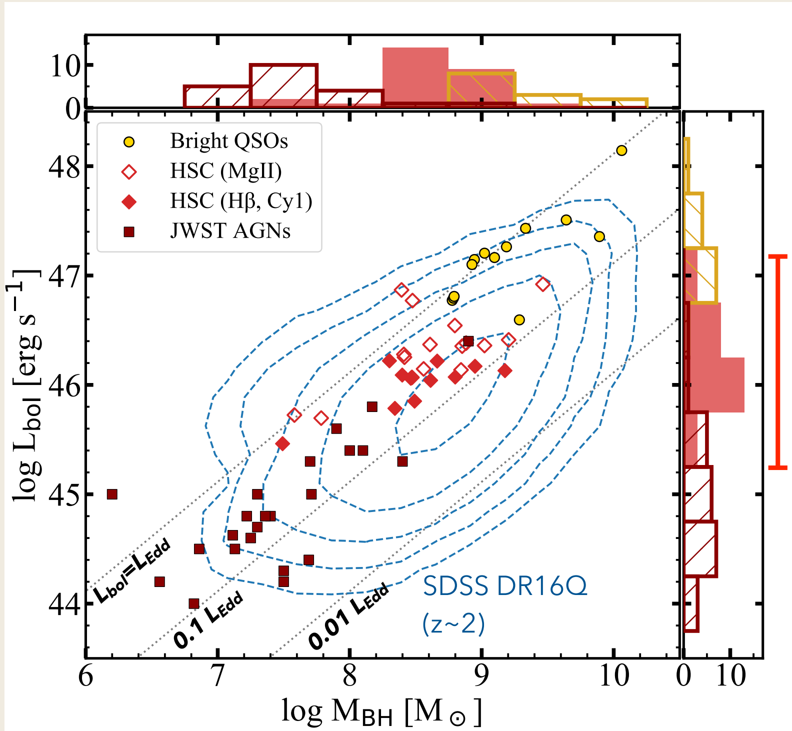
A rich variety of z>6 hosts (7 detection out of 10)

Ding. MO et al. in prep.

M_{BH} vs Bolometric Luminosity







Eilers+22
Yang+23
Yue+23

This work

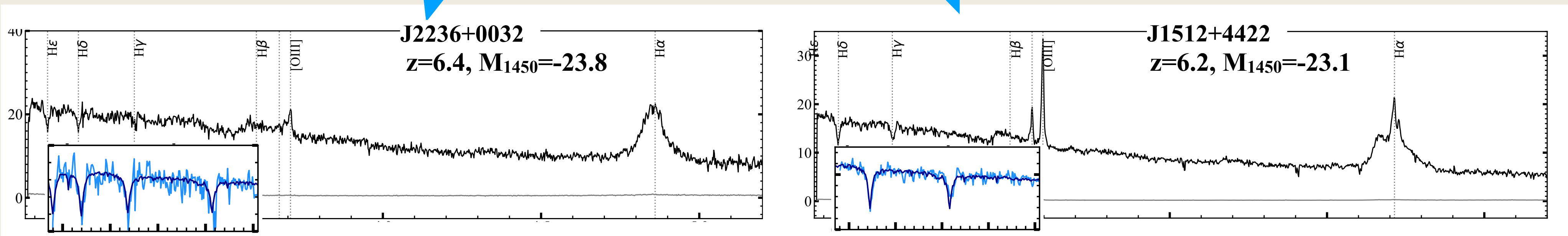
Kocevski+23
Maiolino+23c
Greene+23

z=6 BHMF measurement ongoing…

Moderate-luminosity HSC quasars prefer log M_{BH}/M_{sun} ~ 8.5, 20-30% Edd limit

A Rich Variety of z>6 Hosts (7 detection out of 10)

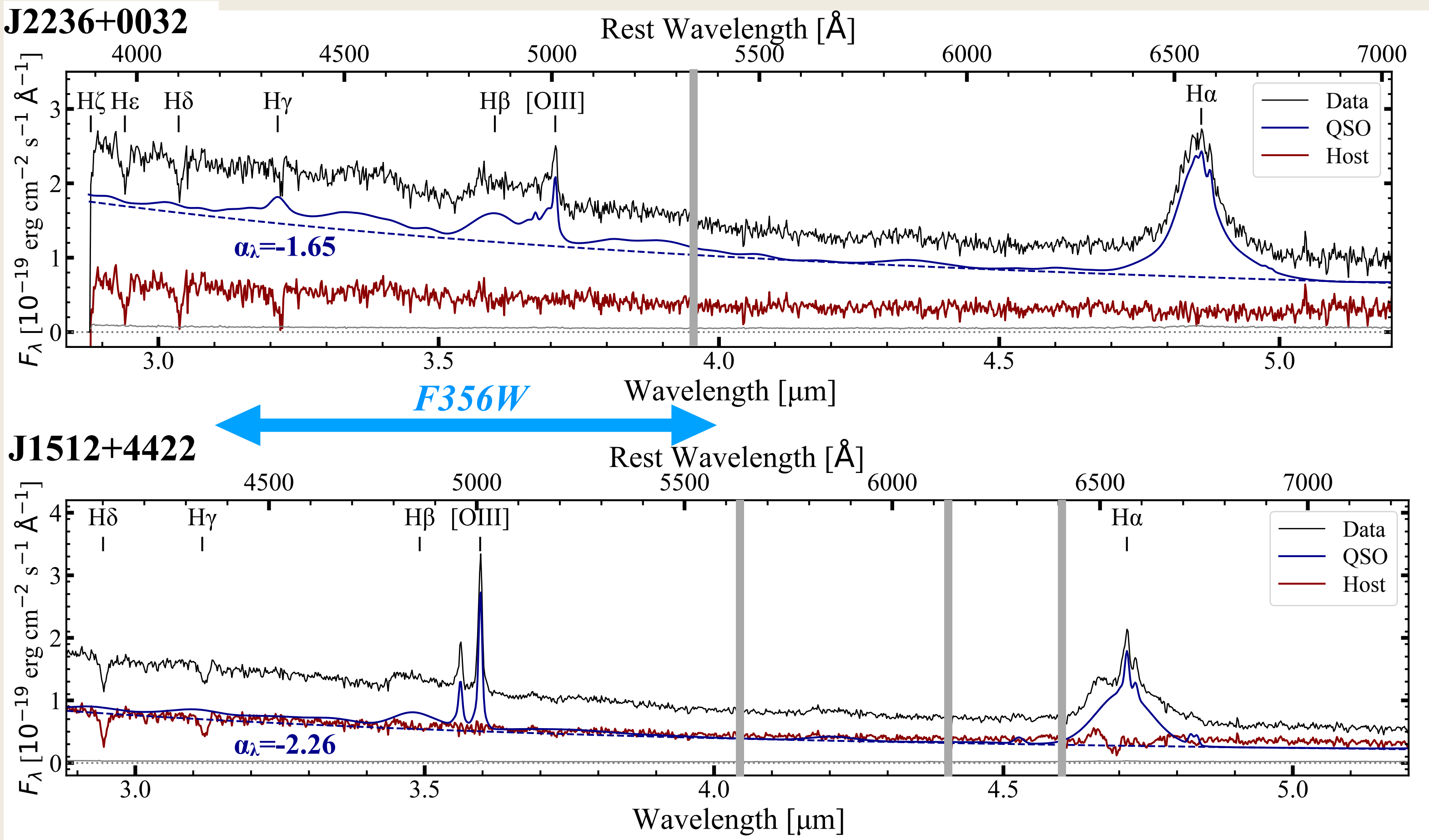
Post-starburst signature in z=6 quasar hosts



$\sigma_* < 240$ km/s (2σ)

$\sigma_* = 200^{+40}_{-40}$ km/s

Spec decomposition



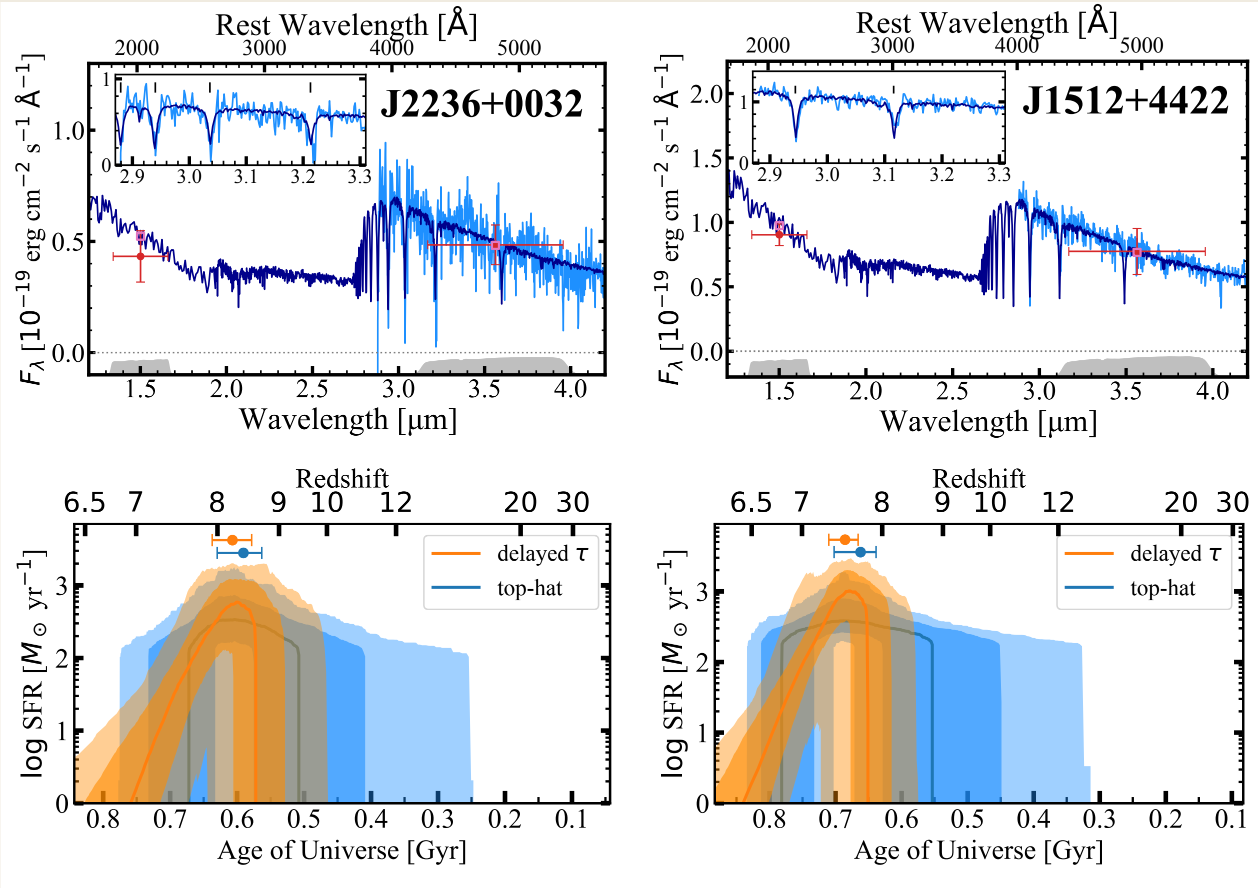
✦Extraction of host spectrum

1. QSO: single PL + emission lines (QSOFitMORE: Fu+21)
2. Quasar model matched to F356W PSF photometry
3. Host = Total - QSO (scaled by x1.04 for J2236 & x1.38 for J1512)
4. Run Bagpipes

✳Step 1-4 iterated to update QSO PL slope (α_λ; $F_\lambda \propto \lambda^{\alpha_\lambda}$)

Onoue+in prep.

Spectrophotometric SED fit



ID	J2236+0032		J1512+4422	
SFH	delayed-τ	top hat	delayed-τ	top hat

✦ ***Joint SED fit with NIRCam & NIRSpec data***

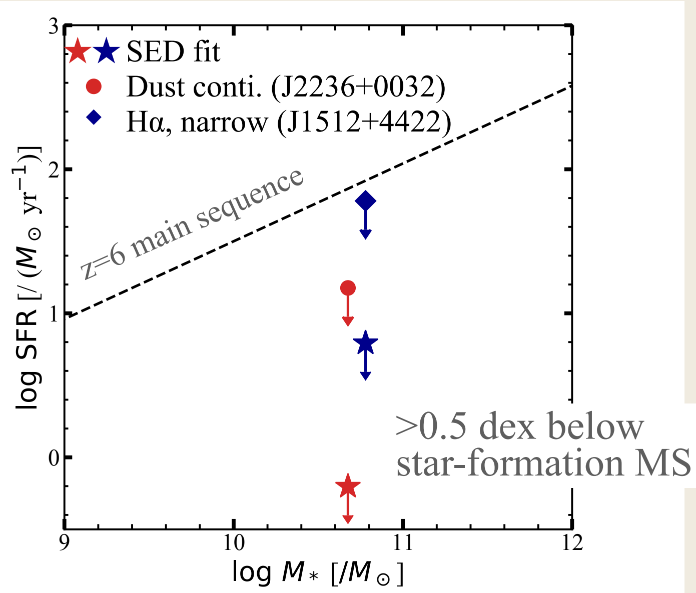
- SFH: delayed tau & constant
- Z_{star}=0.5 Z_{sun} (fixed)

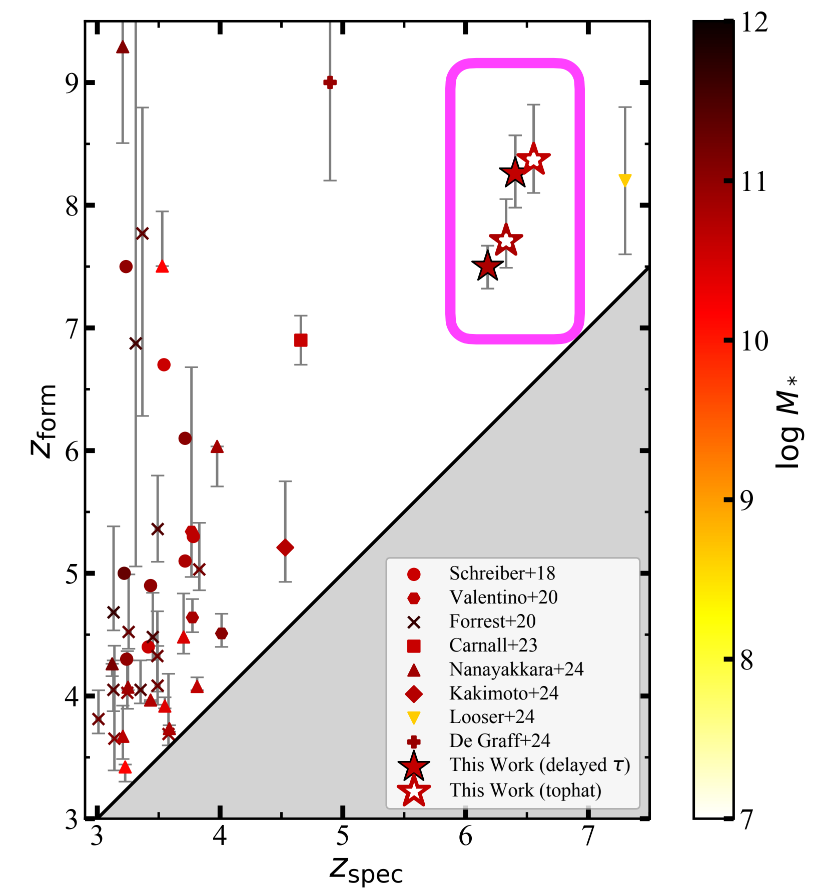
✦***Massive (log M^*/M_{sun} > 10) galaxies formed via starburst <u>200-250 Myr</u> before these quasars are observed***

- z_{form} = 8.3+/- 0.3 (J2236), 7.5 +/- 0.2 (J1512)
- SFR_{peak} = 1500 - 2000 M_{sun} yr^{-1}

Onoue+in prep.

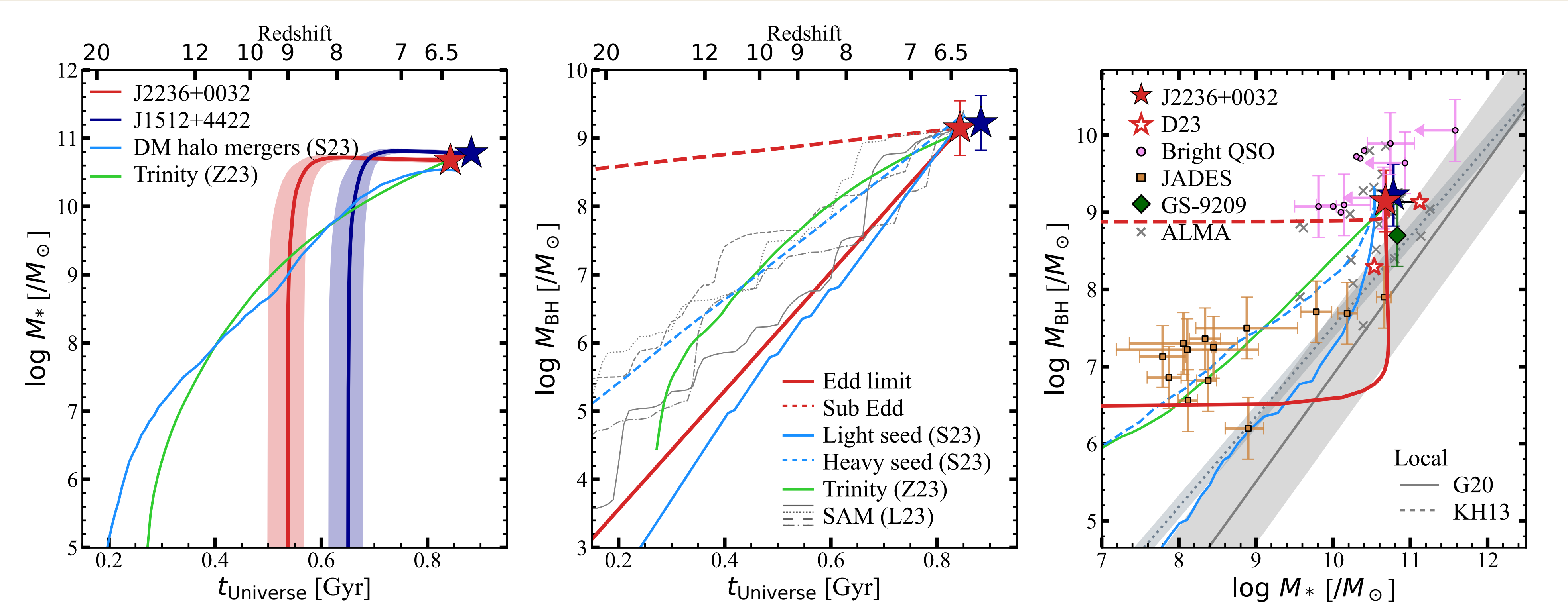
Quasar Hosts as Quiescent Galaxies



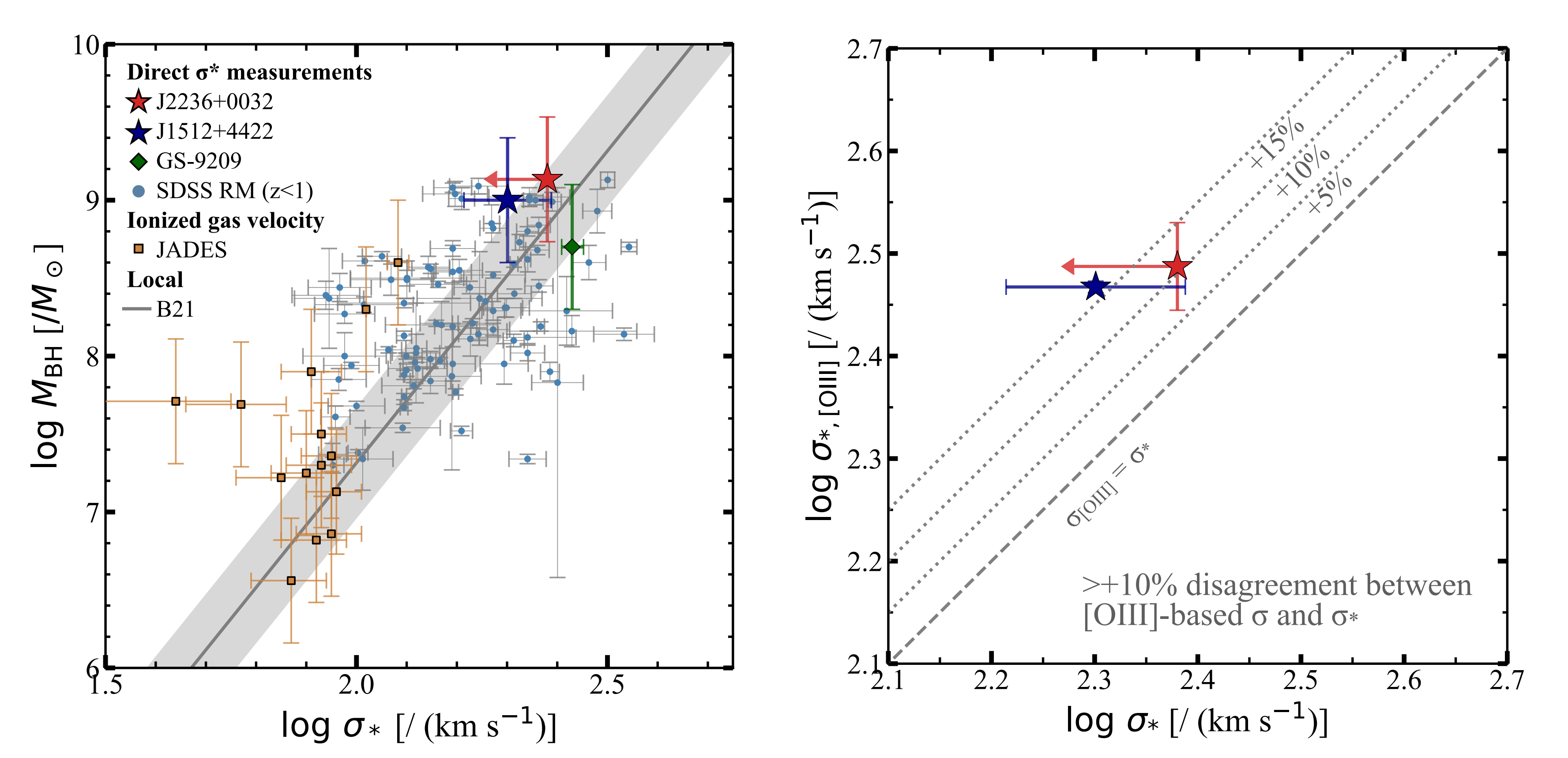


We observed the most distant massive (log M_*/M_{sun} > 10) quiescent galaxies as quasar hosts

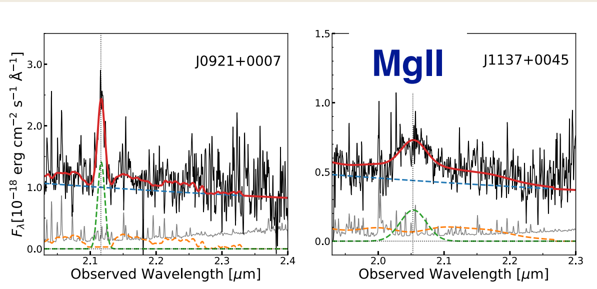
Initial Mass Assembly of SMBH and Host

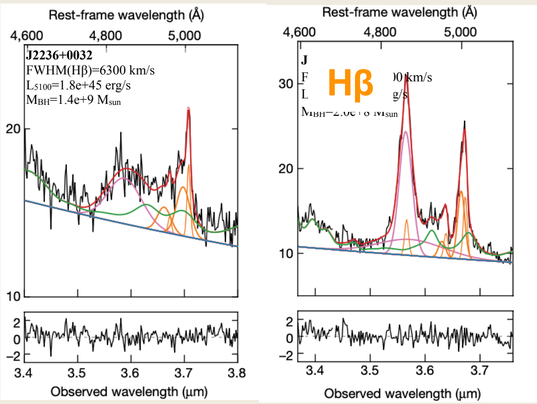


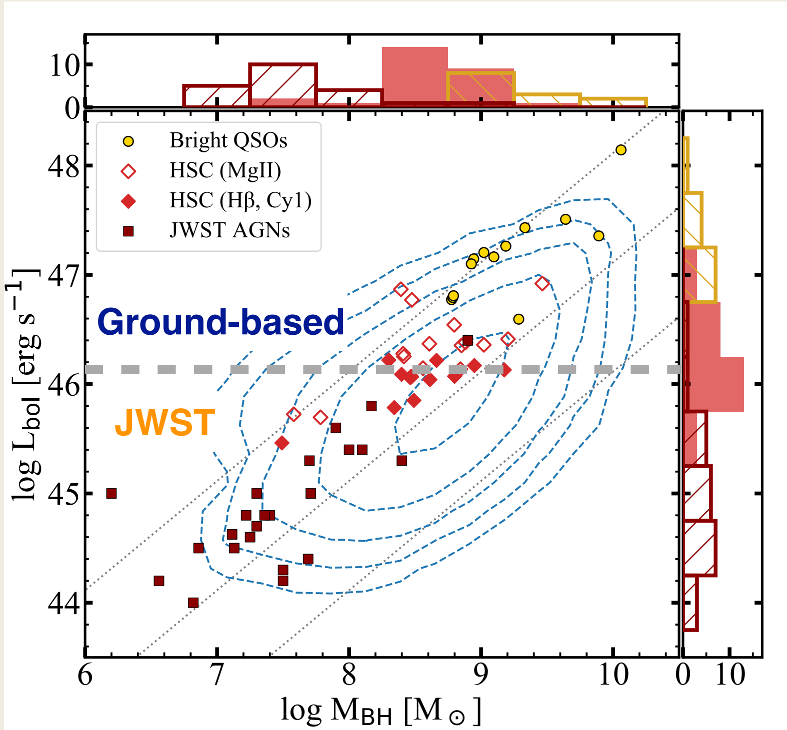
M_{BH} - σ_* distribution at z>6



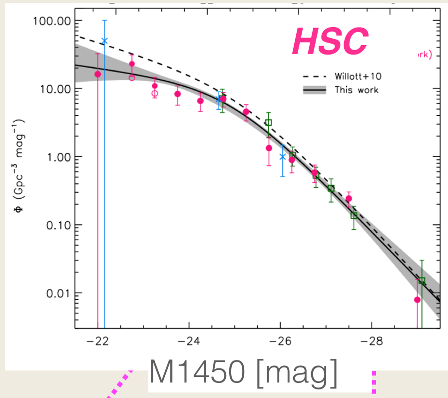
Ongoing study: z>6 BH Mass Function



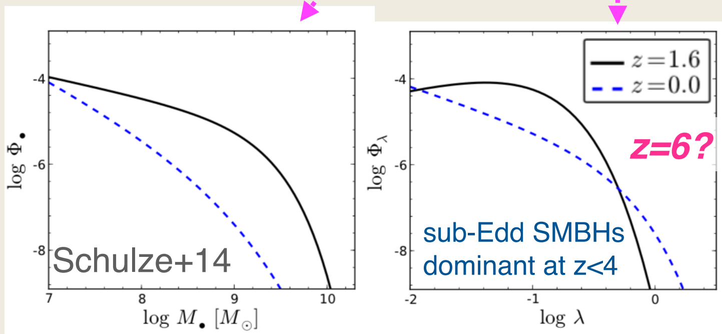




✦z=6 Quasar luminosity function

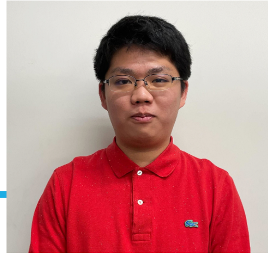


➡ BH mass & Edd ratio distributions



Ground-based (MgII) + JWST (Hβ) M_{BH} samples will be combined to derive M_{BH} stats

HAE survey around J2236+0032



J. Arita (U. of Tokyo)

Target

- HAEs at $z = 6.4$ around J2236 with $EW_{\mathrm{H}\alpha} \geq 100$ Å.

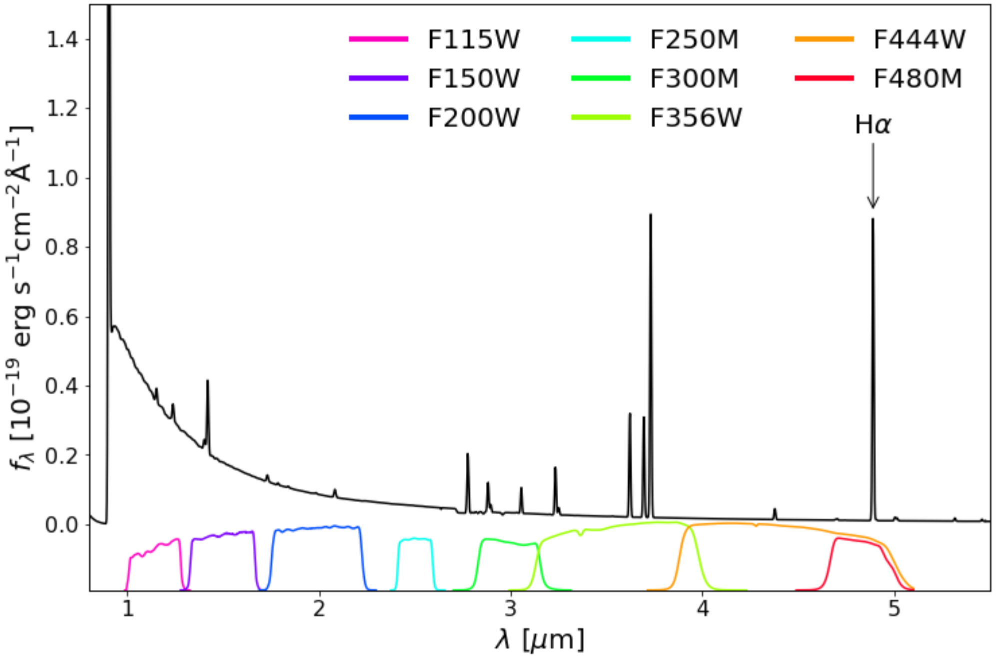
NIRCam imaging (color selection)

- F444W - F480M catches color excess.
- The other filters exclude low/high-z interlopers (e.g., Paα emitters at $z = 1.6$, [O III] emitters at $z = 8.6$).

Goals

- Overdensity in the quasar field (to be compared with EIGER & ASPIRE results).
- Halo mass of the quasar.
- HAE properties (e.g., M_*, SFR).

Mock HAE spectrum



from JAGUAR (Williams+18)

Summary

- ✦ Stellar emission is detected from 7 moderate-luminosity quasars at z=6. Host is generally massive with log M_*/M_{sun}~10-11
- ✦ Stellar absorption lines are detected for 2 bright quasar hosts. Spectrophotometric analysis suggests post-starburst-like SEDs with mass-weighted age 200-250 Myr.
- ✦ The two galaxies are also likely massive quiescent galaxies formed at z=7.5-8.0, supported by Cy2 and ALMA multi-wavelength data
- ✦ Observed z=6 M_{BH} - M_* distribution can be explained by the local scaling relation when luminosity bias is taken into accounts. We aim to increase the sample size in the coming JWST cycles.