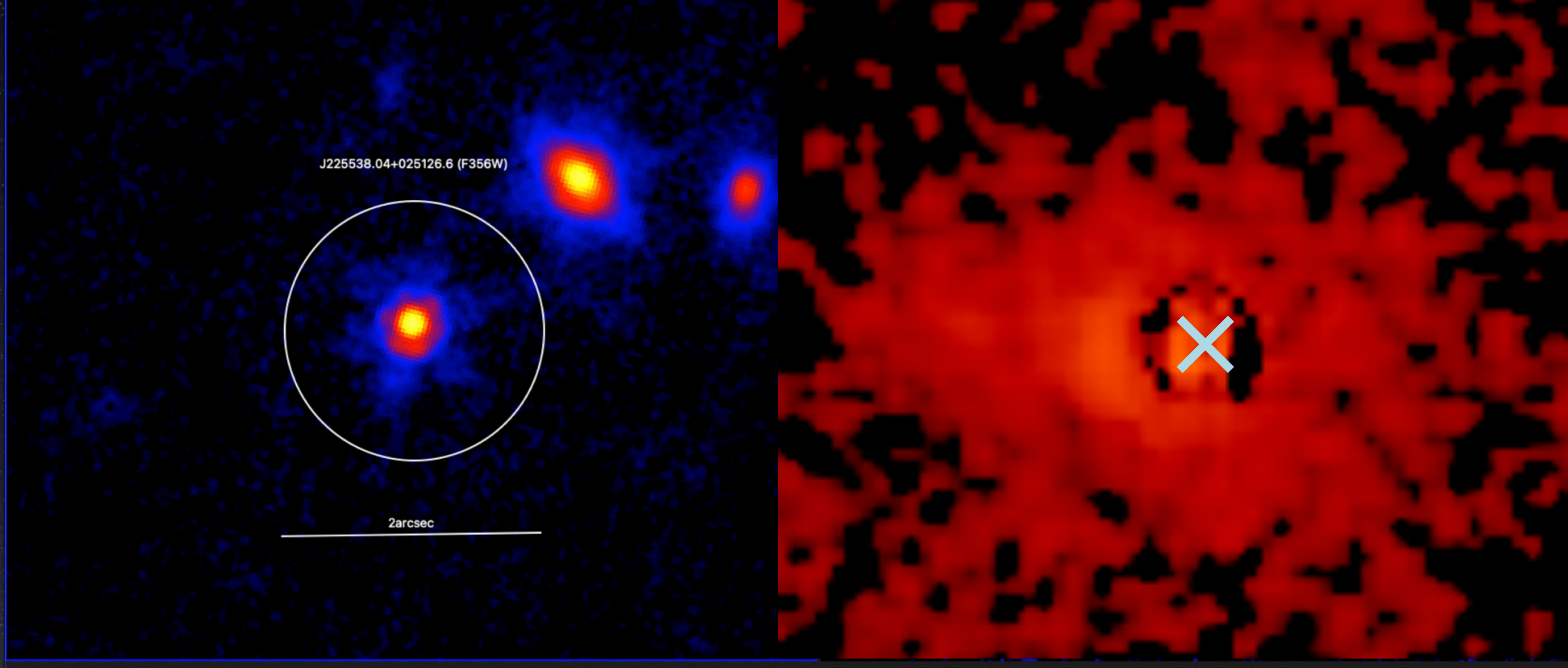


First-Year Observations of High-z AGN with JWST

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

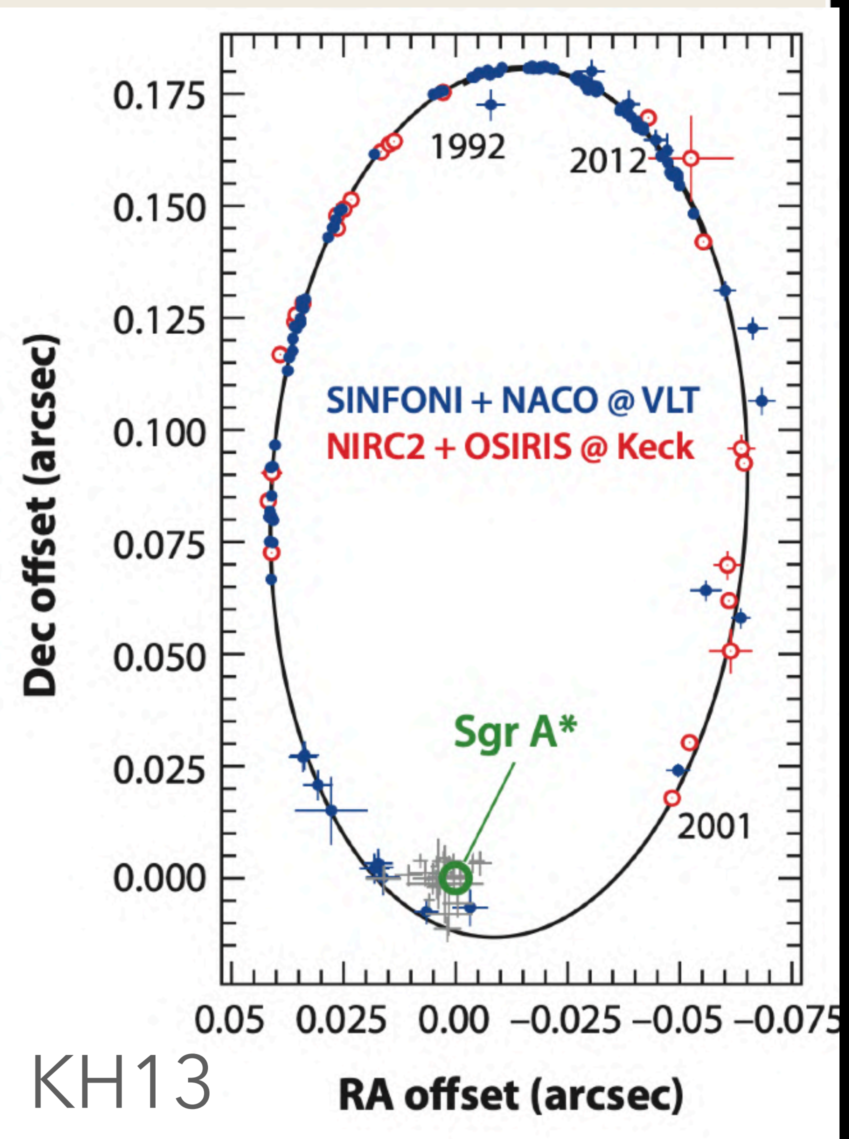
HSC

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

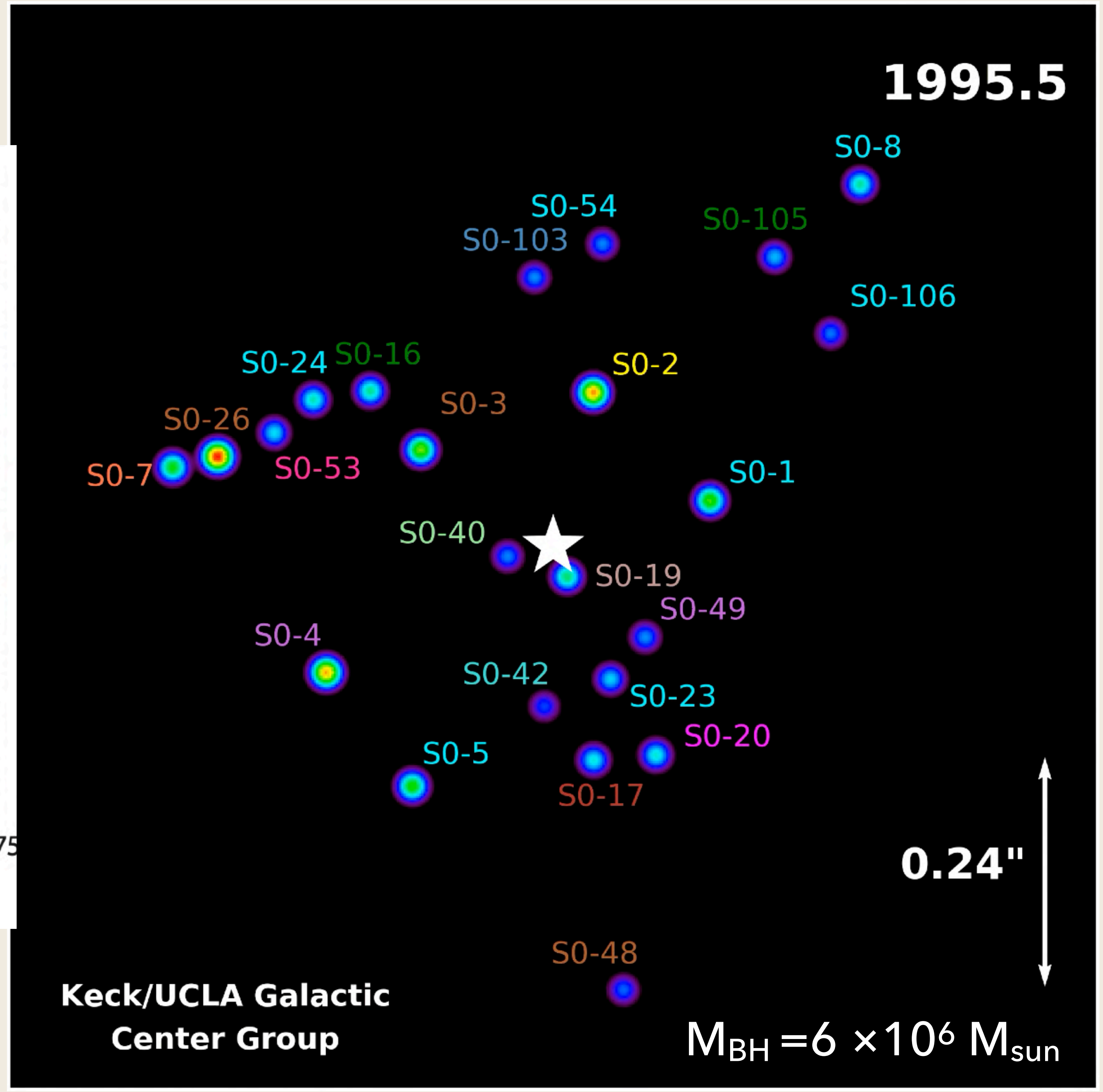
KIAA-PKU

Super Massive Black Hole (SMBH)

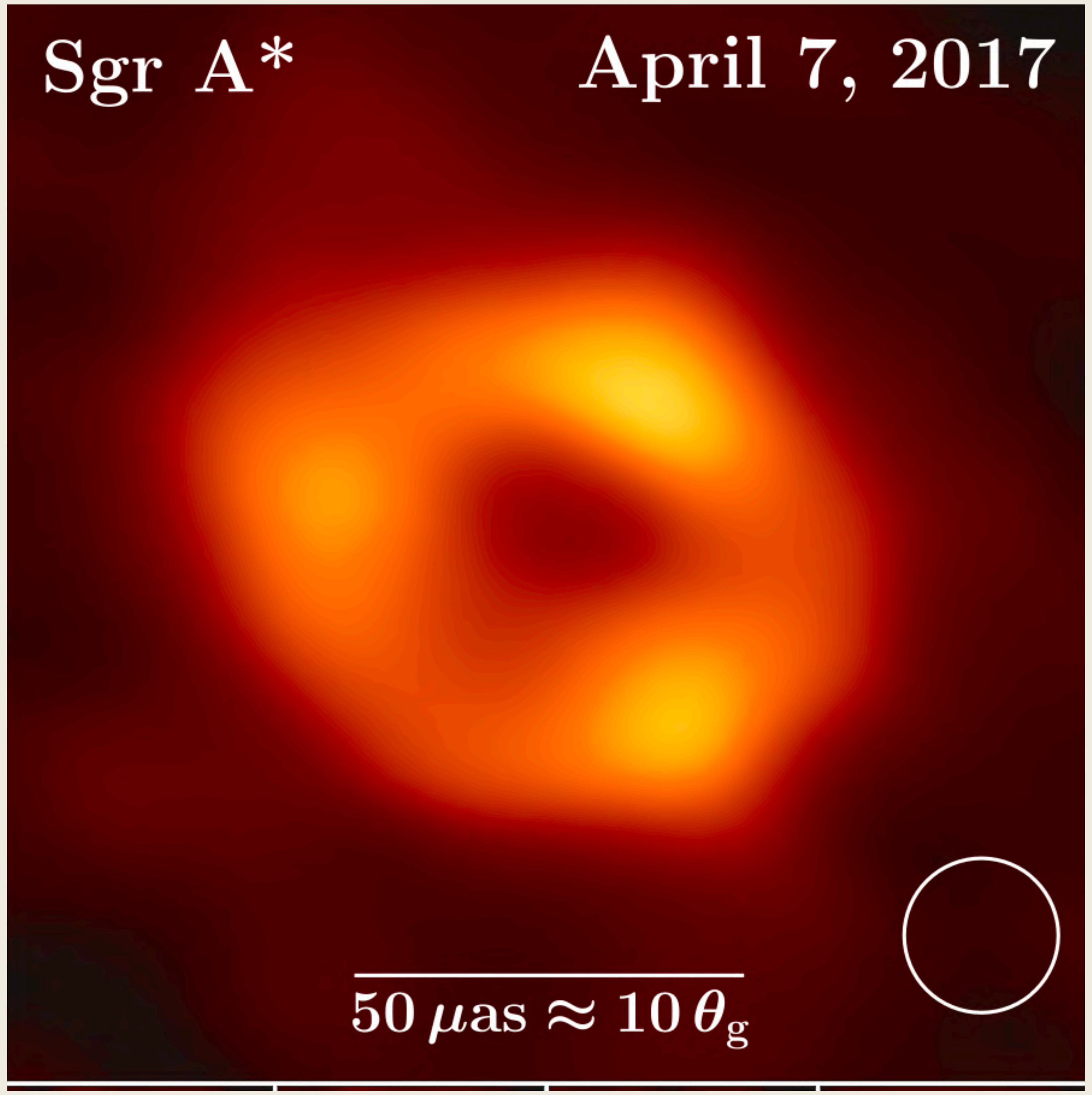
- Stellar orbit around Galactic center



KH13



- EHT image of BH shadow

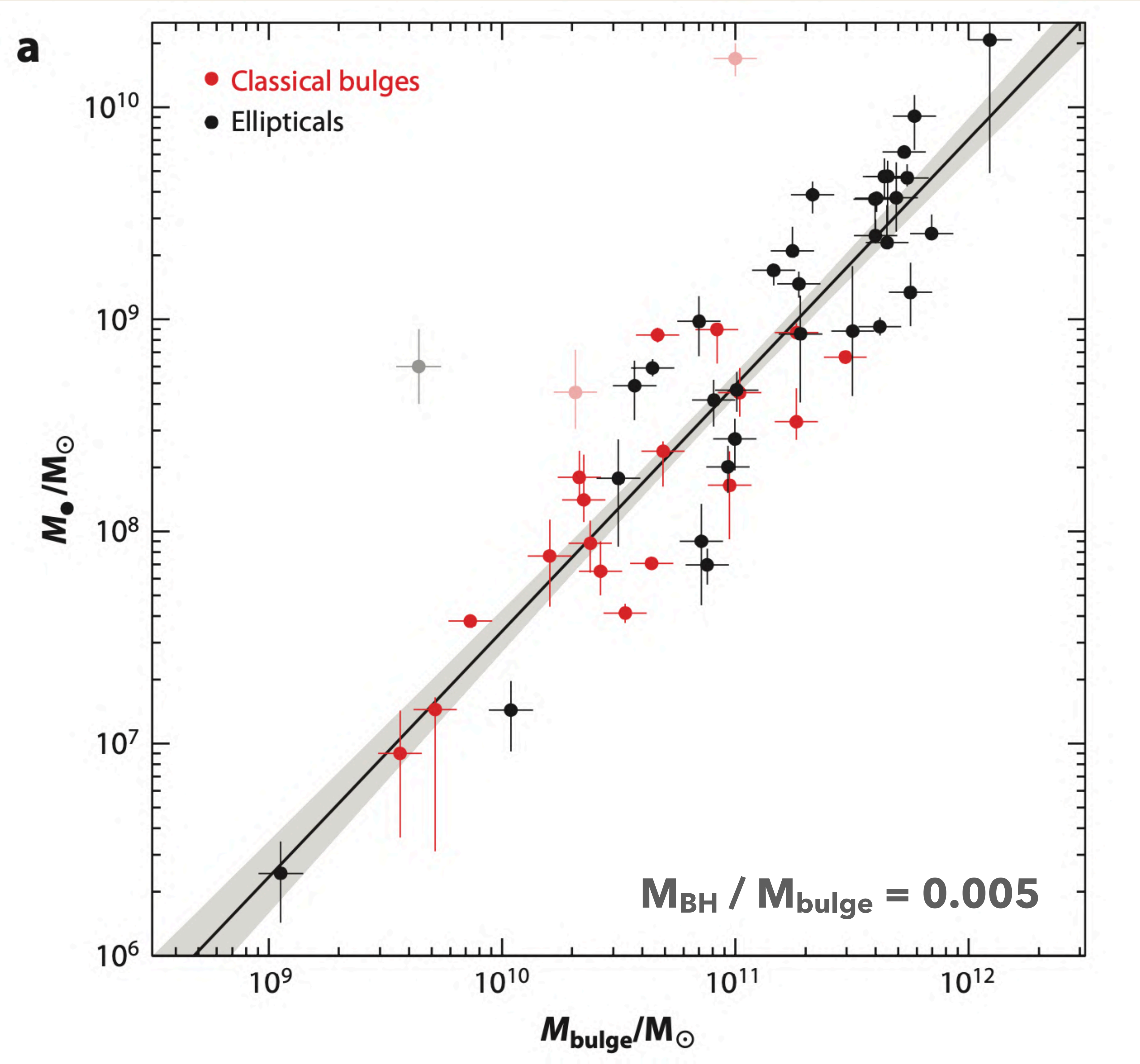


EHT collab. 2022

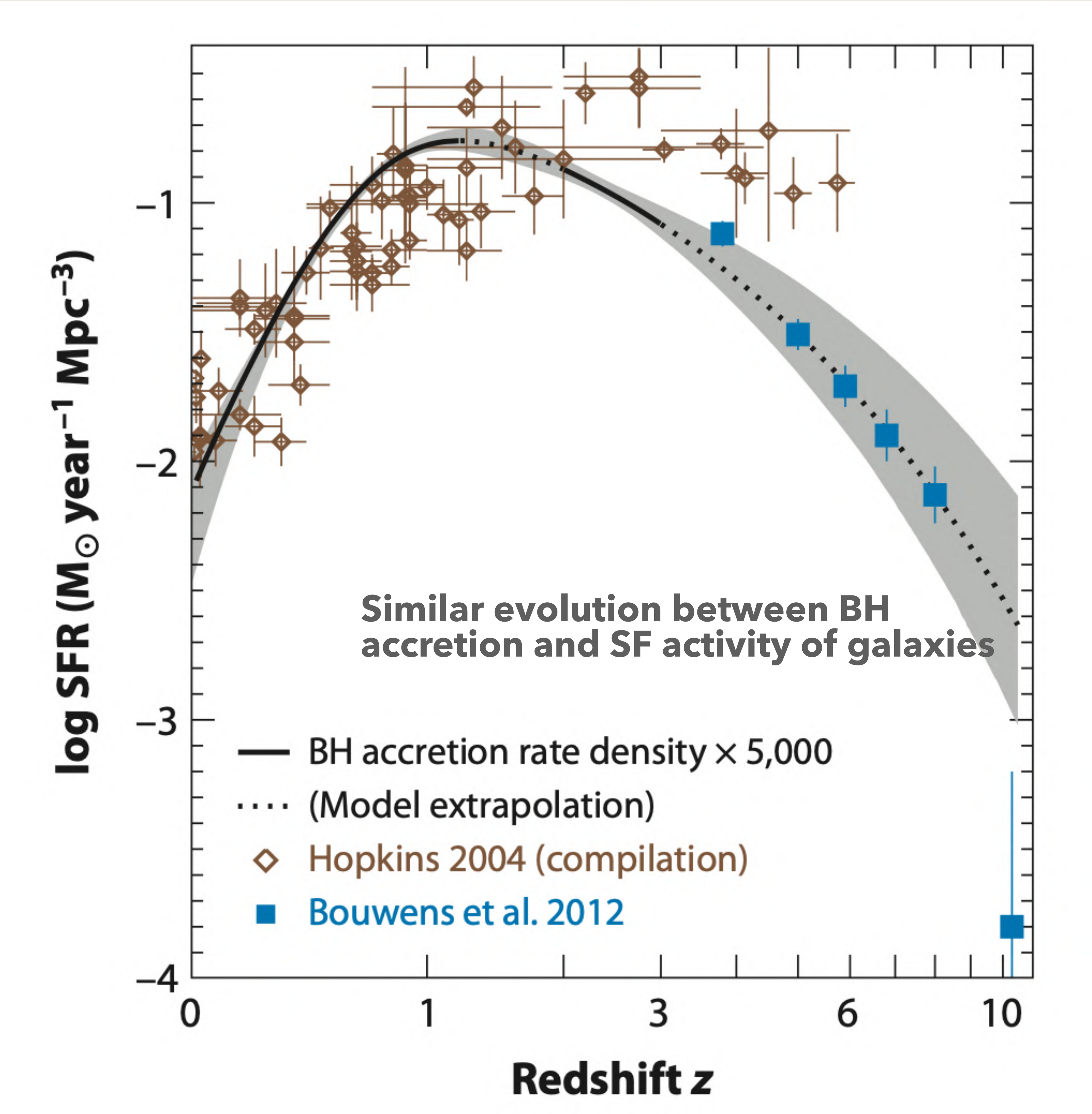
What is their origin? –> high-redshift quasars

SMBH - Galaxy Co-evolution

- BH - bulge mass relation



- Evolution of BH accretion density

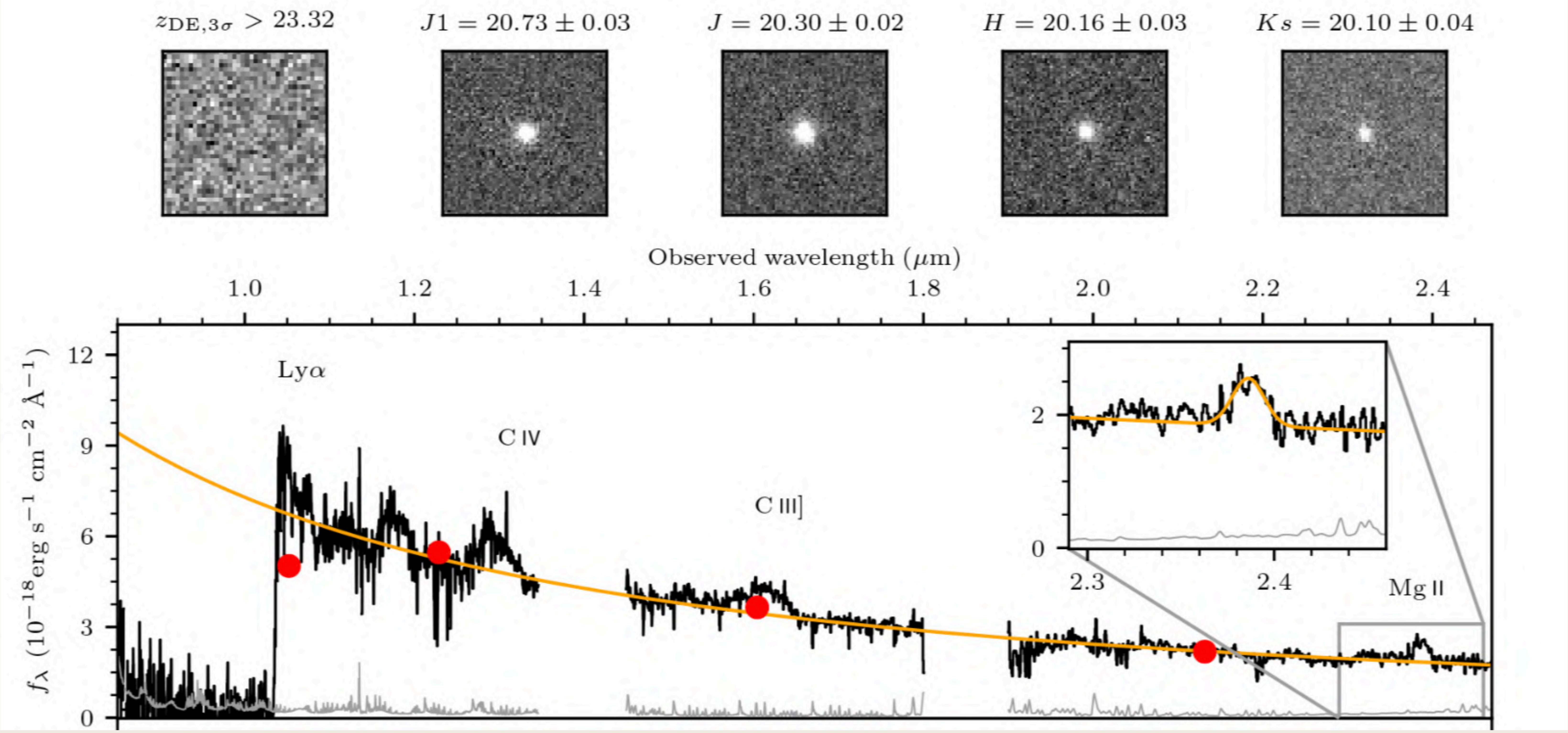


Kormendy & Ho (2013)

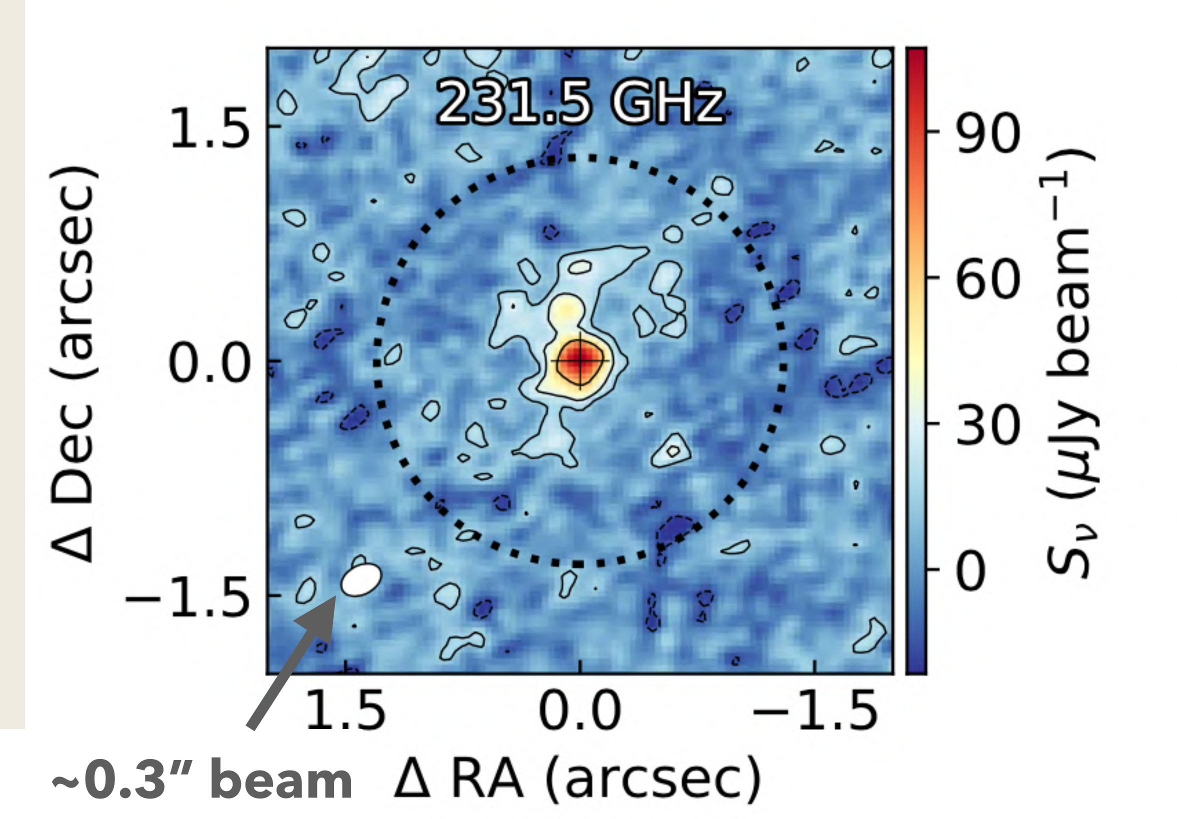
Cosmic ``chicken-or-egg” problem

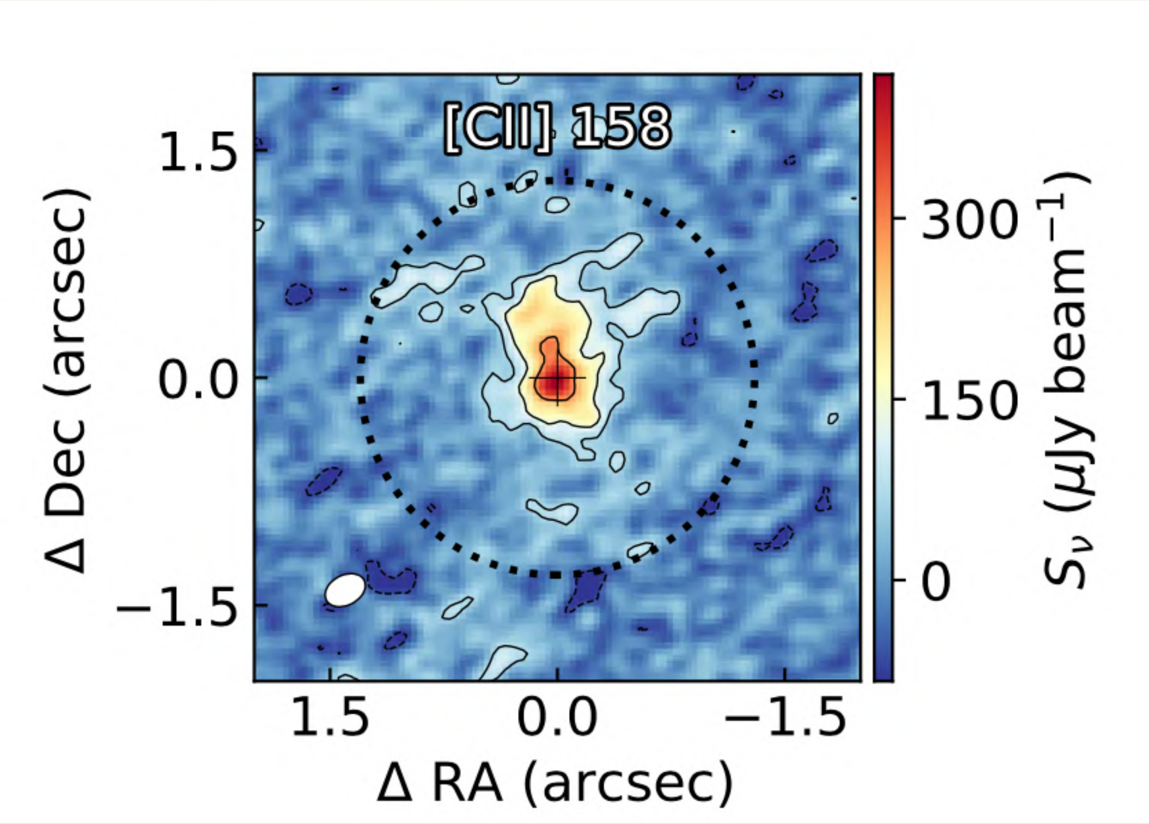
Most Distant BH at z=7.54

- ULAS J1342+0928 (FIRE 3.5 hr + GNIRS 4.7hr Bañados+18)



- ALMA dust (top) and [CII] 158 μm (bottom) Bañados+19

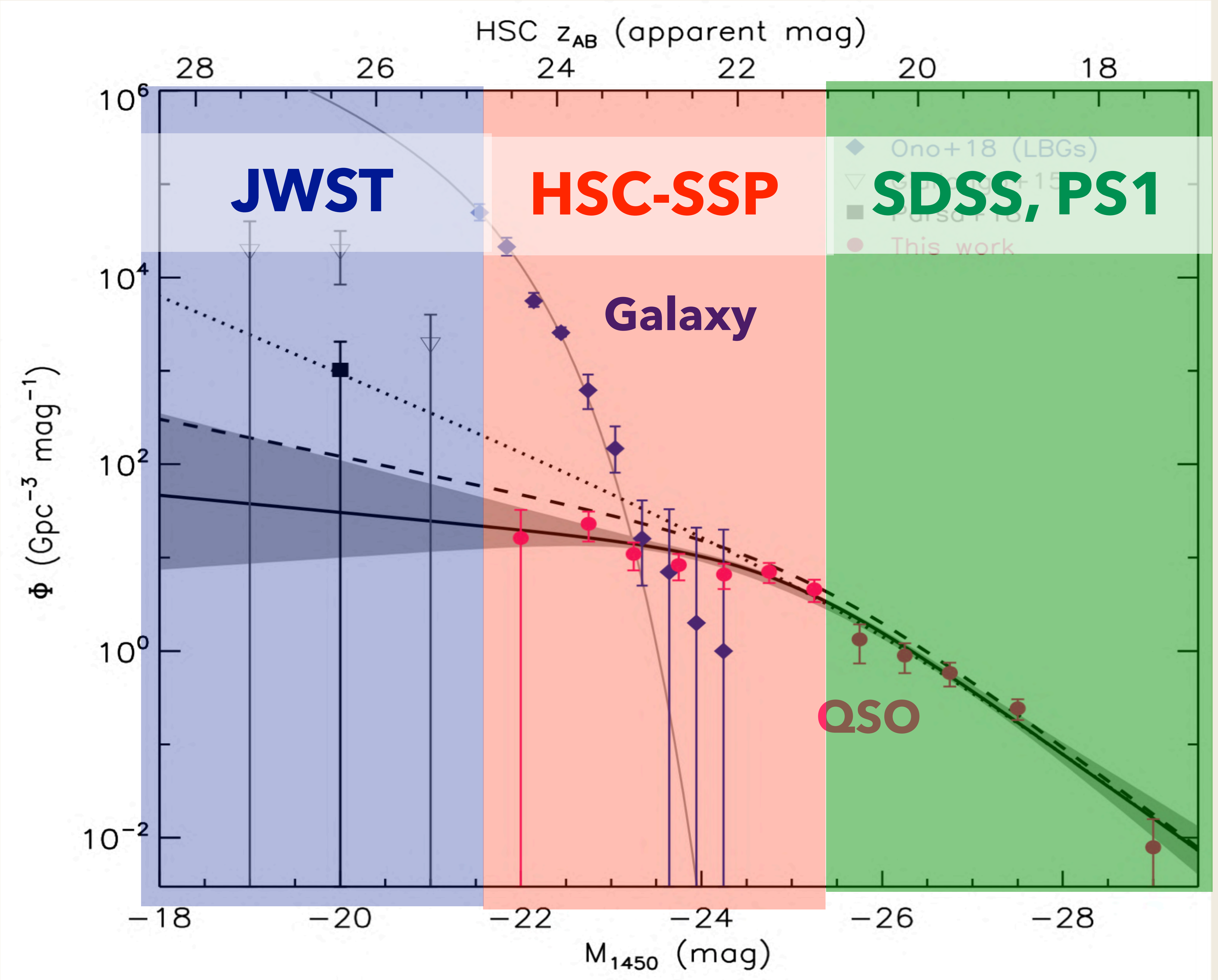


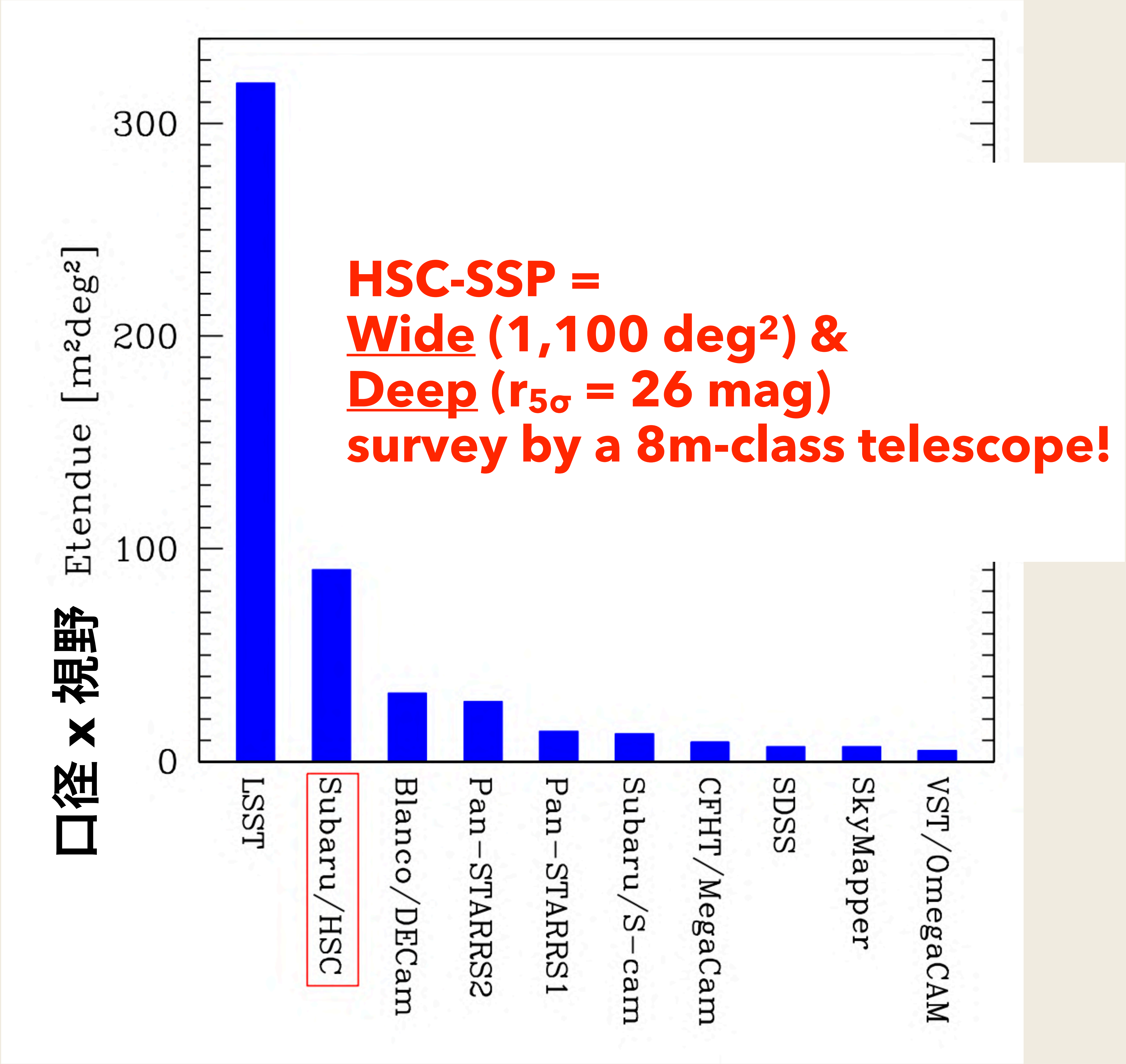


- ✦ SMBH: $M_{BH}=8\times10^8\,M_{sun}$, $L_{bol}/L_{Edd}=1.5$ (Bañados+18 Onoue+20)
- ✦ Host: SFR=150M_{sun}/yr, Dust mass: $4\times10^7\,M_{sun}$ (Venemans+17, Novak+19), Merger? (Bañados+19)

Quasar Discovery & Wide-Field Survey

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



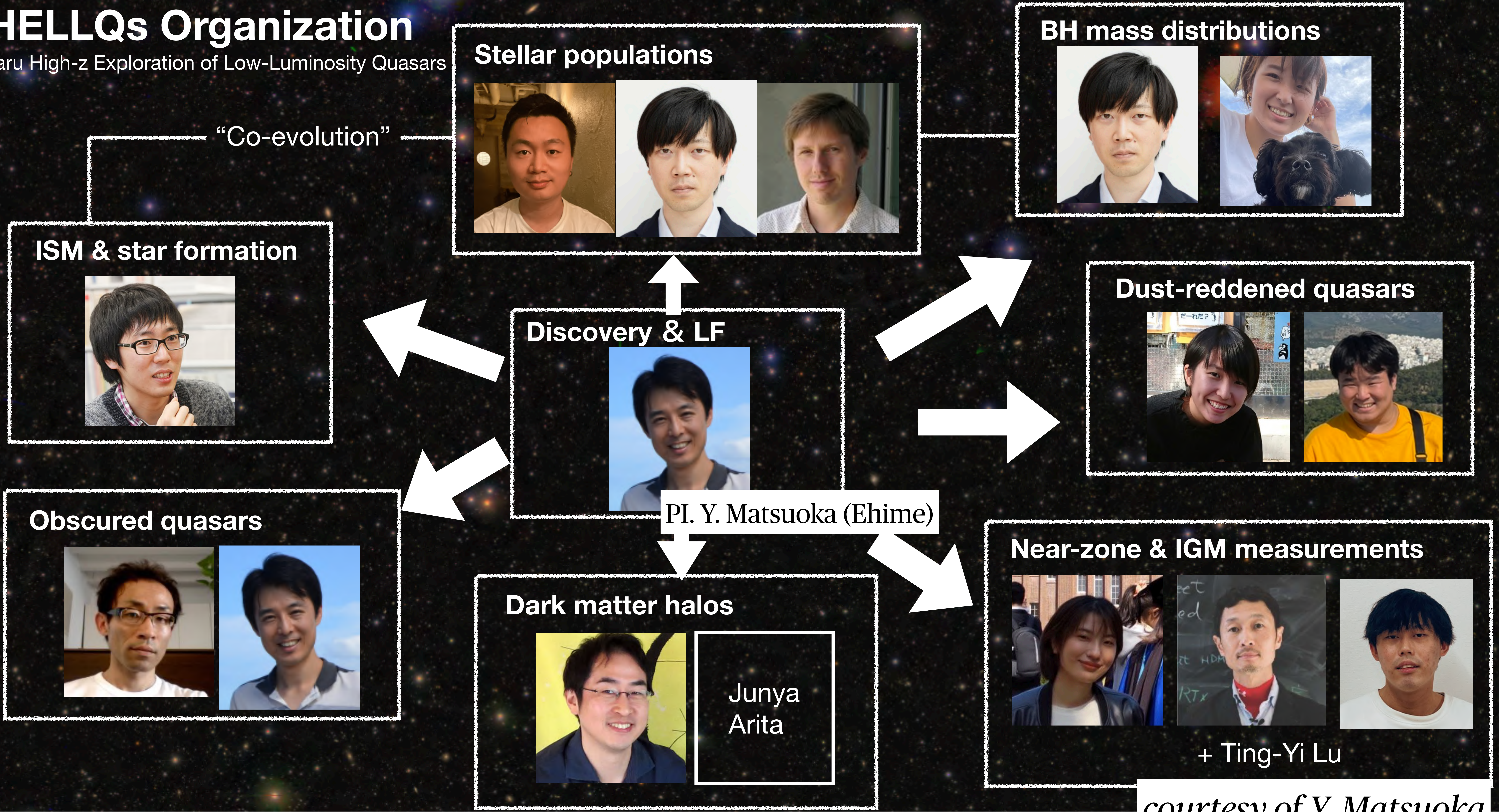


HSC-SSP white paper

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

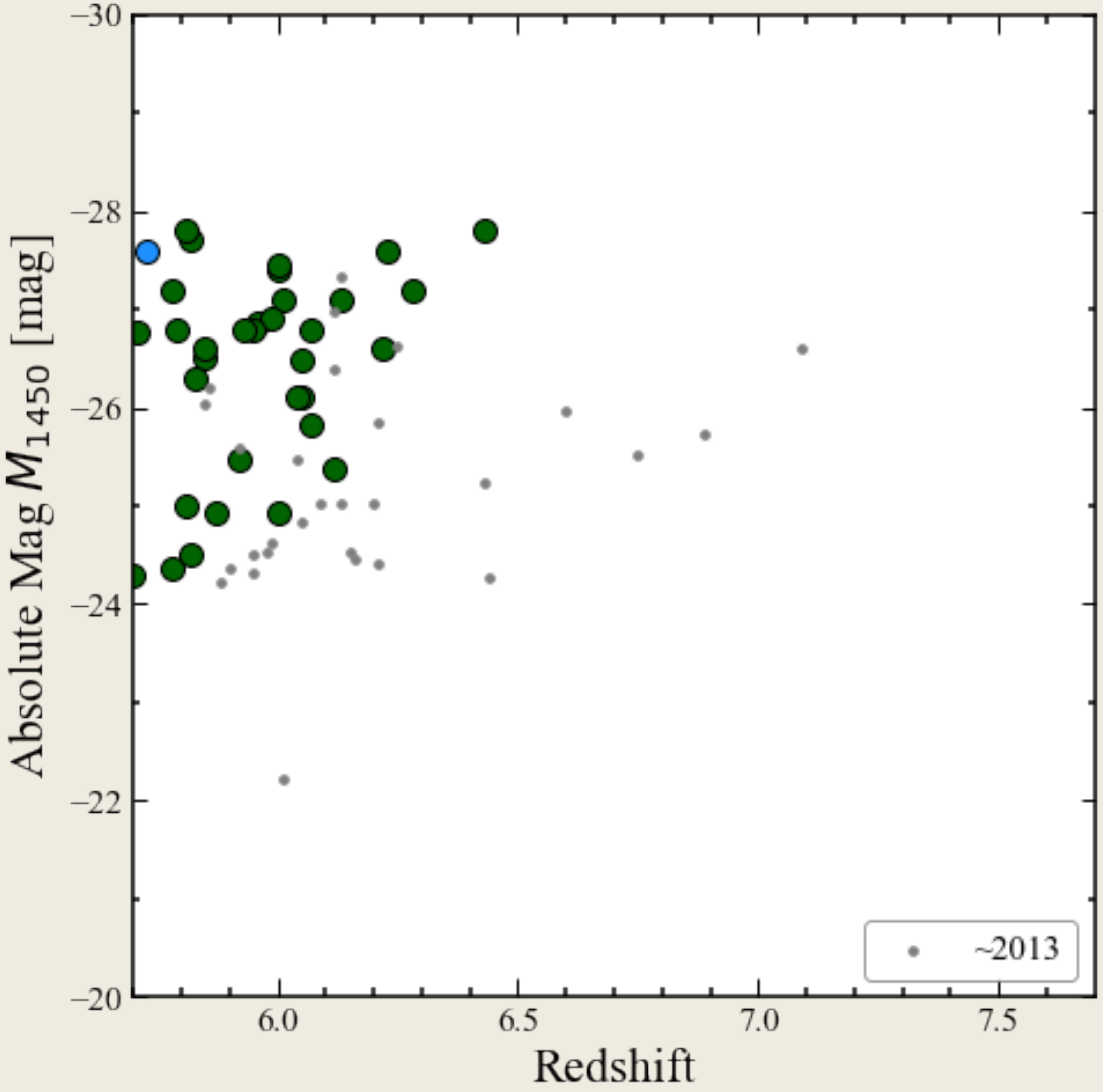
SHELLQs Organization

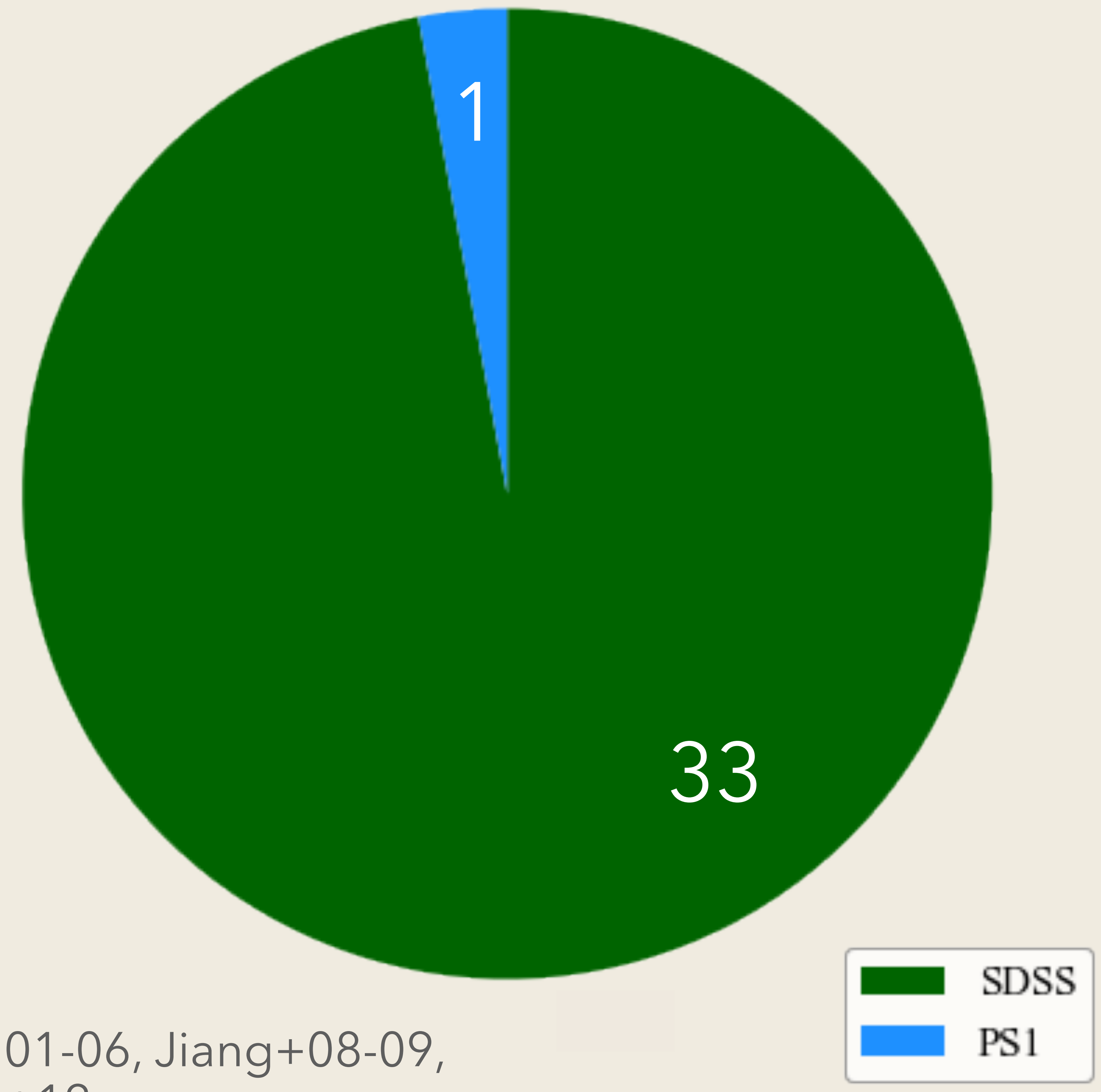
Subaru High-z Exploration of Low-Luminosity Quasars



courtesy of Y. Matsuoka

QSO Discovery (~2013)

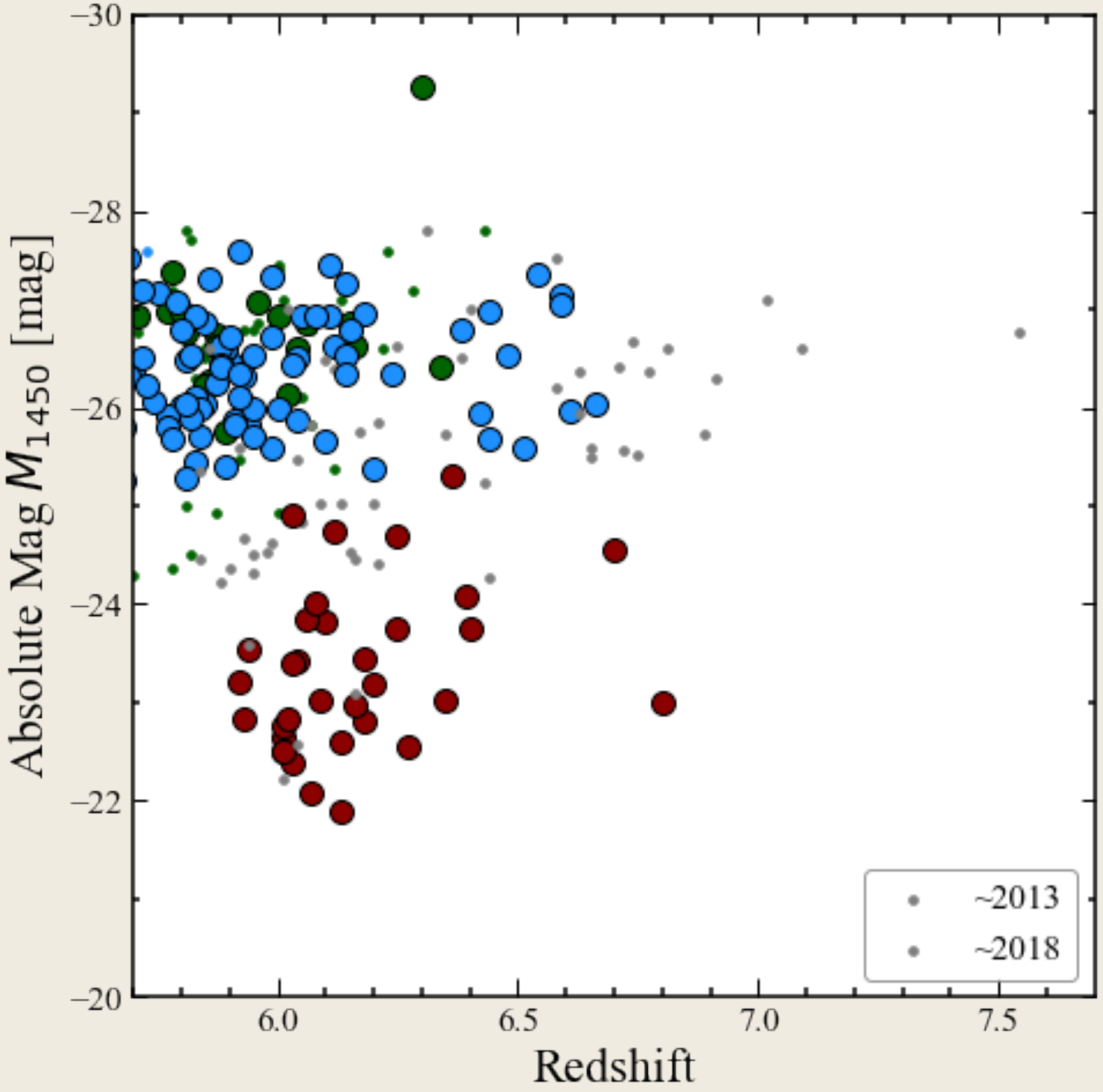


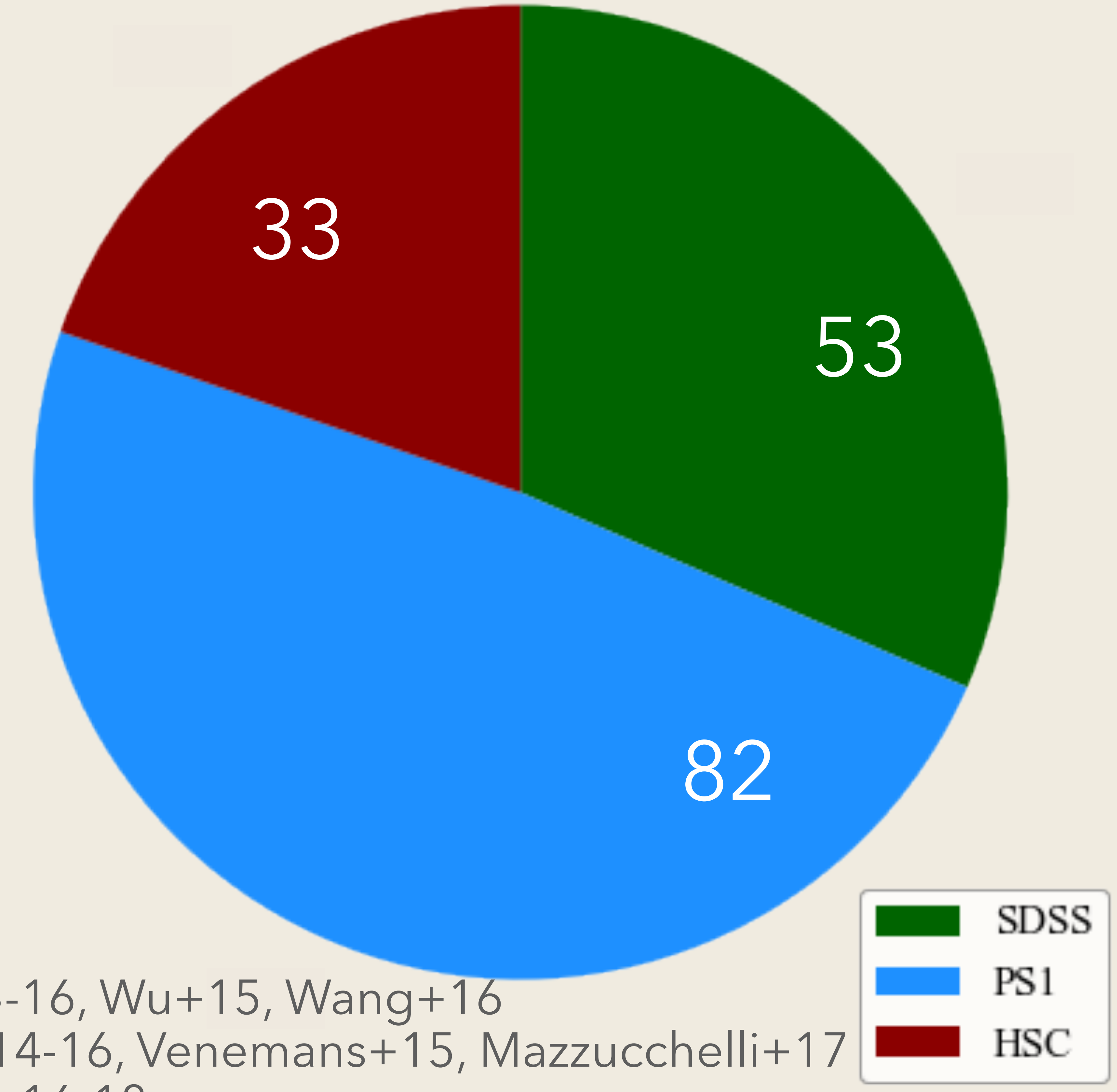


SDSS: e.g., Fan+01-06, Jiang+08-09,
PS1: Morganson+12
Others: e.g., Willott+07-10, Mortlock+11, Venemans+13

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

QSO Discovery (~2018)

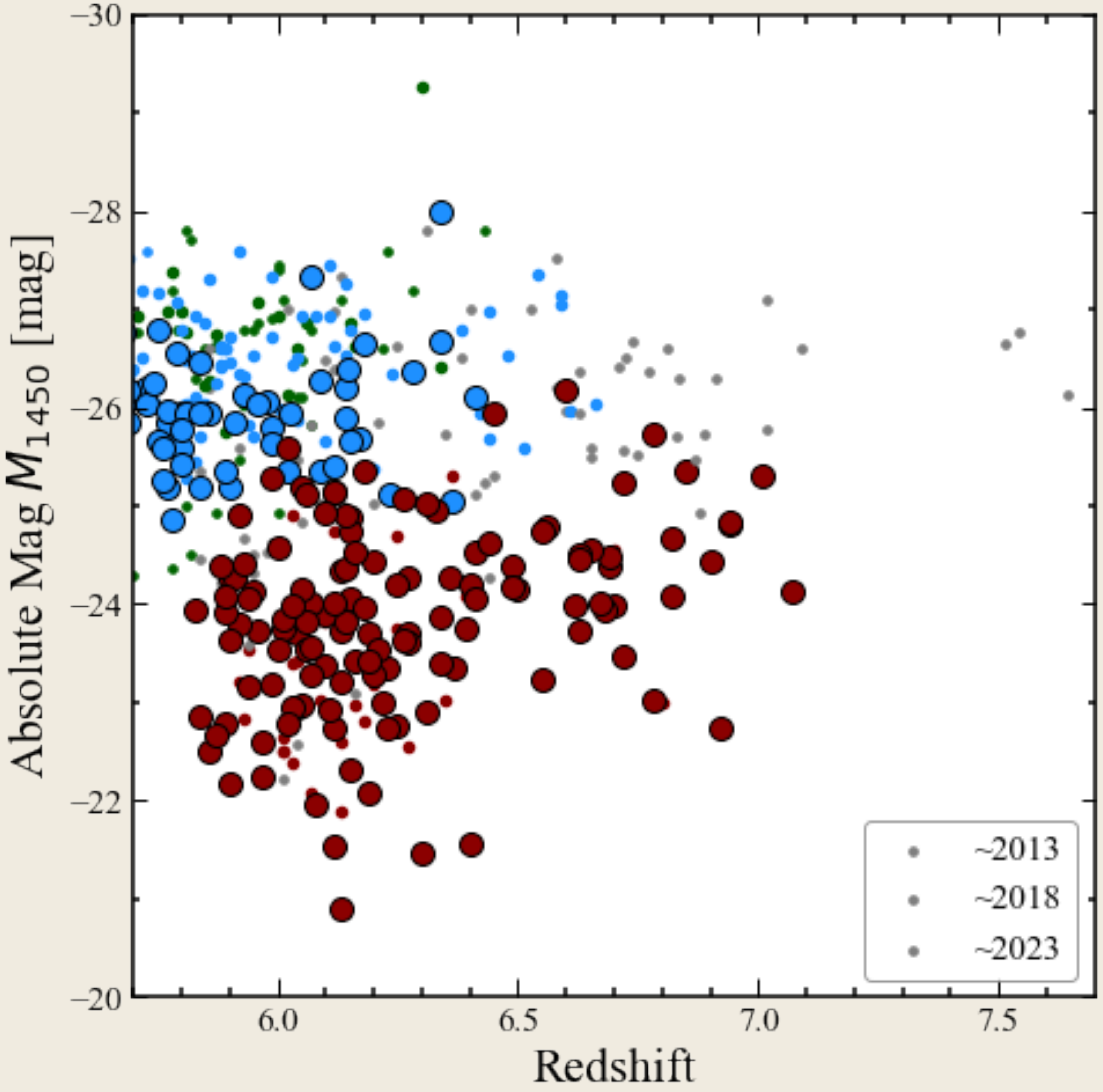


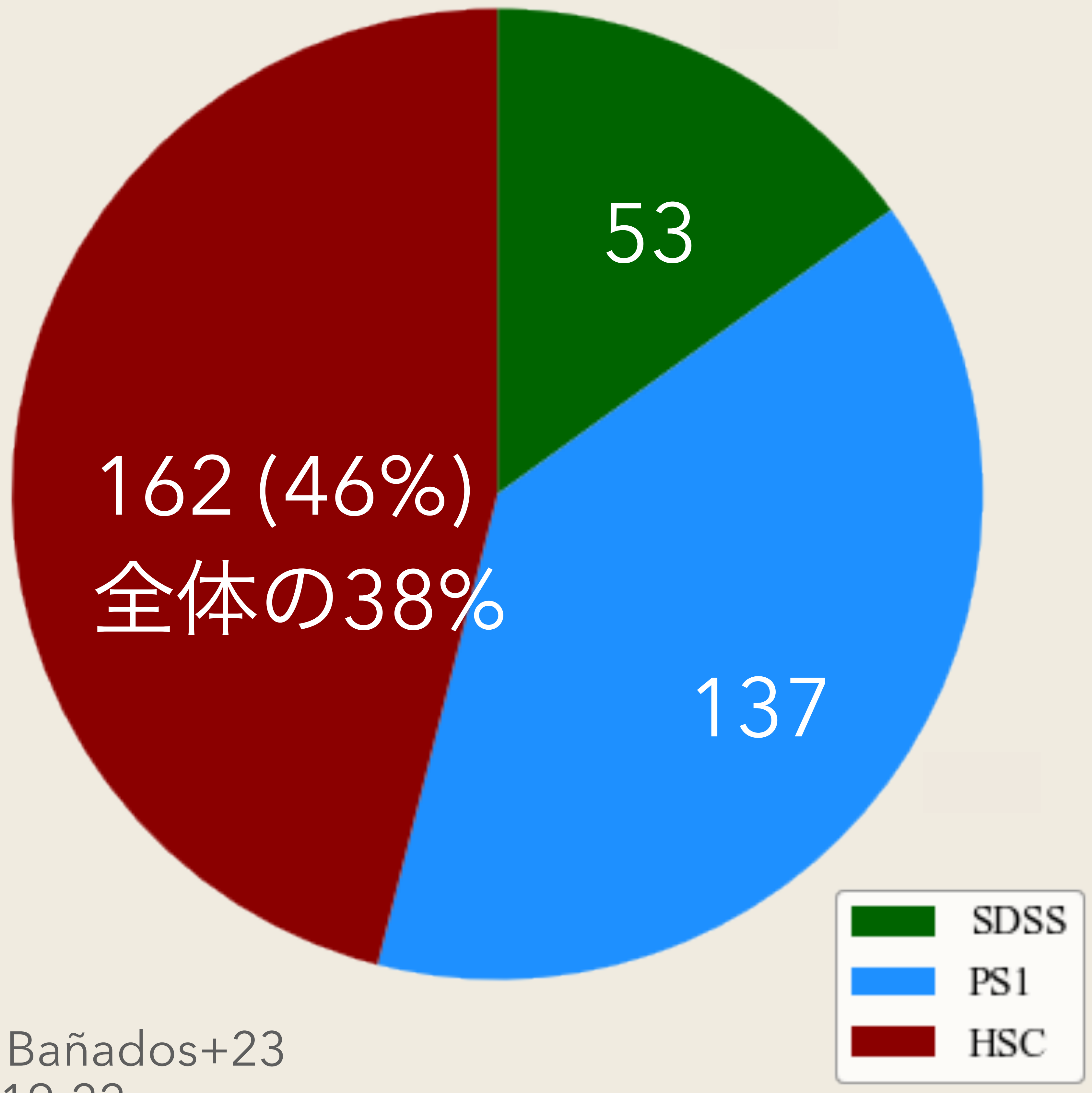


SDSS: Jiang+15-16, Wu+15, Wang+16
PS1: Bañados+14-16, Venemans+15, Mazzucchelli+17
HSC: Matsuoka+16-18
Others: e.g., Kashikawa+15, Reed+15, Bañados+18, Wang+18

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

QSO Discovery (now)

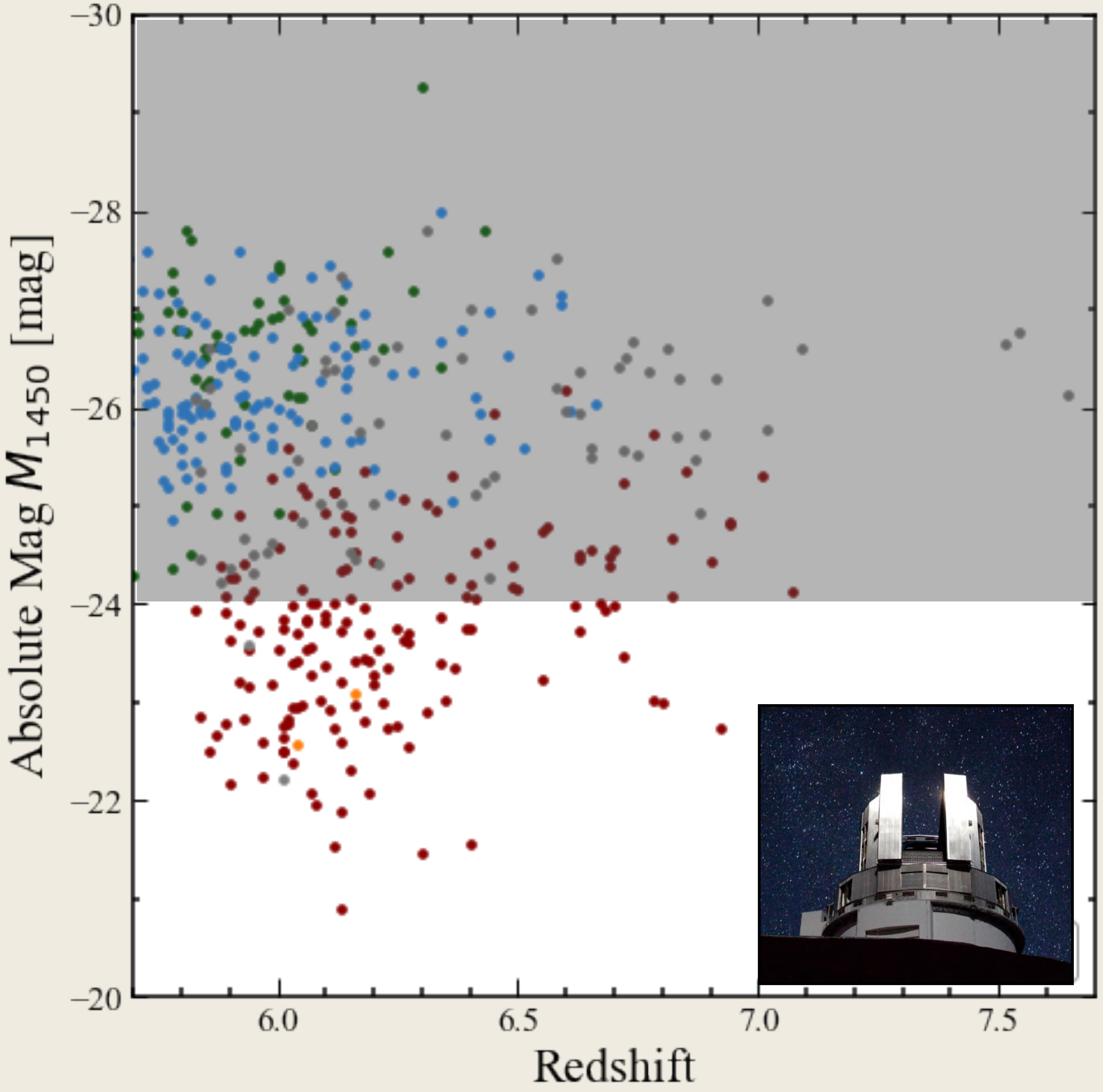




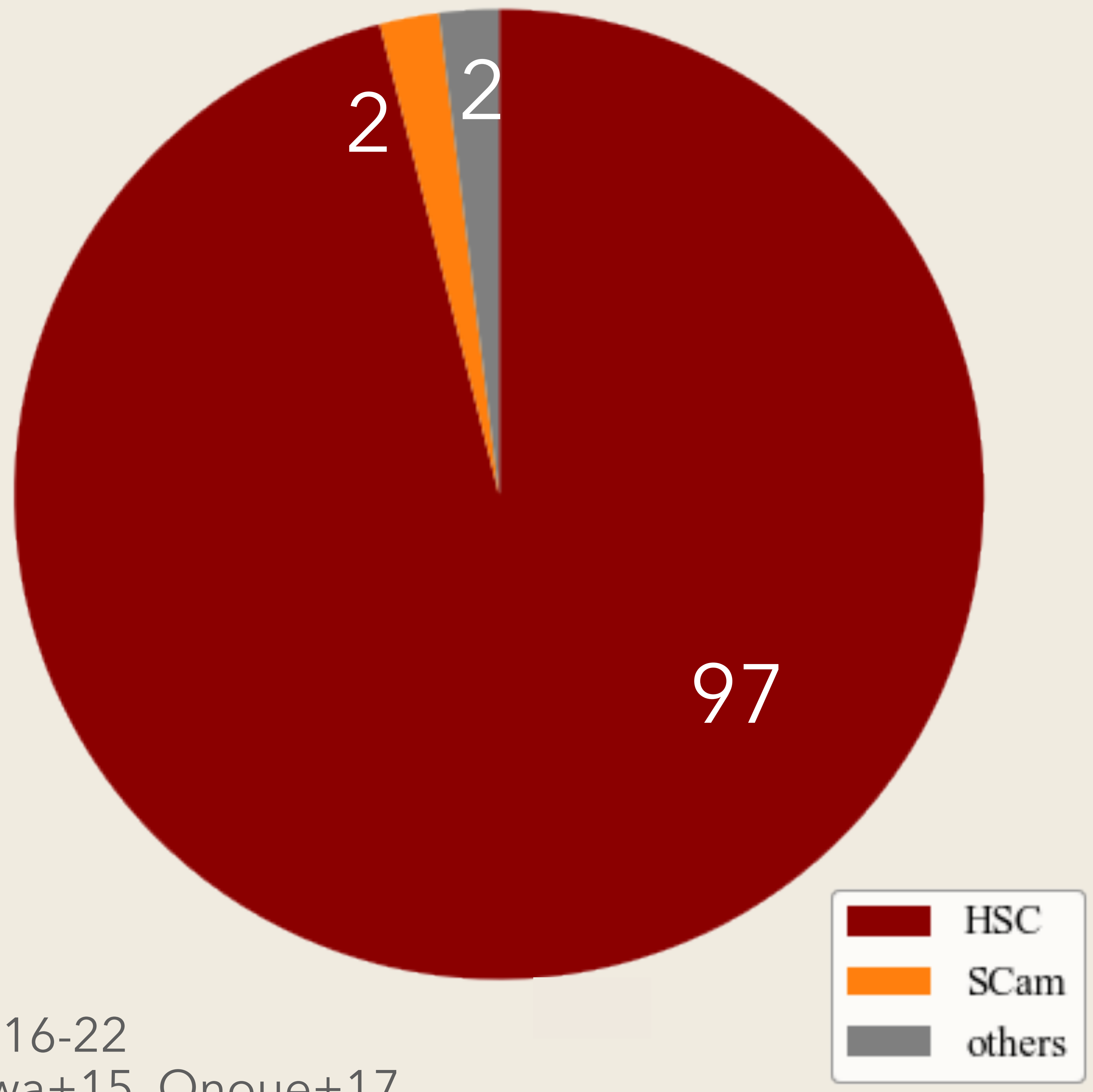
PS1: Andika+20, Bañados+23
HSC: Matsuoka+19-22
Others: e.g., Reed+19, Yang+19-20, Wang+21, Yang+23

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

QSO Discovery (M_{1450}>-24)



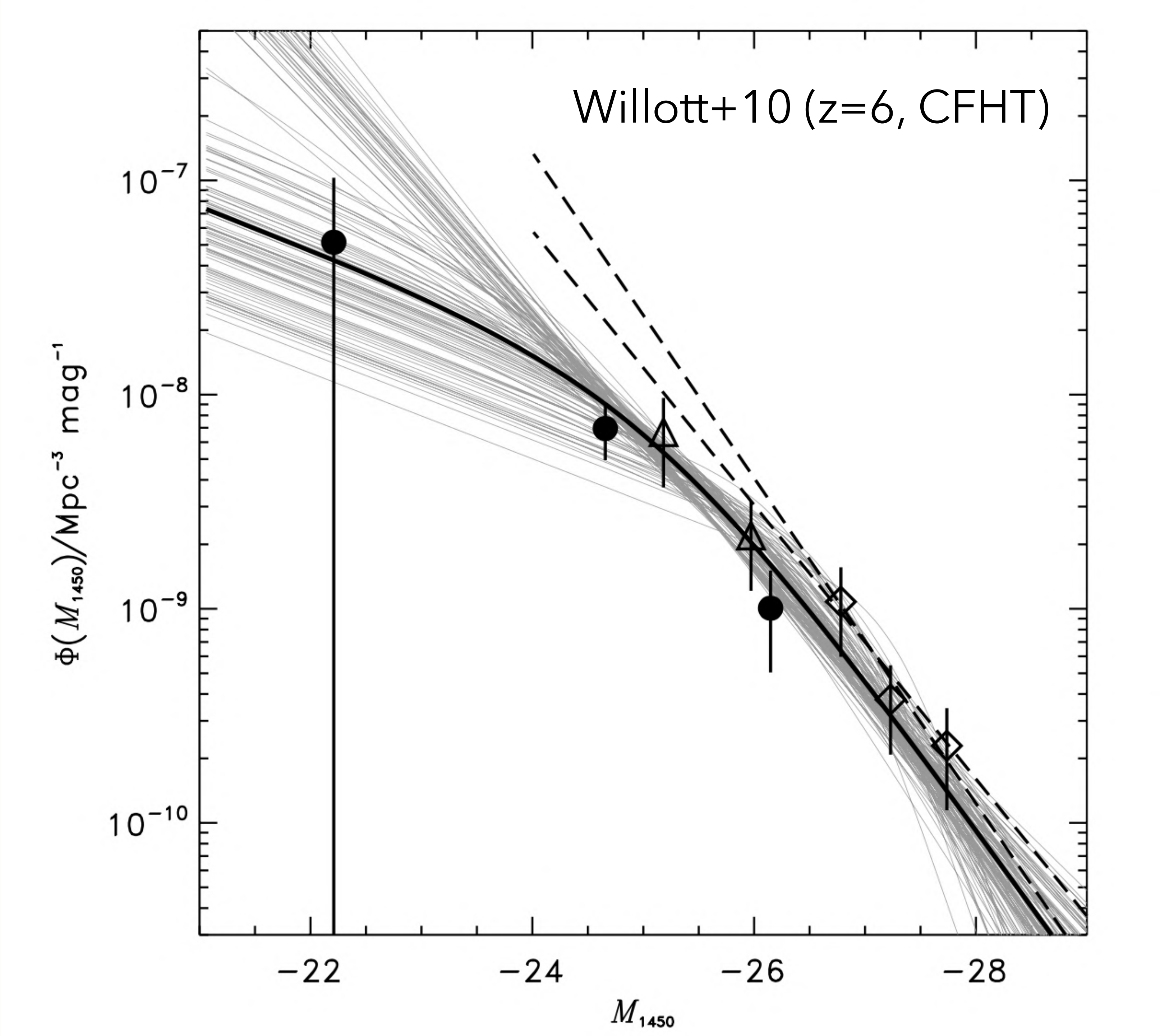
Subaru has a dominant position in high-z ``faint" quasar discovery!



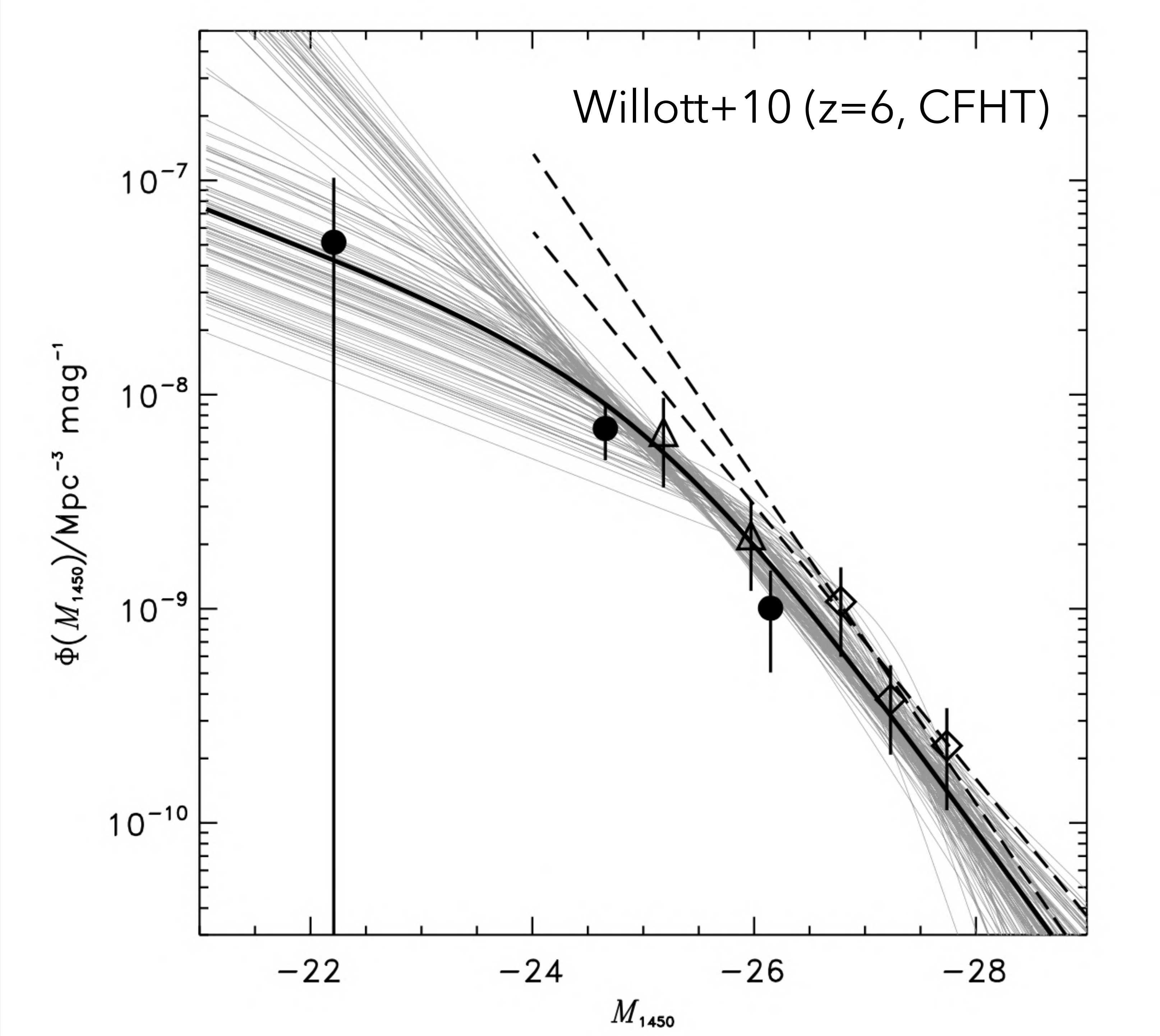
HSC: Matsuoka+16-22
Subaru: Kashikawa+15, Onoue+17
Others: Willott+09, Kim+15

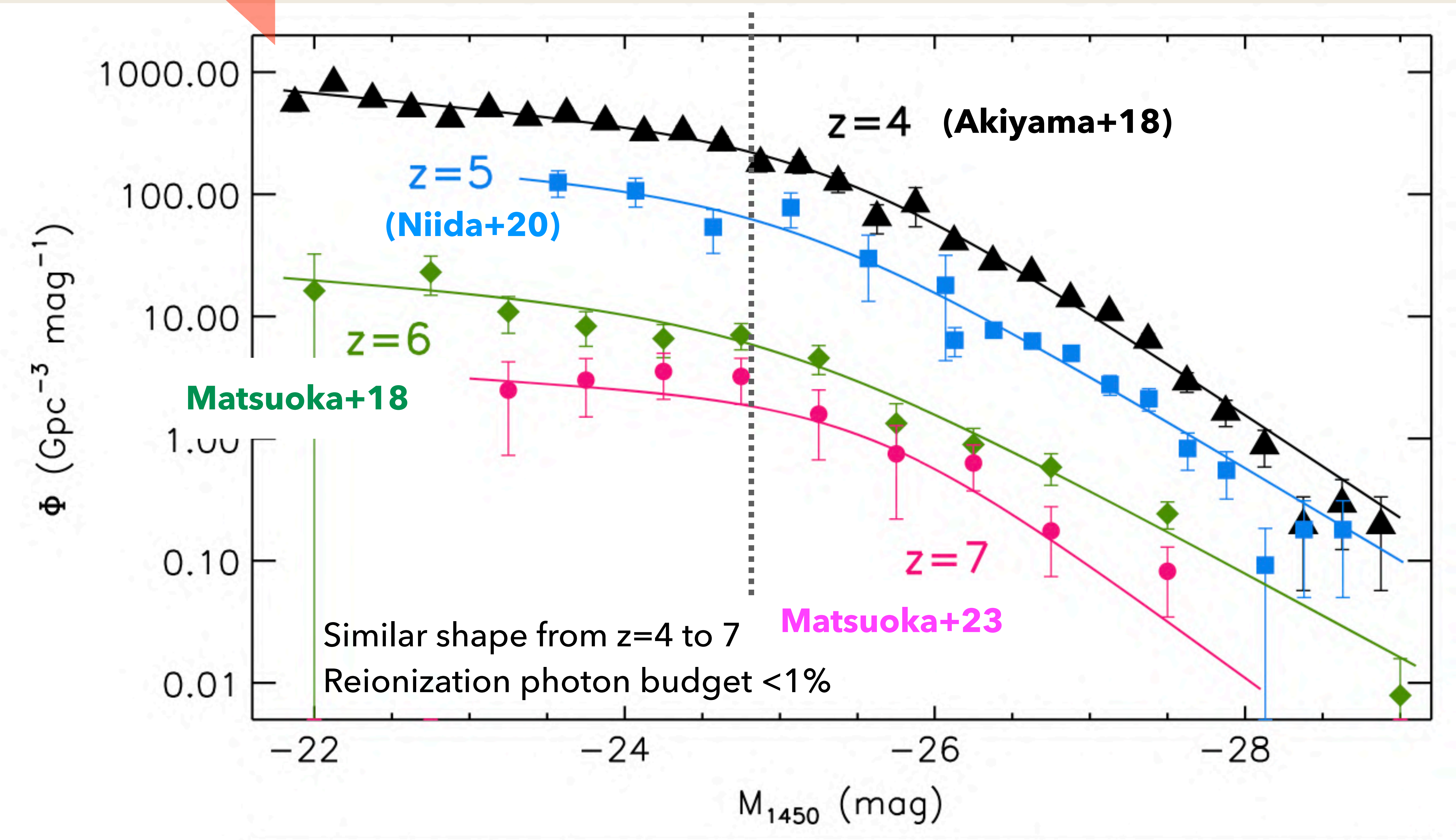
* w/o JWST AGN (e.g., Kocevski, MO+23; Harikane+23, Matthee+23, Maiolino+23, Greene+23)

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



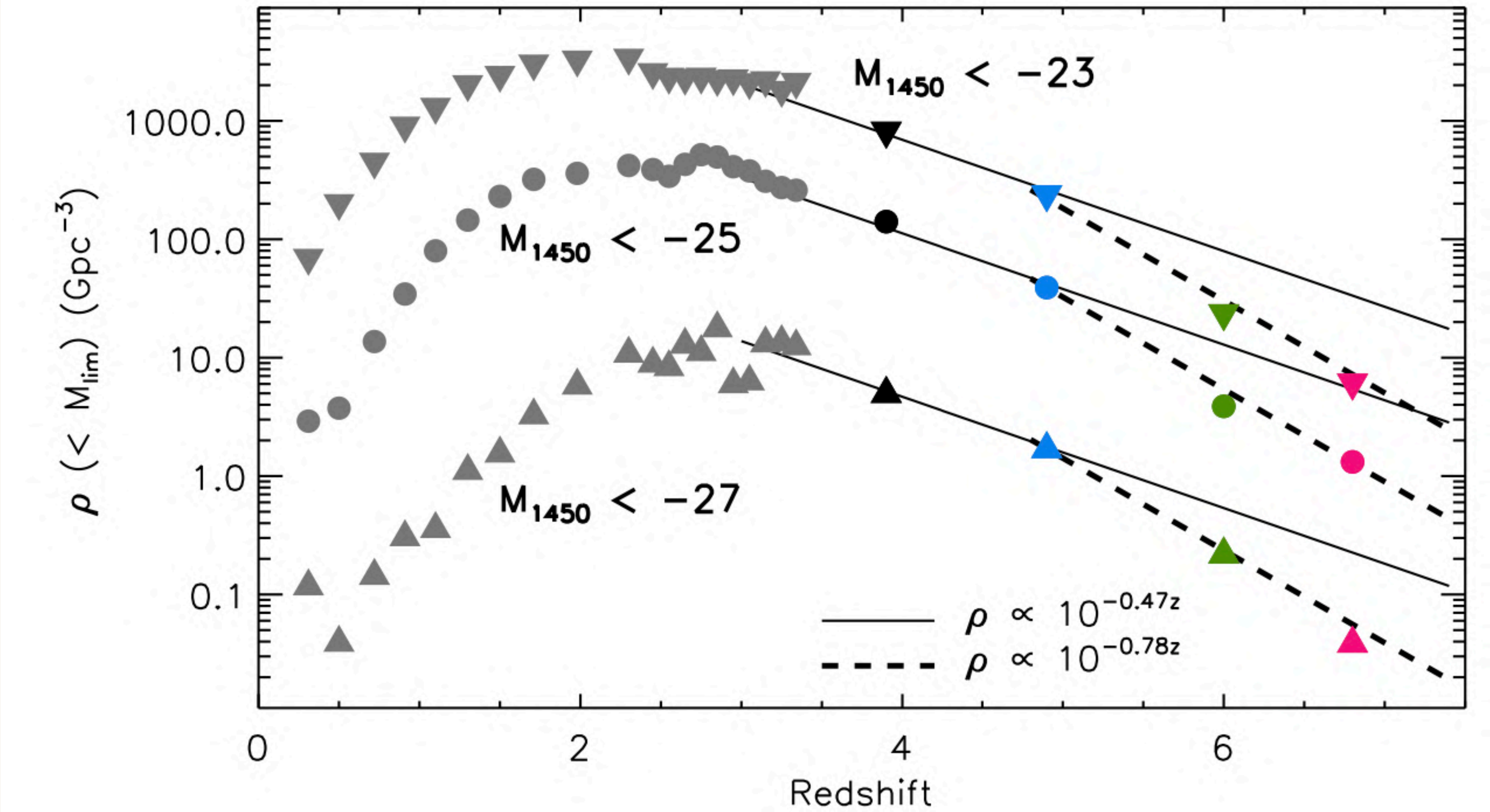
z=6-7 Quasar Luminosity Function (Paper V & XIX)

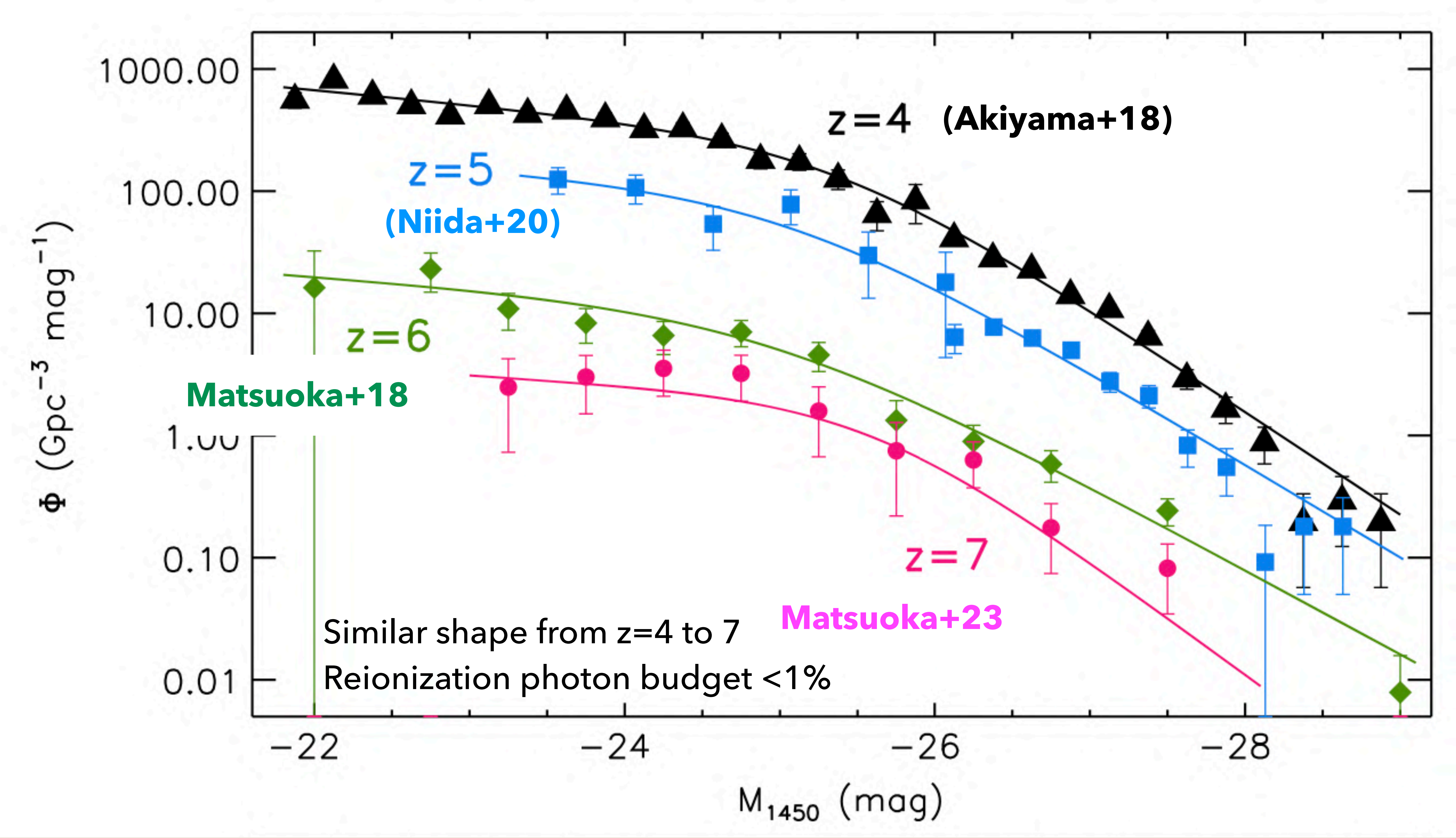




See also: e.g., Venemans+13, Jiang+16, Wang+19, Kulkarni+19, Schindler+22, and recent JWST red AGN works (e.g., Kocevski+23, Harikane+23, Matthee+23, Maiolino+23, Greene+23)

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)

Yoshiki Matsuoka (Ehime U)

AGN observations in PFS-SSP

- ✶ ~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?)

PFS-AGN town mtg at Waseda (March 4) !!

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.

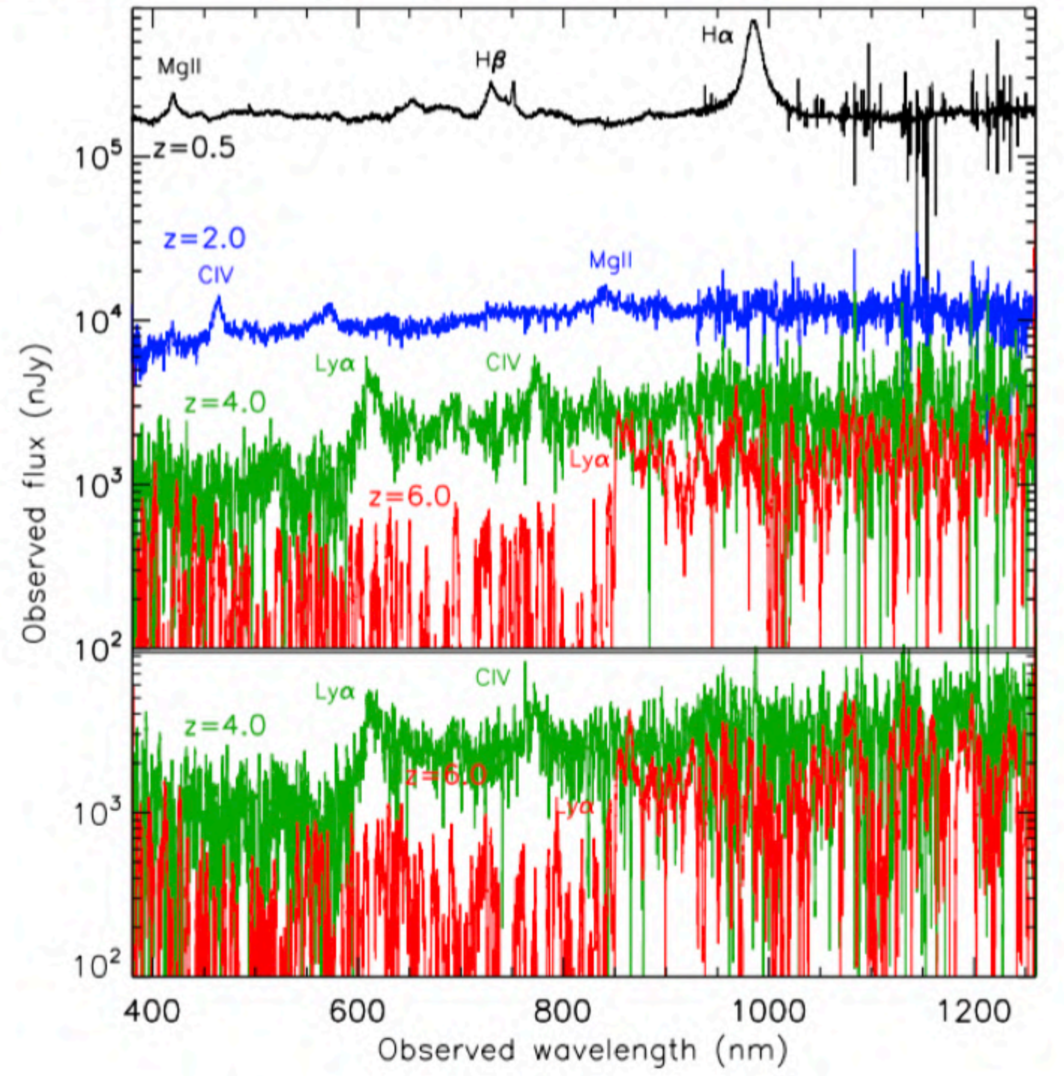
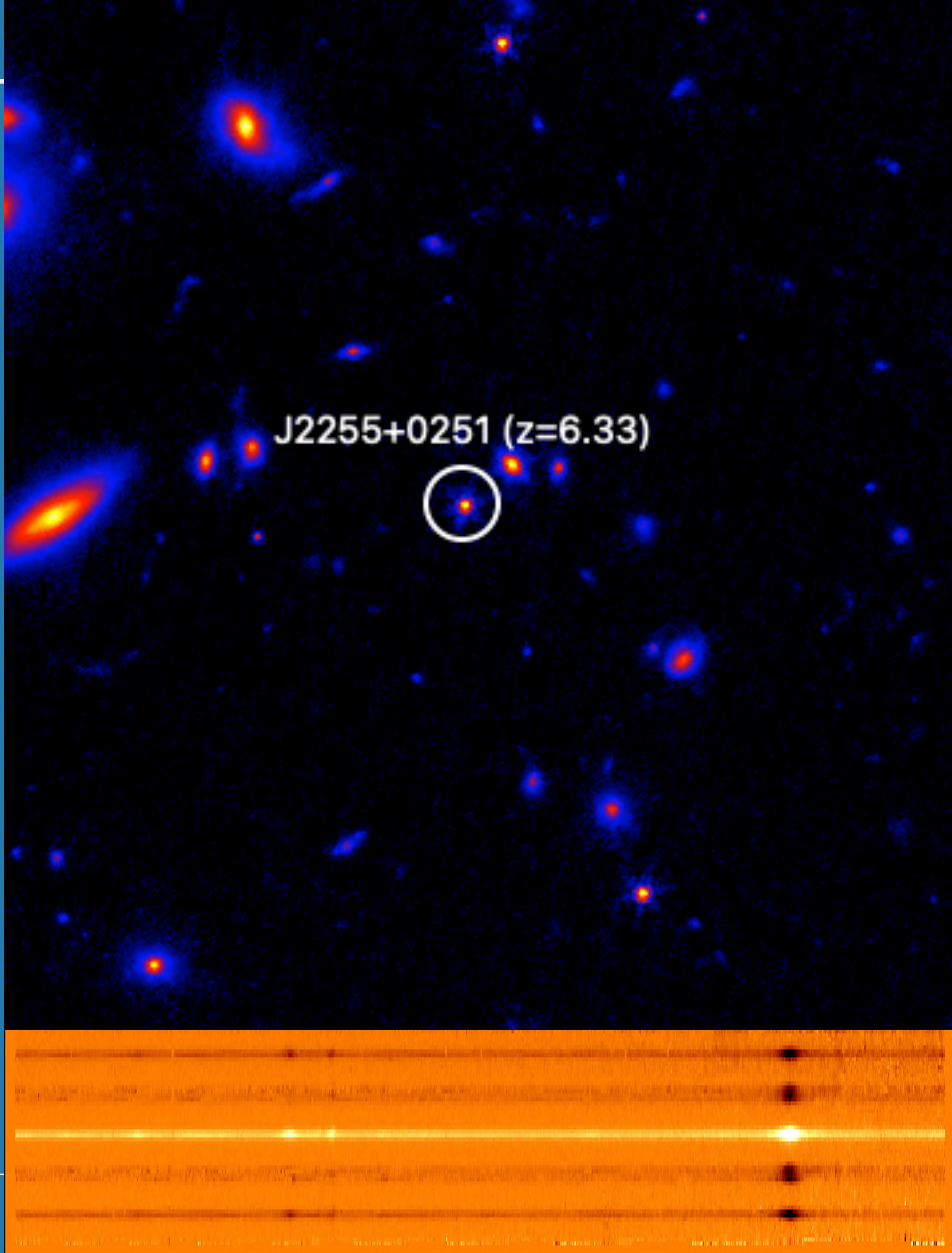


Figure 16. *Top*: Simulated PFS spectra of quasars with $M_{1450} = -23$ mag placed at $z = 0.5$ (black), 2.0 (blue), 4.0 (green), and 6.0 (red). The average observing conditions and 1-hr on-source integration are assumed in the simulations. *Bottom*: Simulated 30-min spectra of simulated CO quasars placed at z = 4.0 and 6.0. As above, $M_{1450} = -23$ mag.

courtesy of Y. Matsuoka



JWST follow-up of z~6 HSC quasars

Cy1 JWST #1967 (50hr)

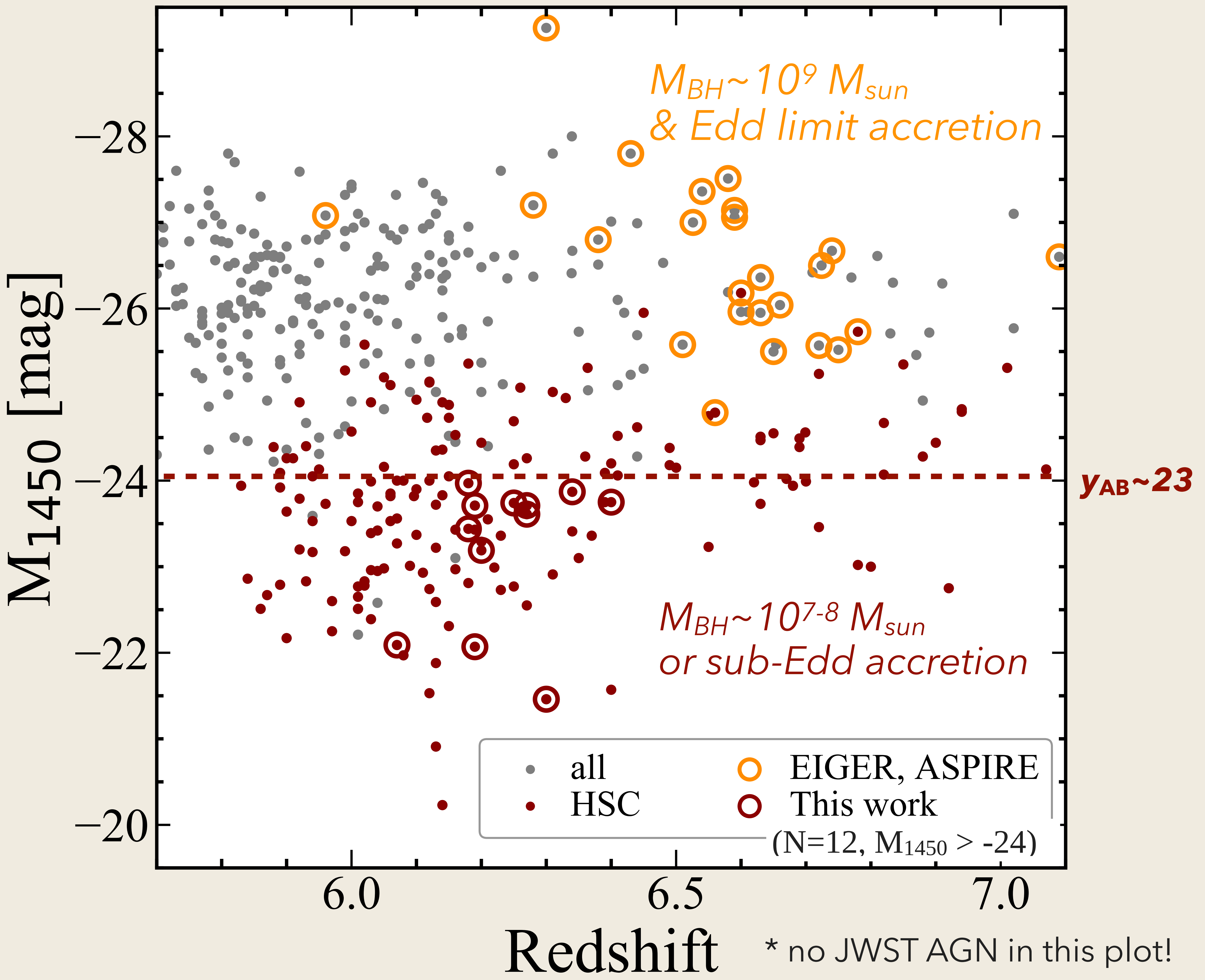
``Full Census of SMBHs and Host galaxies at z=6”

PI: M.Onoue (KIAA/IPMU)

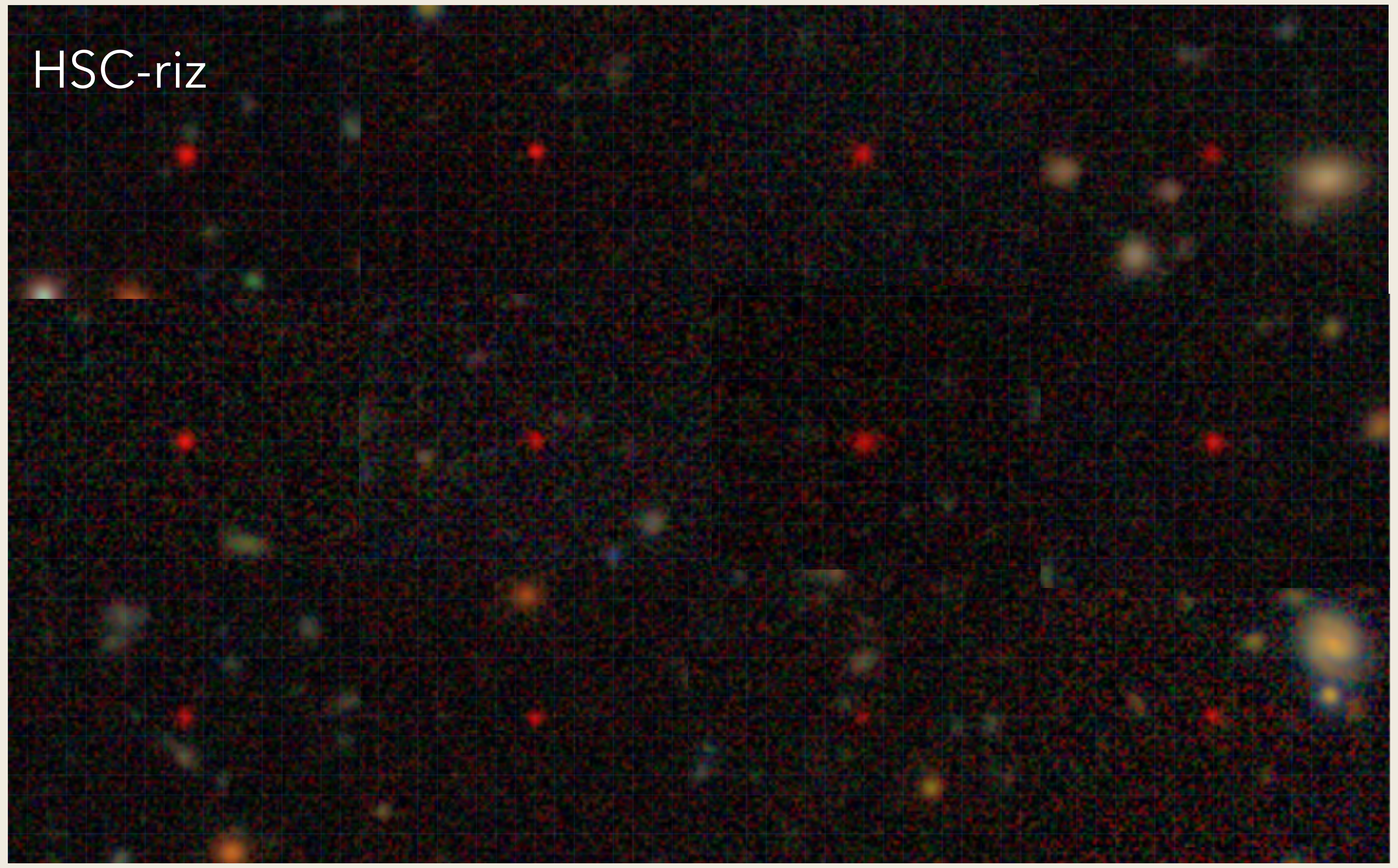
Co-PIs: X.Ding, J.Silverman (IPMU), T.Izumi (NAOJ), Y.Matsuoka (Ehime)

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)

- Target
  - 12 HSC-SSP quasars at 6.18 ≦ z ≦ 6.40, $M_{1450} > -24$
  - Selection completeness known (Matsuoka+18c)

- 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)

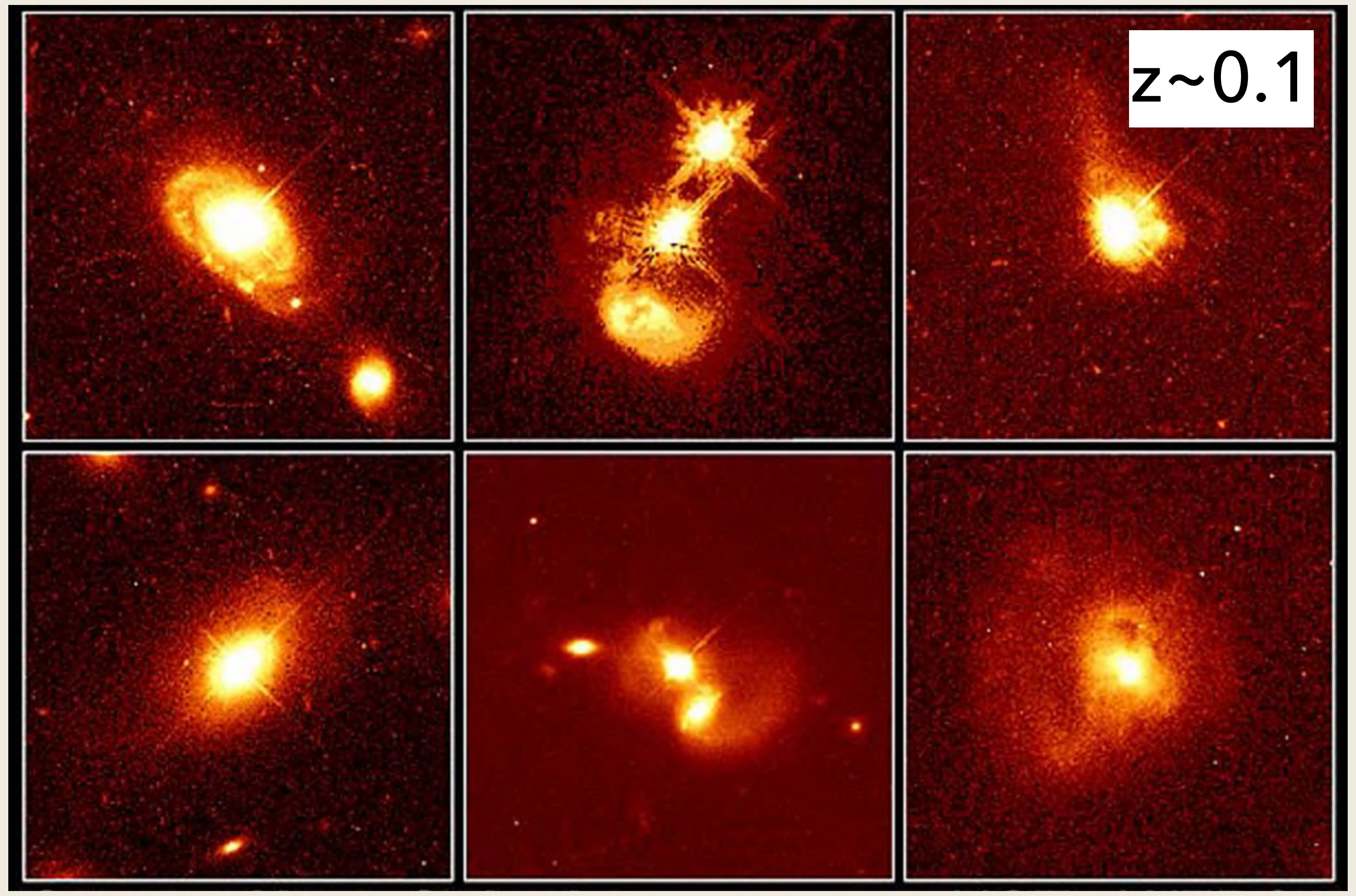
➡ Rest-optical emission line measurements
  - Hβ-based $\mathbf{M_{BH}}$, BLR/NLR, [OIII] outflow

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

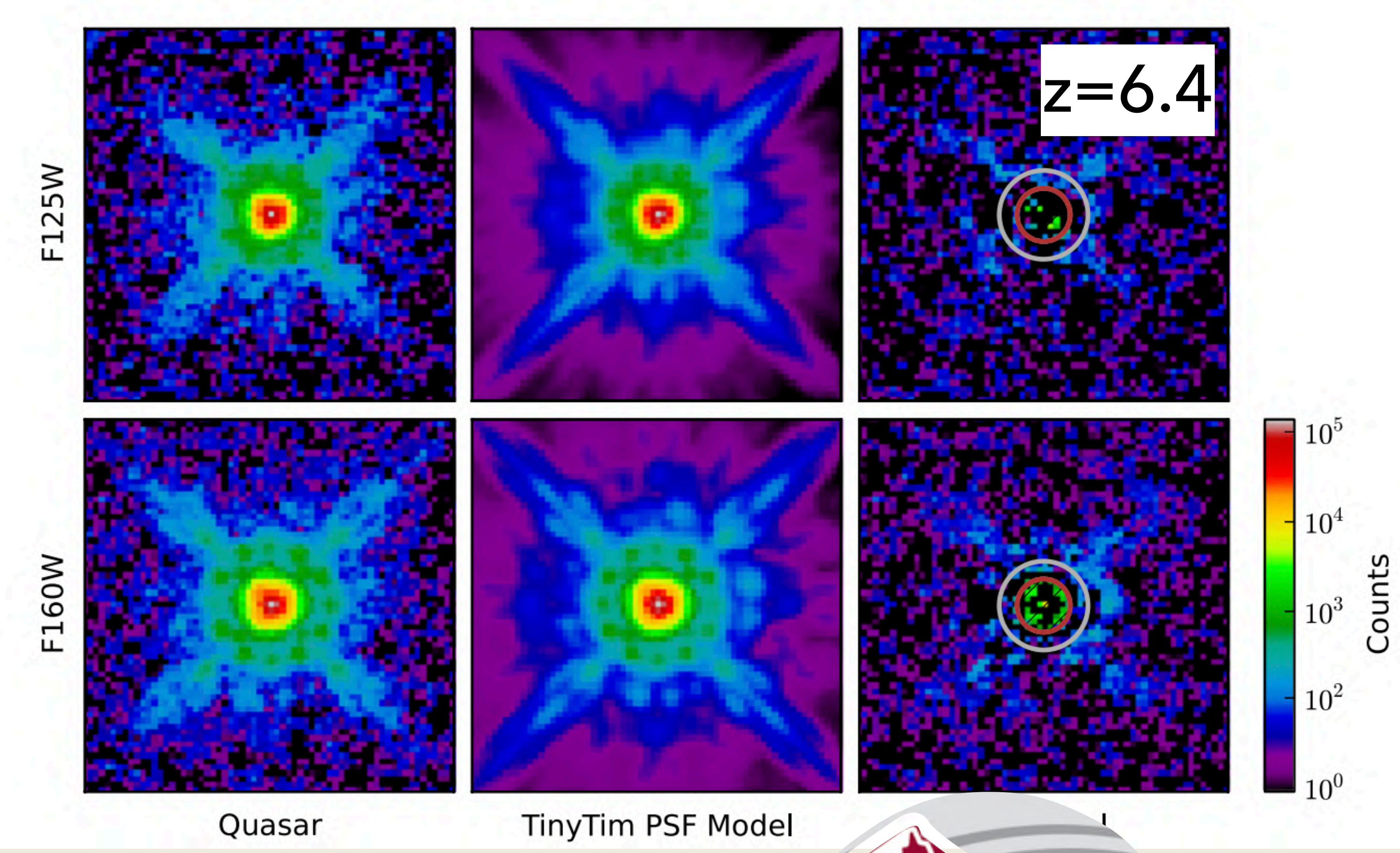
✦ BH mass function, Eddington ratio distribution

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

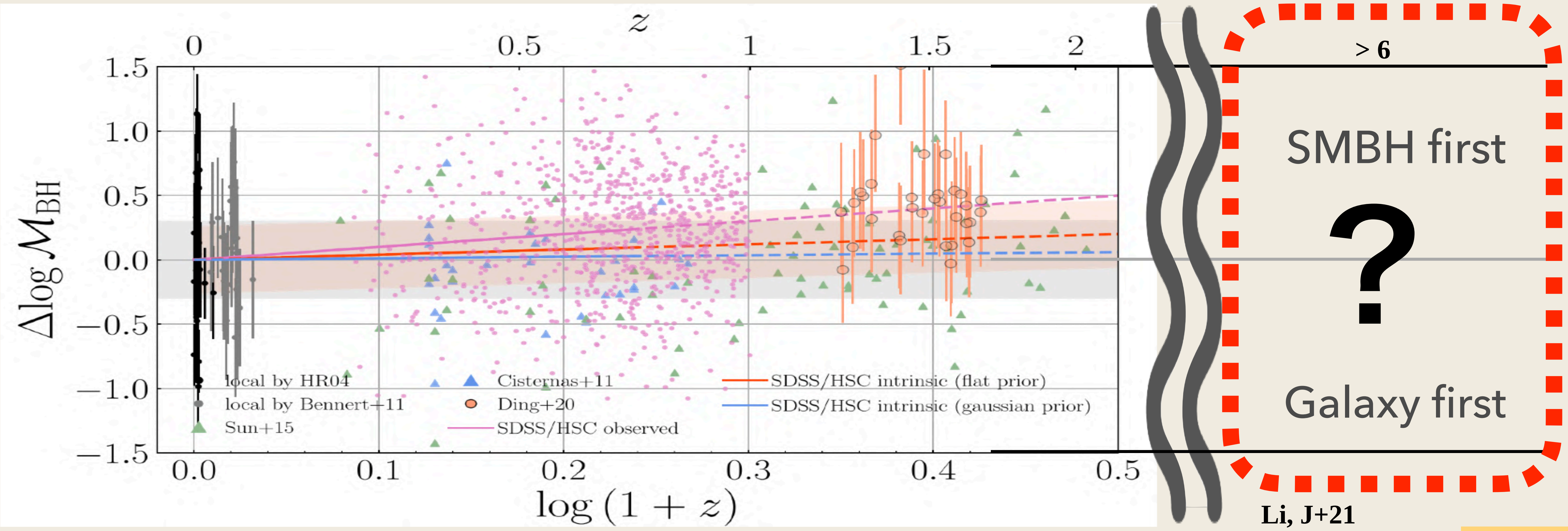
Challenge in Resolving Host Stellar Emission



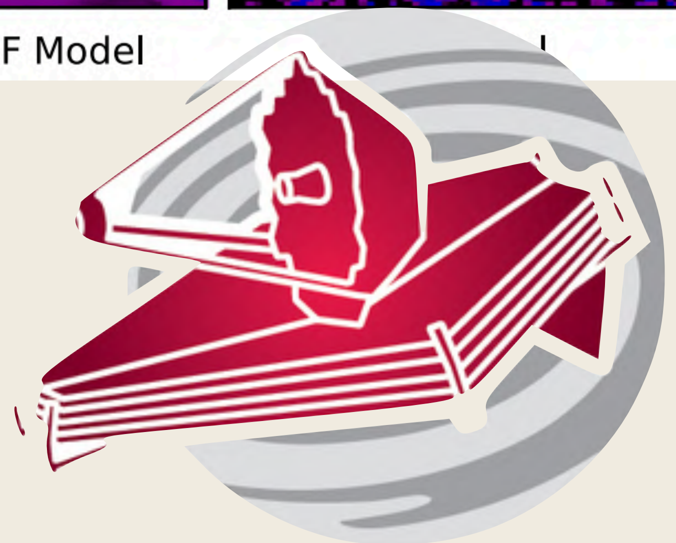
Credit: John Bahcall/Mike Disney/NASA/ESA



Mechtley+12



Li, J+21

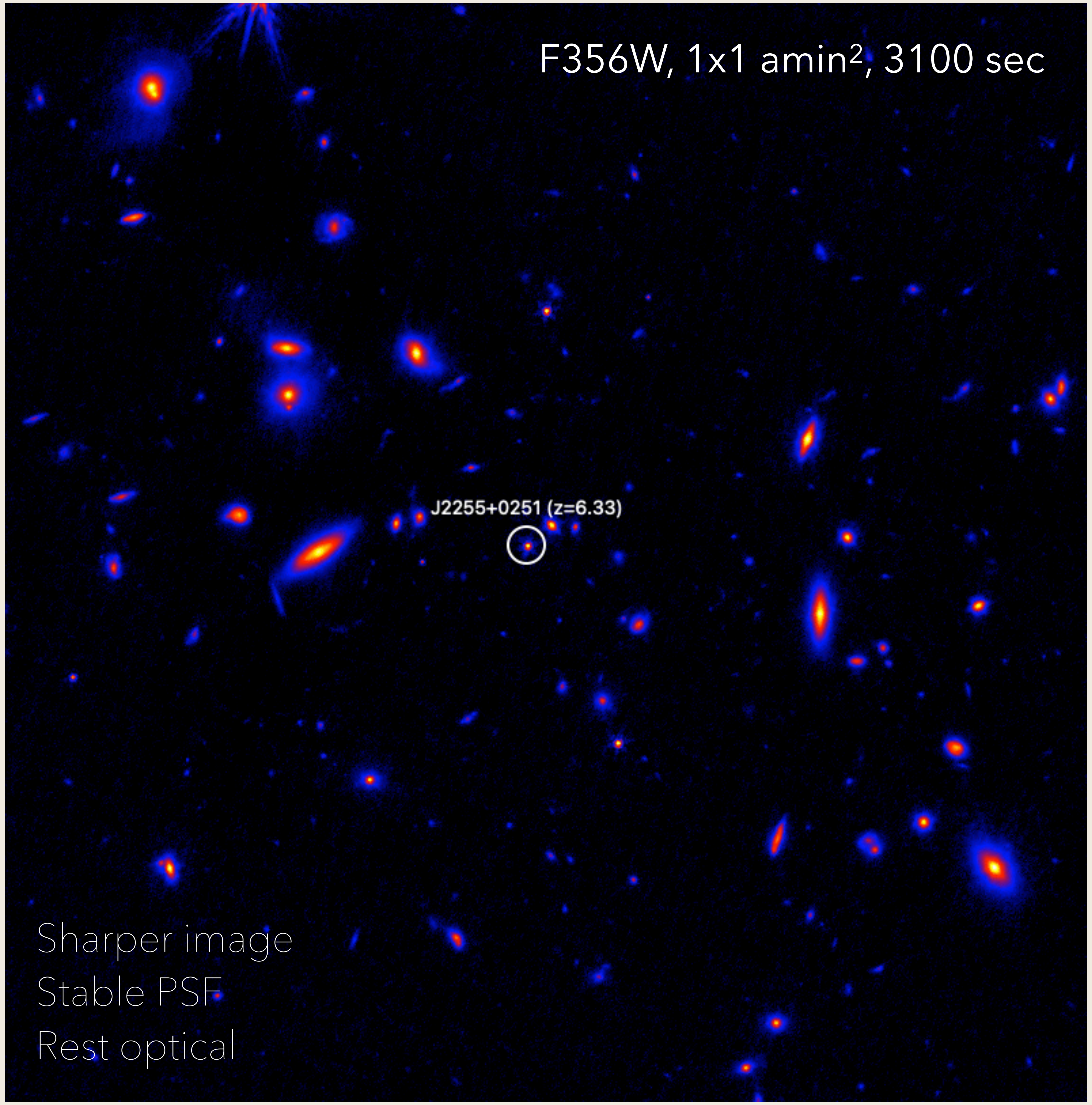


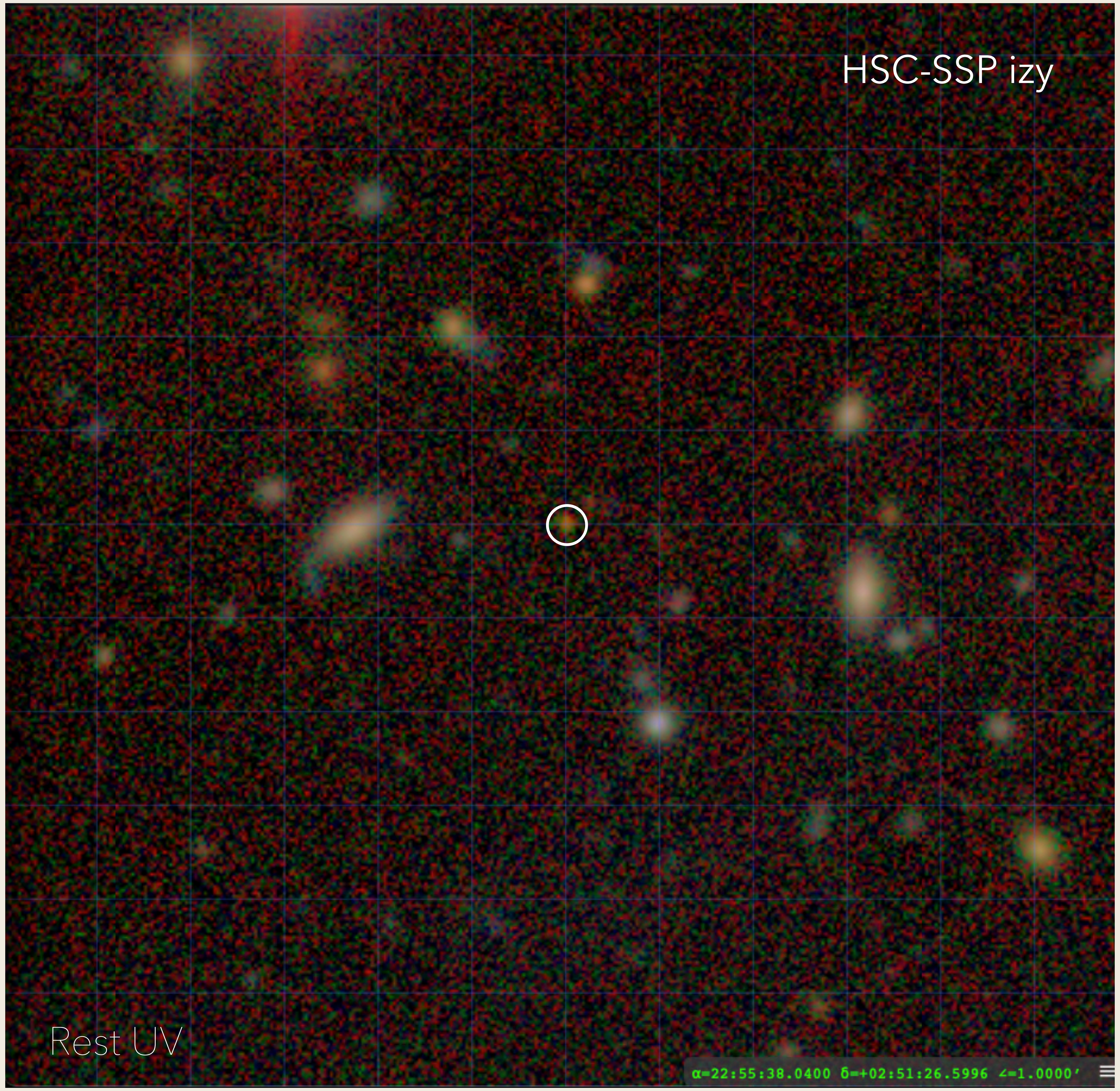
HST and ground-based studies are limited up to z~1.5

JWST!

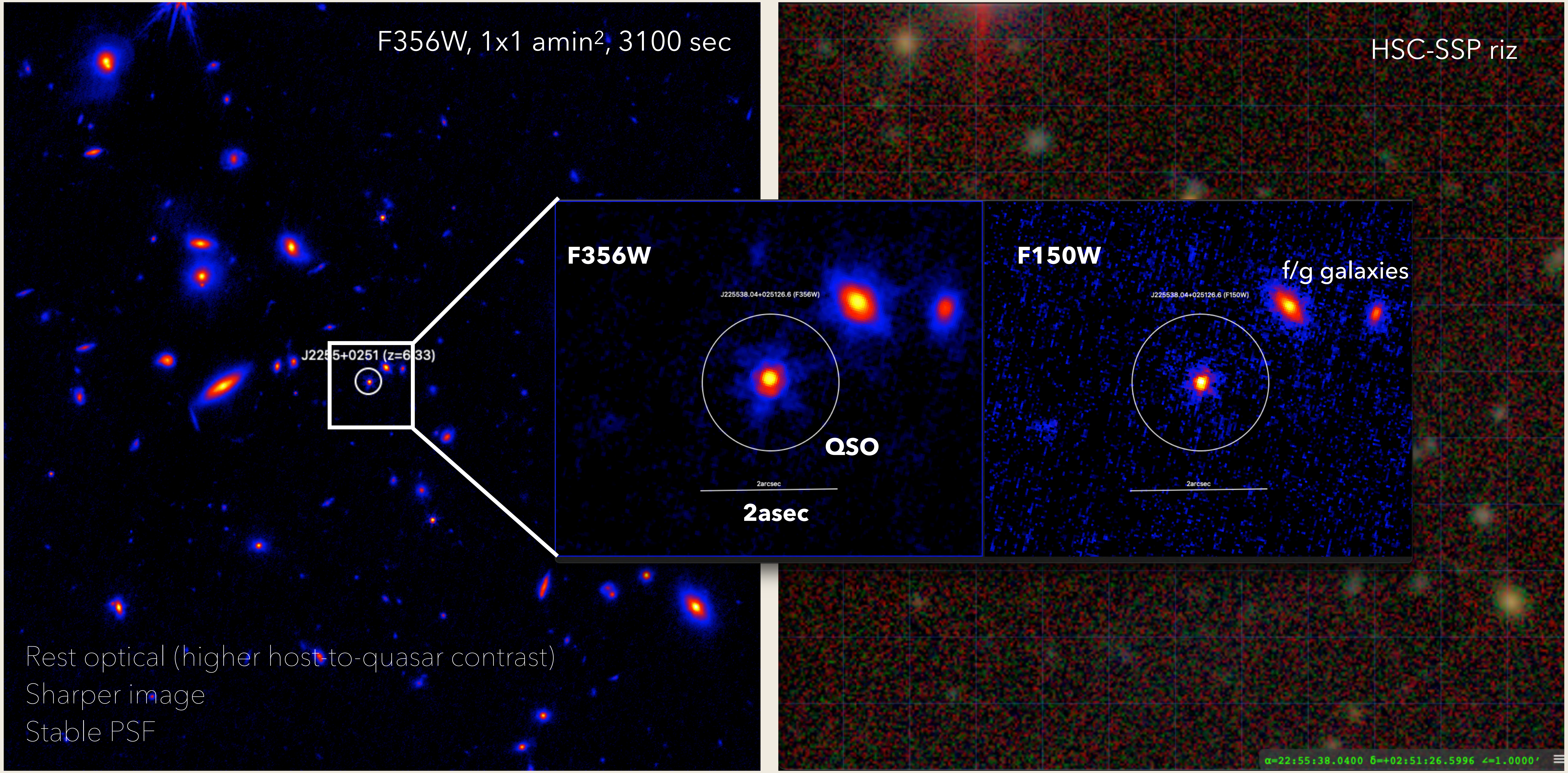
cf. Tanaka-san's talk at z~2

NIRCam: HSC J2255+0251 (z=6.33)





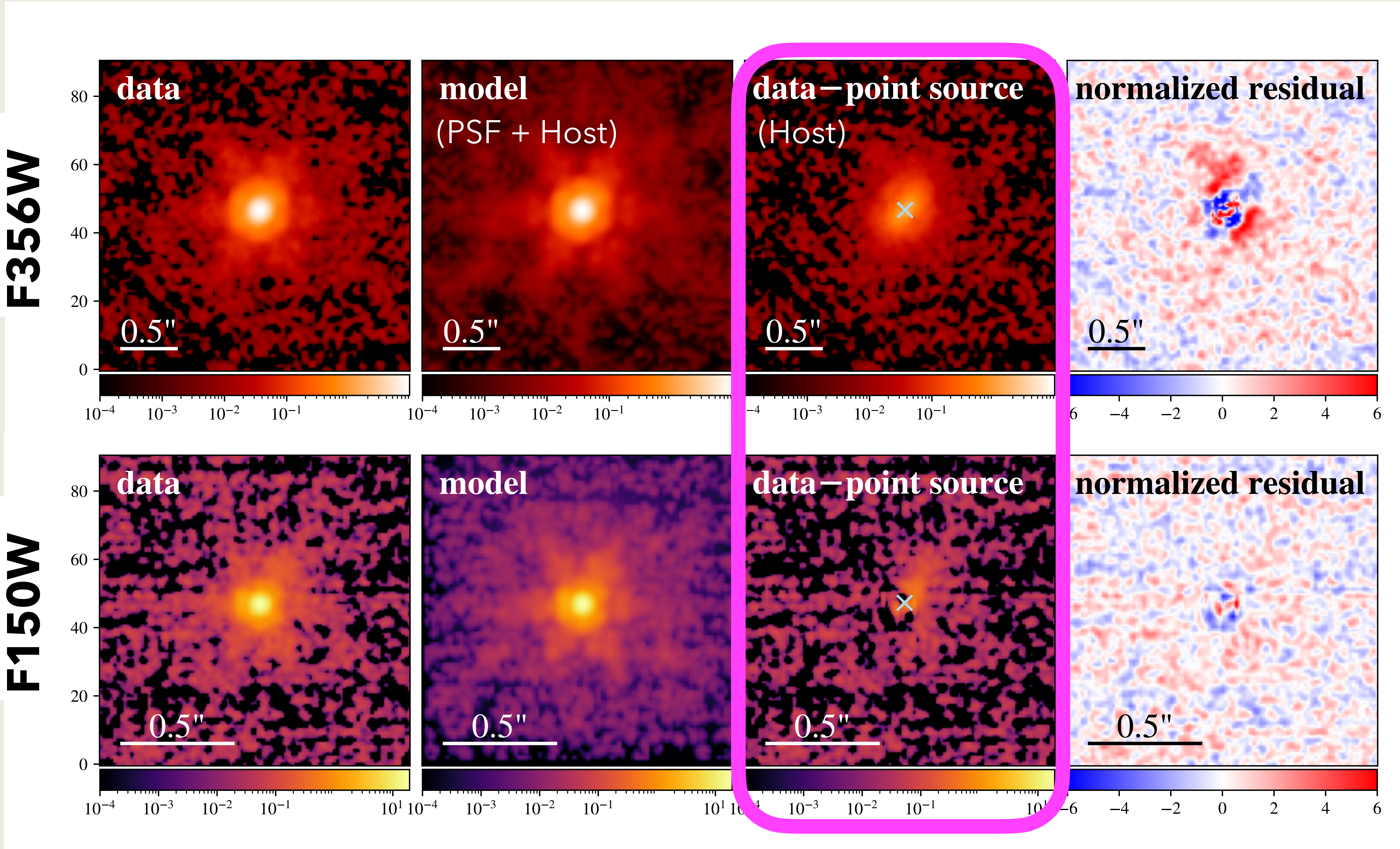
NIRCam: HSC J2255+0251 (z=6.33)

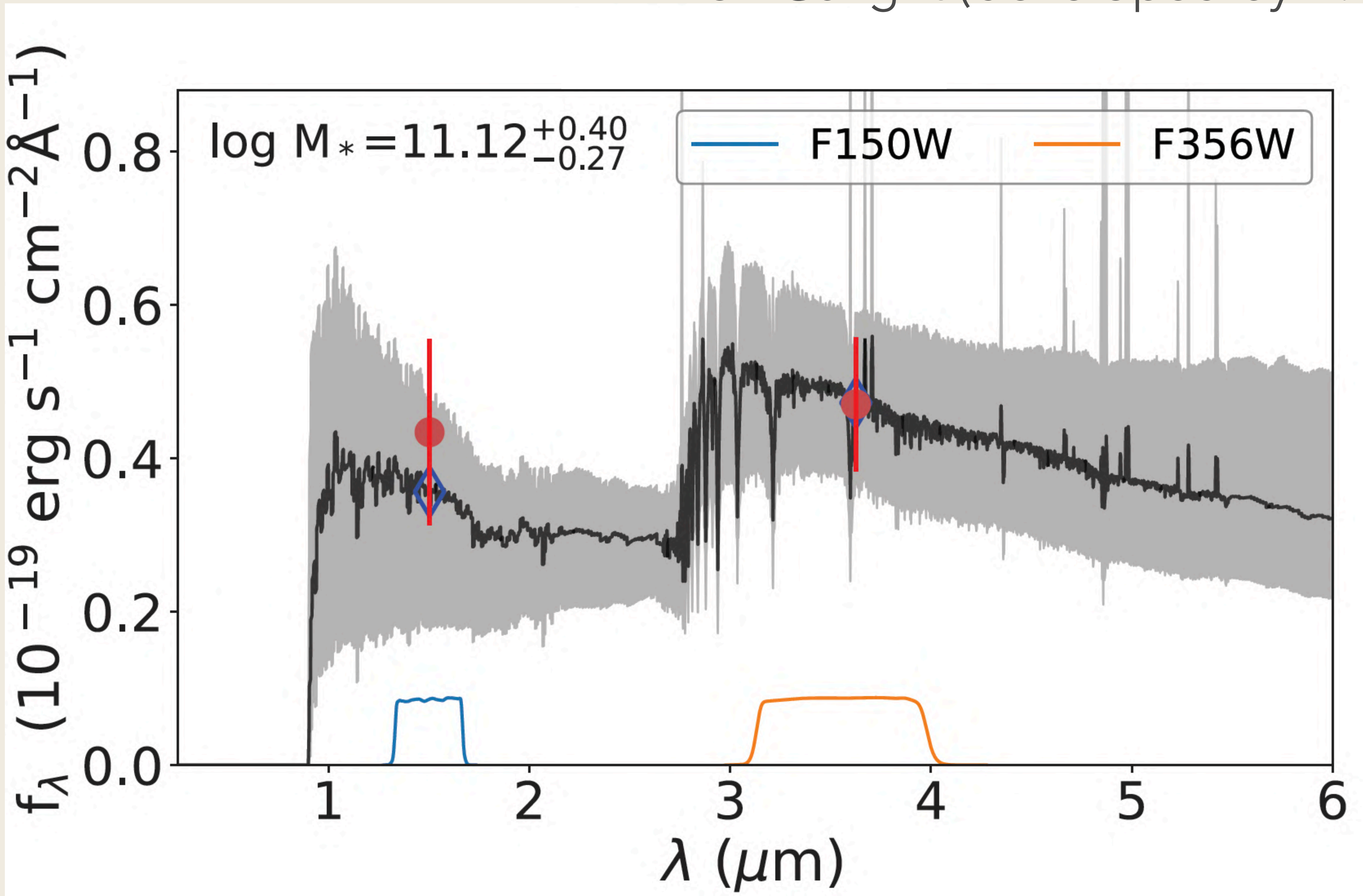


Host Starlight Detection at z>6:

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

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



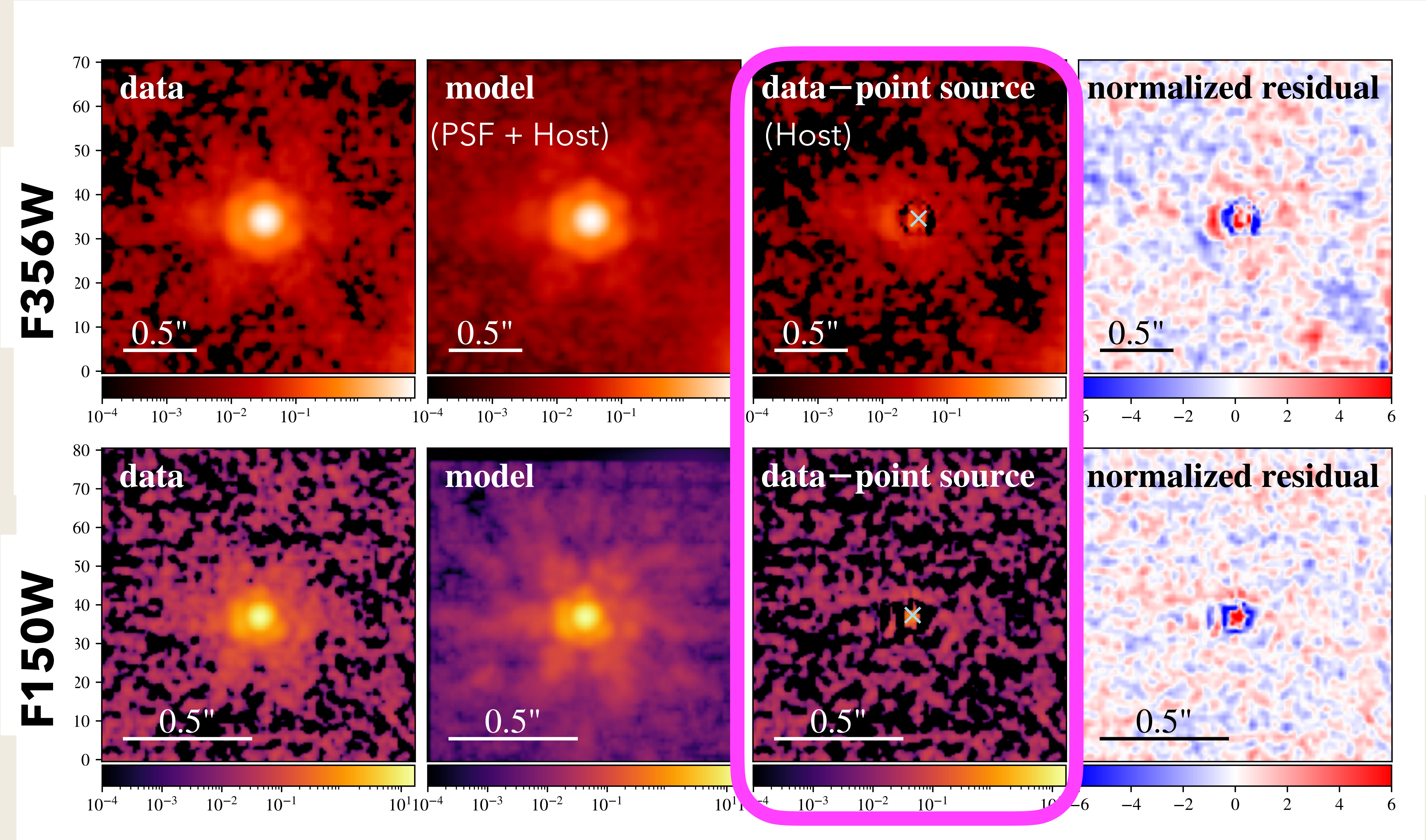


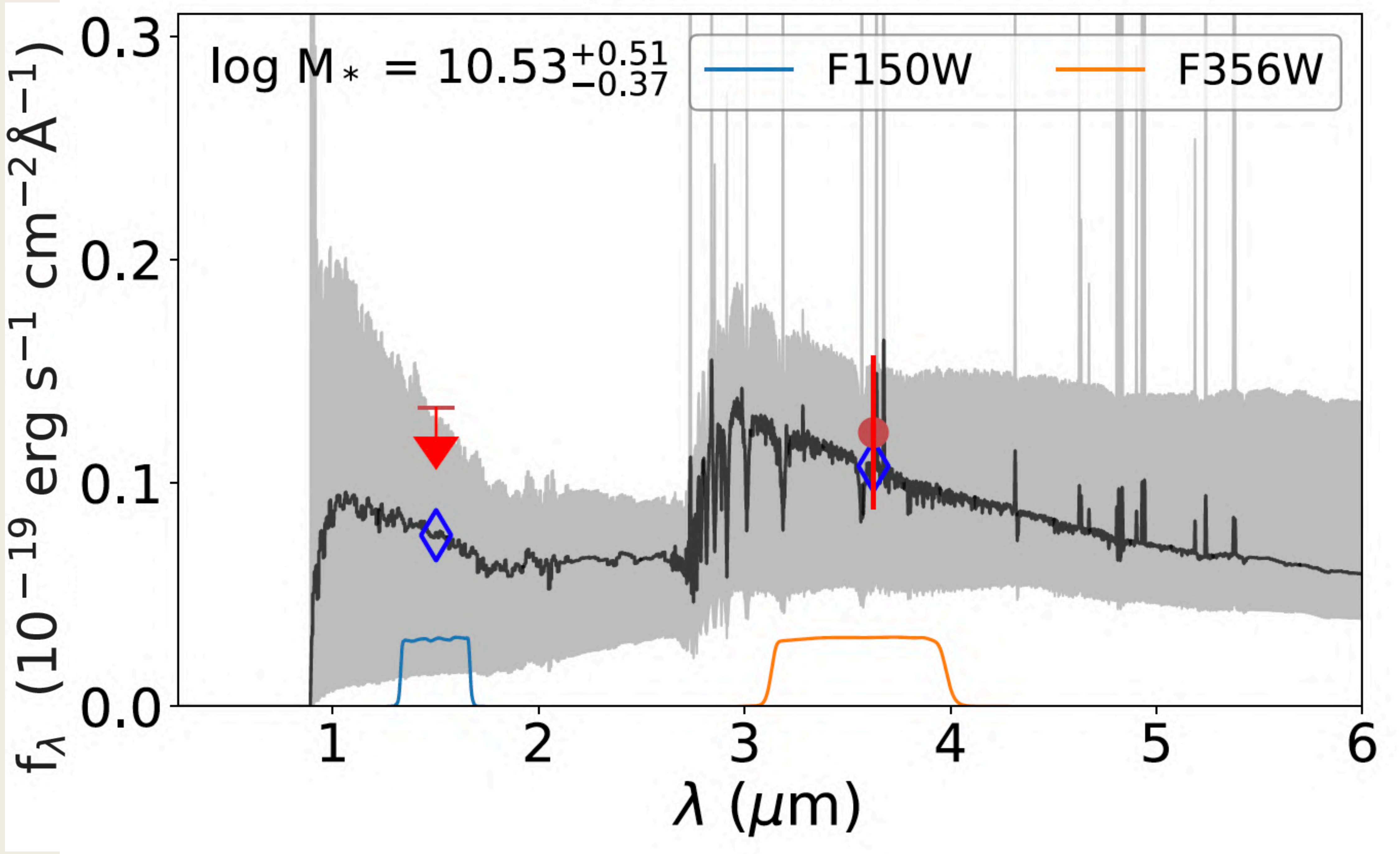
Host fraction		Host mag		Stellar mass
F356W	F150W	F356W	F150W	[log M*/M⊙]
25.5%	10.2%	23.12 (0.20)	25.12 (0.29)	$11.12^{+0.40}_{-0.27}$

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)

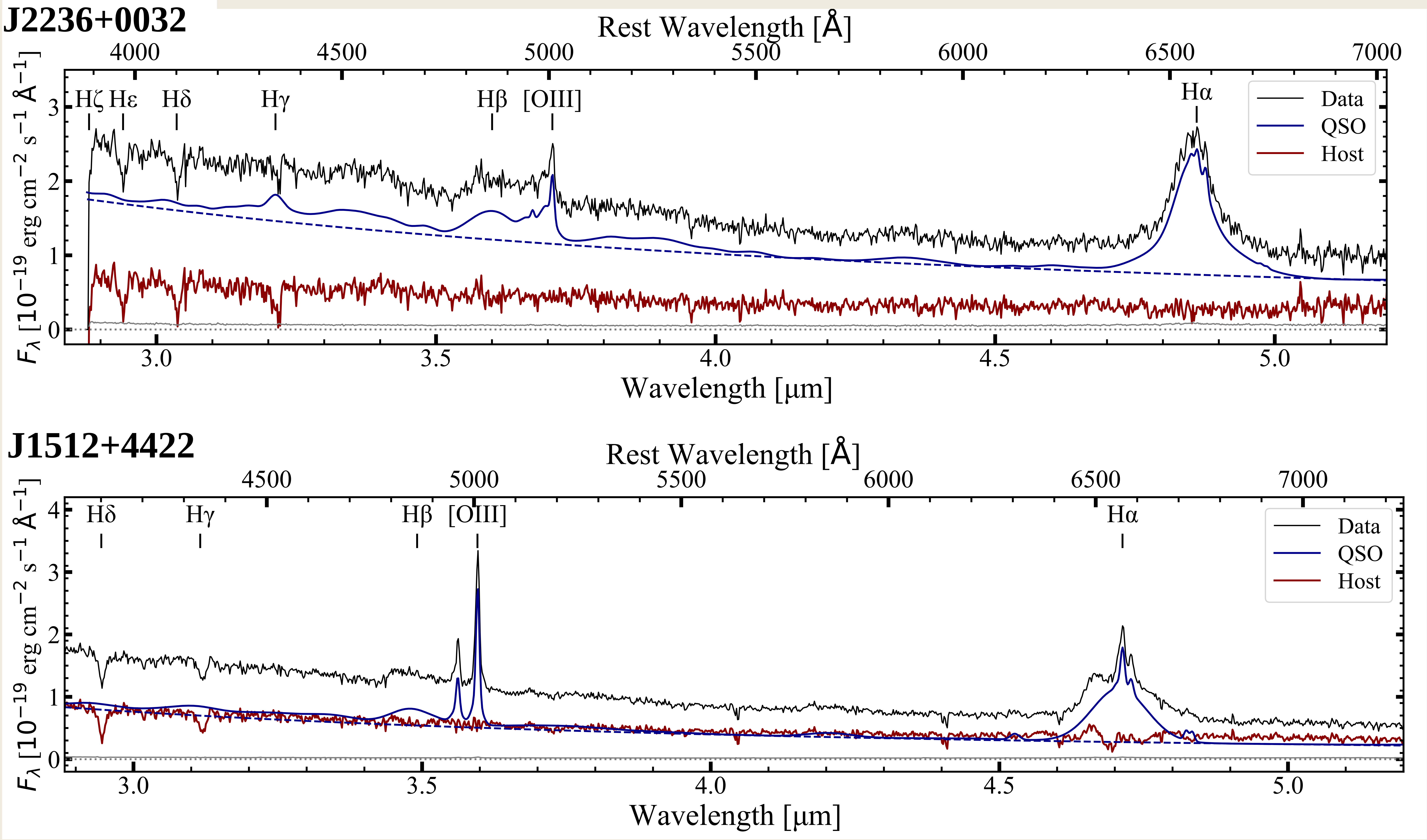




Host fraction		Host mag		Stellar mass
F356W	F150W	F356W	F150W	[log M*/M☉]
9.8%	< 3.8%	24.58 (0.30)	> 26.3	$10.53^{+0.51}_{-0.37}$

Ding, Onoue, Silverman et al. (2023)

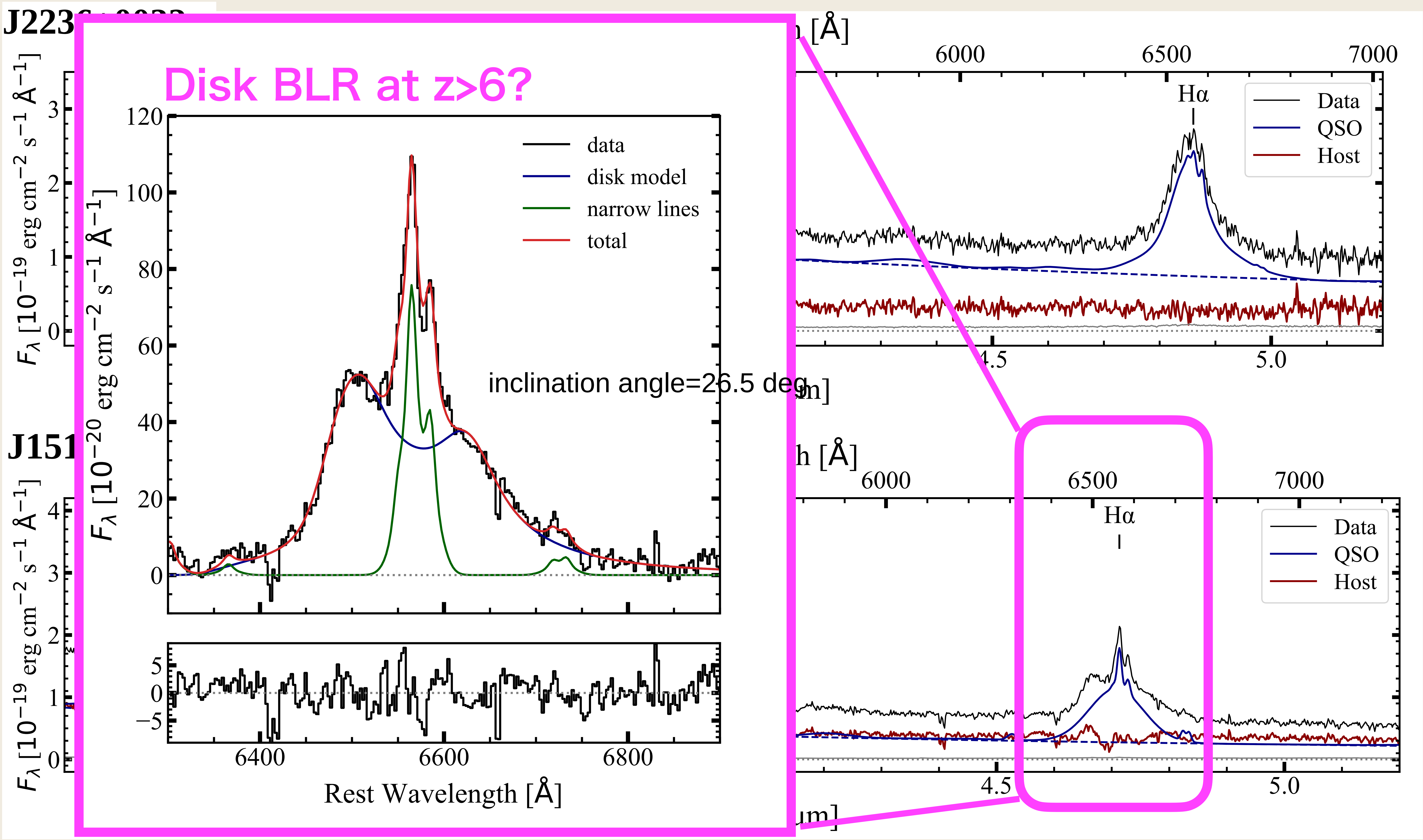
Post-starburst signature in z=6 quasar hosts



- Quasar continuum & host stellar emission are iteratively fitted during Bagpipes SED fit
- Quasar power-law continuum is matched to F356W photometry
- Host spectrum is derived by subtracting the quasar model and scaled to match NIRCam F356W photometry (x1.04 for J2236, x1.38 for J1512)

Onoue+in prep.

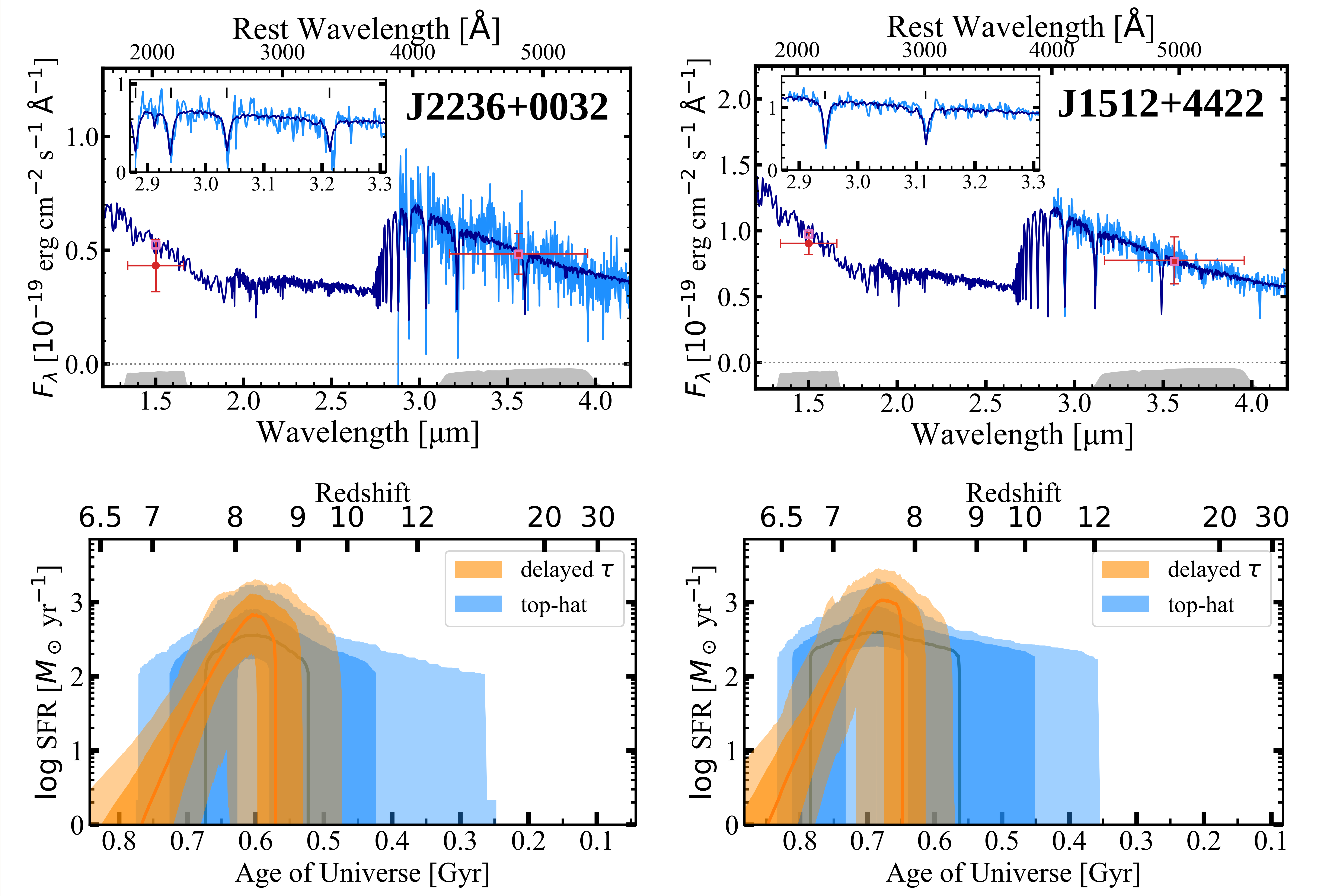
Post-starburst signature in z=6 quasar hosts



- Quasar continuum & host stellar emission are iteratively fitted during Bagpipes SED fit
- Quasar power-law continuum is matched to F356W photometry
- Host spectrum is derived by subtracting the quasar model and scaled to match NIRCam F356W photometry (x1.04 for J2236, x1.38 for J1512)

Onoue+in prep.

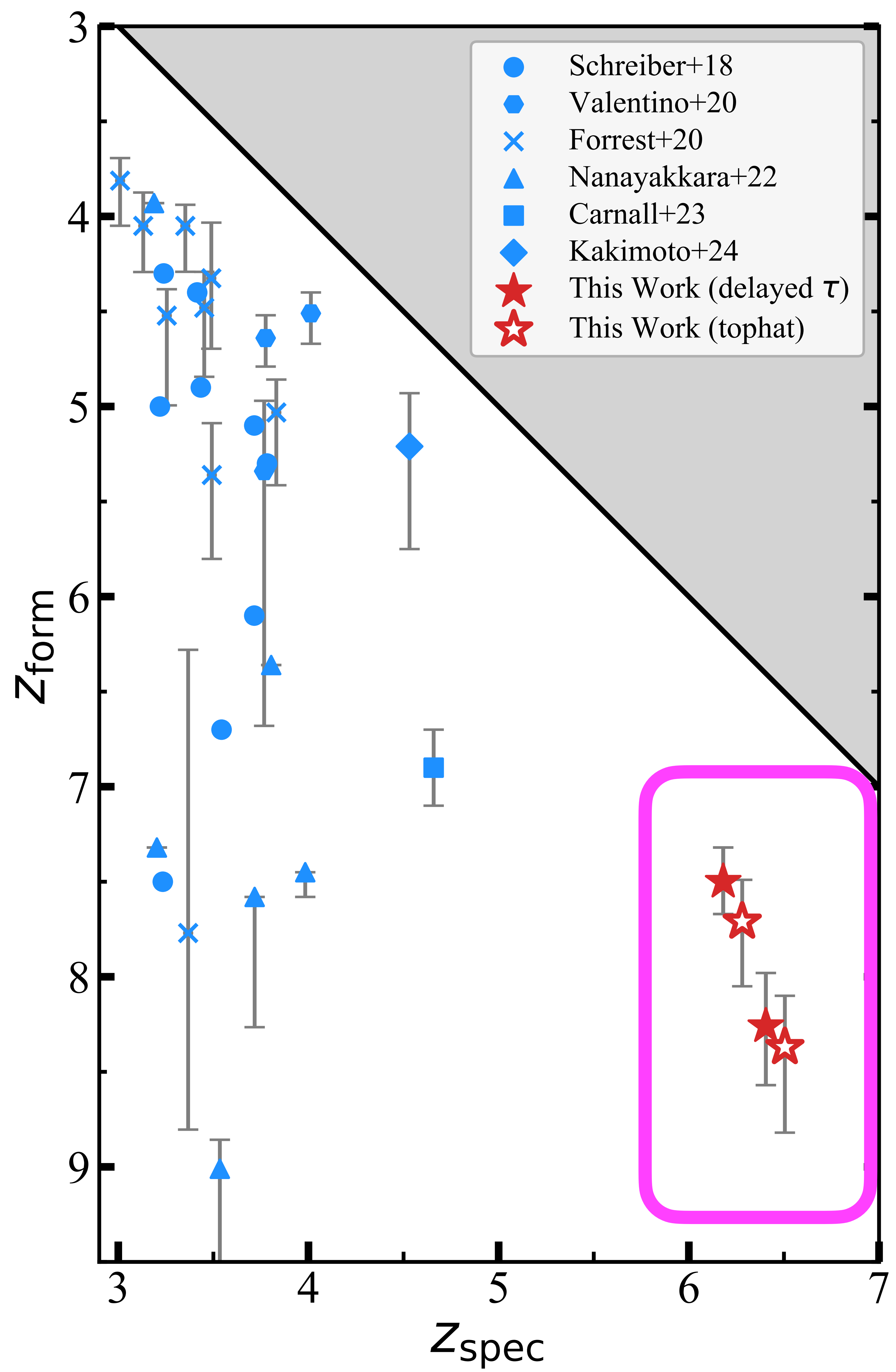
Spectrophotometric SED fit with Bagpipes



ID	J2236+0032		J1512+4422	
SFH	delayed-τ	top hat	delayed-τ	top hat
α_λ	-1.65 ± 0.01	-1.65 ± 0.01	-2.26 ± 0.01	-2.27 ± 0.01
z	$6.4048^{+0.0007}_{-0.0006}$	$6.4048^{+0.0006}_{-0.0006}$	$6.1806^{+0.0003}_{-0.0004}$	$6.1805^{+0.0004}_{-0.0004}$
$\log M_*/M_\odot$	$10.63^{+0.04}_{-0.03}$	$10.64^{+0.03}_{-0.04}$	$10.78^{+0.02}_{-0.02}$	$10.79^{+0.03}_{-0.03}$
mass-weighted age [Myr]	240^{+20}_{-30}	250^{+30}_{-30}	200^{+20}_{-20}	220^{+40}_{-30}
τ [Myr]	16^{+10}_{-5}		18^{+8}_{-6}	
age_max [Myr]		320^{+100}_{-50}		320^{+110}_{-80}
age_min [Myr]		170^{+40}_{-50}		100^{+50}_{-30}
A_V [mag]	$0.04^{+0.07}_{-0.03}$	$0.03^{+0.06}_{-0.01}$	$0.08^{+0.09}_{-0.05}$	$0.09^{+0.10}_{-0.05}$
σ_* [km s^{-1}]	< 240	< 240	200^{+40}_{-40}	200^{+50}_{-40}
noise scaling factor	$1.46^{+0.05}_{-0.05}$	$1.45^{+0.05}_{-0.05}$	$1.89^{+0.07}_{-0.07}$	$1.89^{+0.08}_{-0.07}$

- Massive (log M*/M_{sun} > 10) galaxies formed via starburst <u>a few hundred Myr</u> before these quasars are observed

- *Need more data to probe pre-burst & young stellar population (–> Cy2 for J2236)*
- *ALMA Cy9 program ongoing ([CII] + dust)*

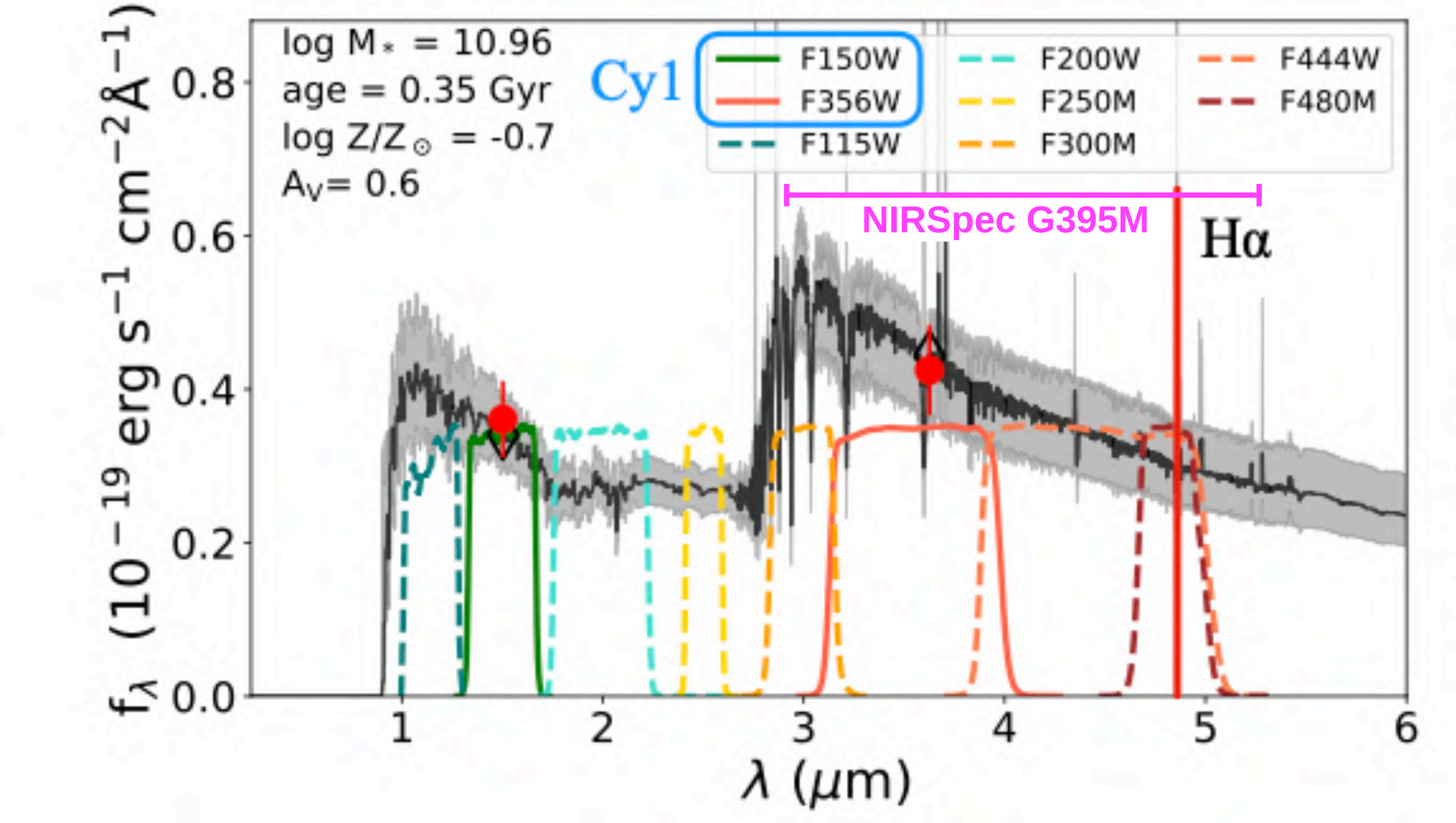


Most distant quiescent galaxies known

- *z_spec: observed redshift*
- *z_form: redshift when 50% of the total stellar mass is formed (= age)*

Additional NIRCam imaging for J2236

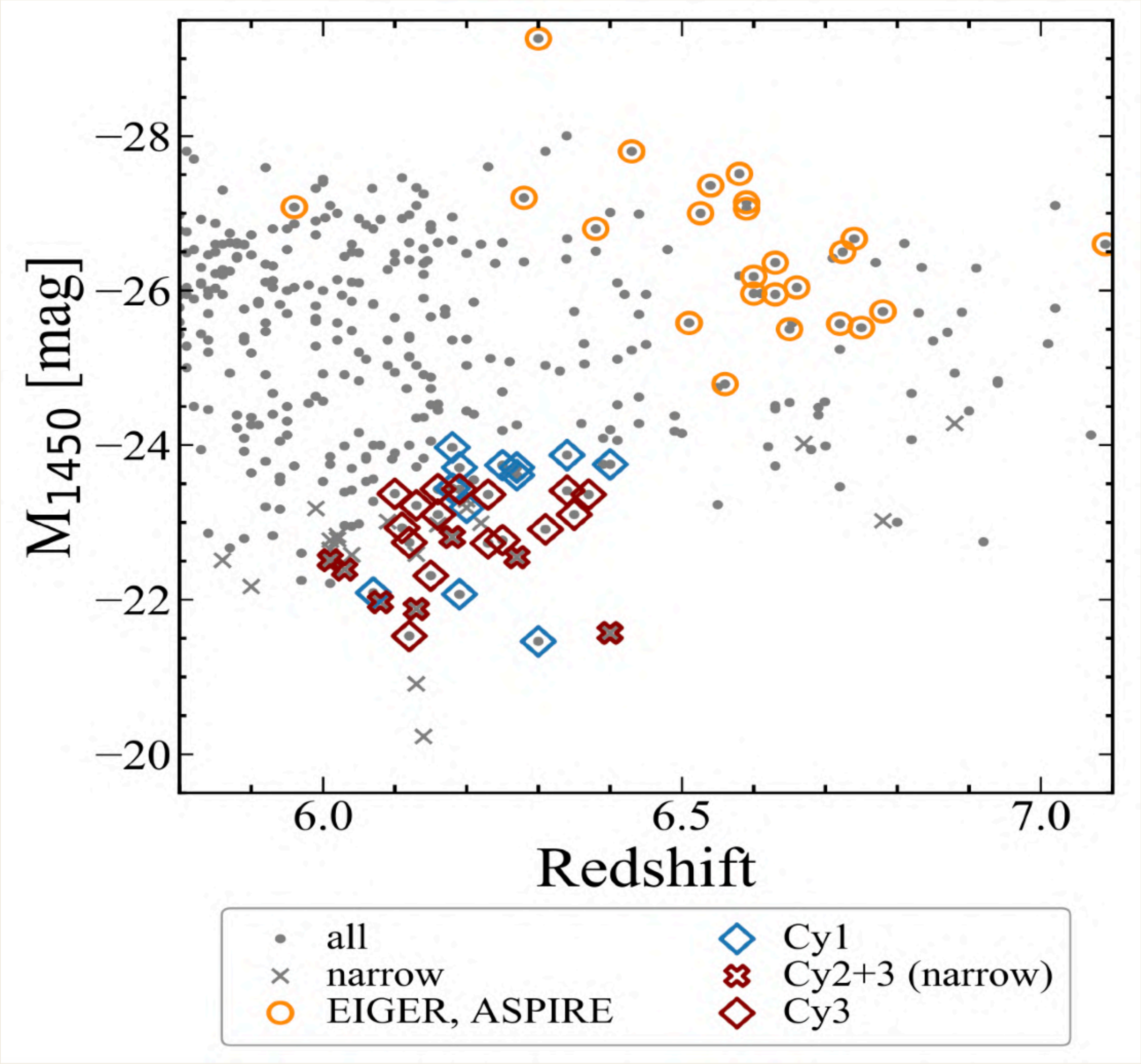
GO #3859 (PI:MO, Co-PI:X.Ding, 11hr w/ NIRCam)

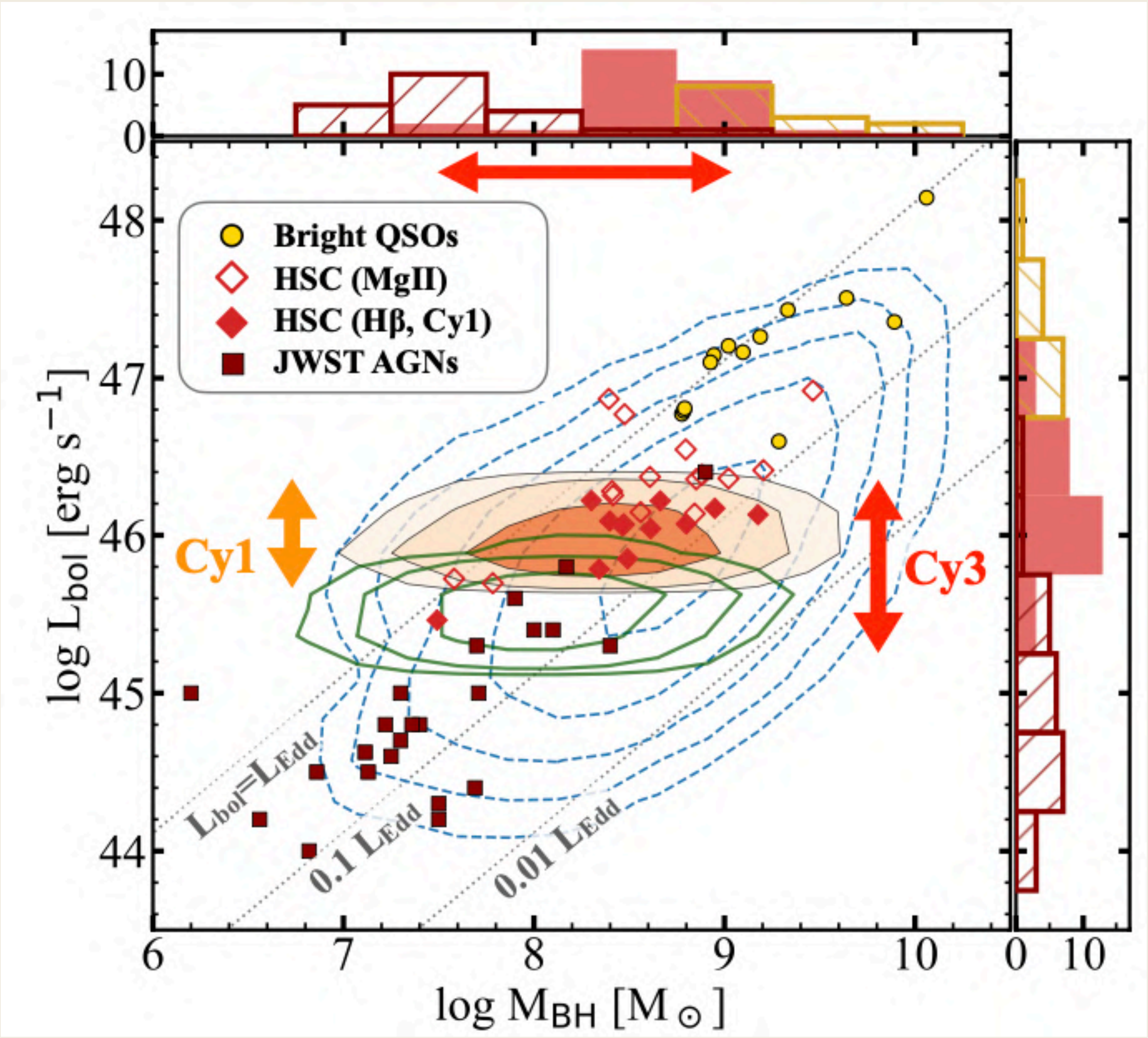


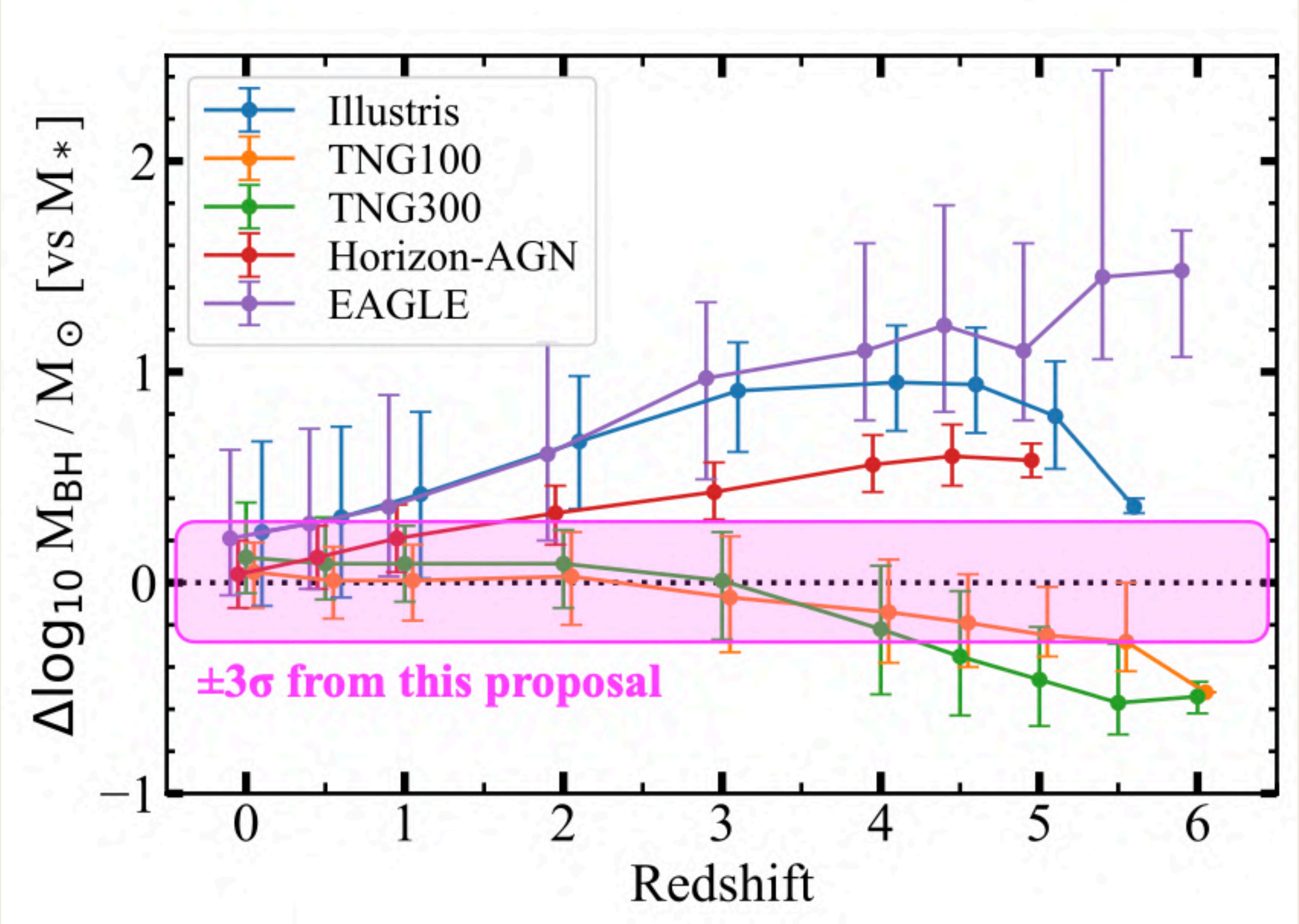
Data just arrived on the Cy3 deadline date!!

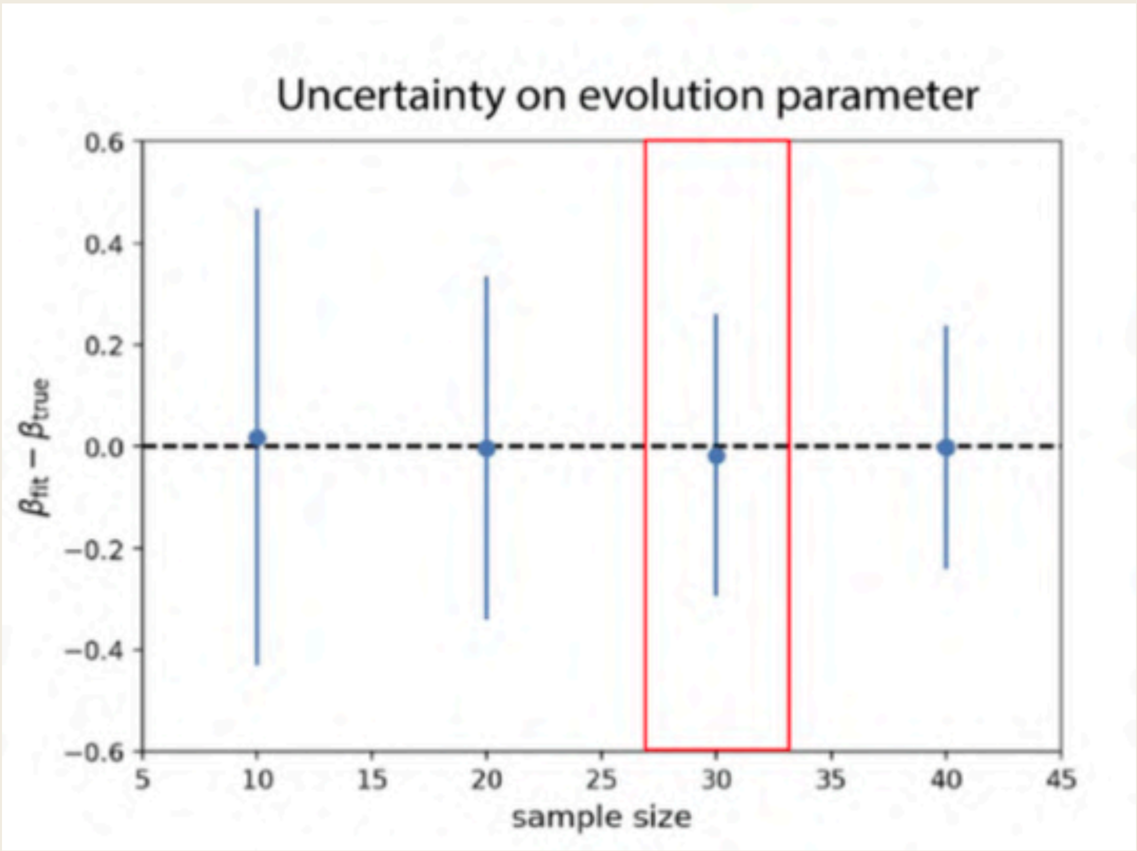
Host SED of J2236 will be better constrained with an imaging spectrum (1-5 um)
F480M will catch z=6.4 HAEs around the central quasar (to be compared with EIGER & ASPIRE results)

Toward Cy3+…







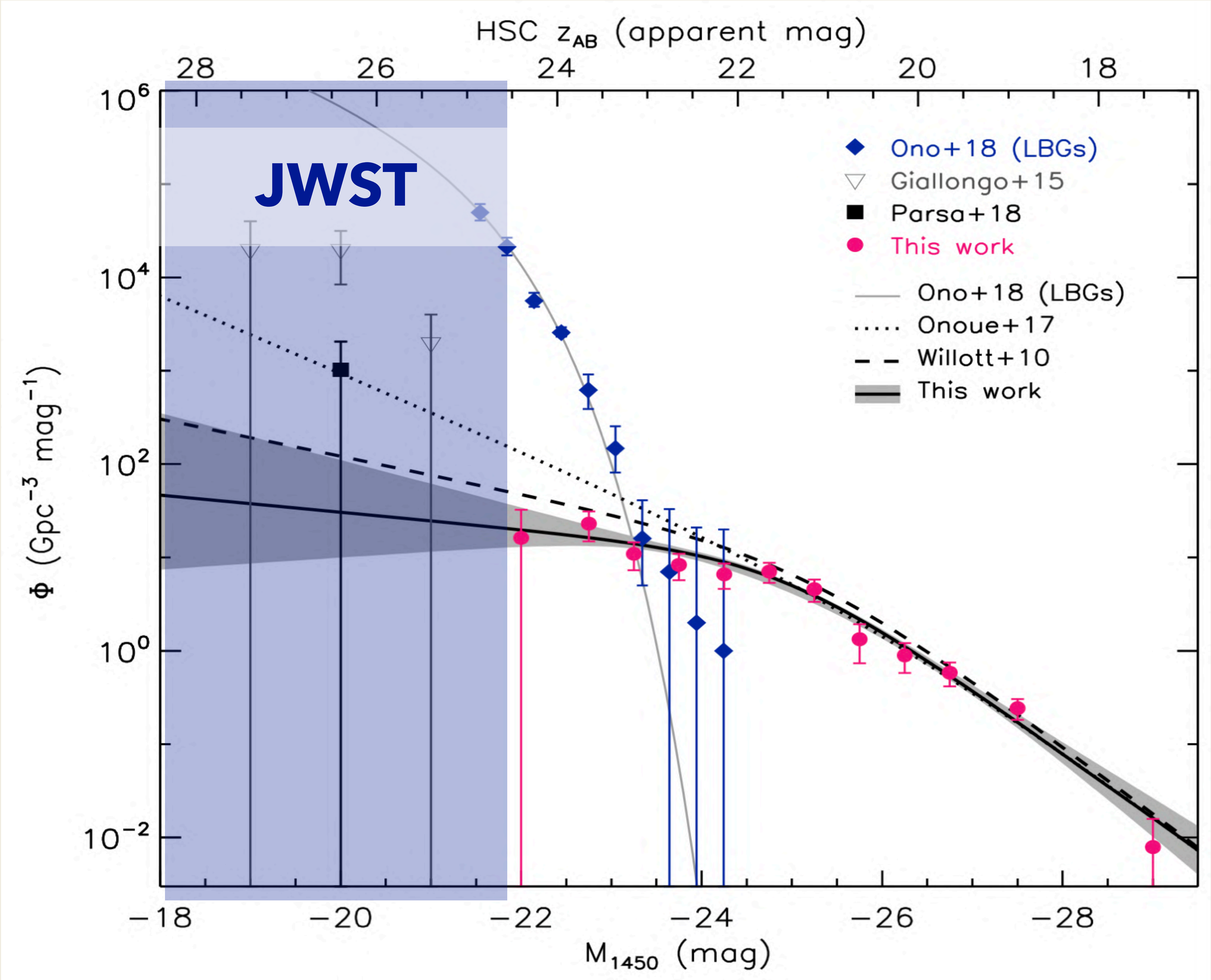


Mock simulation result (M_{BH} = 0.98 × M_*–β)
A sample of N=30 is required to recover β with 0.3 dex accuracy

We need a larger and deeper sample to constrain co-evolution and BH statistics

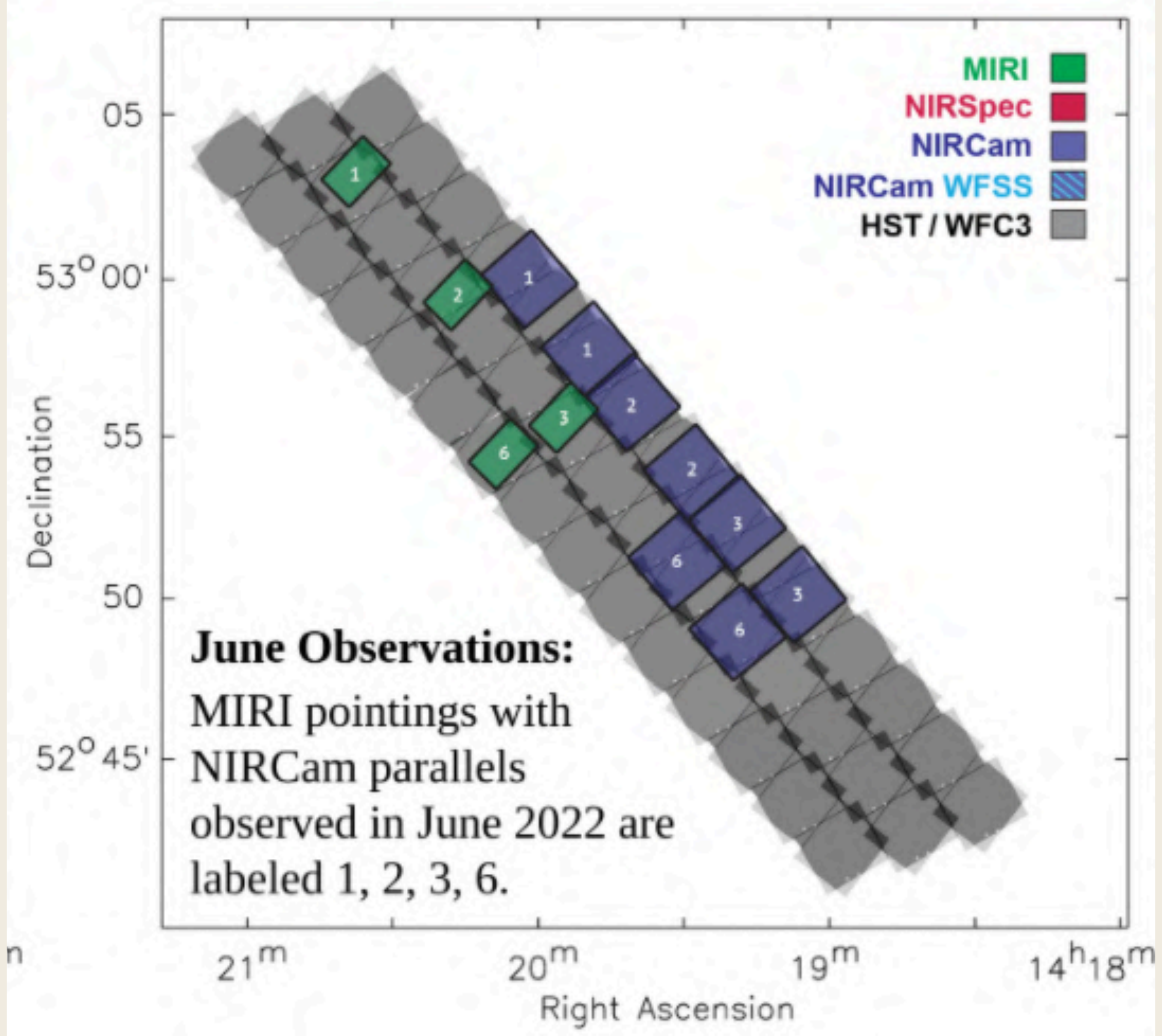
Discovery of z>5 faint AGN with CEERS

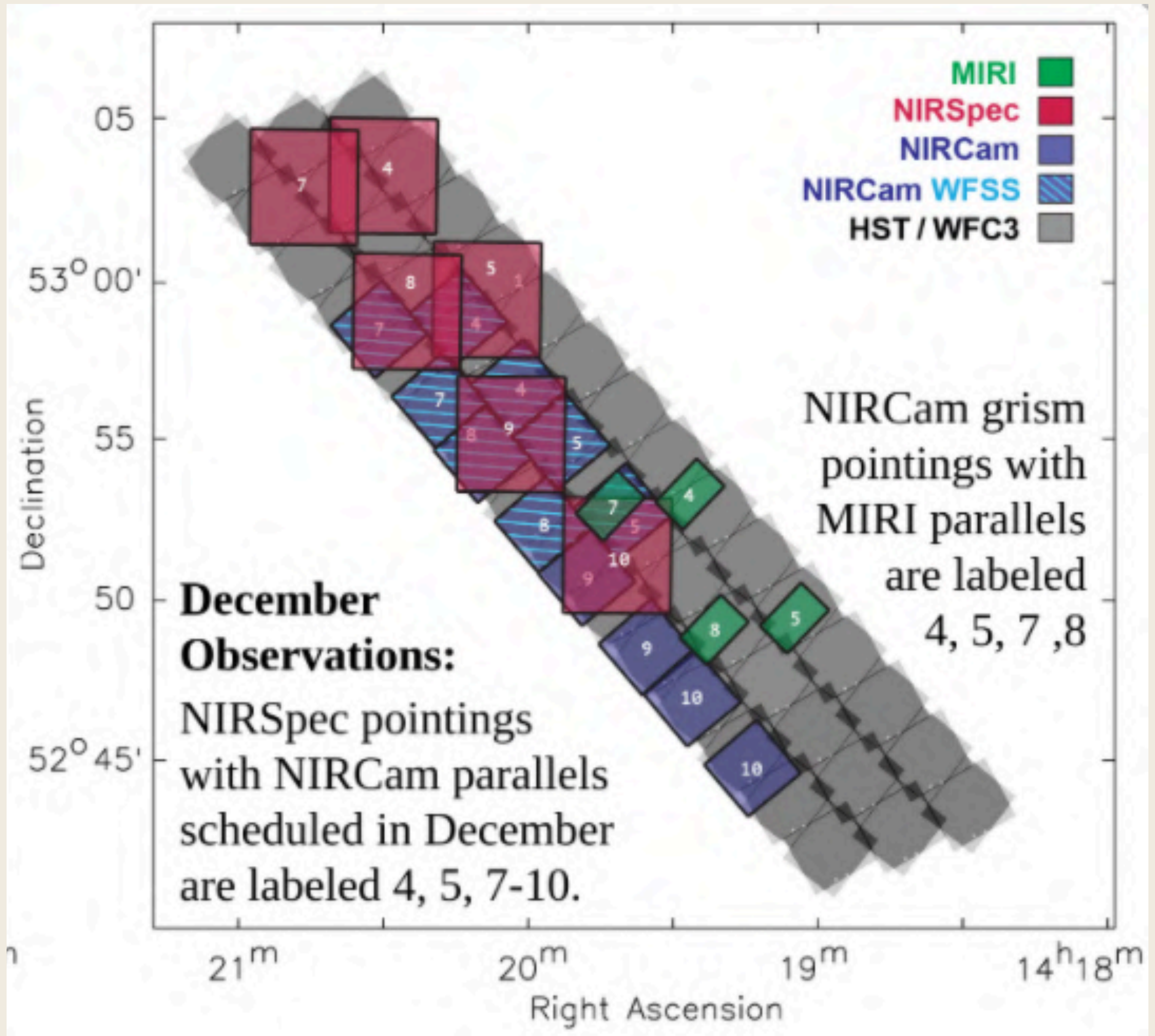
Can we find AGN in JWST surveys?



HSC studies suggest ~1% of galaxies host AGN

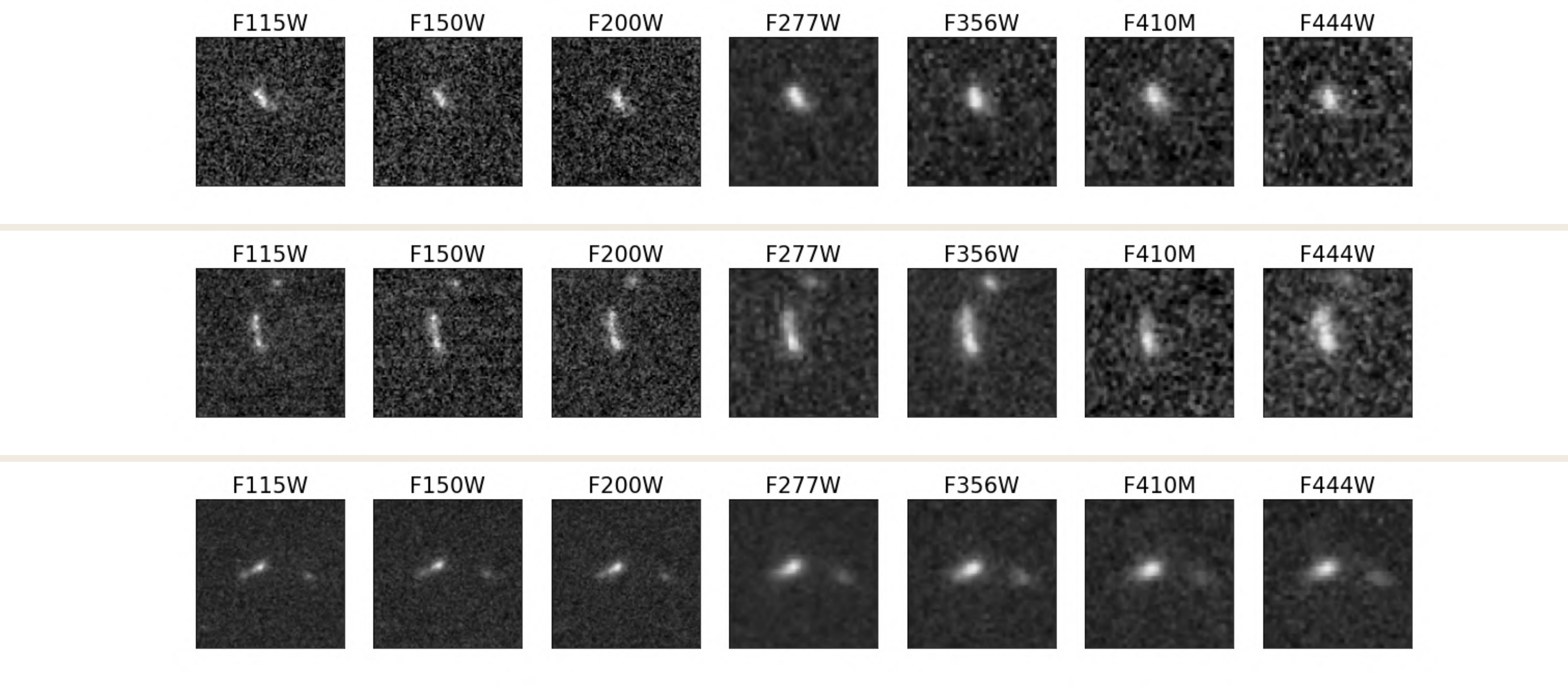
CEERS (Cy1 ERS program, PI: S.Finkelstein)





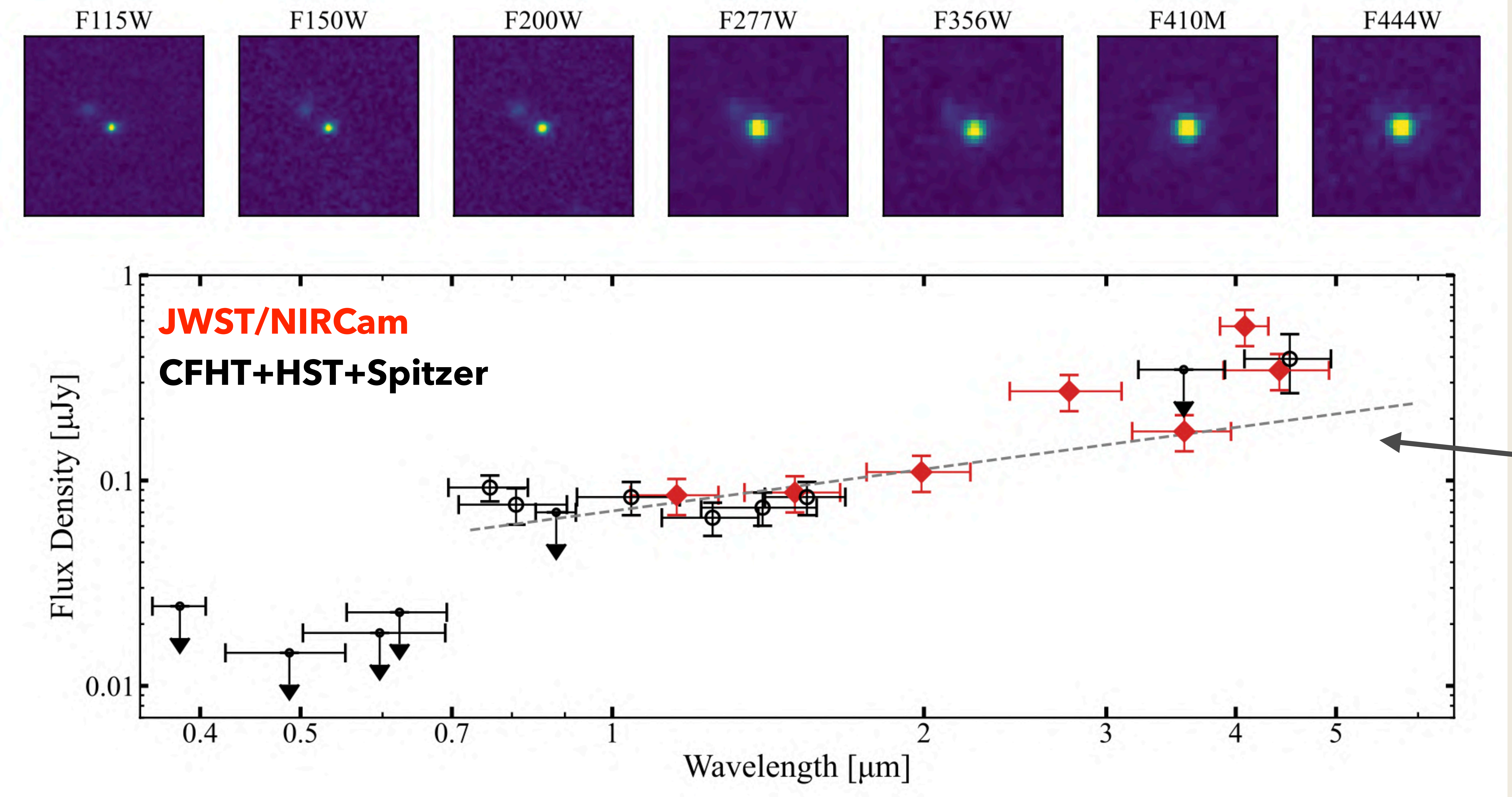
- ✦ A public JWST survey of Extended Groth Strip **(EGS)**: One of the HST/CANDELS fields
- ✦ 100 arcmin^2 covered by 6 BB + 1 MB NIRCam filter, 5sigma depth = 29.6 in F356W)
  - Catalog of HST-selected LBGs available (Stefanon+17)

Visual Inspection of z>4 LBGs



- Most LBGs have extended morphology or have companions (FWHM = 0.040 asec, or 1.298 pixel in F115W)
- Visual inspection of z>4 HST-selected LBGs –> ~20 compact sources

A Candidate of a Low-Luminosity AGN at z=5



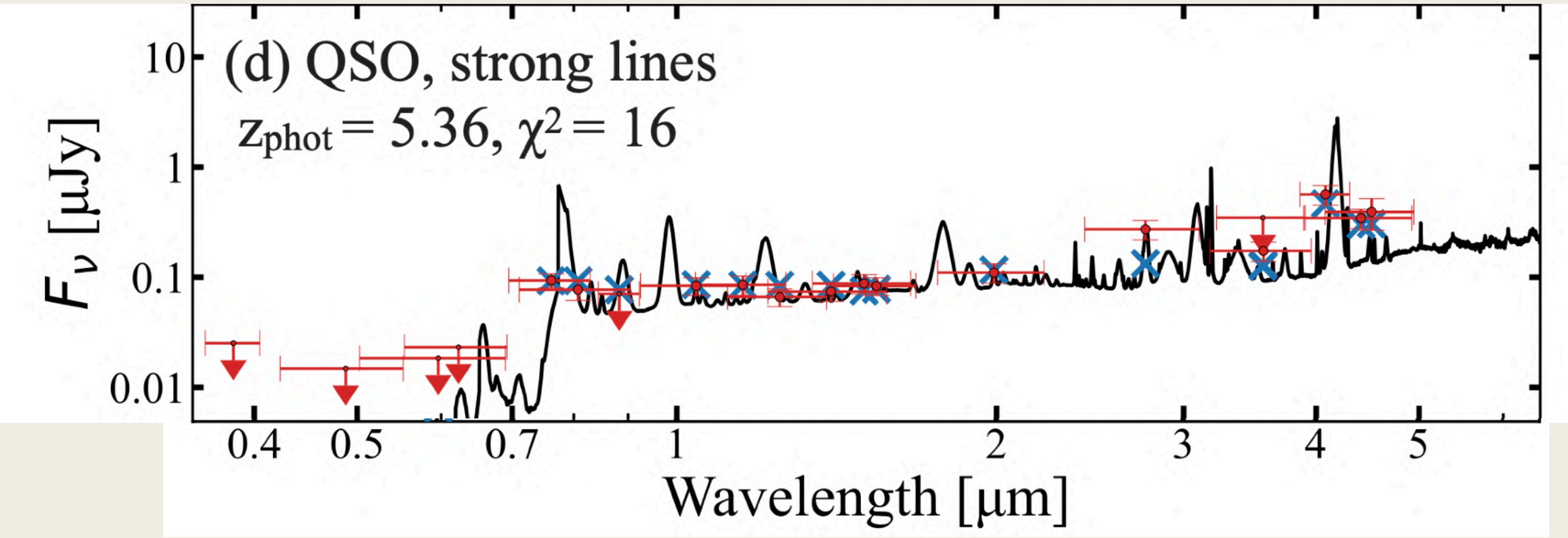
α_λ=-1.32±0.30
(F115W - F356W > 0.5)

✦**CEERS-AGN-z5-1: a z=5 LBG (F115W=26.6±0.2, M_{1450}=-19.5±0.3) with compact morphology & AGN-like SED**
✦**Broad/medium-band excess at F277W (Hβ+[OIII]) & F410M/F444W (Hα)**

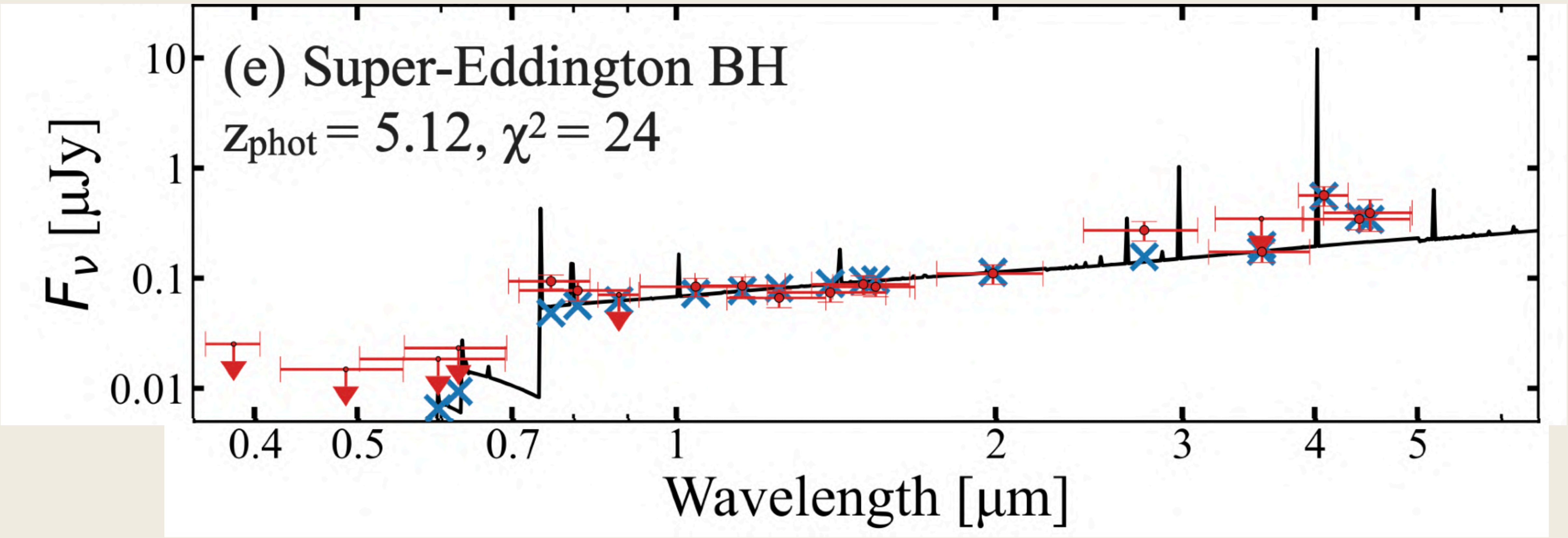
- Hβ+[OIII]: EW_{rest}=1100Å, L=$10^{43.0}$ erg s^{-1}
- Hα: EW_{rest}=1600Å, L=$10^{42.9}$ erg s^{-1}

SED Fitting for CEERS-AGN-z5-1

- Low-z QSO composite (Vanden Berk+01) + additional BLR lines

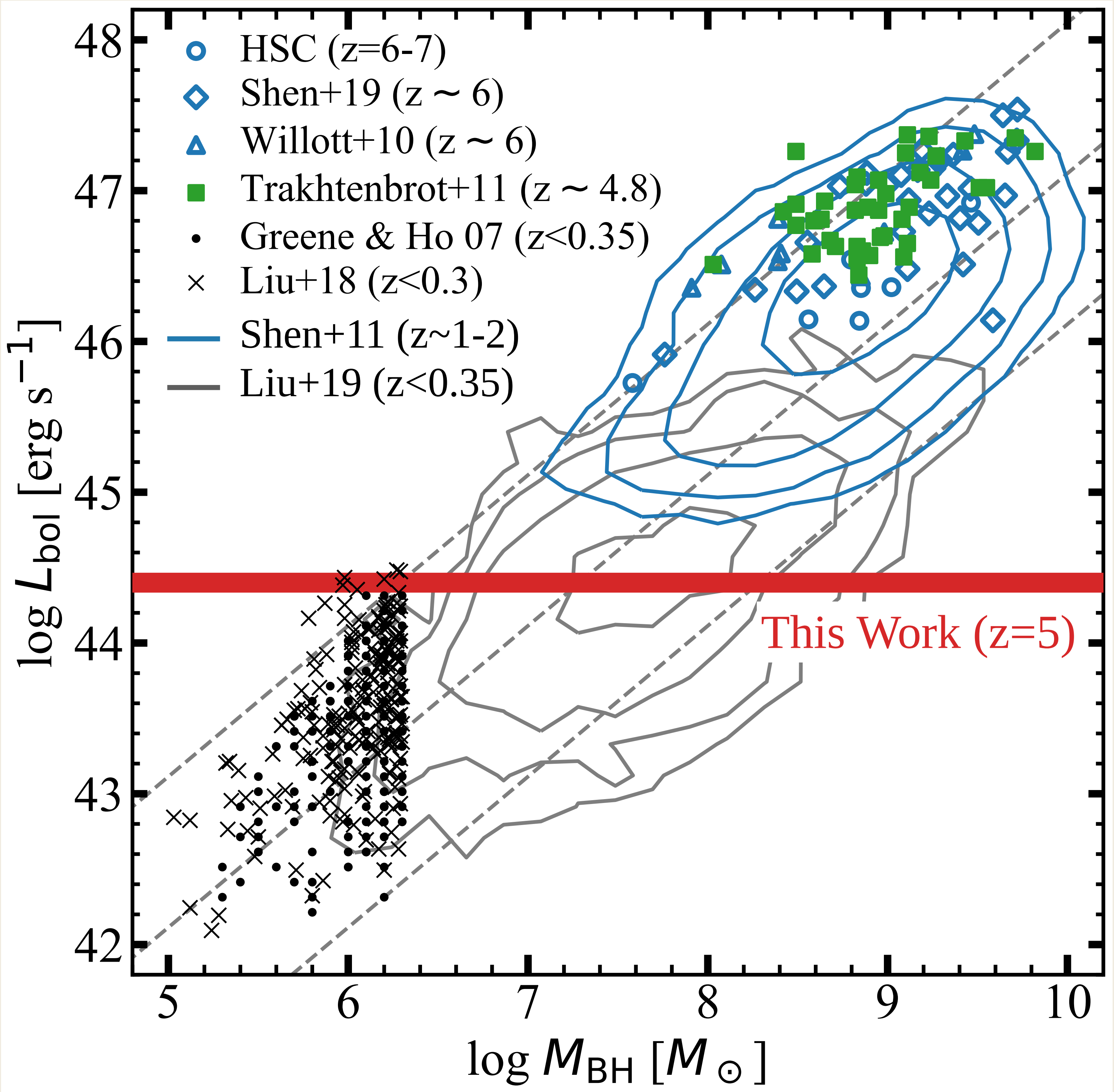


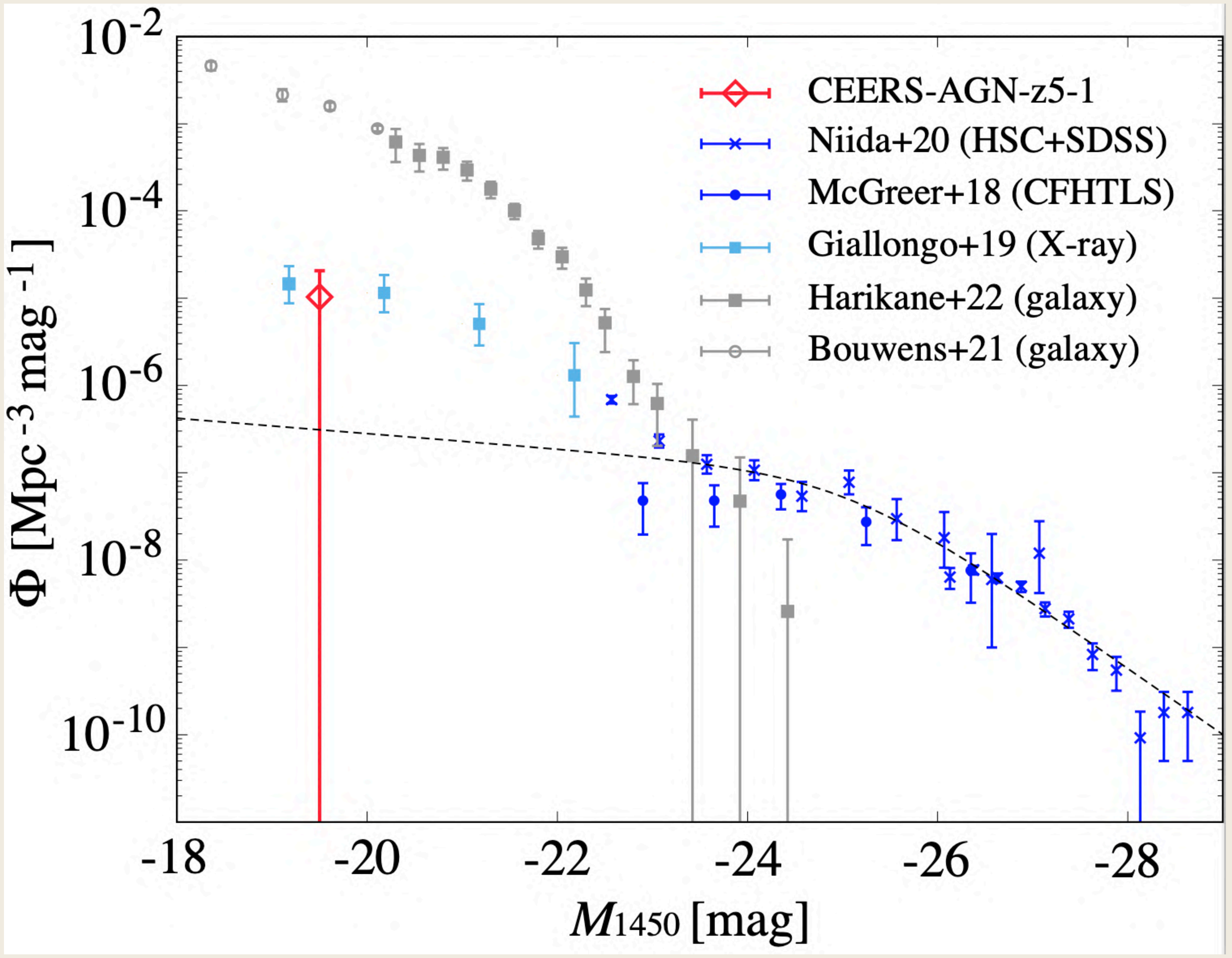
- Super-Eddington BH (from Inayoshi+22, $M_{BH}=10^{6.3}M_{sun}$)



✦**AGN models are preferred, while the host likely contributes to [OIII]** (top-heavy IMF or O-enriched ISM)
- Maybe followed-up in CEERS's NIRSpec MSA observations in Dec 2022

A New Parameter Space Probed by JWST



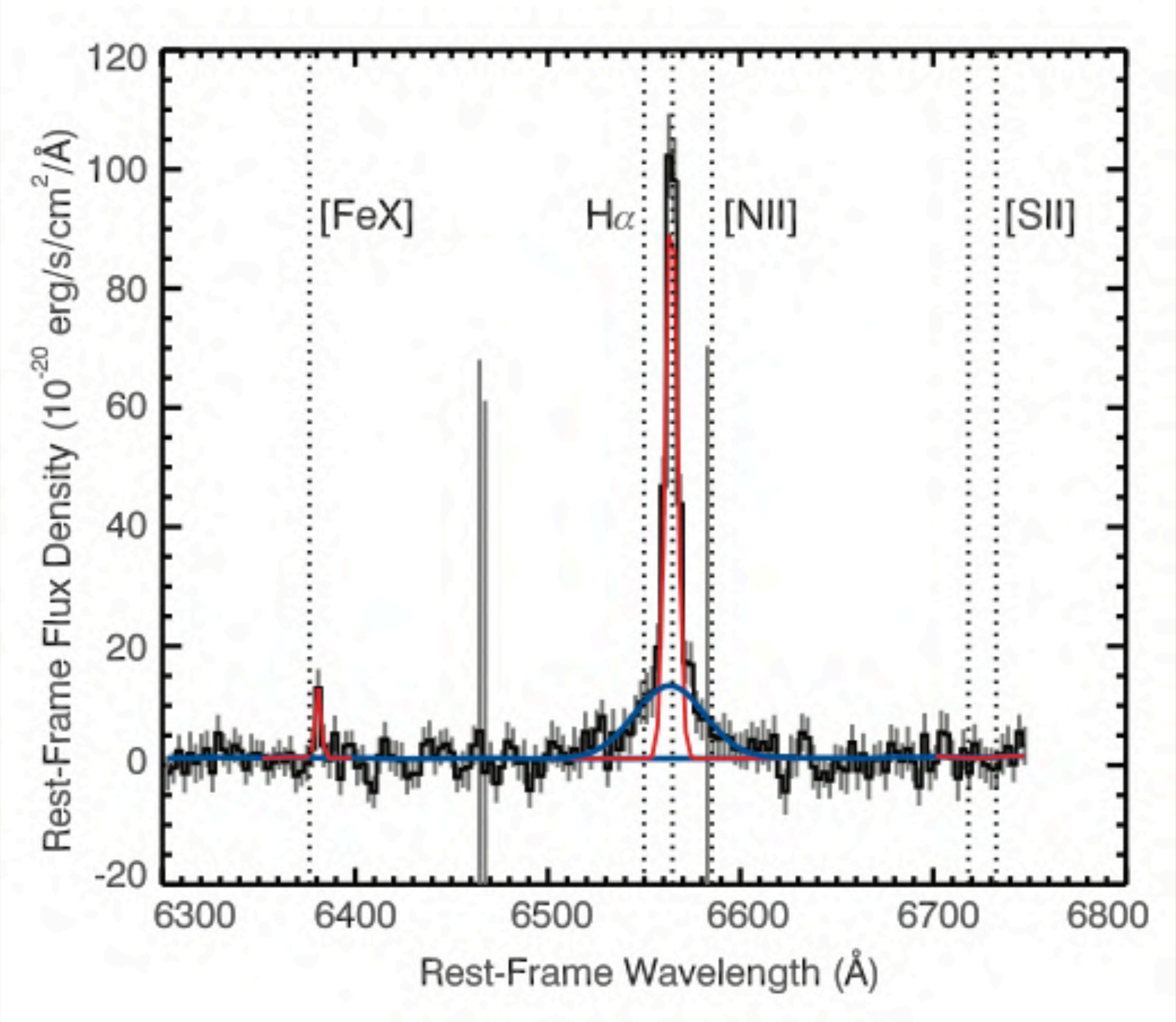


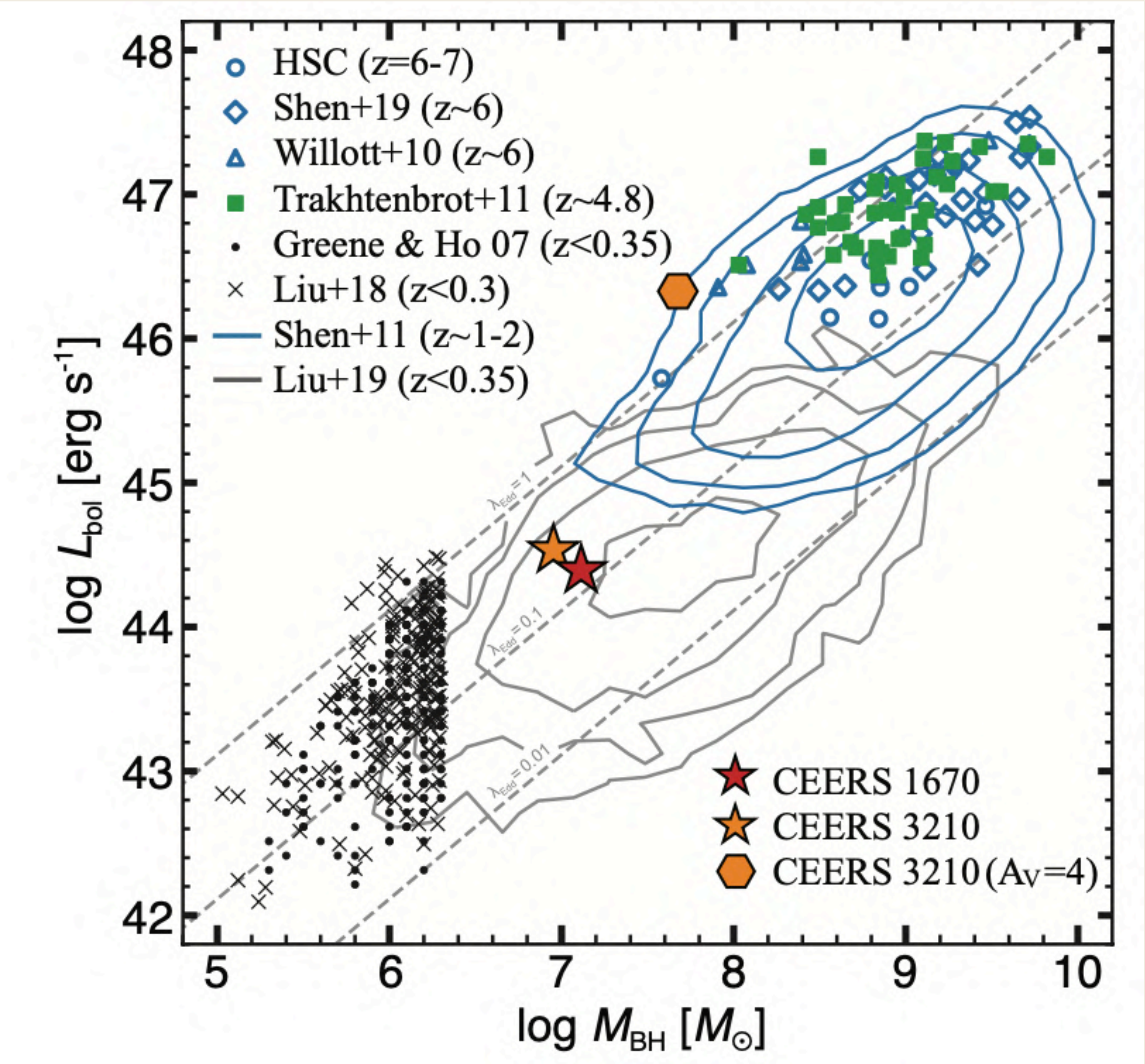
✦L_{bol} comparable to z<0.4 AGNs with $M_{BH}=10^6$ M_{sun}

✦the AGN LF at M_{1450}=−19.5 gets >1 dex higher than expected from optical studies
(and consistent with Giallongo+19's rest-frame hard X-ray-selected sample)

➡High-z Low-luminosity AGN surveys are feasible with 4 NIRCam pointings

Broad Hα detection with NIRSpec MSA



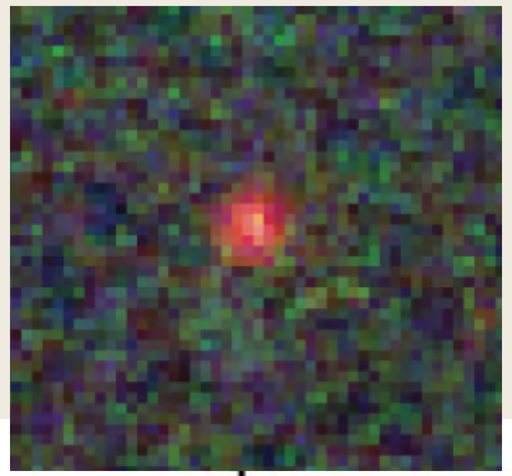


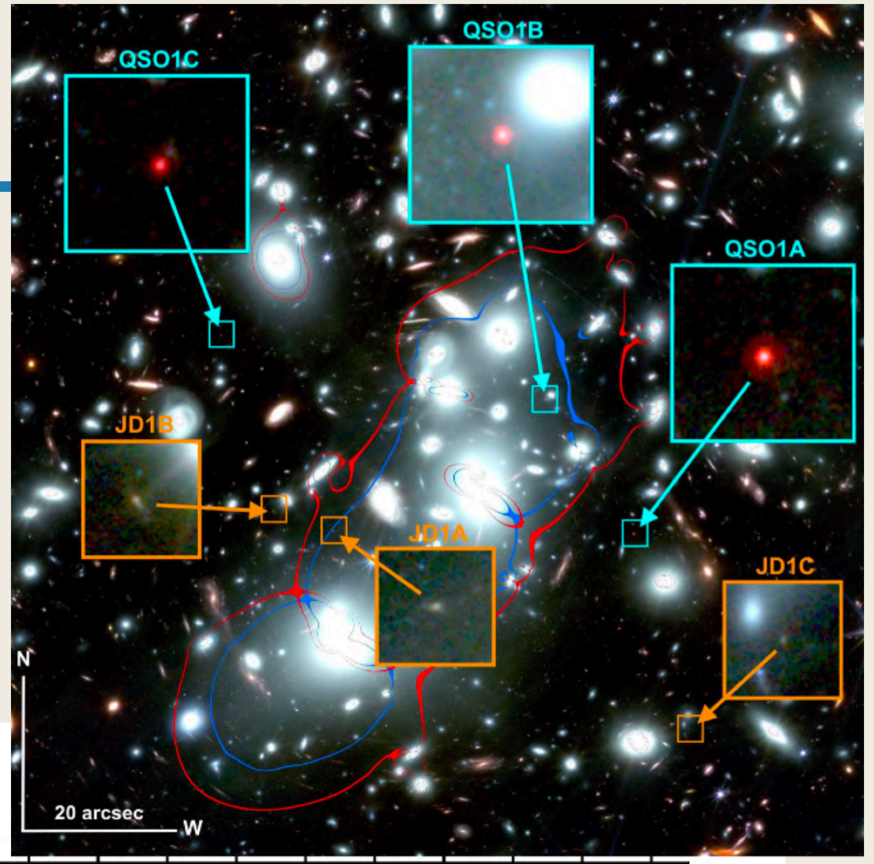
Kocevski, Onoue, Inayoshi et al. (2023)

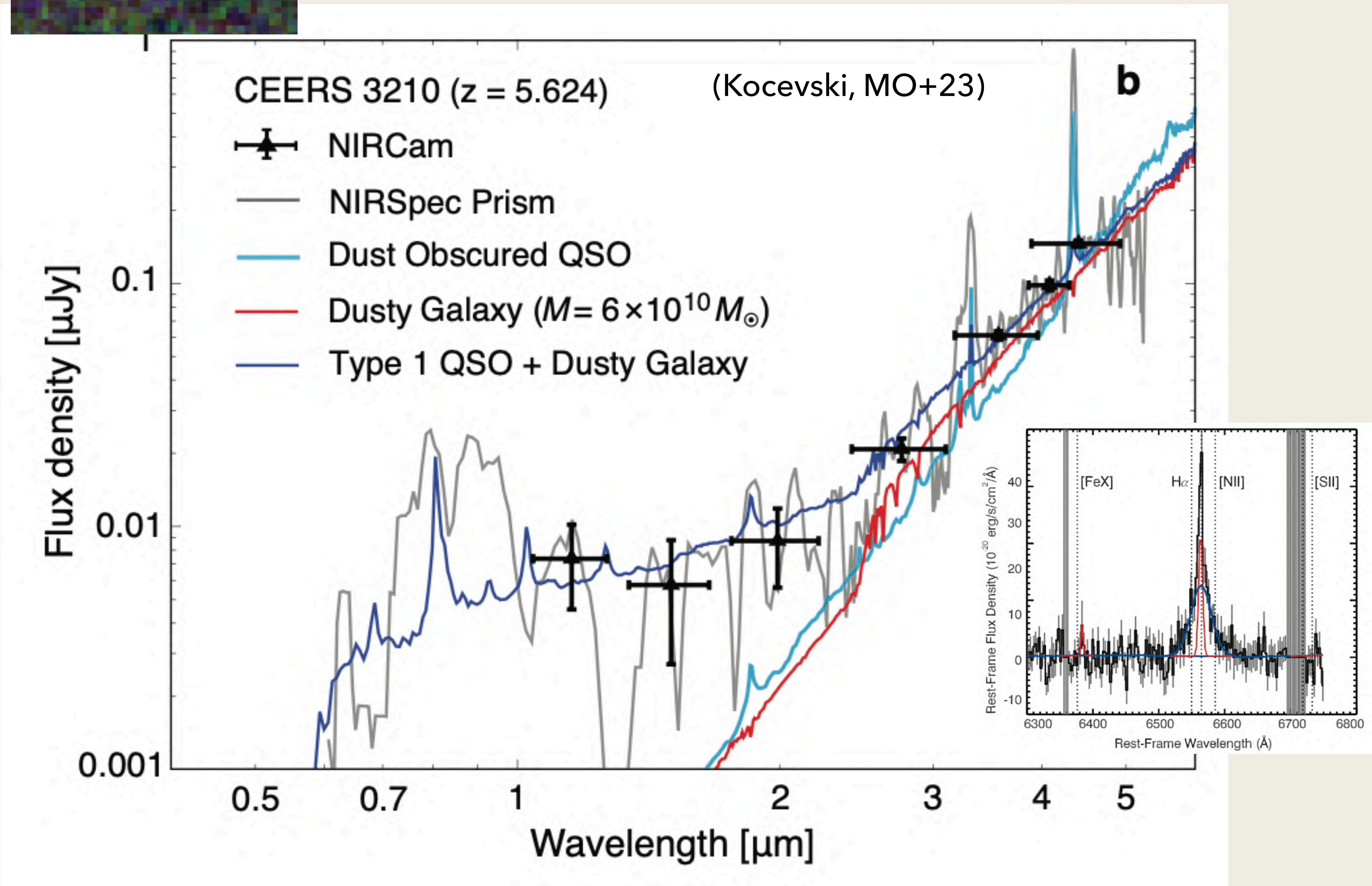
- **FWHM$_{broad}$(Hα)=2060 ± 290 km/s, L_{5100} = 4.48±0.08 × 10^{43} erg/s**
- **M_{BH}** (FWHM$_{Hα}$ converted to FWHM$_{Hβ}$; Greene & Ho 05) **= 1.3±0.4 × 10^7 M_{sun}**

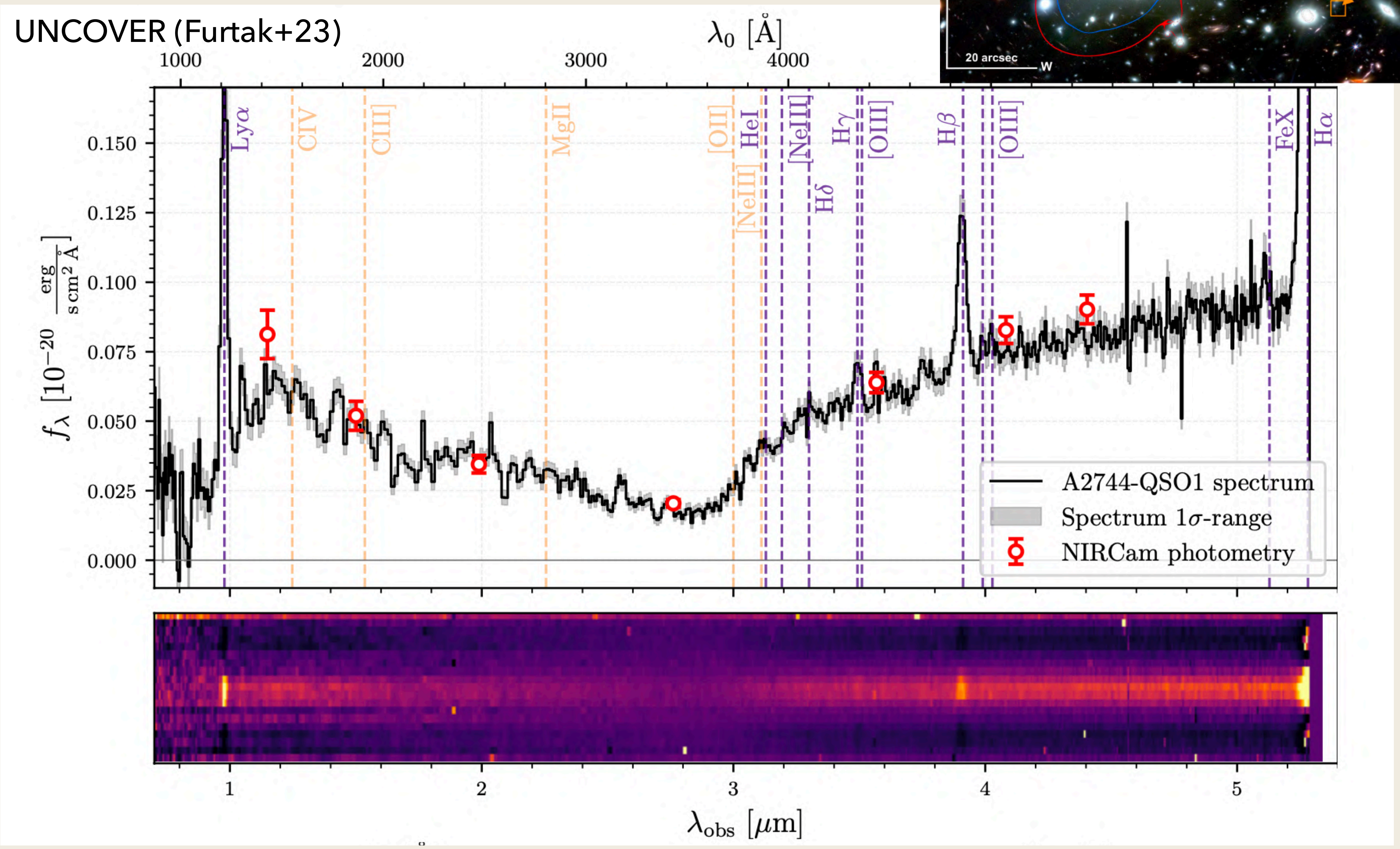
➡Least-massive BH at z>5 (JWST can be a high-z AGN survey telescope!)

``Little Red Dots”









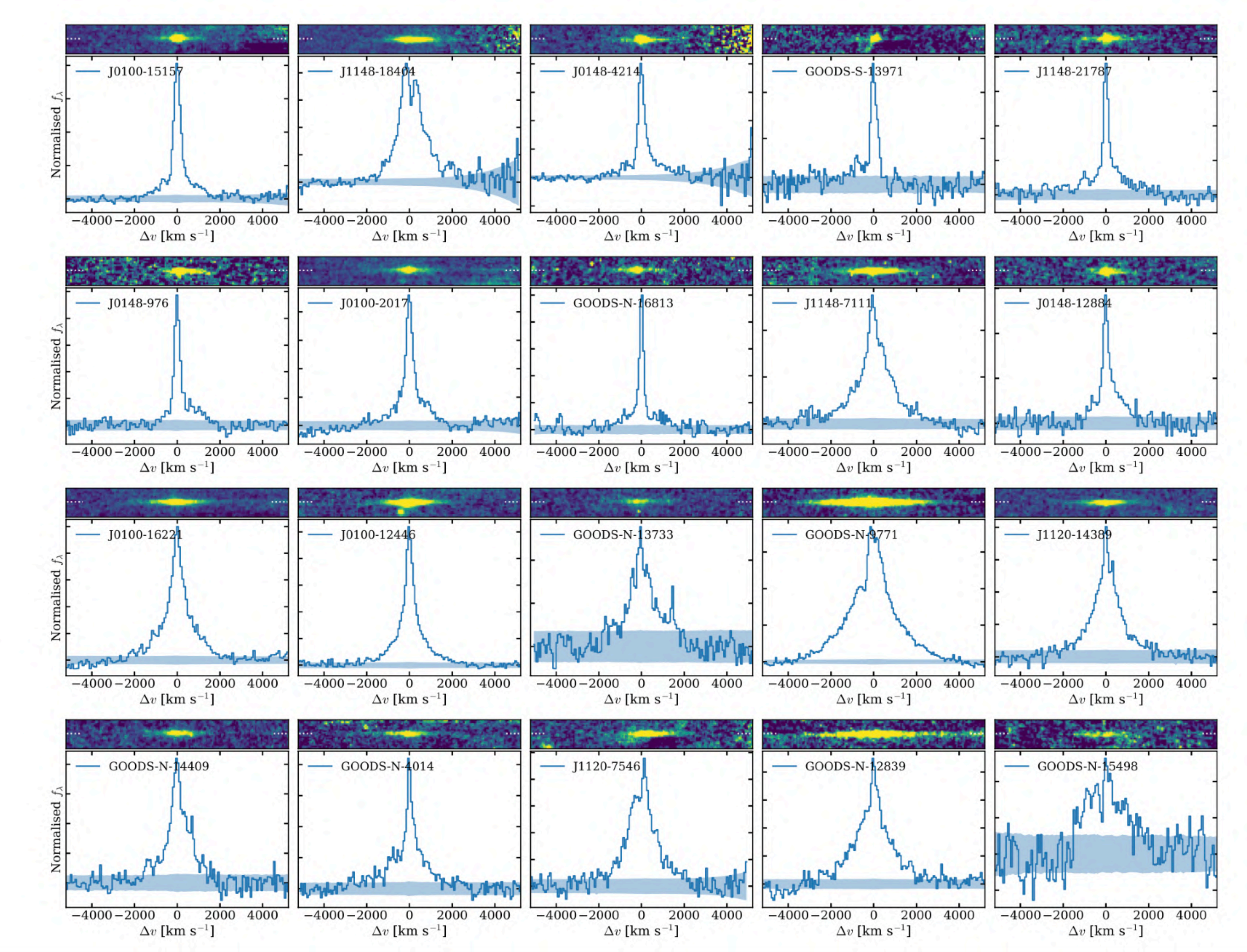
See also Matthee+, Labbe+, Greene+, Kokorev+

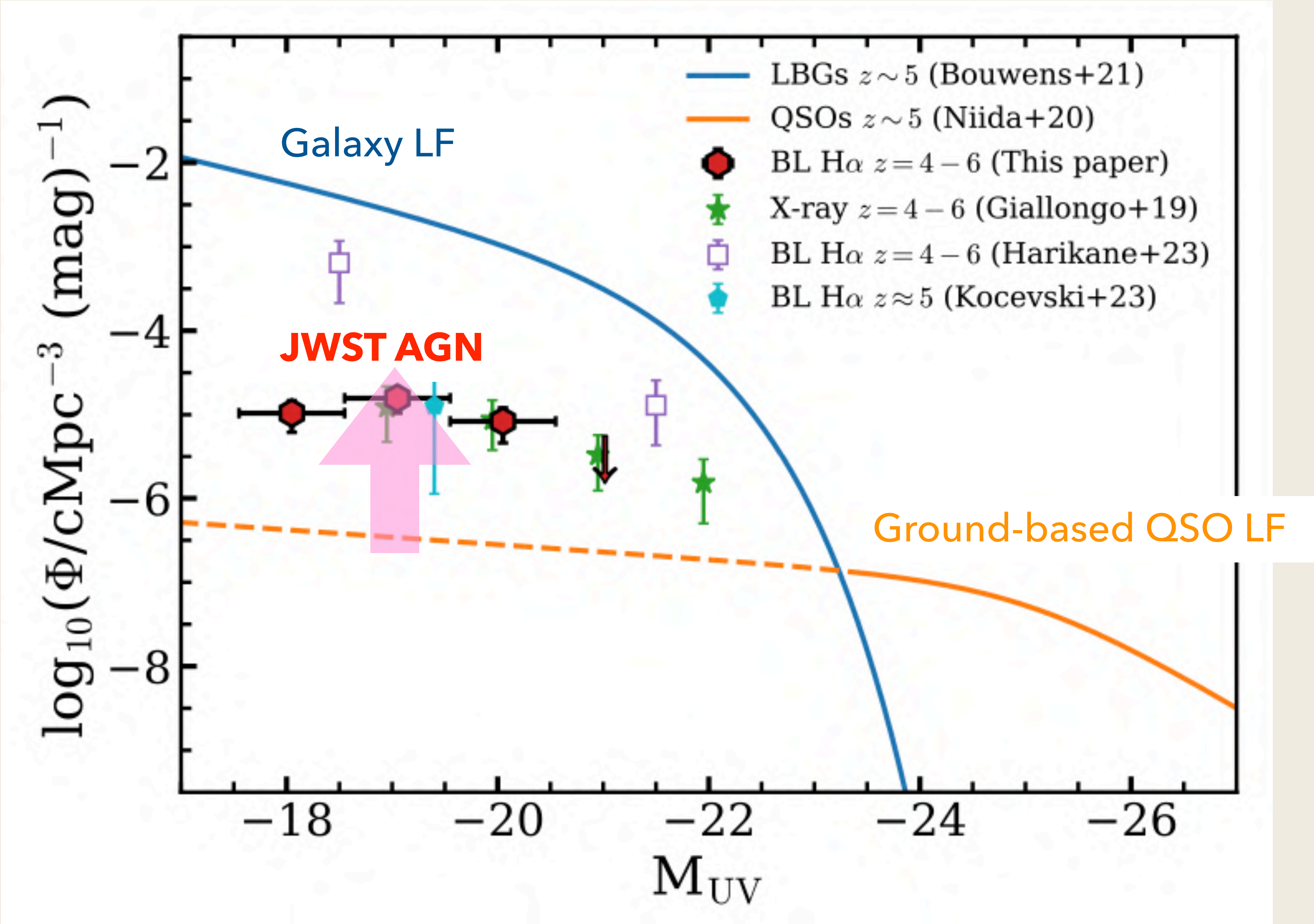
Blue UV & red optical continuum with broad line detection
-> High-z analogs of ULIRG / Blue DOG?

See Noboriguchi-san’s talk!

Z~5 AGN LF

Broad Hα detection from 20 AGN (Matthee+24)





JWST AGN have >1 dex higher number density than expected (up to 10% of galaxy LF)

host contamination? High fraction of dust-reddened AGN? non-AGN BL sources?

Summary

- ✦ Stellar emission is detected from 7 moderate-luminosity quasars at z=6. Host is generally massive with log M_*/M_{sun}~11
- ✦ Stellar absorption lines are detected for 2 bright quasar hosts. Spectrophotometric analysis suggests post-starburst-like SEDs with mass-weighted age ~ 200 Myr
- ✦ Large offset in M_{BH} - M_* relation is not found, consistent with ALMA M_{dyn} measurements. We aim to increase the sample size in the coming JWST cycles
- ✦ A low-luminosity AGN is found from the first CEERS data. Many more discoveries follow to find >1 dex higher number density of Seyfert-class AGN at high-z, including modestly dust-reddened AGN.