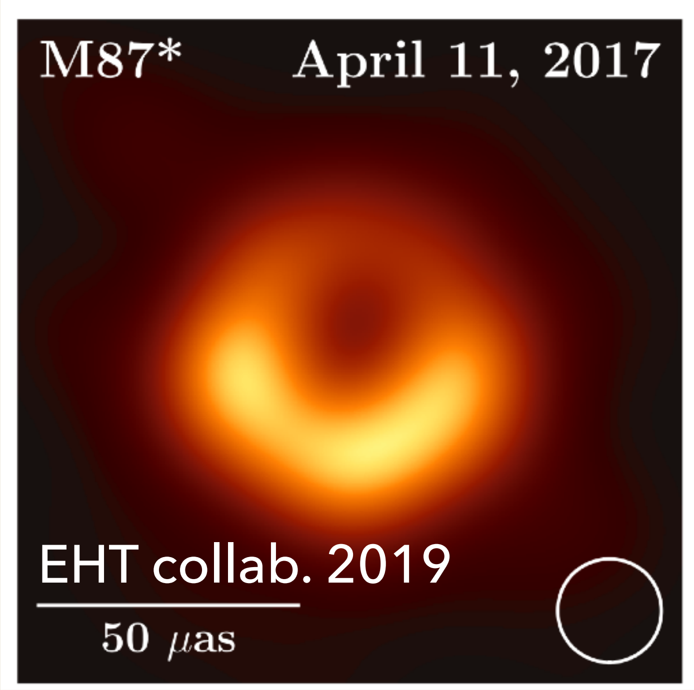
Full Census of Supermassive Black Holes in the Early Universe

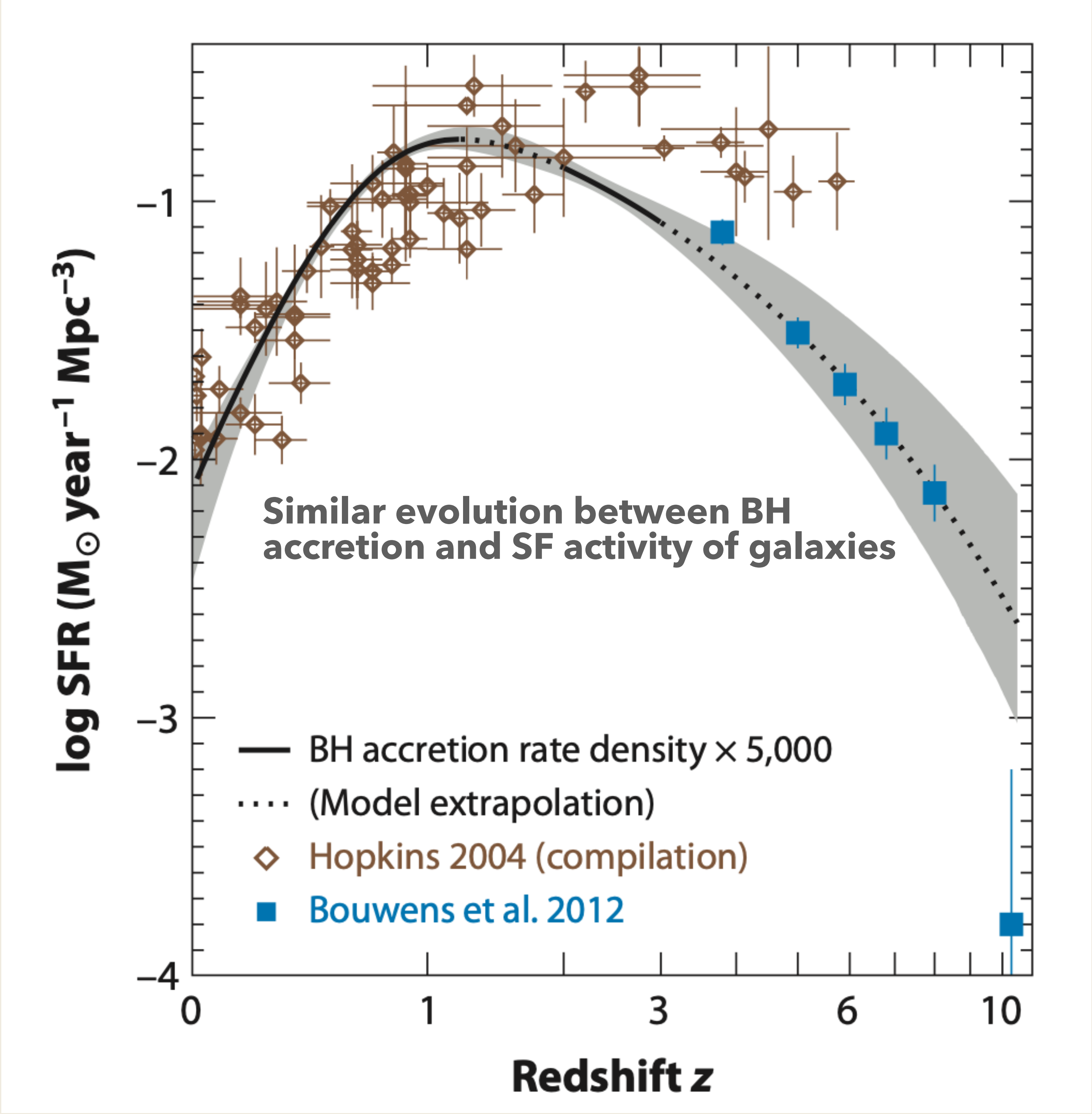
Masafusa Onoue (MPIA -> KIAA / Kavli IPMU)

Brief Overview of High-z QSO Studies

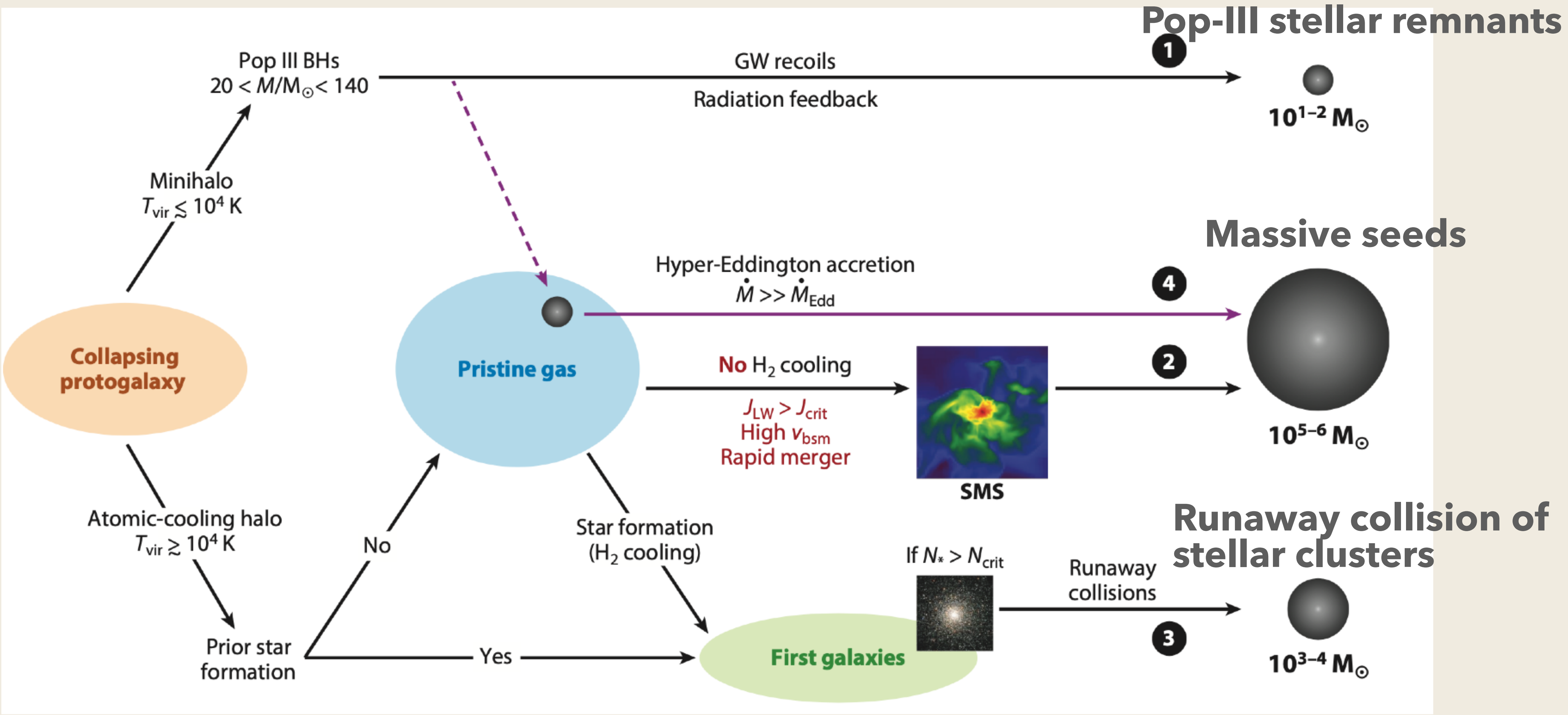
Why Do We Care High-z SMBHs?



- Cosmological evolution of BH accretion density w/ SFRD (Kormendy & Ho 2013)

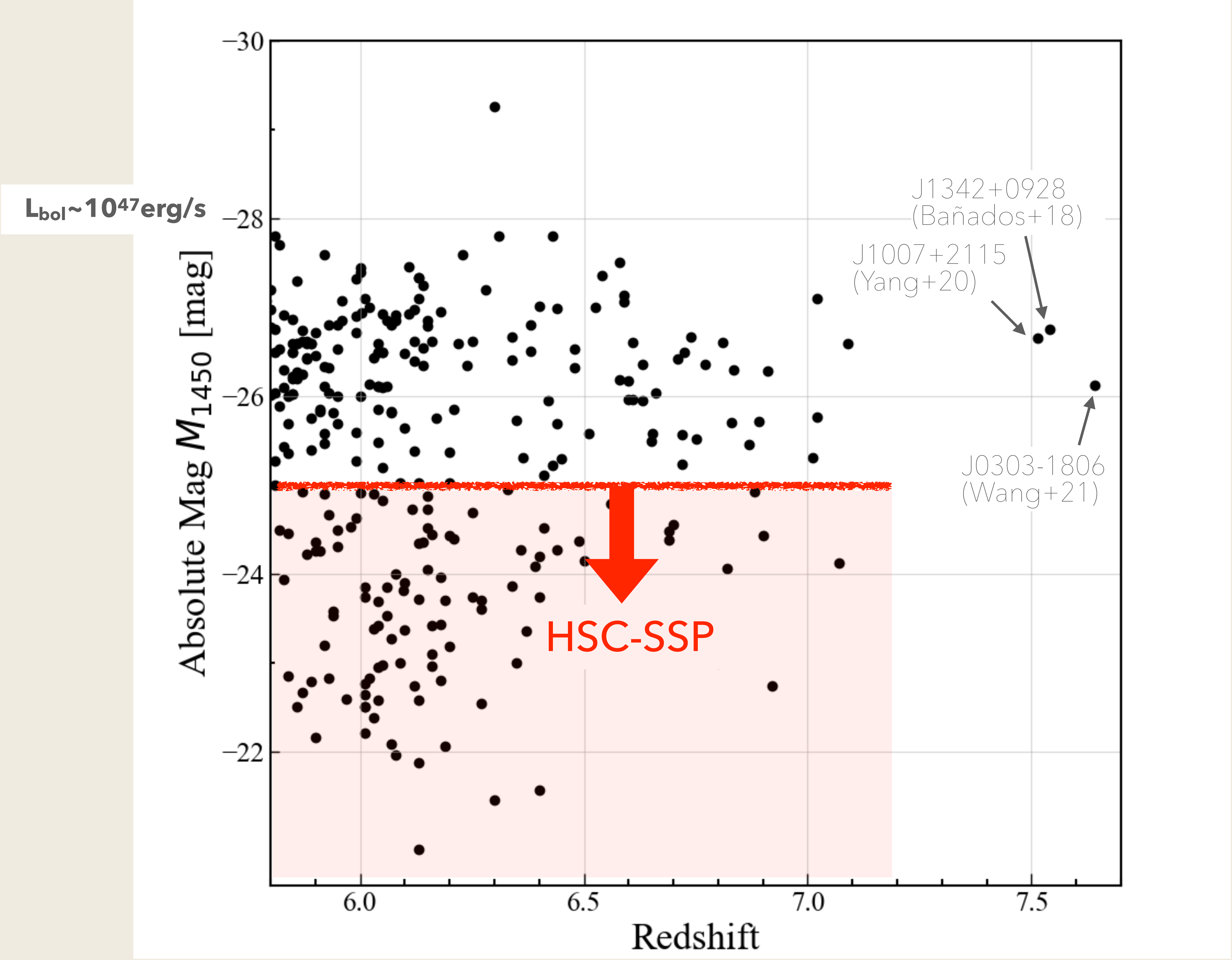


- SMBH formation paths (Inayoshi+2019)



z>6 Quasars

- Known z>5.8 quasars (as of July 2021)

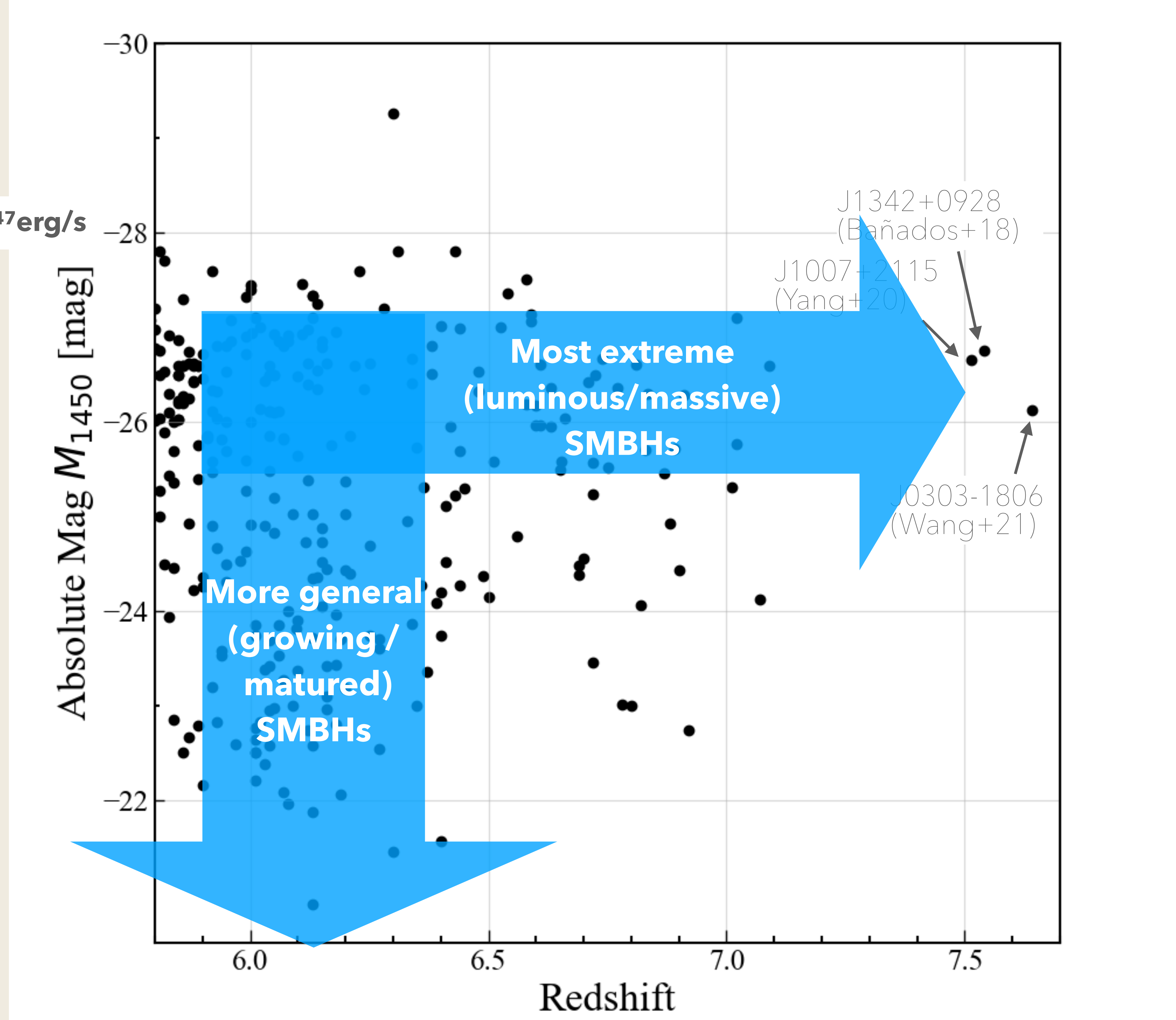


- **~300 known at z>6** (<10 in Gpc^{-3} per mag; M_{UV}>-24)
  - Need >100 deg^2 coverage
  - SDSS/PS1/HSC/DES/UKIDSS/VIKING/WISE, etc.
- **Frontier: z~7.5** (Bañados+18; Yang+20; Wang+21)
  - 8 at z>7, 50 at z>6.5
  - The low-luminosity regime dominated by the HSC sample (Matsuoka+16-19)
- **z=8-10 discoveries expected in 2020s with Euclid, Roman, and Rubin**

z>6 Quasars

- Known z>5.8 quasars (as of July 2021)

L_{bol}~10^{47}erg/s



- **~300 known at z>6** (<u>$\lesssim$10 in Gpc^{-3} per mag</u>; M_{UV}>-24)
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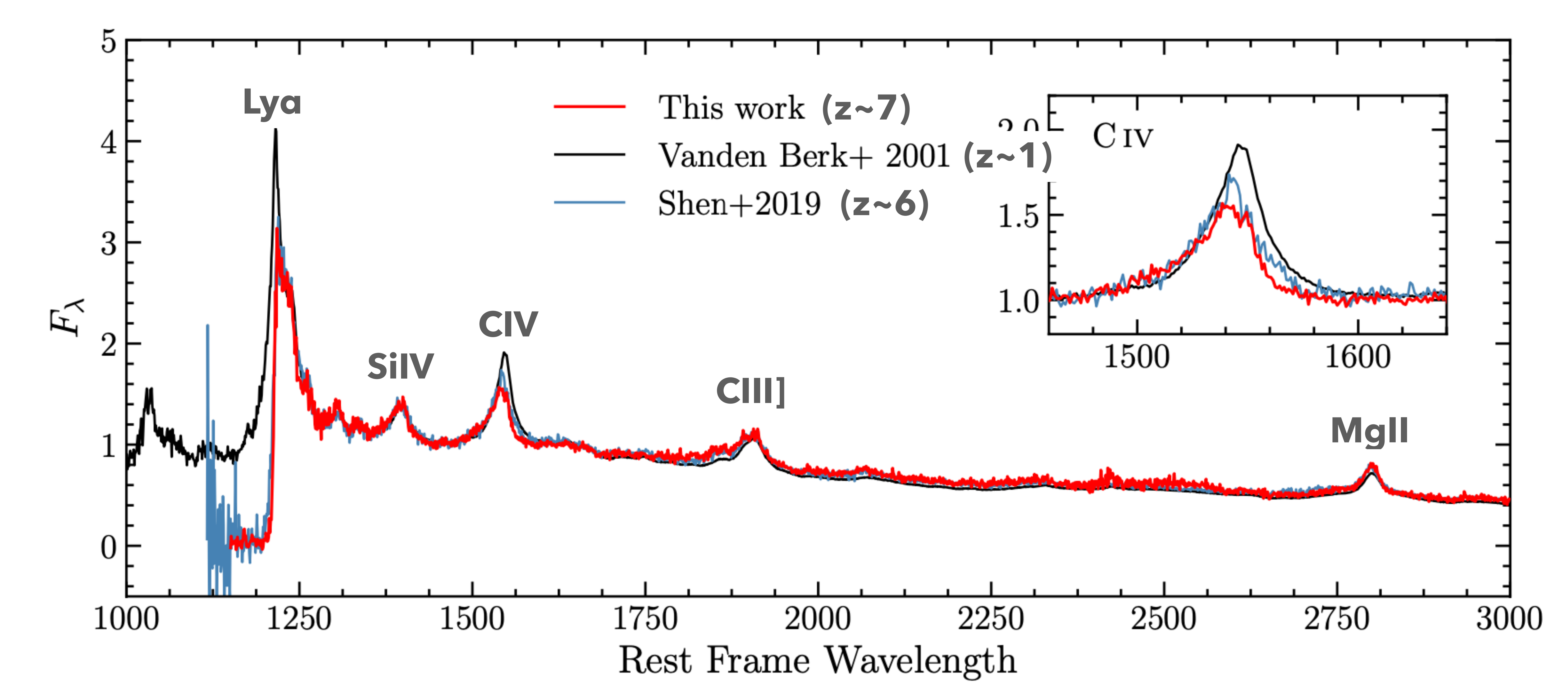
Rest-UV Spectrum

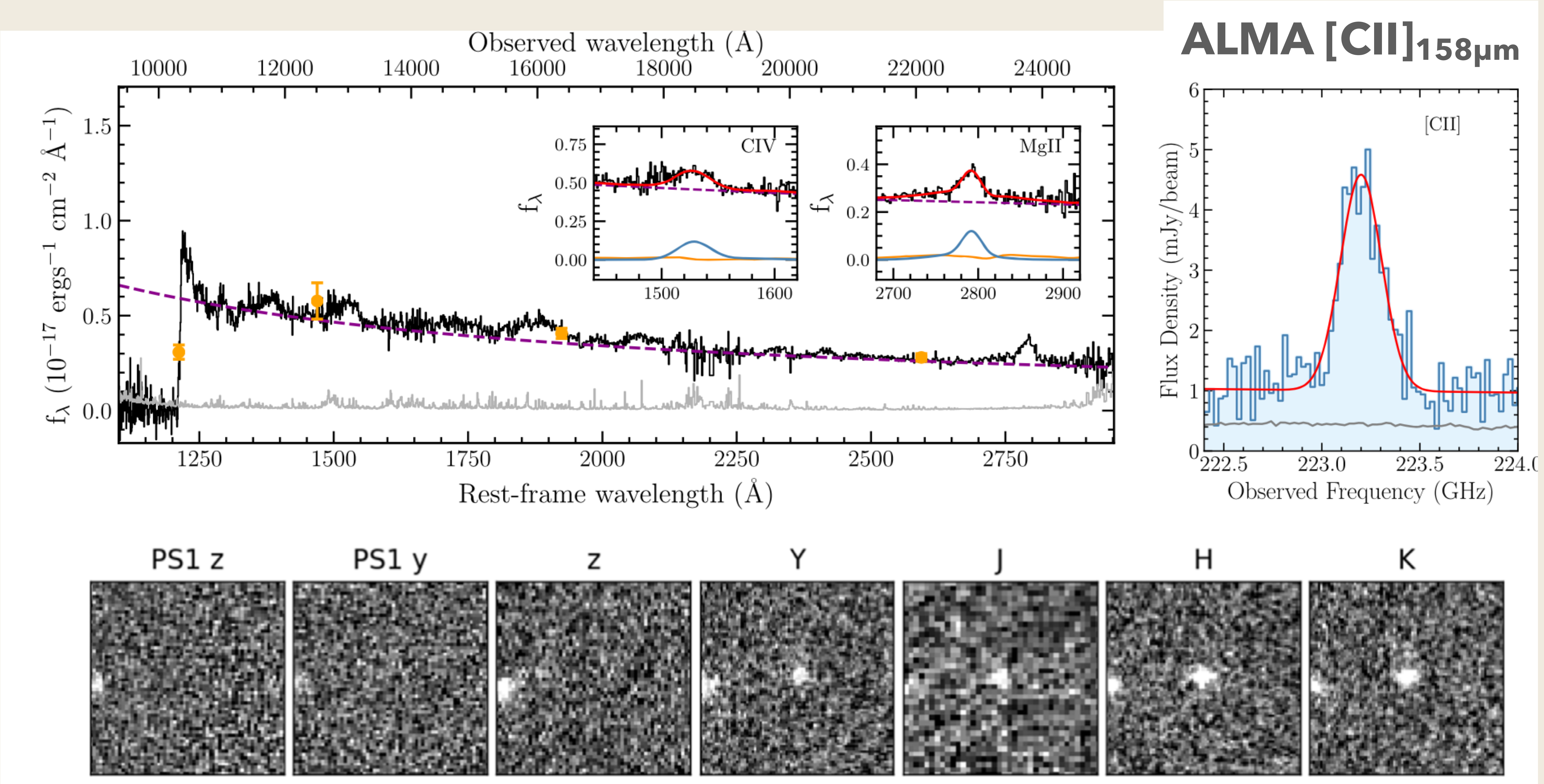
- Composite spectrum of luminous 6.3<z<7.6 quasars (Yang+21)



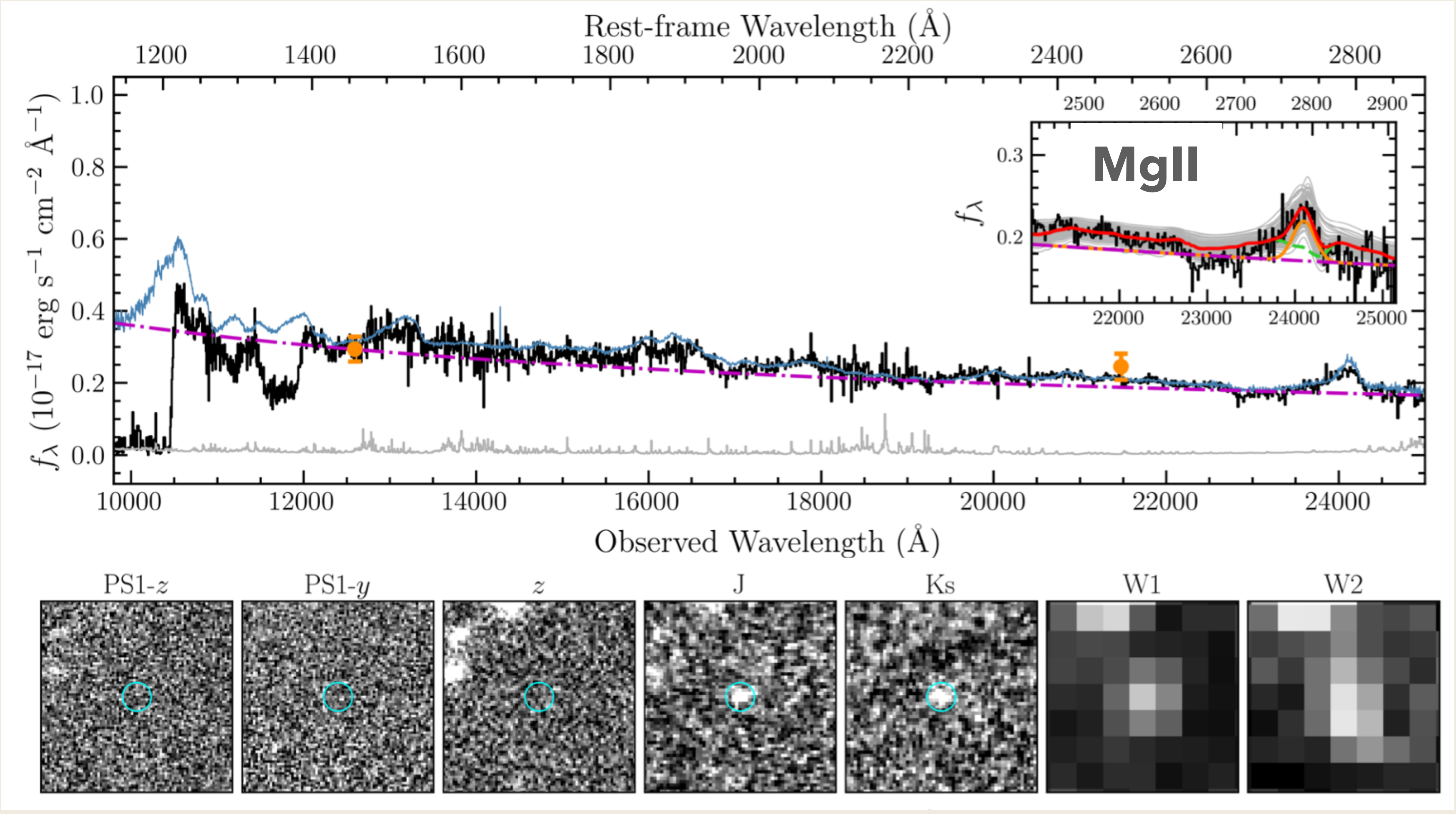
- The rest-UV spectrum shapes of quasars does not show significant redshift evolution down to z=7.6!
- High-ionization BLR emission lines do show larger velocity blueshifts at higher-z

Two New z~7.5 Quasars

- J1007+2115 at z=7.515 (“Pōniuā’ena”; Yang+20)



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

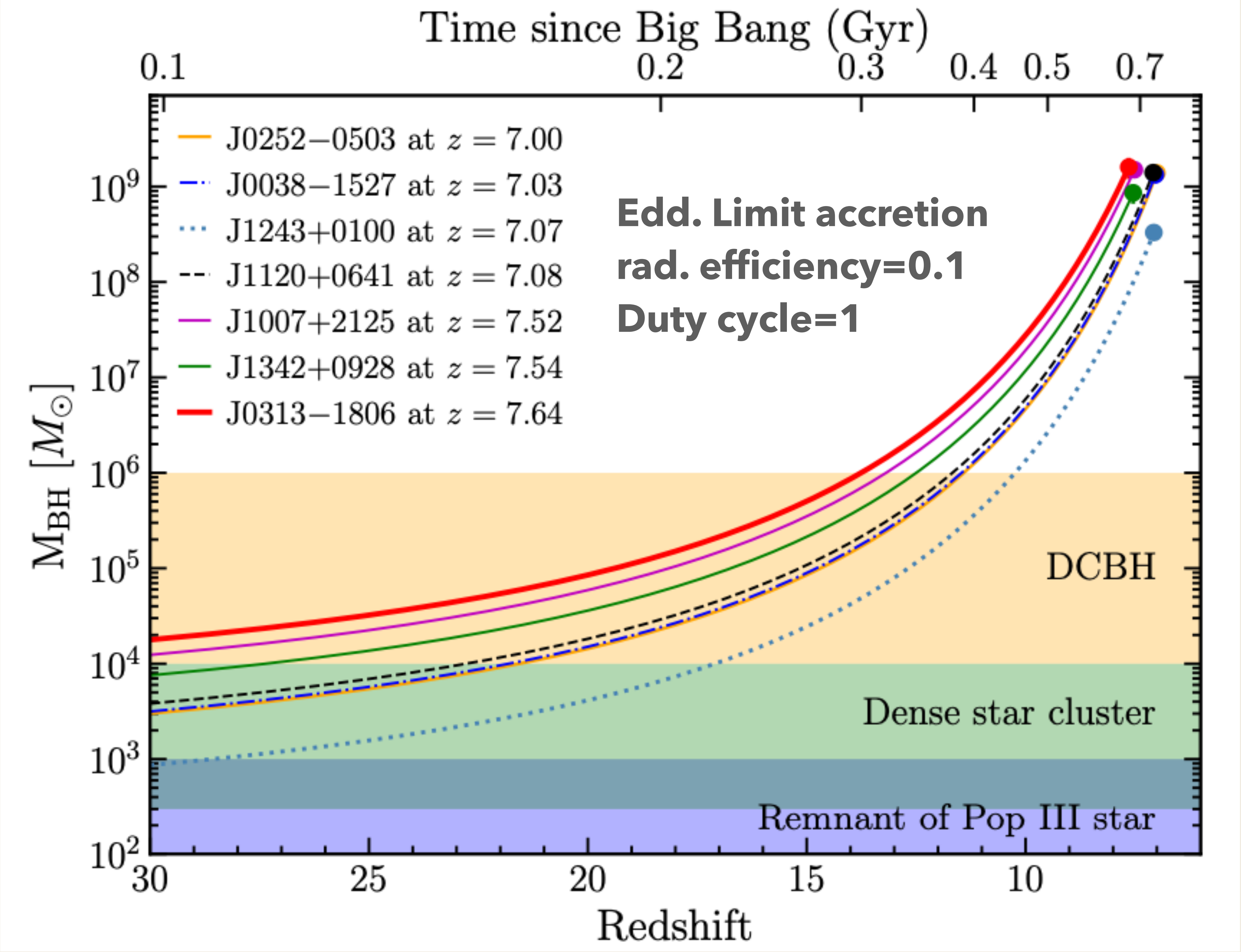


- Selection: J & WISE detection + color cuts
- J_{AB}=20.20, M_{UV}=-26.66
- M_{BH} =1.5 x 10^9 M_{sun}, L_{bol}/L_{Edd}=1.06

- 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?)

Billion-solar-mass SMBHs at z>7

- Growth history of known z>7 SMBHs (Wang+21)



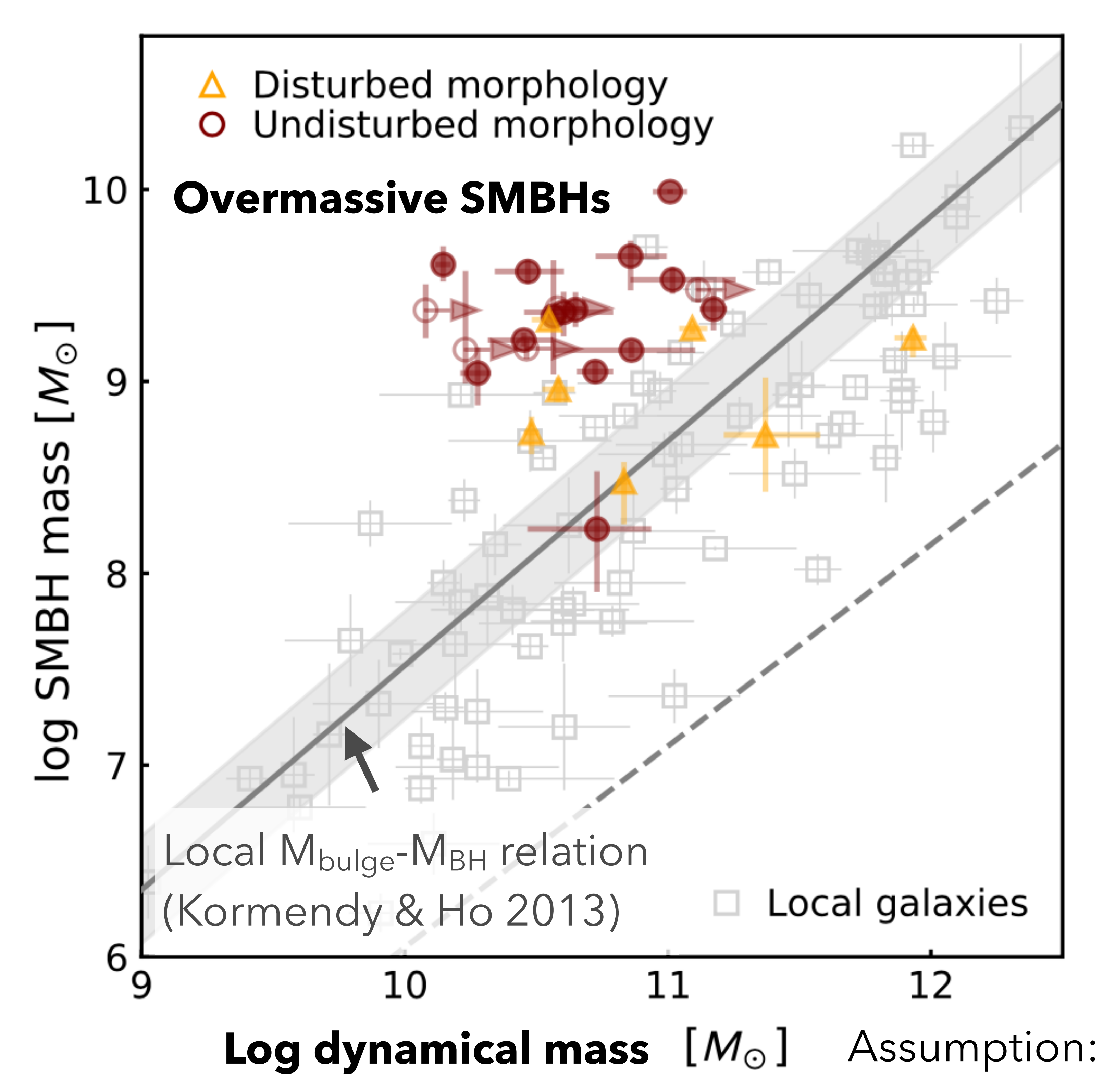
- Known SMBHs at z>7.5 all have M_{BH}~$10^9 M_{sun}$ (t_{uni}~0.7Gyr)
- BH mass reaches only down to ~$10^{4\text{-}5}$ M_{sun} if constant Edd. Limit accretion is assumed
  - still too massive for stellar remnant seeds (<10^3 M_{sun})

➡ Did SMBHs form through the DCBH channel?

➡ Or, they originated from light-seed channel and experienced super-Eddington phase?

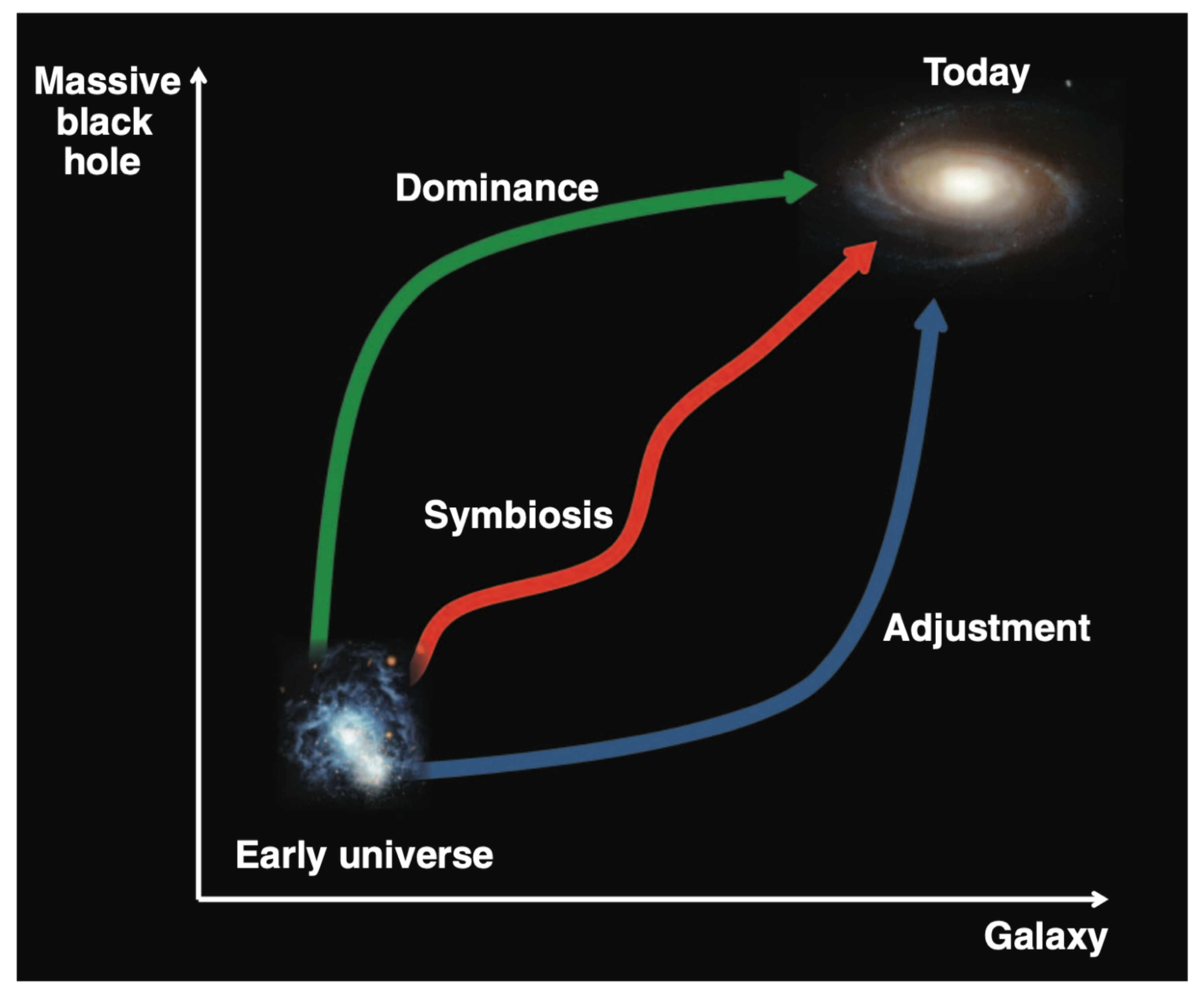
SMBH vs host dynamical mass

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



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

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



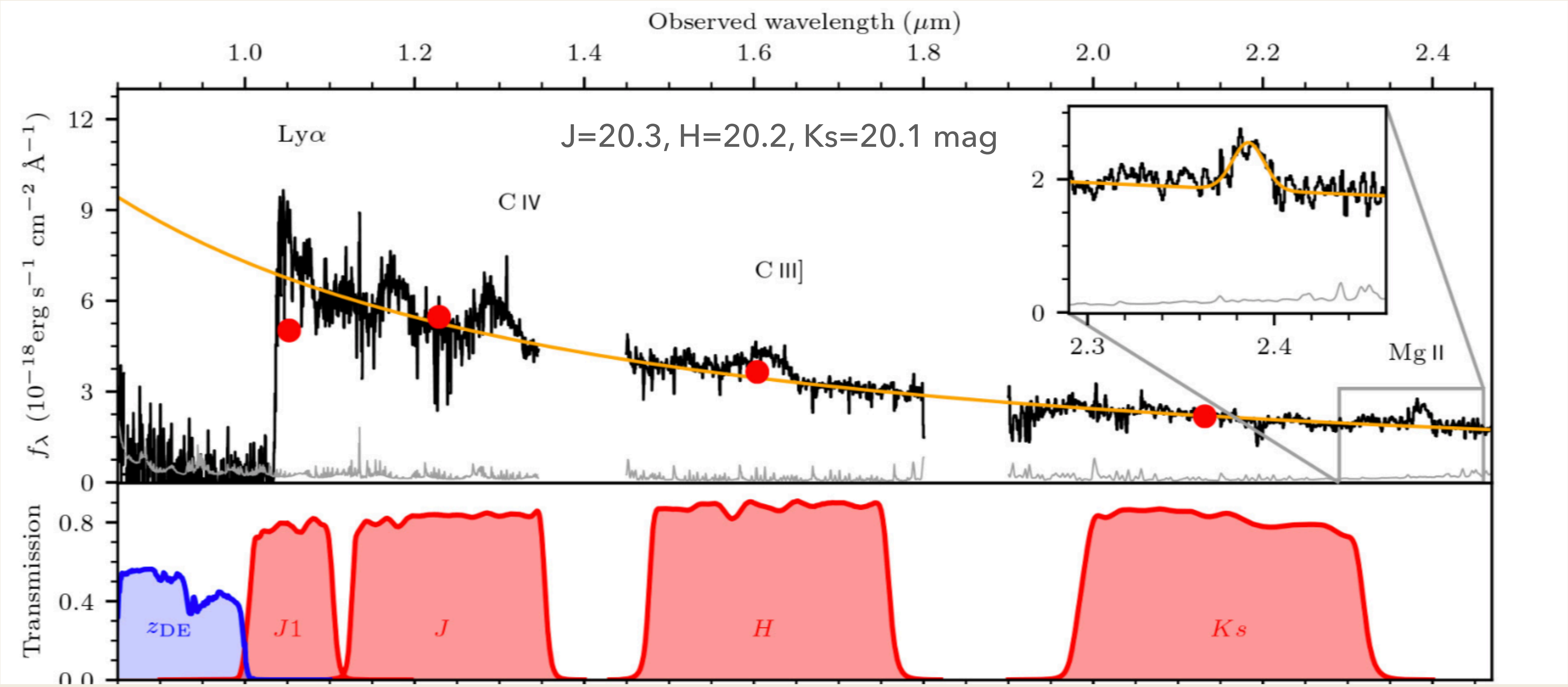
BH growth first and host stellar mass growth next?

Deep NIR Spectroscopy of a z=7.54 QSO

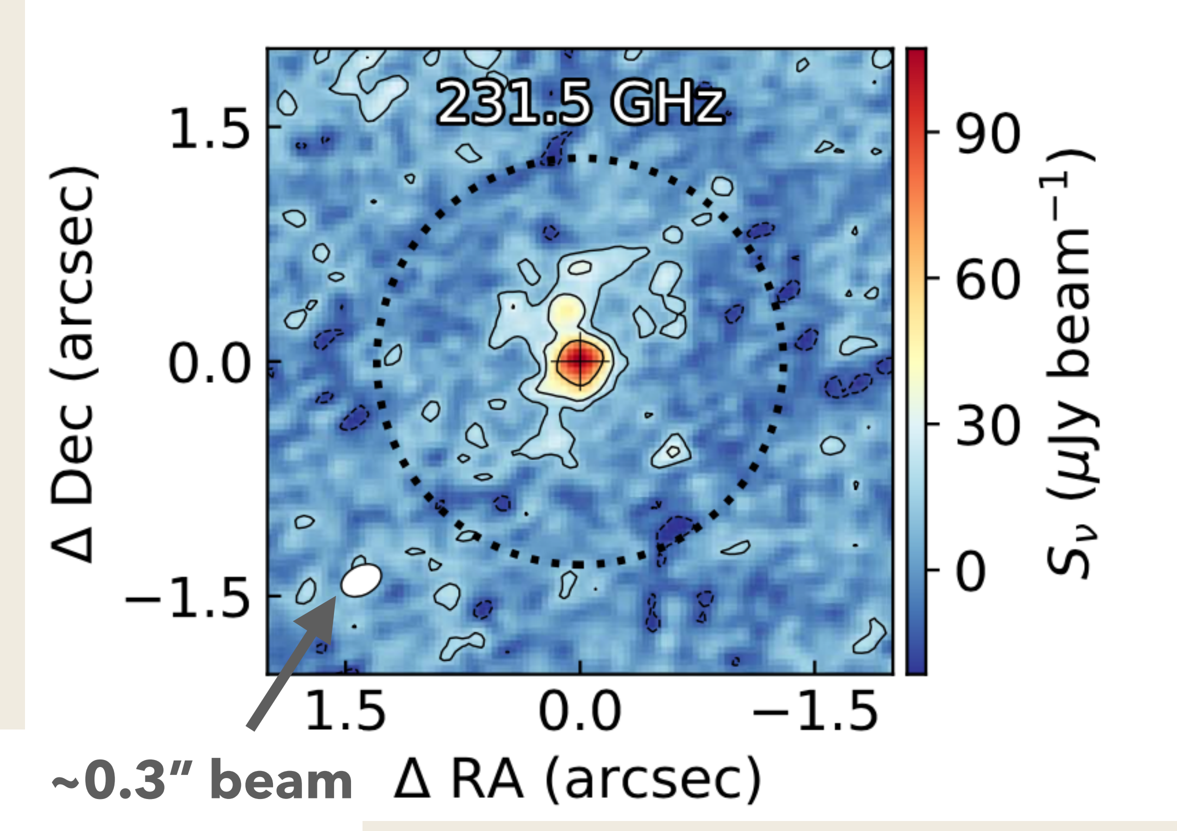
Onoue+20, ApJ, 898, 105

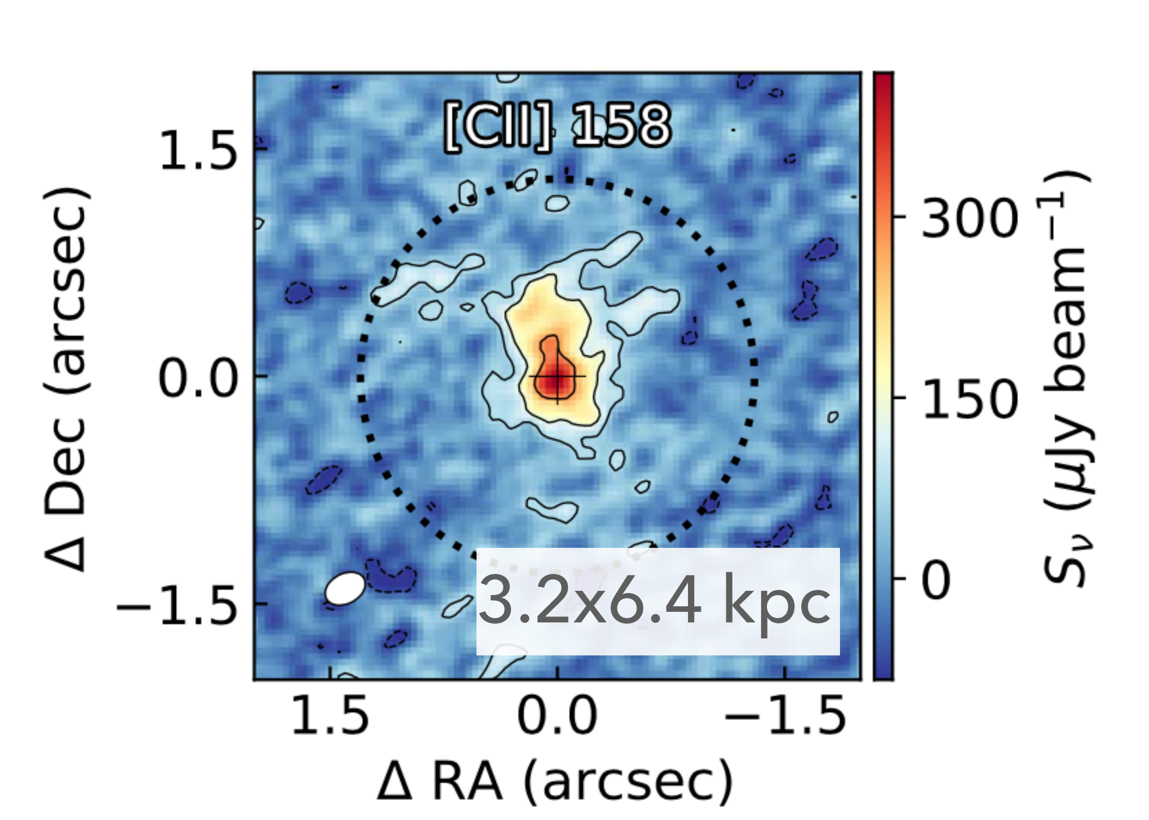
ULAS J1342+0928 at z=7.54

- NIR spectrum (FIRE 3.5 hr + GNIRS 4.7hr; Bañados+18)



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

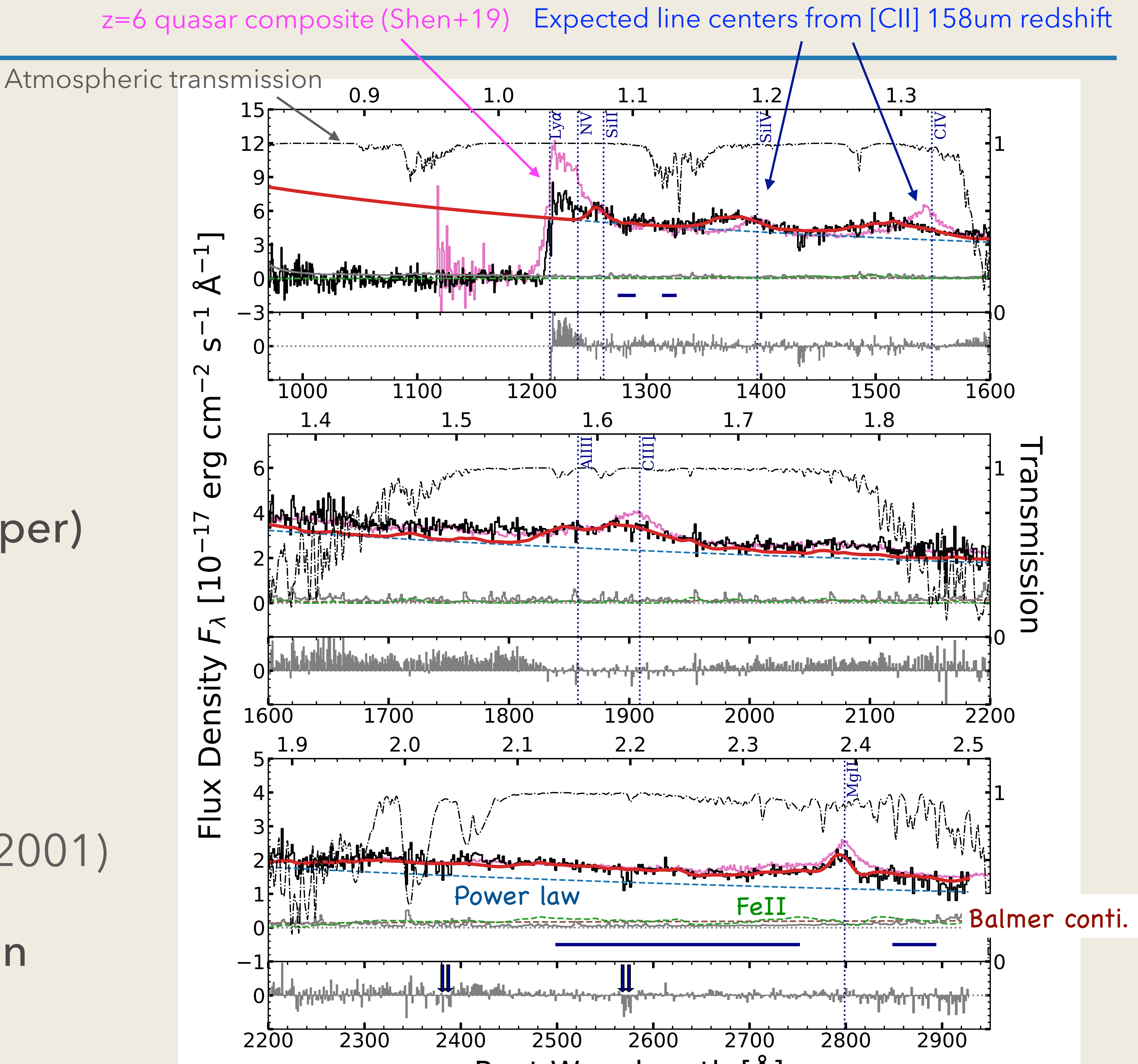




- SMBH: $M_{BH}=8\times10^8$ M_{sun}, $L_{bol}/L_{Edd}=1.5$ (Bañados+18; Onoue+20)
- Host: SFR=150M_{sun}/yr, Dust mass: 4×10^7 M_{sun} (Venemans+17, Novak+19), Merger? (Bañados+19)

Deep Gemini/ GNIRS Follow-up

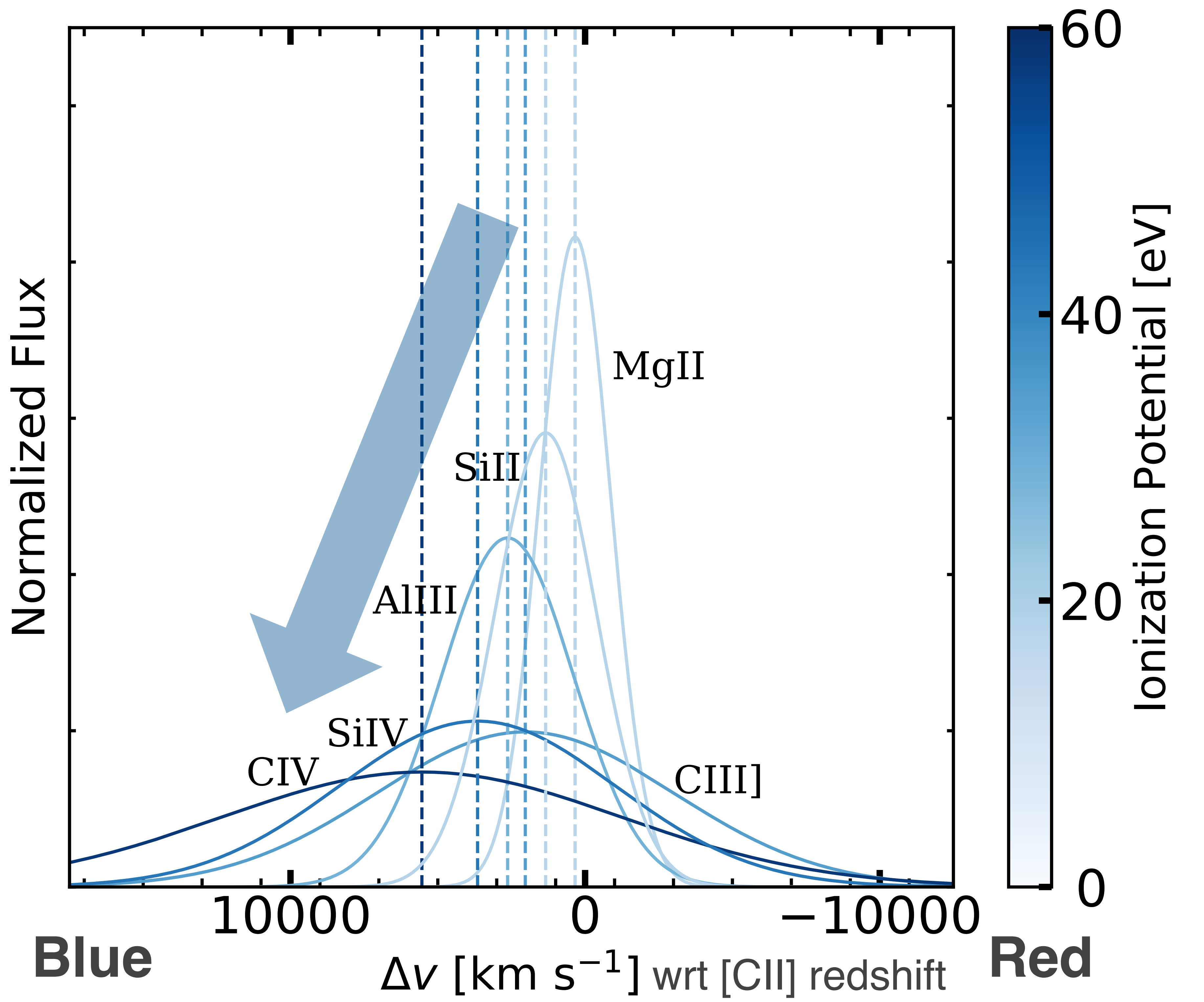
- T_{exp}=9hr (+4.3hr from the discovery paper)
- Data reduction: PypeIt (Prochaska+20)
- Continuum modeling:
  power-law + Balmer conti. + Fe forest
  (Tsuzuki+06 and Vestergaard & Wilkes 2001)
- Emission line modeling: single Gaussian



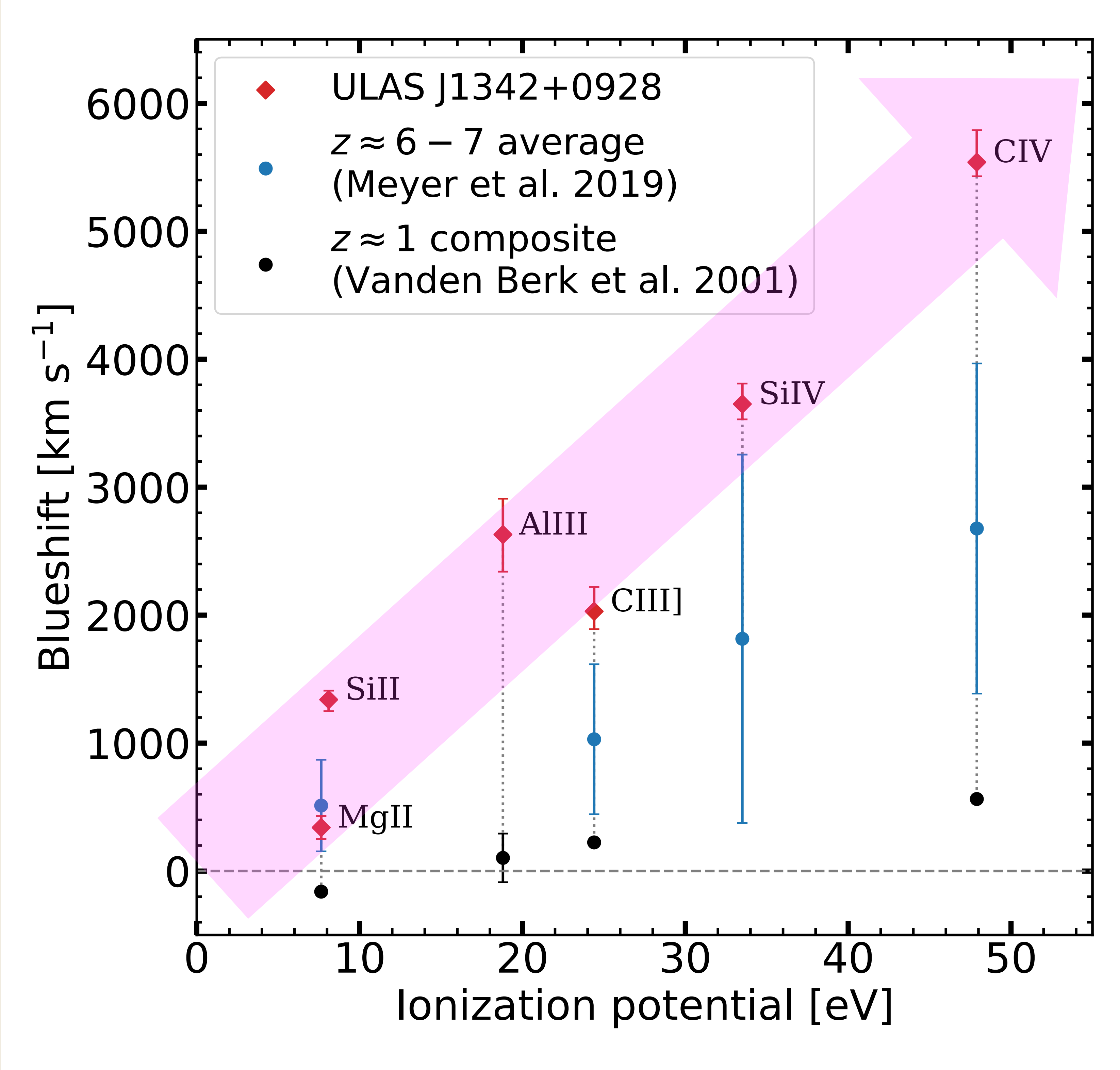
Onoue+20

Blueshifts of High-ionization Lines

- Normalized BLR line profiles

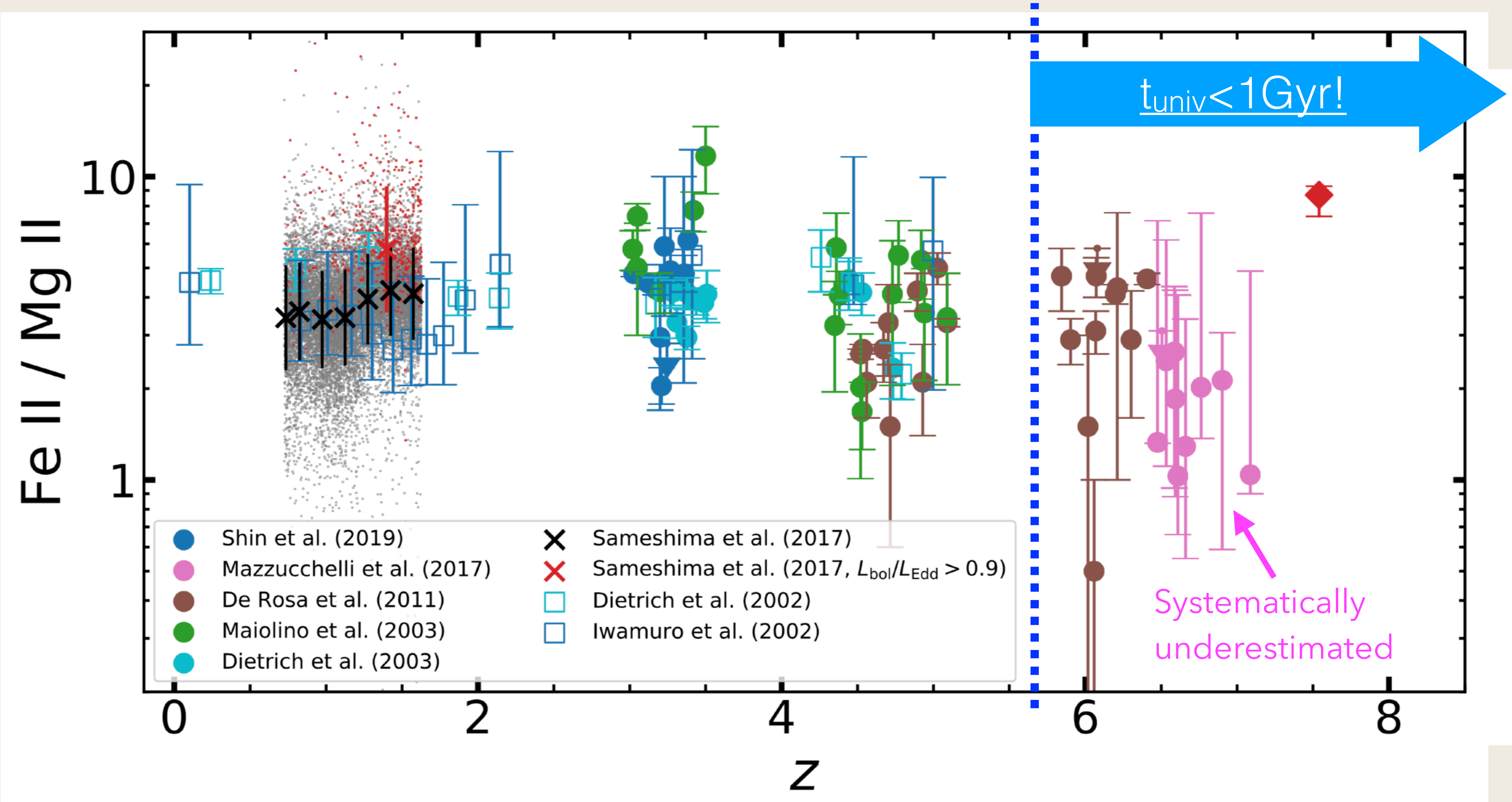


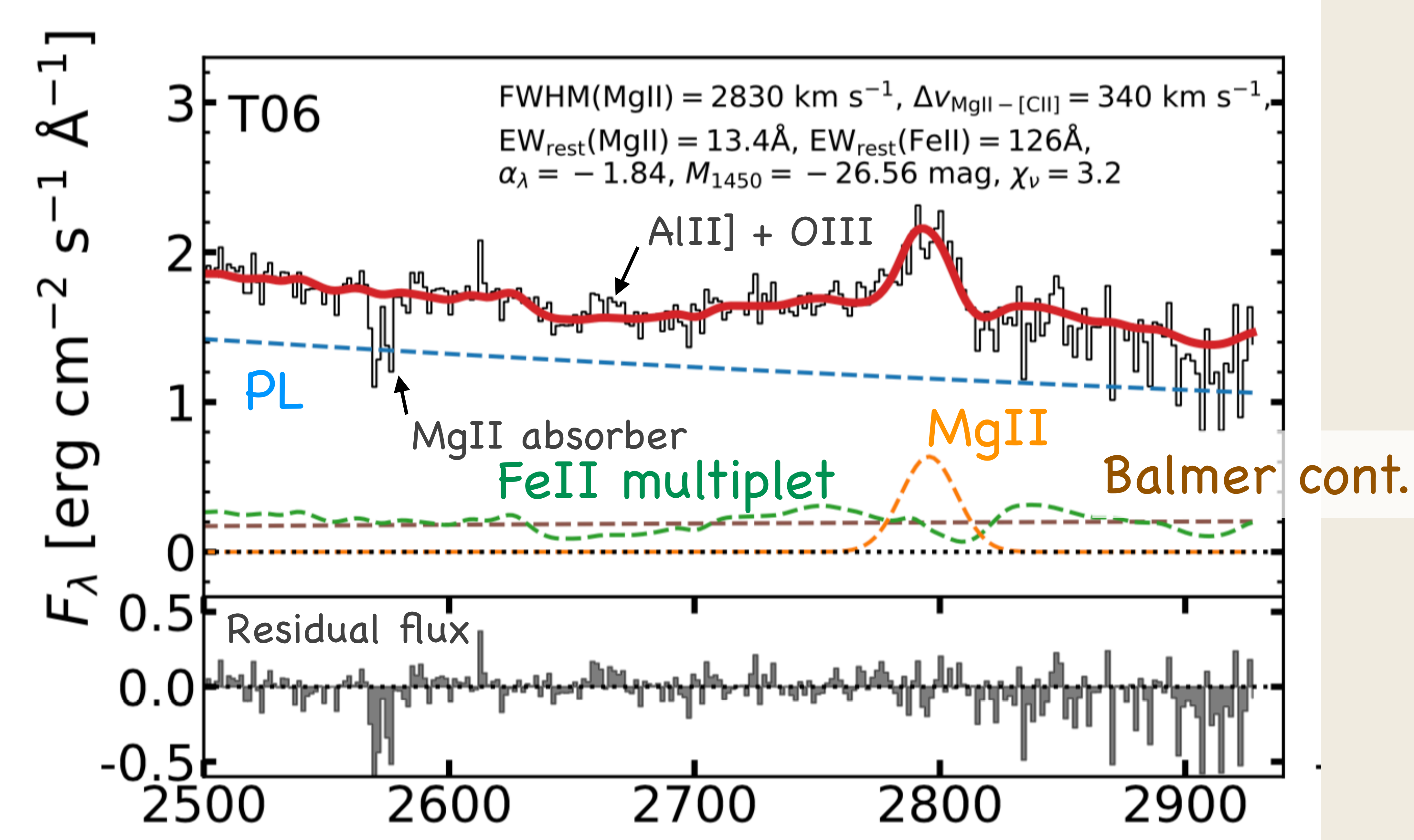
- BLR blueshifts (wrt [CII] 158μm) vs ionization potential



✦ Large BLR blueshift at z=7.5 in high ionization lines -> nuclear-scale outflow

Rapid Fe enrichment in BLR clouds

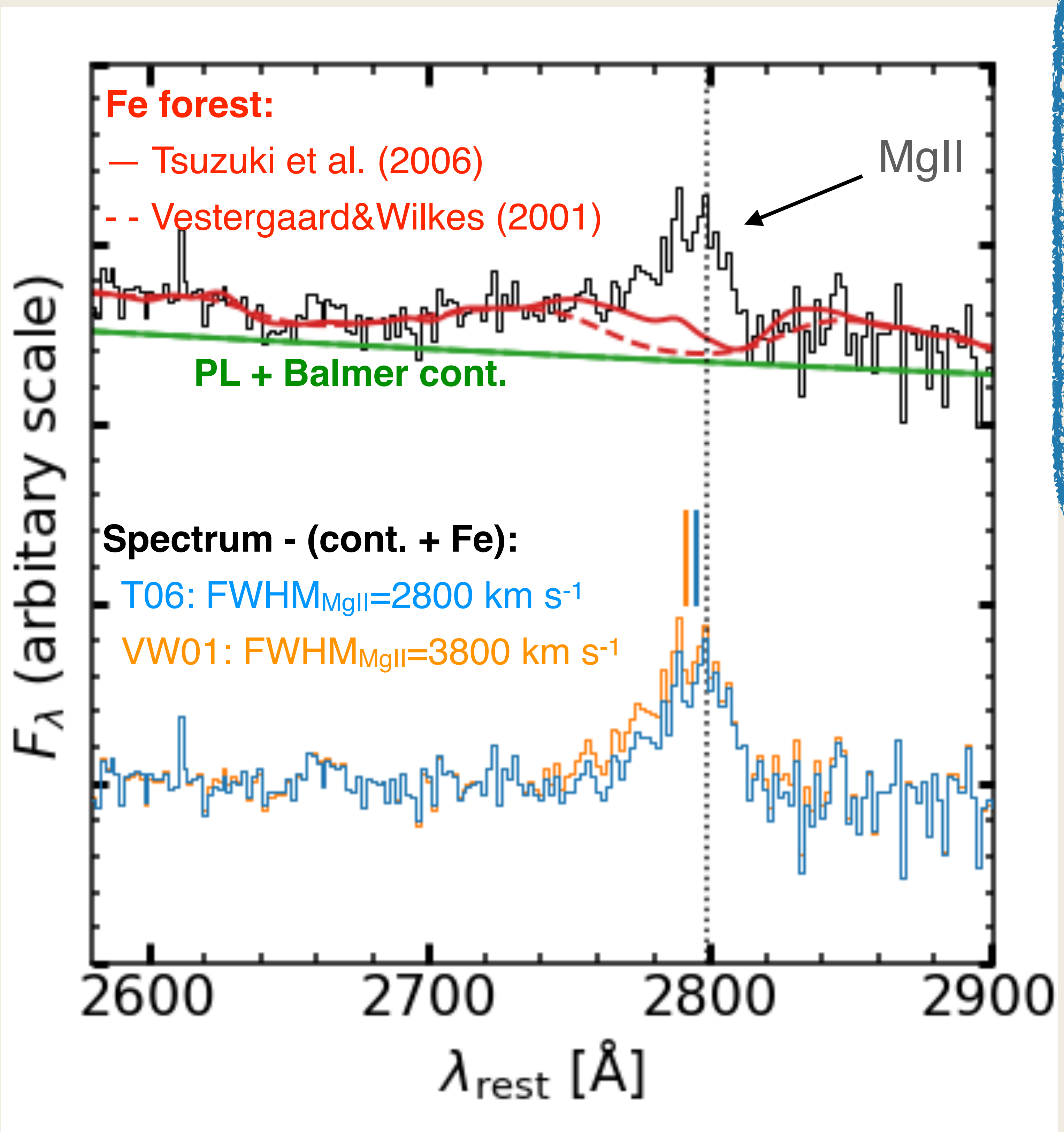




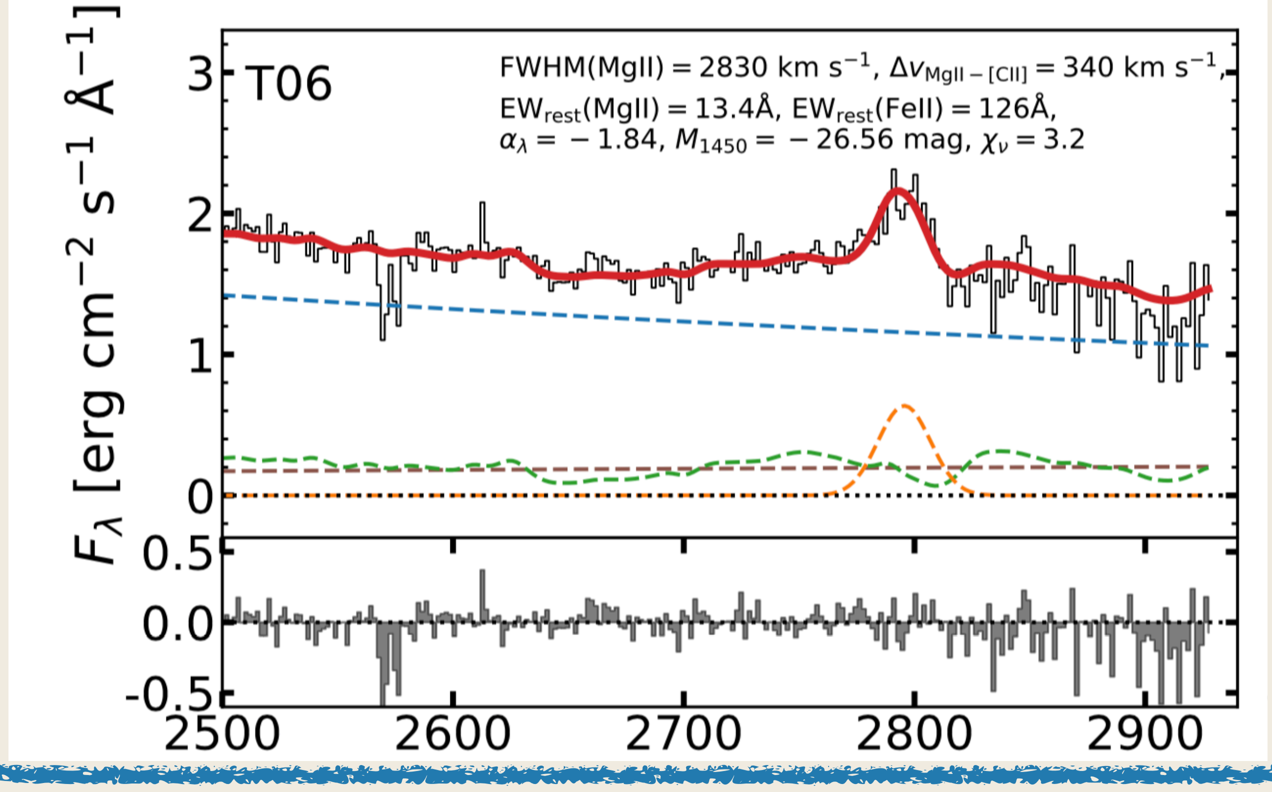
See also Schindler+20, Yang+21

- **FeII/MgII**: "cosmic clock" (e.g., Hamann & Ferland 93)
  α-elements…SNe II, Fe…SNe Ia (t_{Ia} ~ 1Gyr) -> time delay of Fe enrichment expected at z>6
- No FeII/MgII break found up to t_{univ}=0.7Gyr: PISNe or prompt SNIa?

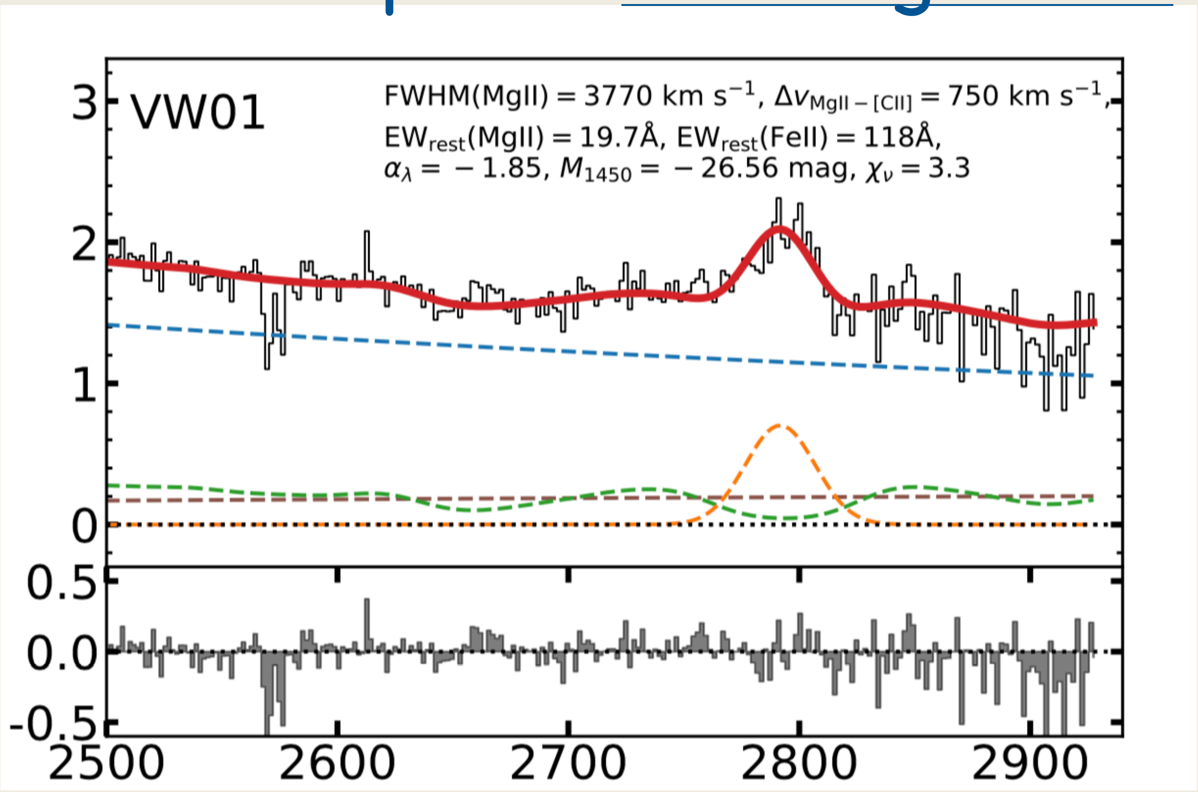
Systematic uncertainty in MgII fitting



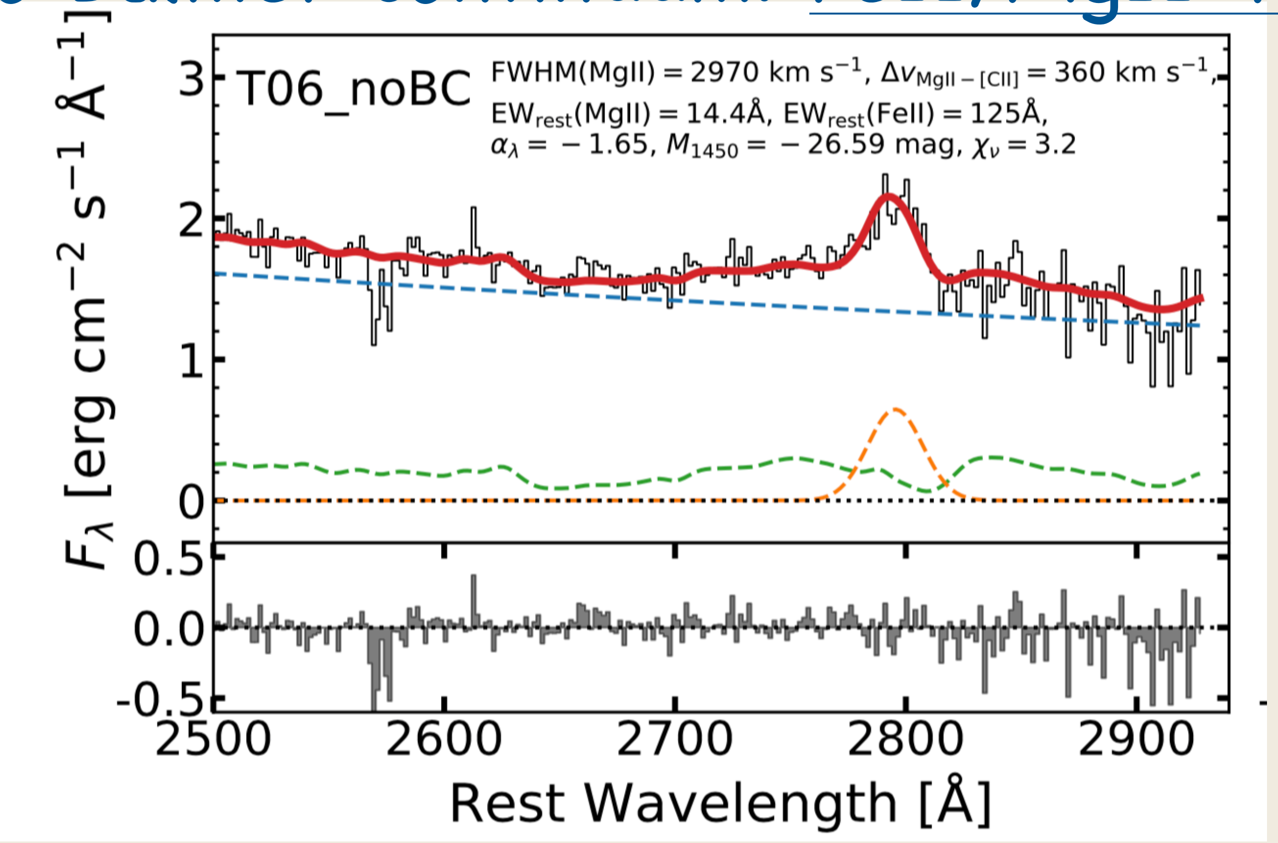
Tsuzuki+06 template: FeII/MgII=8.7



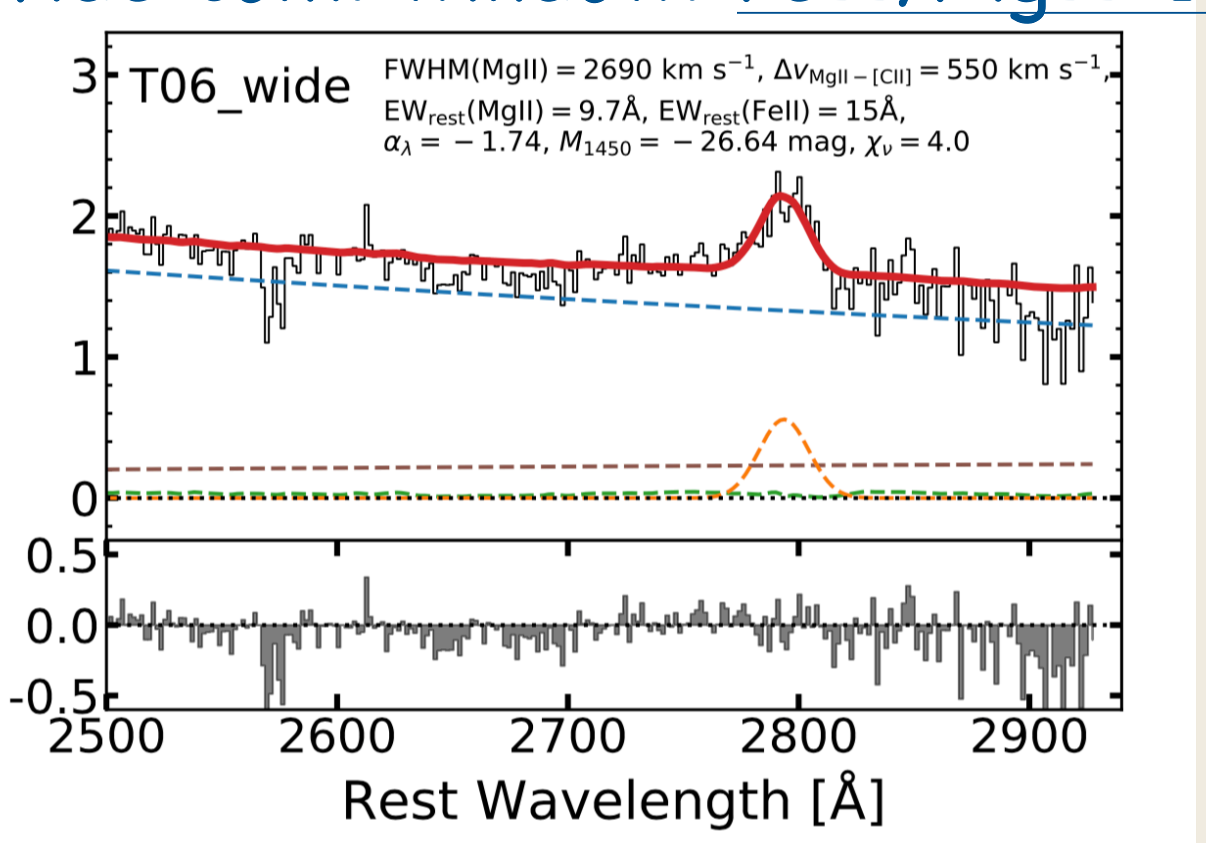
VW+01 template: FeII/MgII=5.5



w/o Balmer continuum: FeII/MgII=7.7



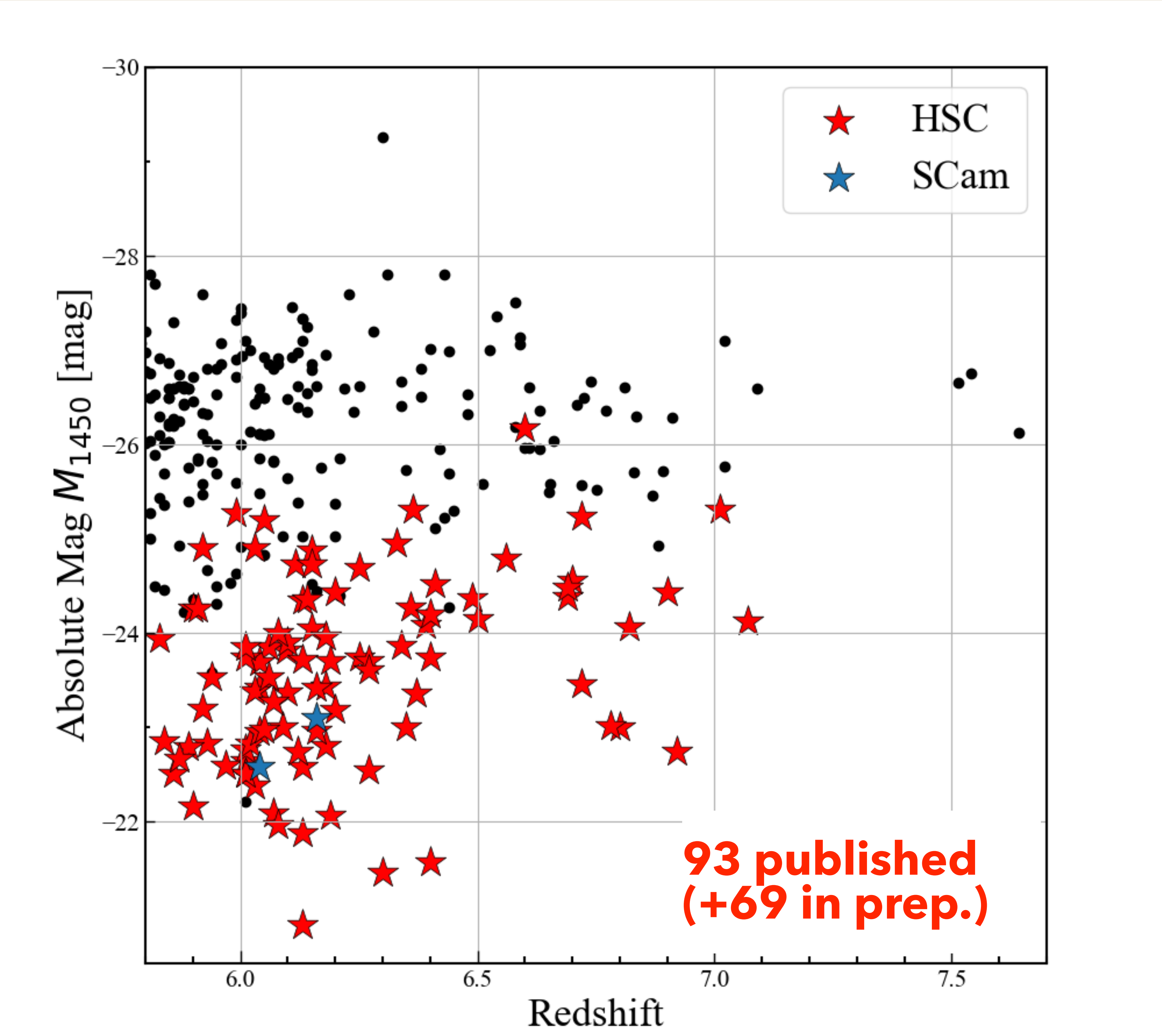
Wide cont. window: FeII/MgII=1.4

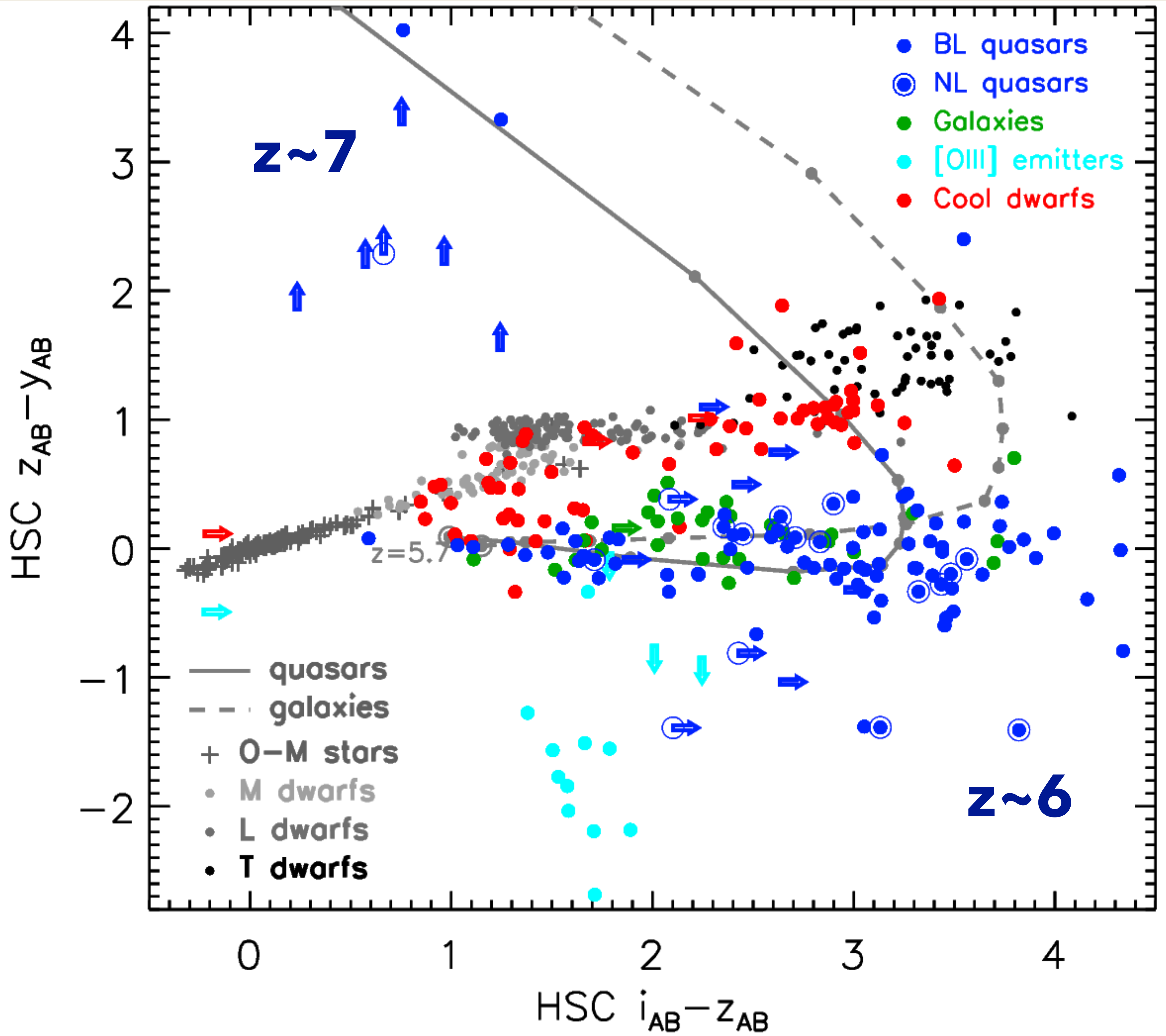


- Large systematic uncertainties associated with rest-UV FeII/MgII measurements due to different FeII+FeIII templates (Woo+18, Shin+19) & continuum windows

Low-luminosity Quasars at z>6

z>6 Quasar Search with HSC-SSP



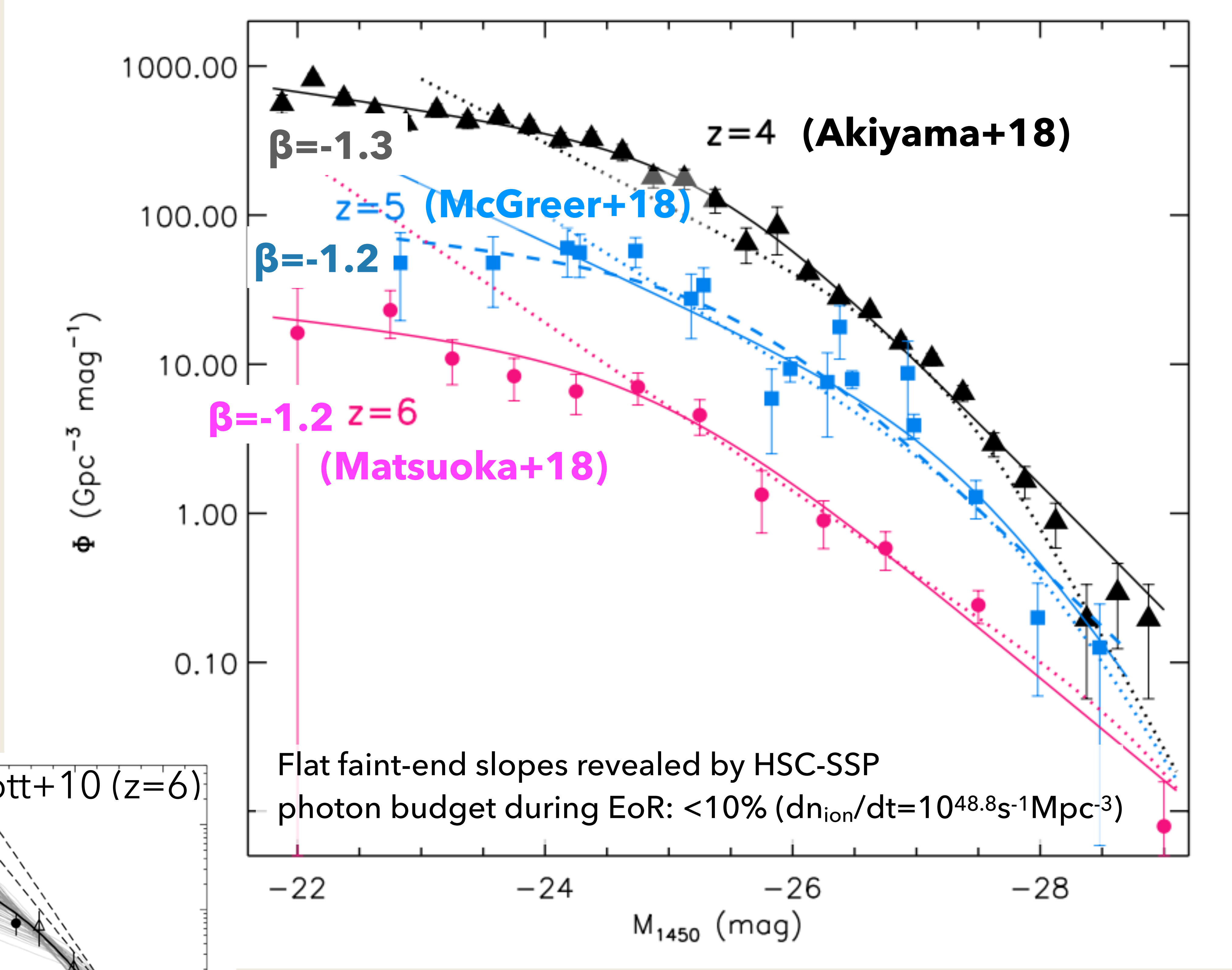


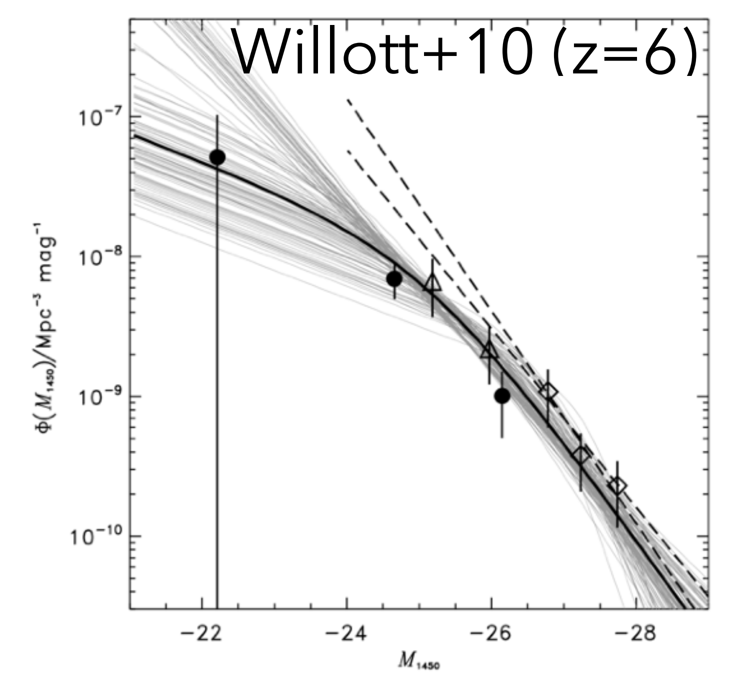
- Selection: HSC colors
- Follow-up spectroscopy: Subaru/FOCAS, GTC/OSIRIS

>100 low-luminosity z=6-7 quasars found thanks to the moderately deep HSC-SSP imaging

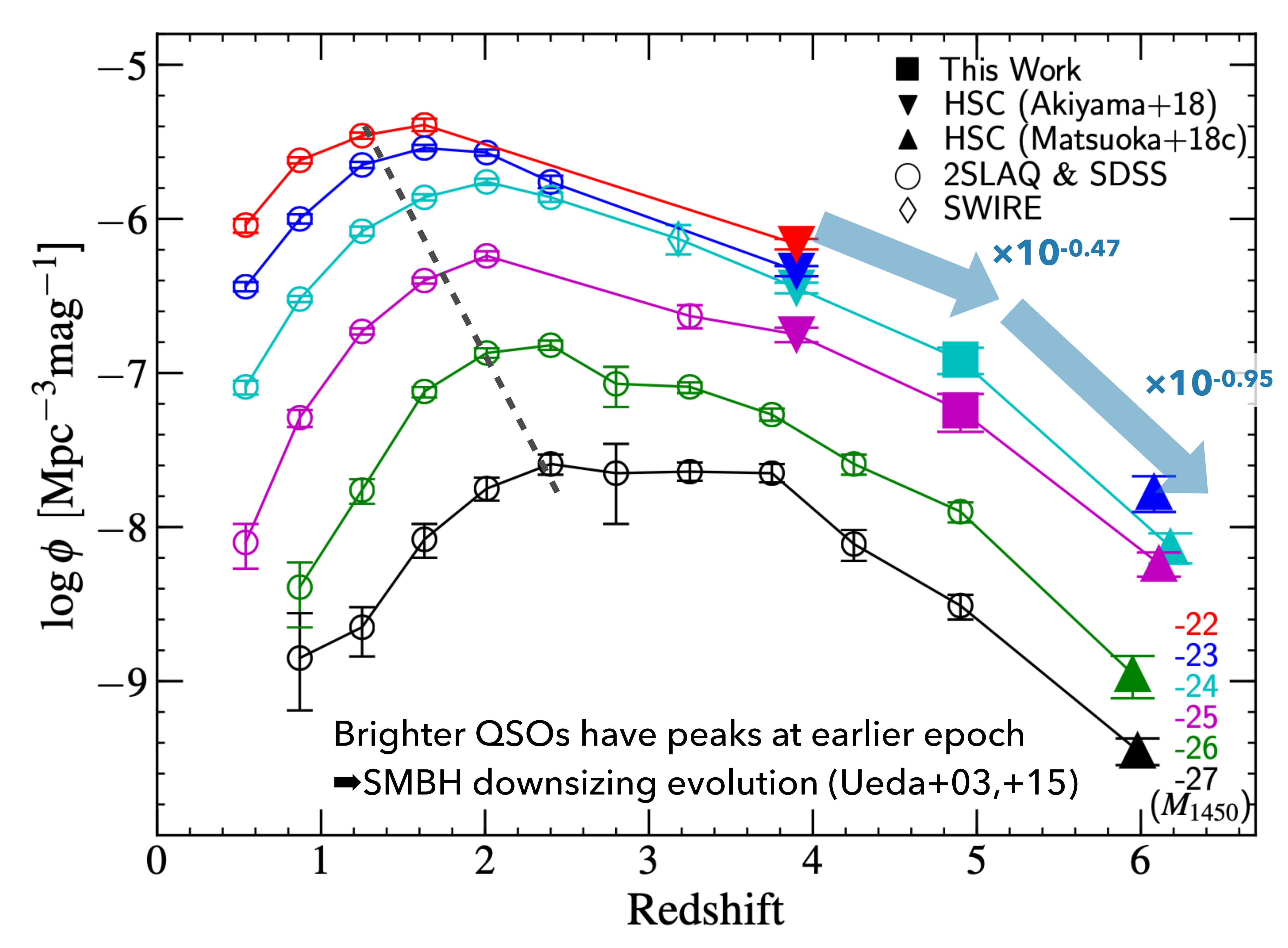
Quasar LF

- z=4-6 QLF (Matsuoka+18)



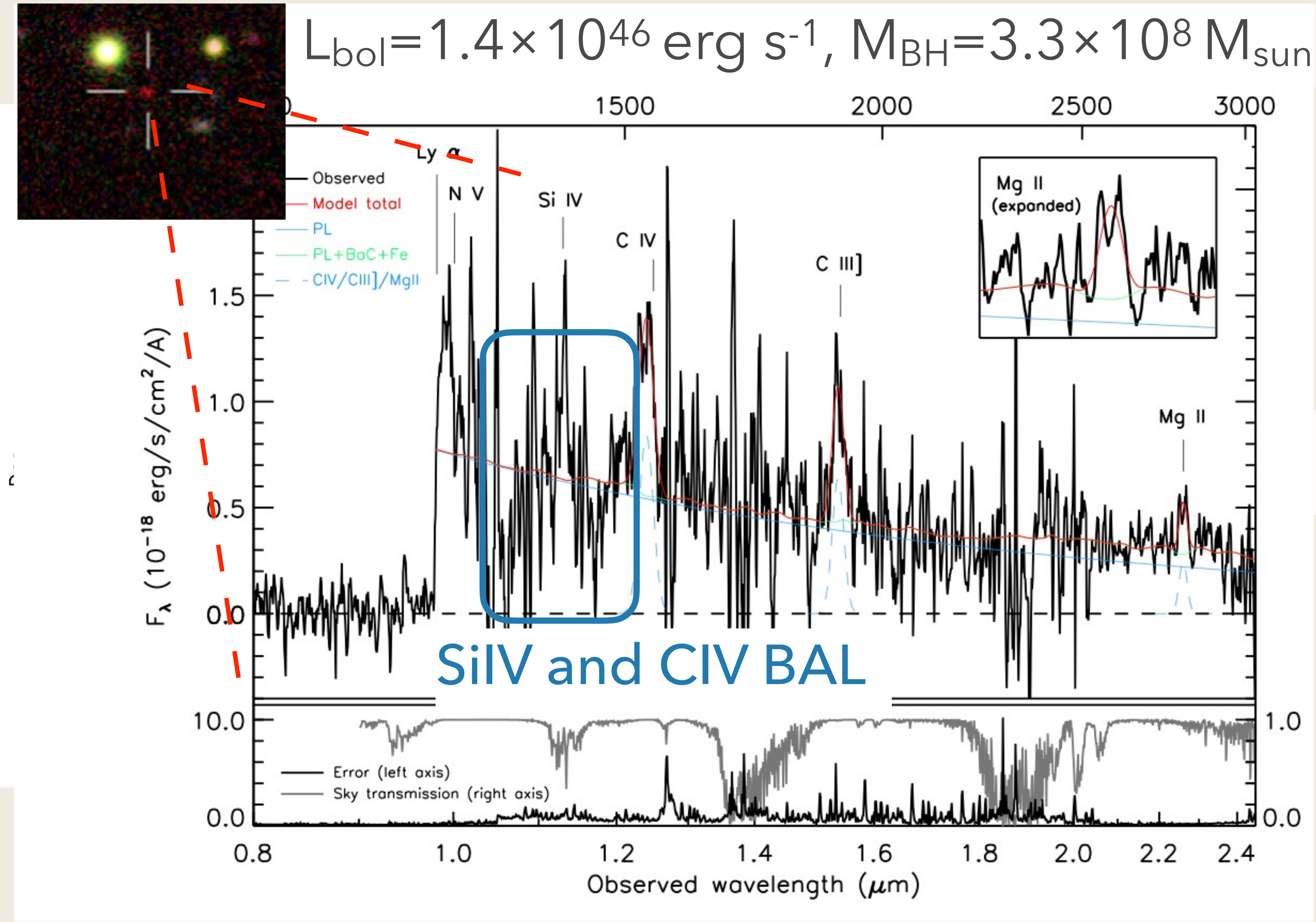


- QLF evolution at z=0-6 (Niida+20)

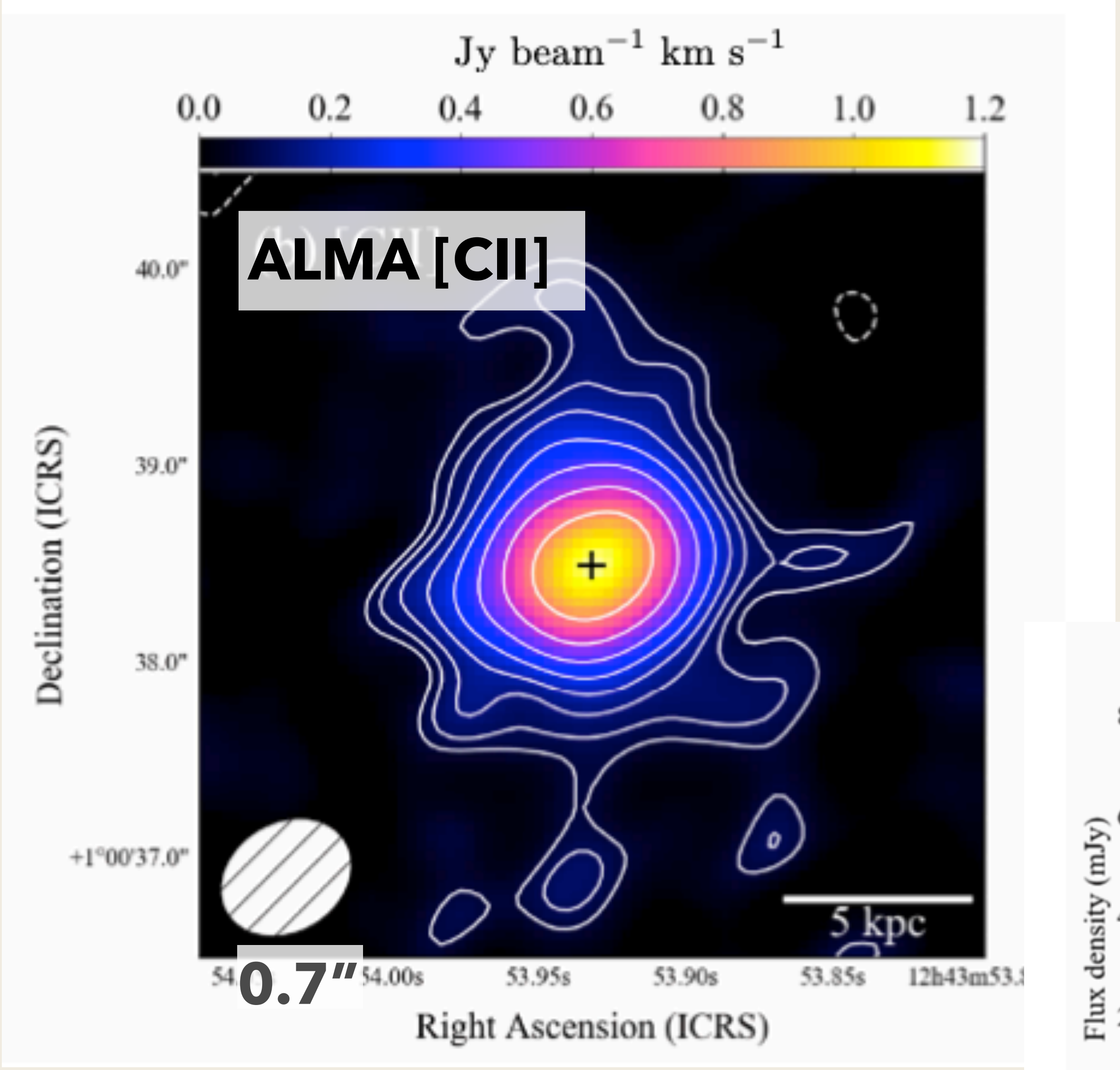


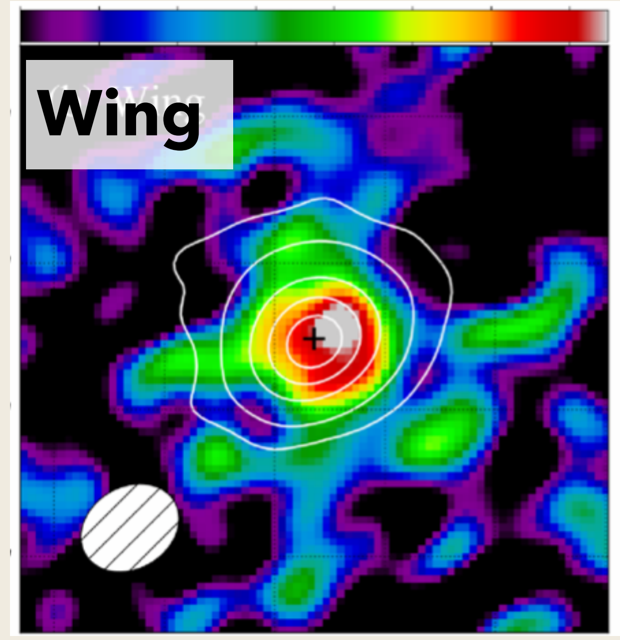
Low-luminosity QSO at z=7

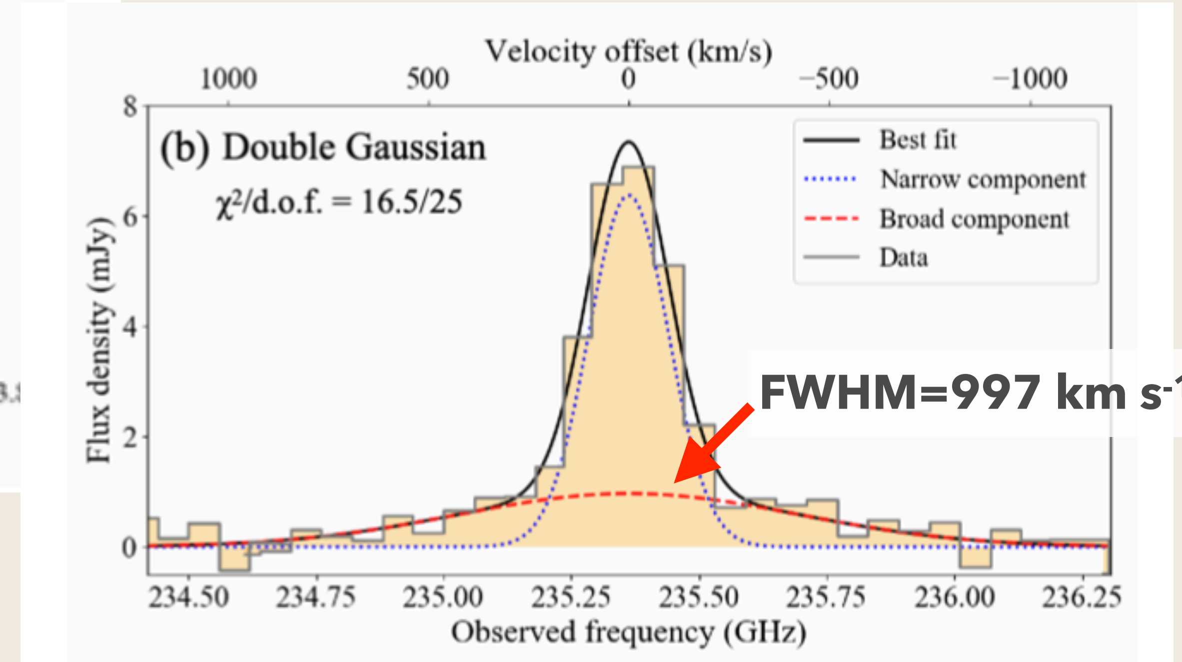
- HSC J1243+0100 at z=7.07 (Matsuoka, MO+19a)



- Quasar-driven [CII] outflow (Izumi+21b)





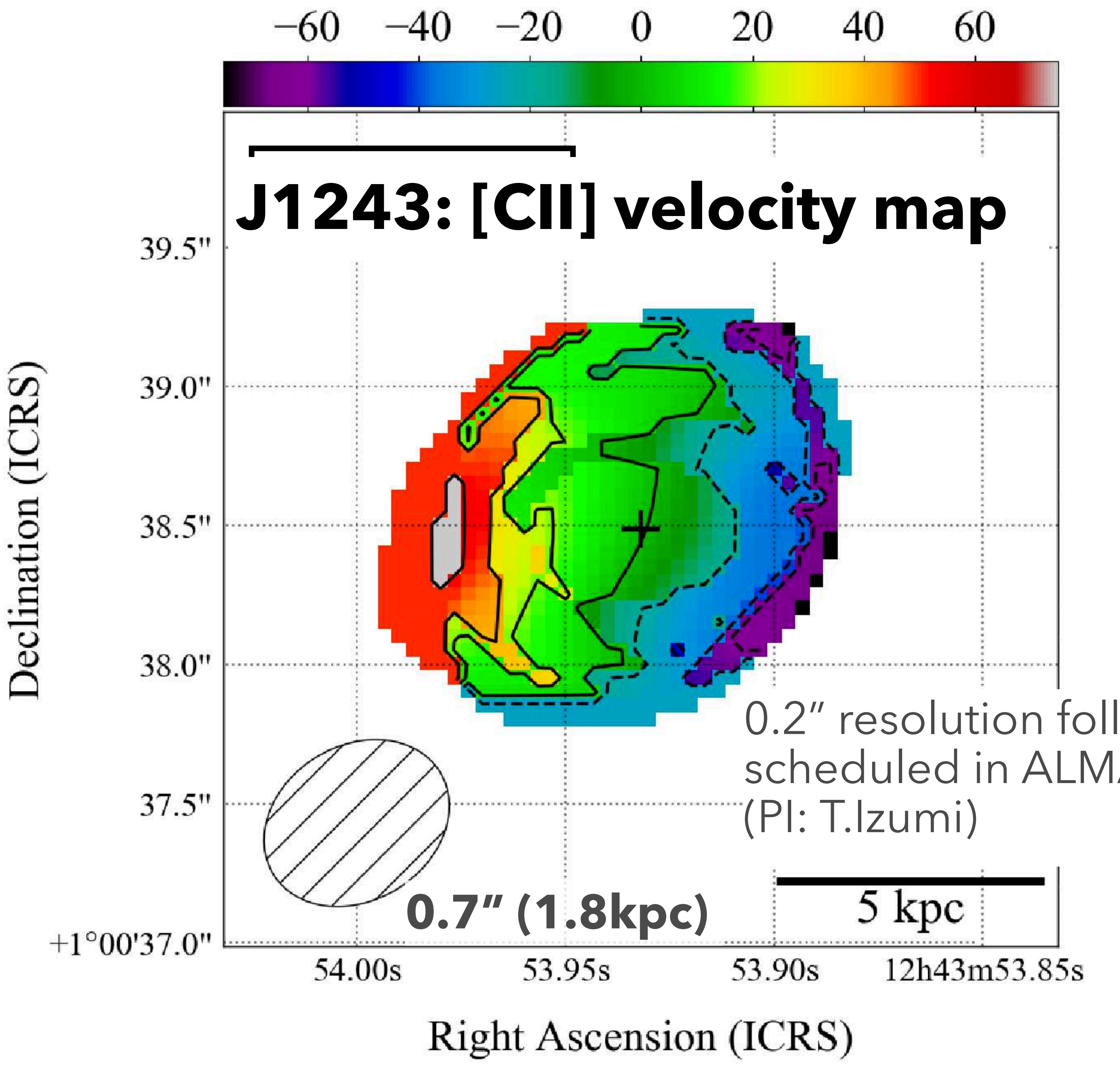


See also Maiolino+12; Izumi+21a

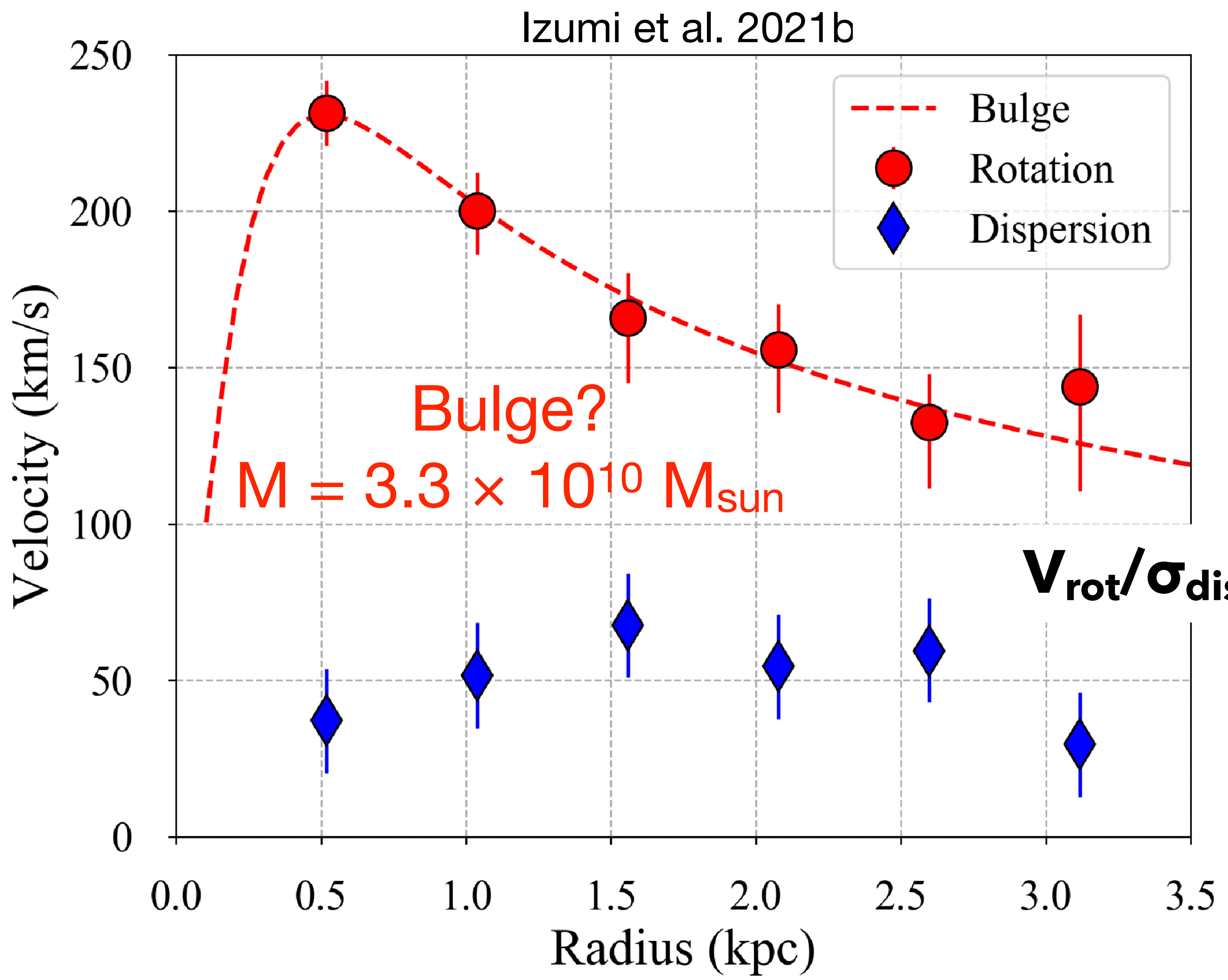
Large-scale outflow just starting to regulate host star formation:
Propagation of nuclear-scale (BAL) wind, or radiation pressure-driven dusty wind?

Early Bulge Formation at z ~ 7??

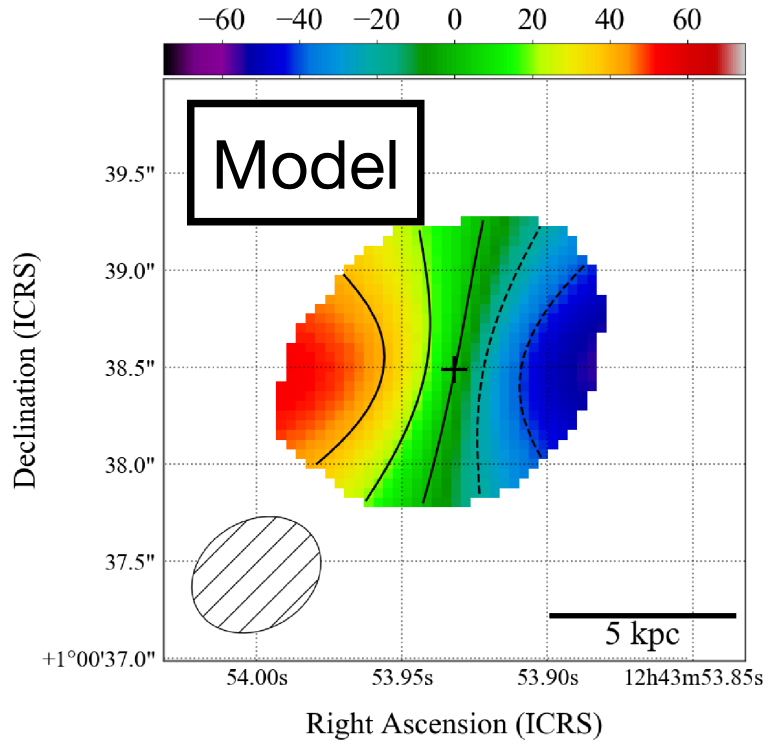
Courtesy of T.Izumi

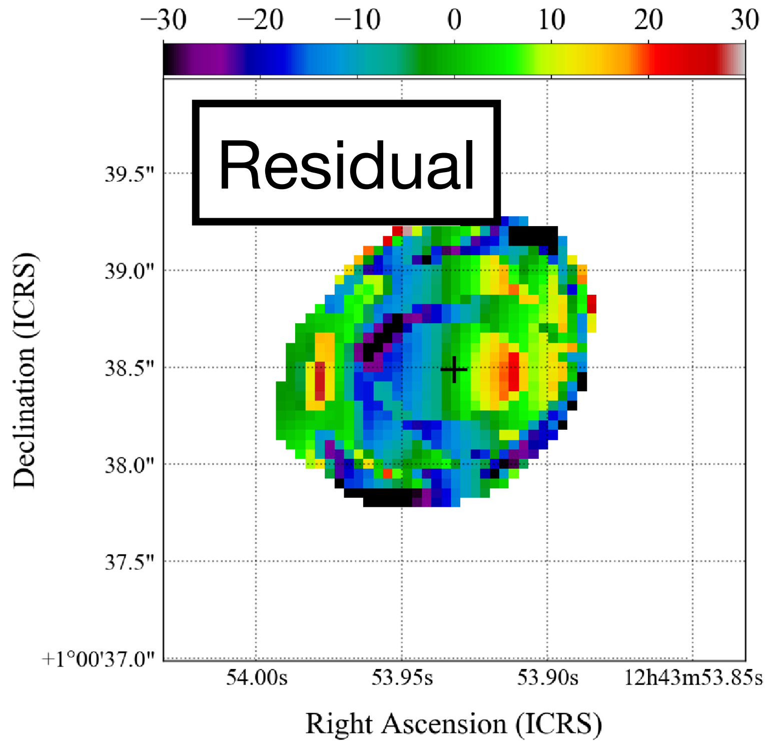


0.2″ resolution follow-up scheduled in ALMA C8! (PI: T.Izumi)



V_{rot}/σ_{disp}=3-5



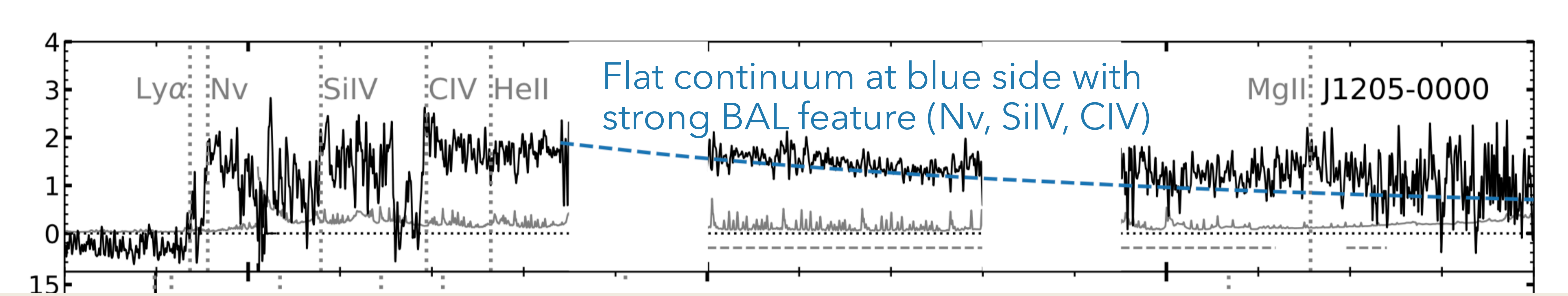


- We experimentally extracted a [CII] rotation curve by decomposing (modeling) the observed velocity field.
- We found a gradual rise in V_{rot} toward the center → Indication of a nuclear bulge??
- Would be consistent with simulations.

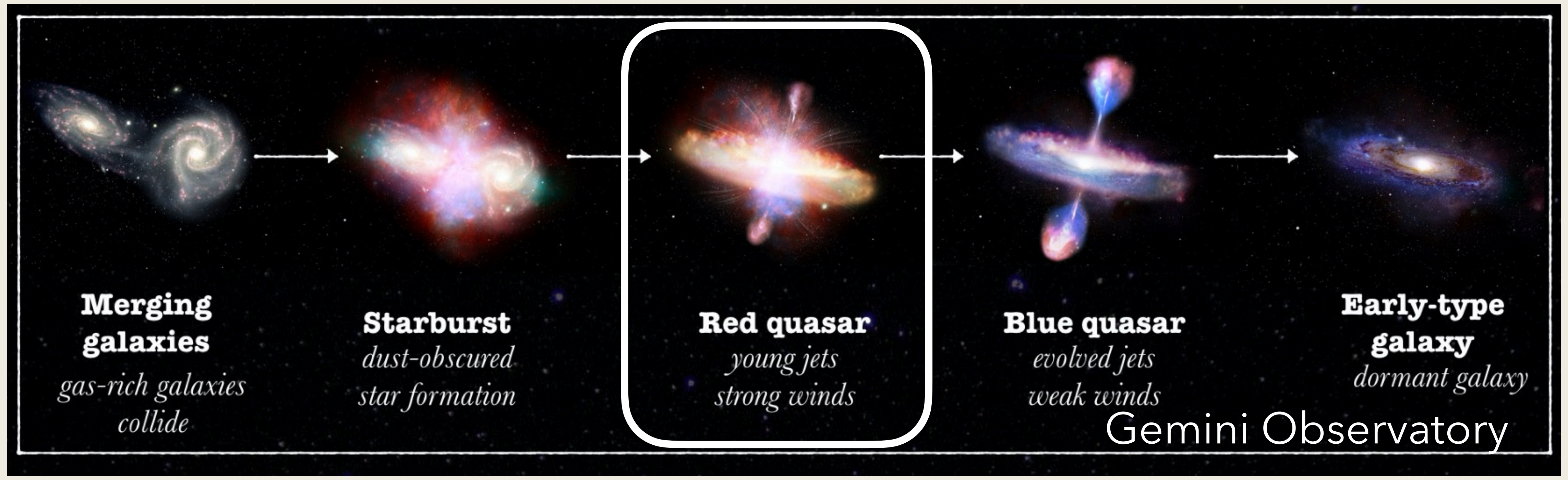
See also Smit+17; RIzzo+20; Neeleman+20

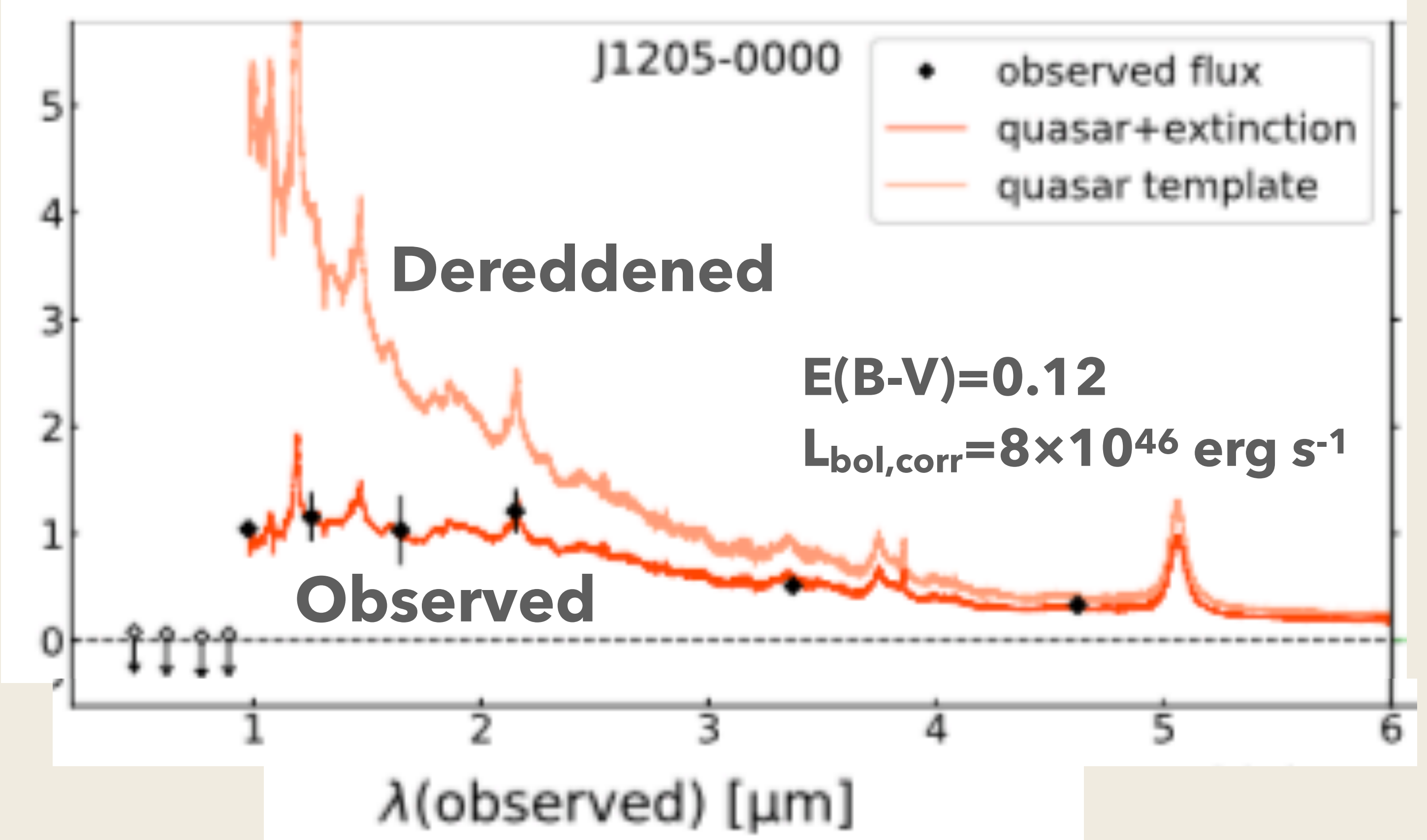
Dust-Reddened Quasar at z=6.7

- VLT/XShooter spectrum of J1205-0000 (T_{exp}=7hr)



- SED fitting with HSC/VIKING/WISE (Kato+20)



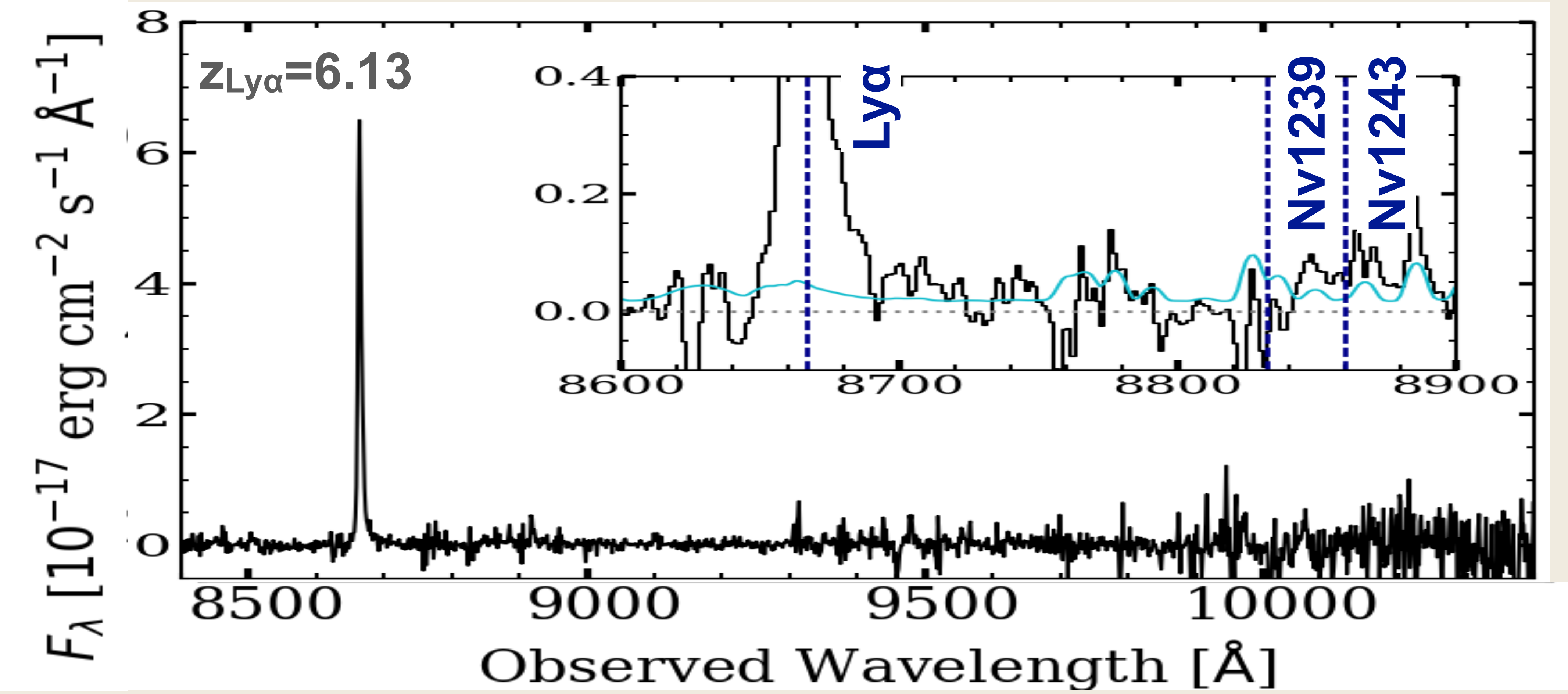


	Onoue et al. (2019)	Extinction-corrected
λL_{3000} (10^{45} erg s^{-1})	8.96 ± 0.66	$16.15^{+2.68}_{-2.53}$
$M_{\rm BH}$(Mg II) (10^9 $M_\odot$)	$2.2^{+0.2}_{-0.6}$	$2.9^{+0.3}_{-0.8}$
$L_{\rm bol}/L_{\rm Edd}$	$0.16^{+0.04}_{-0.02}$	$0.22^{+0.04}_{-0.03}$

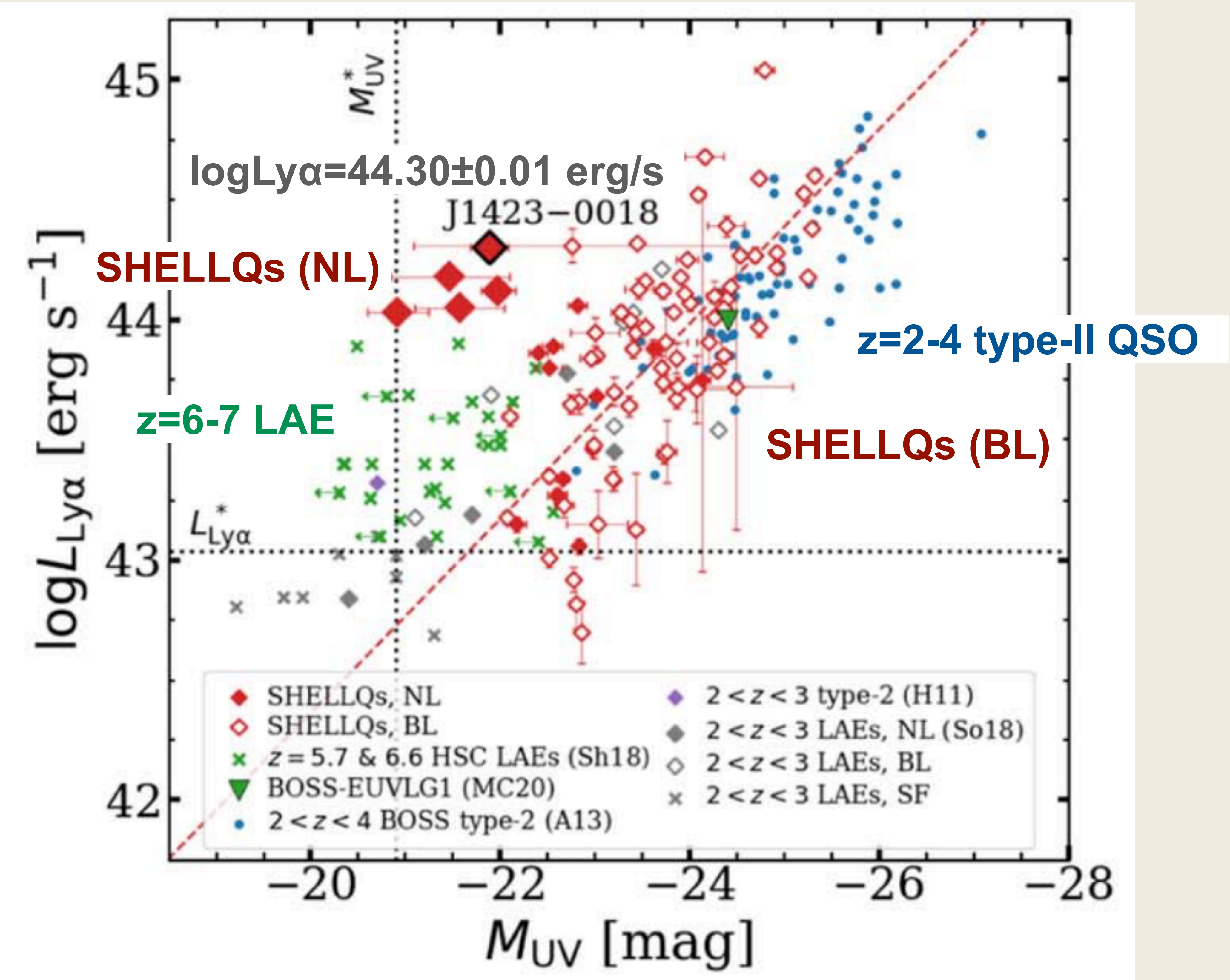
A modestly dust-obscured quasar found from the HSC's low-luminosity quasar sample at z>6

A Candidate Obscured Quasar at z>6

- J1423-0018 at z=6.13 (Matsuoka+18)

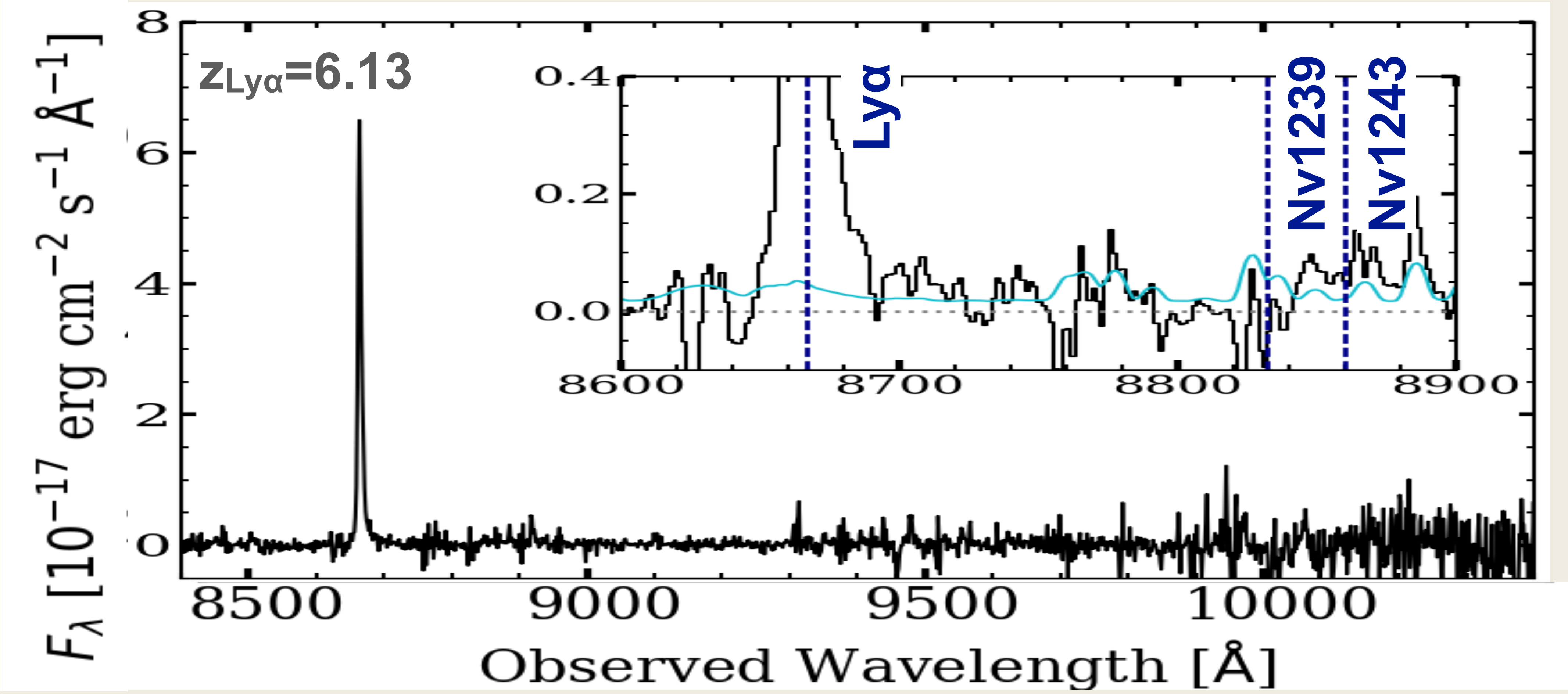


- MUV vs Lya luminosity of NL/BL quasars and LAEs

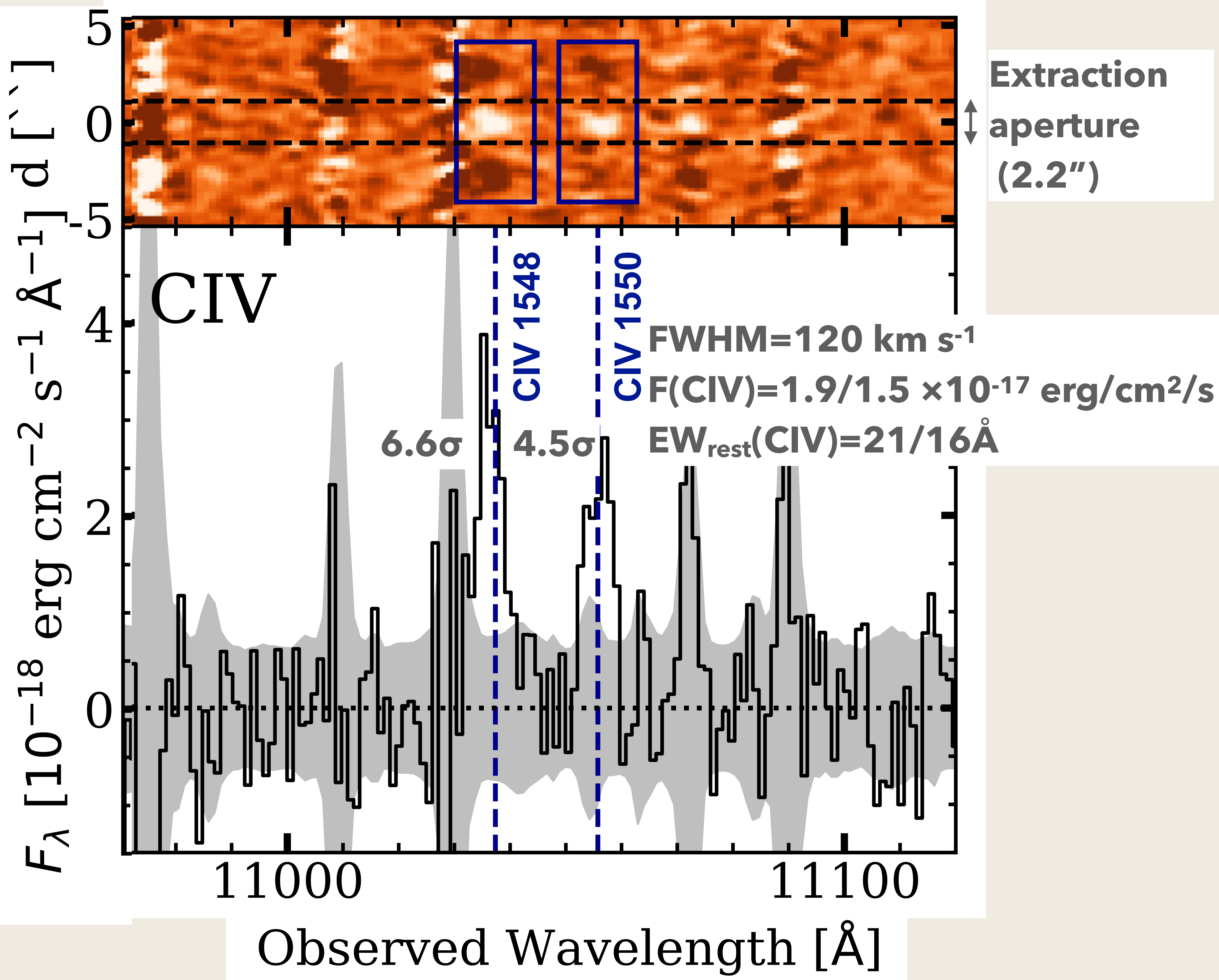


A Candidate Obscured Quasar at z>6

- J1423-0018 at z=6.13 (Matsuoka+18)



- MOSFIRE Y-band (2hr; Onoue+21)



- **A clear detection of CIVλλ1548,1550 doublet from a narrow Lyα source** (originally selected as quasars)
  - z=6.1292±0.0002, Δv(CIV-Lyα)=-30 km/s
  - FWHM=120±20 km s^{-1}
  - Total EW_{rest}(CIV)=37_{-5}^{+6} Å
- CIV EW cannot be explained by stellar photoionization (Nakajima+18)
- Chandra and VLT/XSHOOTER follow-up scheduled (with 3 others)

Cy1 JWST GO project:
Full Census of SMBHs and Host Galaxies at z=6

Webb arrives at Pariacabo harbour

12/10/2021 111 VIEWS 4 LIKES 459985 ID

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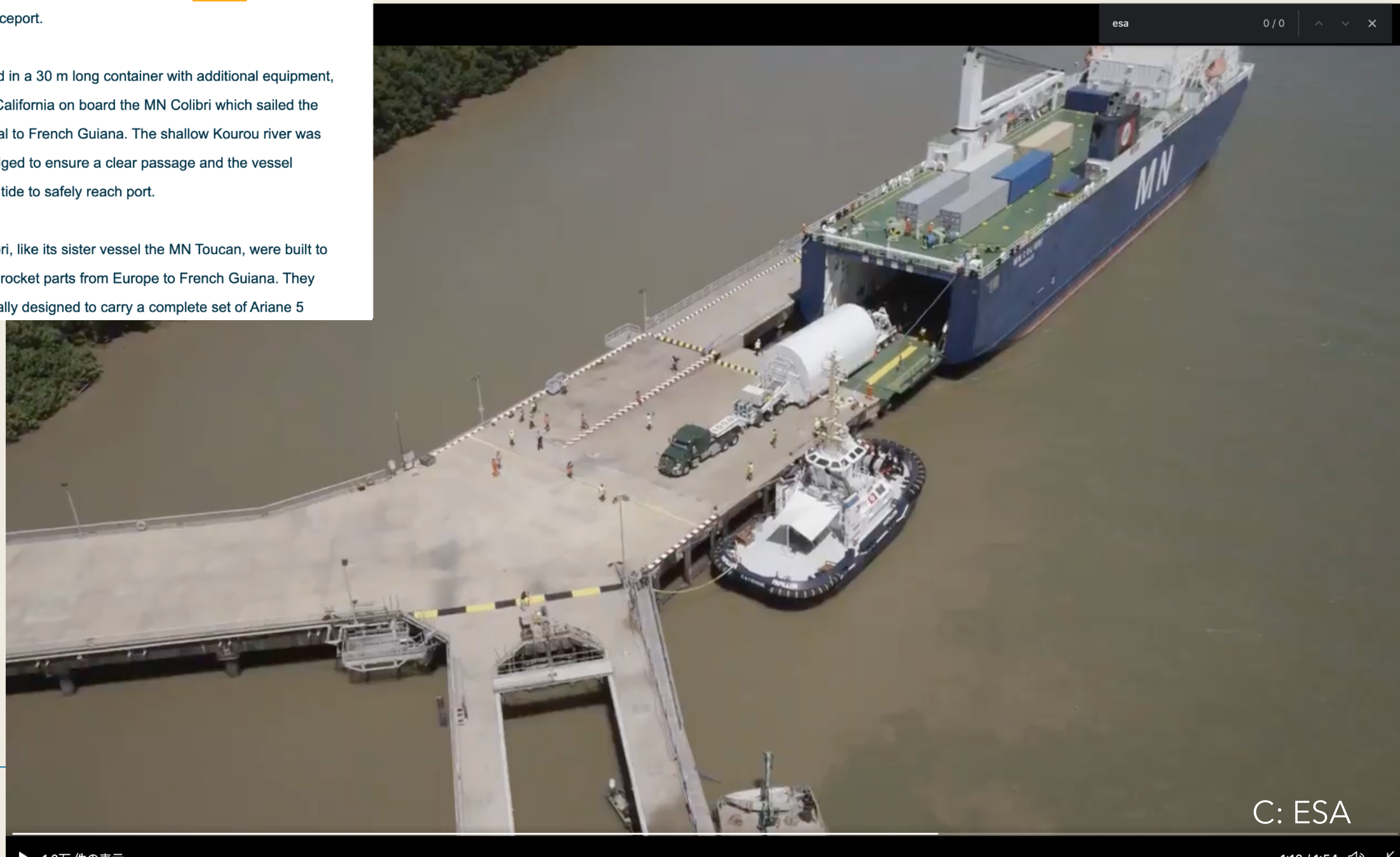
DETAILS RELATED

The James Webb Space Telescope, a once in a generation space mission, arrived safely at Pariacabo harbour in French Guiana on 12 October 2021, ahead of its launch on an Ariane 5 rocket from Europe's Spaceport.

Webb, packed in a 30 m long container with additional equipment, arrived from California on board the MN Colibri which sailed the Panama Canal to French Guiana. The shallow Kourou river was specially dredged to ensure a clear passage and the vessel followed high tide to safely reach port.

The MN Colibri, like its sister vessel the MN Toucan, were built to ship Ariane 5 rocket parts from Europe to French Guiana. They were specifically designed to carry a complete set of Ariane 5

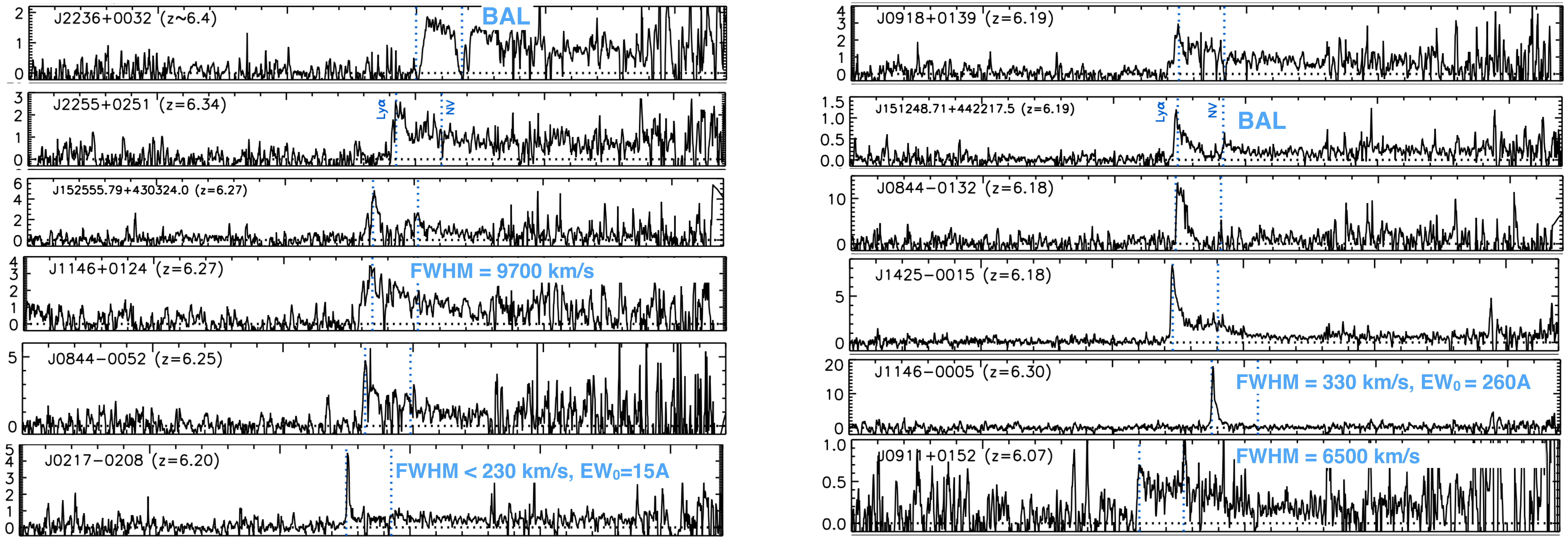


Cy1 GO programs (High-z QSO only)

ID	program	PI	Prime/ Parallel Time	instrument	science	targets	Notes
1554	Nebular line diagnostics in a merger at cosmic dawn	Dr. R. Decarli	7.8	NIRSpec IFU G395H	z=6.2 merger in Decarli+19 (M*, SFR, ionized gas kinematics, metallicity, ionization parameter)	PJ308-21	Satellite galaxy with tidal-stripping signature seen in HST + ALMA
1760	First Accreting BH candidates" IR-dropout heavily obscured X-ray AGNs	Dr. H. Suh	23.6	NIRSpec FS G395H + MIRI LRS	Spec confirmation of IR-dropout obscured X-ray sources	7 IRAC sources in COSMOS	DCBHs or heavily obscured AGNs?
1764	A Comprehensive JWST View of the Most Distant QSOs Deep into the EoR	Prof. X. Fan Dr. J. Yang Dr. E. Bañados	65.5/8.6	NIRCam + MIRI imaging/ MRS + NIRSpec FS/IFU	Everything on highest-z qsos (host, environment, BH mass, BLR, IGM)	Three z=7.5 QSOs	
1813	Unveiling Stellar Light from Host Galaxies at z=6 QSOs	Dr. M. Marshall	15.9	NIRCam F150W, F200W, F277W, F356W, F444W	Host (SED, M*), companions	J2054 J0129 (both SDSS)	HST+ALMA presented in Marshall+20
1964	The Role of Radio AGN Feedback in Massive Galaxies at z=4-6	Prof. R. Overzier Dr. A. Saxena	23.8	NIRSpec IFU	HzRGs (ionized gas kinematics and metallicity, host stellar population)	TN J1338-1942 TGSS J1530+1049	Most distant radio galaxies
1967	A Complete Census of SMBHs and Host Galaxies at z=6	Dr. M. Onoue Prof. Y. Matsuoka Prof. J. Silverman Dr. T.Izumi, Dr. X.Ding	49.5	NIRCam + NIRSpec	Host M* + BH mass, BHMF, BLR, etc.	12 lowest-L QSOs	
2028	Mapping a Distant Protocluster Anchored by a Luminous QSO in the EoR	Dr. F. Wang Dr. J. Yang	16.3/5.8	NIRSpec MSA+IFU	Protocluster member confirmation (targets from HST pre-imaging) + quasar characterization	z=6.63 QSO field	Protocluster identified with HSC+JCMT+ALMA
2249	Monster in the Early Universe: Unveiling the Nature of a Dust Reddened QSO Hosting a 10^{10} Msun BH at z=7.1	Dr. F. Wang Dr. J. Yang	5.5	NIRSpec IFU + MIRI Imaging	Constraining dust extinction, BH mass	J0038-0653	Unpublished dusty qso?
2078	ASPIRE: A JWST QSO Legacy Survey	Dr. F. Wang Prof. X. Fan Prof. J. Hennawi	61.5/29.6	NIRCam WFSS	Large-scale environments	25 QSOs at 6.5<z<6.8	350 galaxies at 5.3<z<7 from Slitless spectroscopy
2073	Towards Tomographic Mapping of EoR QSO Light Echos with JWST	Prof. J. Hennawi Dr. F. Davies	24.3/6.3	NIRCam + NIRSpec MOS	QSO light echos	J0252-0503 J1007+2115	

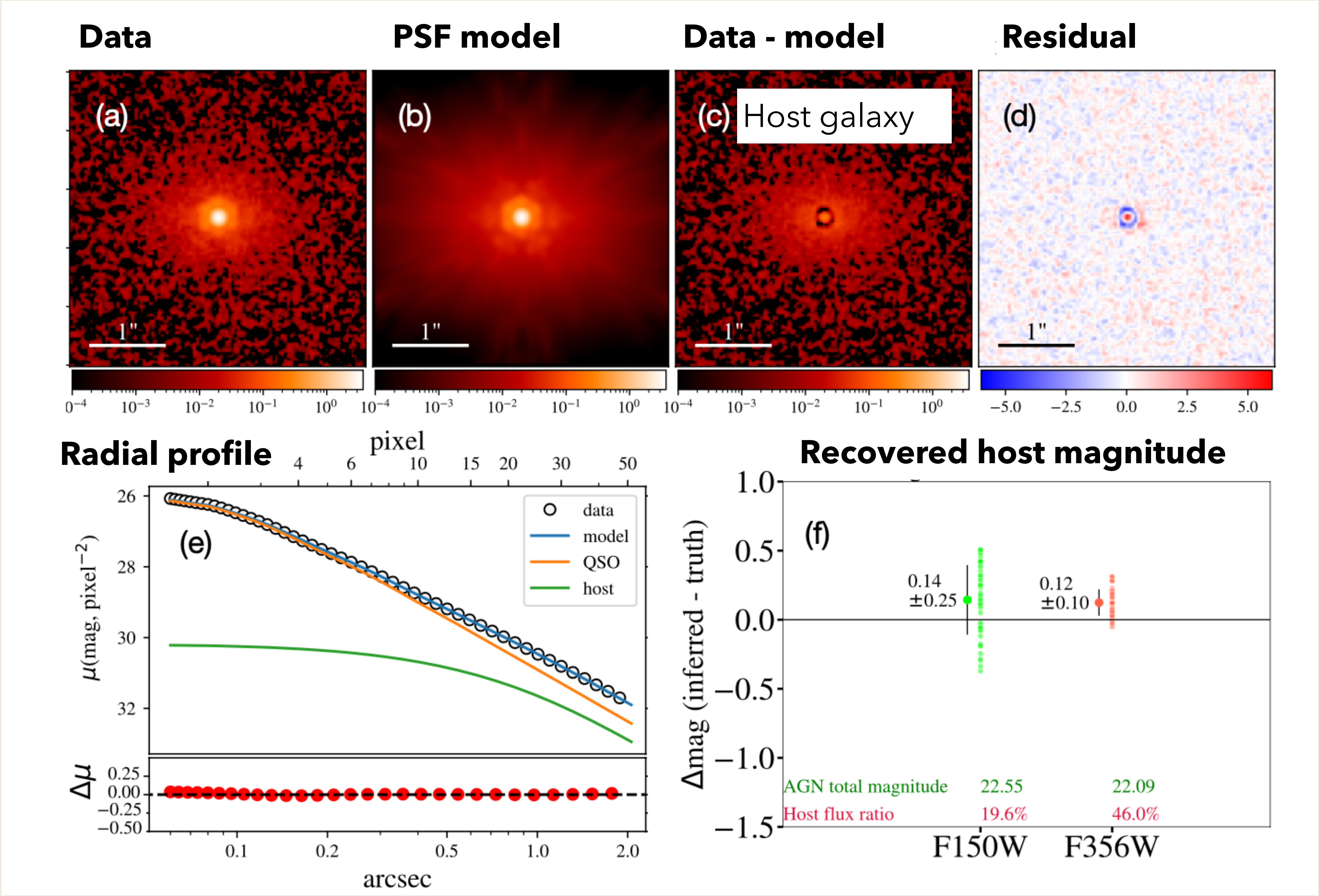
Targets: Lowest-luminosity Quasars at z=6

- Discovery spectra of 12 JWST targets (y_{HSC}=23.0-24.8 AB mag, 10 from QLF sample) -> least-biased SMBH sample!



- 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



- NIRCam Imaging (FoV: 2.2x2.2 amin^2)
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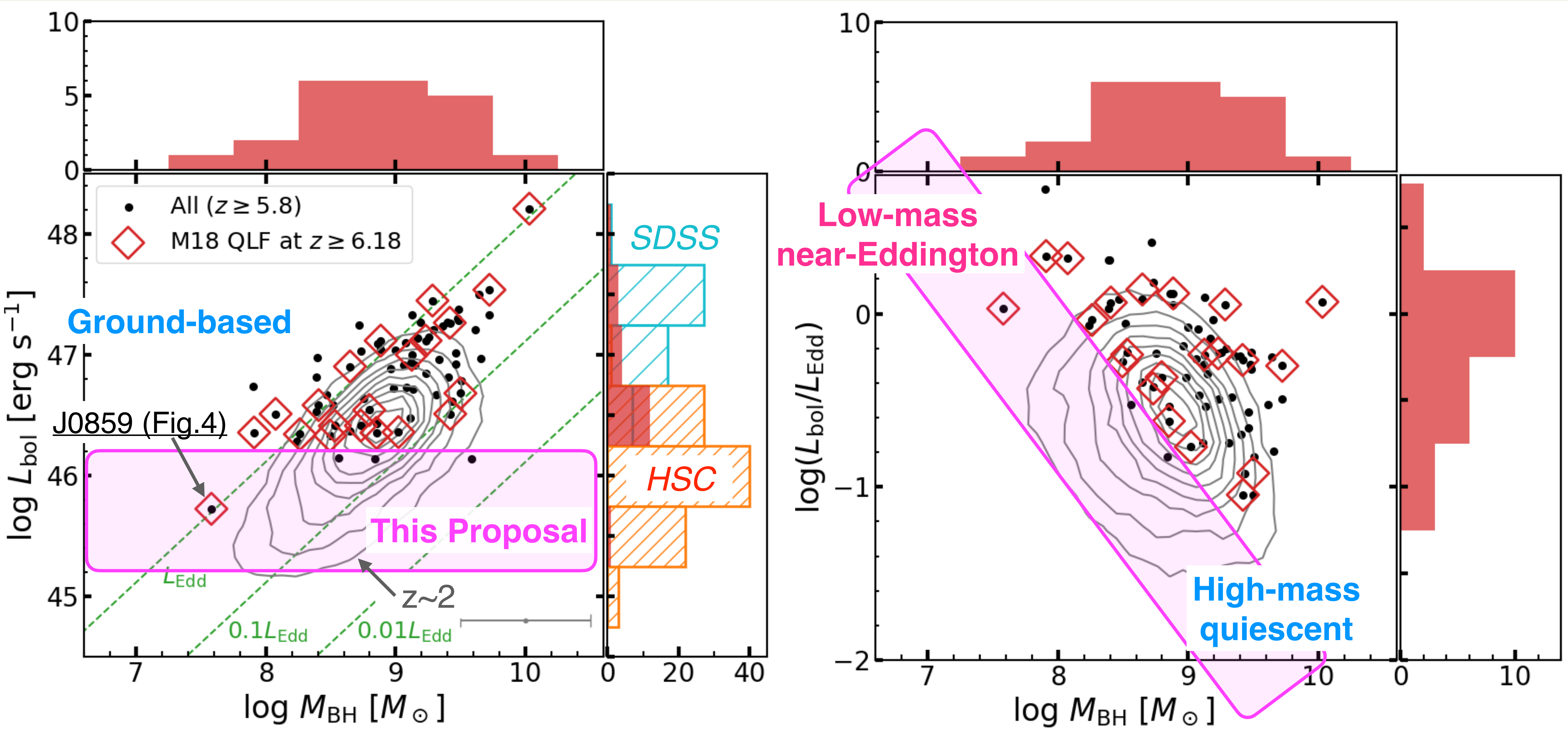
- Quasar- Host decomposition -> host stellar light detection!
  - **M$_*$**, age, companions, environment, etc.

+

- 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 **M_{BH}**, [OIII] gas outflow, etc.

- Mean (and scatter of) **M_{BH} / M_*** ratio at z=6
  -> Do BHs and galaxies grow together, or one went faster than the other?
  -> 12 faintest z=6 quasars = the *least-biased* BH sample

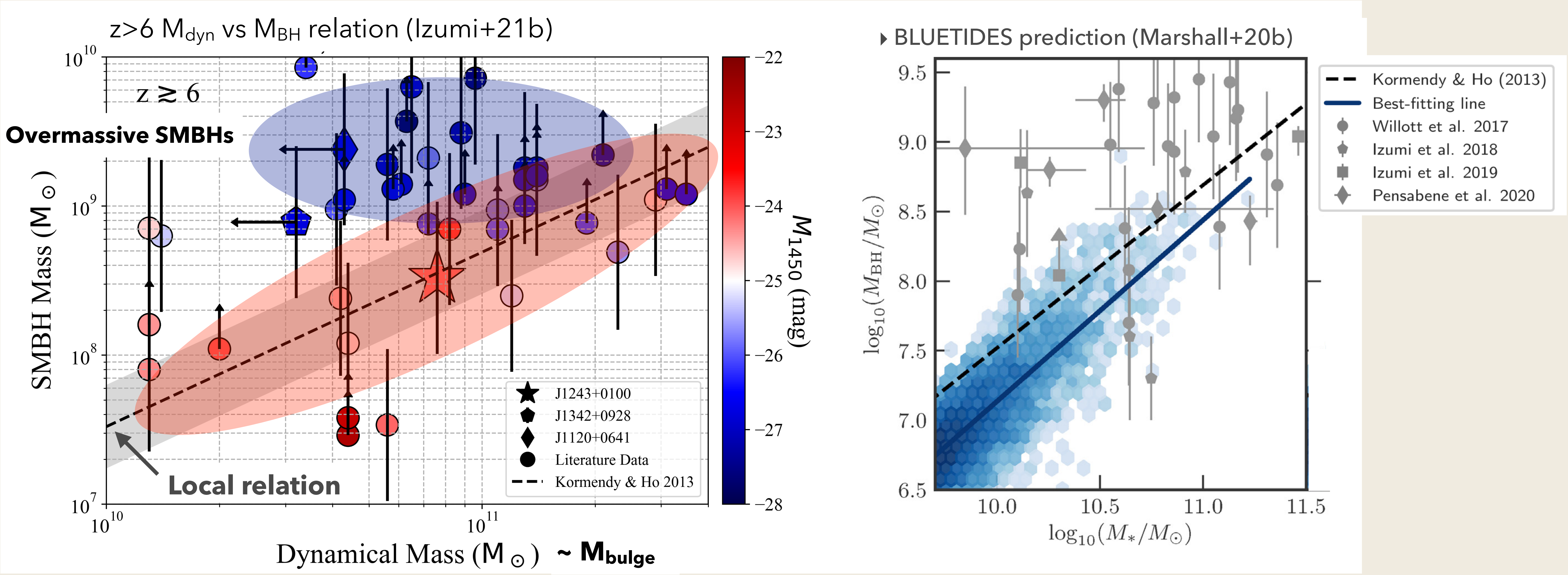
z>6 SMBH mass - L_{bol} distribution



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

BLR Velocity　　BLR Radius (+ R - L relation)

ALMA Views of Co-evolution at z>6



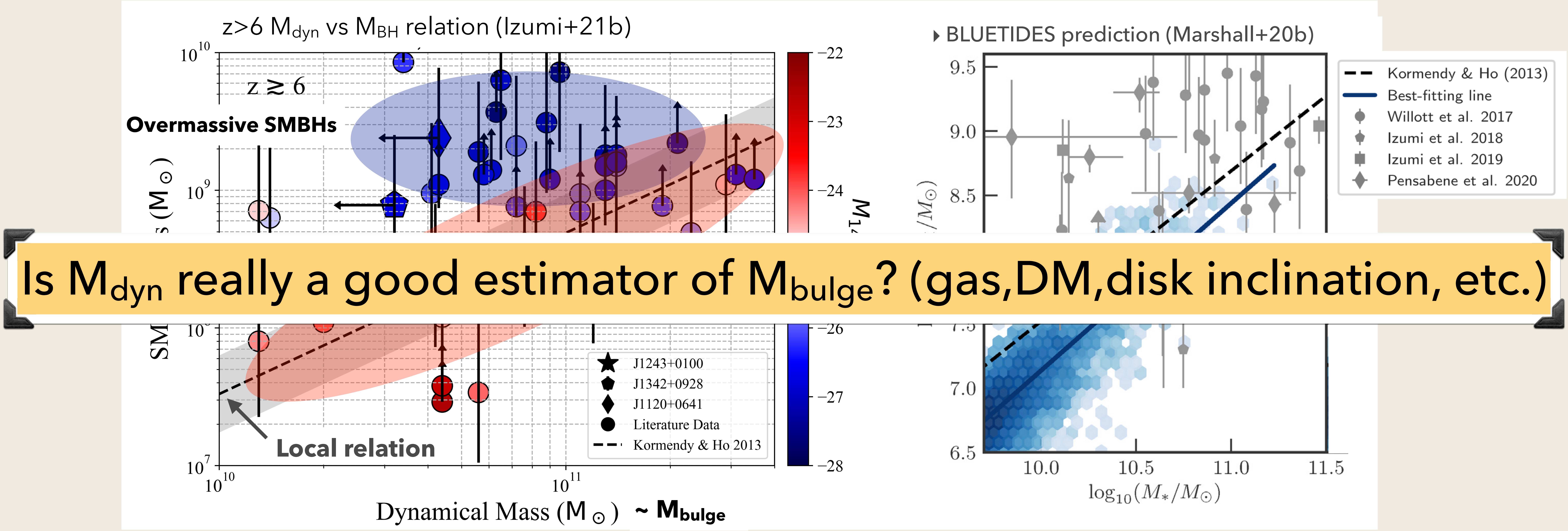
✦Co-evolution relation established already at z=6-7?

✦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



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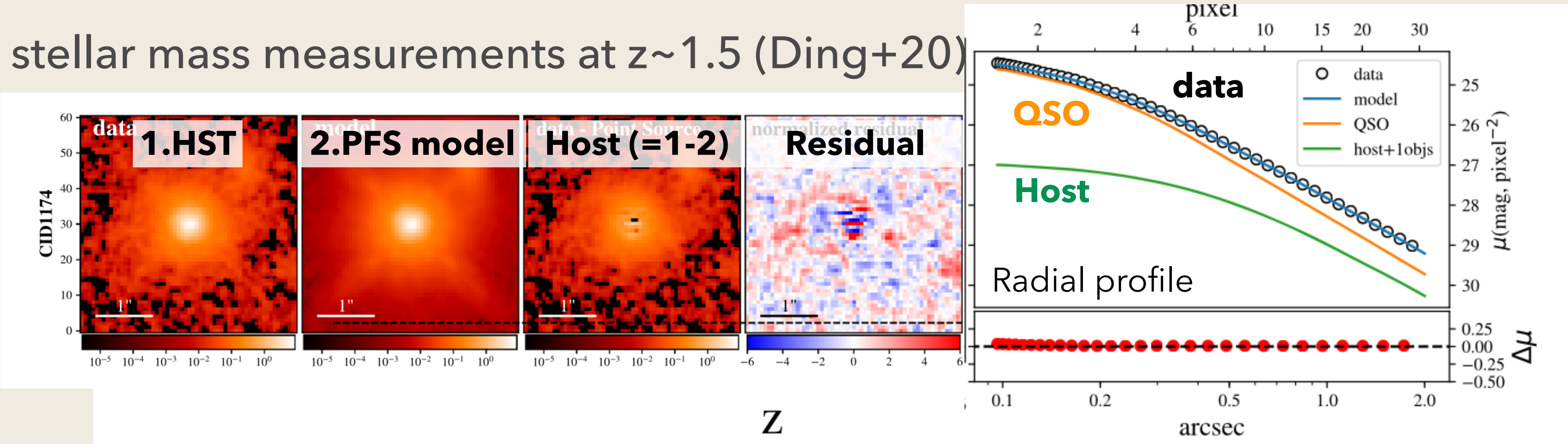
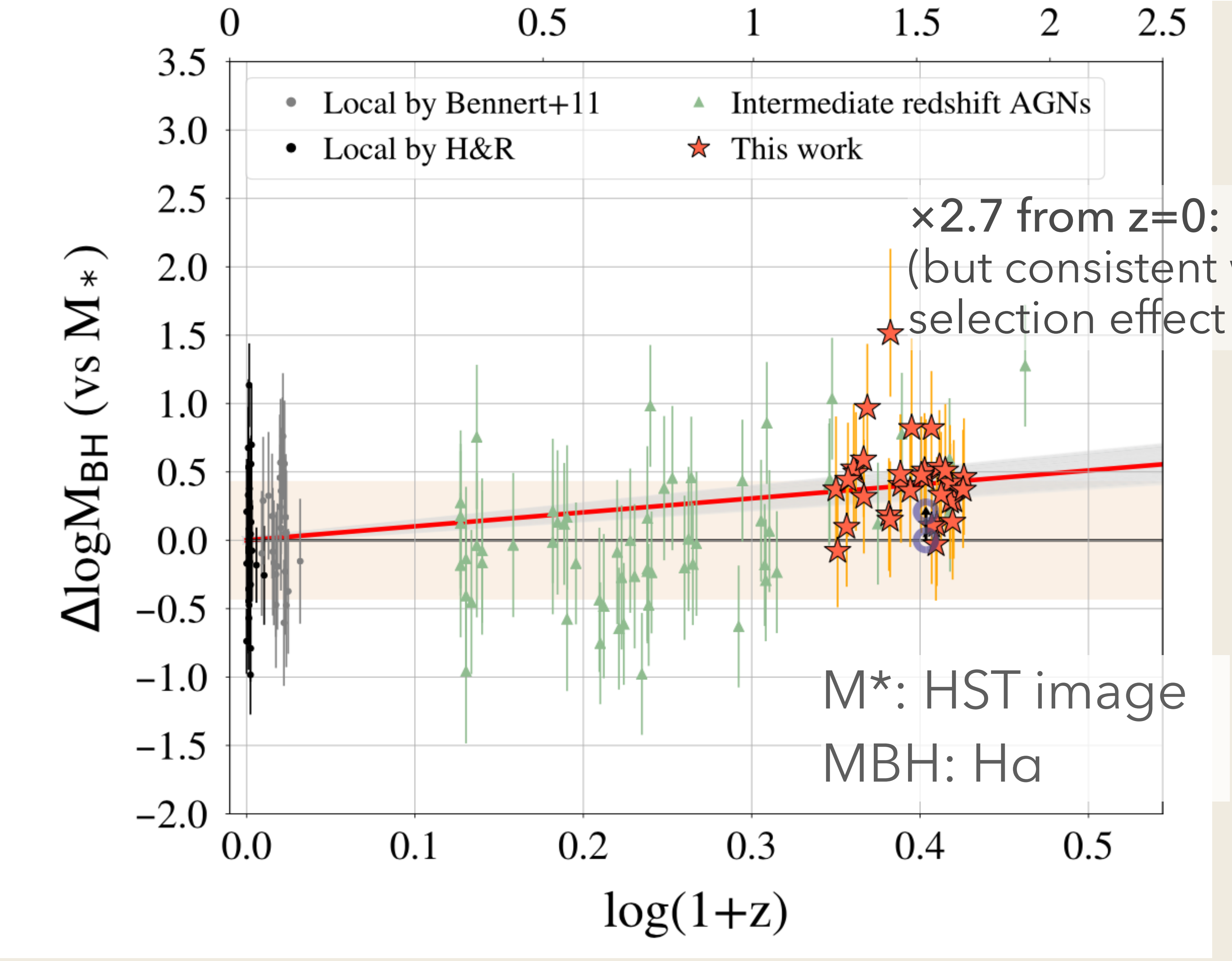
Redshift Evolution of M_{BH}/M_* Ratio

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

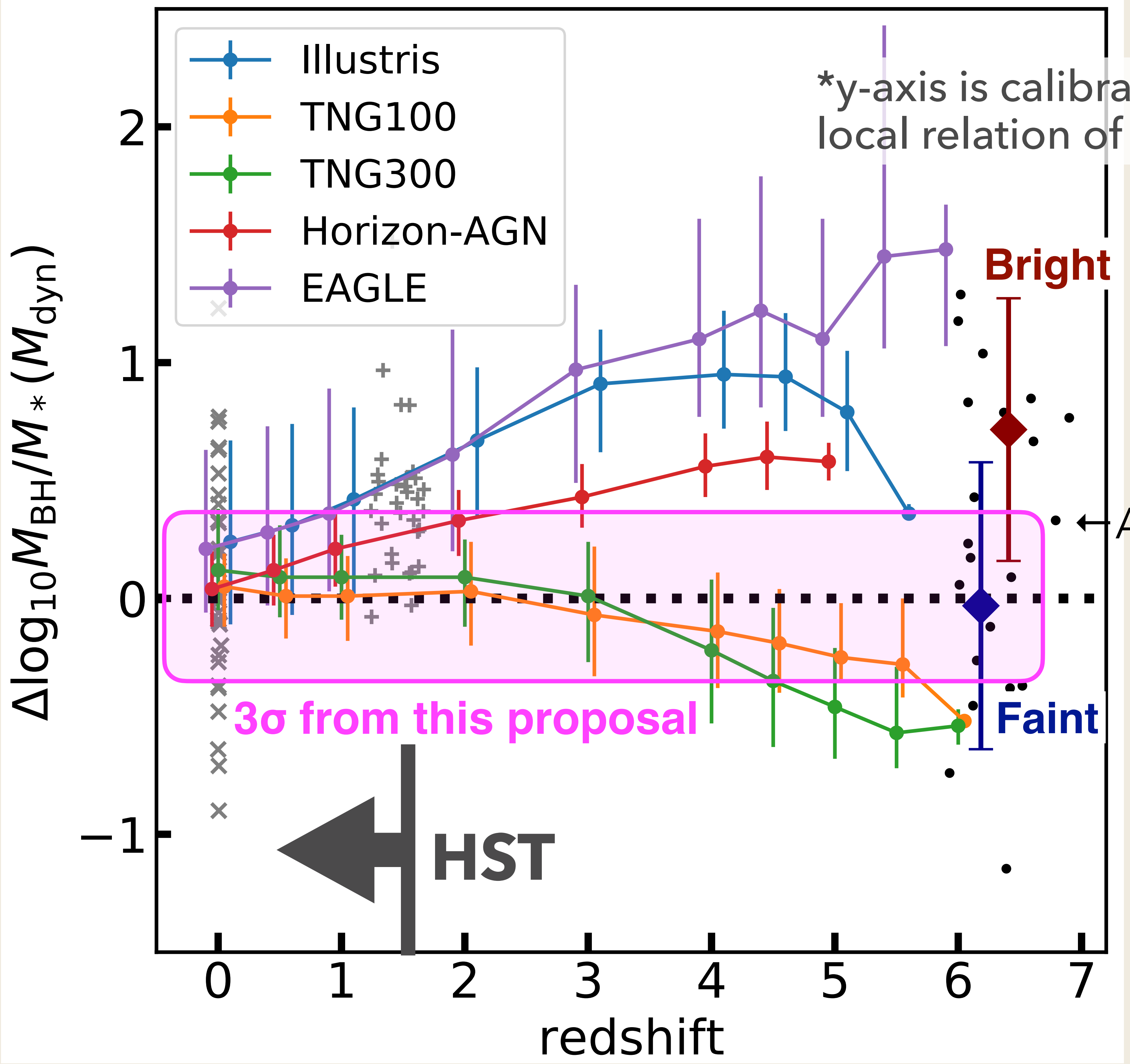




×2.7 from z=0: BH-dominant growth?
(but consistent with no evolution when selection effect taken into account)

M*: HST image
MBH: Hα

- Prediction from six cosmological simulations (Habouzit+ in prep.):
  Completely different predictions due to different modeling of AGN feedback



*y-axis is calibrated with the local relation of each simulation

Summary

- ✦ Wide-field optical and NIR surveys have revealed ~300 EoR quasars up to z=7.5. More to come with next-generation survey telescopes in mid-to-late 2020s
- ✦ Deep NIR spectroscopy of ULAS J1342+0928 at z=7.54 suggests the presence of strong nuclear-scale outflow and metal-rich BLR gas
- ✦ The z>6 low-luminosity quasar search with the HSC-SSP has revealed obscured quasar populations that may hold the key to understanding the triggering mechanism of high-z quasars
- ✦ With JWST and ground-based follow-up observations of z>6 low-luminosity quasars, we will derive the comprehensive picture of SMBHs, host galaxies, and their relative growth within the first billion years of the universe