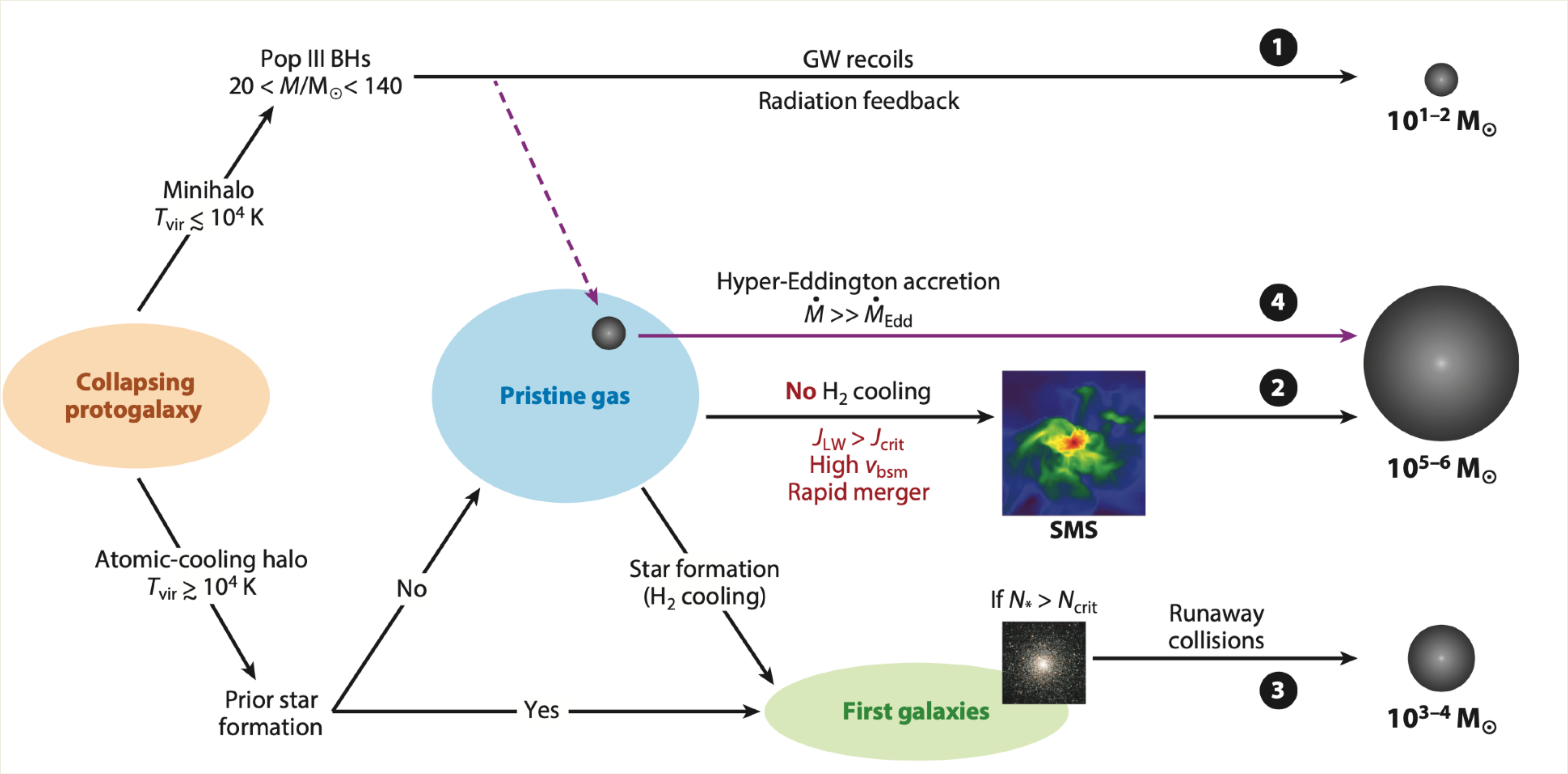
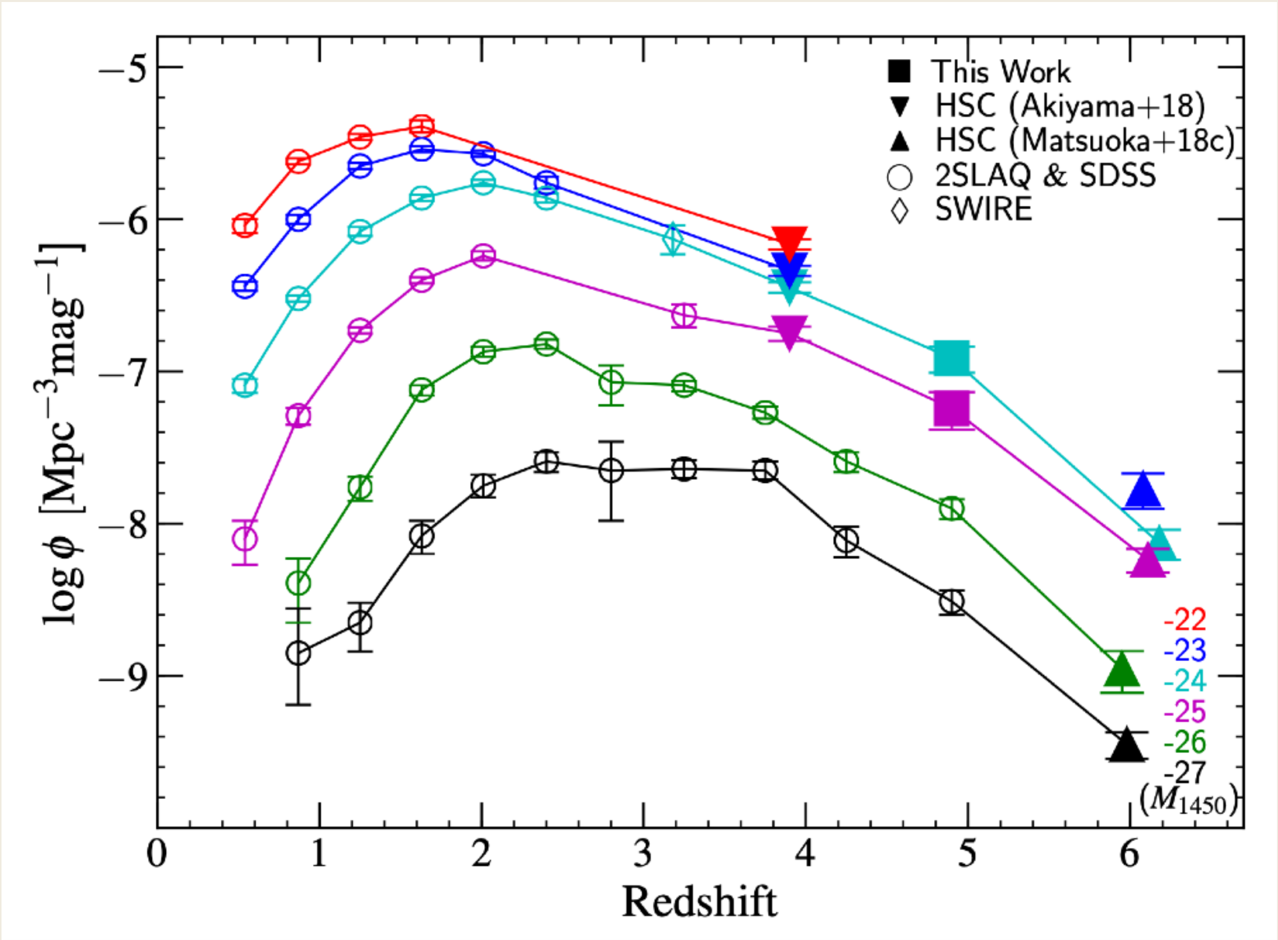
AGN observations Reviews

Masafusa Onoue (MPIA -> KIAA / Kavli IPMU)

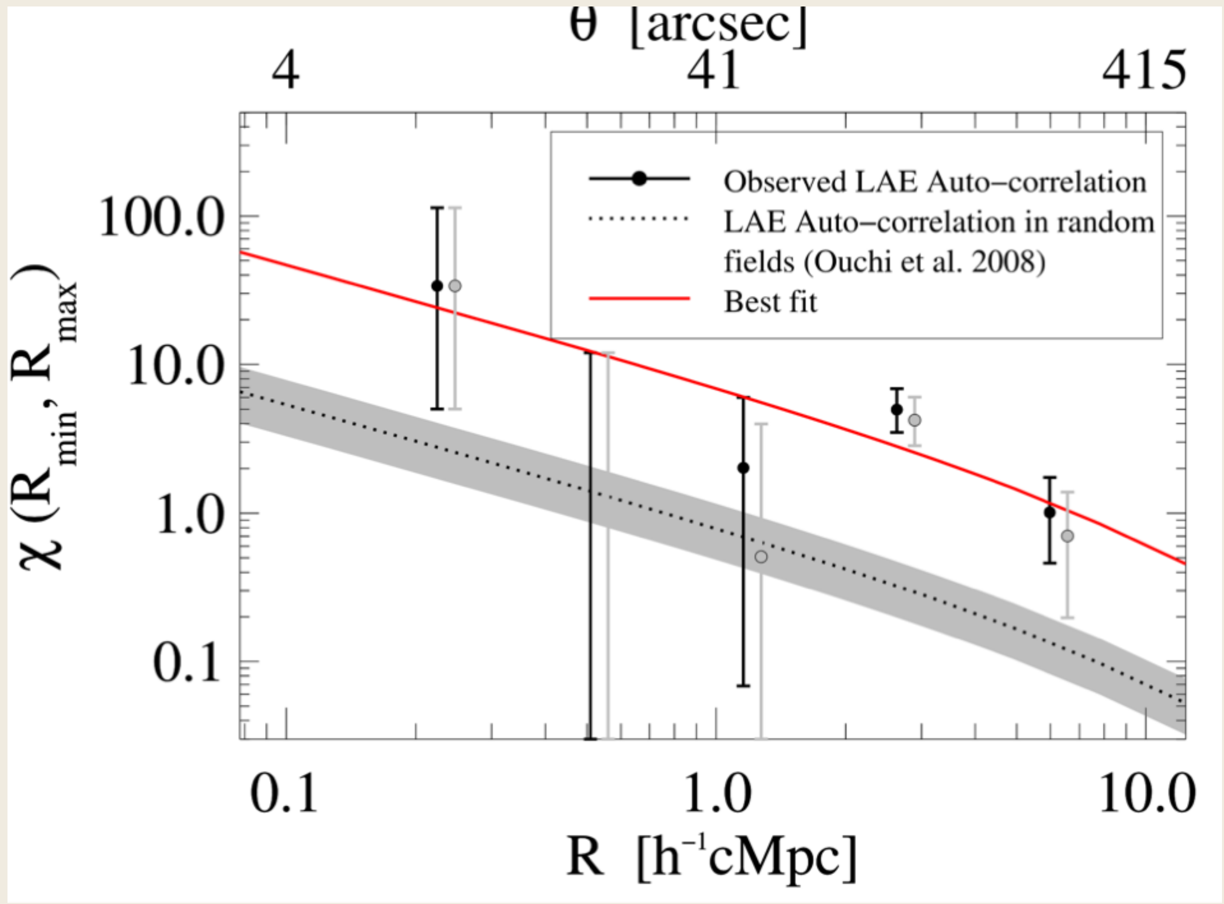
- SMBH formation paths (Inayoshi+19)



- Cosmic evolution of Type-I quasar LF (Niida+20)



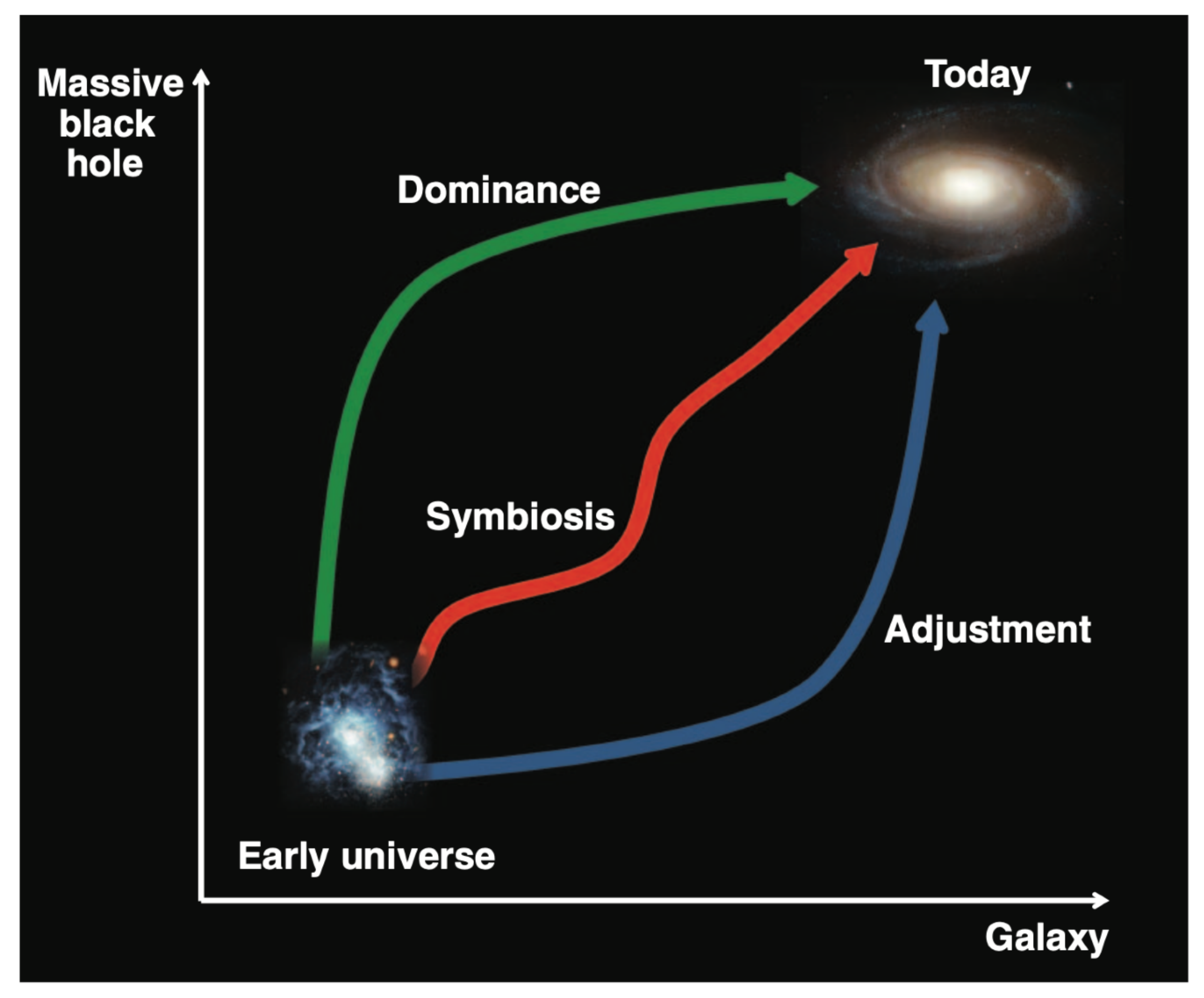
- Quasar-LAE clustering at z=4 (Garcia-Vergara+19)



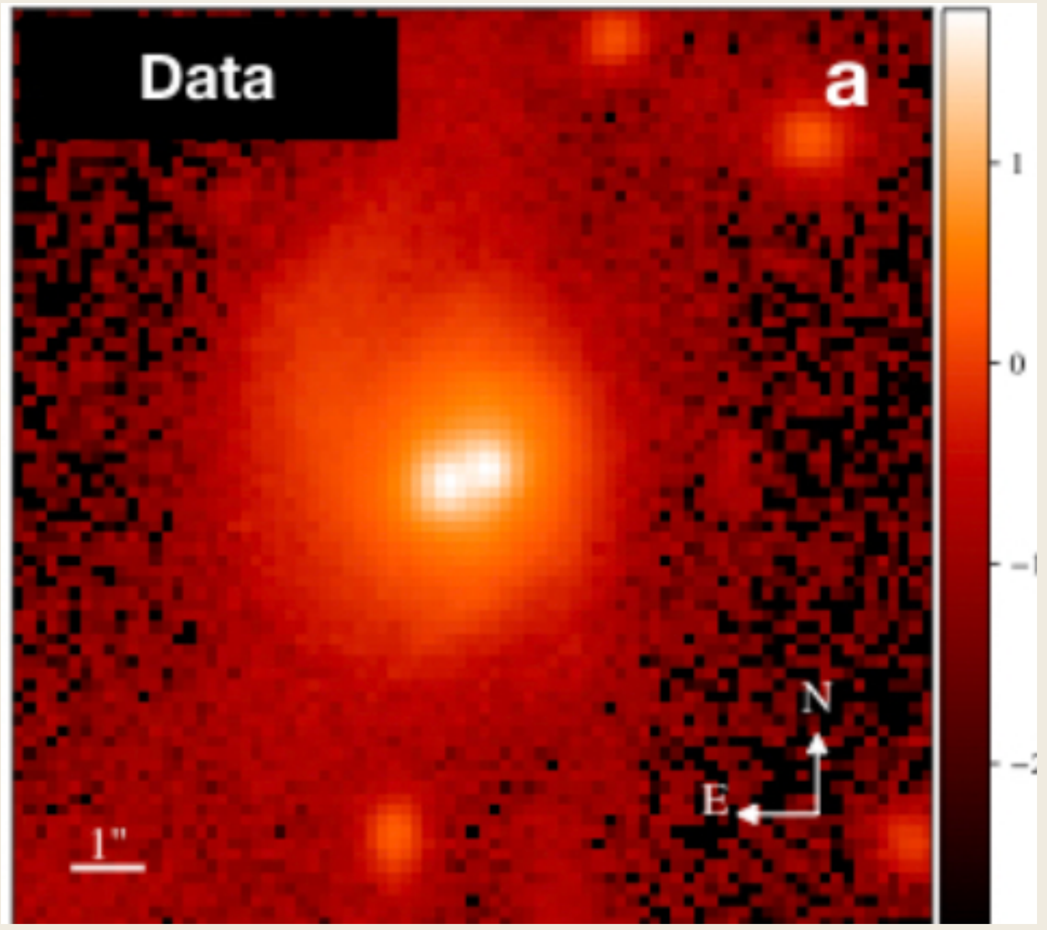
Why do we observe AGNs/quasars?

- Formation and Evolution of supermassive black holes (SMBHs; M_{BH}~10^{5-10} M_{sun})
  - How did they form at high redshift?
  - How did they accrete billion solar mass? (cf. Inayoshi-san's review)
  - In what local/large-scale environments is the AGN activity triggered?

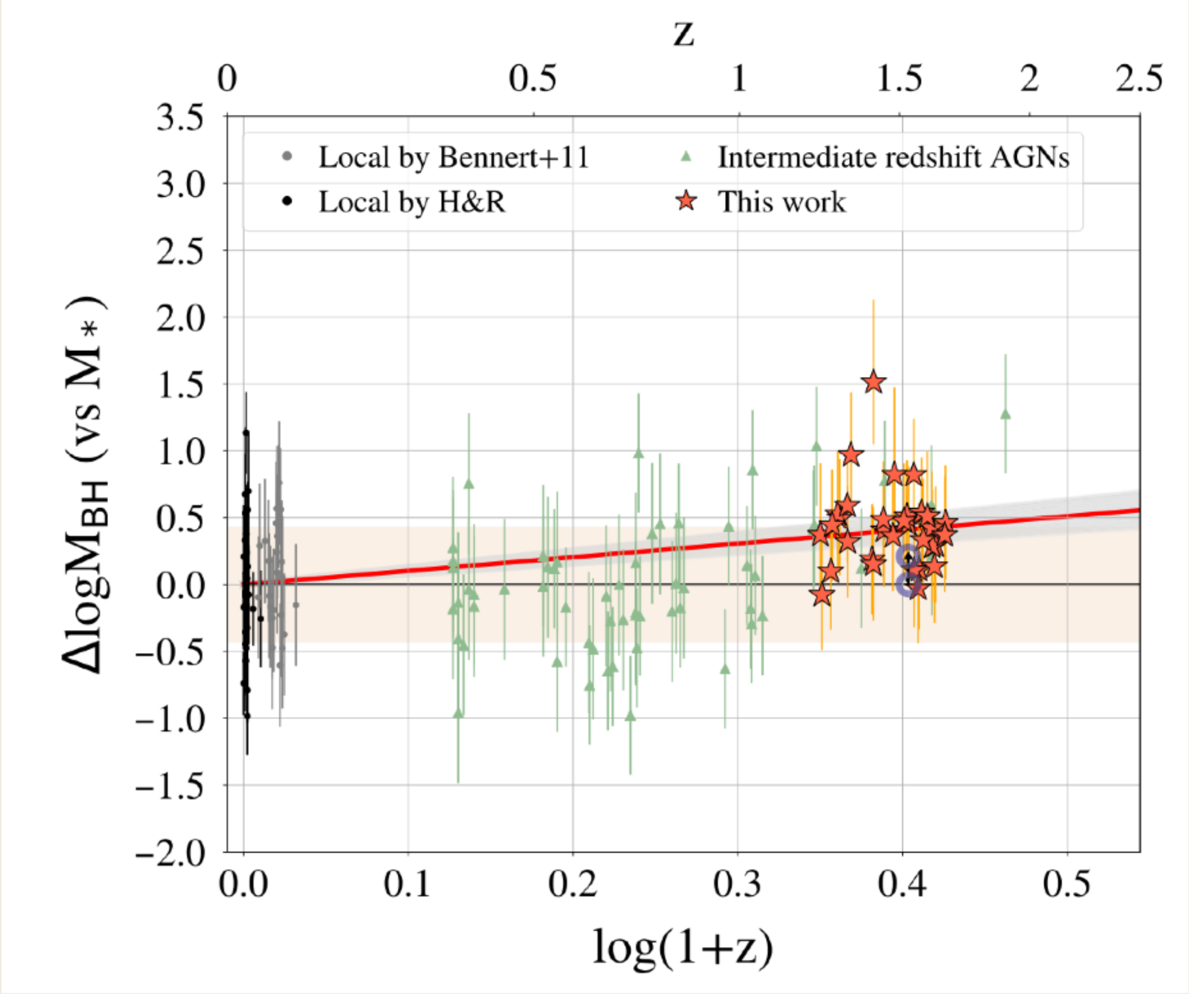
- Schmatic picture of SMBH-galaxy co-evolution (Volonteri12)



- z=0.4 dual SMBH (Silverman+20)



- Redshift evolution of M_{BH} / M_* (Ding+20)

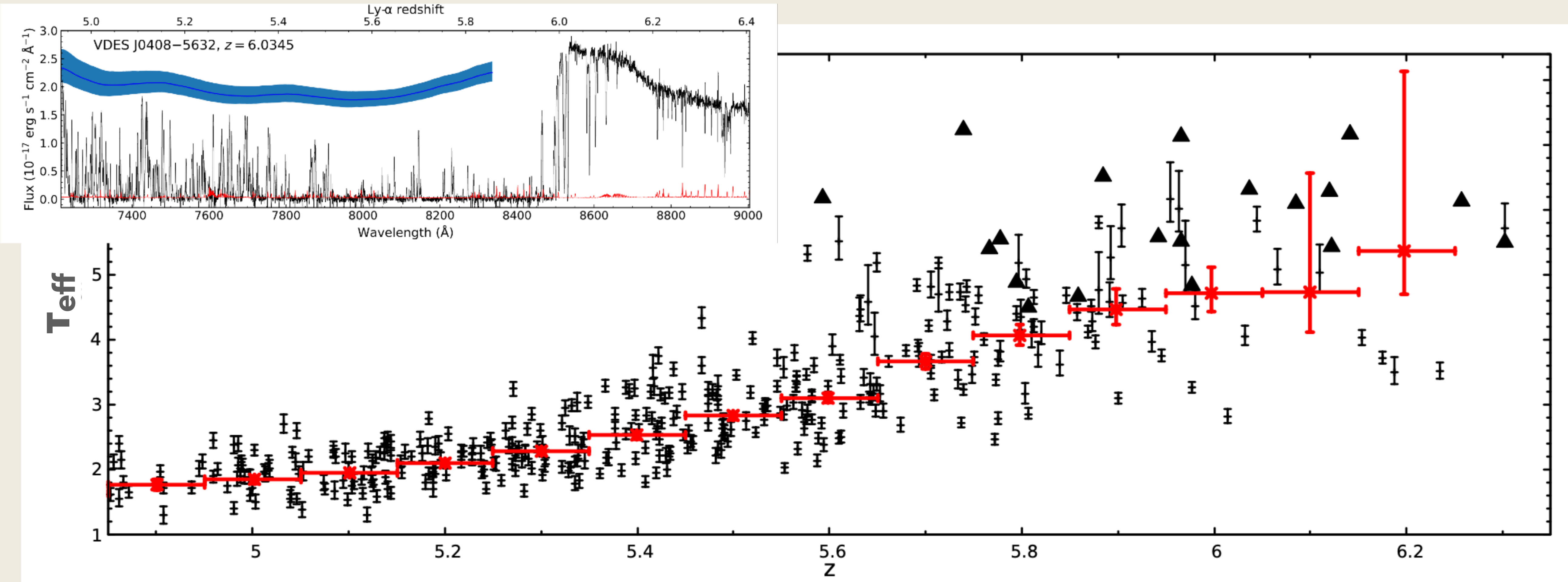


Why do we observe AGNs/quasars?

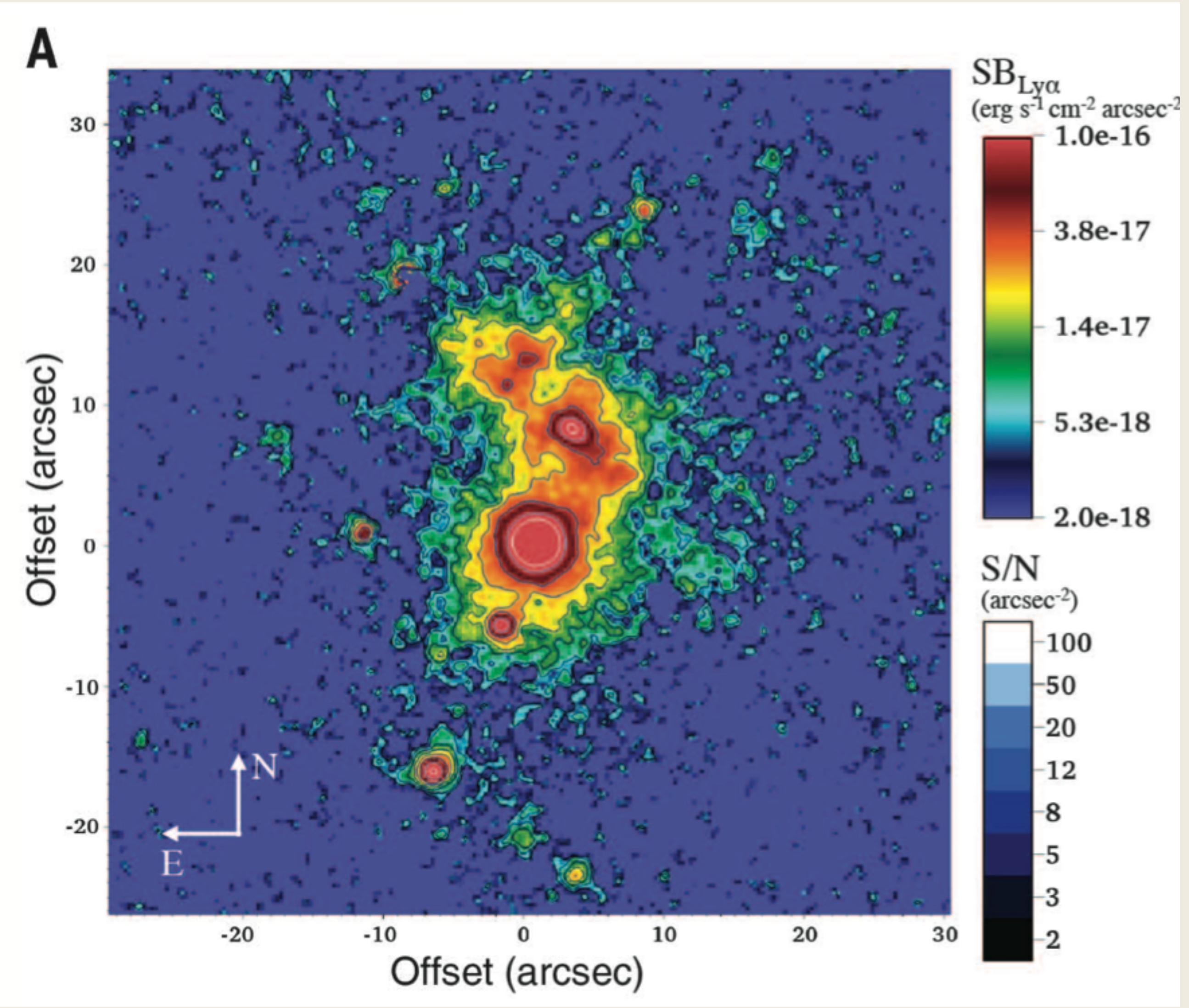
- Co-evolutionary growth of SMBHs and host galaxies
  - Do SMBHs grow in lock step with the host galaxies over the cosmic time?
  - How does the AGN-driven feedback regulate host star-formation activity?
  - How do gas-rich galaxy mergers affect SMBH growth?

Why do we observe AGNs/quasars?

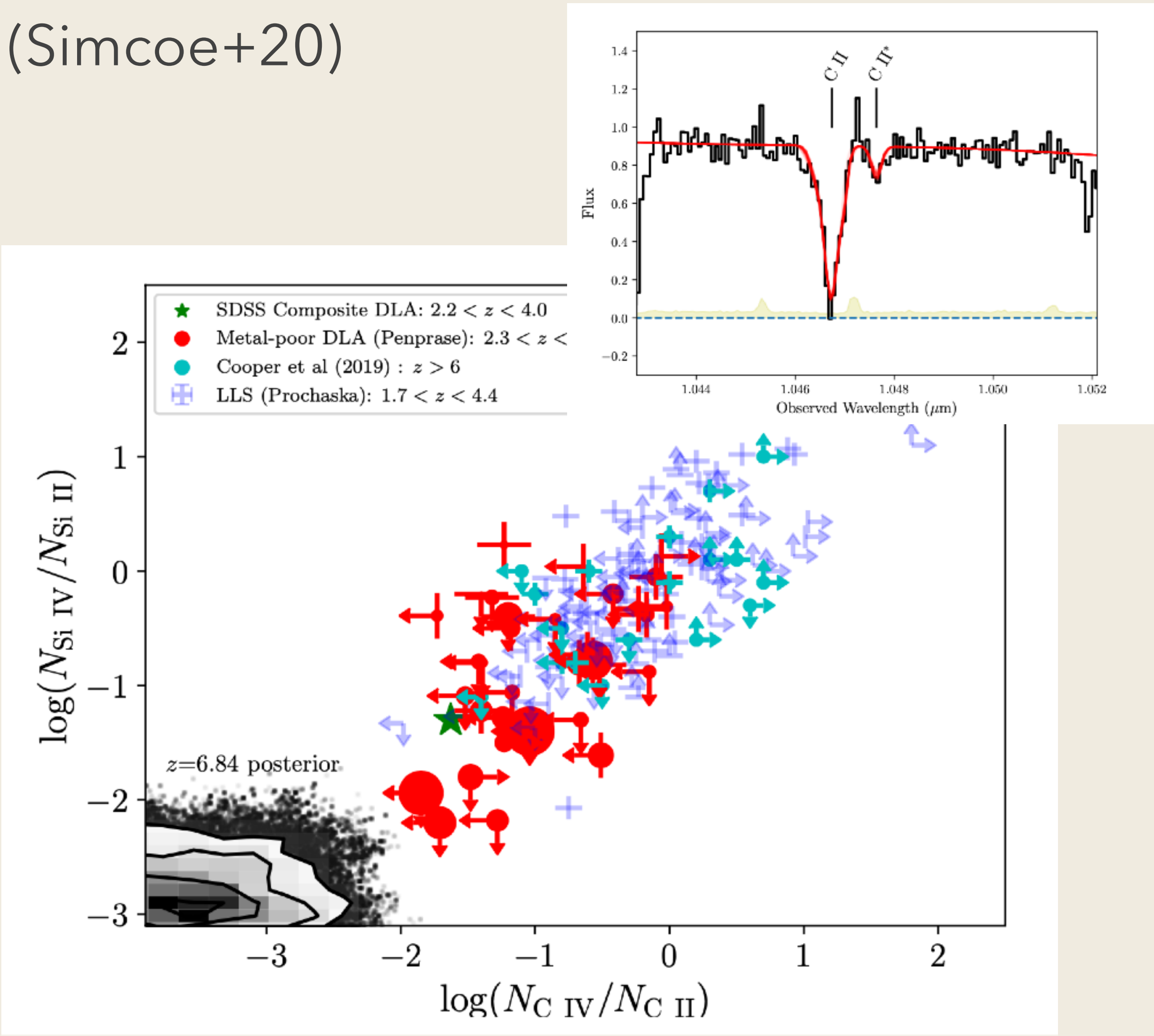
- z evolution of Lya optical depth (Bosman+21)



- Jackpot nebula (Hennawi+15)



- A z=6.8 metal absorber in a z=7.5 quasar (Simcoe+20)

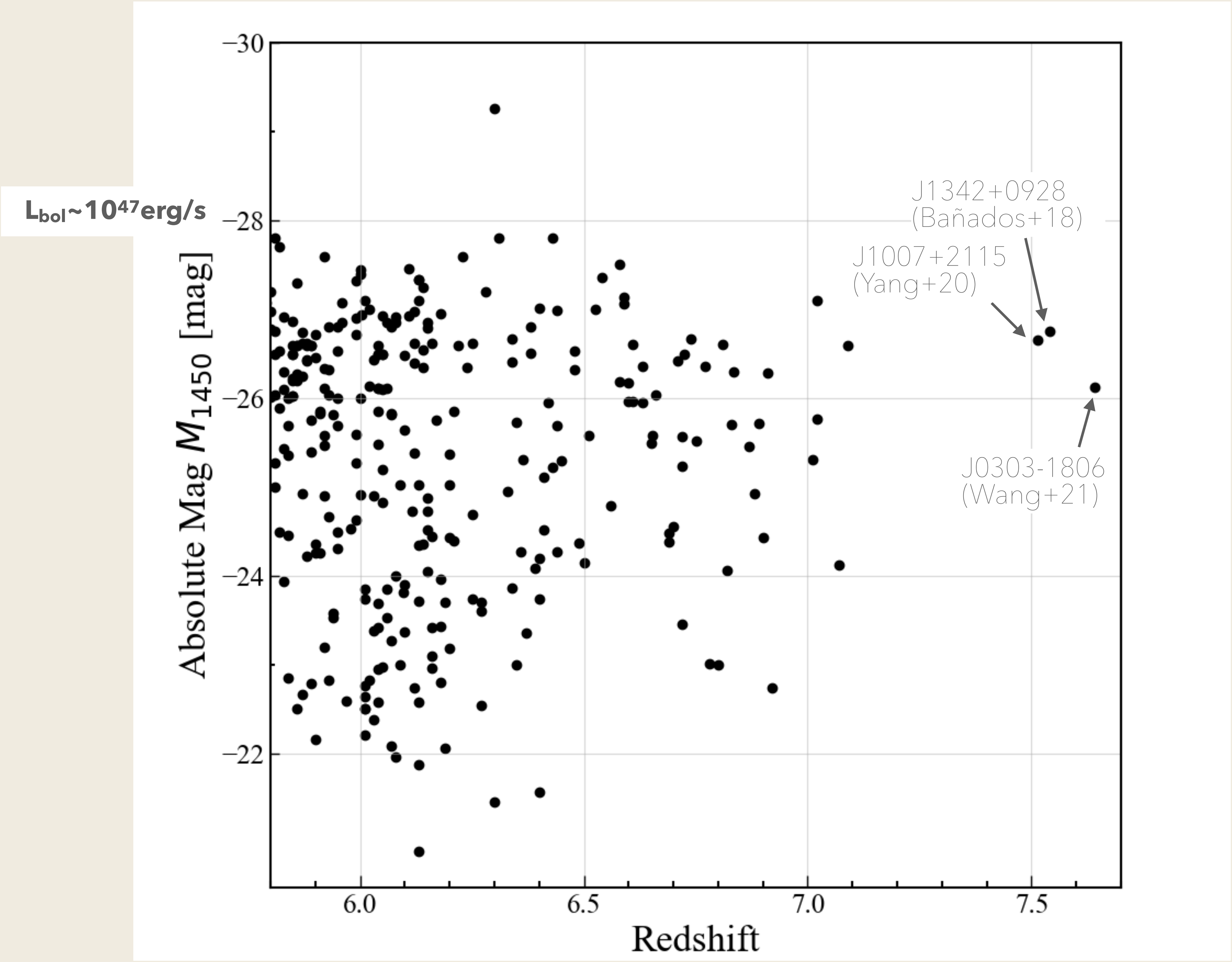


- High-z Quasars as bright light sources
  - Reionization history
  - Extended Lya blobs irradiated by QSOs
  - Metal abundance and ionization of metal absorbers imprinted on quasar spectra

Highest-redshift quasar studies

Discovery

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





- **~300 known at z>6** (<u><10 in Gpc^{-3} per mag</u>; M_{UV}>-24)
  - Need >1000 deg^2 coverage rather than depth
  - 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**

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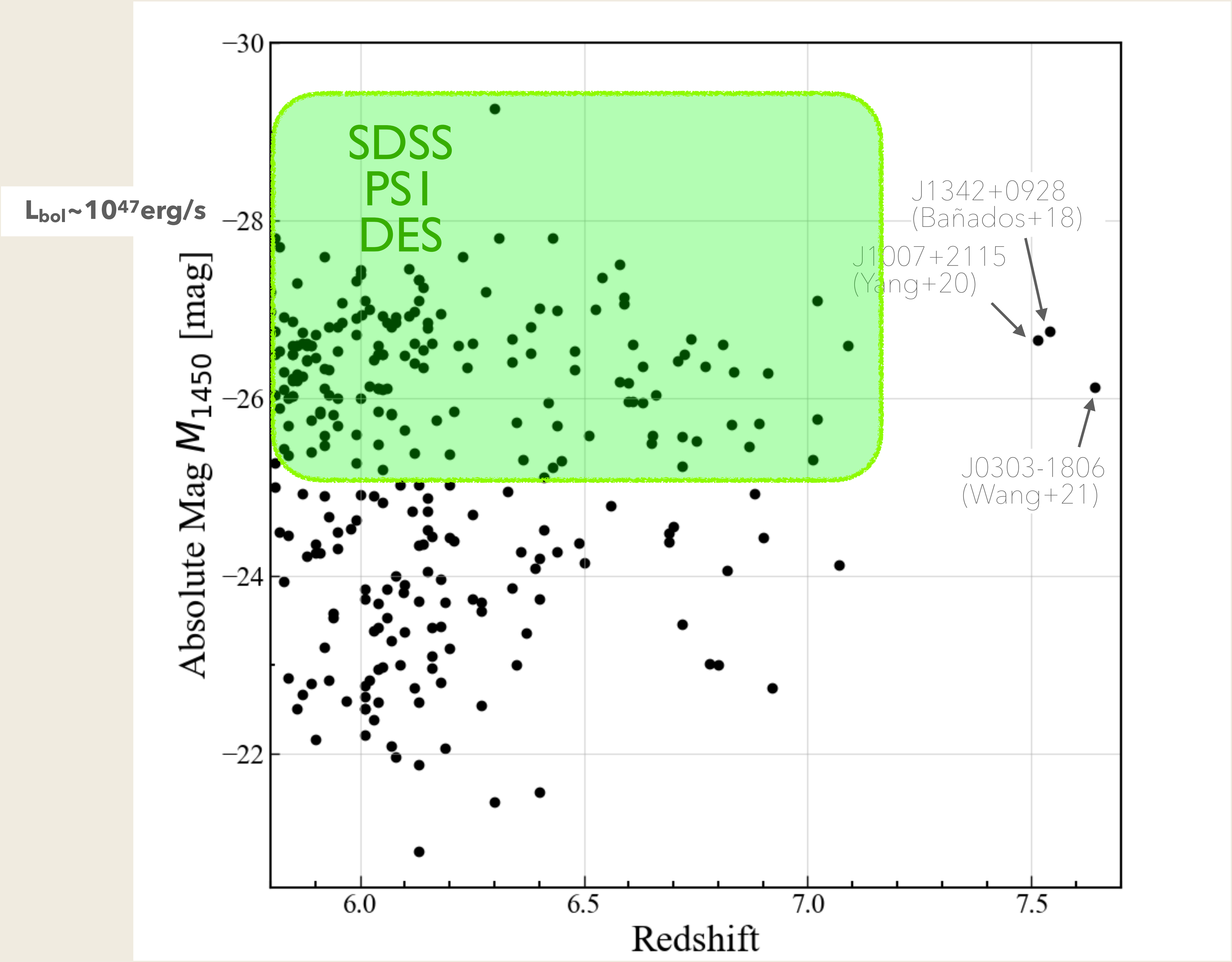



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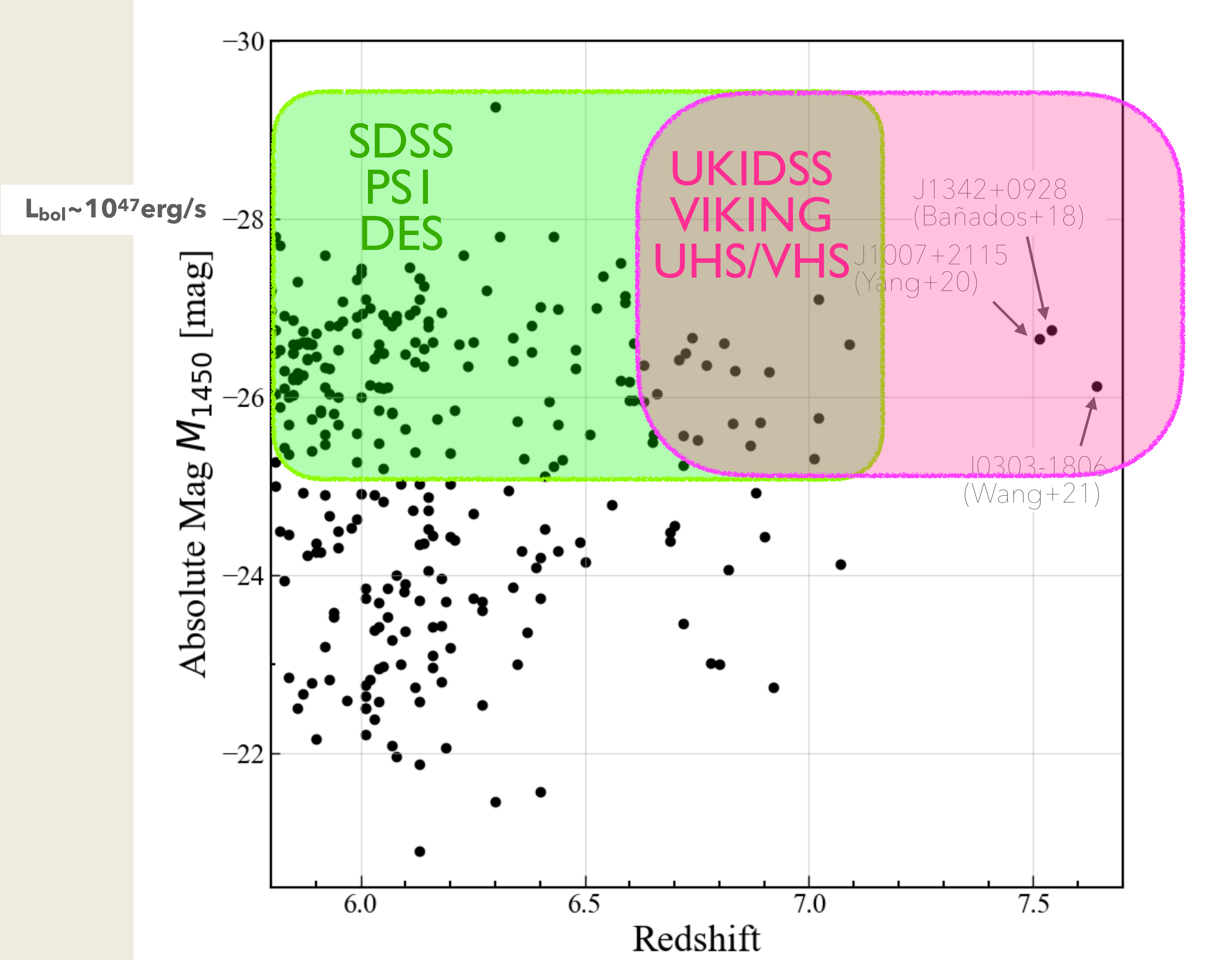



- **~300 known at z>6** (<u>$\lesssim$10 in Gpc^{-3} per mag</u>; M_{UV}>-24)
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Discovery

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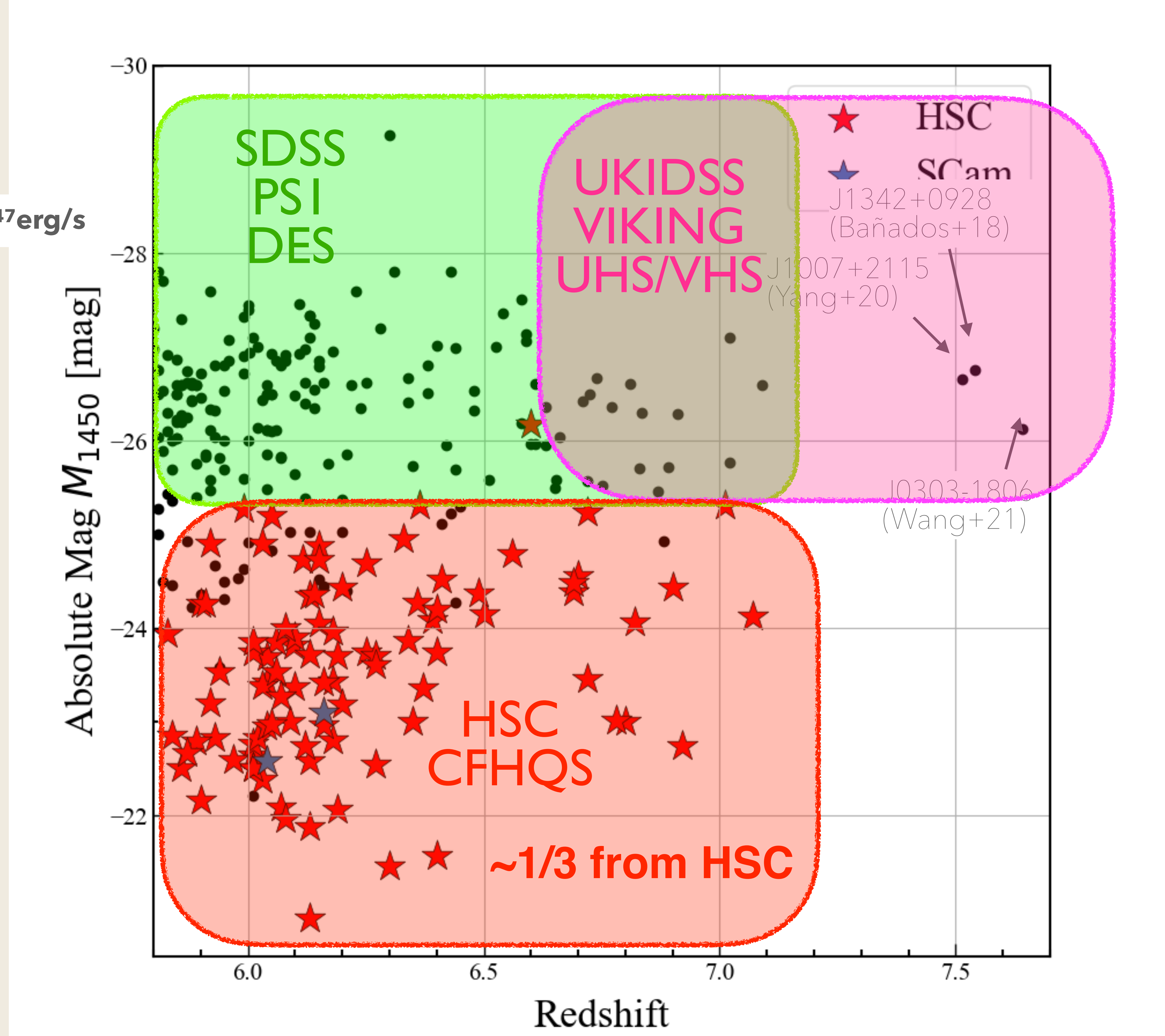
L_{bol}~10^{47}erg/s



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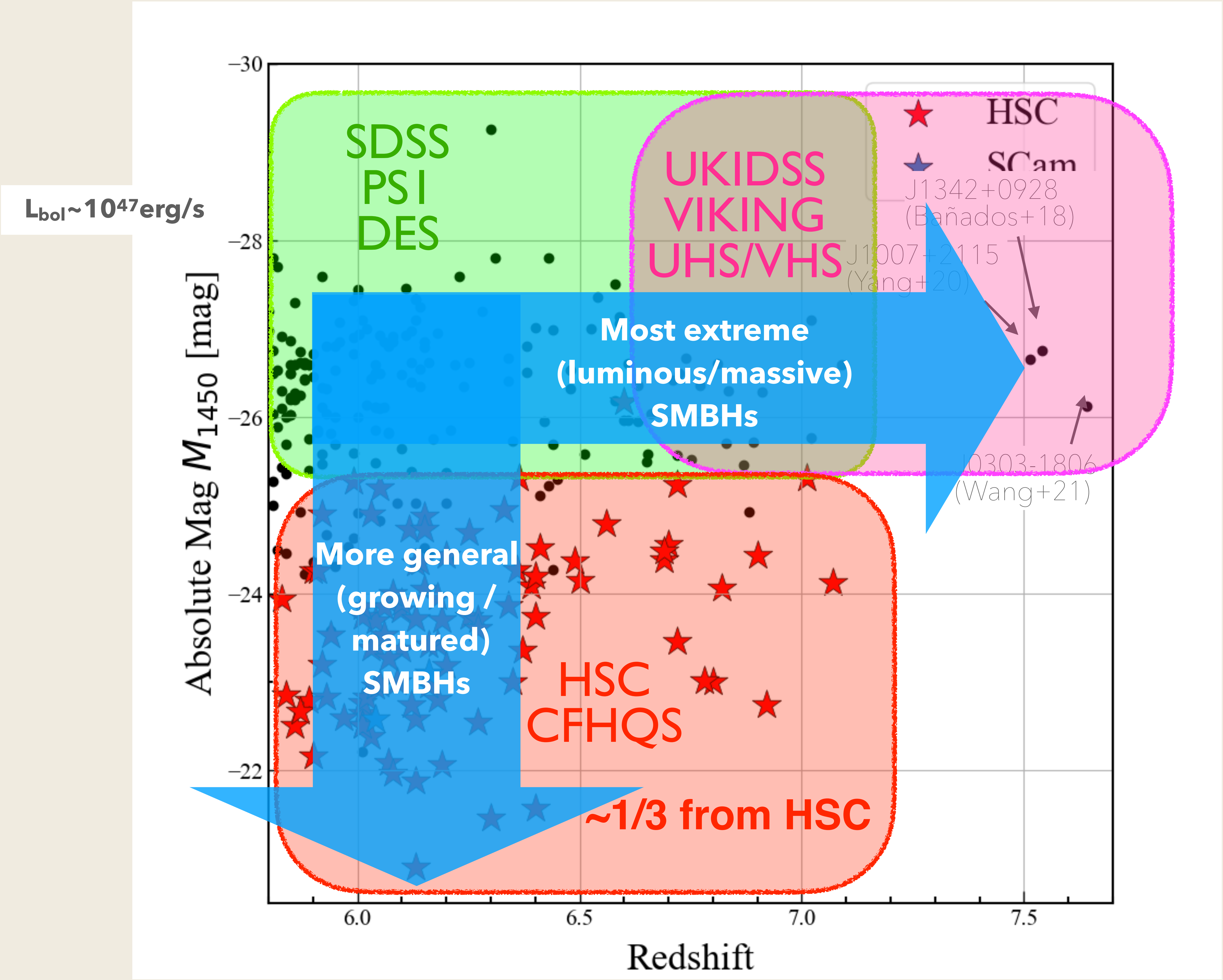

- ~300 known at z>6 (<u>≲10 in Gpc^{-3} per mag</u>; M_{UV}>-24)
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  - SDSS/PS1/HSC/DES/UKIDSS/VIKING/WISE, etc.
- **Frontier: z~7.5** (Bañados+18; Yang+20; Wang+21)
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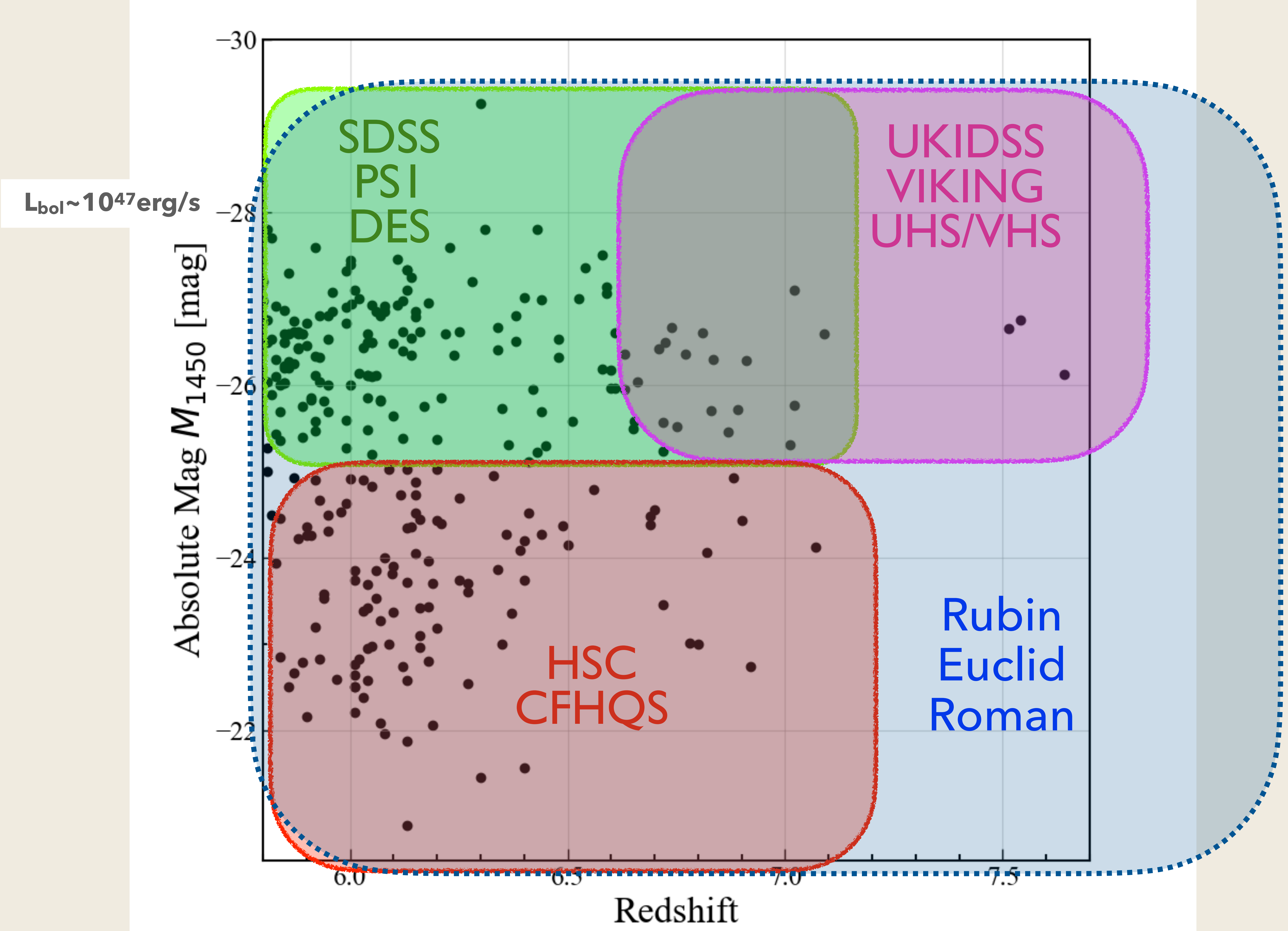
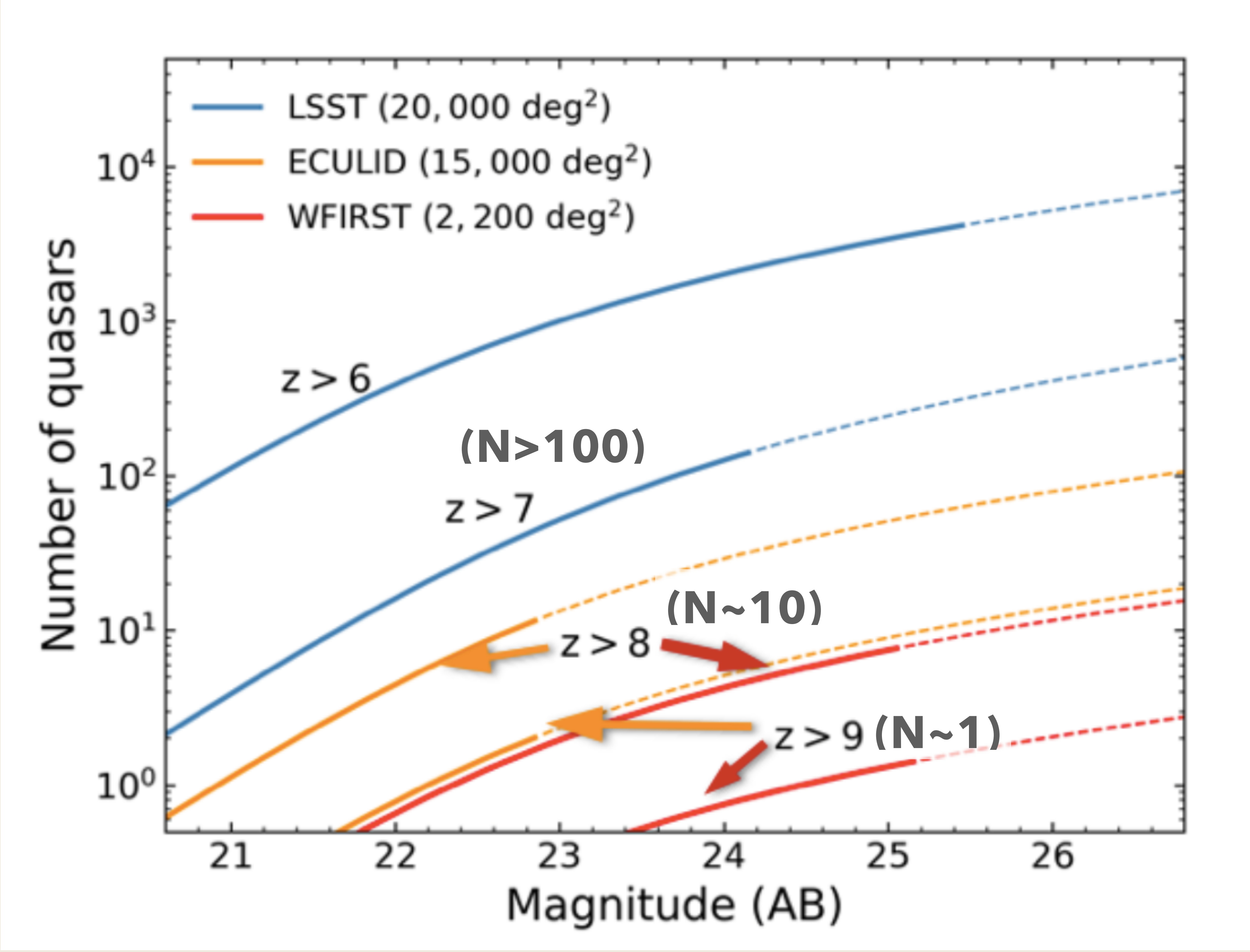
Toward mid 2020s

Euclid: launch in Fall 2022!

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

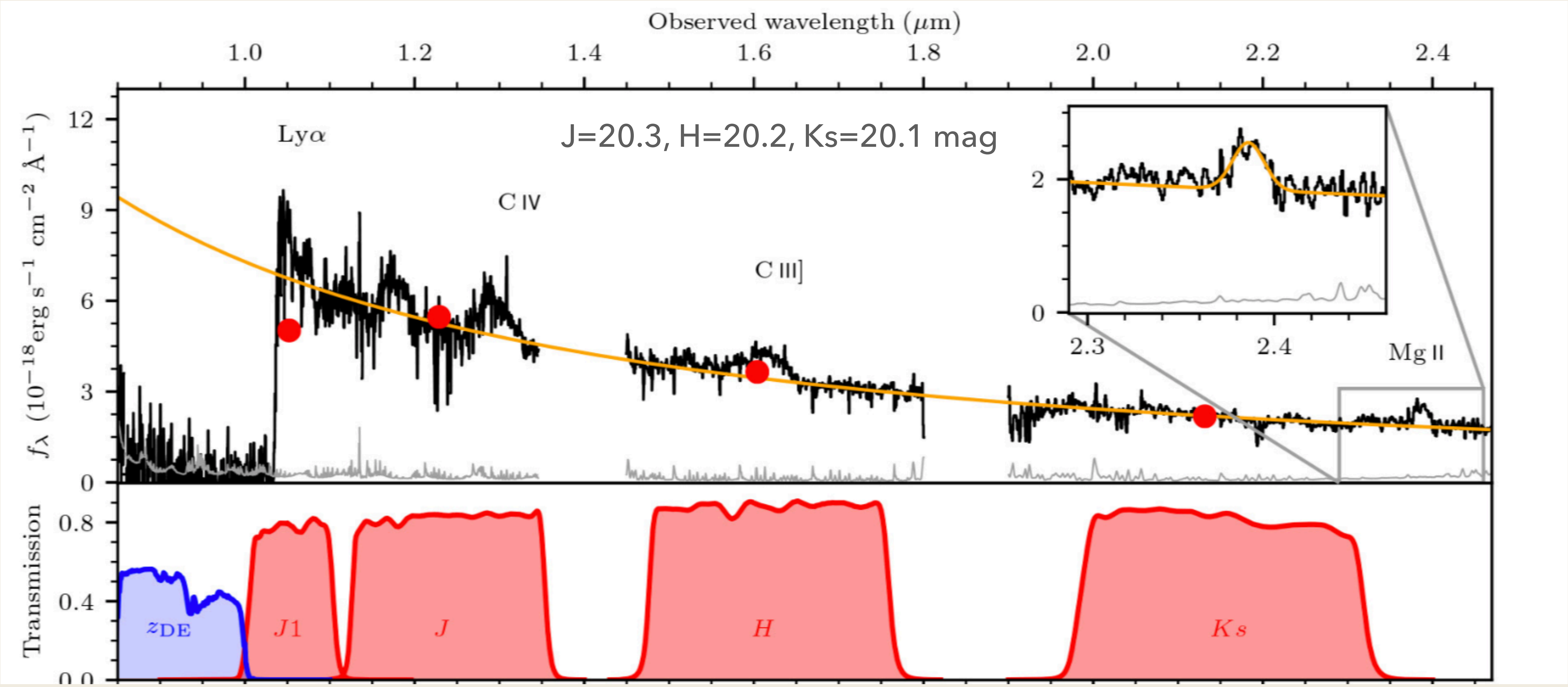


- Expected number of z>6 quasars from Rubin/Euclid/Roman (Fan+, Astro2020)

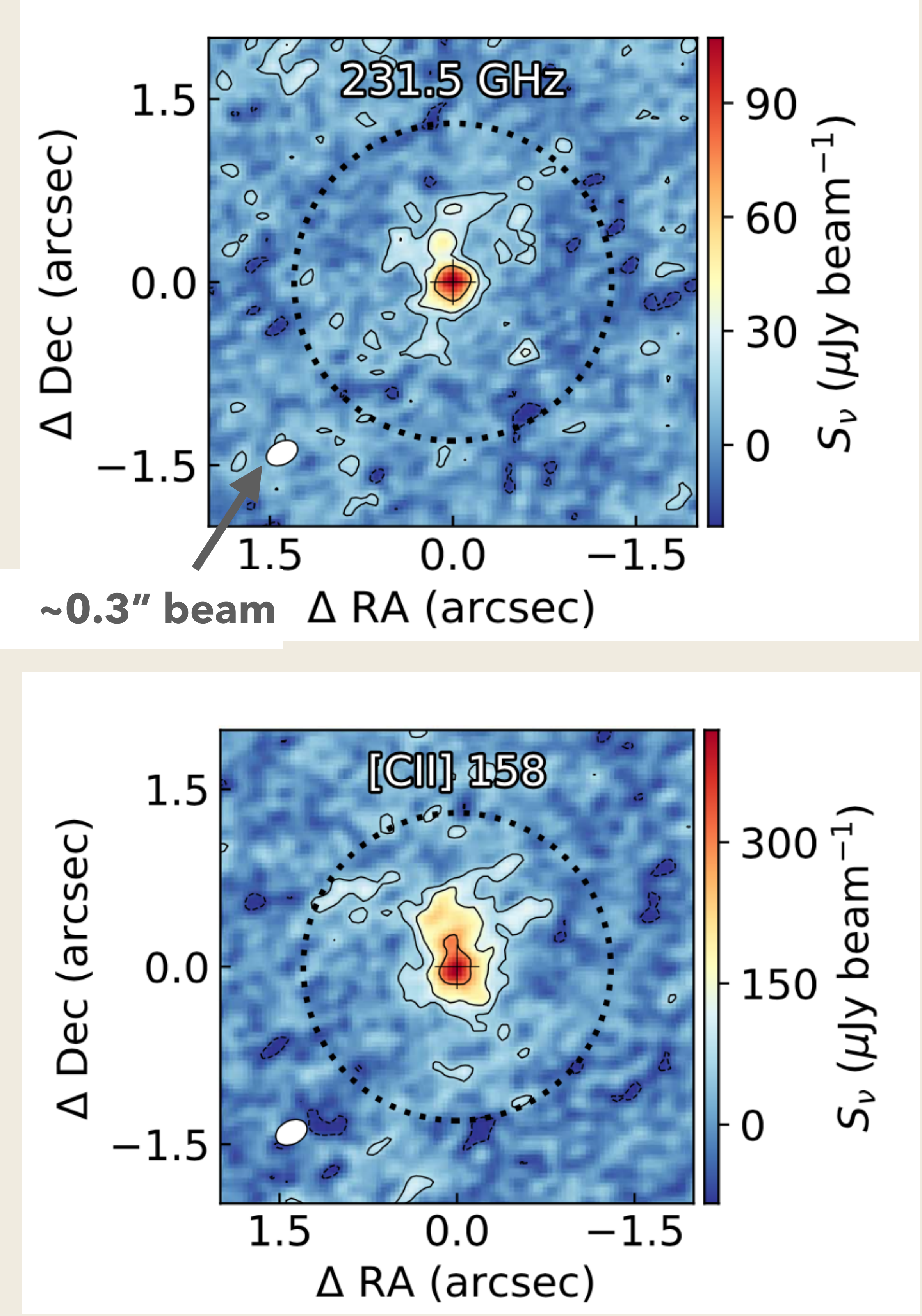


ULAS J1342+0928 at z=7.54

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



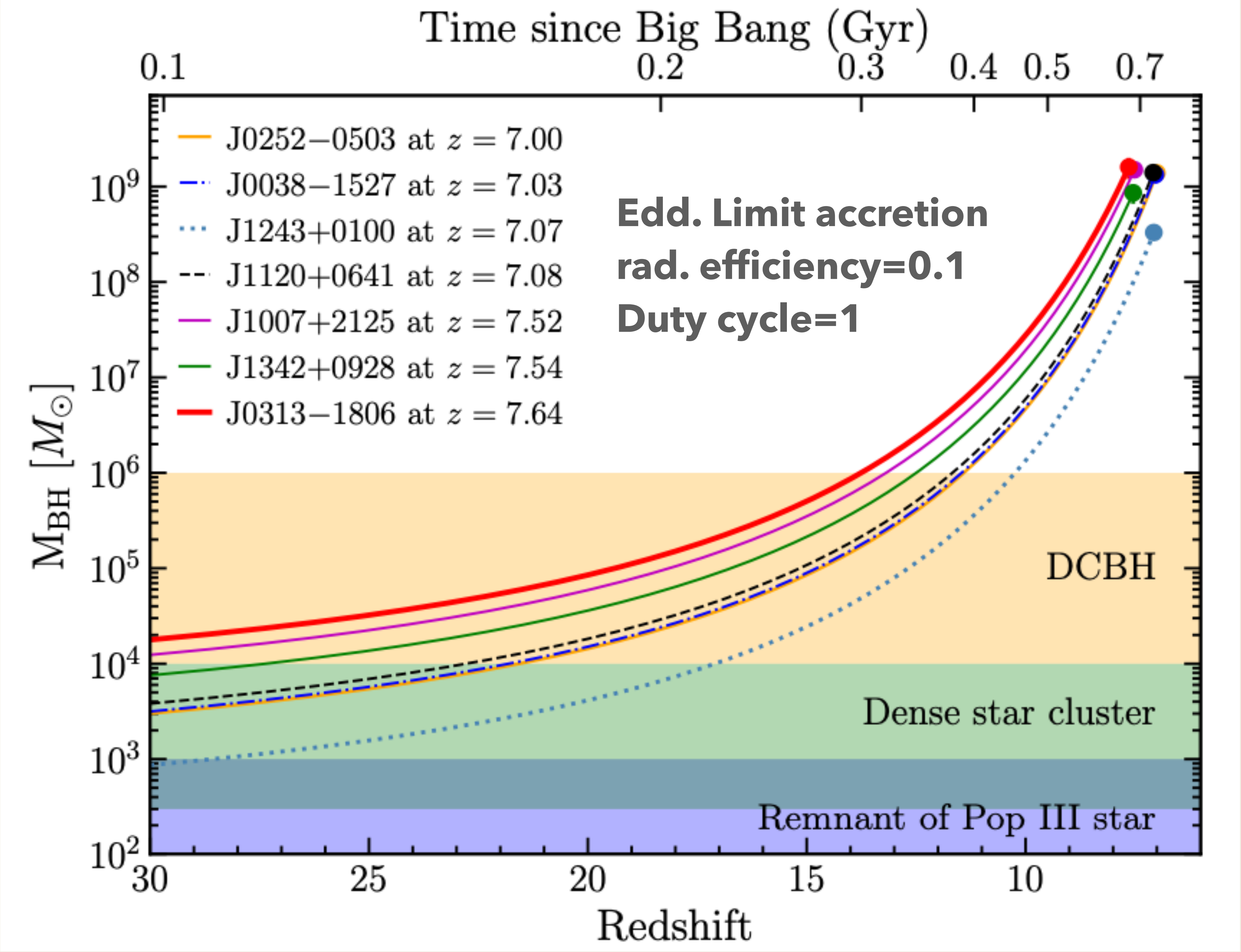
- ALMA dust (top) and [CII] 158 μm (bottom); Bañados+19



- SMBH: M_{BH}=8×10^8 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)

Billion-solar-mass SMBHs at z>7

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



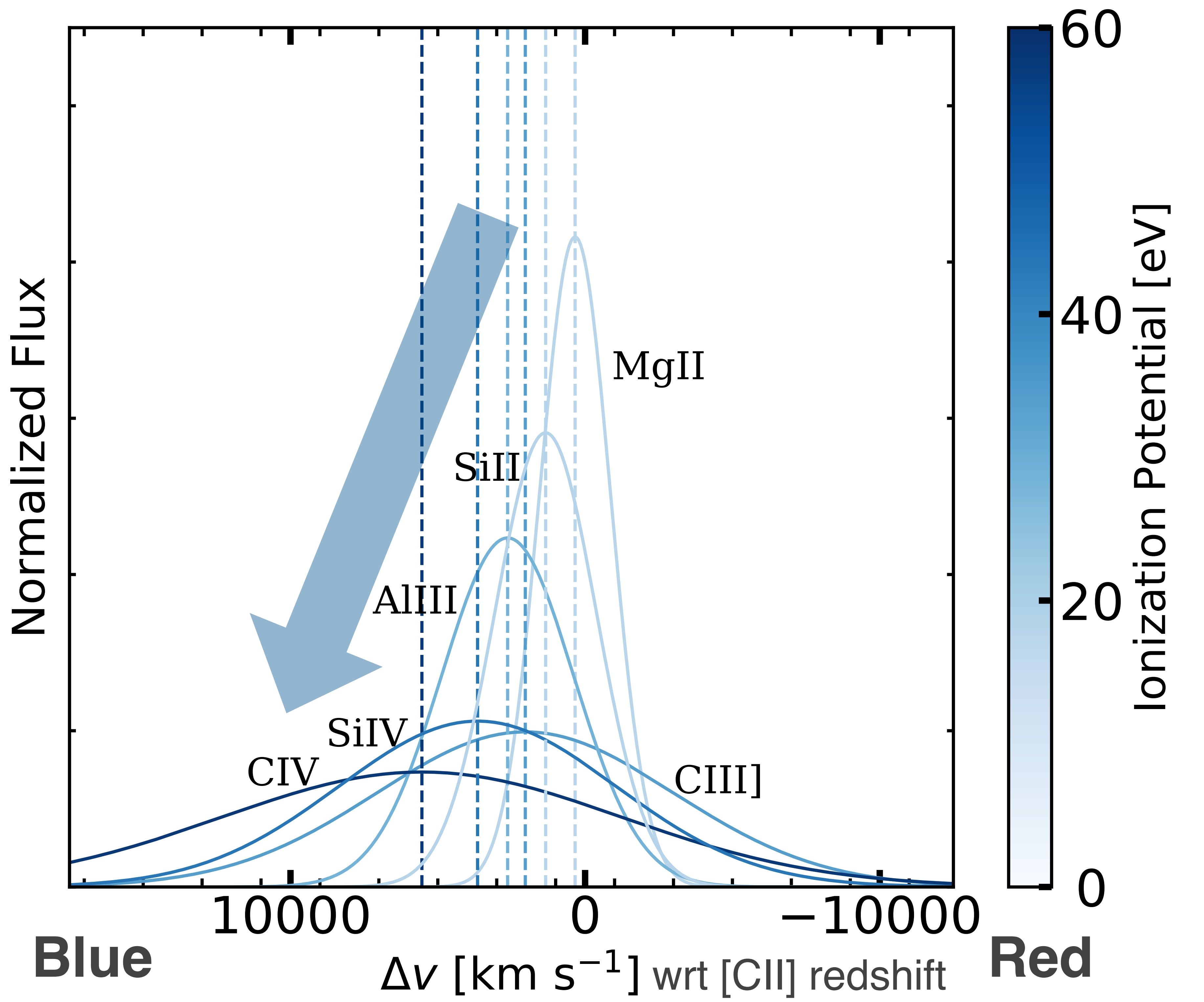
- The z~7.5 SMBHs all have M_{BH}~$10^9 M_{sun}$ (t_{uni}~0.7Gyr)
- BH mass reaches only down to ~$10^{4\text{-}5}$ M_{sun} if constant Edd. Limit accretion is assumed
  - still too massive for stellar remnant seeds (<10^3 M_{sun})

➡ Did SMBHs form through the DCBH channel?

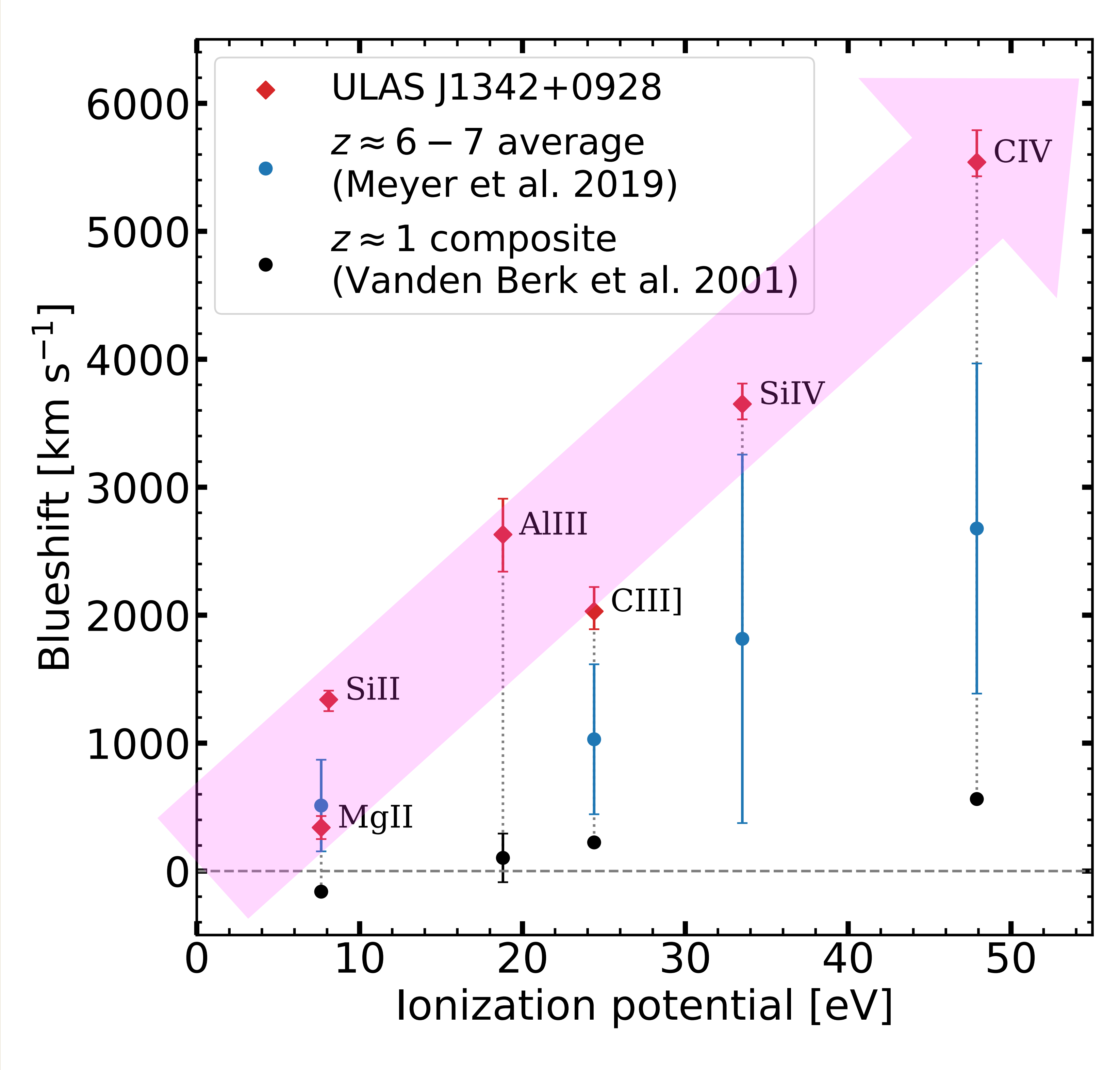
➡ Or, they originated from light-seed channel and experienced super-Eddington phase?

Blueshifts of High-ionization Lines

- Normalized BLR line profiles of J1342+0928 (Onoue+20)

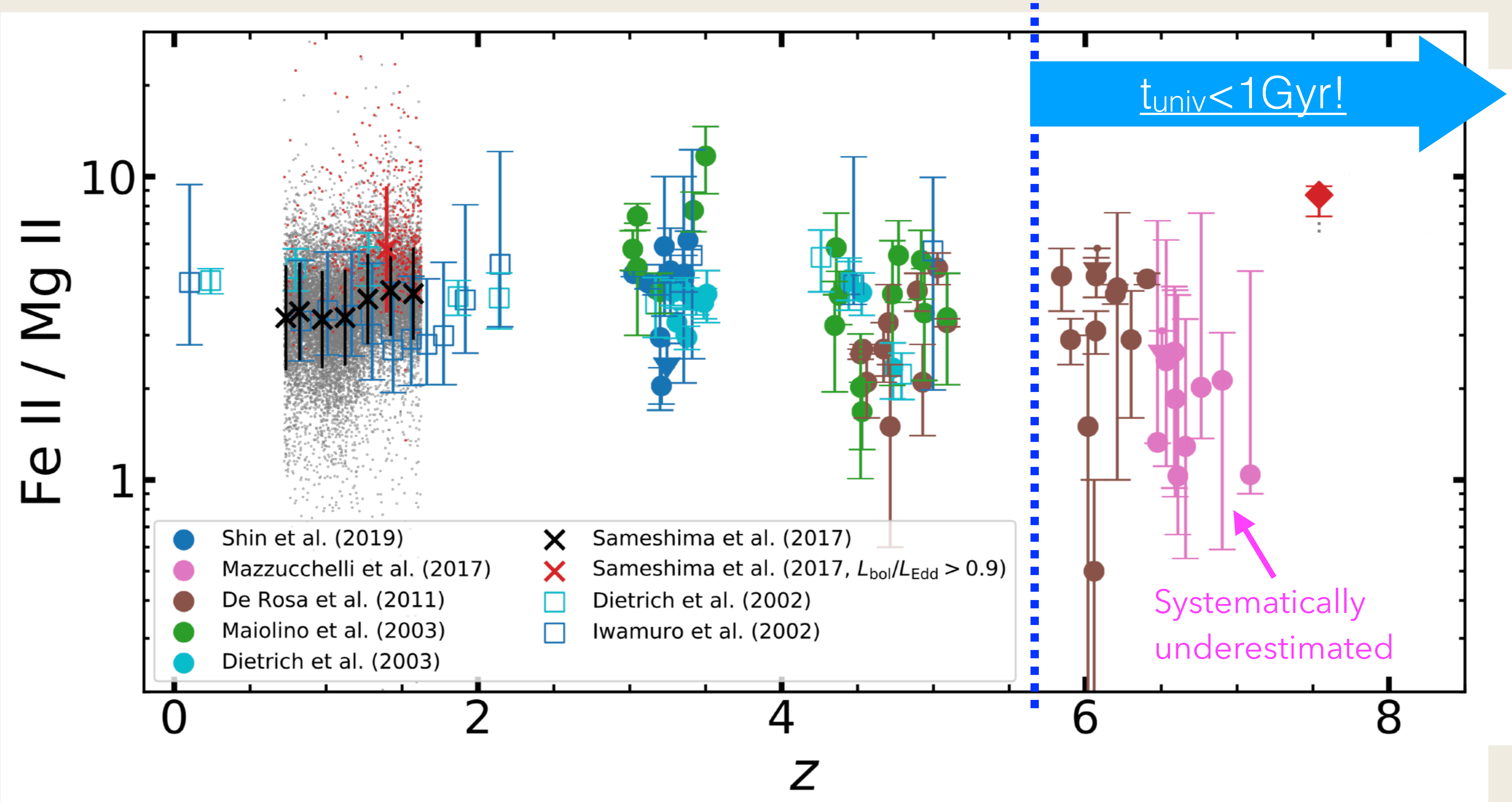


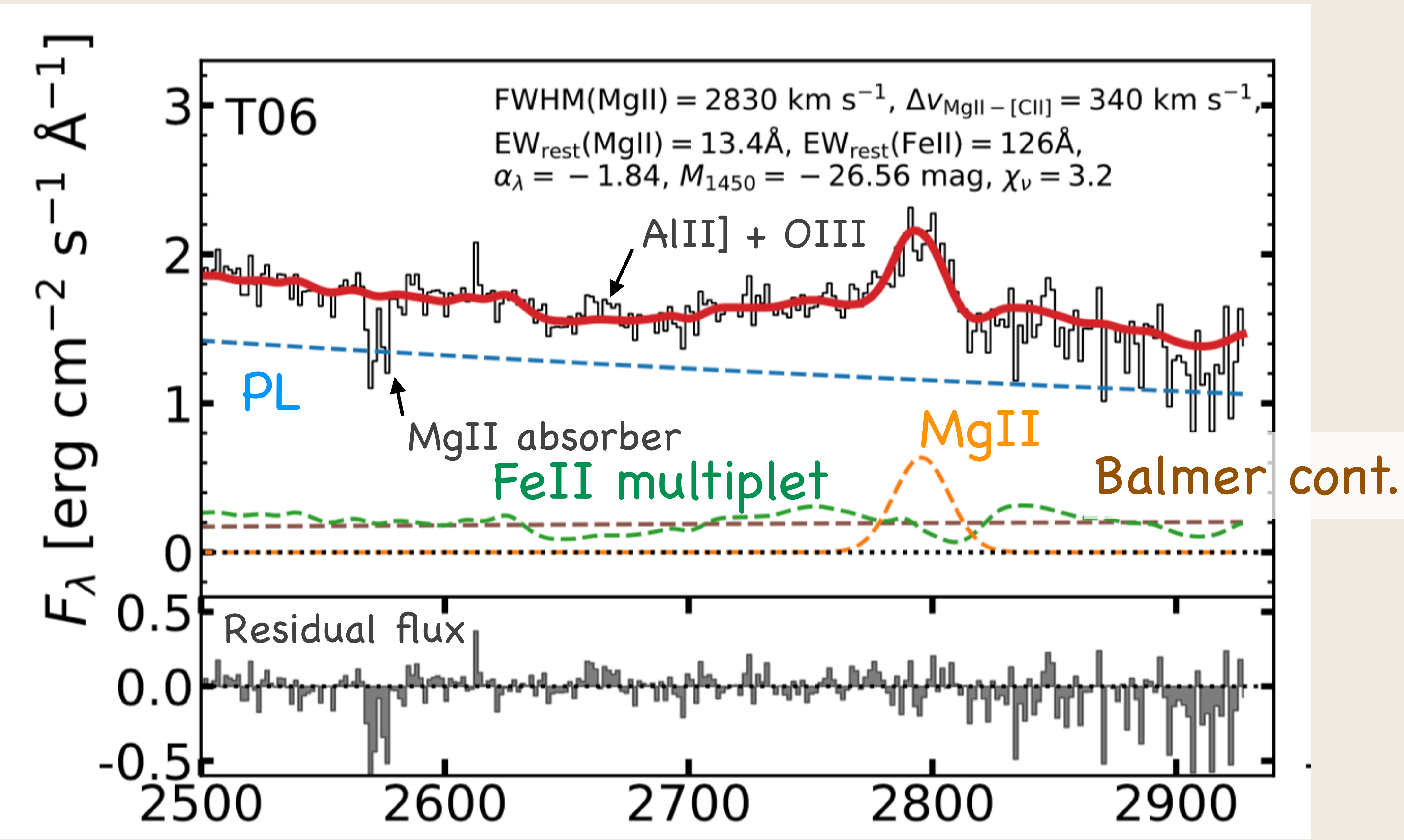
- BLR blueshifts (wrt [CII] 158μm) vs ionization potential



- ✦ Large BLR blueshift at z=7.5 in high ionization lines -> nuclear-scale outflow
- ✦ Higher-ionization gas traces the gas that is closer to SMBHs?

Rapid Fe enrichment in BLR clouds



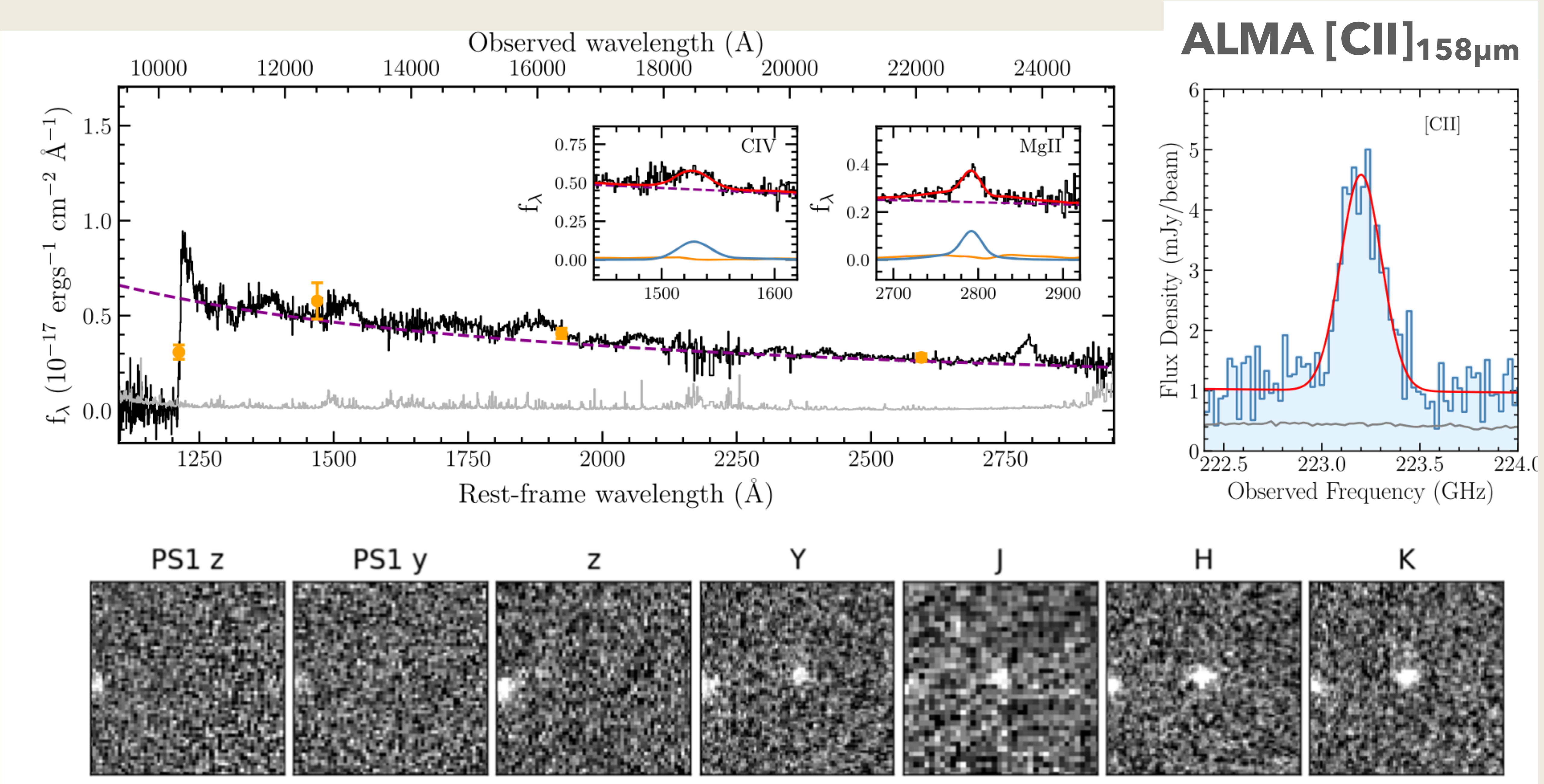


See also Schindler+20

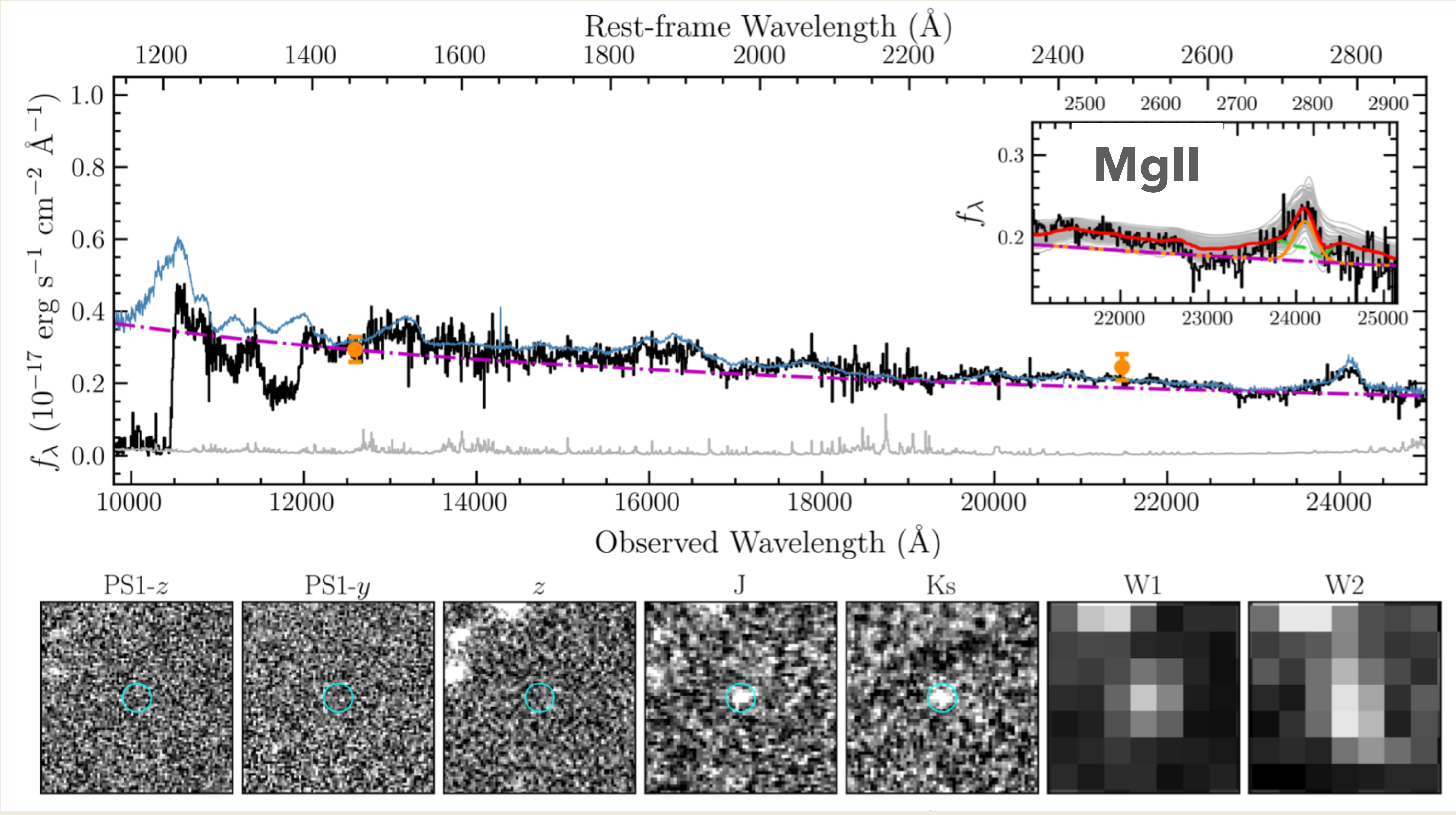
- ✦ **FeII/MgII:** "cosmic clock" (e.g., Hamann & Ferland 93)
  α-elements…SNe II, Fe…SNe Ia (t_{Ia} ~ 1Gyr) -> time delay of Fe enrichment expected at z>6
- ✦ No FeII/MgII break found up to t_{univ}=0.7Gyr: prompt SNIa / PISNe, or nucleosynthesis in accretion disk?

Two New z~7.5 Quasars

- J1007+2115 at z=7.515 ("Pōniuāʻena"; Yang+20)



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



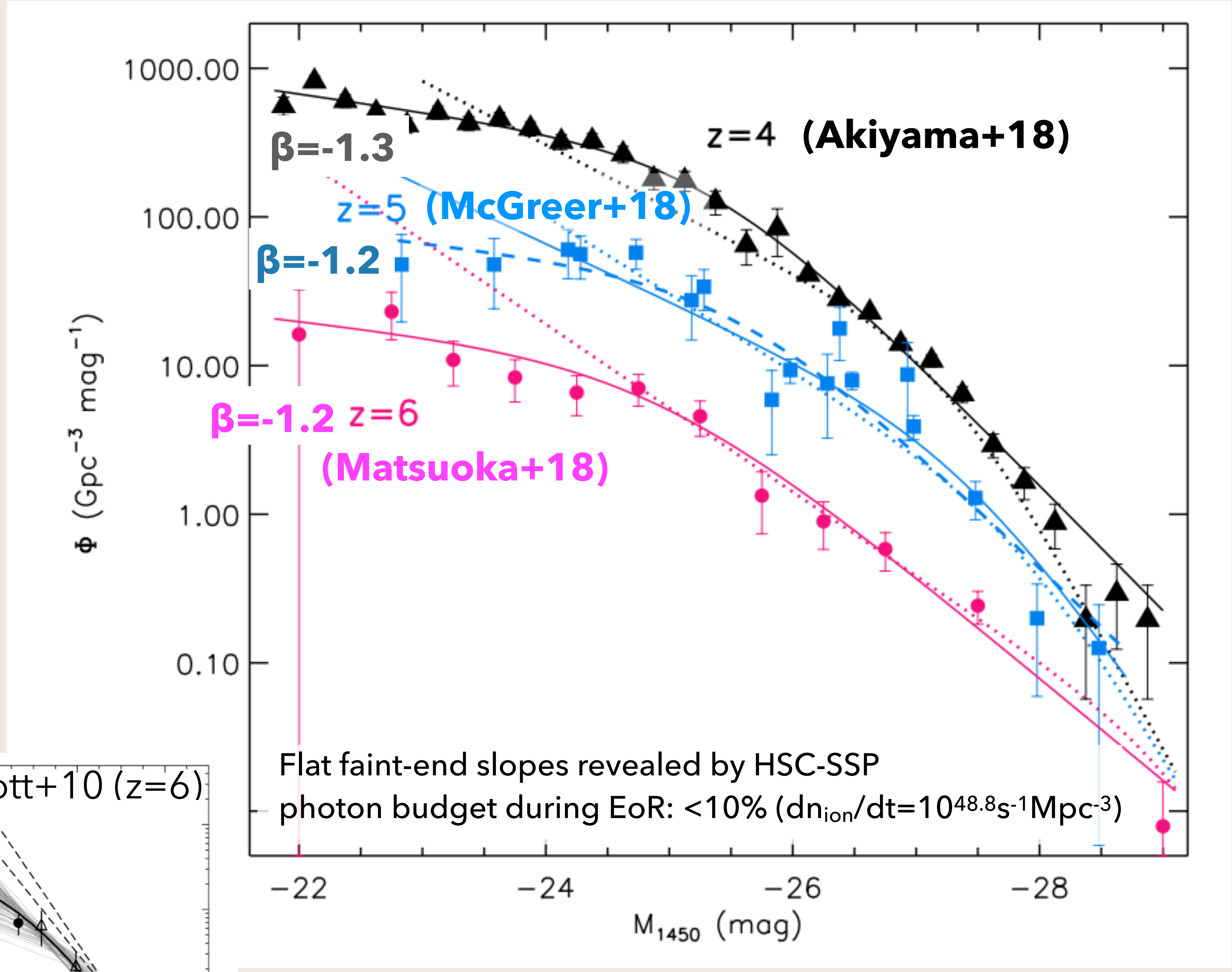
- Selection: J & WISE detection + color cuts
- J_{AB}=20.20, M_{UV}=-26.66
- M_{BH} =1.5 x 10^9 M_{sun}, L_{bol}/L_{Edd}=1.06

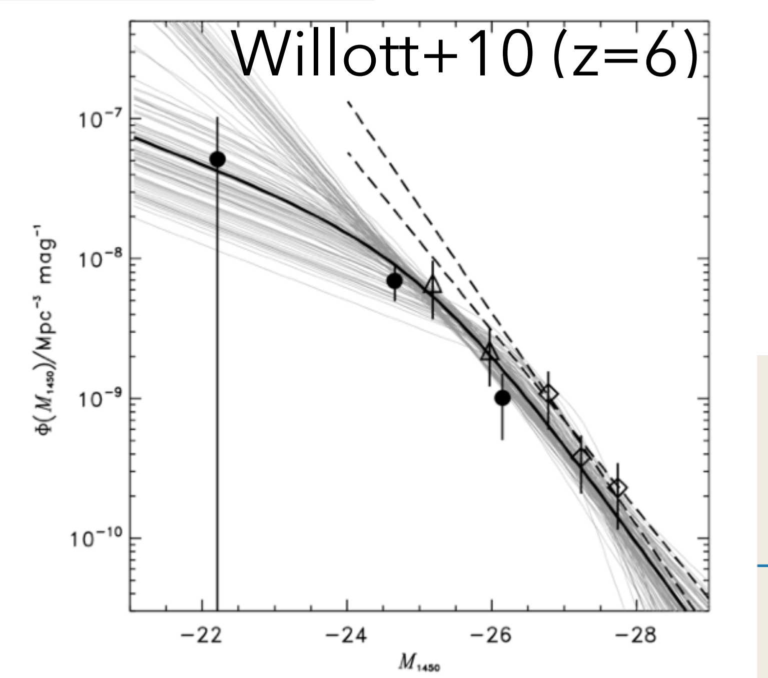
- Selection: J & WISE detection + color cuts
- J_{AB}=20.92, M_{UV}=-26.13
- M_{BH} =1.6 x 10^9 M_{sun}, L_{bol}/L_{Edd}=0.67
- Strong BAL feature in CIV & SiIV (+ MgII?)

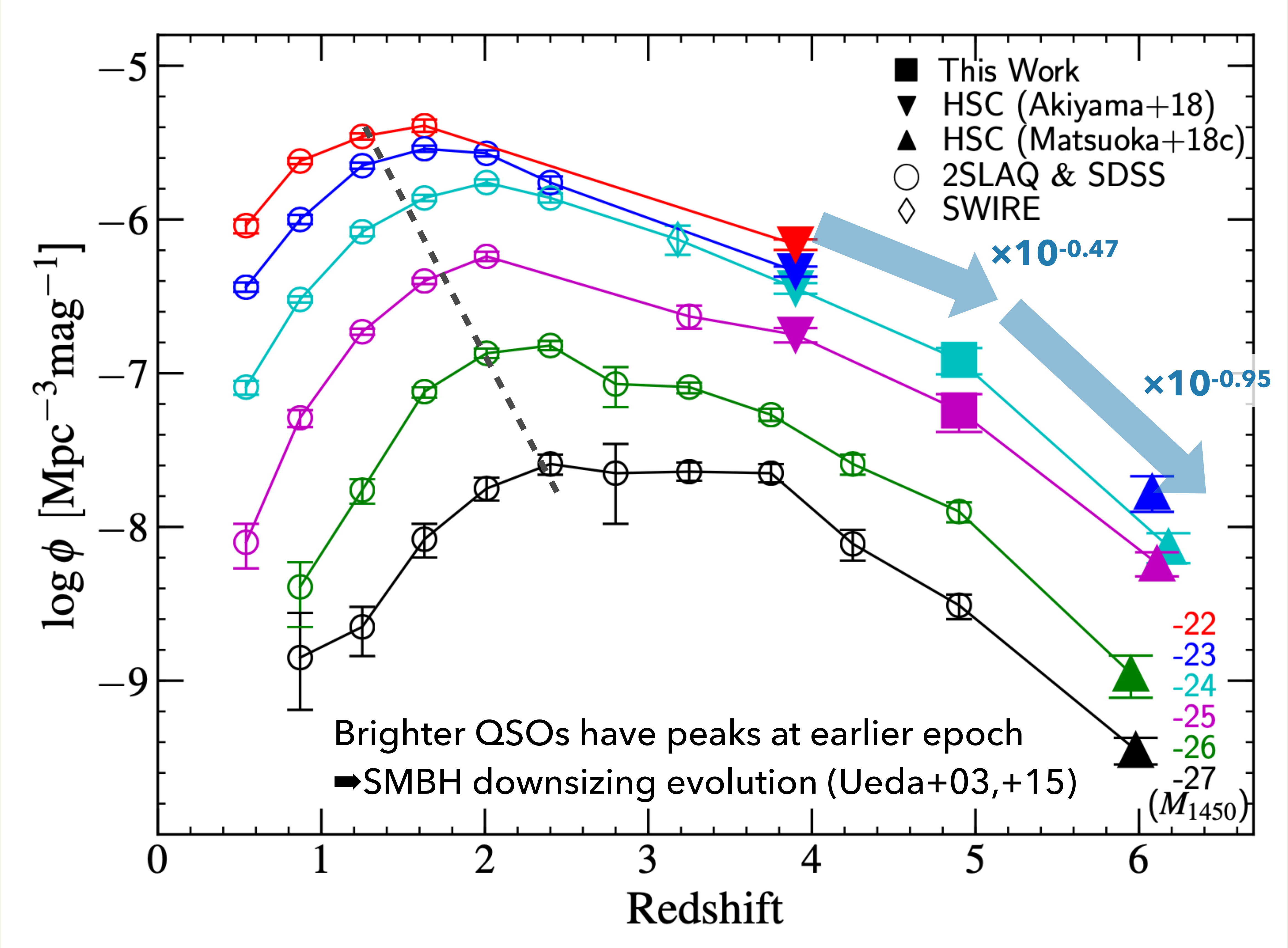
Statistical Properties of z>6 SMBHs and Host Galaxies

Quasar LF

- z=4-6 QLF (Matsuoka+18)
- QLF evolution at z=0-6 (Niida+20)

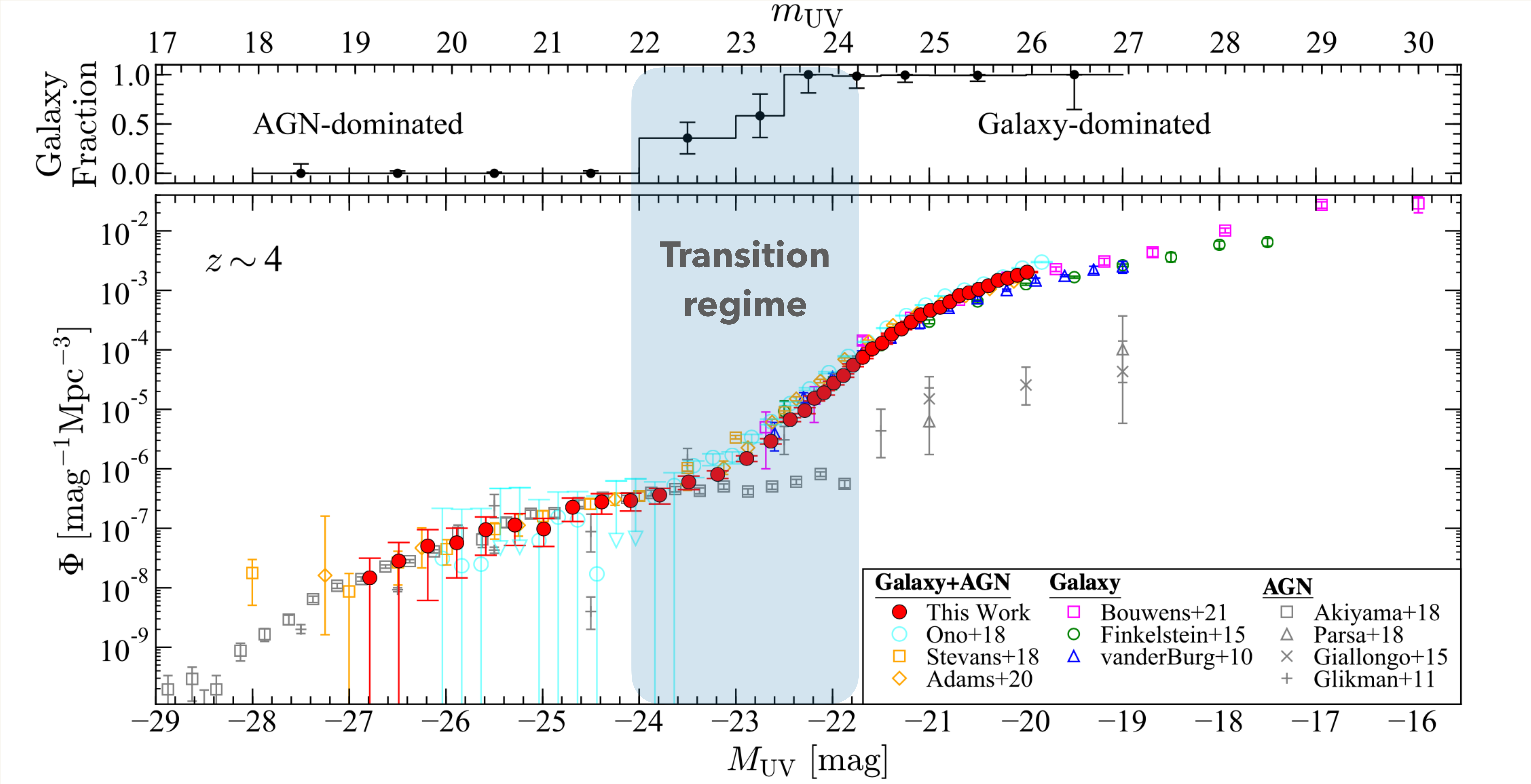




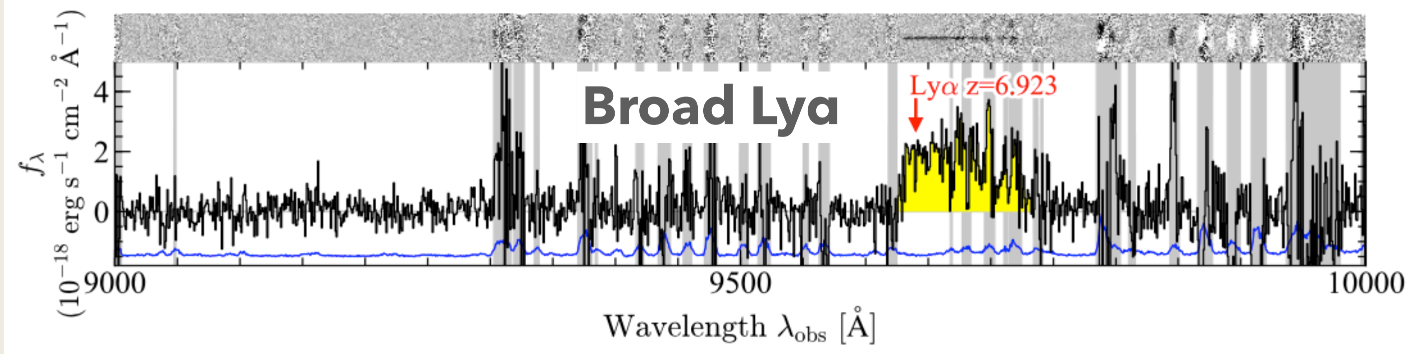


Galaxy/AGN Transition in UV LF

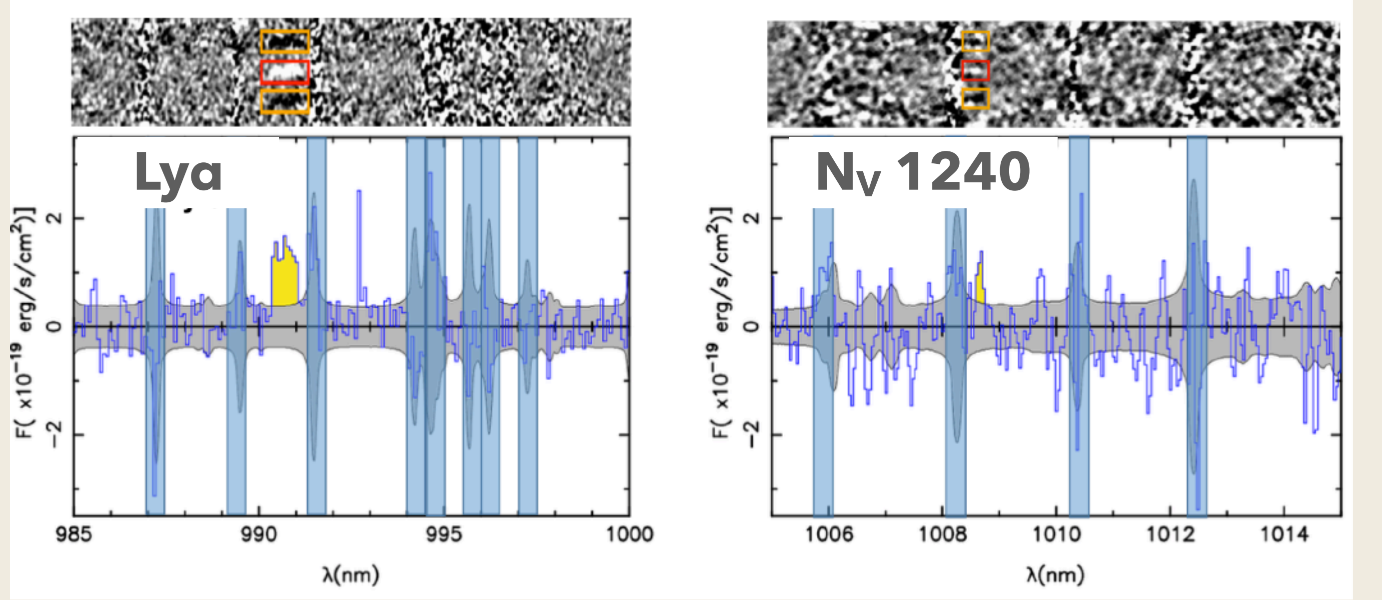
- z=4 UV LF (Harikane+21)



- HSC J1609+5328 (z=6.923, M_{UV}=-22.7)



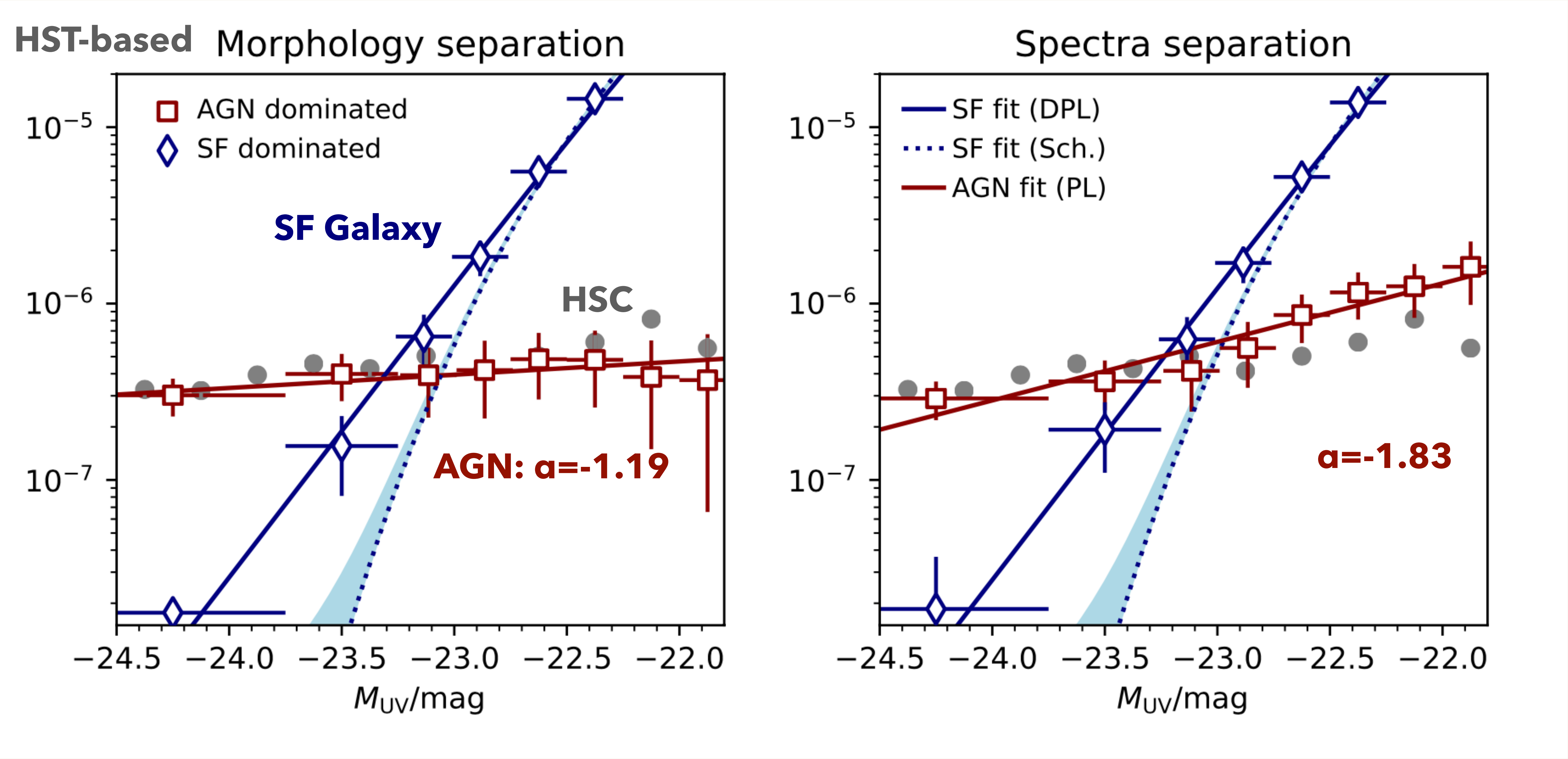
- COSY (z=7.149, M_{UV}=-21.8; Laporte+17)



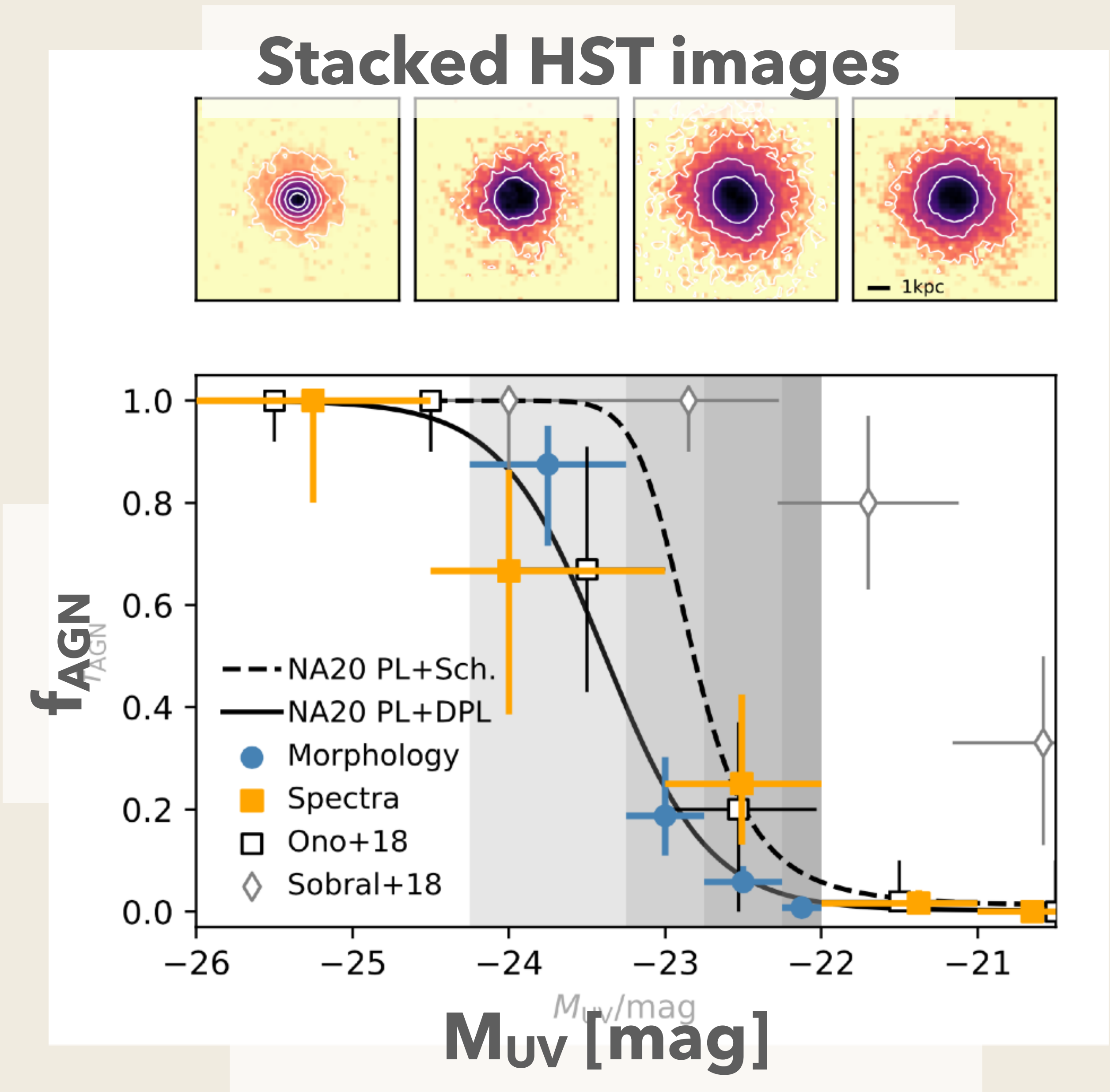
Stellar light contamination is non-negligible at the faint end (i.e., bright galaxies or faint AGNs)

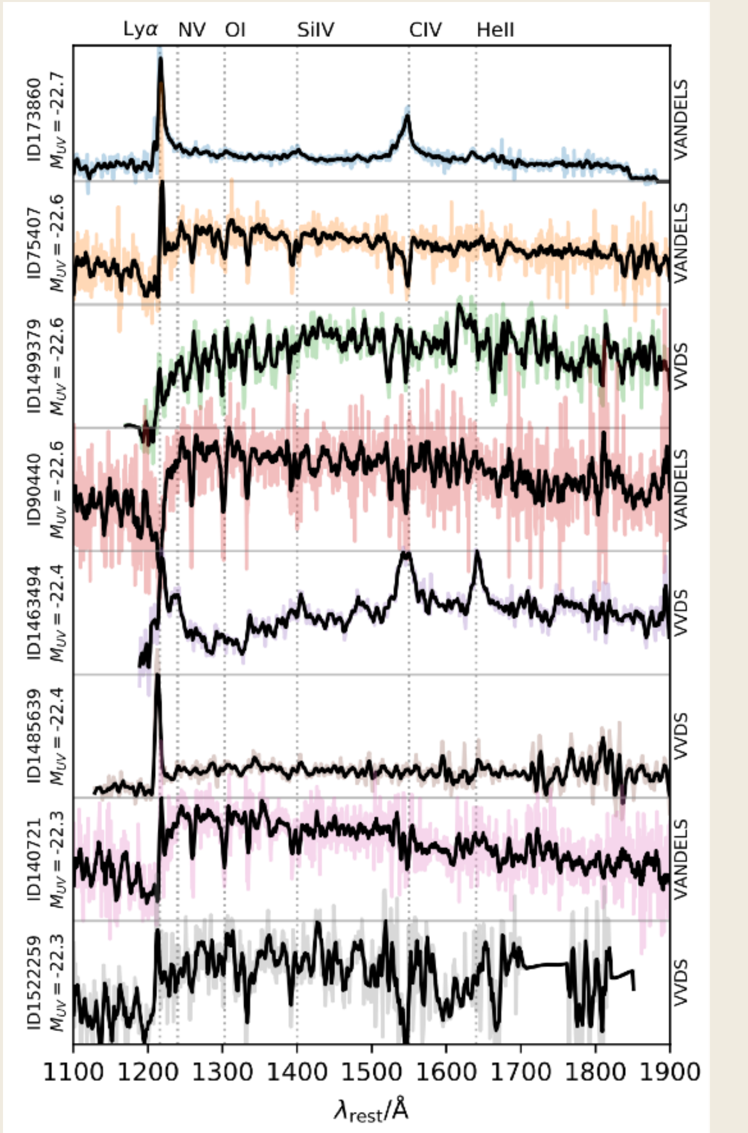
Biases in Morphology-based QSO Selection

- The effects of different AGN selection on z=4 UV LF (Bowler+21): QSO selection = point source + color cut



- AGN fraction (left) and spectra of M_{UV}~-22.5 sources (right)





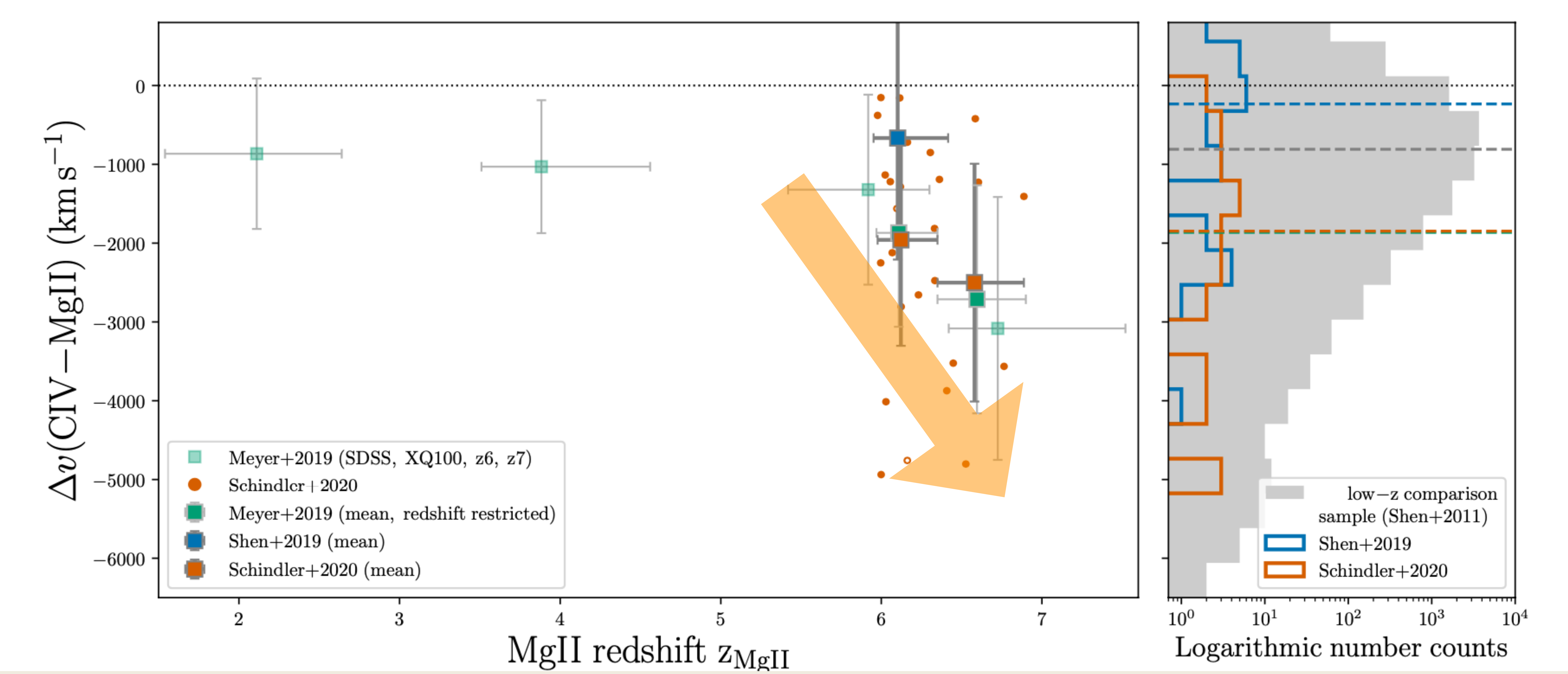
See also Laporte+17; Sobral+18; Grazian+20; Boutsia+21; Zhang+21; Calhau+21

The observed flat faint-end slopes seem partly owing to the morphology-based selection cut

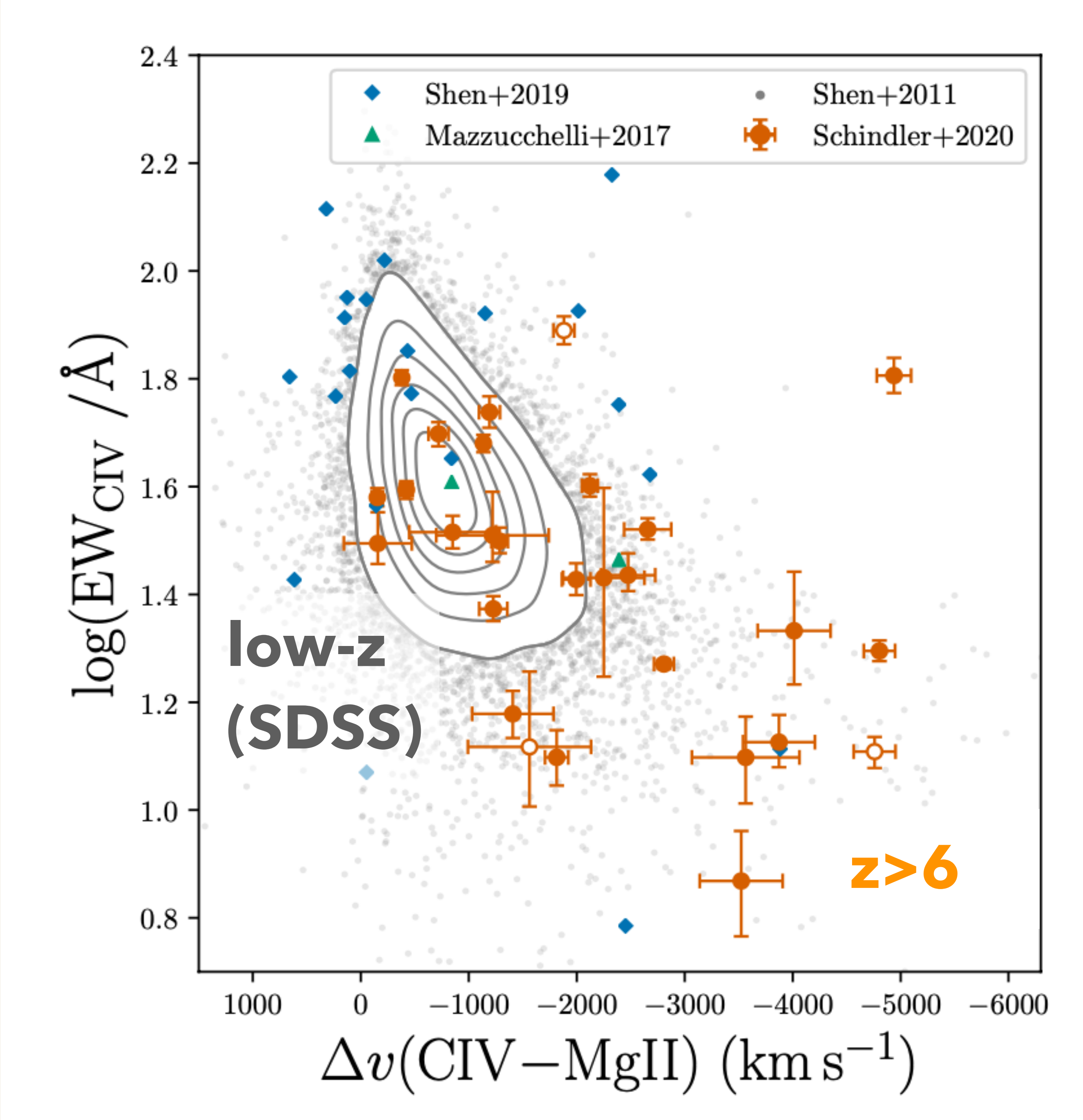
➡ Spectroscopic or Xray studies are required (e.g., PFS, JWST, Lynx)

Velocity Shifts of BLR High-Ionization Lines

- Redshift evolution of CIV blueshifts at z=6-7 (Schindler+20)



- Δv(CIV-MgII) vs EW(CIV)

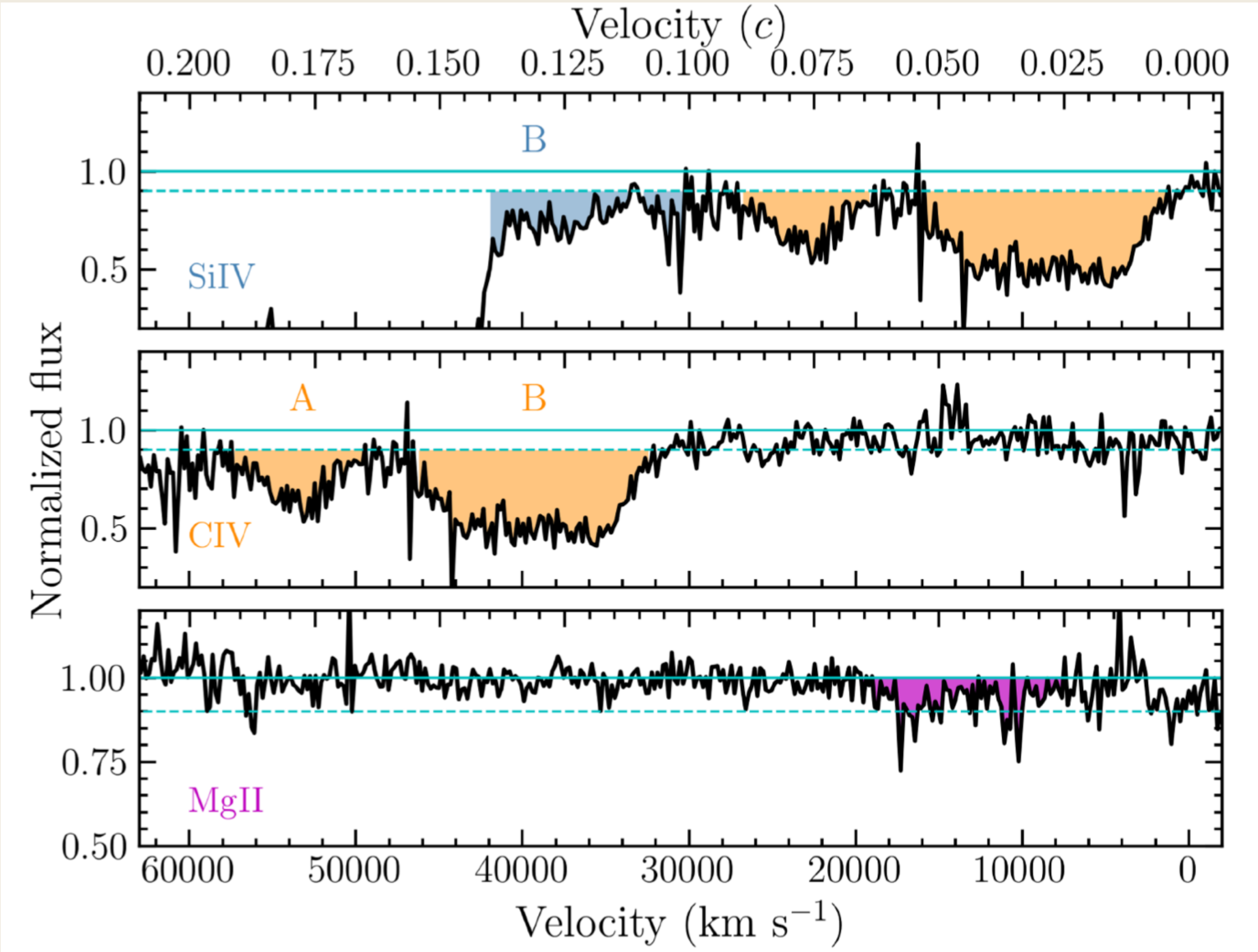


See also Mazzucchelli+17; Shen+19

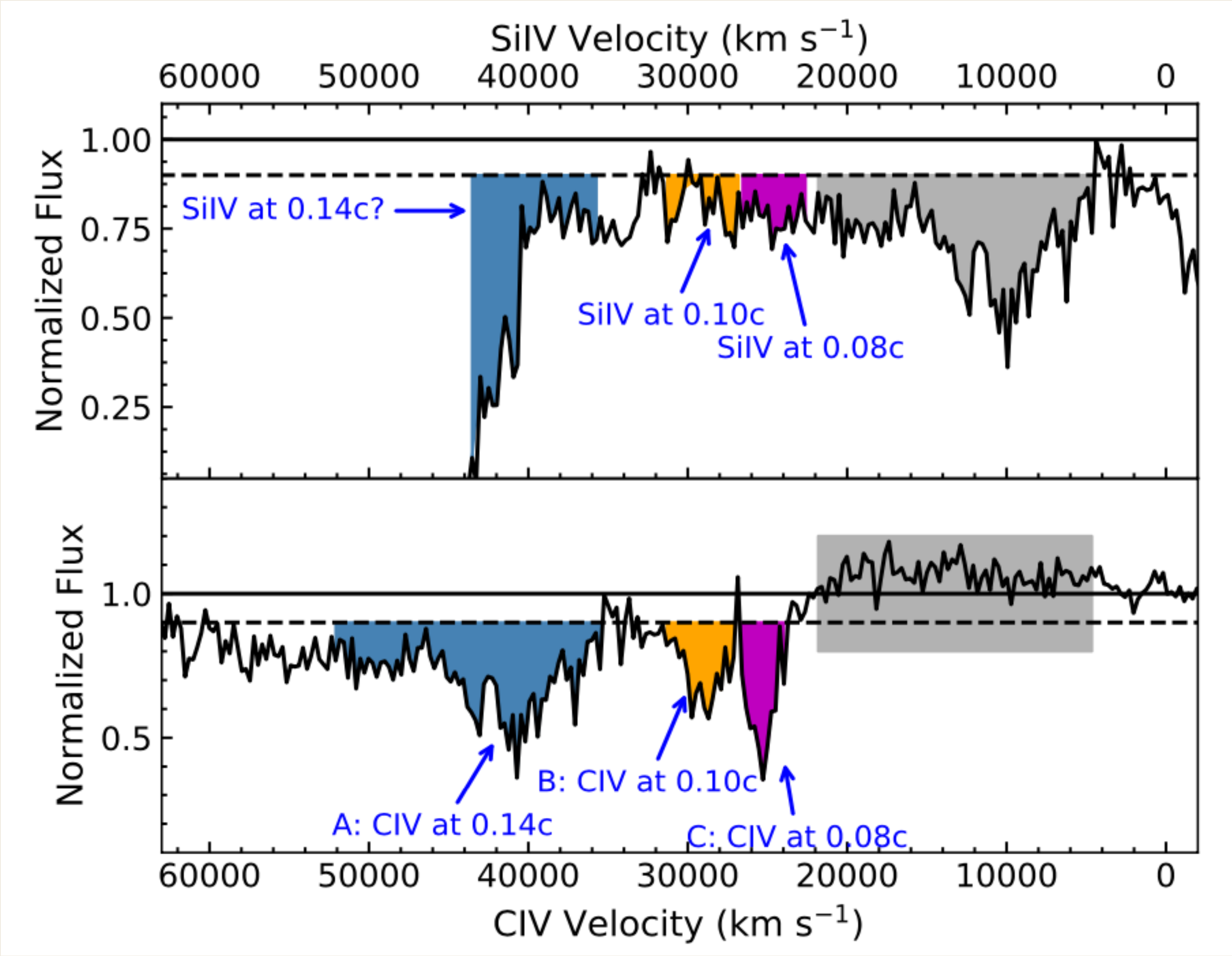
Larger CIV velocity shifts at z>6; stronger BLR-scale outflow (distinct changes in the BLR properties?)

High-velocity Nuclear outflow: Broad Absorption Line (BAL) quasars at z>7

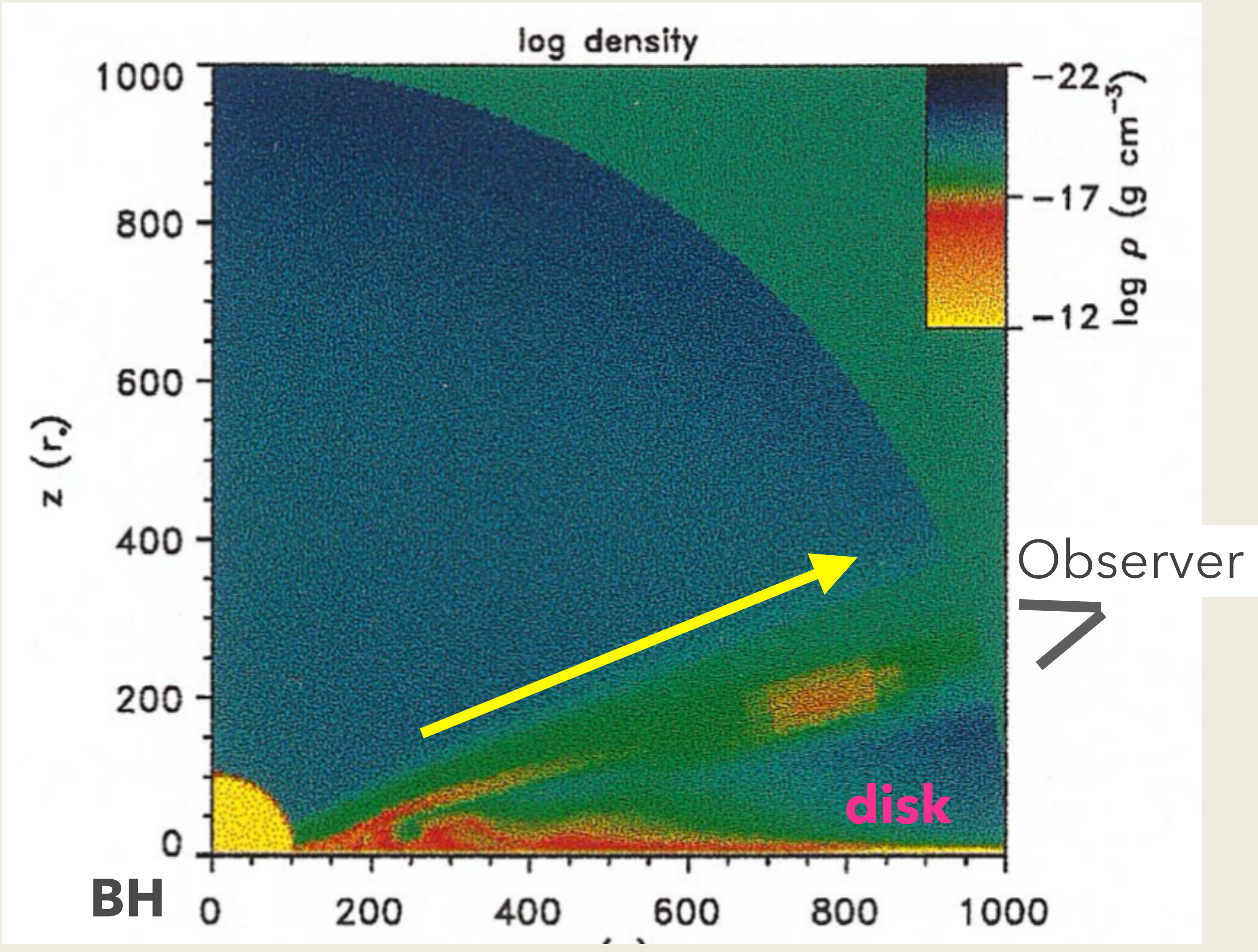
- Normalized spectrum of J0313-1806 at z=7.6 (Wang+21)



- Normalized spectrum of J0038-1527 at z=7.0 (Wang+18)



- AGN disk wind simulation (Proga+00)



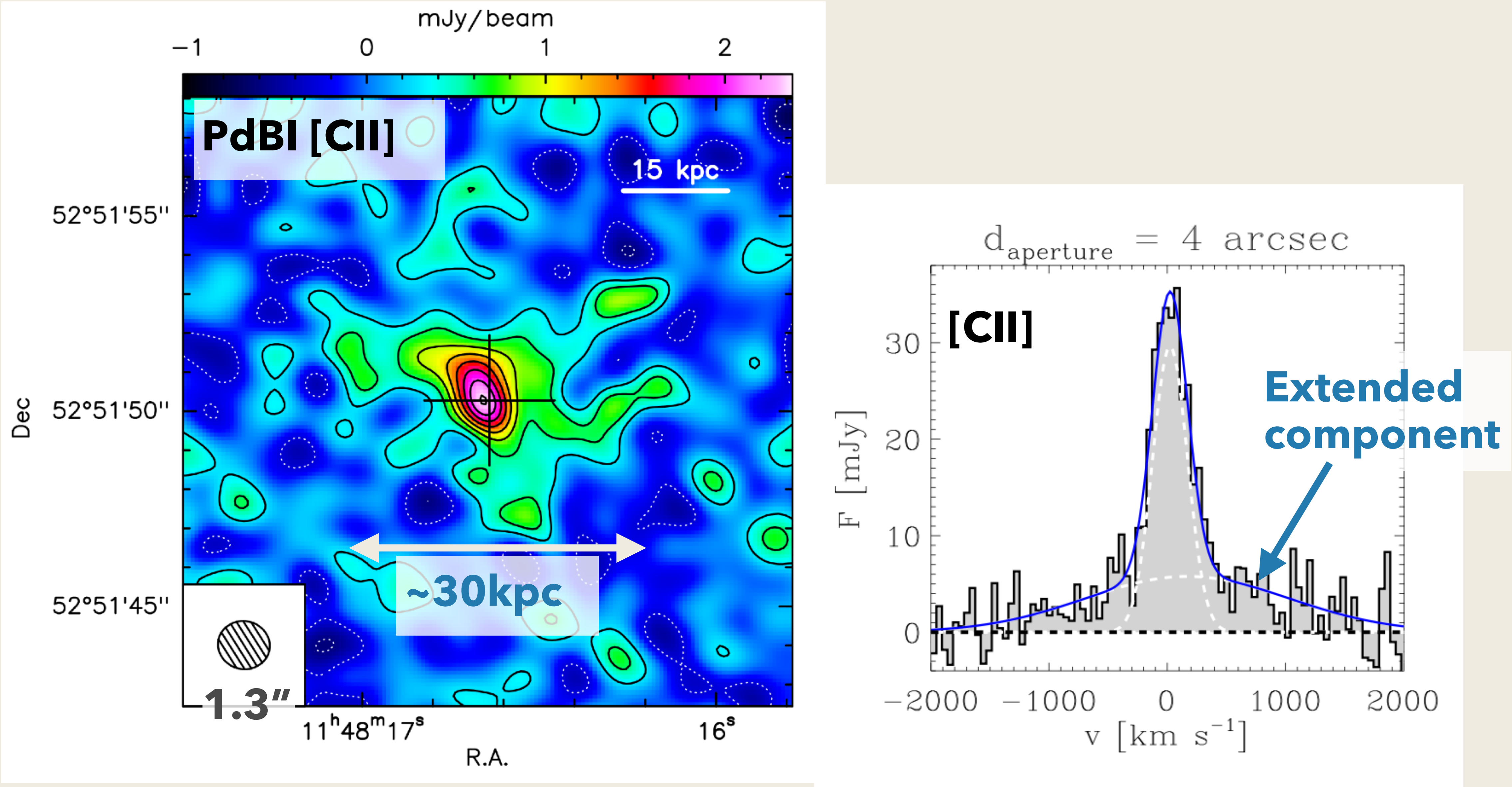
See also Matsuoka+19; Xu+20; Bischetti+ in prep.

2/8 z>7 quasars have >0.1c outflow (0.6% at z=2-5; Rodriguez Hidalgo+20)

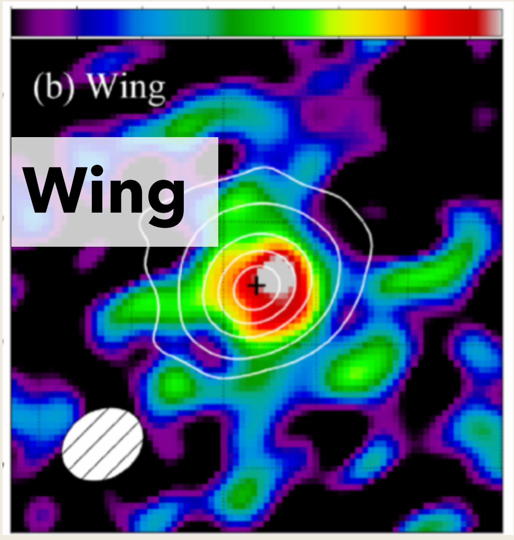
Quasar-driven fast outflow more common at z>6?

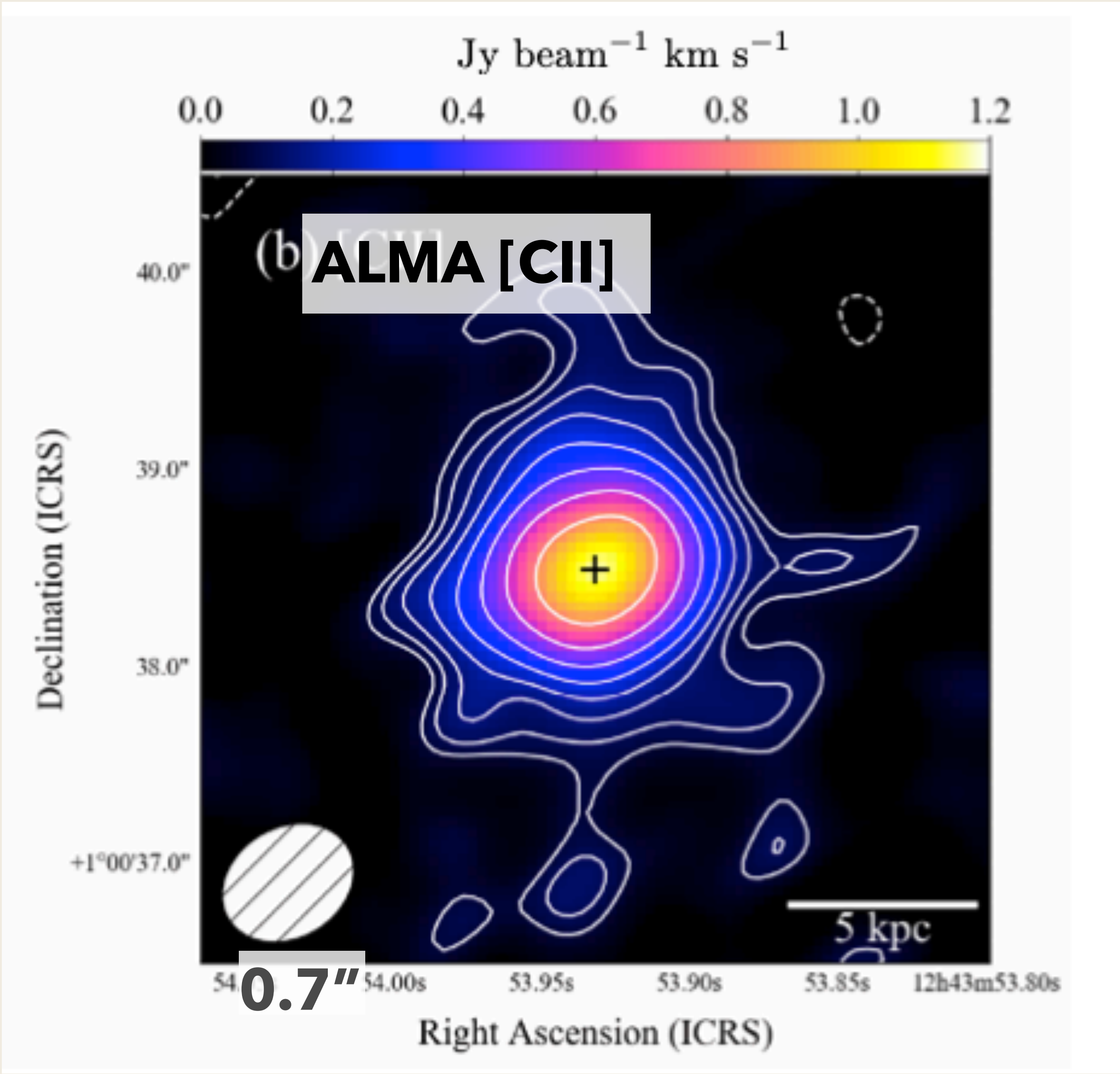
Quasar-Driven [CII] Outflow: Individual Detection at z>6

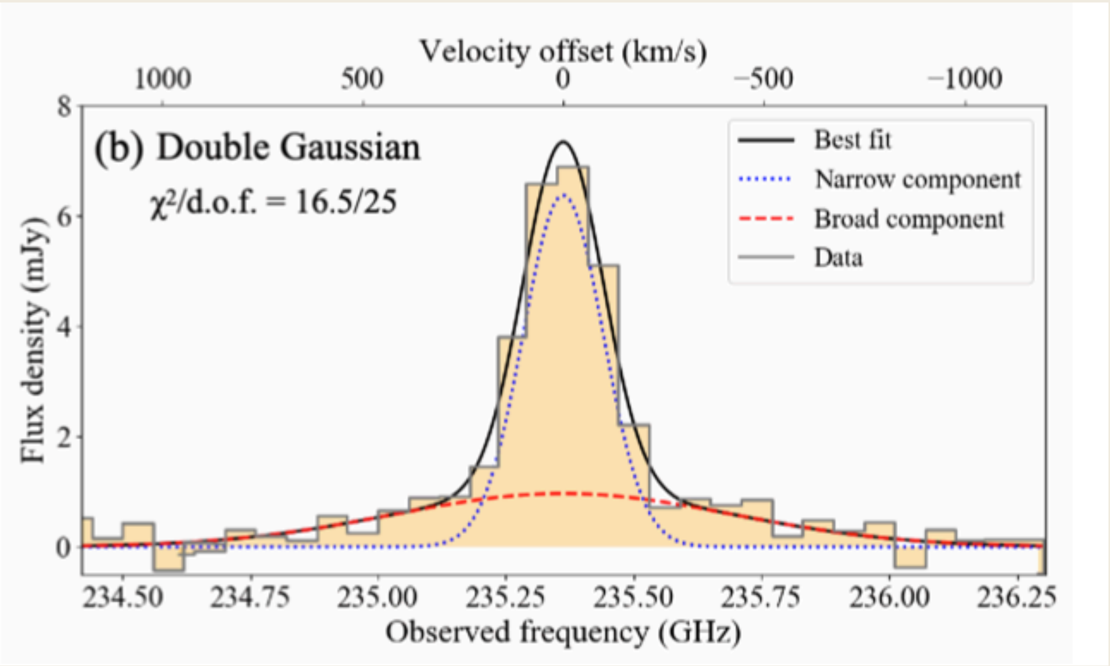
- J1148+5152 (z=6.42; Cicone+15)



- J1243+0100 at z=7.07 (Izumi+21b)





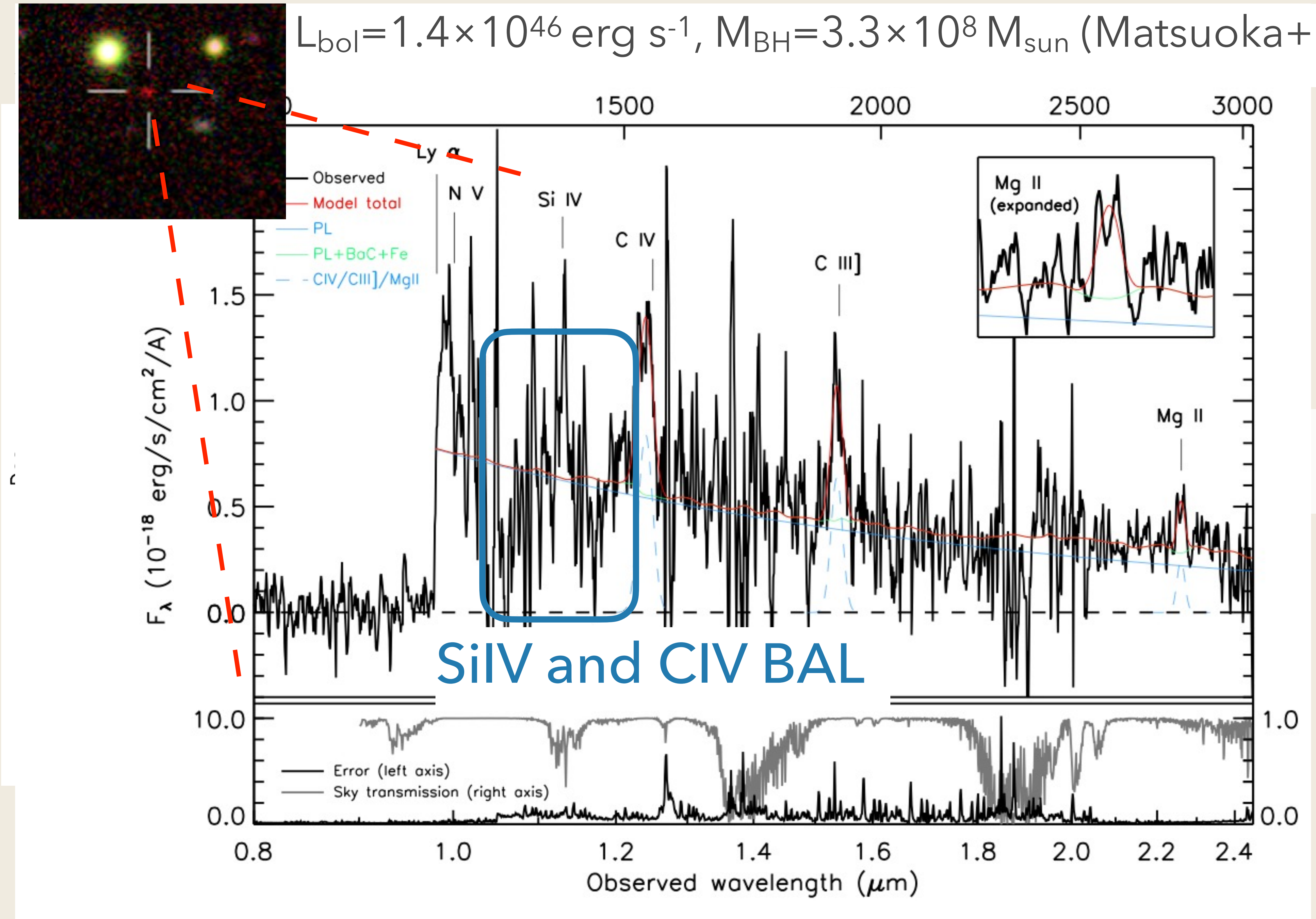


See also Maiolino+12; Izumi+21a

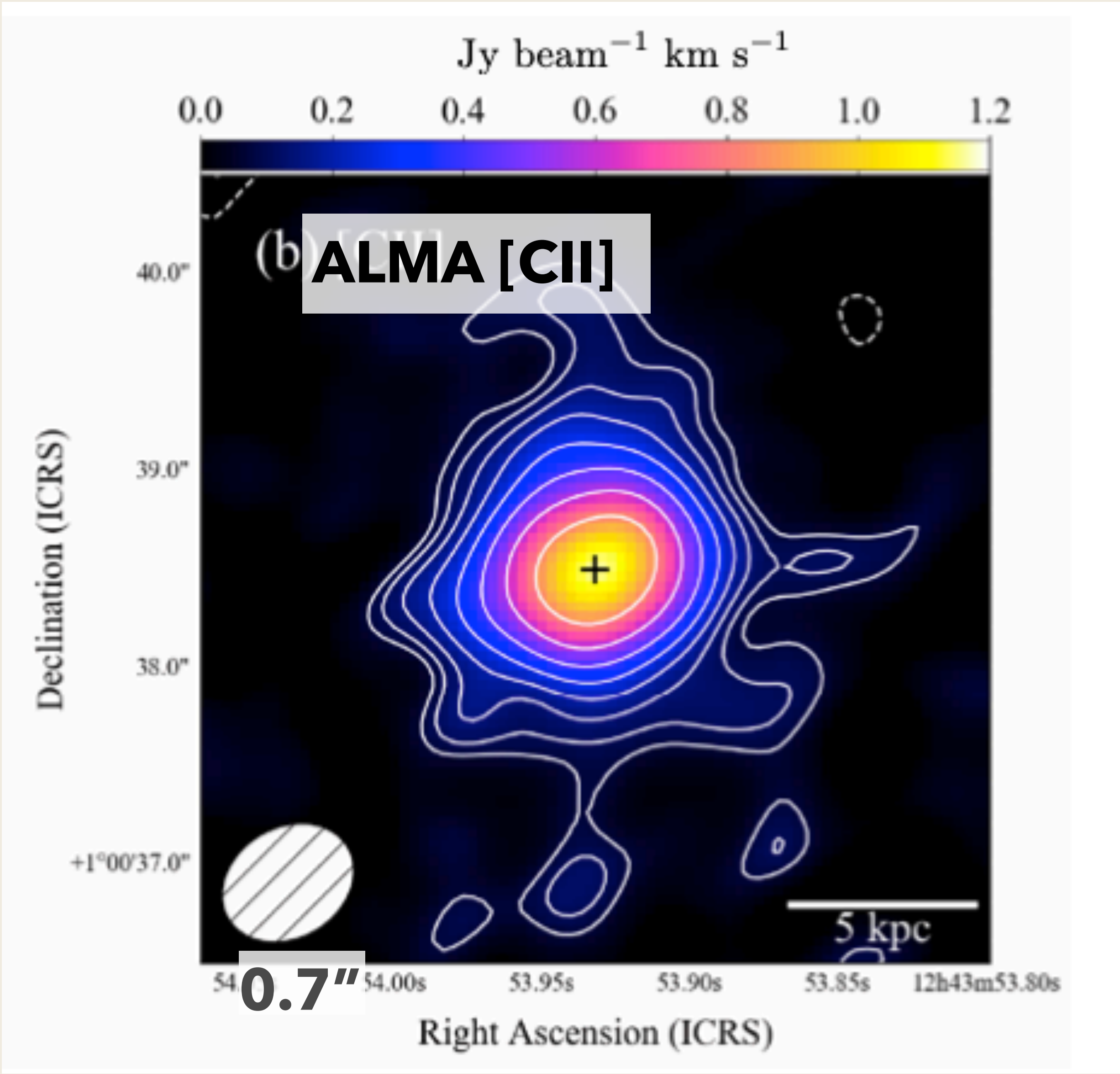
Large-scale outflow just starting to regulate host star formation: Propagation of nuclear-scale wind, or radiation pressure-driven dusty wind?

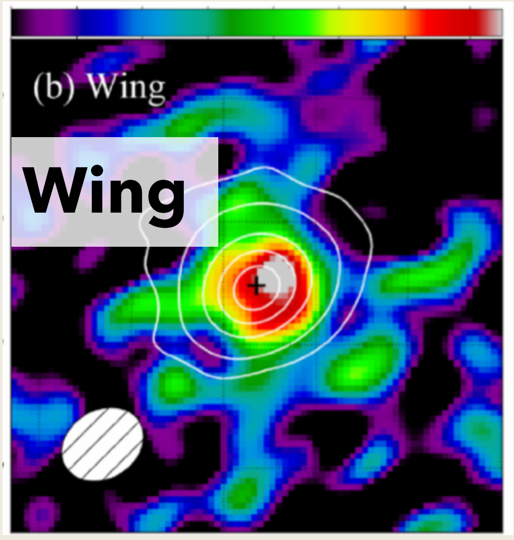
Quasar Driven [CII] Outflow: Individual Detection at z>6

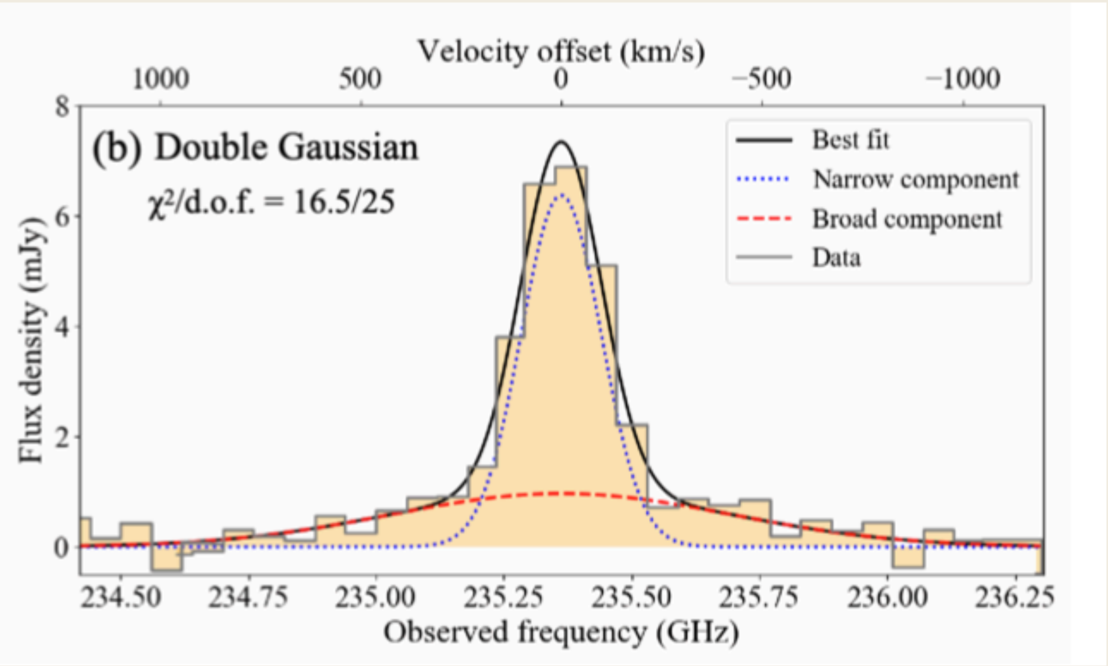
- $L_{bol}=1.4\times10^{46}$ erg s^{-1}, $M_{BH}=3.3\times10^{8}$ M_{sun} (Matsuoka+19)



- J1243+0100 at z=7.07 (Izumi+21b)





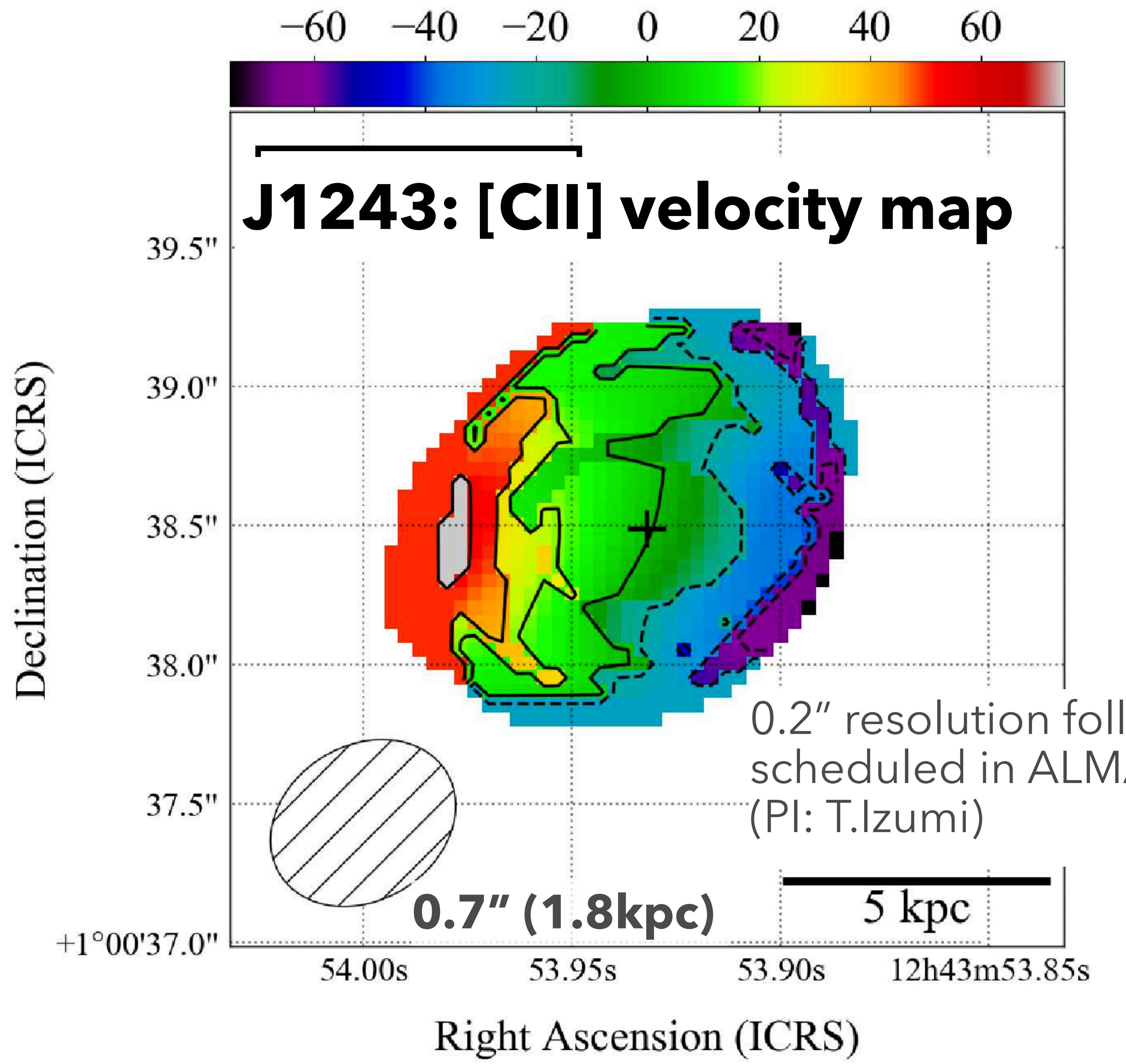


See also Maiolino+12; Izumi+21a

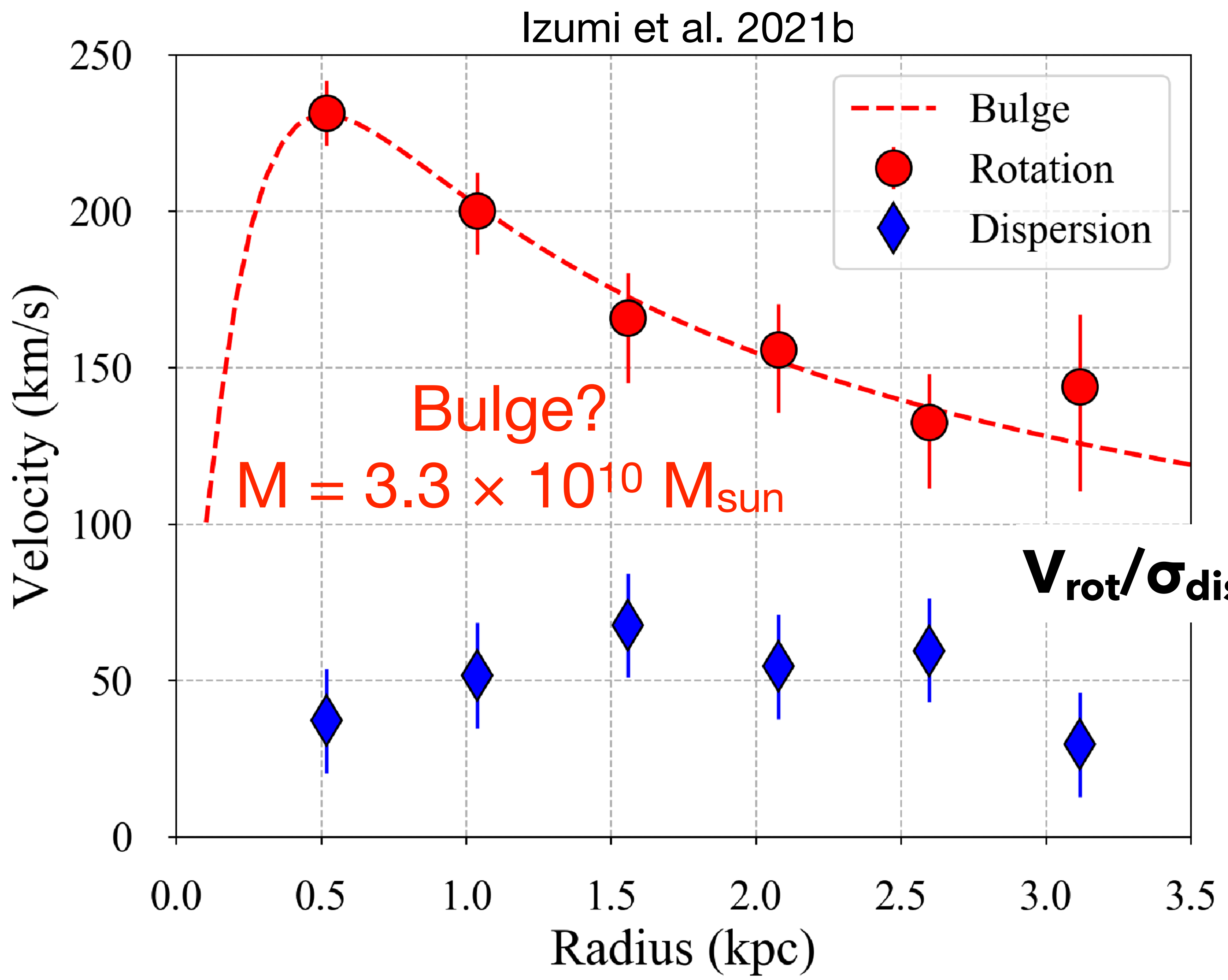
Large-scale outflow just starting to regulate host star formation:
Propagation of nuclear-scale wind, or radiation pressure-driven dusty wind?

Early Bulge Formation at z ~ 7??

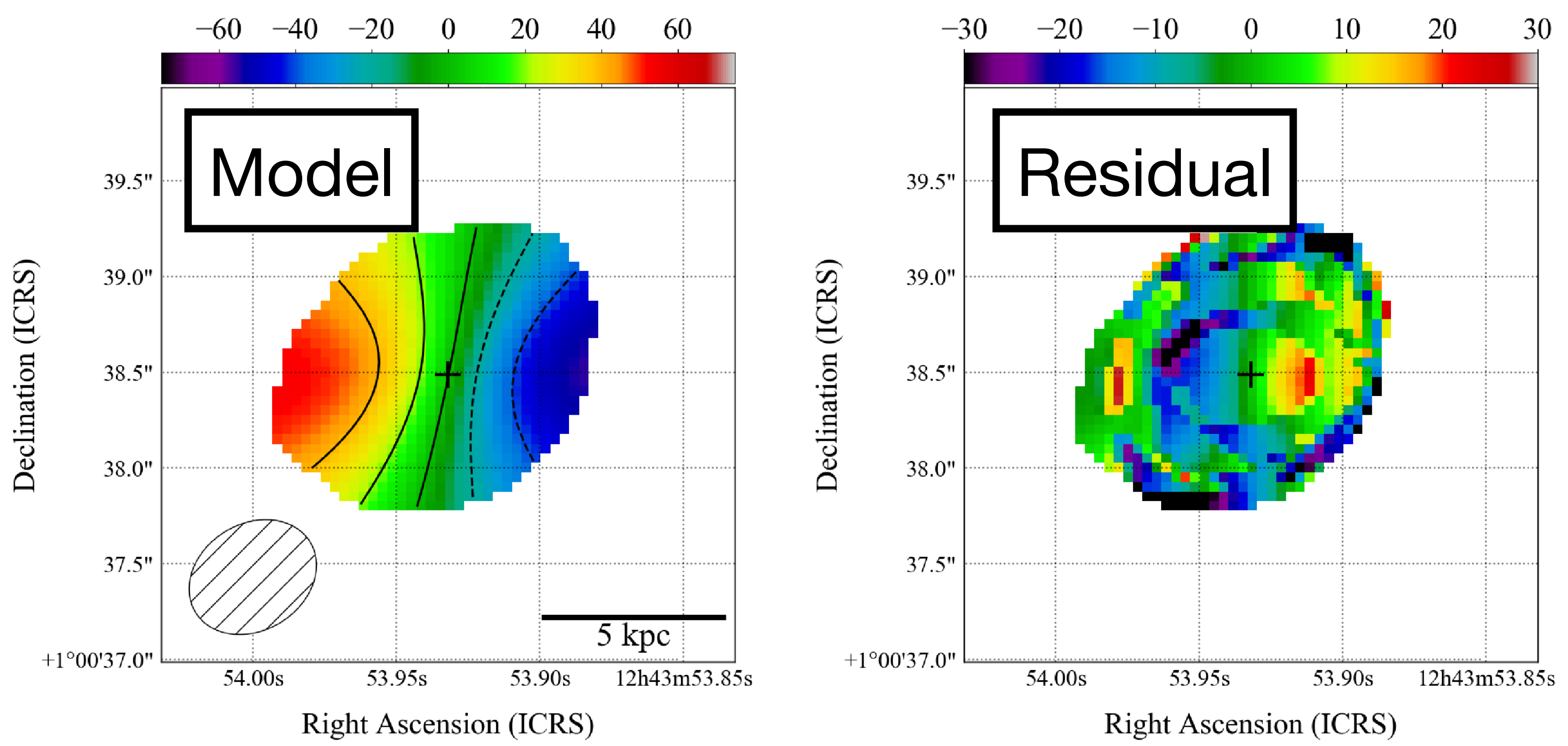
Courtesy of T.Izumi



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



V_{rot}/σ_{disp}=3-5

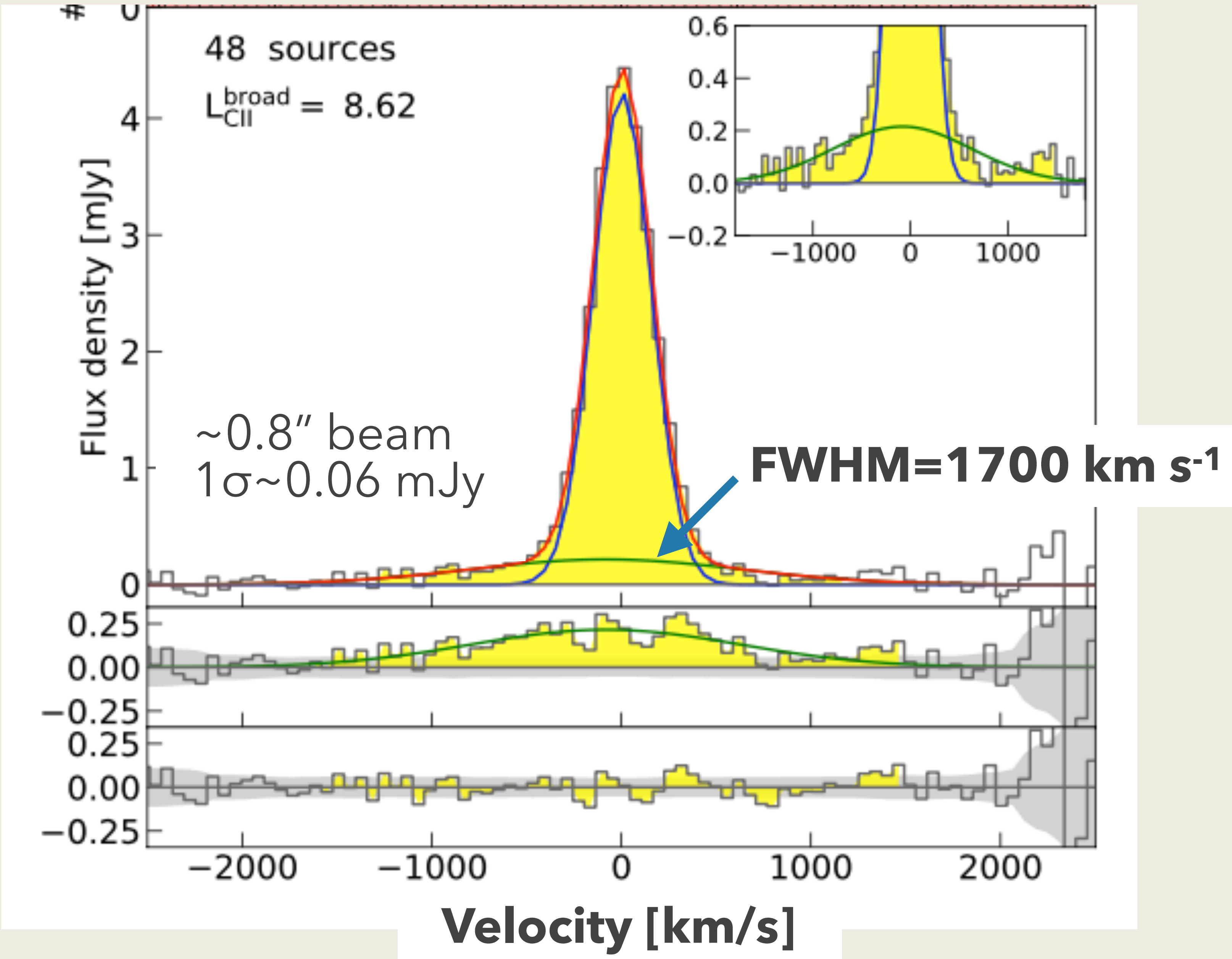


- We experimentally extracted a [CII] rotation curve by decomposing (modeling) the observed velocity field.
- We found a gradual rise in V_{rot} toward the center → Indication of a nuclear bulge??
- Would be consistent with simulations.

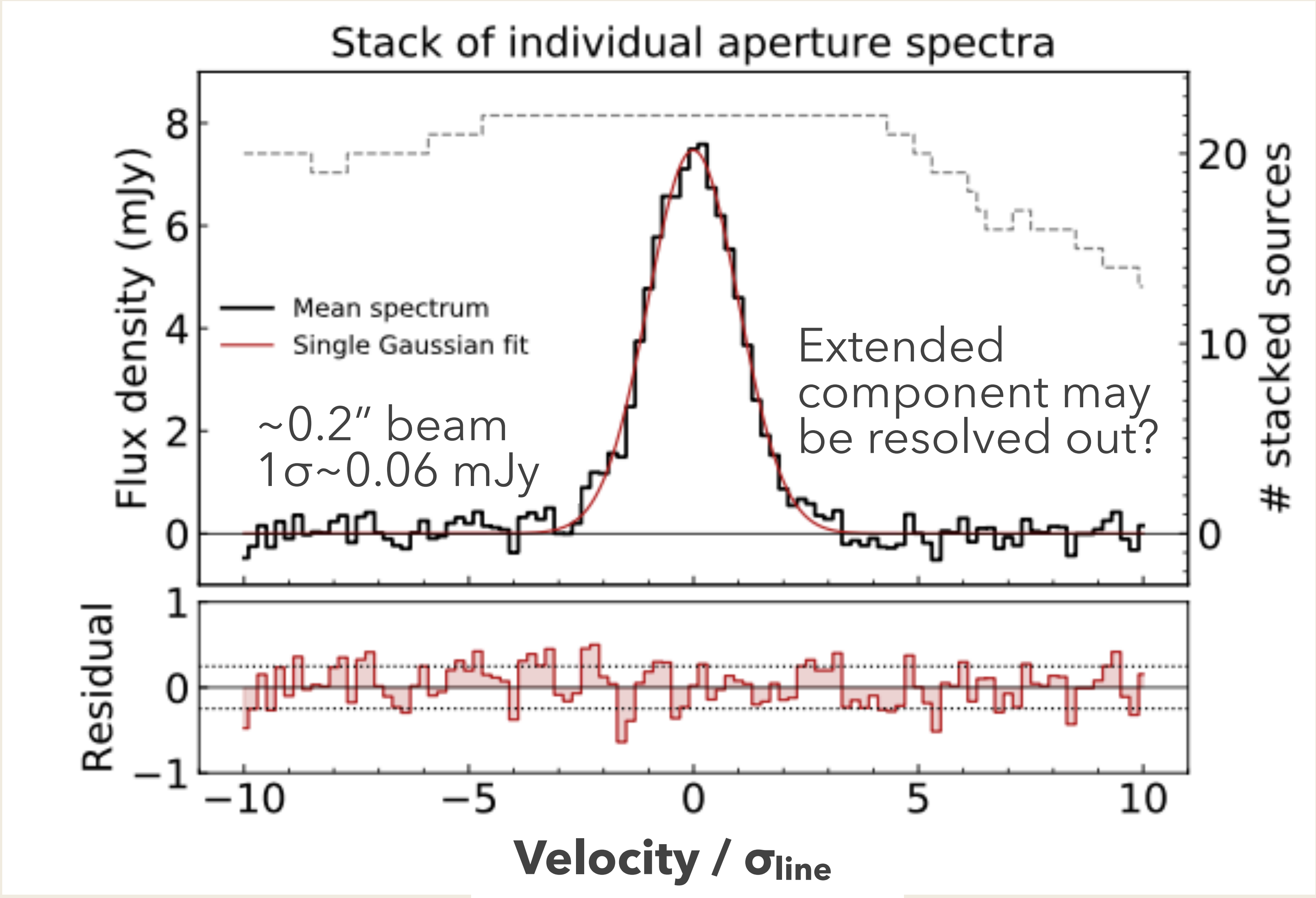
See also Smit+17; RIzzo+20; Neeleman+20

[CII] Outflow of z>6 Quasar Hosts: Stacking Analysis

- Compilation of 48 sources at z>6 (Bischetti+19): [CII] stacking in the *velocity* space



- 1kpc-resolution ALMA sample (N=27; Novak+20): [CII] stacking of *velocity-normalized* spectra

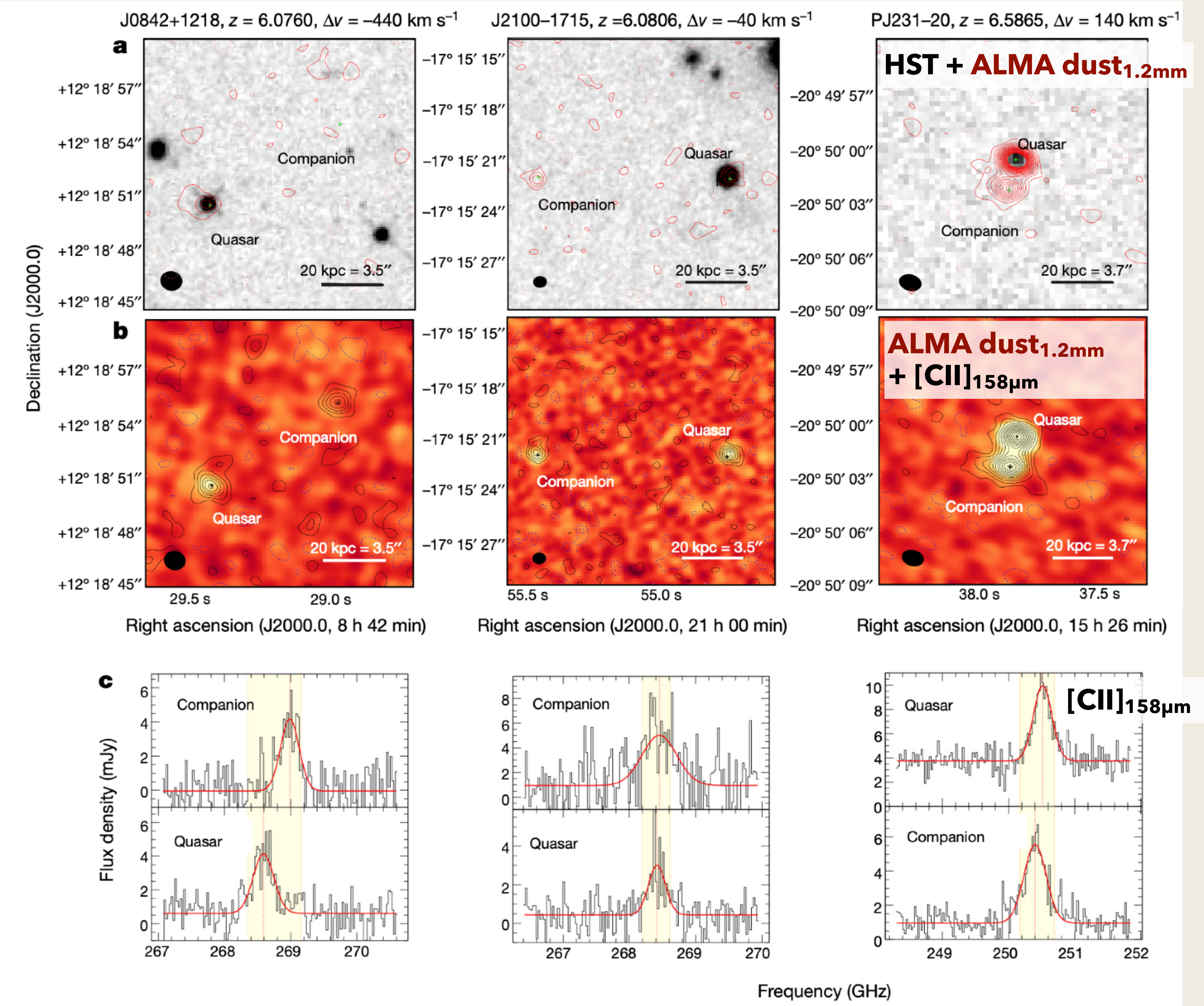


✳The broad wing in the stacked spectra may be the contribution of QSOs with relatively wide [CII] (FWHM<800 km s^{-1}; Novak+20)

The ubiquity of cold outflowing gas is unclear; Further systematic studies are needed

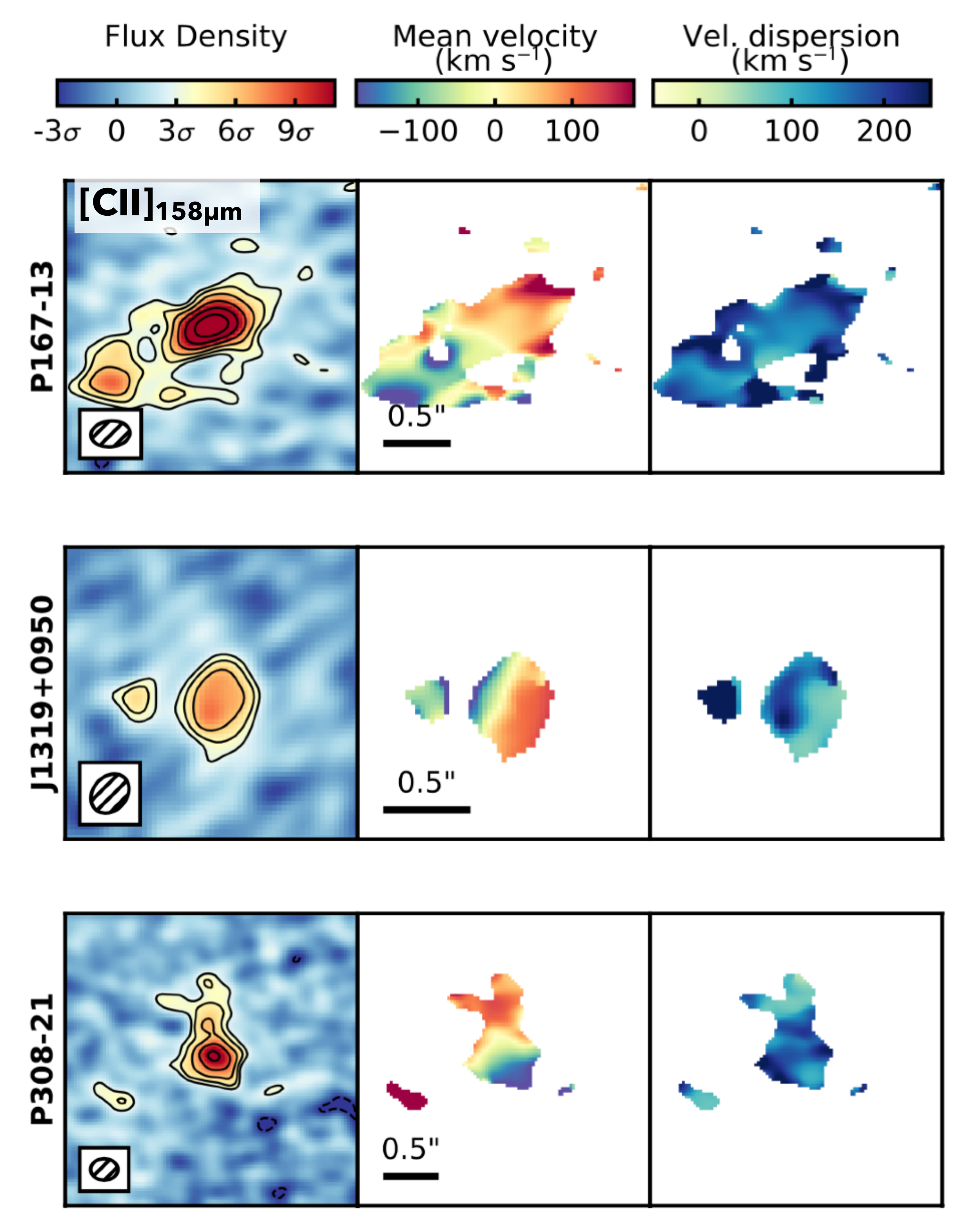
QSO Companion Galaxies at z>6

- 10-100 kpc-scale companion galaxies at z>6 (Decarli+17)



- <1.2 kpc (<0.″25) resolution ALMA imaging of 27 z>6 quasars (Neeleman+21):

  9/27 show disturbed [CII] morphology



Walter+18; Mazzucchelli+19; Decarli+19; Venemans+19; Bañados+20; Pensabene+21

Dusty companion galaxies / mergers common at z>6

Short summary 1

	Properties
No evolution	Maximum M_{BH}, BLR metallicity, host dust/gas enrichment
Evolution	QLF, BLR velocity shift, BAL fraction, merger/companion rate

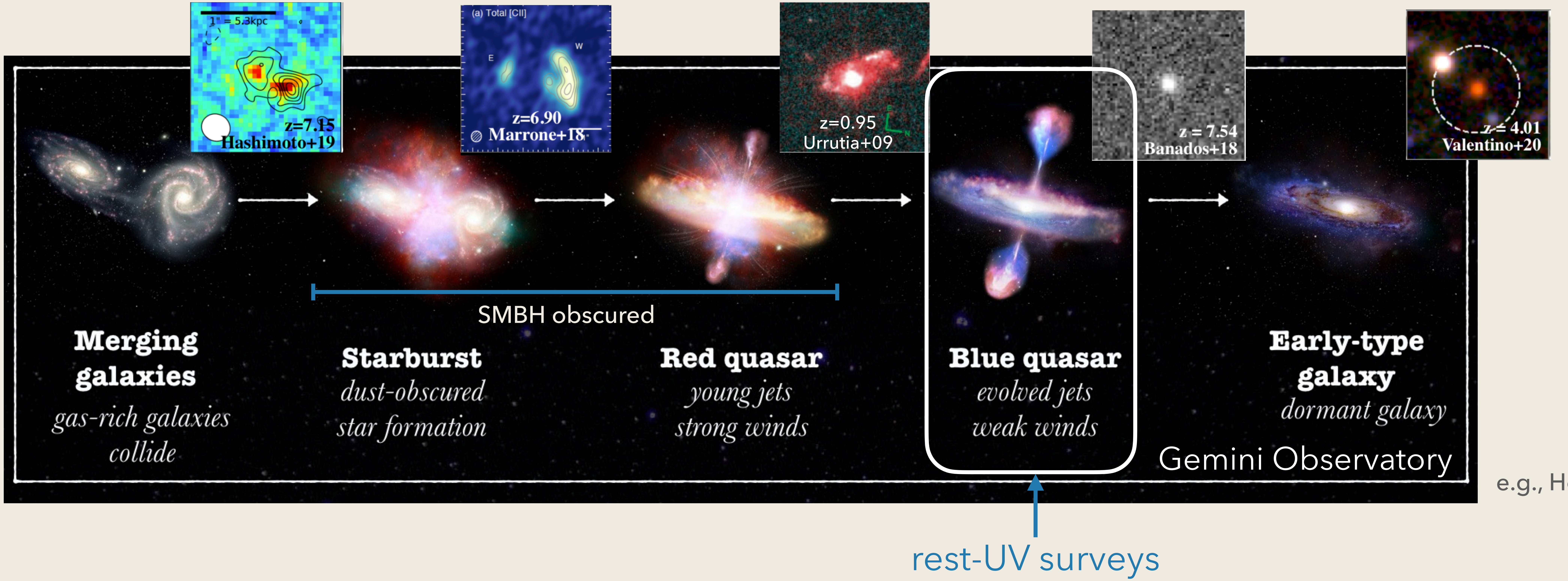
A large sample of z>6 quasars have recently enabled statistical analyses

z>6 SMBHs seem to be matured, whereas some properties do manifest redshift evolution

➡ Hints of rapid assembly of SMBHs and host galaxies?

Missing AGN Populations at z>6

Quasar Evolutionary Sequence

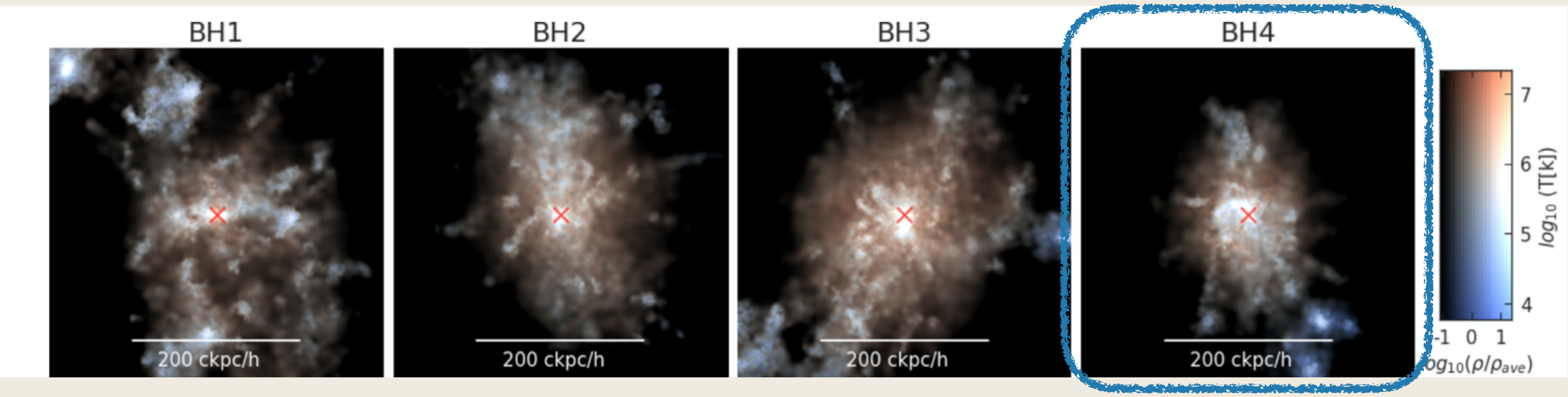


e.g., Hopkins+08

Current z>6 AGN sample mostly consists of luminous unobscured quasars

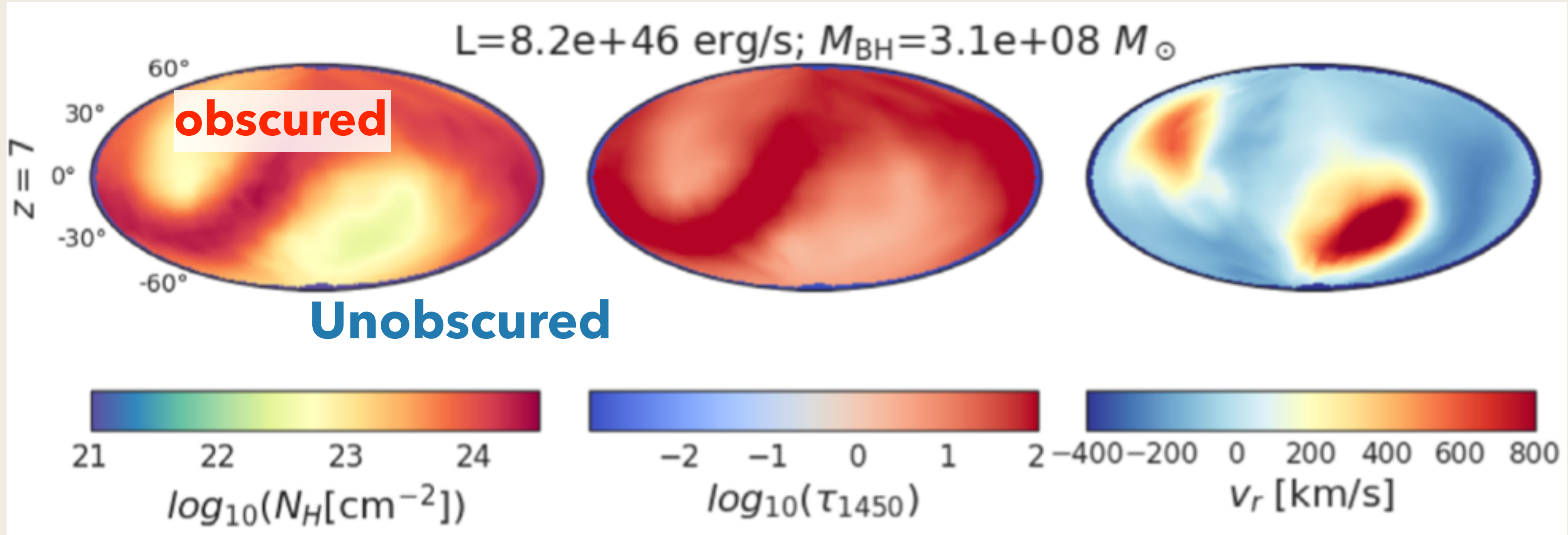
Host Environments of z>7 SMBHs

- BLUETIDES simulation of z=7 SMBHs (Ni+20)

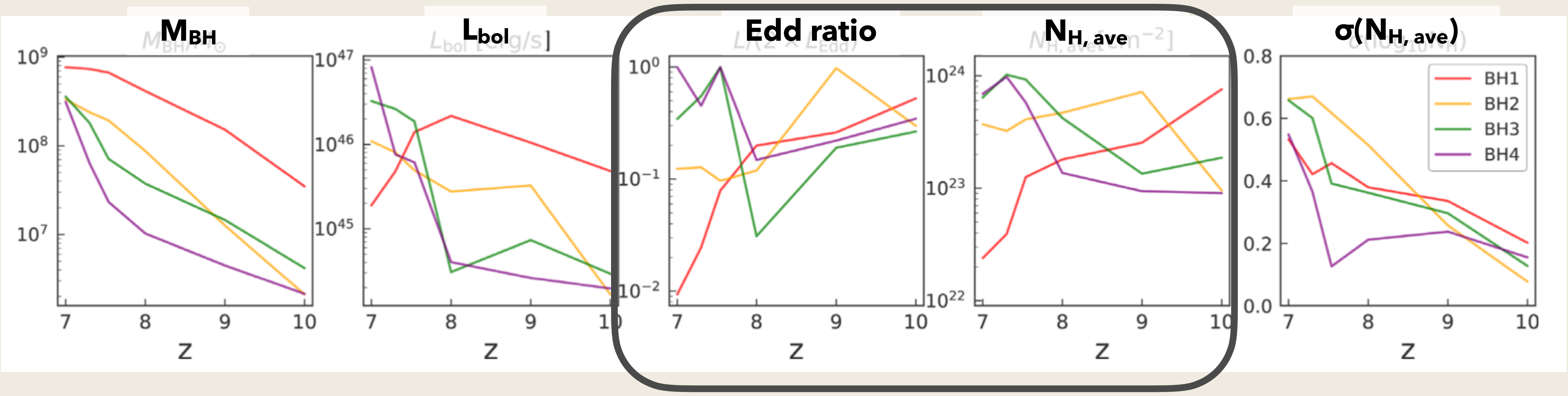


High-column density gas and dust in the innermost region can significantly contribute to the total NH, which highly depends on the observers' LoS

- BH4's angular variation of N_H, τ_{1450}, rad. velocity



- Time evolution

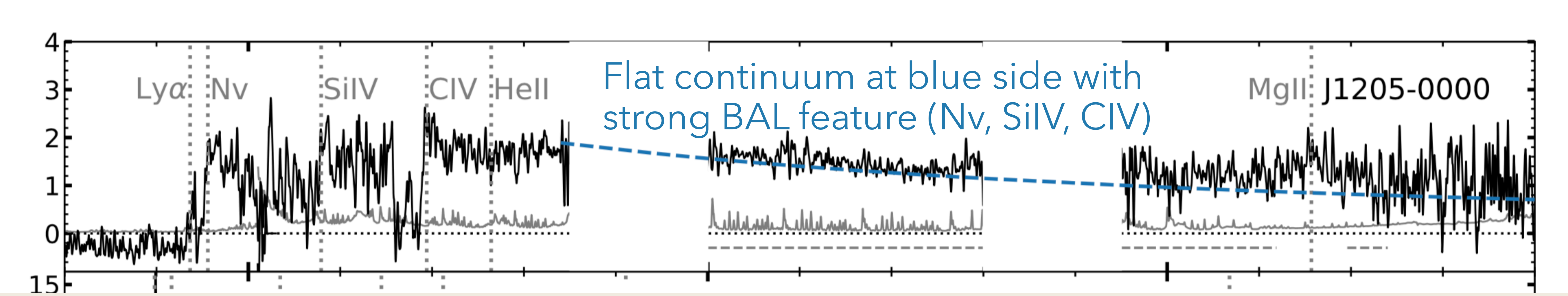


The most active growth is associated with high N_H gas!

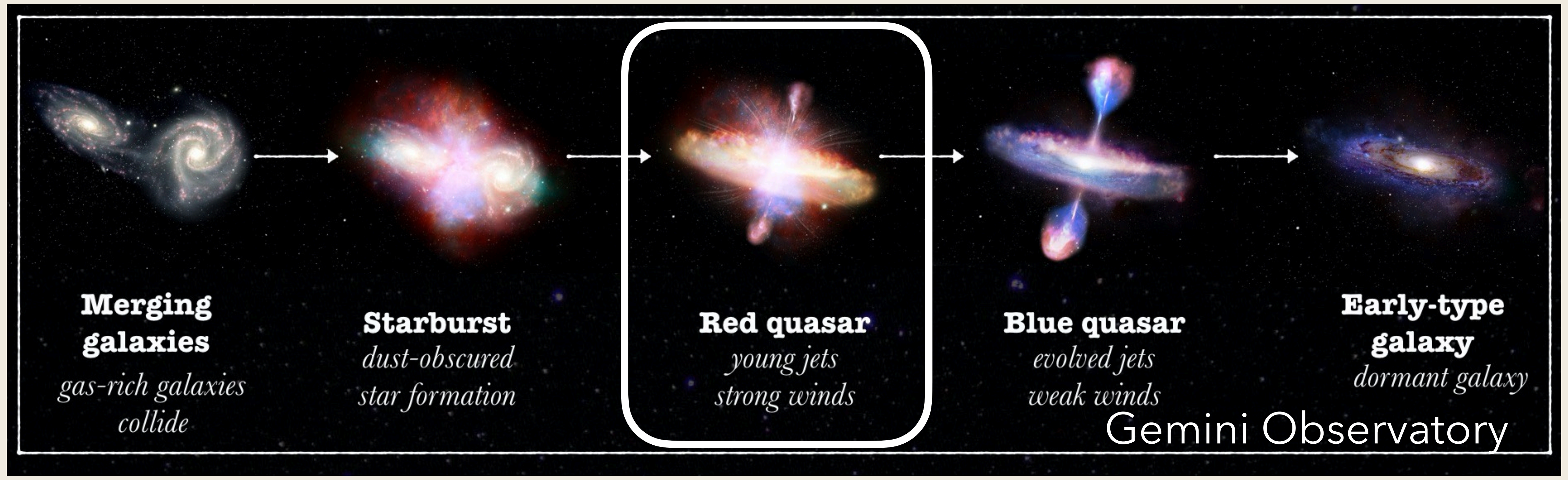
Obscured phase is the key to rapid SMBH growth and SMBH demographics?

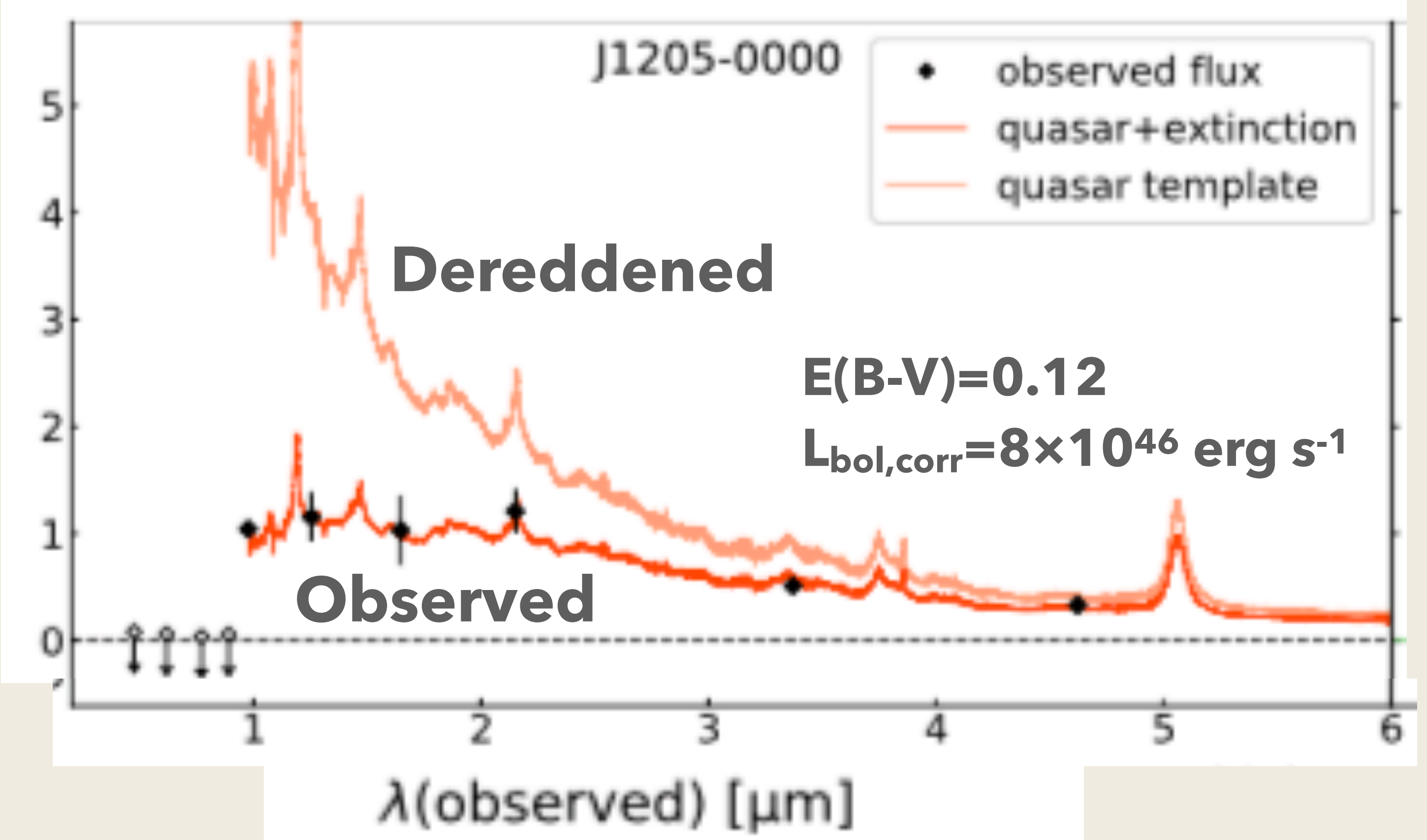
Dust-Reddened Quasar at z=6.7

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



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



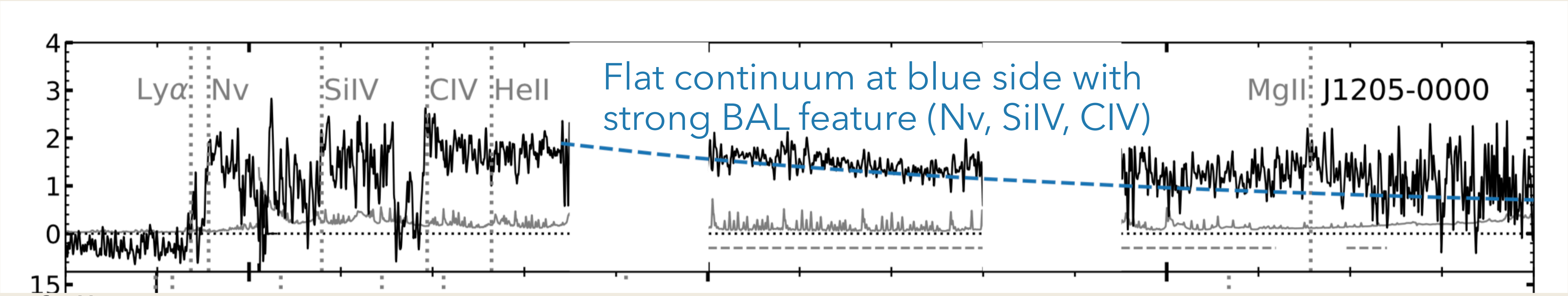


	Onoue et al. (2019)	Extinction-corrected
λL_{3000} (10^{45} erg s^{-1})	8.96 ± 0.66	$16.15^{+2.68}_{-2.53}$
$M_{\rm BH}$(Mg II) (10^9 $M_\odot$)	$2.2^{+0.2}_{-0.6}$	$2.9^{+0.3}_{-0.8}$
$L_{\rm bol}/L_{\rm Edd}$	$0.16^{+0.04}_{-0.02}$	$0.22^{+0.04}_{-0.03}$

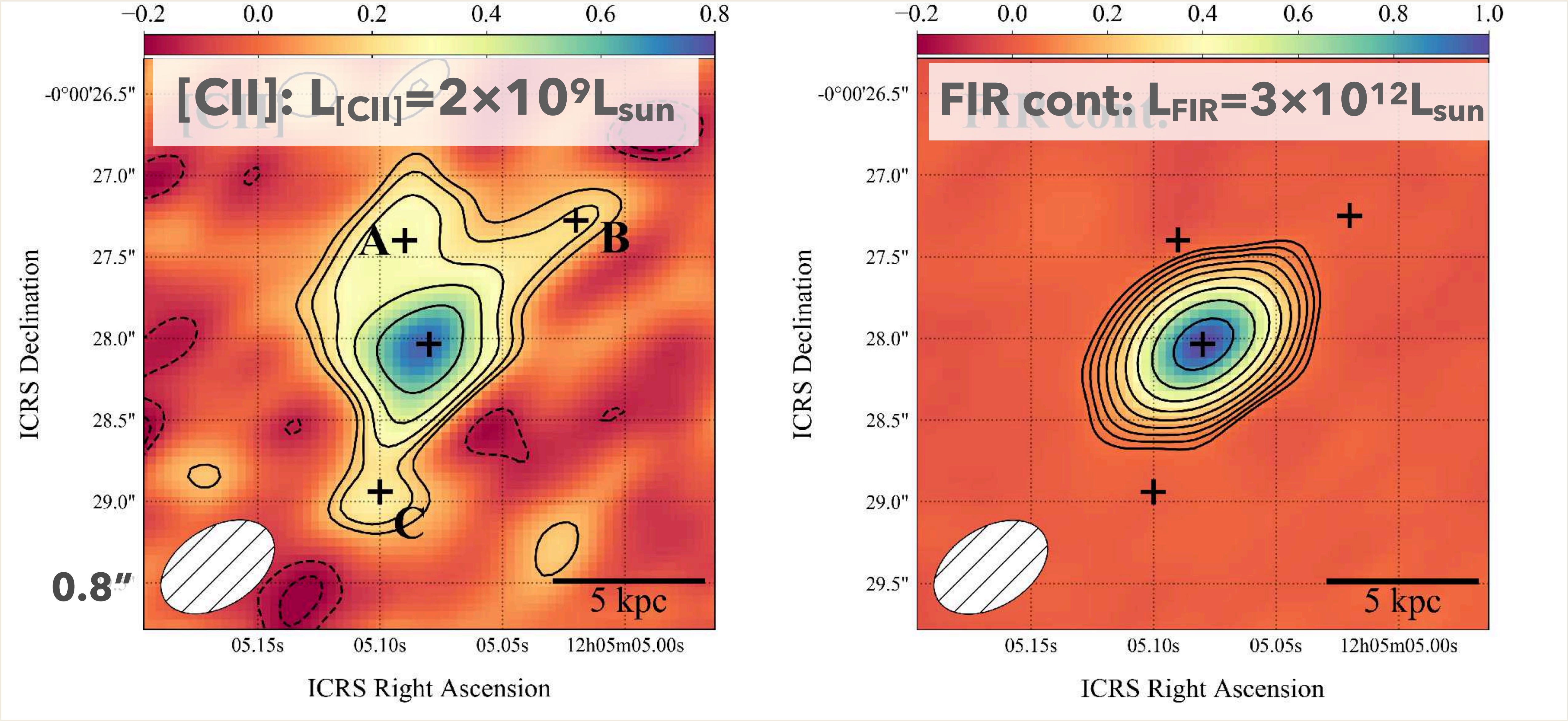
A modestly dust-obscured quasar found from the HSC's low-luminosity quasar sample at z>6

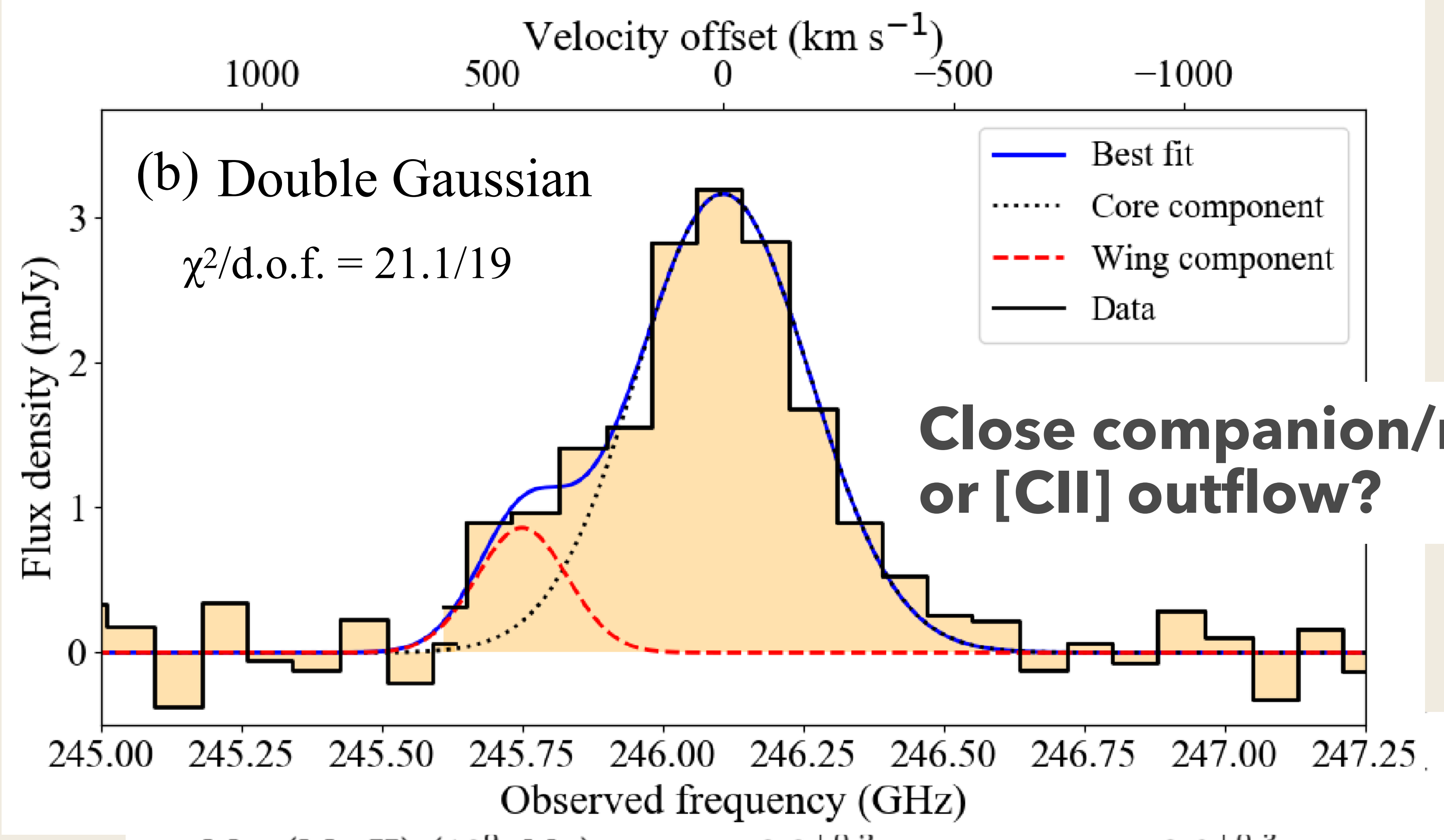
Dust-Reddened Quasar at z=6.7

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



- ALMA dust+[CII] followup (Izumi+21a)



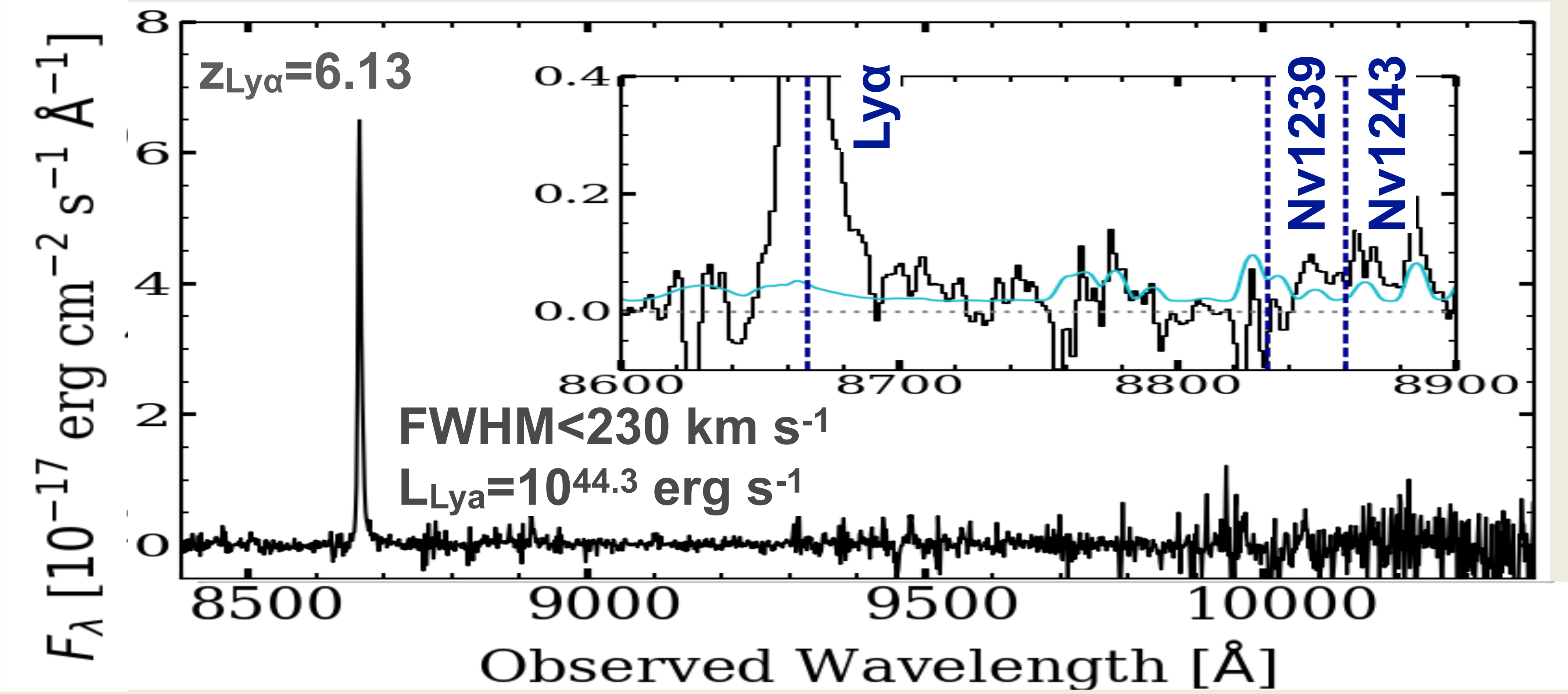


Close companion/merger or [CII] outflow?

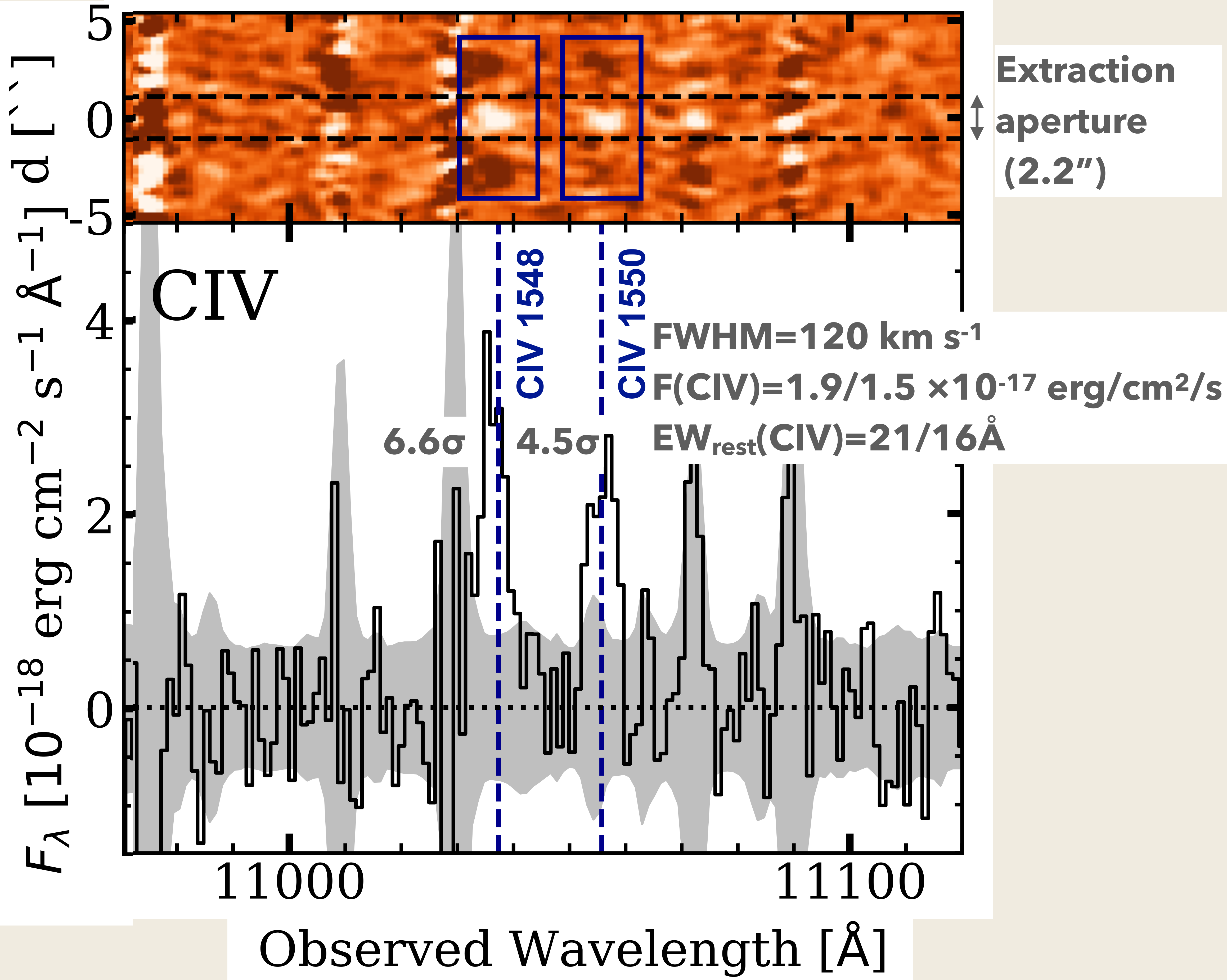
M_{BH}(Mg II) (10^9 $M_\odot$)	$2.2^{+0.2}_{-0.6}$	$2.9^{+0.3}_{-0.8}$
L_{bol}/L_{Edd}	$0.16^{+0.04}_{-0.02}$	$0.22^{+0.04}_{-0.03}$

A Candidate Obscured Quasar at z>6

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



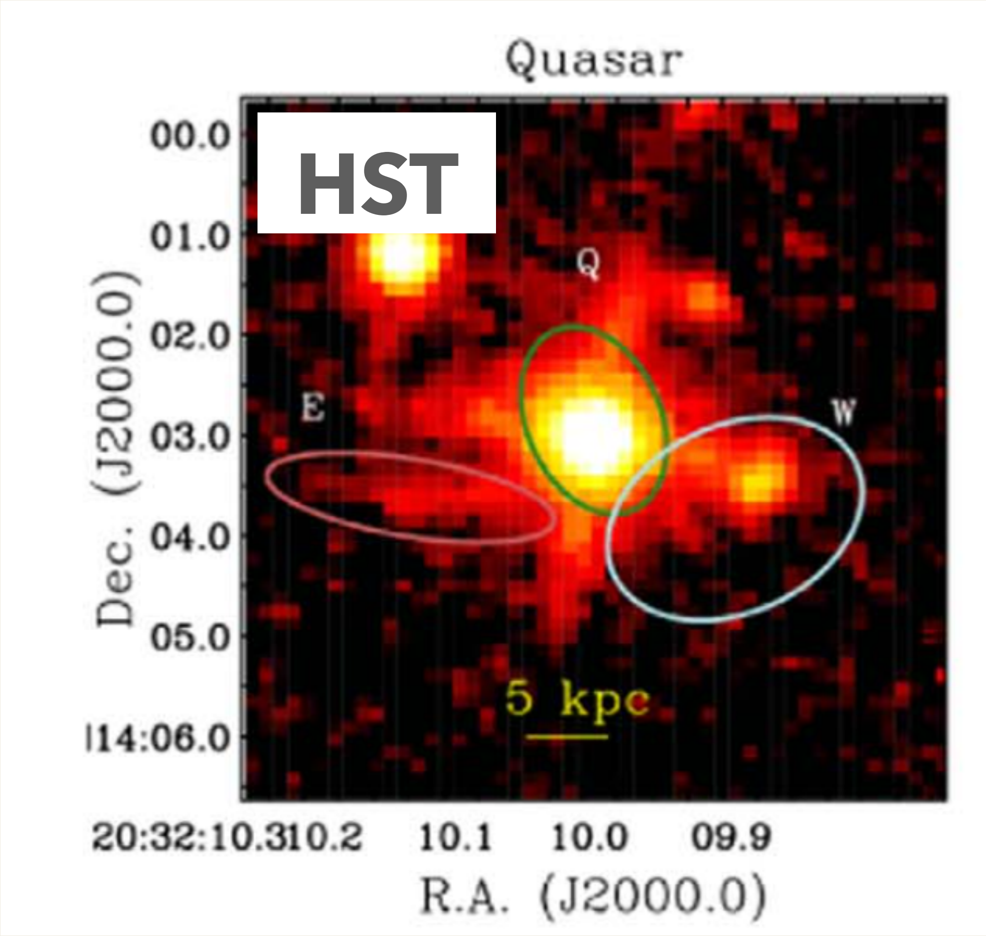
- MOSFIRE Y-band (2hr; Onoue+20)

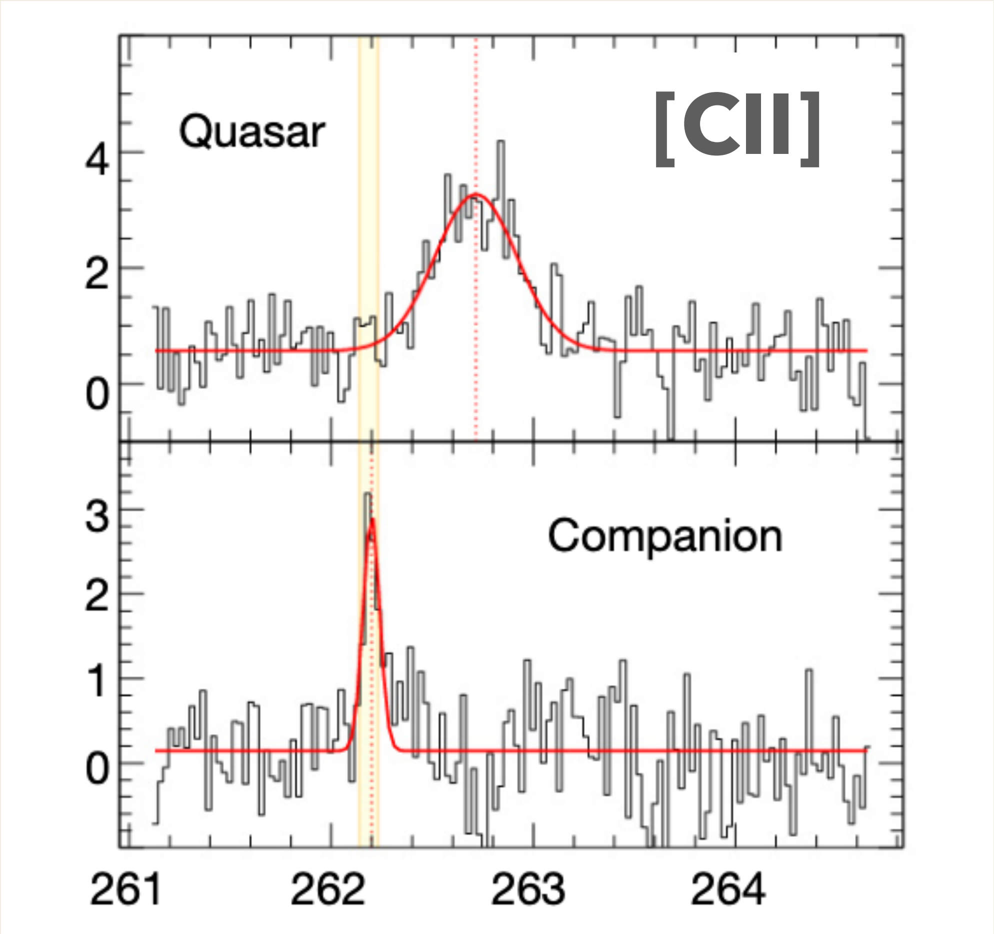


- A clear detection of CIVλλ1548,1550 doublet from a narrow Lyα source (originally selected as quasars)
  - z=6.1292±0.0002, Δv(CIV-Lyα)=-30 km/s
  - FWHM=120±20 km s^{-1} (not type-I)
- **Total EW_{rest}(CIV)=37_{-5}^{+6} Å**: cannot be explained by stellar photoionization (Nakajima+18)
- Cy23 Chandra program accepted (with 3 other similar sources)

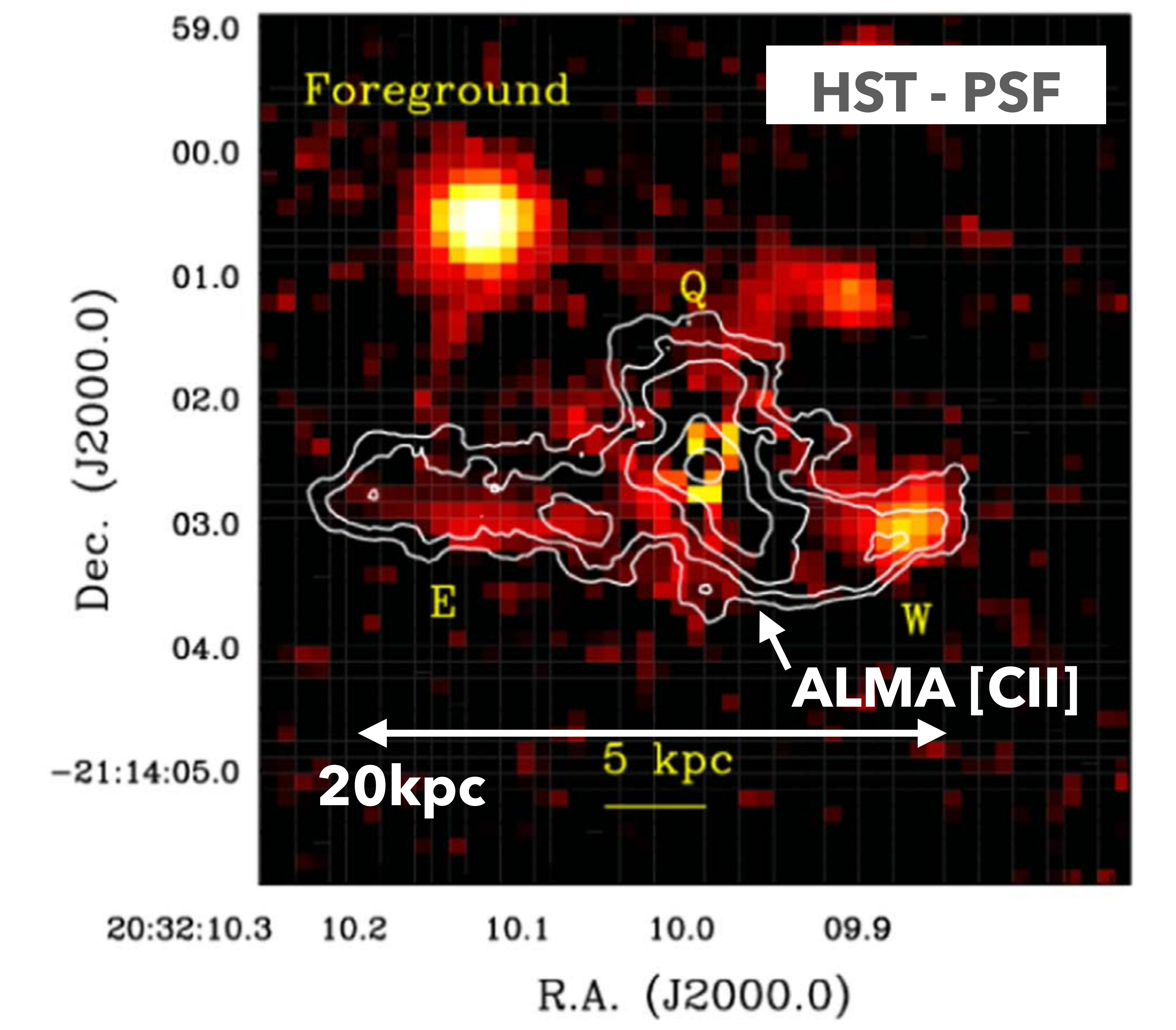
See also: Connor+20; Vito+19 & 21

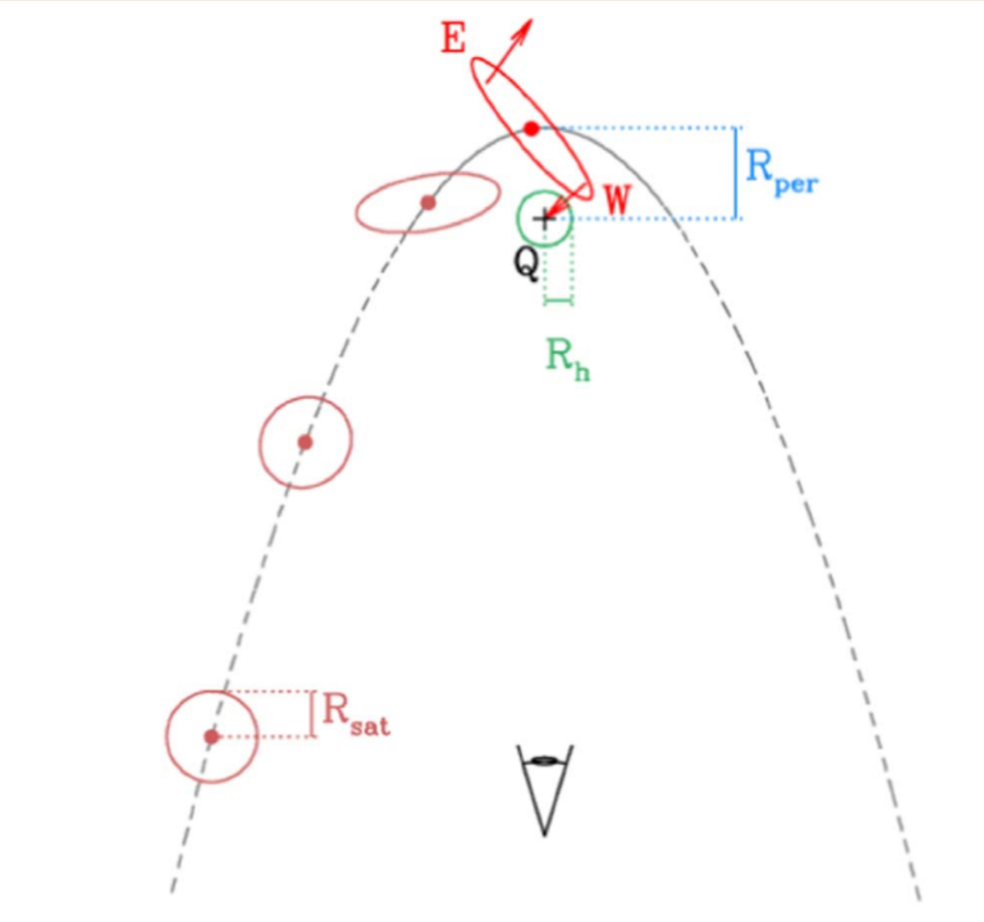
A QSO-Galaxy Merger at z=6.2





- PJ308-21 (Decarli+19)





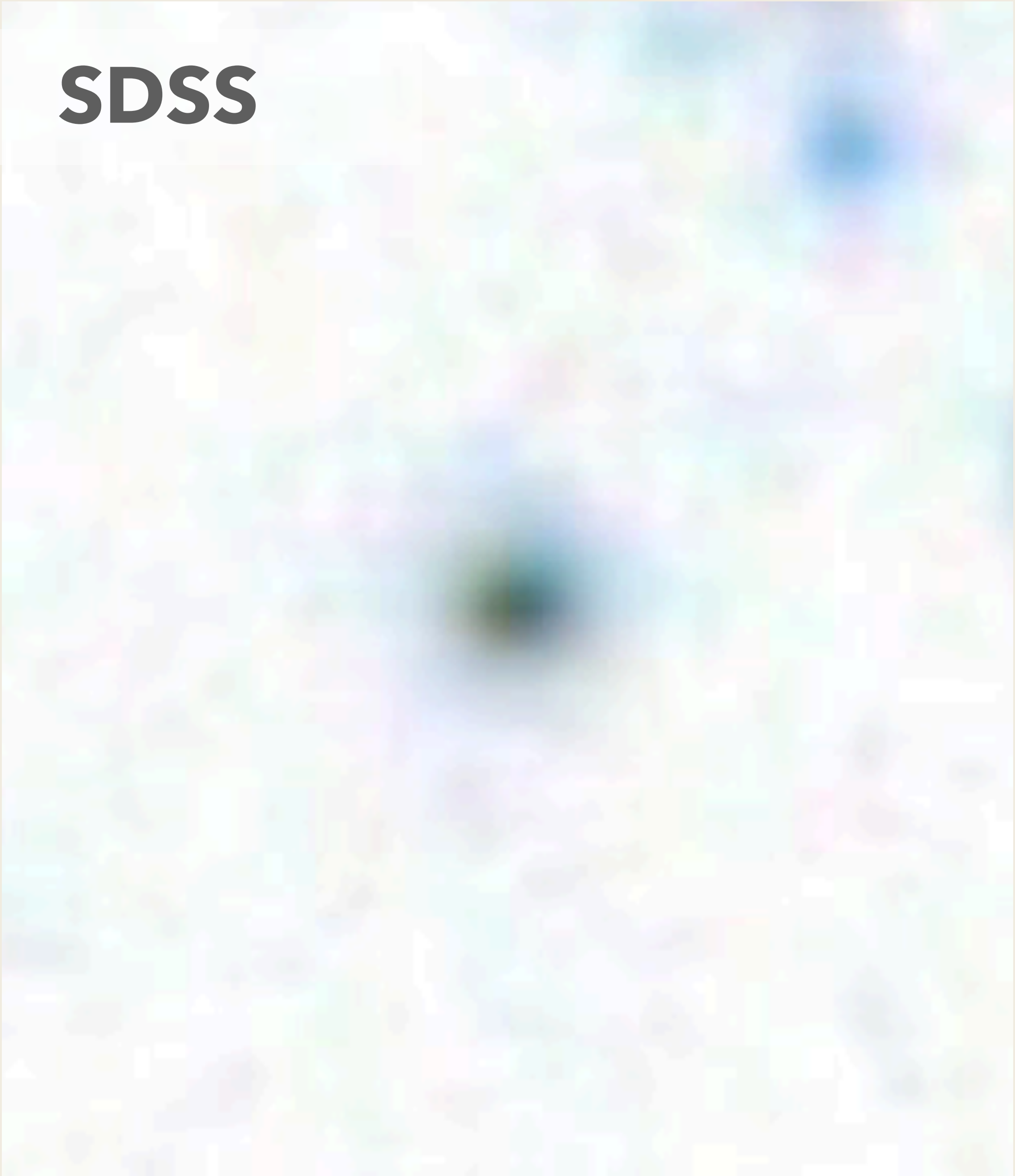
Satellite galaxy is tidally stripped by interaction with the central quasar

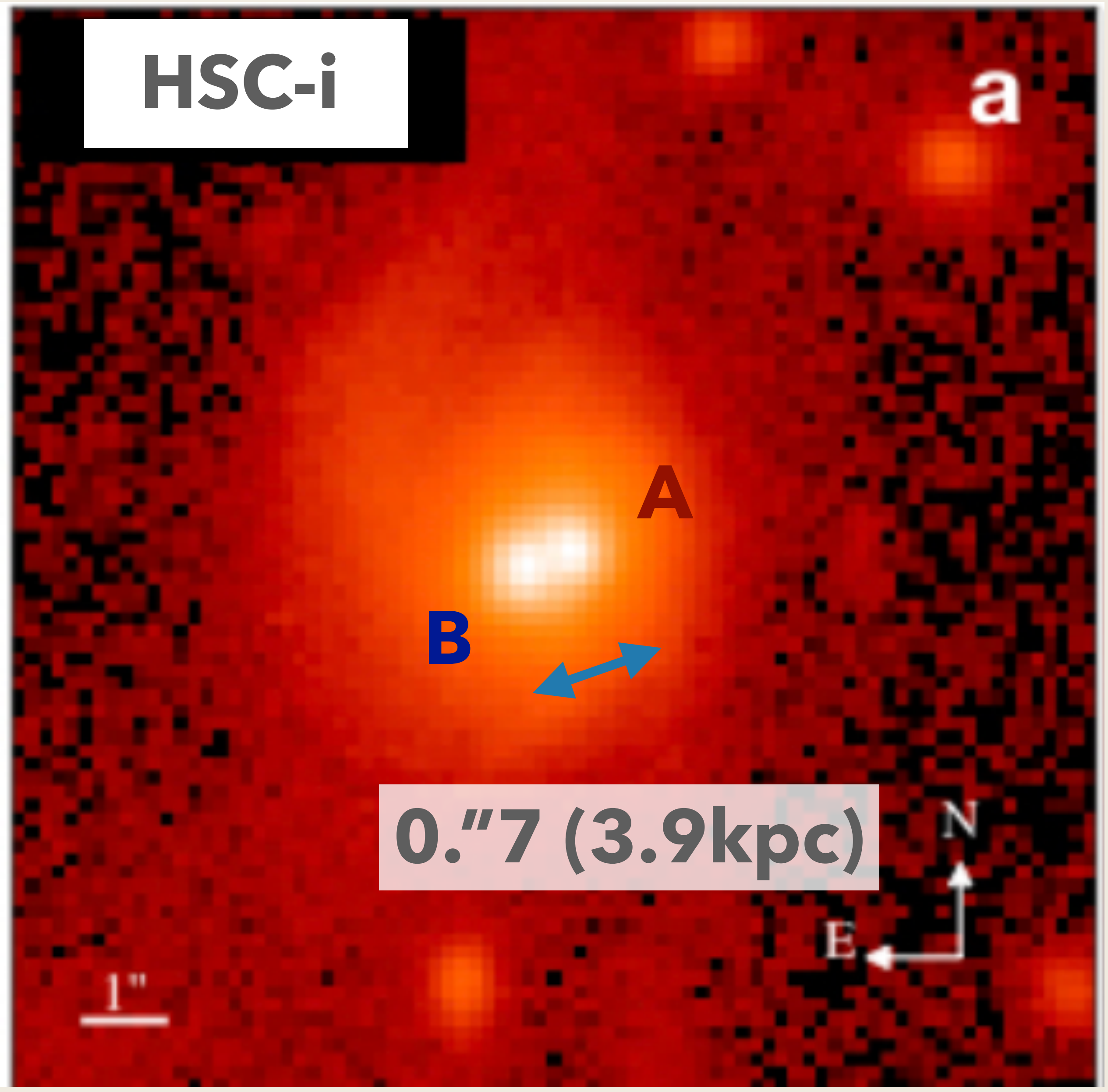
✦JWST Cy1 GO: NIRSpec IFU (Hβ+[OIII], Hα+[NII], etc.)
- Kinematics of ionized gas
- Host M_*, metallicity, etc.

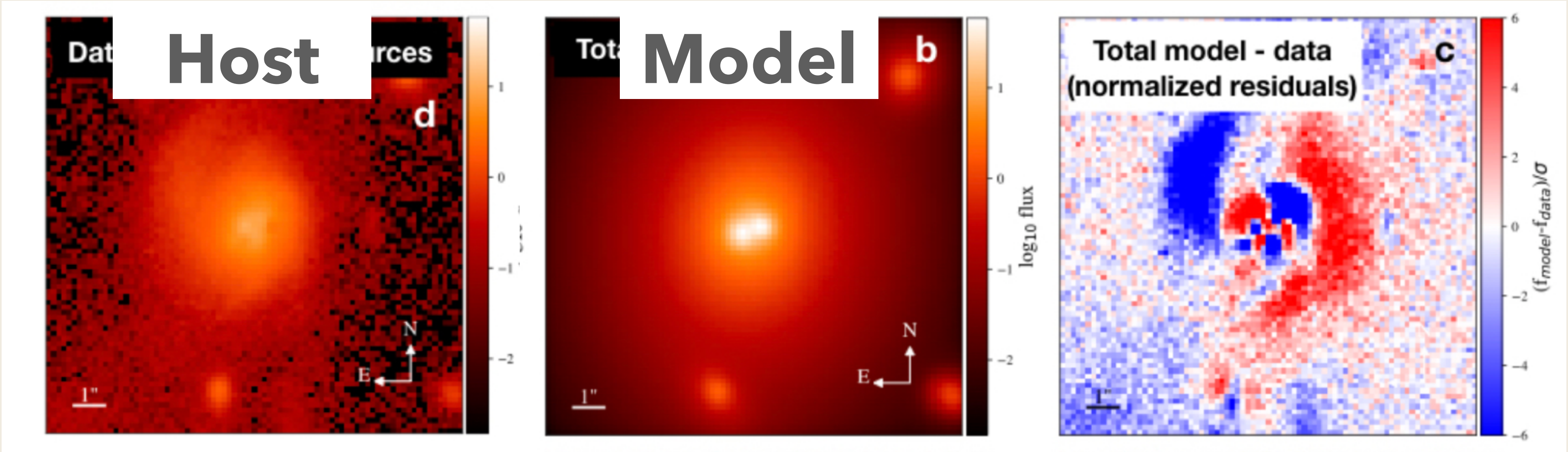
See also: Pensabene+21; Matsuoka+ in prep.

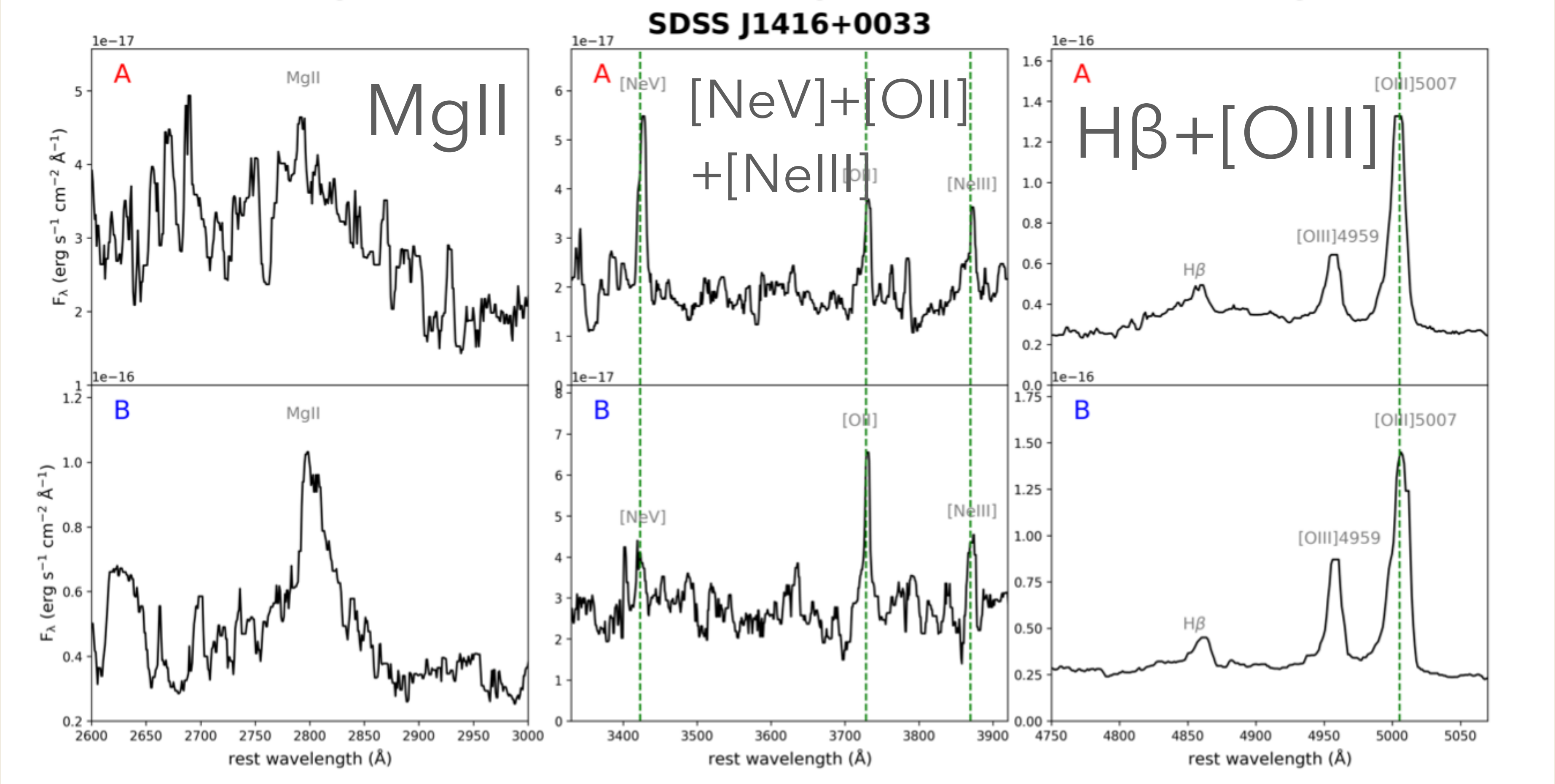
Dual AGN Search with HSC-SSP

- SDSS J1416+0033, z=0.43, i_{AB}=18.2









Silverman+20; Tang+21

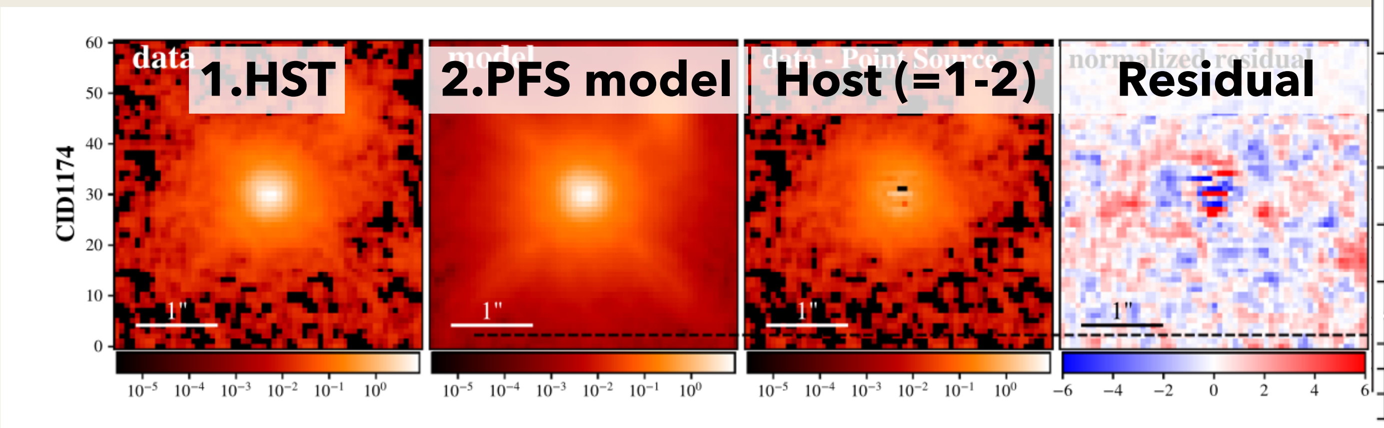
HSC images of SDSS quasars revealing dual SMBHs at z<3 (<20 kpc separation)

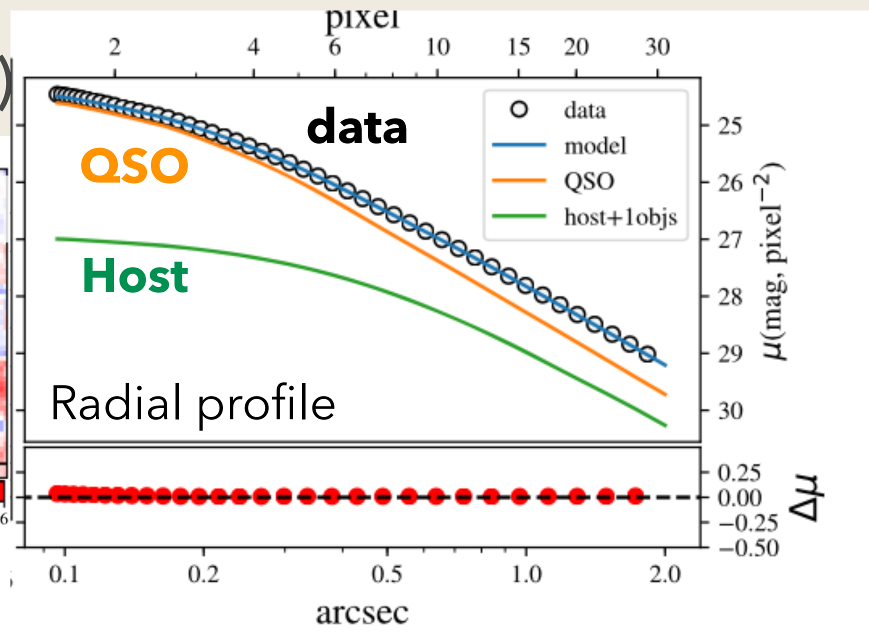
multi-wavelength follow-up observations ongoing with Subaru, ALMA, etc. (M_{BH}, M*, gas kinematics, etc.)

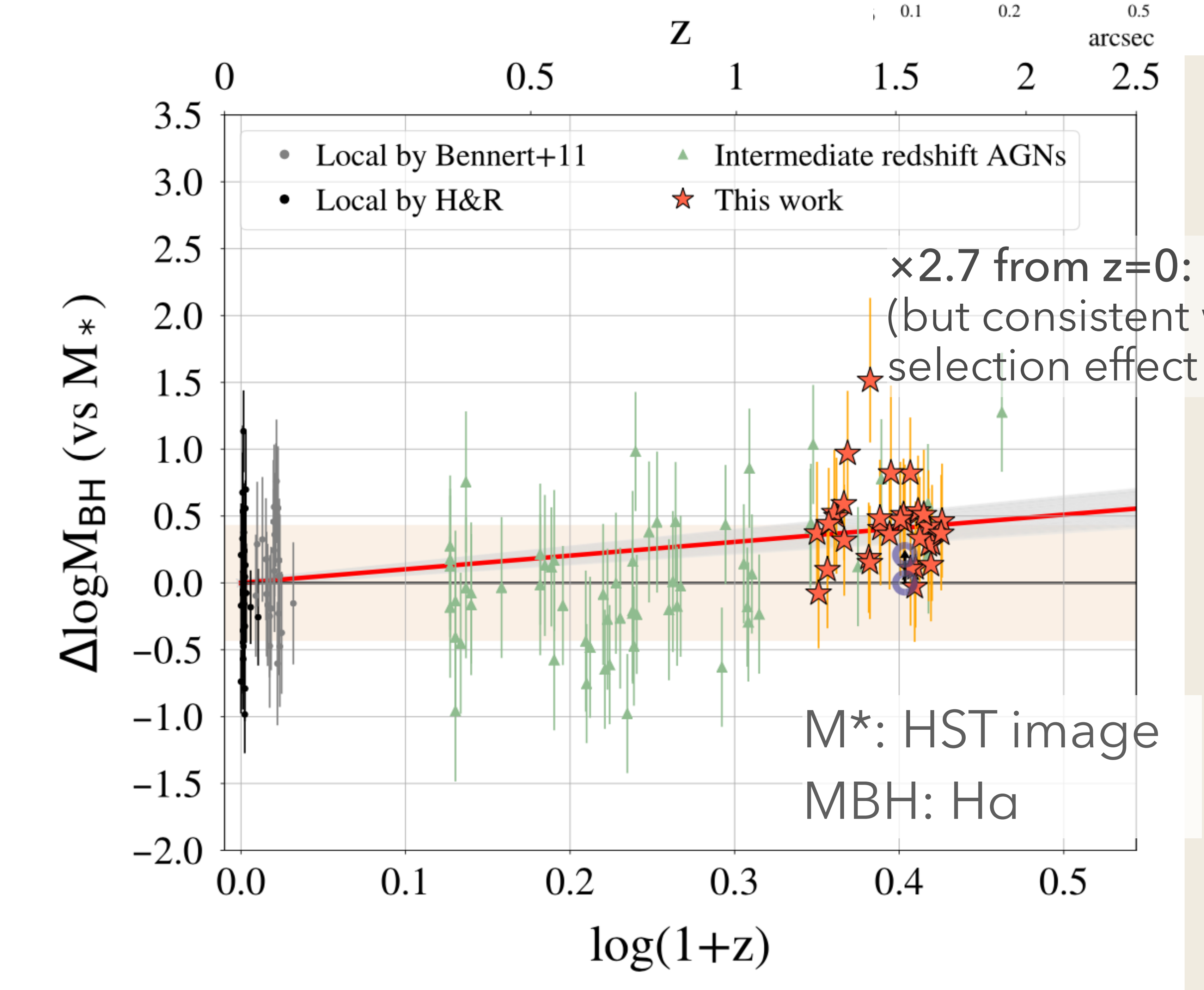
Origin of SMBHs - Host Co-evolution

Redshift Evolution of M_{BH}/M_{*} Ratio

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



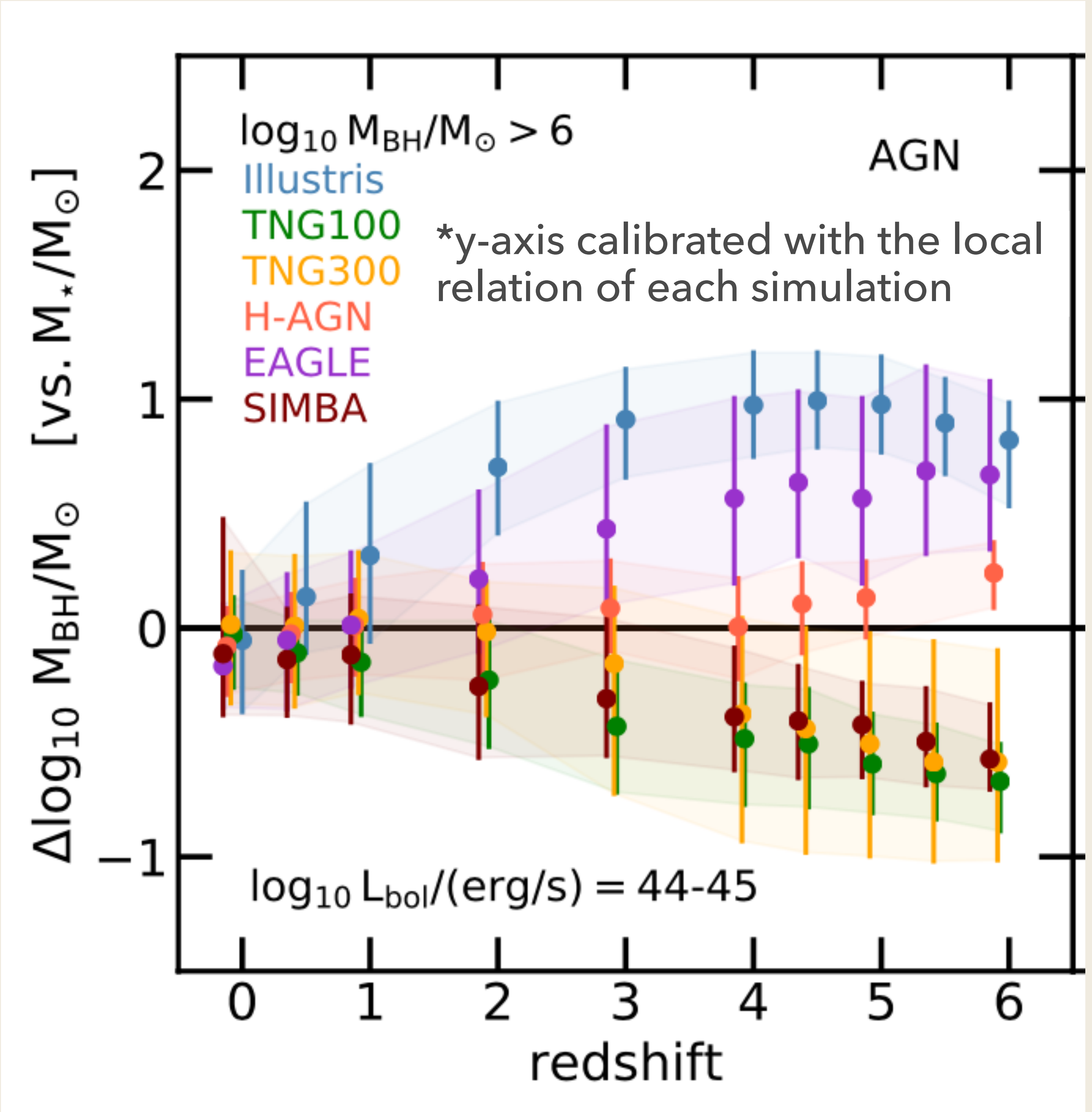




×2.7 from z=0: BH-dominant growth?
(but consistent with no evolution when selection effect taken into account)

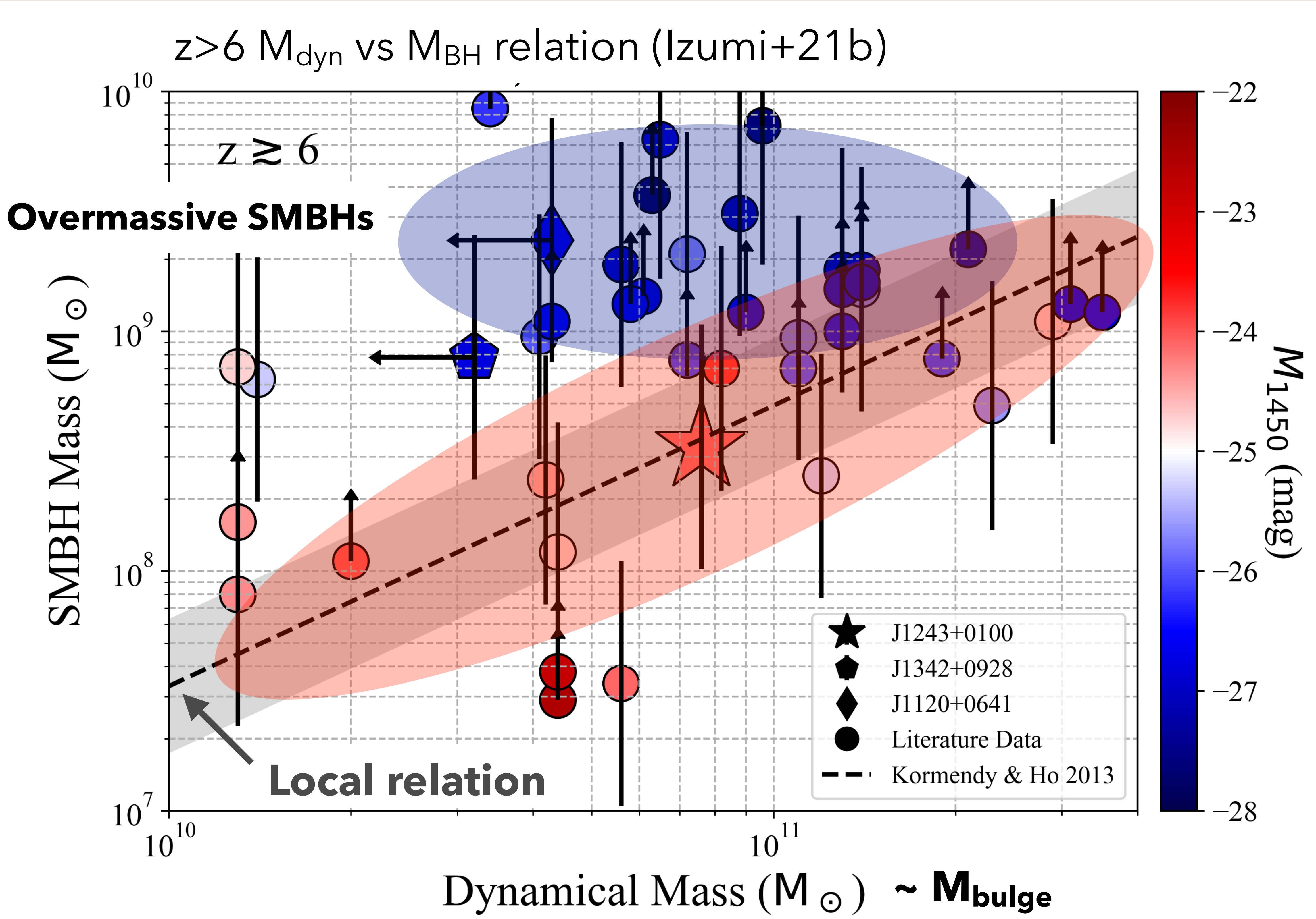
M*: HST image
MBH: Hα

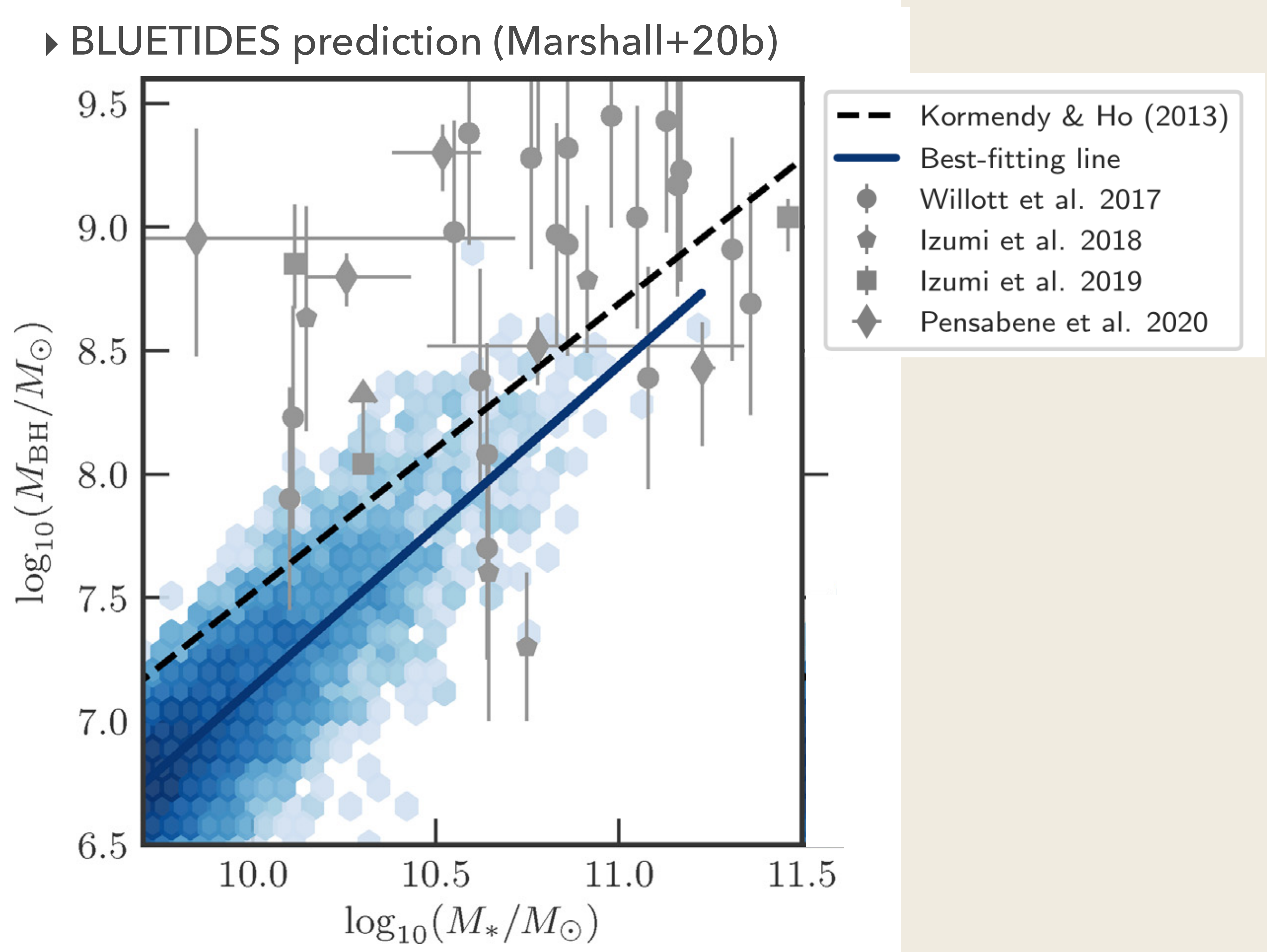
- Prediction from six cosmological simulations (Habouzit+ in prep.):
  Completely different predictions due to different modeling of AGN feedback



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

ALMA Views of Co-evolution at z>6

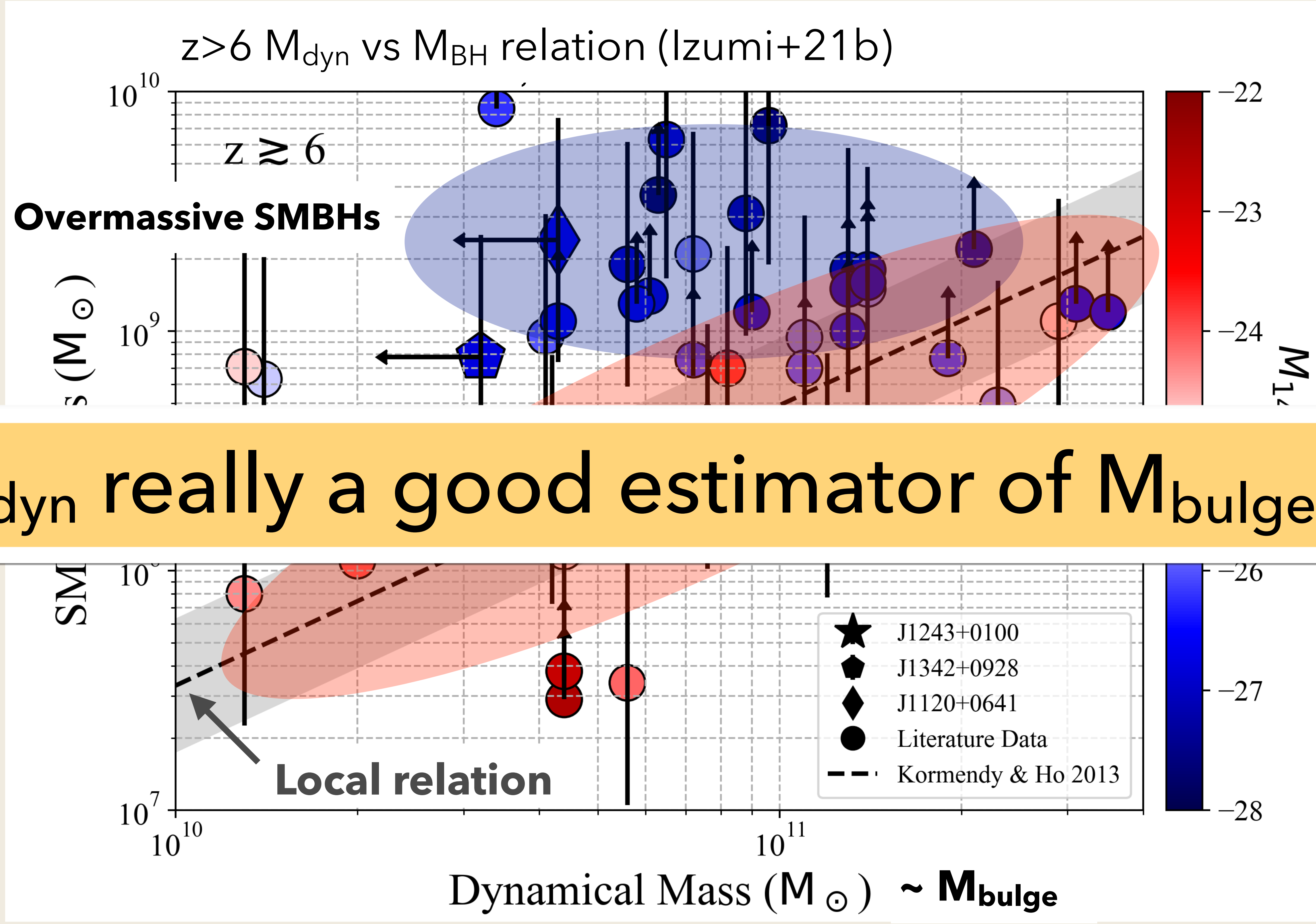


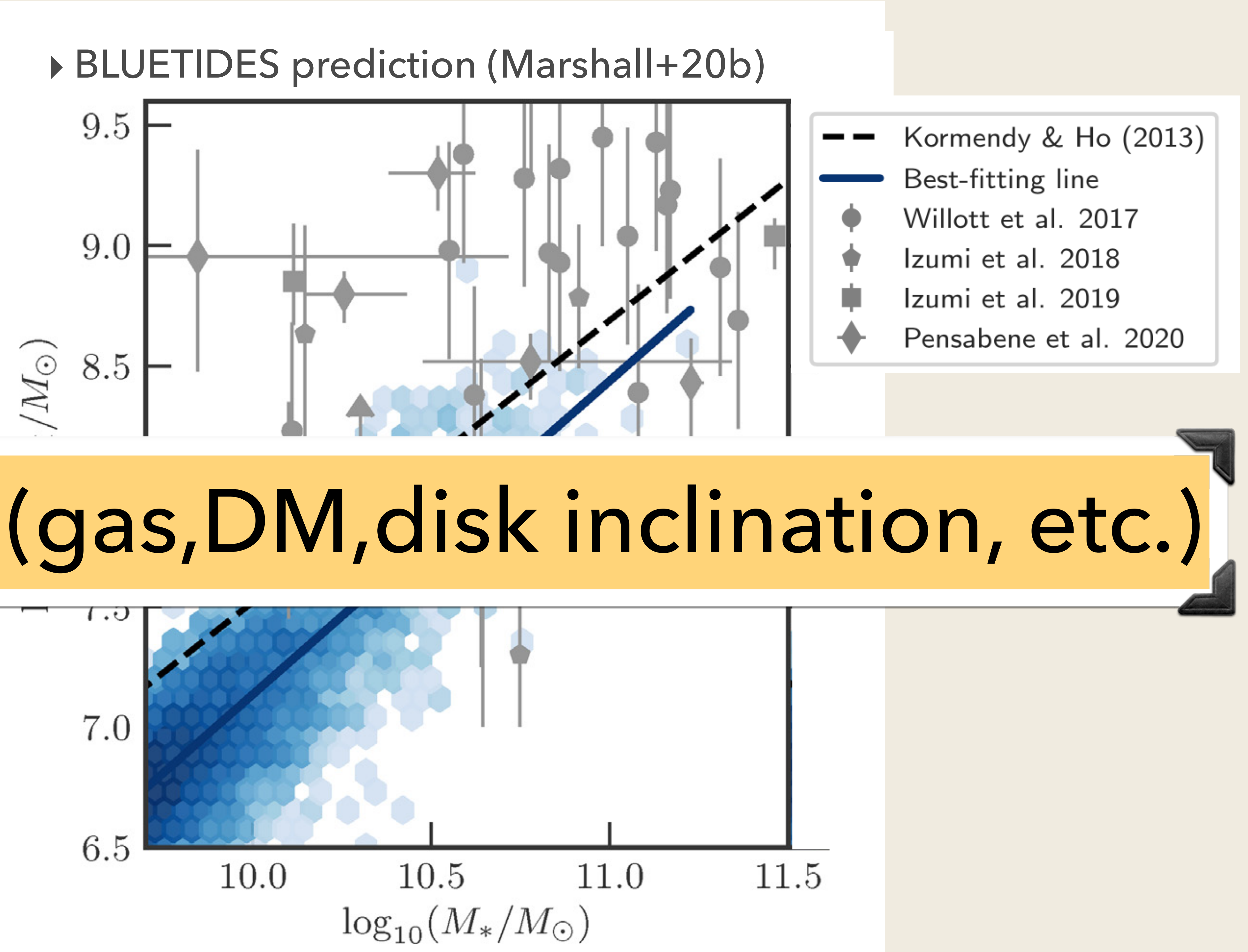


- ✦Co-evolution relation established already at z=6-7?
- ✦Less-biased low-luminosity quasars essential to trace the general SMBH trend
- ✦Consistent with a recent hydrodynamical model prediction

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

ALMA Views of Co-evolution at z>6





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

- ✦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

Stellar Mass vs BH Mass at z=6

- JWST Cy1 GO medium ``*A Complete Census of SMBHs and Host Galaxies at z=6*" (PI:MO, co-PI: Y.Matsuoka, T.Izumi, X.Ding, J.Silverman)
  - NIRSpec G395M Fixed-Slit spectroscopy + NIRCam F150W+F356W imaging

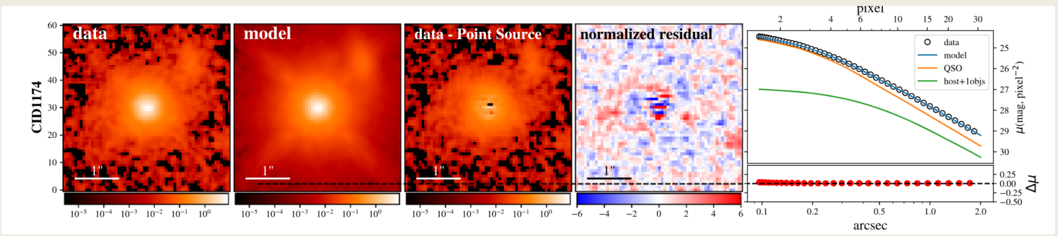
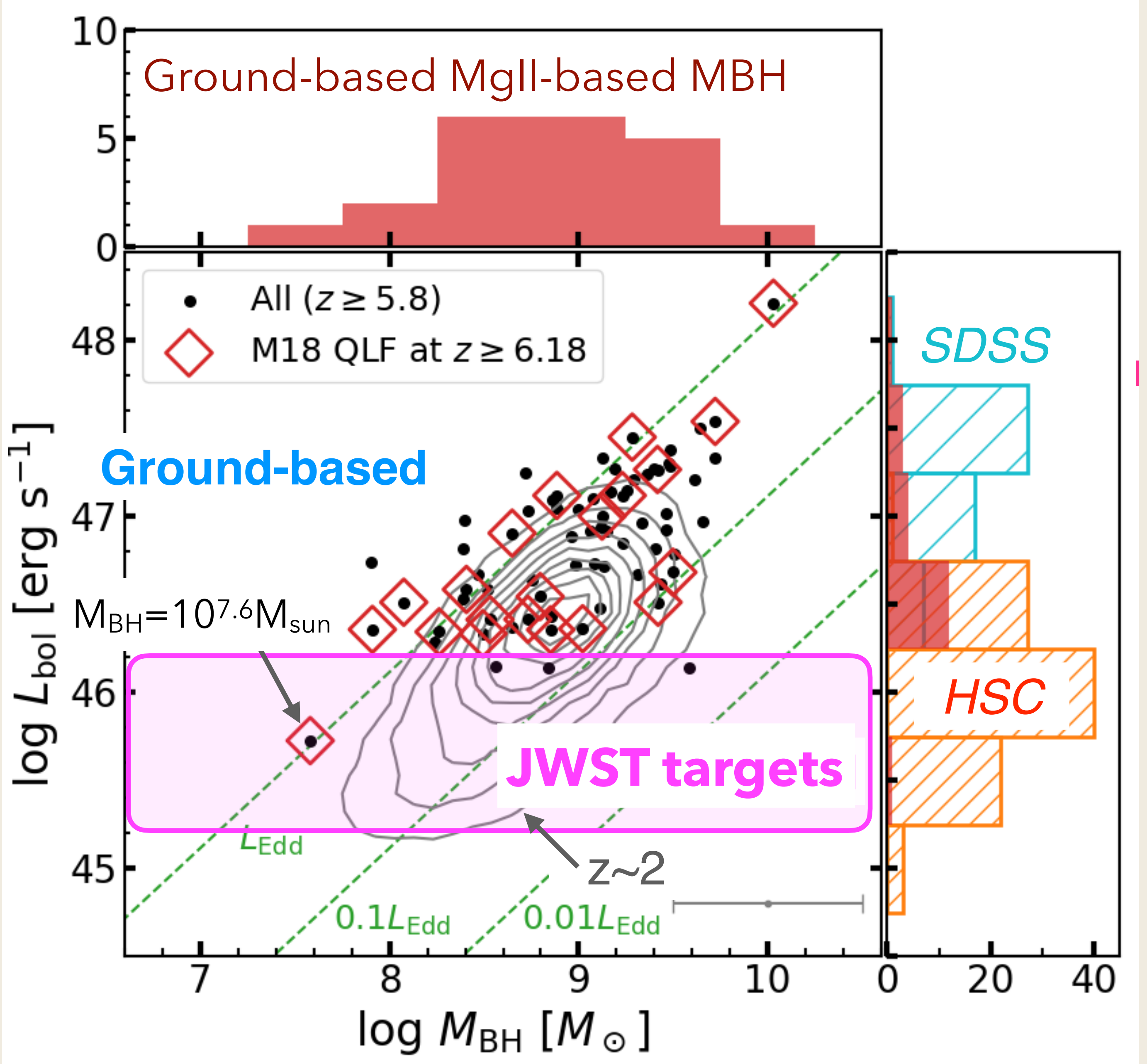


Image decomposition of host stellar and quasar emission with JWST!



Characterization of SMBH-galaxy co-evolution with 12 lowest-luminosity HSC quasars at z=6:
Hβ-based M_{BH} and host M_* (+age) measurements (+ many ancillary science)

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 -> M*, SFR, ionized gas kinematics, metallicity, ionization parameter	z=6.2 merger in Decarli+19	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 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-qsos	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	Ionized gas kinematics and metallicity, host stellar population, morphology	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* + MBH, BHMF, 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	PC member confirmation (target sfrom HST 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. J. Yang Dr. F. Wang	5.5	NIRSpec IFU + MIRI Imaging	Constraining dust extinction, MBH,	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	QSO 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	

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 coming in mid-to-late 2020s.
- ✦ Billion-solar-mass SMBHs within the first billion years of the universe have put a stringent constraint on the early SMBH growth
- ✦ The most luminous quasars are powered by already matured SMBHs and host galaxies, whereas there are some possible signatures of BLR that are in the rapid process of formation
- ✦ AGNs in the early stages of merger-induced quasar activity (early mergers, modestly/heavily-obscured quasars) have started to be identified from the HSC-SSP
- ✦ ALMA dynamical mass measurements have shown that the SMBH-galaxy co-evolution may have already been establishes at z>6; JWST's direct stellar mass measurements at z>6 will provide more robust evidence