High-redshift ($z > 6$) accreting SMBHs in the X-rays

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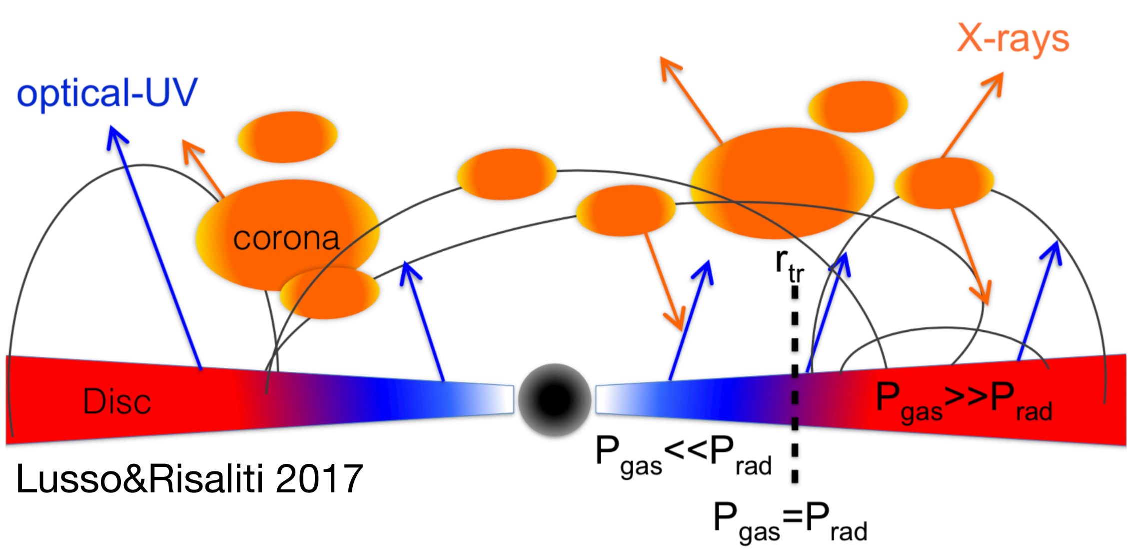
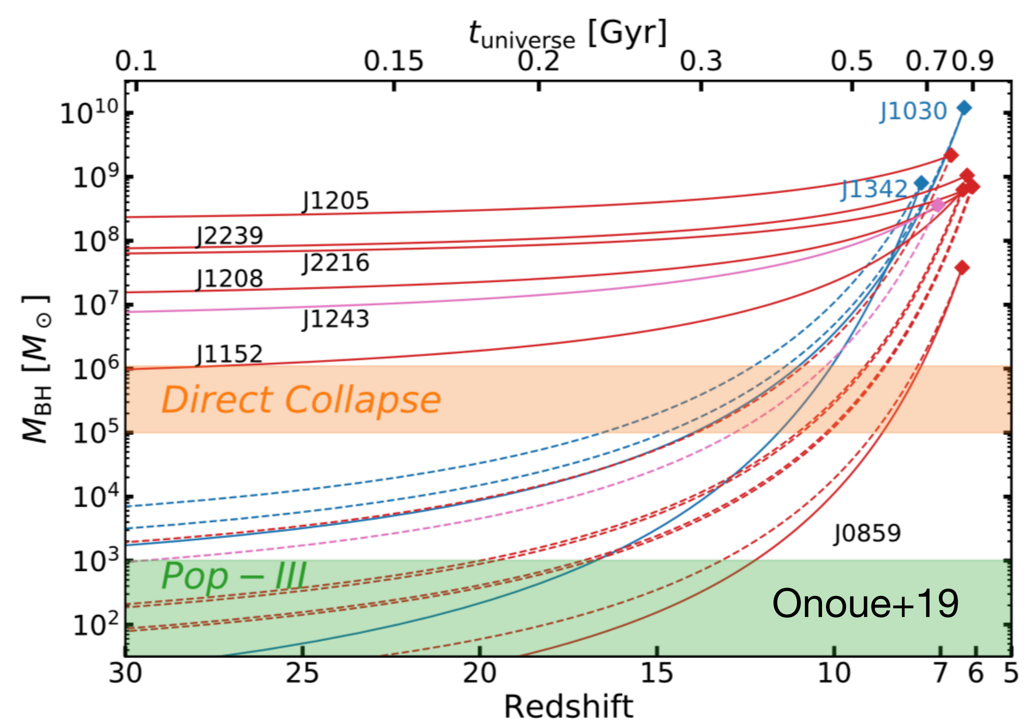
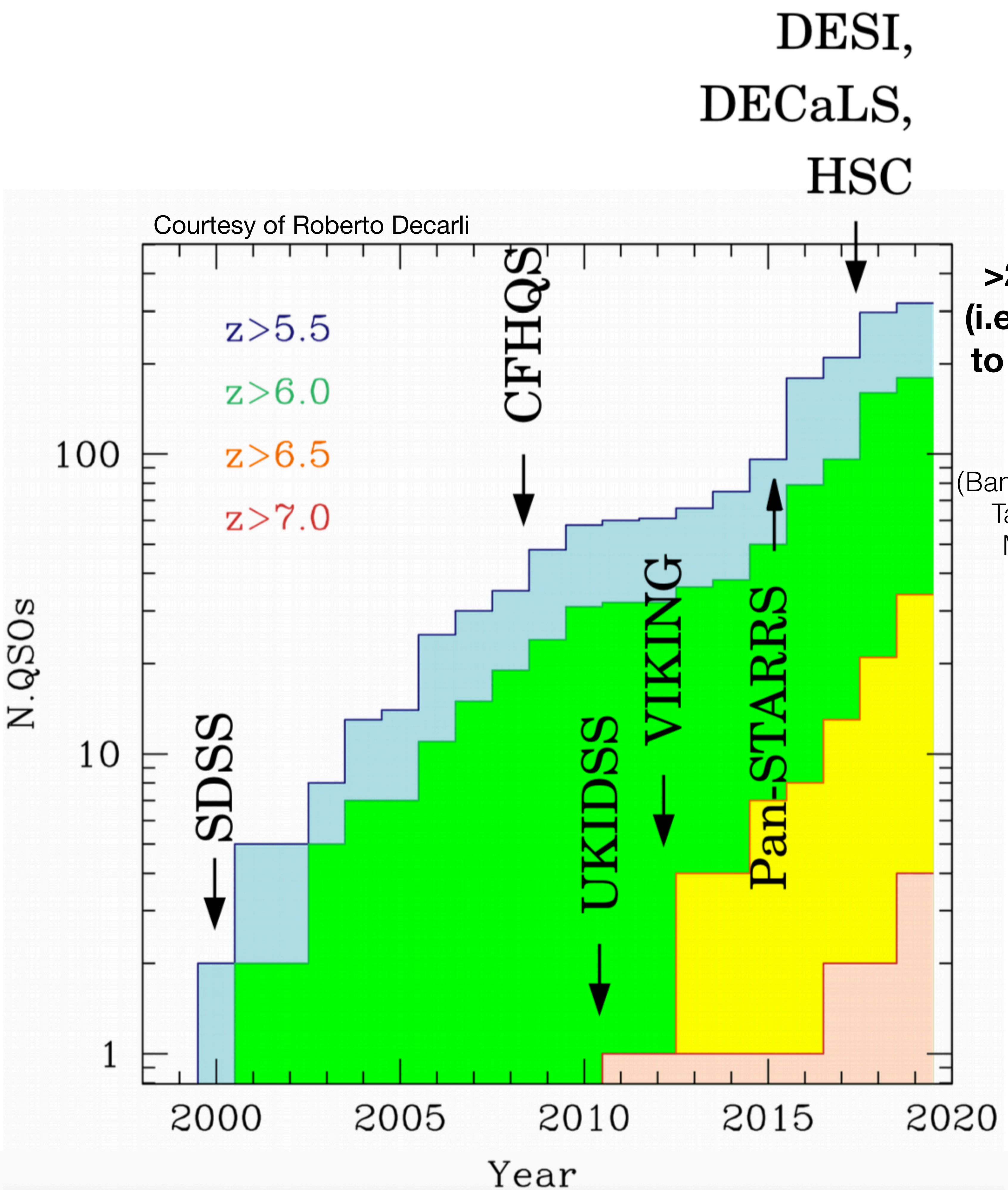


Testing self-similarity of QSO accretion physics up to $z > 6$



Witnessing SMBH accretion as close as possible to the initial conditions of SMBH formation



>200 QSOs discovered so far at z>6 (i.e. <1 Gyr after the Big Bang), thanks to wide area (>1000 deg²) optical/NIR surveys

(Banados+16, +18, Mazzucchelli+17, Reed+17, +19, Tang+17, Wang+17, +18a, +18b, Chehade+18, Matsuoka+18a,+18b, +19, Yang+18, Fan+19, Pons+19)

(only ~15 z>6 QSOs with X-ray data, <8% of the known population)

Selection of high-z QSO candidates

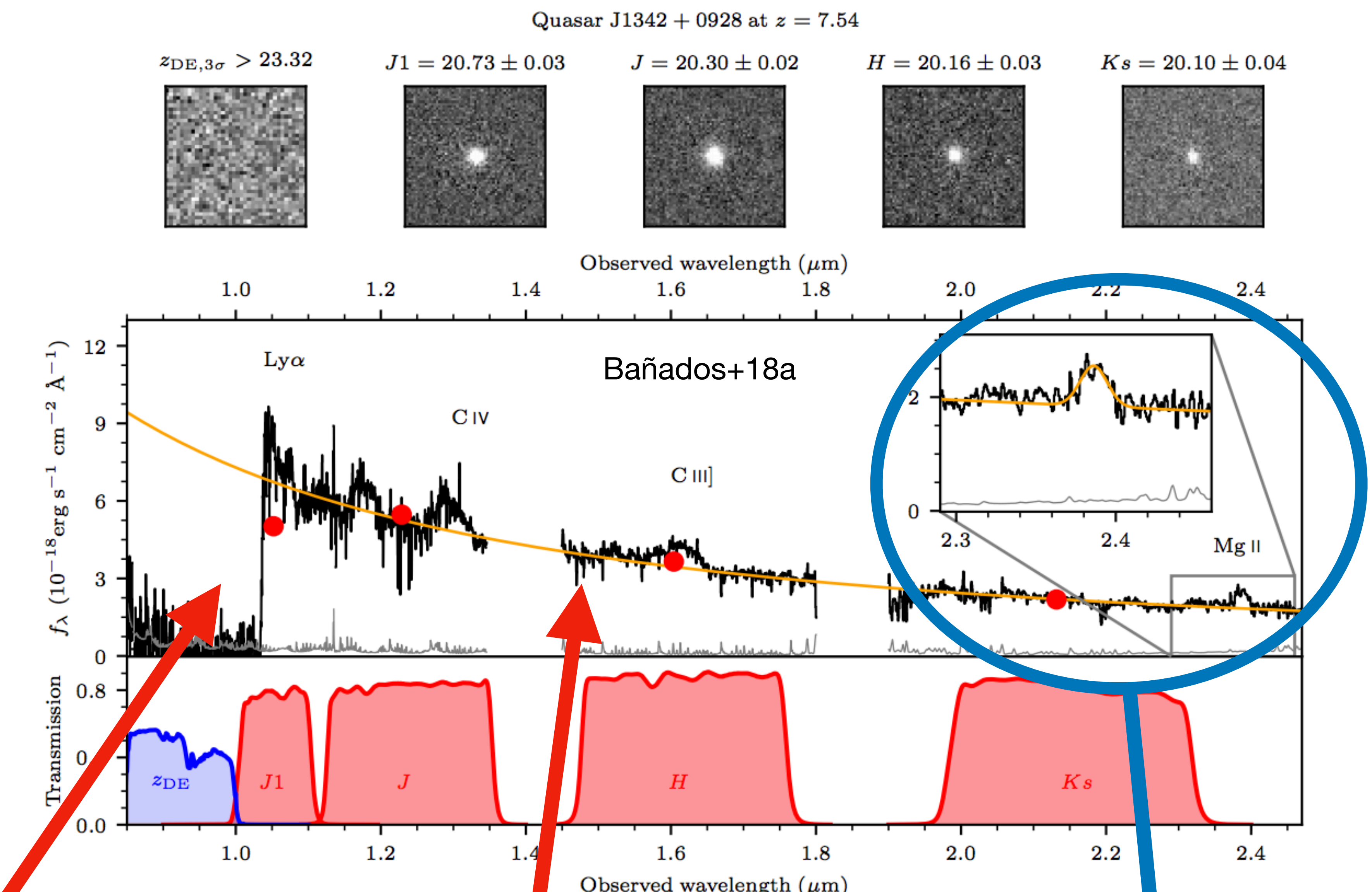


Figure 1. **Photometry and combined Magellan/FIRE and Gemini/GNIRS near-infrared spectrum of the quasar J1342+0928 at $z = 7.54$.** The FIRE data were taken on 11–12 March 2017 for a total integration time of 3.5

***Lyα* forest (λ<1216 Å)**
+
Lyman break (λ<912 Å)

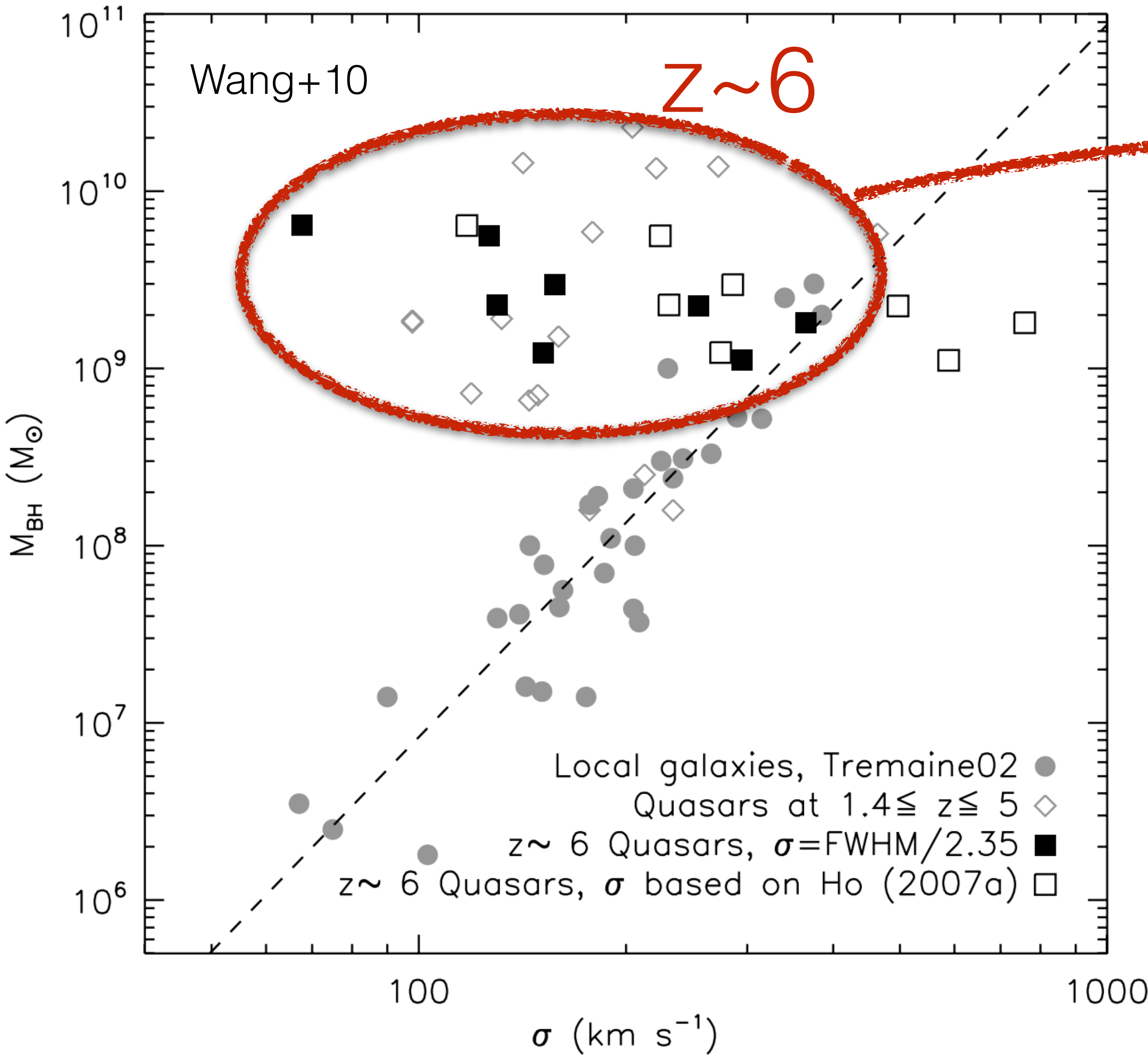
Blue continuum emission
***(by selection* only Type I QSOs!)**

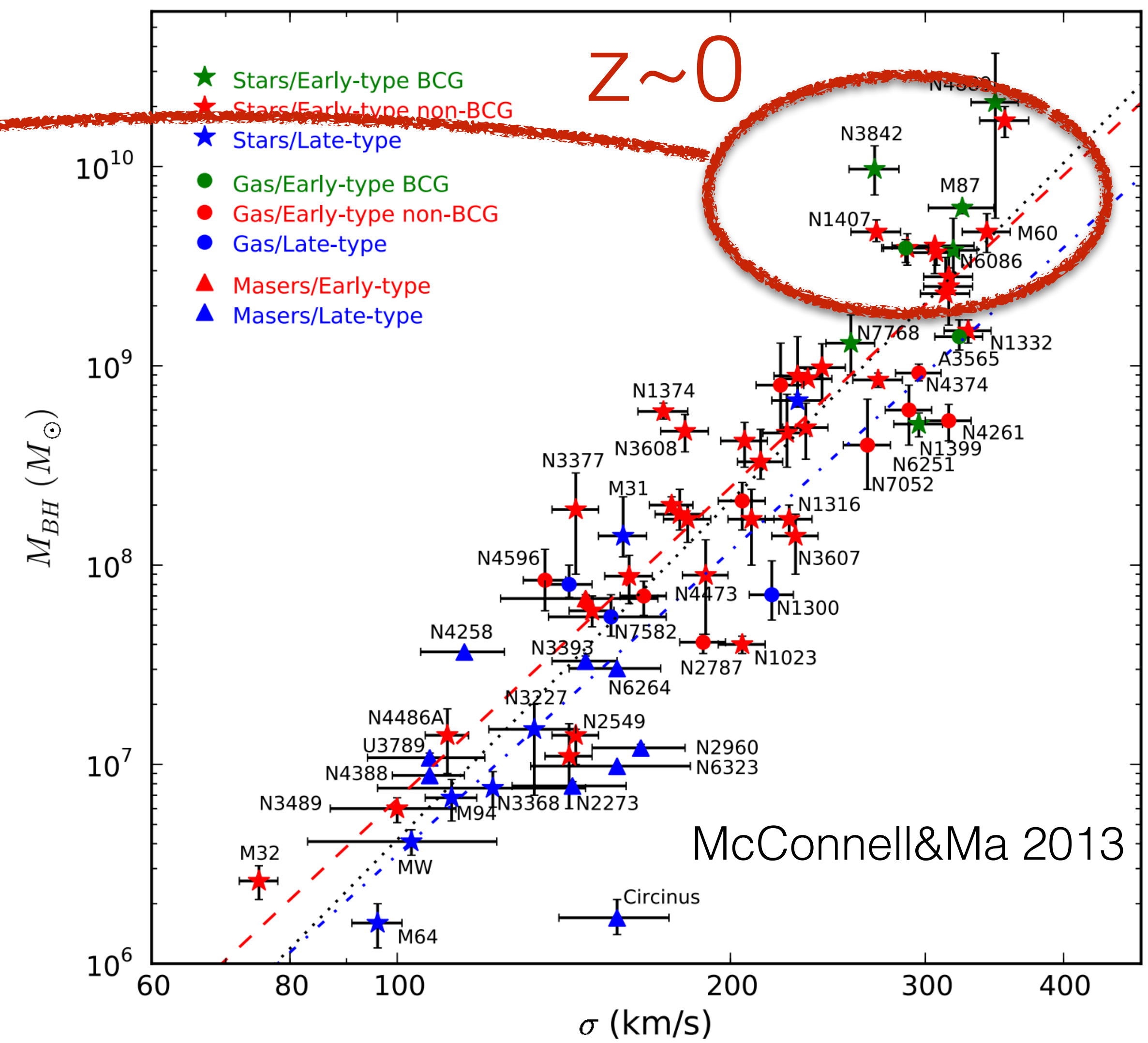
Virial BH mass estimate

Optically selected z≳6 QSOs are extremely massive!

log(M_BH/Msun)~9-10 (with large uncertainties)

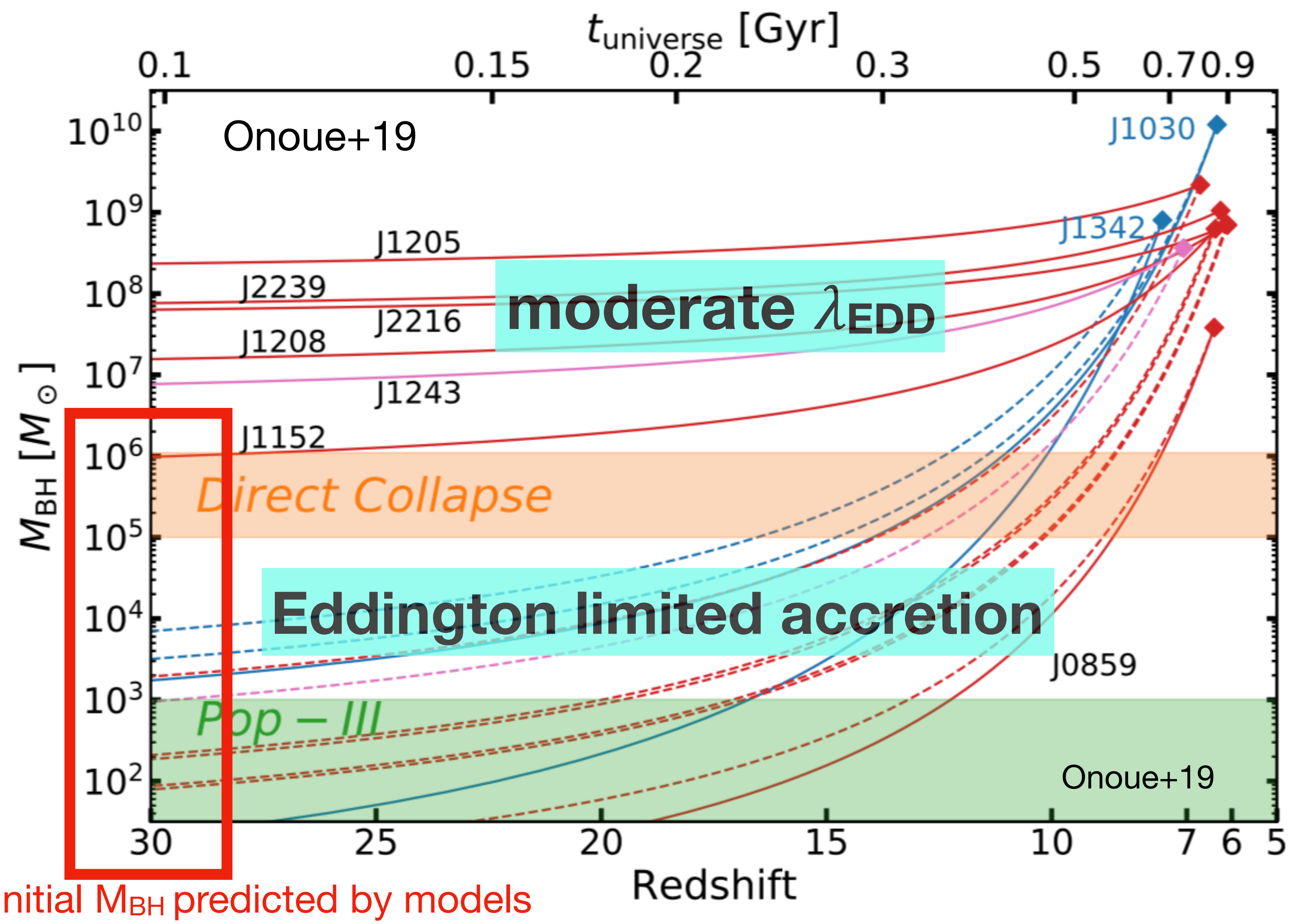
(e.g., Mortlock+11, Wu+15, Banados+18)

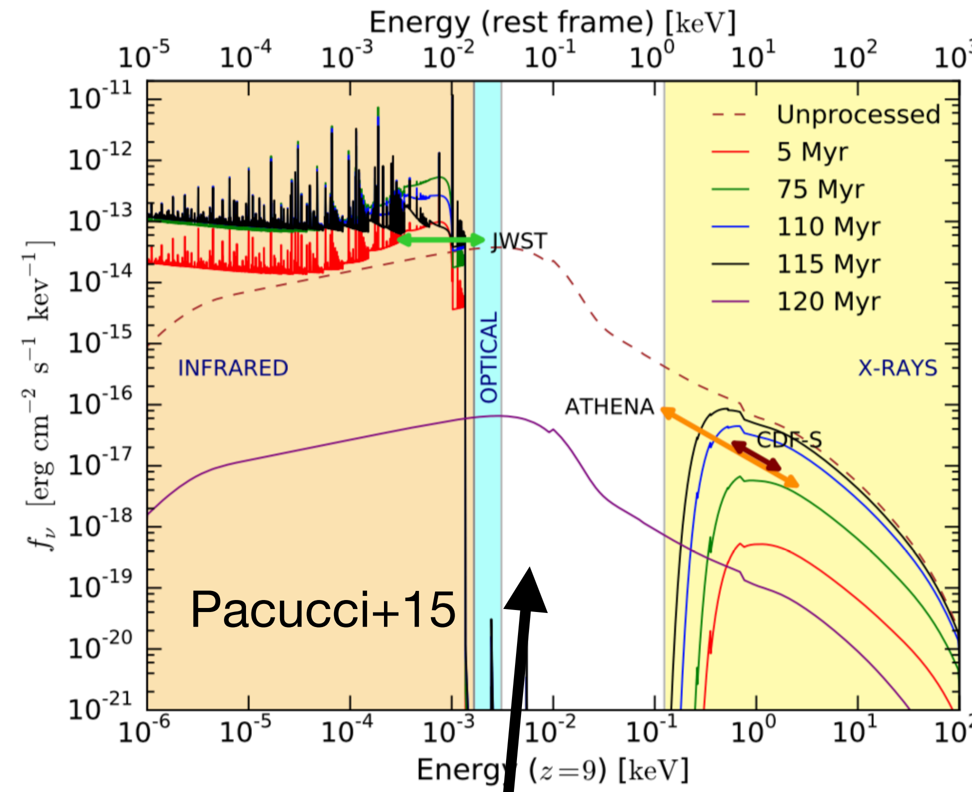




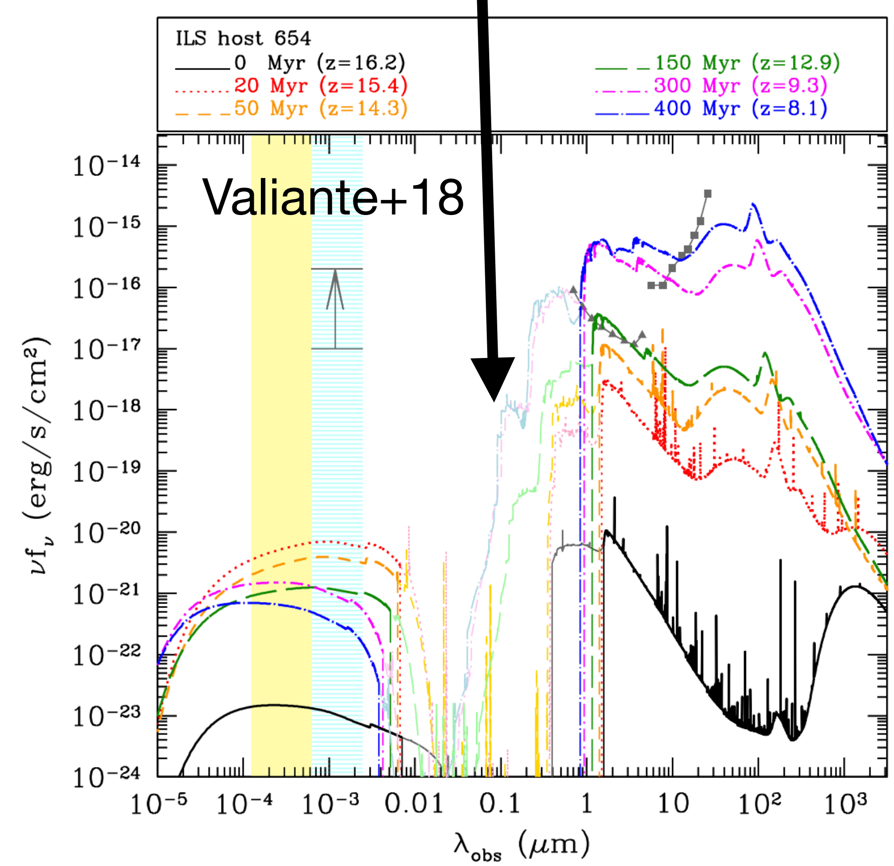
How can you form such massive BH in <1Gyr??

$M_{SMBH}(t) = M_{seed}(t_{form})\, e^{[(1-\varepsilon)/\varepsilon]\Delta t/t_{Edd}}$ $\varepsilon = 0.1$ $t_{Edd} = 0.45$ Gyr





Obscuration

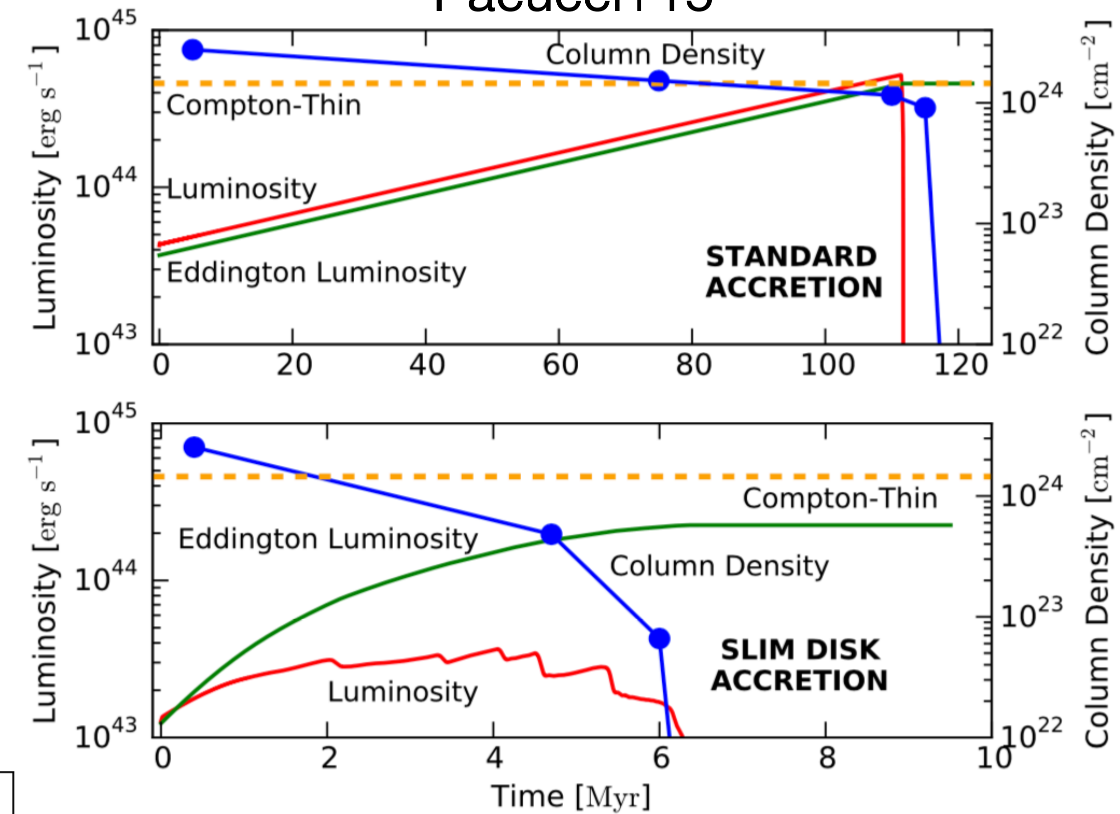


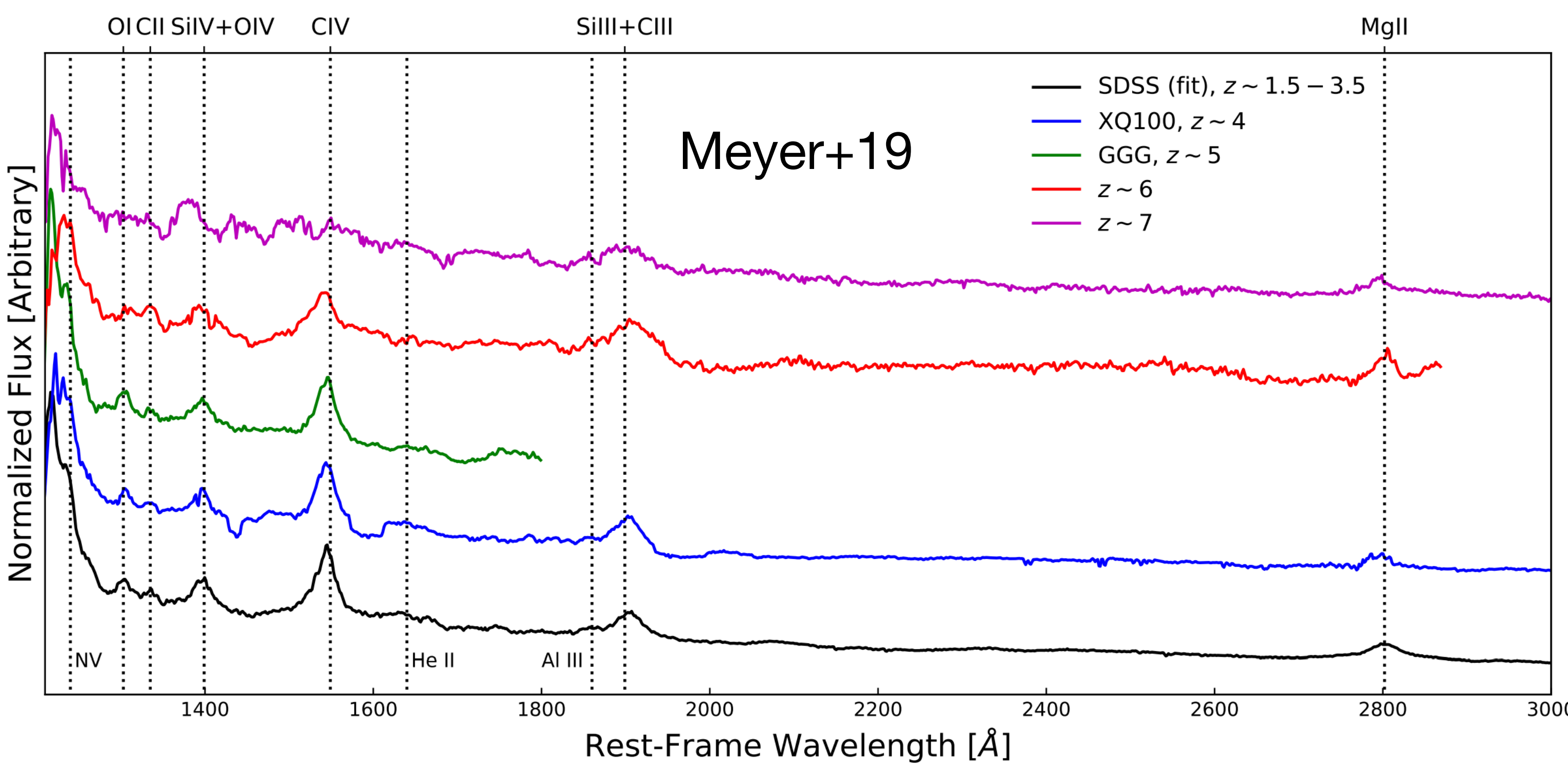
Models require fast accretion (i.e., high Eddington ratio λ_{EDD}), possibly in heavily obscured conditions, to match the observed M_{BH} at z=6-7.5

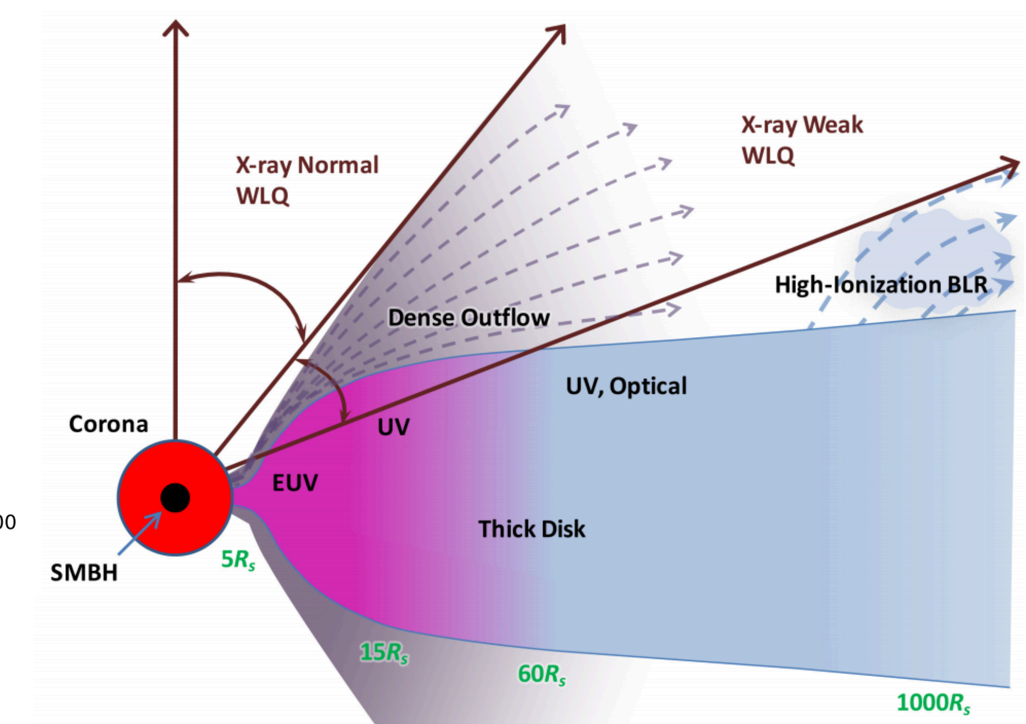
Different accretion modes at high L/Ledd?

(e.g. Jiang+17, Mayer+18, and reference therein)

Pacucci+15





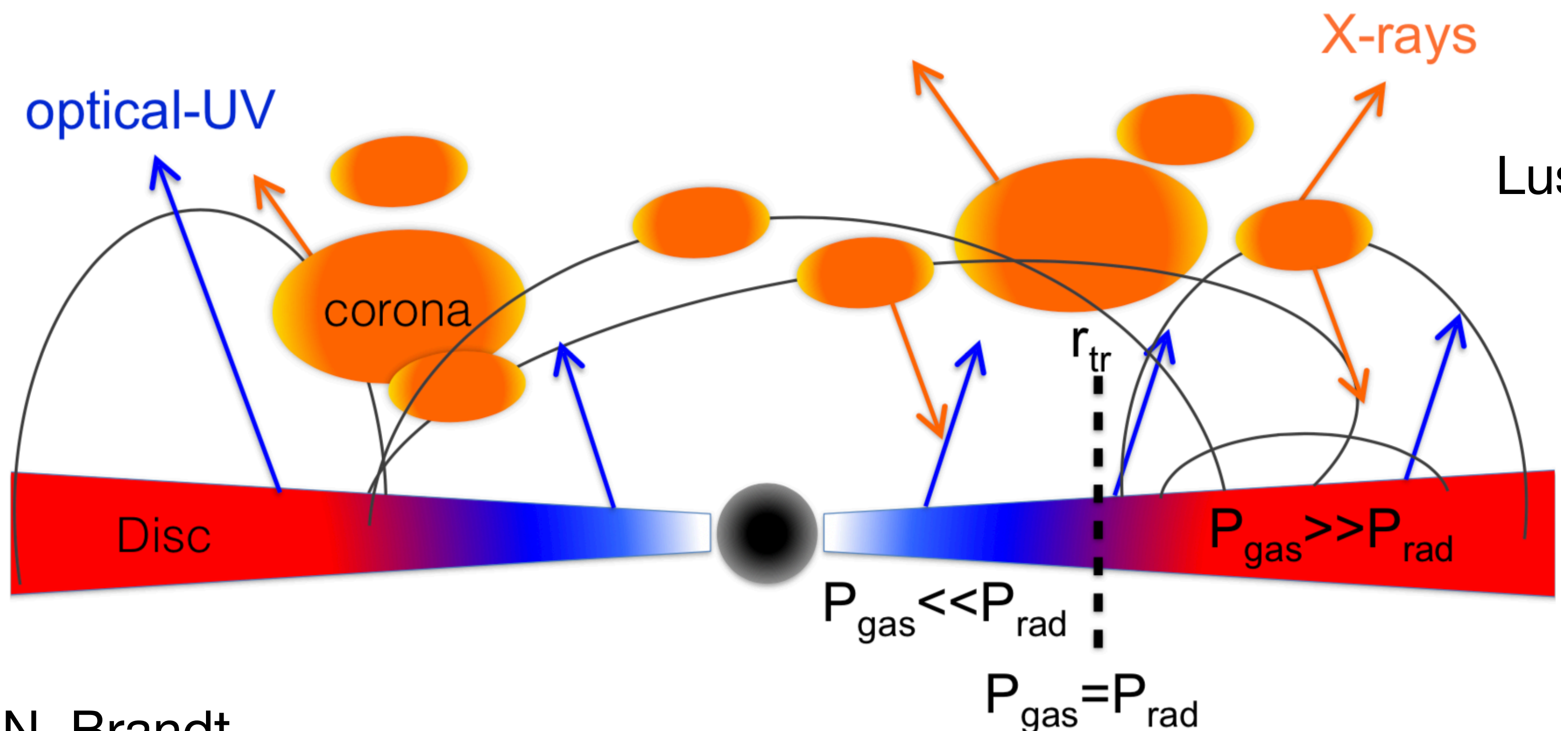


Ni+18

Higher fraction of WLQs at z>6 suggesting a change in the accretion mode?

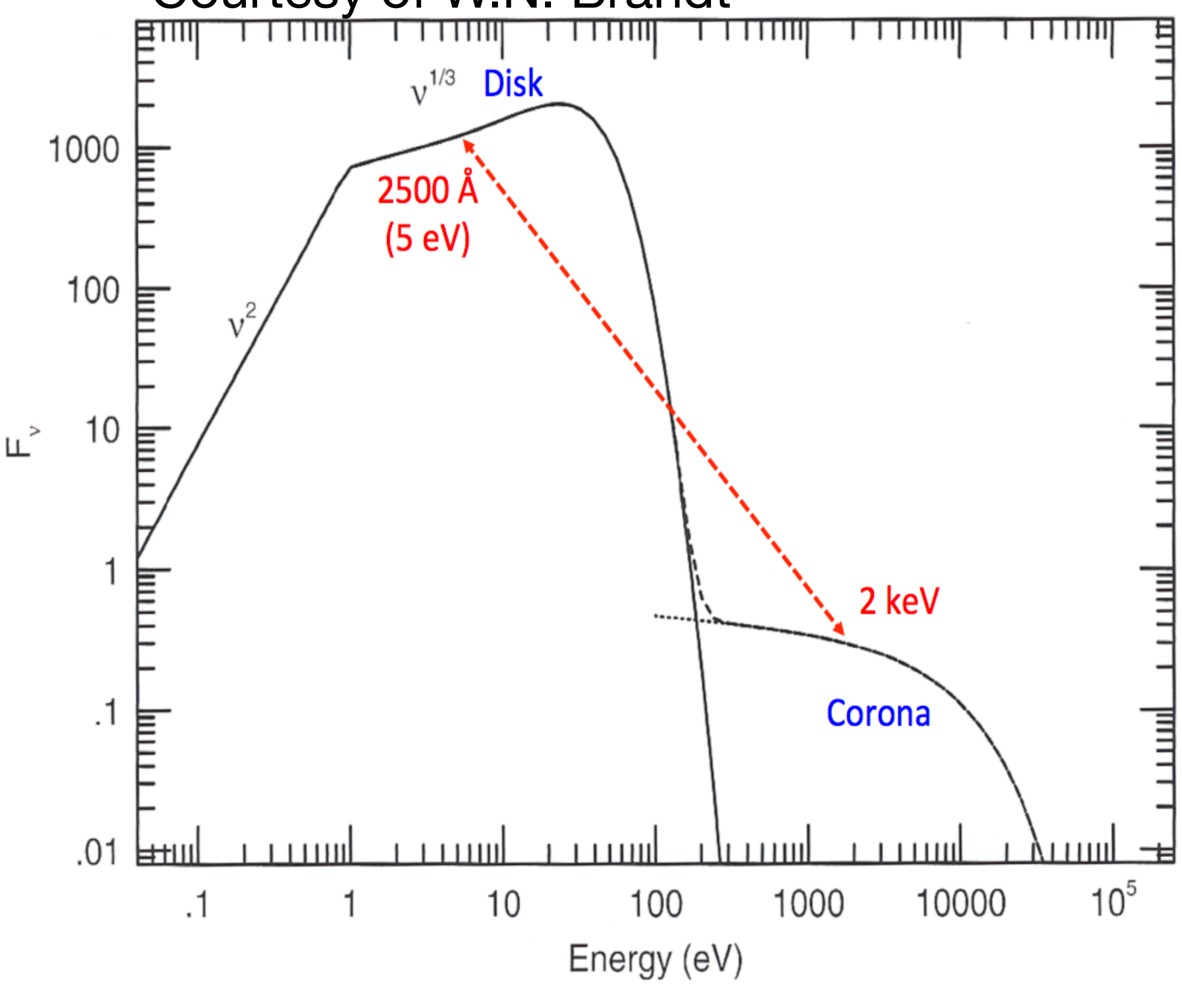
(see also Shen+19, Bañados+16)

Testing accretion mode (accretion disk + hot corona)



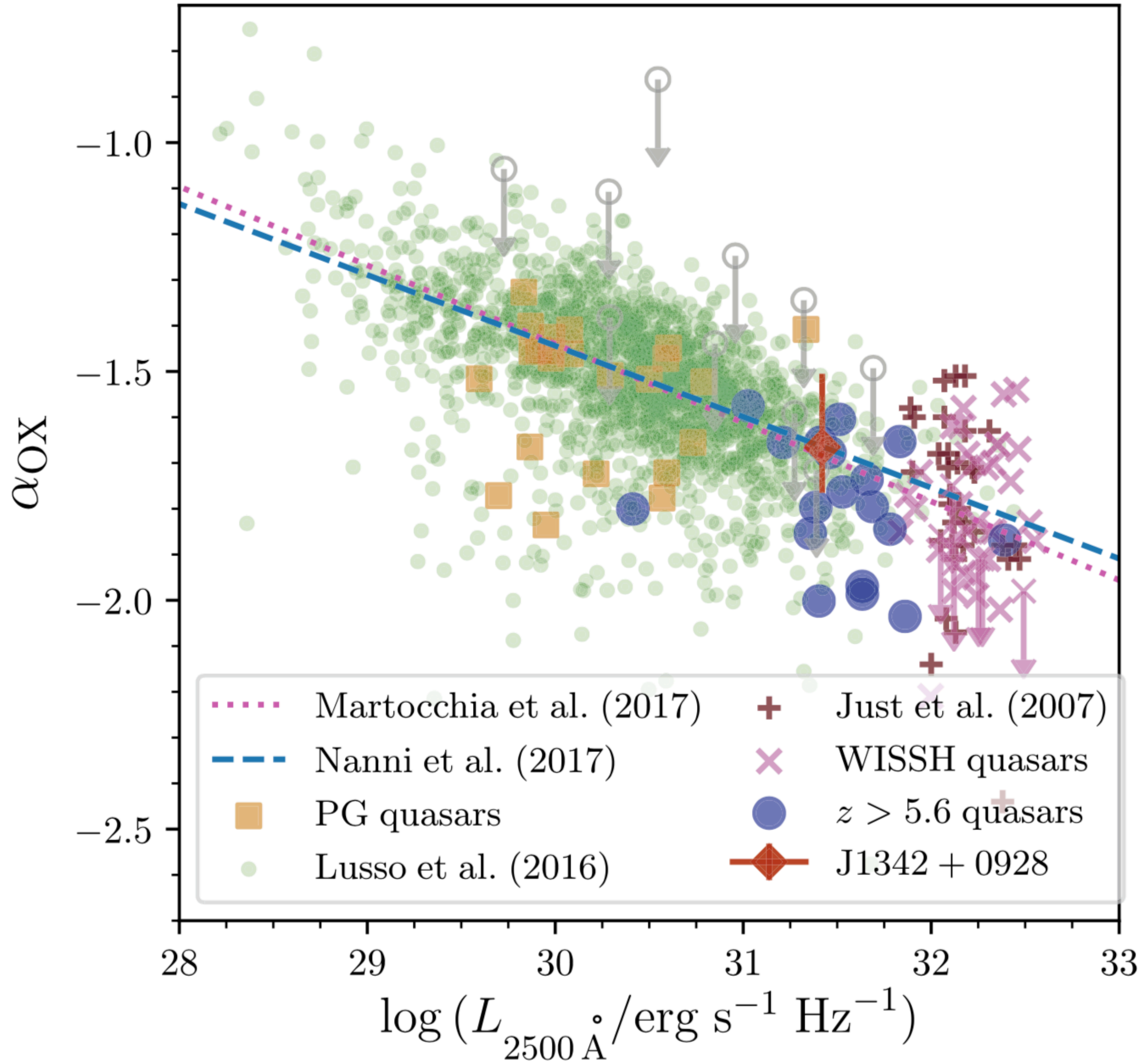
Lusso&Risaliti 2017

Courtesy of W.N. Brandt



$$\alpha_{ox} = 0.38 \times \log \frac{L_{2\,\mathrm{keV}}}{L_{2500\,\text{Å}}}$$

(Tananbaum+1979 and many others since)



$$\alpha_{ox} \propto -0.15 \times \log L_{2500\,\text{Å}}$$

(e.g., Steffen+06, Just+07, Lusso+10,+16, Nanni+17)

Hot corona contribution decreases at high luminosity

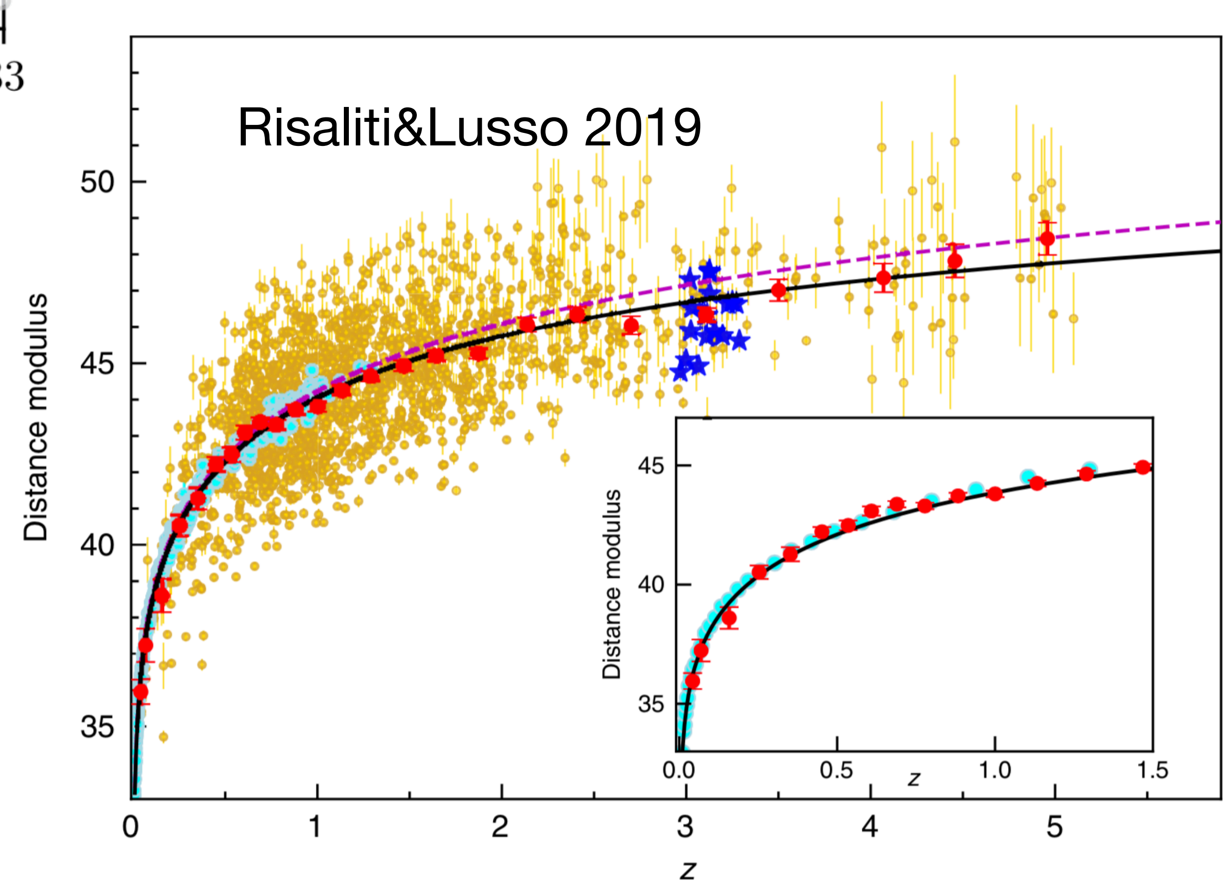
No (strong) evolution with redshift

(e.g. Lusso&Risaliti 2017)

but poorly sampled at *z*>6!!

Possible implications for cosmology

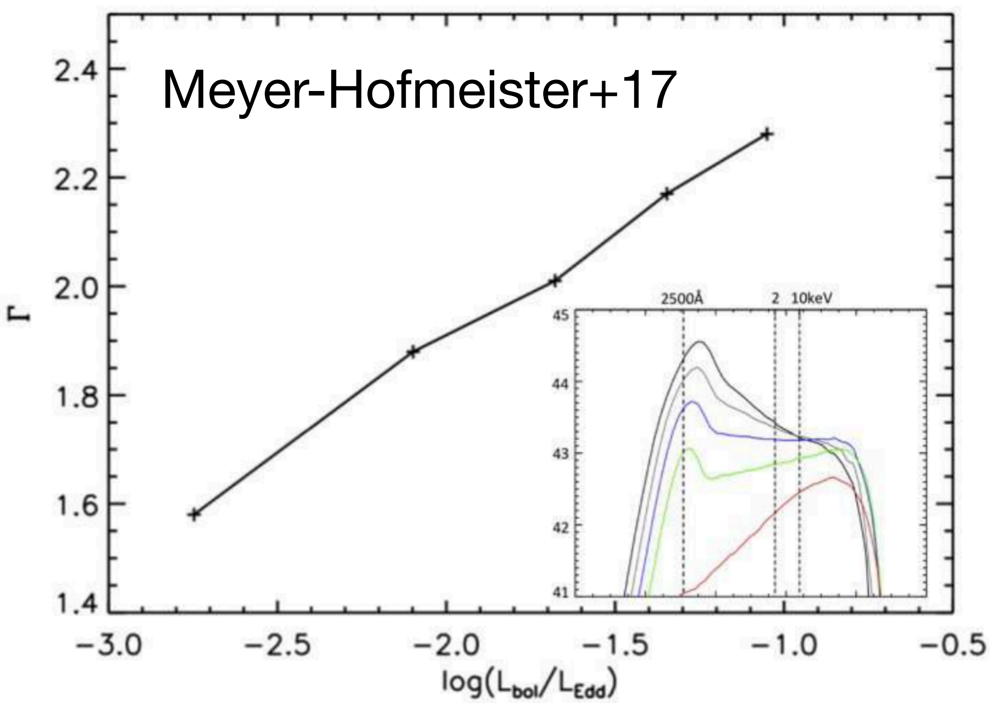
(Risaliti&Lusso 2018)

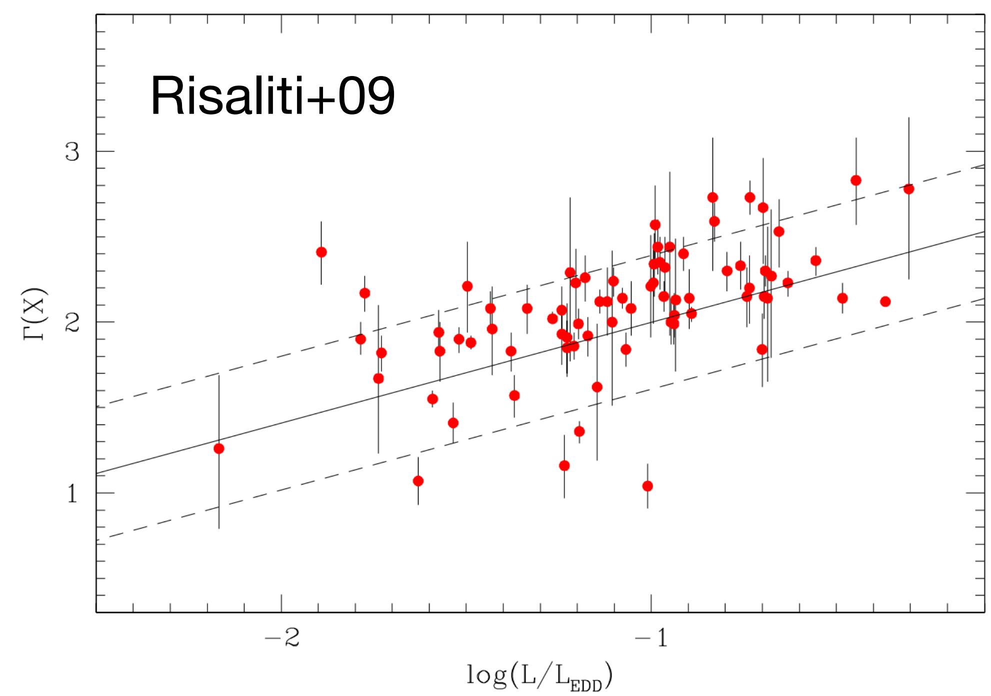


X-ray photon index (Γ) as a probe of accretion

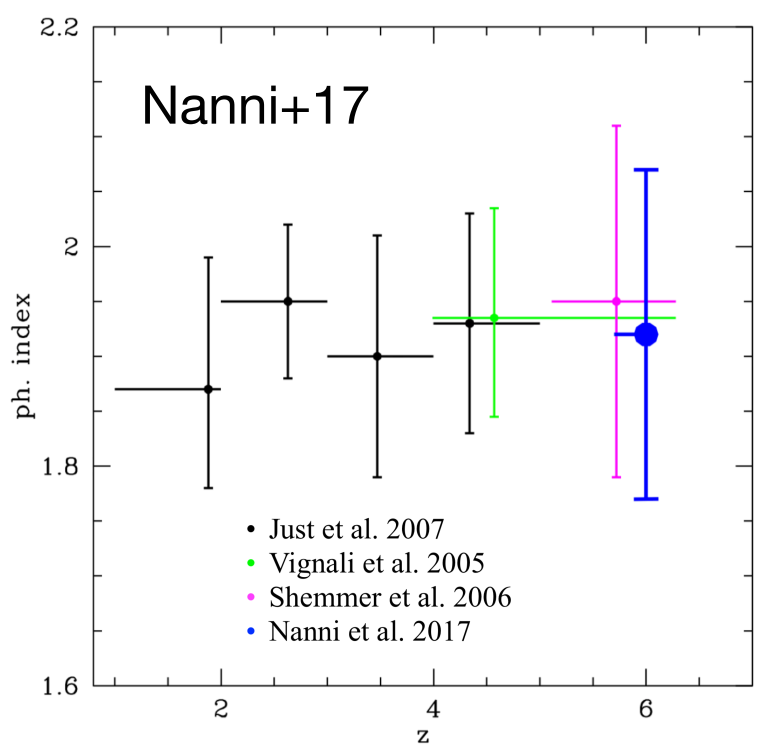
$$N(E) \propto E^{-\Gamma}$$

Γ includes information on the physical conditions (e.g. temperature) of the hot corona and its interplay with the accretion disk





e.g., Shemmer+08, Brightman+13, Fanali+13, but see also Trakhtenbrot+17



No (strong) evolution with redshift

(e.g. Lusso&Risaliti 2017)

but poorly sampled at *z*>6!!

New *Chandra* observations of 10 *z*>6 QSOs

Chandra Cycle 19 Large Program (~430 ks, PI: Brandt)

New observations

Archival data

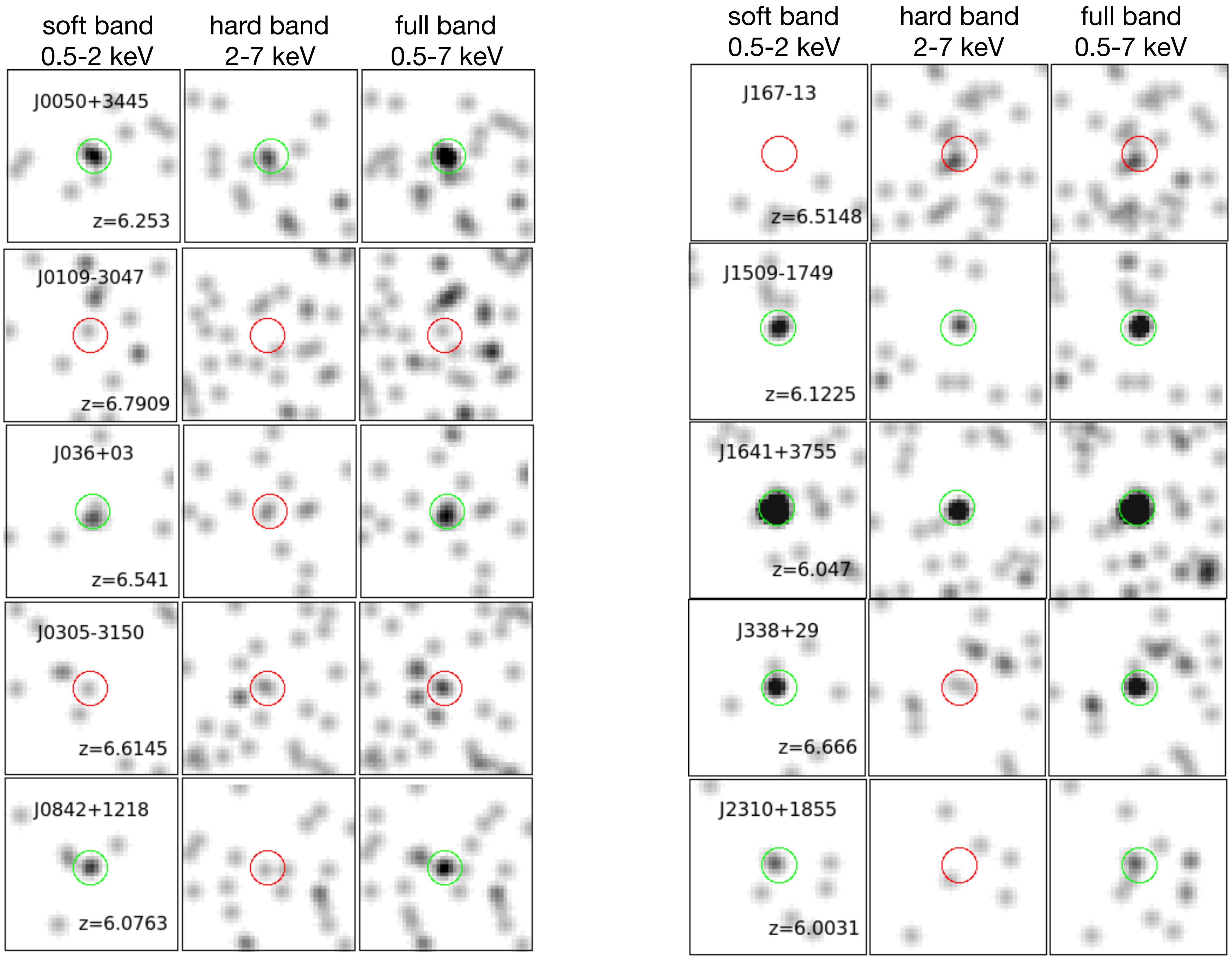
Vito+19b.

Table 1. Physical properties of the $z > 6$ QSOs with new or archival X-ray observations.

ID (1)	RA (2)	DEC (3)	z (4)	$M_{1450\text{Å}}$ ($m_{1450\text{Å}}$) (5)	$\log(\frac{L_{bol}}{L_\odot})$ (6)	$\log(\frac{M_{BH}}{M_\odot})$ (7)	λ_{Edd} (8)	Ref. (disc./z/M_{BH}) (9)	R (10)
				New targets					
CFHQSJ0050+3445	00:50:06.67	+34:45:21.65	6.253 (Mg II)	−26.70 (20.11)	13.45	9.41	0.34	W10/W10/W10	< 11.4
VIKJ0109−3047	01:09:53.13	−30:47:26.31	6.7909 ([C II])	−25.64 (21.30)	13.06	9.12	0.27	V13/V16/M17	< 34.1
PSOJ036+03	02:26:01.87	+03:02:59.4	6.541 ([C II])	−27.33 (19.55)	13.67	9.48	0.48	V15/B15/M17	< 2.1
VIKJ0305−3150	03:05:16.92	−31:50:55.9	6.6145 ([C II])	−26.18 (20.72)	13.26	8.95	0.63	V13/V16/M17	< 20.0
SDSSJ0842+1218	08:42:29.43	+12:18:50.5	6.0763 ([C II])[a]	−26.91 (19.86)[a]	13.52	9.29	0.53	dR11/D18/dR11*[a]	< 1.3
PSOJ167−13	11:10:33.98	−13:29:45.60	6.5148 ([C II])[b]	−25.57 (21.25)	13.03	8.48	1.11	V15/M17/M17	< 34.3
CFHQSJ1509−1749	15:09:41.78	−17:49:26.80	6.1225 ([C II])[a]	−27.14 (19.64)[a]	13.61	9.47	0.42	W07/D18/W10[a]	< 1.2
CFHQSJ1641+3755	16:41:21.73	+37:55:20.15	6.047 (Mg II)	−25.67 (21.09)	13.07	8.38	1.51	W07/W10/W10	< 10.5
PSOJ338+29	22:32:55.14	+29:30:32.31	6.666 ([C II])	−26.14 (20.78)	13.24	9.43	0.20	V15/M17/M17	< 21.0
SDSSJ2310+1855	23:10:38.89	+18:55:19.93	6.0031 ([C II])	−27.80 (18.95)	13.85	9.62	0.52	Wa13/Wa13/J16	< 3.9
				QSOs with previous X-ray data					
SDSSJ0100+2802	01:00:13.02	+28:02:25.92	6.3258 ([C II])	−29.14 (17.69)	14.33	10.03	0.62	Wu15/Wa16/Wu15*	< 1.2
ATLASJ0142−3327	01:42:43.73	−33:27:45.47	6.379 ([C II])[a]	−27.82 (19.02)[a]	13.85	—	—	C15/D18/—	< 4.2
CFHQSJ0210−0456	02:10:13.19	−04:56:20.90	6.4323 ([C II])	−24.53 (22.33)	12.65	7.90	1.76	W10/W13/W10	< 28.1
CFHQSJ0216−0455	02:16:27.81	−04:55:34.10	6.01 (Ly α)	−22.49 (24.27)	11.91	—	—	W09/W09/—	< 23.1
SDSSJ0303−0019	03:03:31.40	−00:19:12.90	6.078 (Mg II)	−25.56 (21.21)	13.03	8.61	0.81	J08/K09/dR11*	< 11.4
SDSSJ1030+0524	10:30:27.11	+05:24:55.06	6.308 (Mg II)	−26.99 (19.84)	13.55	9.21	0.68	F01/K07/dR11*	< 1.5
SDSSJ1048+4637[c]	10:48:45.07	+46:37:18.55	6.2284 (CO 6-5)	−27.24 (19.57)	13.64	9.55	0.38	F03/Wa10/dR11*	< 0.5
ULASJ1120+0641	11:20:01.48	+06:41:24.30	7.0842 ([C II])	−26.63 (20.38)	13.42	9.39	0.33	M11/V12/M17	< 0.7
SDSSJ1148+5251	11:48:16.65	52:51:50.39	6.4189 (CO 6-5)	−27.62 (19.24)	13.78	9.71	0.36	F03/Wa11/dR11*	$0.7^{+0.2}_{-0.2}$
SDSSJ1306+0356	13:06:08.27	+03:56:26.36	6.0337 ([C II])[a]	−26.82 (19.94)[a]	13.49	9.30	0.48	F01/D18/dR11*[a]	< 1.5
ULASJ1342+0928	13:42:08.27	+09:28:38.61	7.5413 ([C II])	−26.76 (20.34)	13.47	8.89	1.14	B18a/V17/B18a	< 4.7
SDSSJ1602+4228	16:02:53.98	+42:28:24.94	6.09 (Ly α)	−26.94 (19.83)	13.53	—	—	F04/F04/—	$0.8^{+0.2}_{-0.2}$
SDSSJ1623+3112	16:23:31.81	+31:12:00.53	6.26 ([C II])	−26.55 (20.27)	13.39	9.15	0.54	F04/Wa11/dR11*	< 2.3
SDSSJ1630+4012	16:30:33.90	+40:12:09.69	6.065 (Mg II)	−26.19 (20.58)	13.26	8.96	0.62	F03/I04/dR11*	< 2.2
HSCJ2216−0016	22:16:44.47	−00:16:50.10	6.10 (Ly α)	−23.62 (23.16)	12.32	—	—	M16/M16/—	< 40.9

Now we have 25 *z*>6 QSOs with sensitive X-ray data and can start doing robust statistical analysis

New *Chandra* observations of 10 *z*>6 QSOs

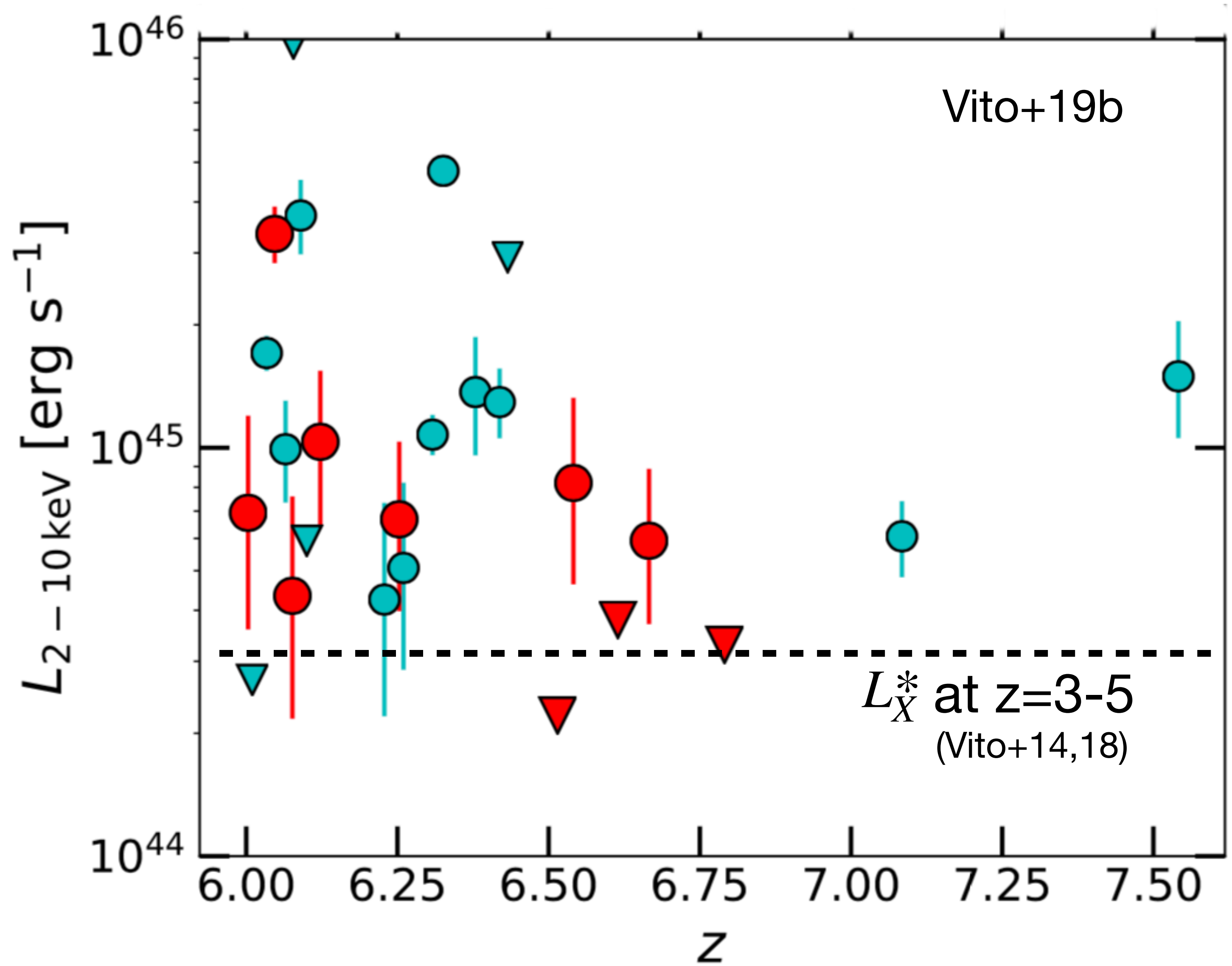


Detected (P>0.99) Vito+19b Undetected

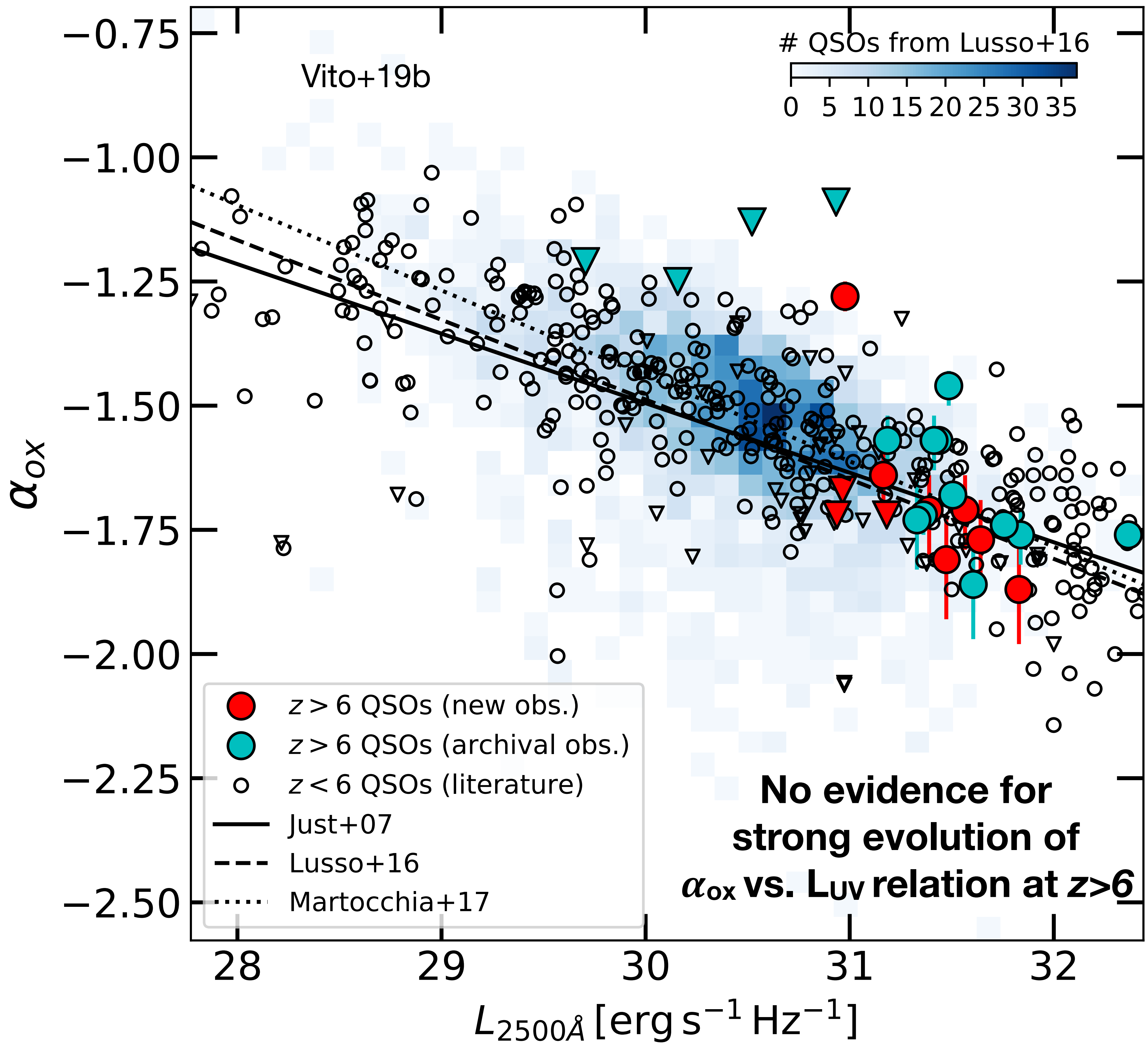
X-ray luminosity derived assuming "standard" Γ=2 (e.g., Shemmer+06, Nanni+17)

ID	$L_{2-10\,\mathrm{keV}}$ $[10^{44}\,\mathrm{erg\,s^{-1}}]$	α_{ox}	$\Delta\alpha_{ox}$
CFHQSJ0050+3445	$6.68^{+3.67}_{-2.70}$	$-1.71^{+0.07}_{-0.09}$	$-0.02^{+0.07}_{-0.09}$
VIKJ0109−3047	< 3.29	< -1.67	< -0.04
PSOJ036+03	$8.20^{+5.05}_{-3.57}$	$-1.77^{+0.08}_{-0.10}$	$-0.05^{+0.08}_{-0.10}$
VIKJ0305−3150	< 3.79	< -1.72	< -0.06
SDSSJ0842+1218	$4.34^{+3.26}_{-2.17}$	$-1.81^{+0.09}_{-0.12}$	$-0.11^{+0.09}_{-0.12}$
PSOJ167−13	< 2.21	< -1.72	< -0.09
CFHQSJ1509−1749	$10.34^{+5.10}_{-3.86}$	$-1.71^{+0.07}_{-0.08}$	$0.01^{+0.07}_{-0.08}$
CFHQSJ1641+3755	$33.39^{+5.56}_{-5.07}$	$-1.28^{+0.03}_{-0.03}$	$0.35^{+0.03}_{-0.03}$
PSOJ338+29	$5.92^{+2.96}_{-2.22}$	$-1.64^{+0.07}_{-0.08}$	$0.01^{+0.07}_{-0.08}$
SDSSJ2310+1855	$6.93^{+5.02}_{-3.34}$	$-1.87^{+0.09}_{-0.11}$	$-0.12^{+0.09}_{-0.11}$
SDSSJ0100+2802	$47.64^{+3.27}_{-3.08}$	$-1.76^{+0.01}_{-0.01}$	$0.07^{+0.01}_{-0.01}$
ATLASJ0142−3327	$13.69^{+4.98}_{-4.11}$	$-1.76^{+0.05}_{-0.06}$	$-0.01^{+0.05}_{-0.06}$
CFHQSJ0210−0456	< 29.31	< -1.13	< 0.44
CFHQSJ0216−0455	< 2.70	< -1.21	< 0.24
SDSSJ0303−0019	< 97.70	< -1.09	< 0.54
SDSSJ1030+0524	$10.77^{+1.27}_{-1.18}$	$-1.68^{+0.02}_{-0.02}$	$0.03^{+0.02}_{-0.02}$
SDSSJ1048+4637	$4.25^{+3.08}_{-2.05}$	$-1.86^{+0.09}_{-0.11}$	$-0.15^{+0.09}_{-0.11}$
ULASJ1120+0641	$6.07^{+1.33}_{-1.25}$	$-1.72^{+0.03}_{-0.04}$	$-0.03^{+0.03}_{-0.04}$
SDSSJ1148+5251	$12.94^{+2.69}_{-2.39}$	$-1.74^{+0.03}_{-0.03}$	$-0.00^{+0.03}_{-0.03}$
SDSSJ1306+0356	$17.06^{+1.73}_{-1.63}$	$-1.57^{+0.02}_{-0.02}$	$0.12^{+0.02}_{-0.02}$
ULASJ1342+0928	$14.96^{+5.46}_{-4.40}$	$-1.57^{+0.05}_{-0.06}$	$0.12^{+0.05}_{-0.06}$
SDSSJ1602+4228	$37.04^{+8.25}_{-7.28}$	$-1.46^{+0.03}_{-0.04}$	$0.24^{+0.03}_{-0.04}$
SDSSJ1623+3112	$5.08^{+3.13}_{-2.22}$	$-1.73^{+0.08}_{-0.10}$	$-0.05^{+0.08}_{-0.10}$
SDSSJ1630+4012	$9.92^{+3.12}_{-2.58}$	$-1.57^{+0.05}_{-0.05}$	$0.09^{+0.05}_{-0.05}$
HSCJ2216−0016	< 5.92	< -1.25	< 0.27

Vito+19b

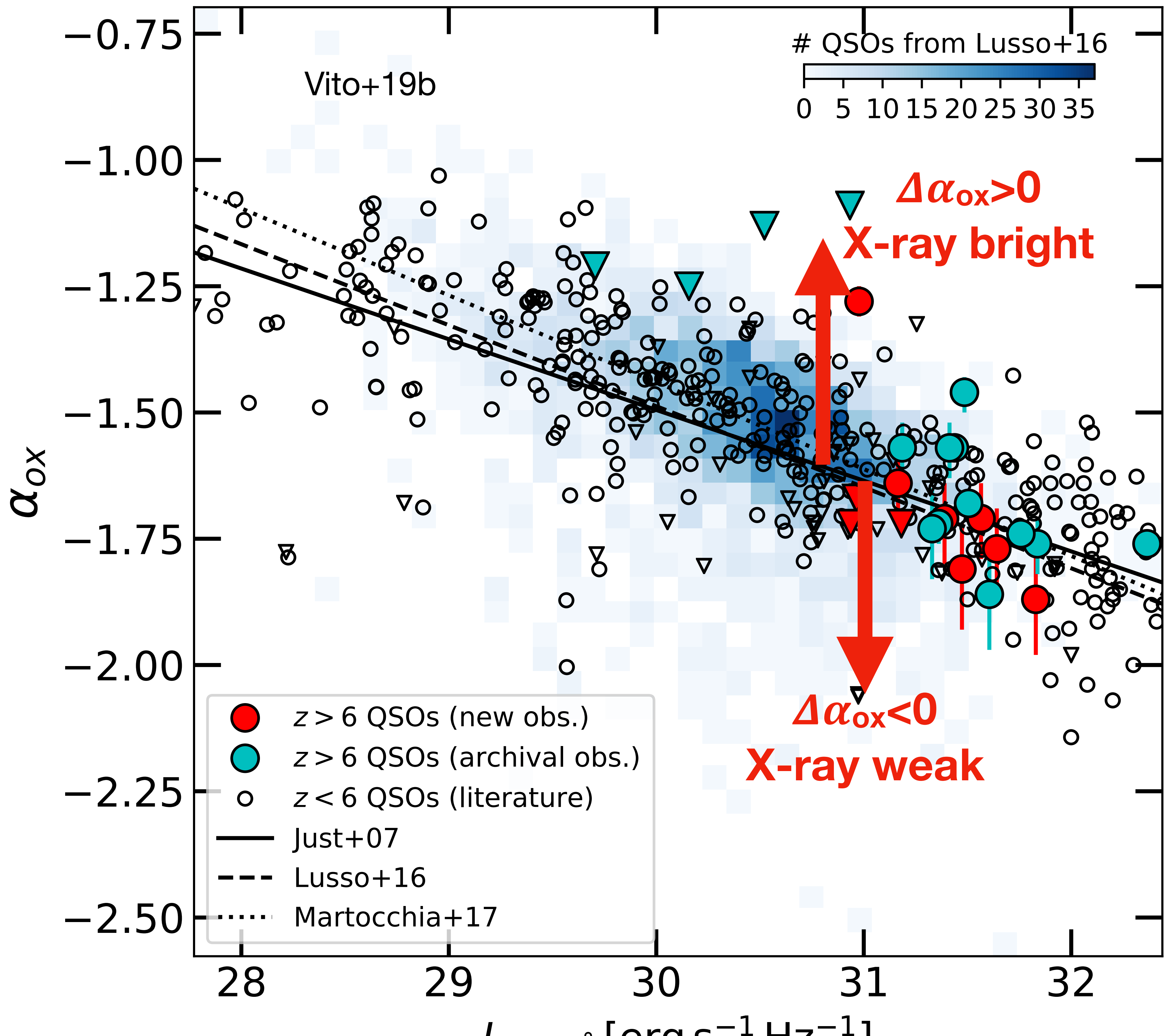


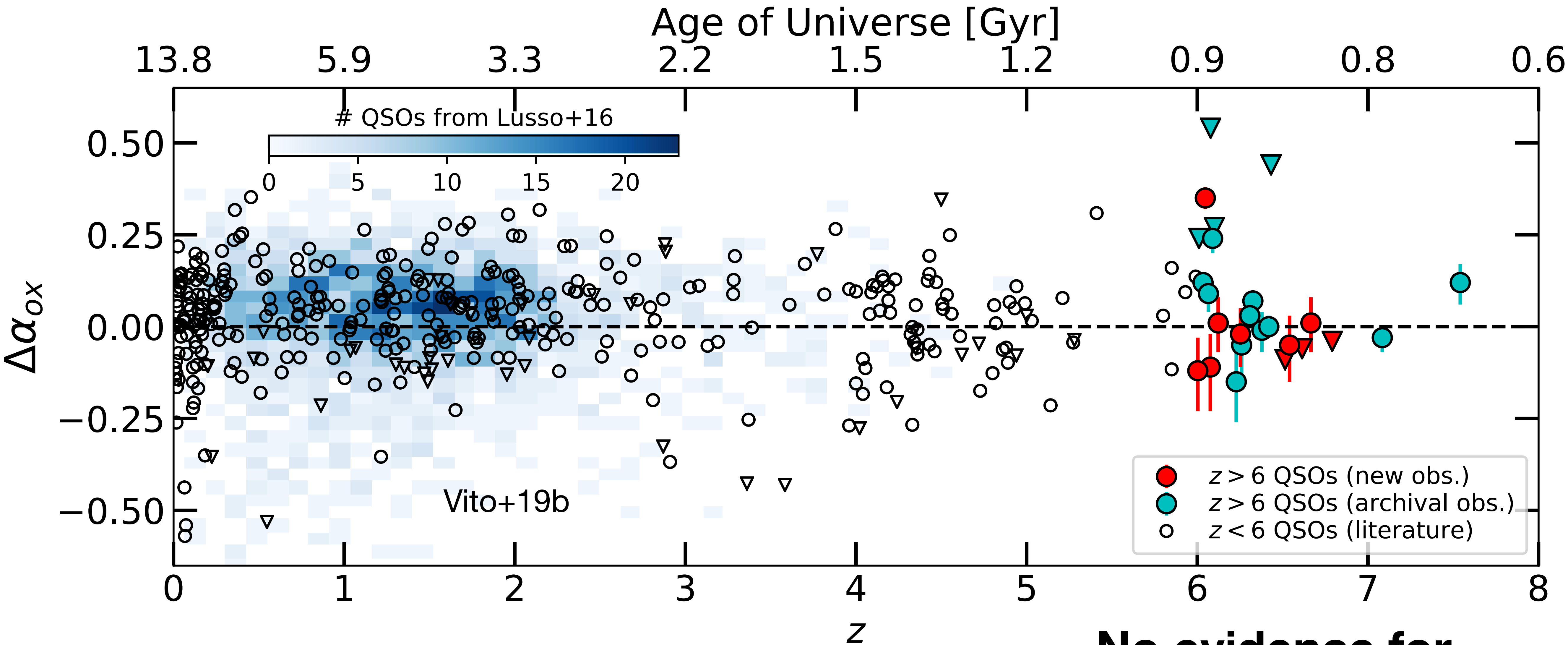
α_{ox} vs. L_{UV} relation extended at $z>6$



No evidence for strong evolution of α_{ox} vs. L_{UV} relation at $z>6$

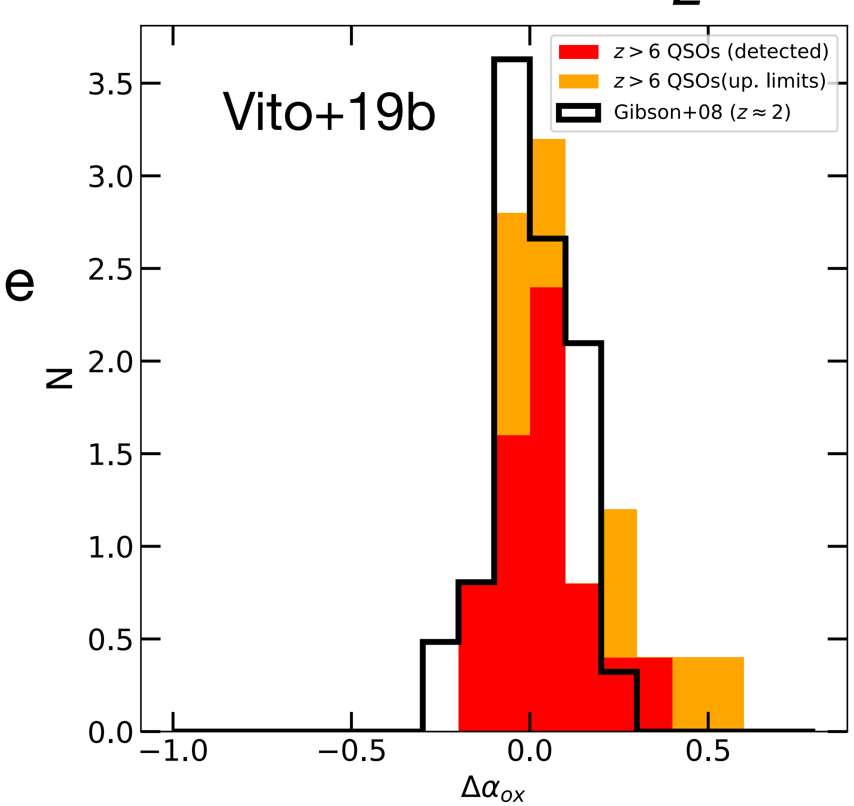
$$\Delta\alpha_{ox}=\alpha_{ox}(\mathrm{obs})-\alpha_{ox}(\mathrm{expect.})$$





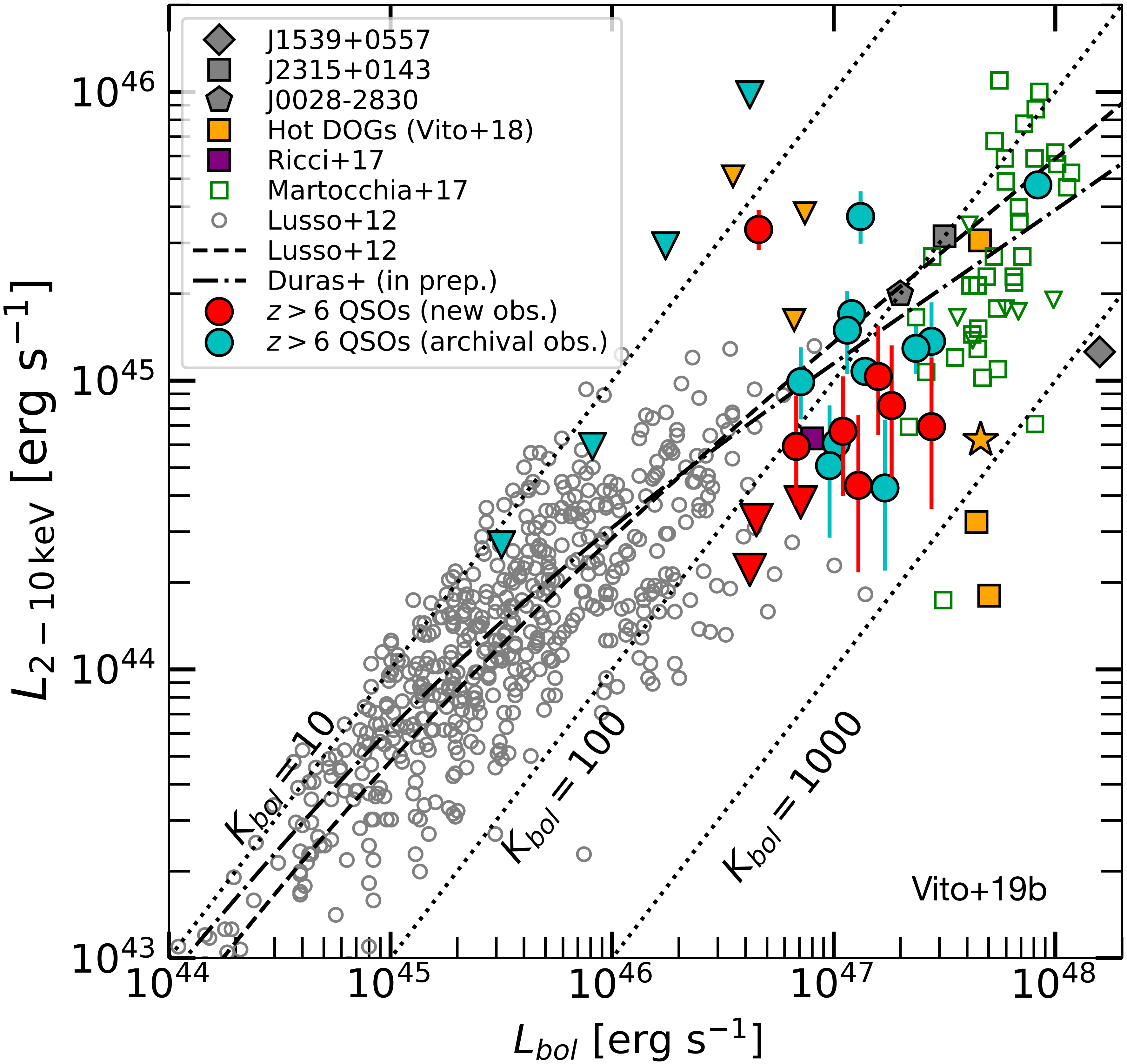
No evidence for strong evolution of α_{ox} vs. L_{UV} relation at $z>6$

Compared also with "ultra-clean" z=2 QSO sample by Gibson+08



No apparent relation b/w α_{ox} and M_{BH} or λ_{EDD}, but small sample size and large uncertainties

Bolometric correction: L_{bol} / L_X

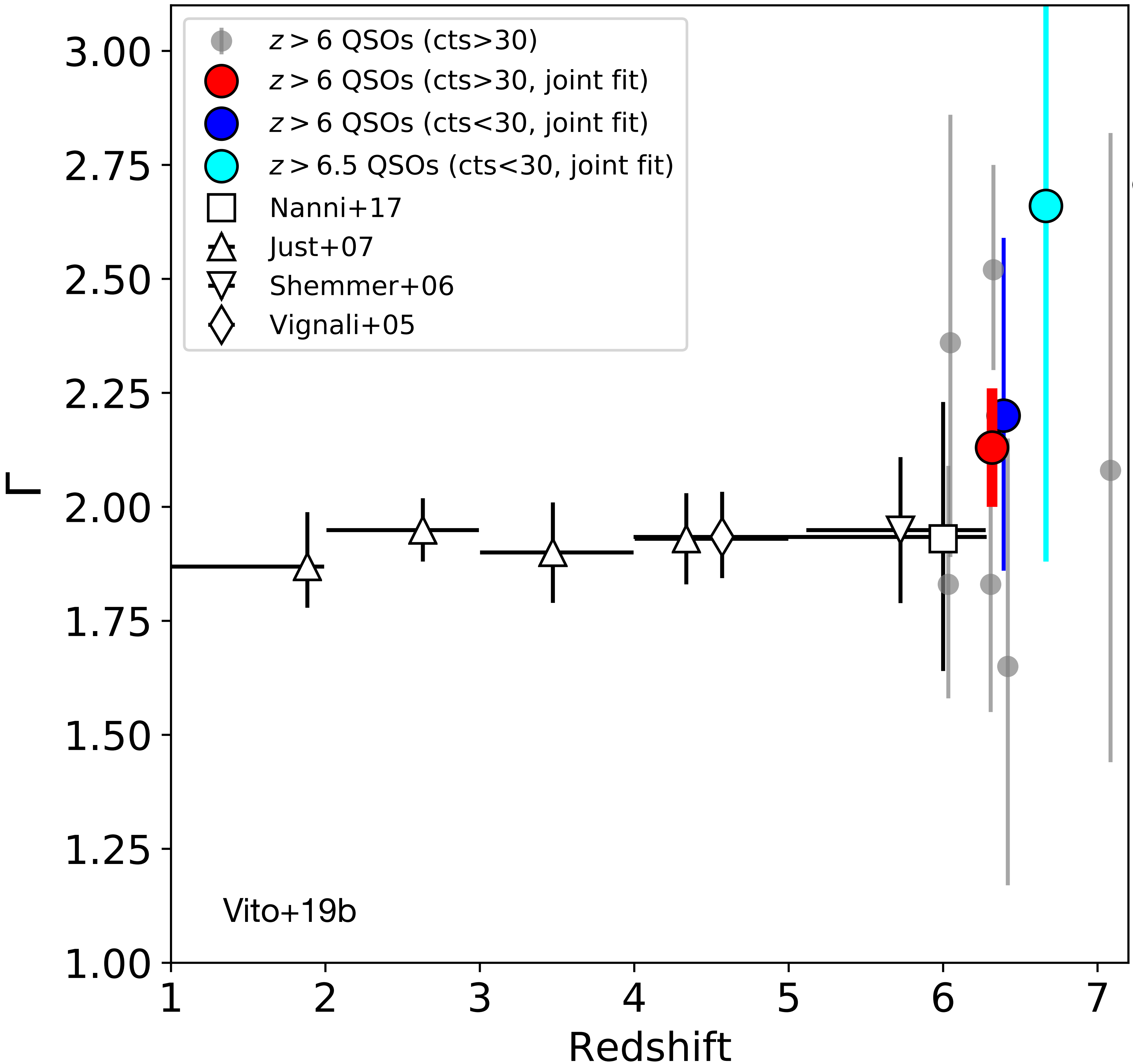


Populate the luminosity regime b/w “normal” AGN and hyper-luminous QSOs, and extend at z>6

Larger K_{bol} at higher luminosities, in agreement with steeper α_{ox} at higher luminosities

Change of the accretion-disk/hot-corona physics/geometry at high luminosities/λ_{EDD} but same change at all redshifts

Average QSO photon index as a function of *z*



Assumed simple power-law emission, i.e. no reflection (ok for luminous type-1 QSOs, e.g. Comastri+92, Picconcelli+05, Shemmer+05)

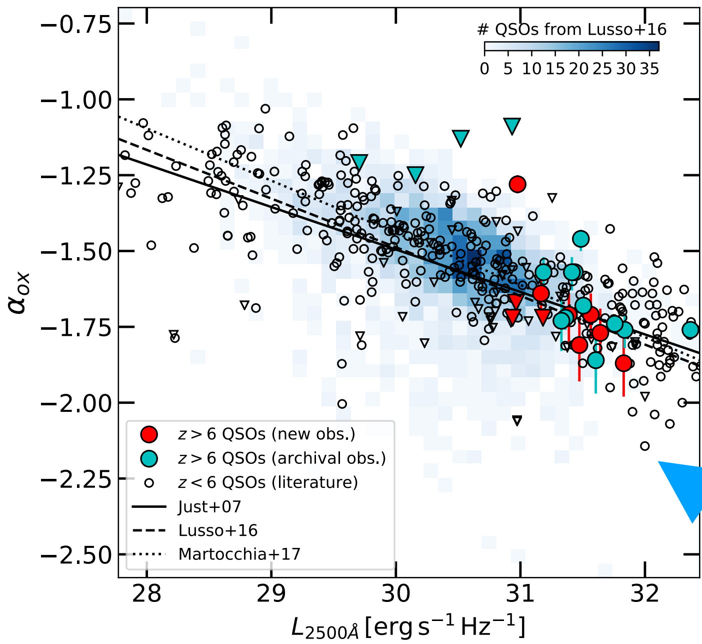
$\langle \Gamma \rangle \approx 2.1$-$2.2$ for $z>6$ QSOs

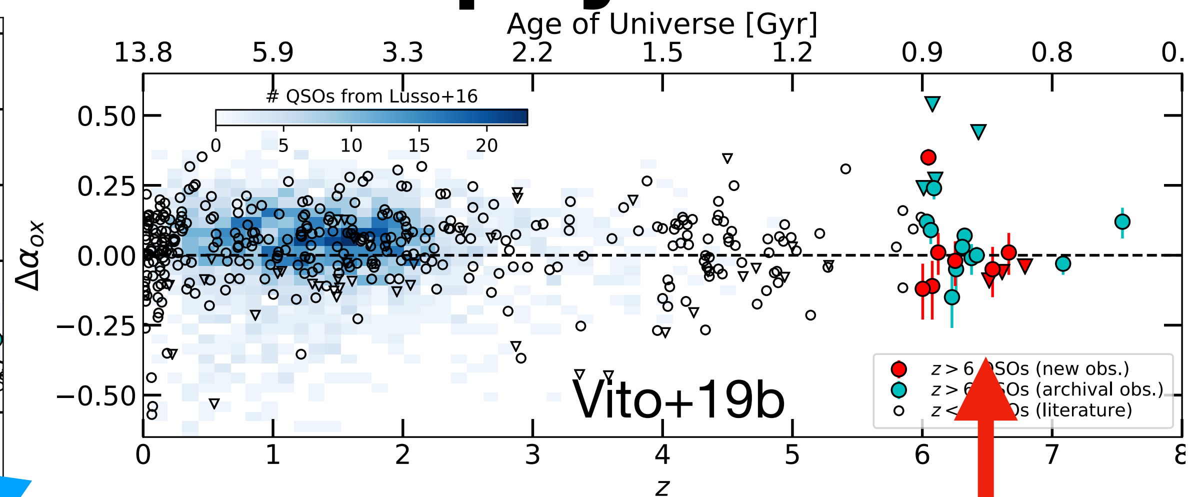
Consistent with z=1-6 results

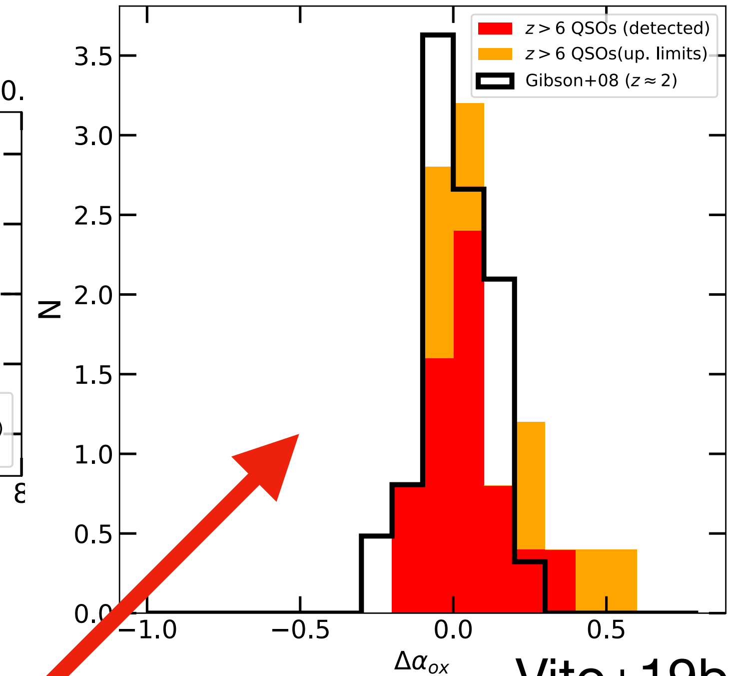
"Universal" accretion mode (λ_{EDD} dependent, redshift independent)

(but hint of a steepening?)

Conclusion: No significant change of the QSO accretion physics at *z*>6

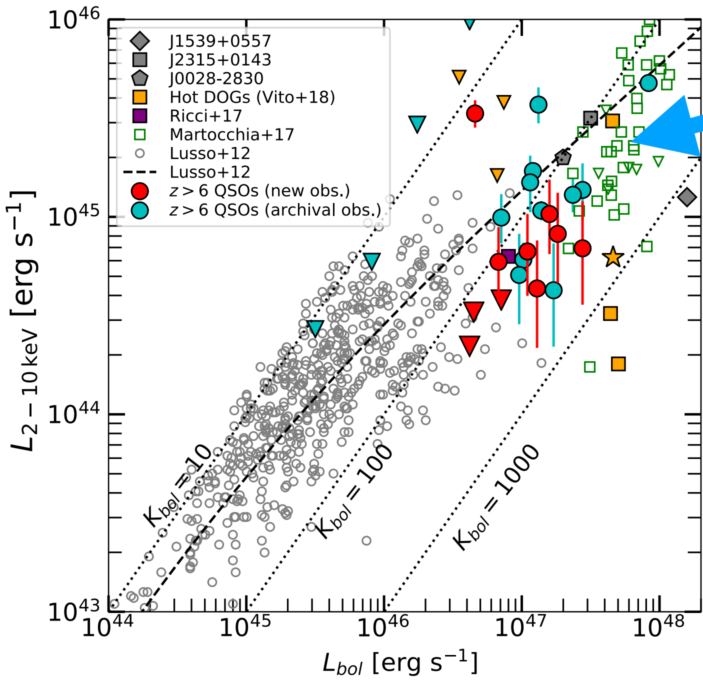




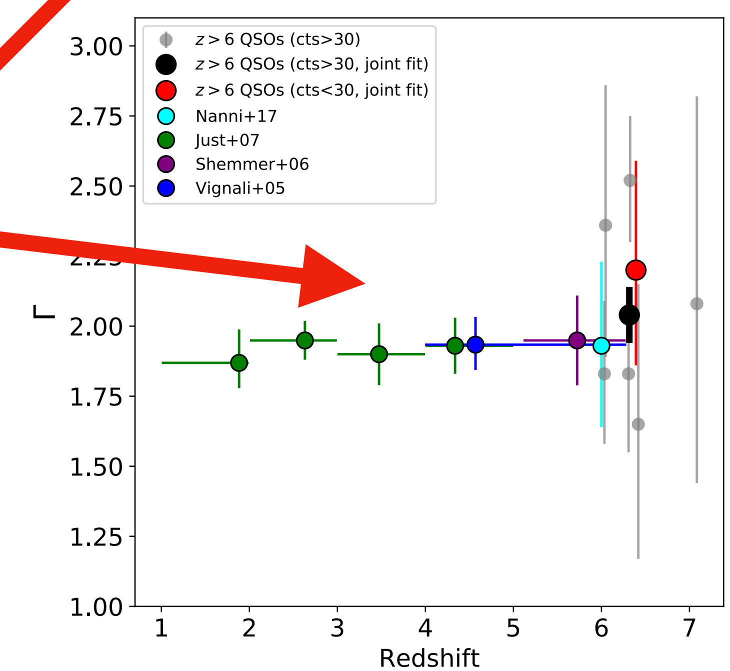


Vito+19b

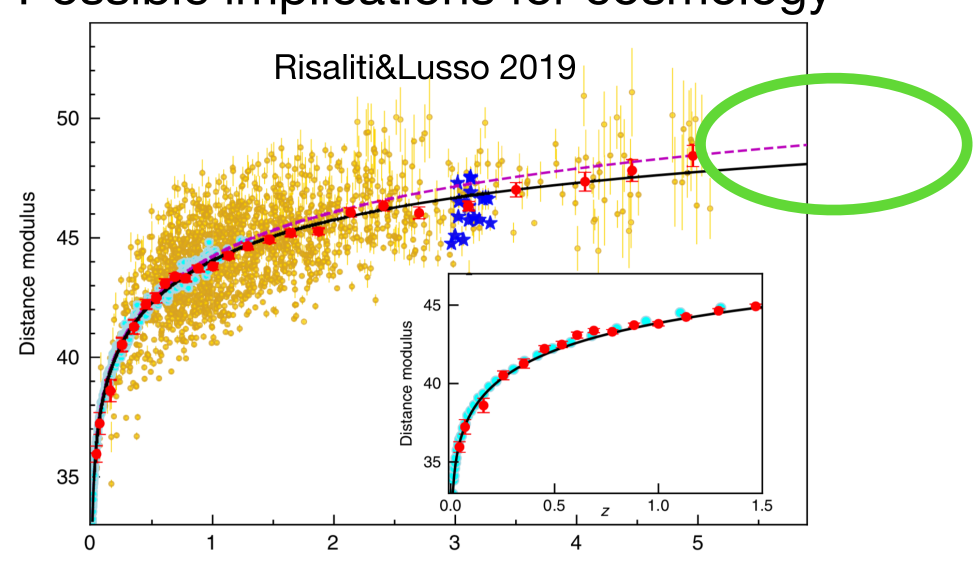
Vito+19b



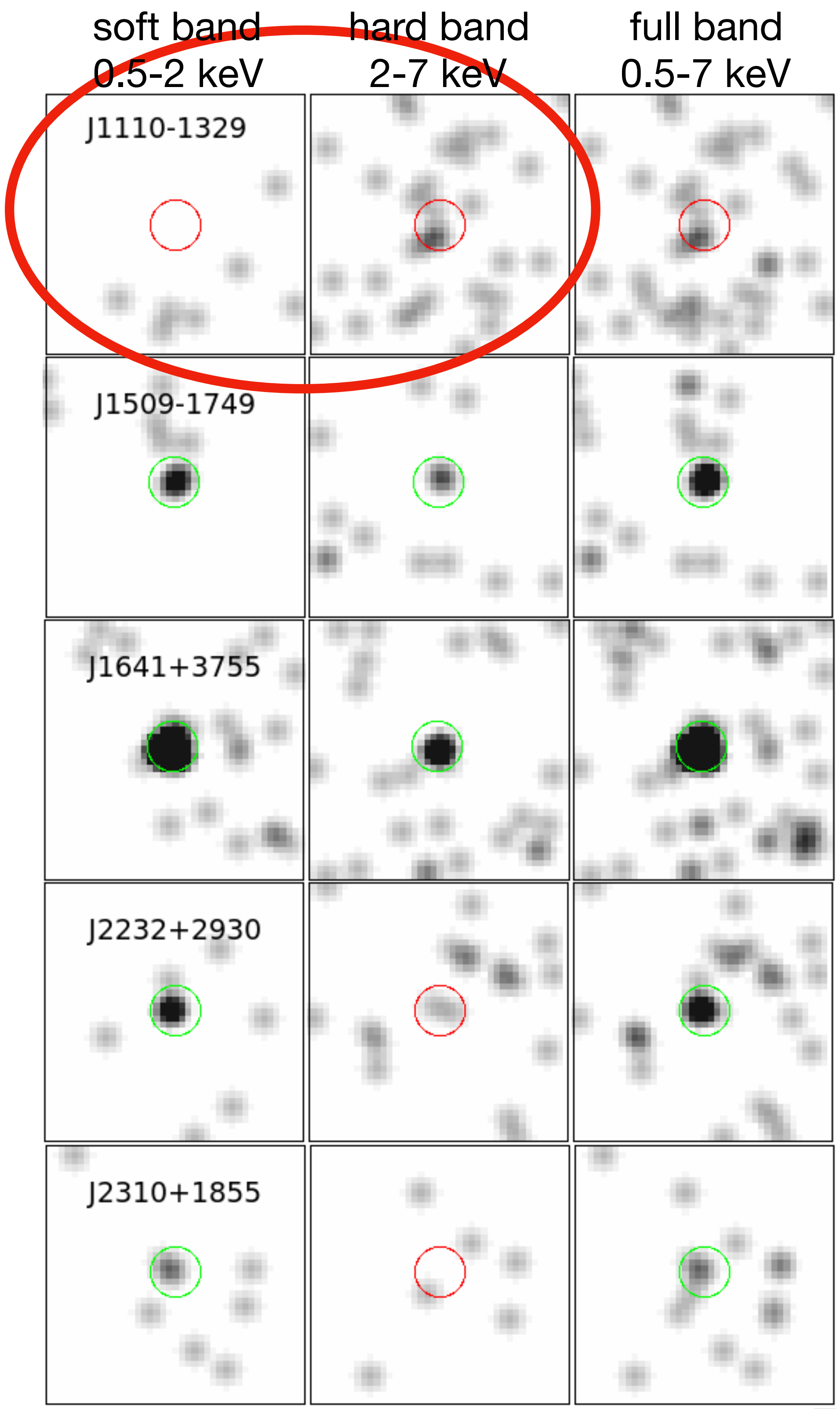
Same dependence on luminosity (i.e., λ_{EDD}?) at all redshifts



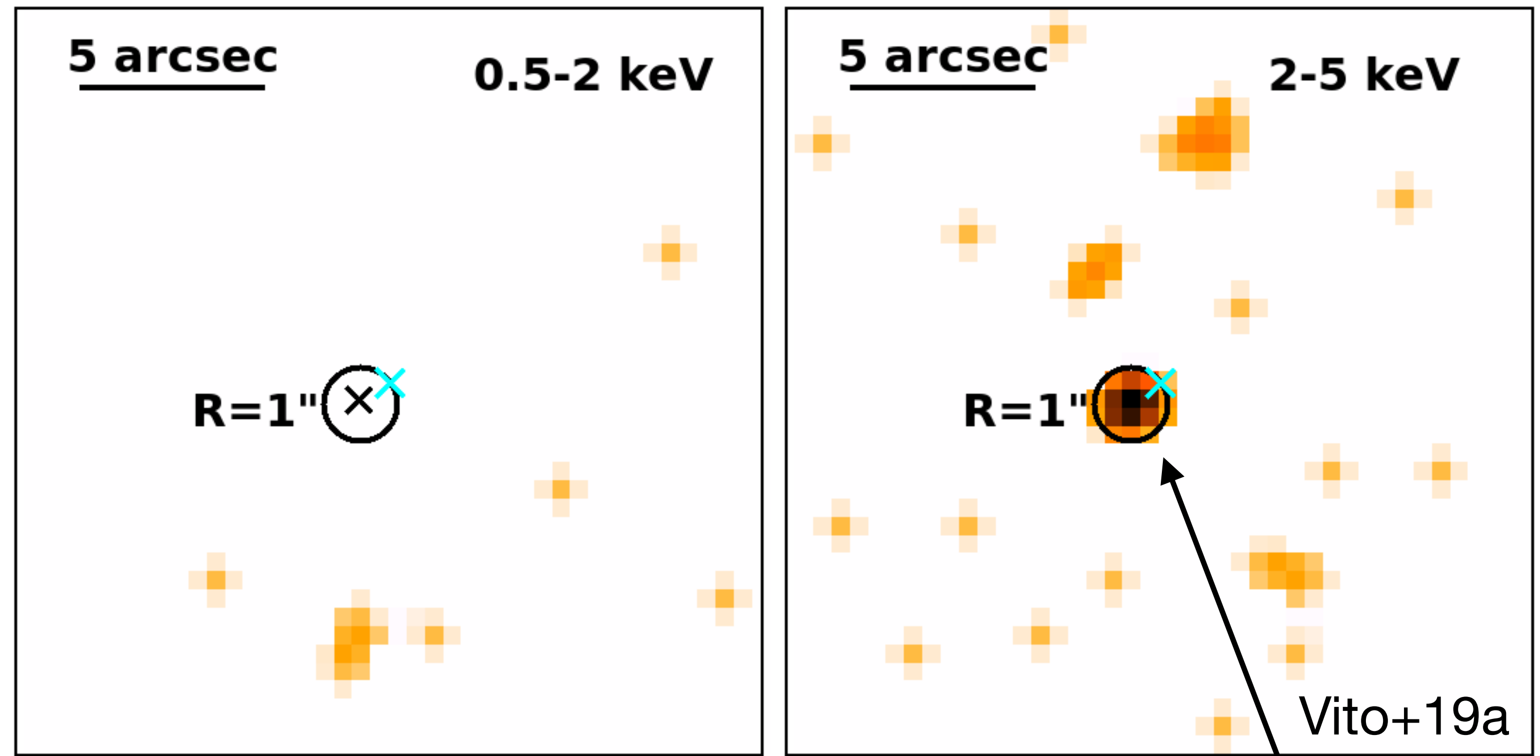
Possible implications for cosmology



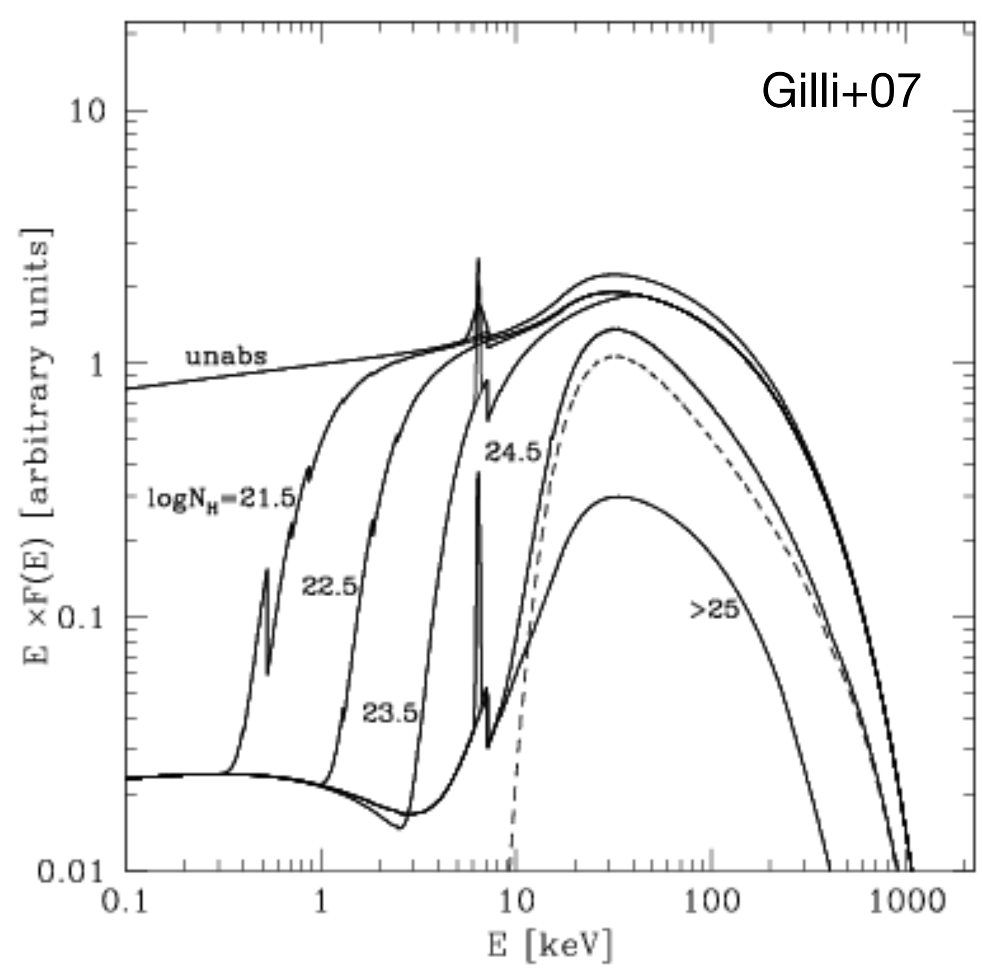
PSO167-13 (z=6.515): first heavily obscured QSO candidate at z>6!



Vito+19b

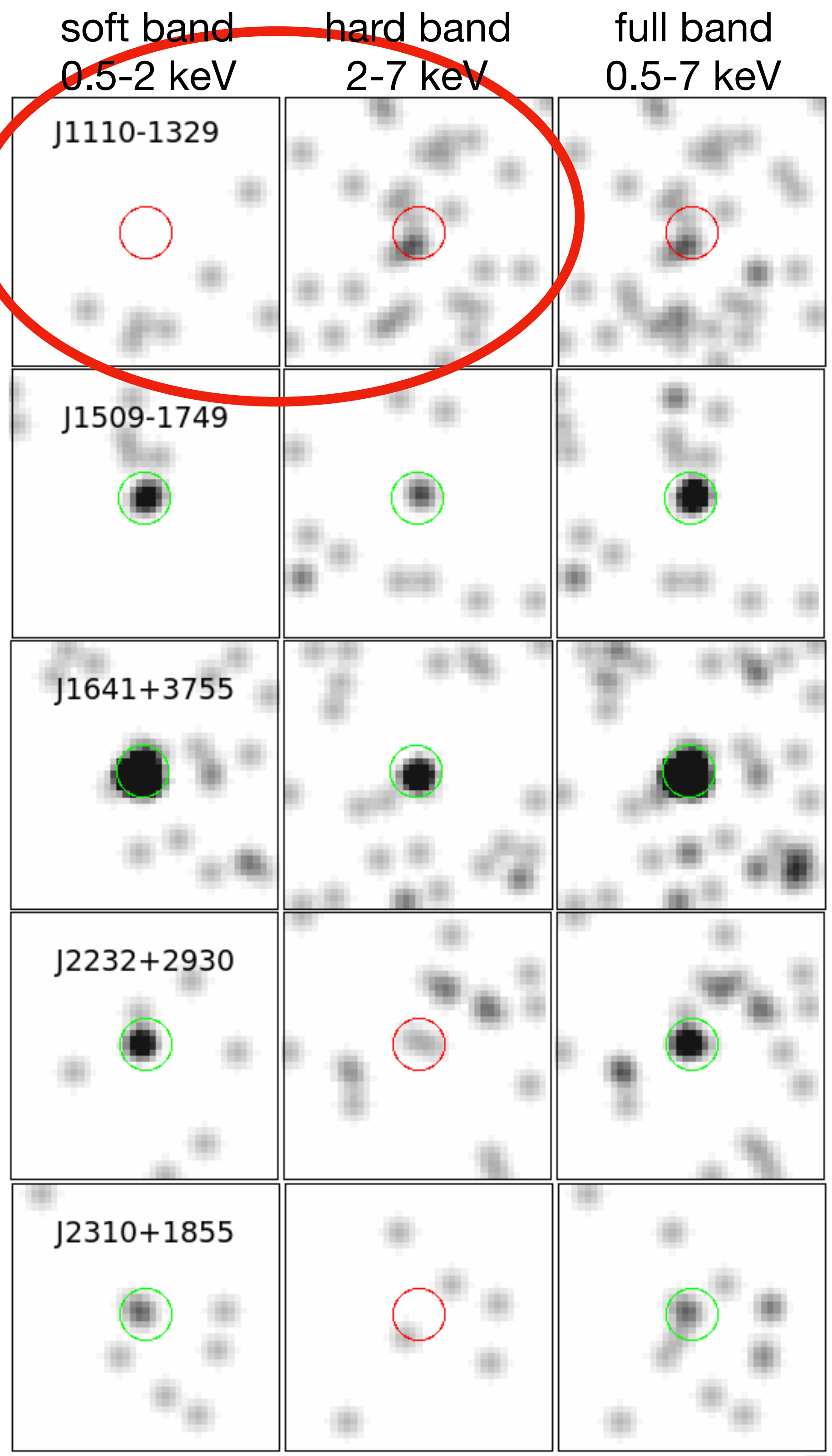


3 photons
(P=0.9996,
Weisskopf+07)

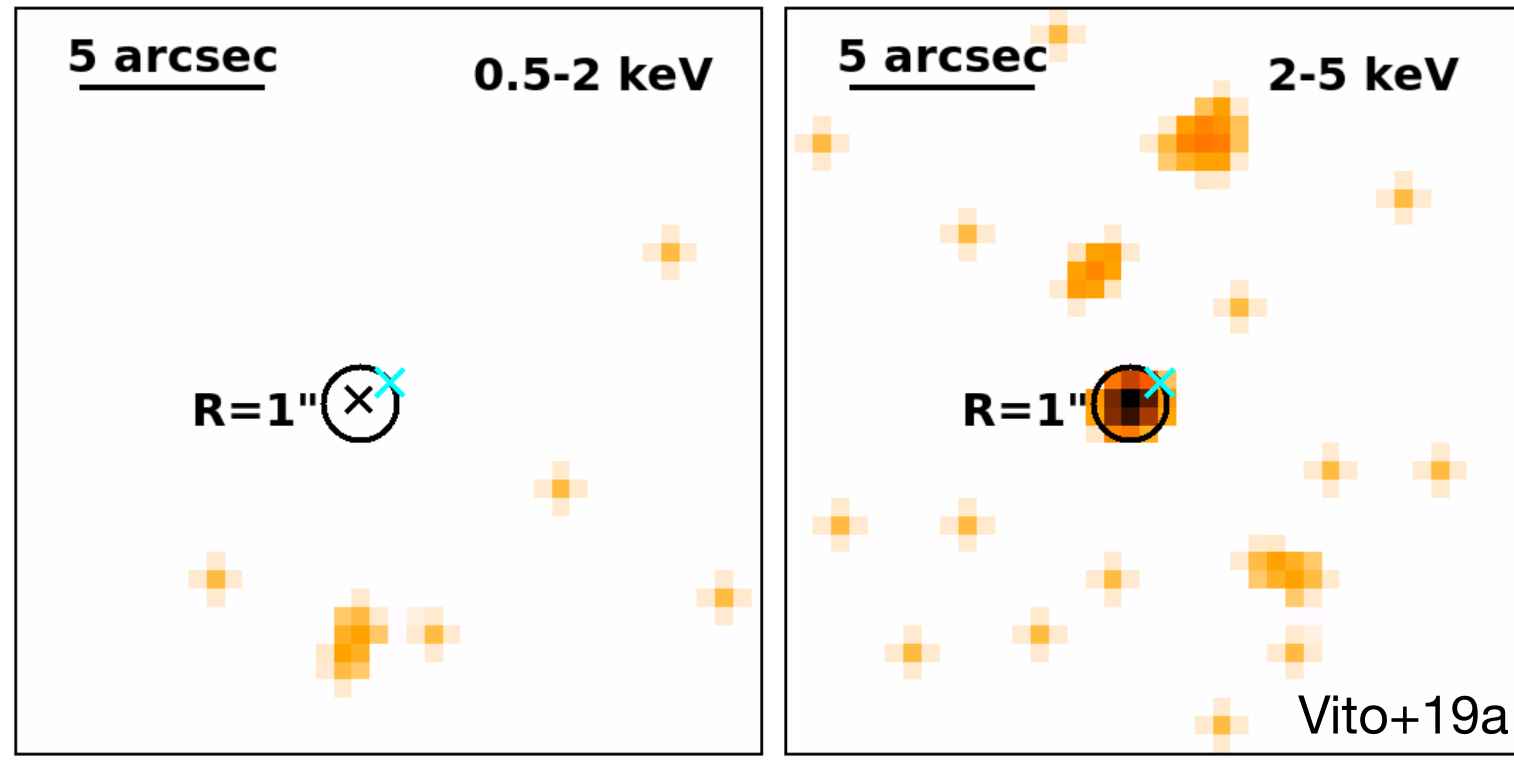


Relative emission
is soft and hard bands
gives indications
of absorption level

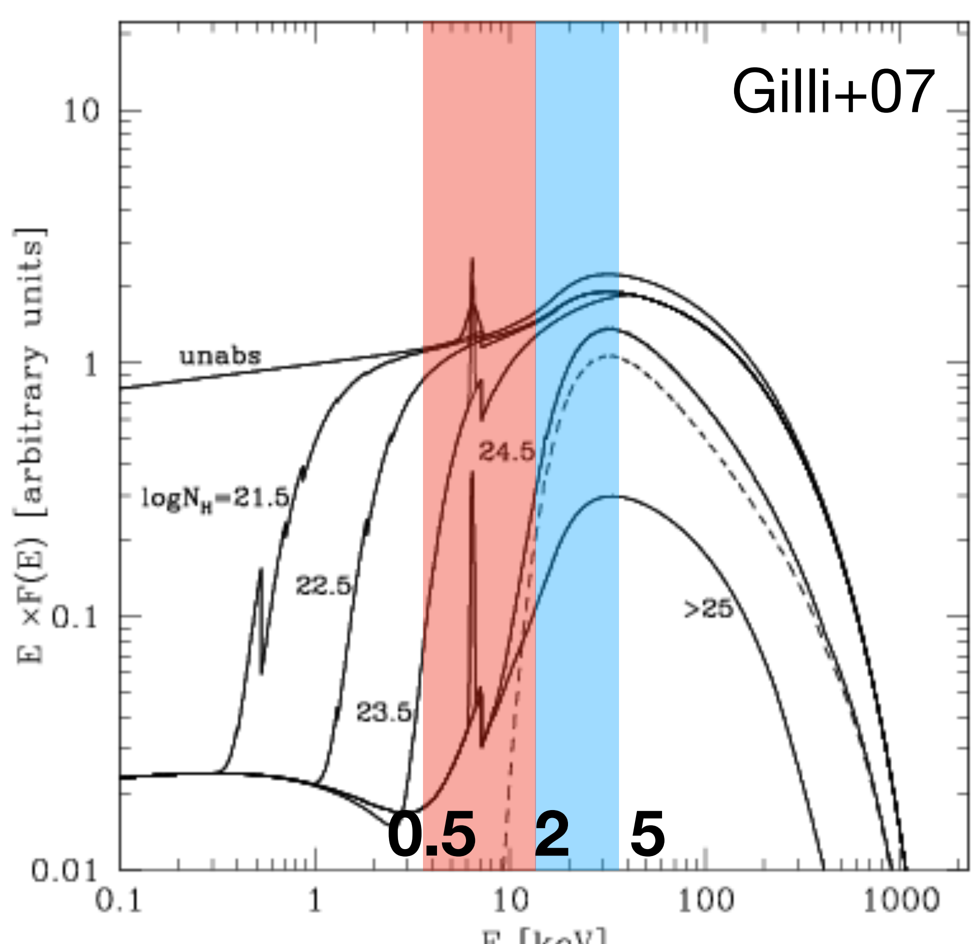
PSO167-13 (*z*=6.515): first heavily obscured QSO candidate at *z*>6!



Vito+19a



Vito+19a



N_H> 2 x 10^{24} cm^{-2}
at 68% confidence level

N_H> 6 x 10^{23} cm^{-2}
at 90% confidence level

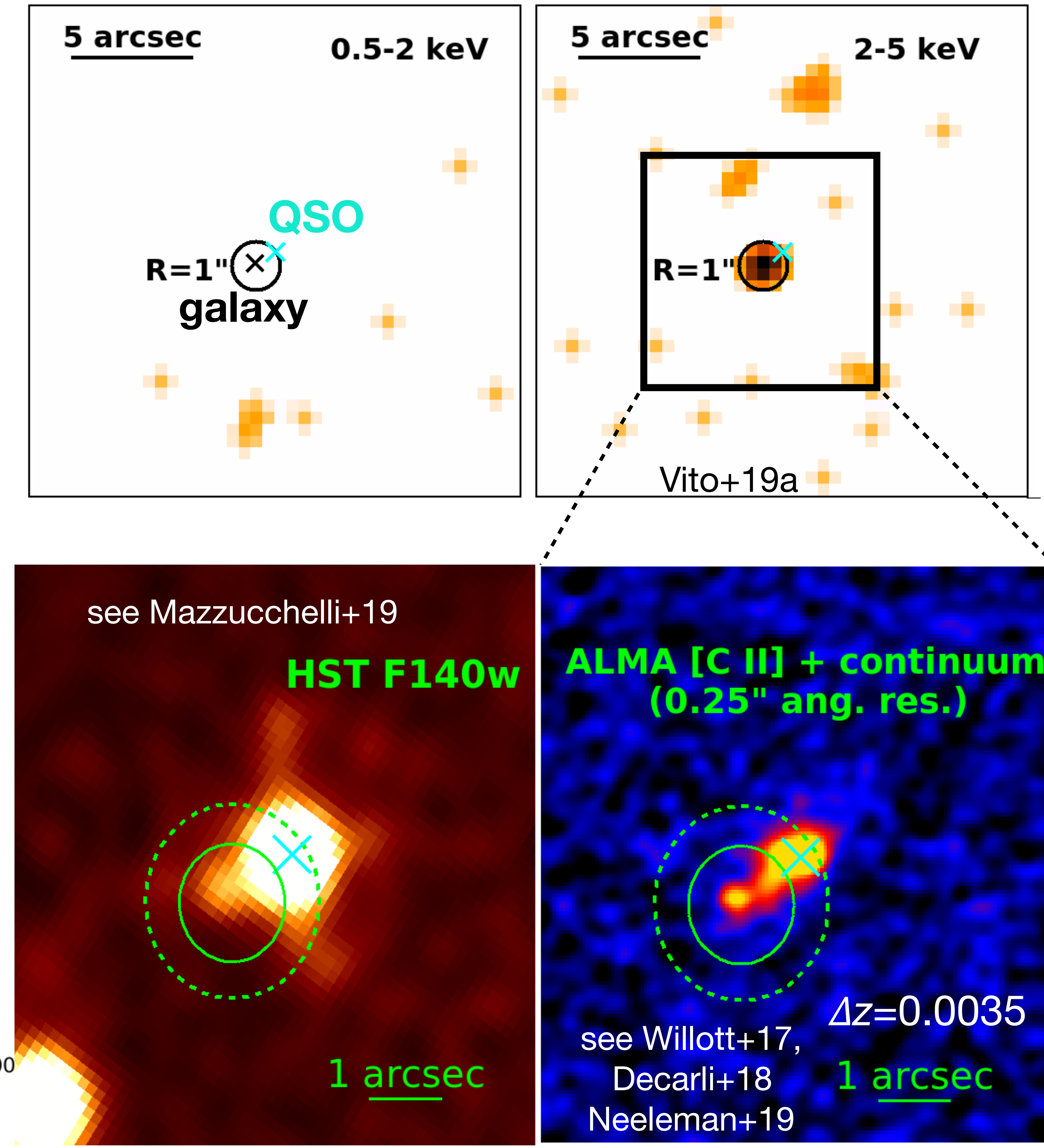
First heavily obscured QSO candidate at *z*>6!

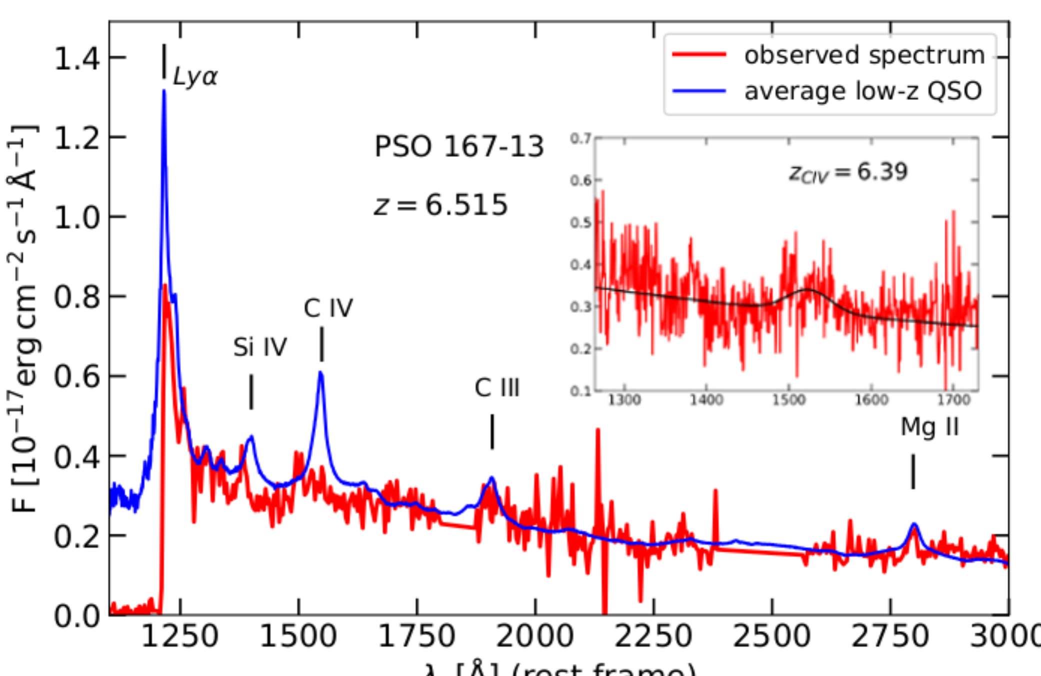
PSO167-13 (*z*=6.515): first heavily obscured QSO candidate at *z*>6!

X-ray to optical/sub-mm offset of ~1 arcsec, but significant positional uncertainty.

Why an optically type I QSO is heavily obscured in X-rays?

- **WLQ?**
- **BALQSO?**
- **Changing look QSO?**





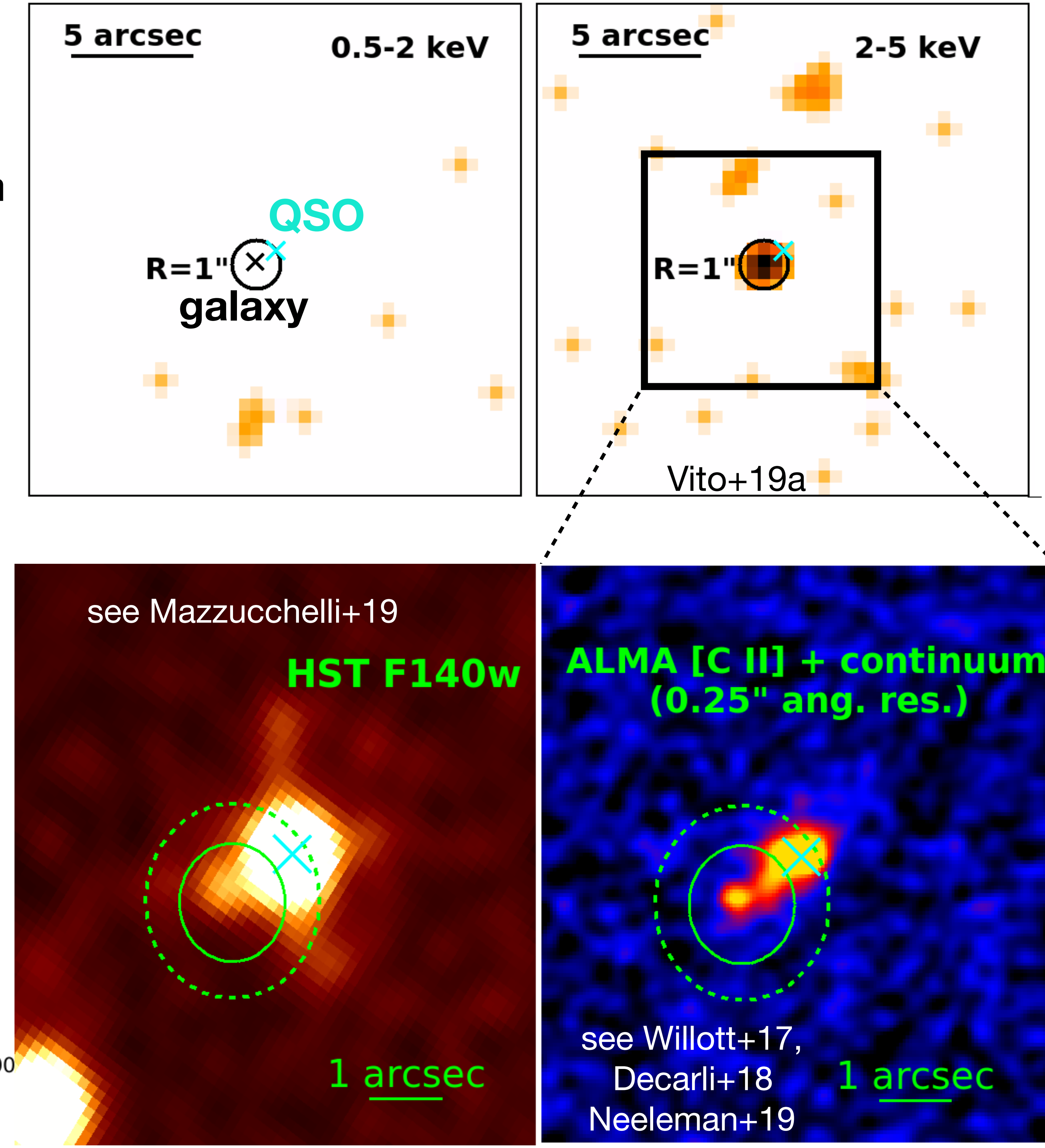
see Venemans+15

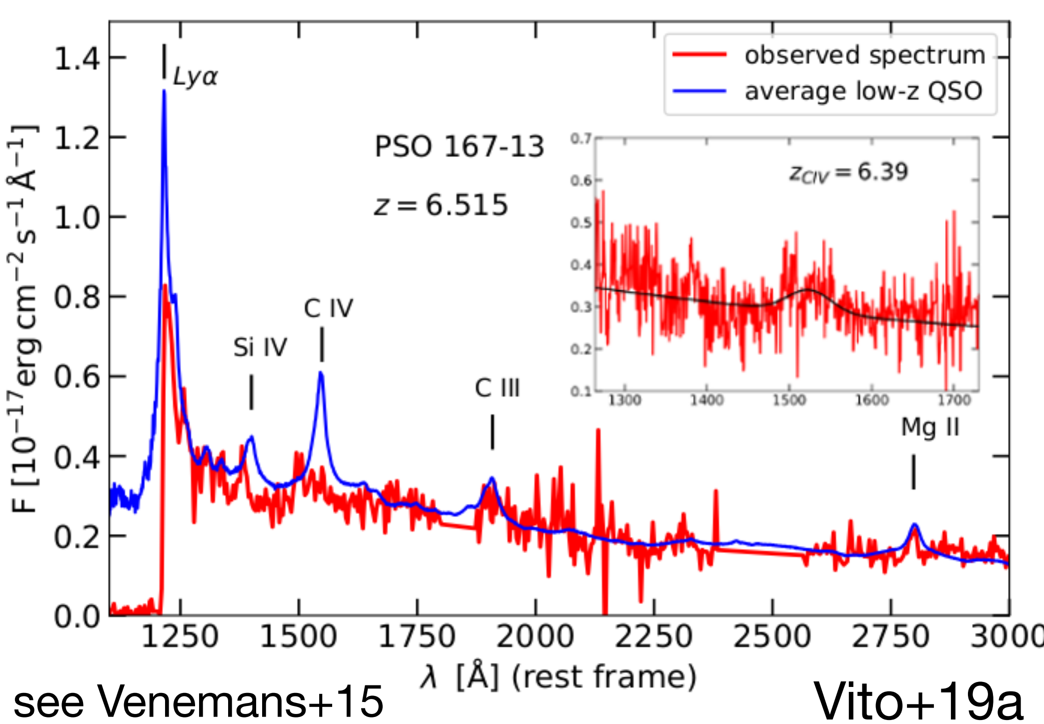
Vito+19a

PSO167-13 (*z*=6.515): first heavily obscured QSO candidate at *z*>6!

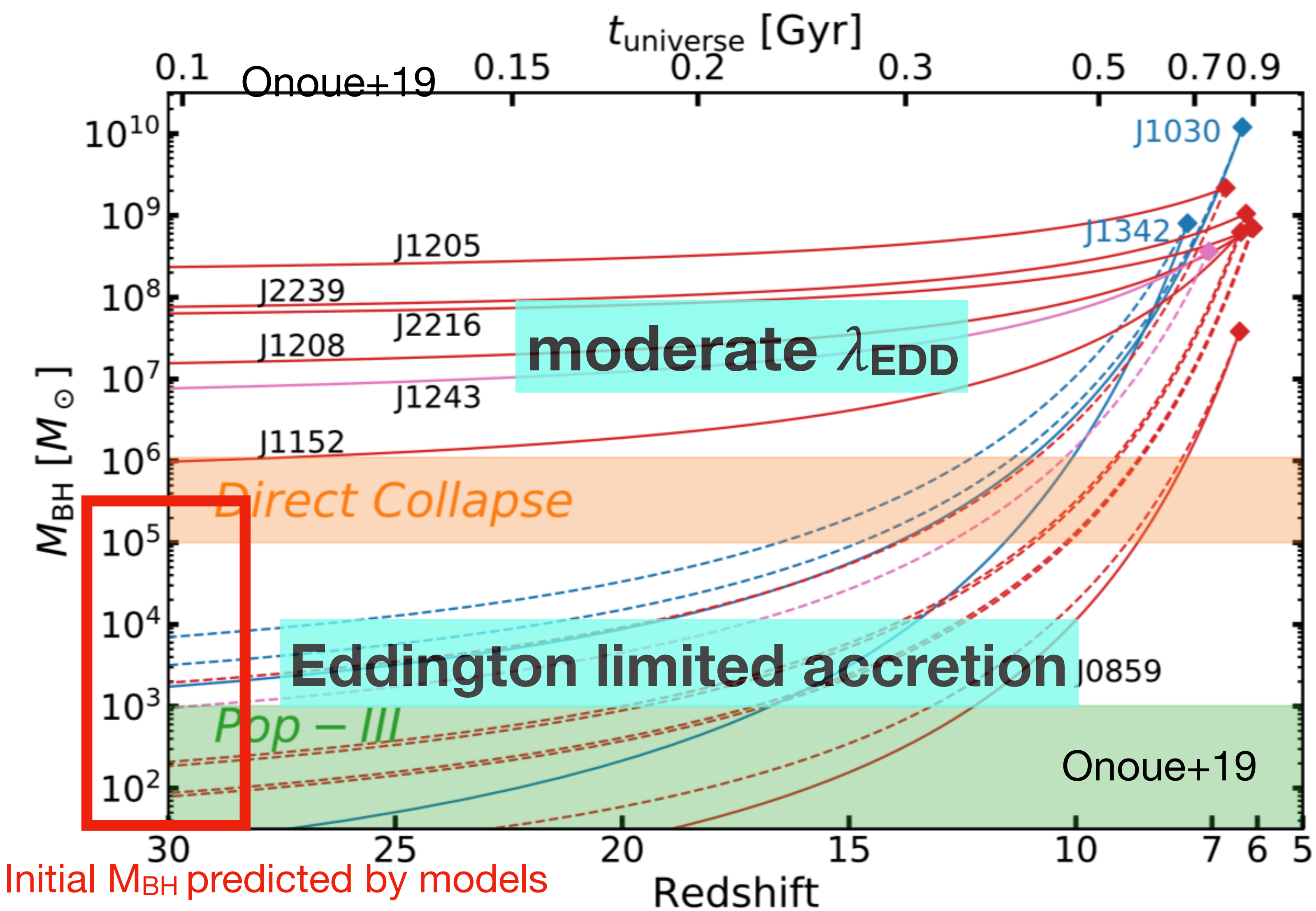
XSHOOTER (11h)
to obtain a rest-frame UV spectrum
with a higher *SNR*

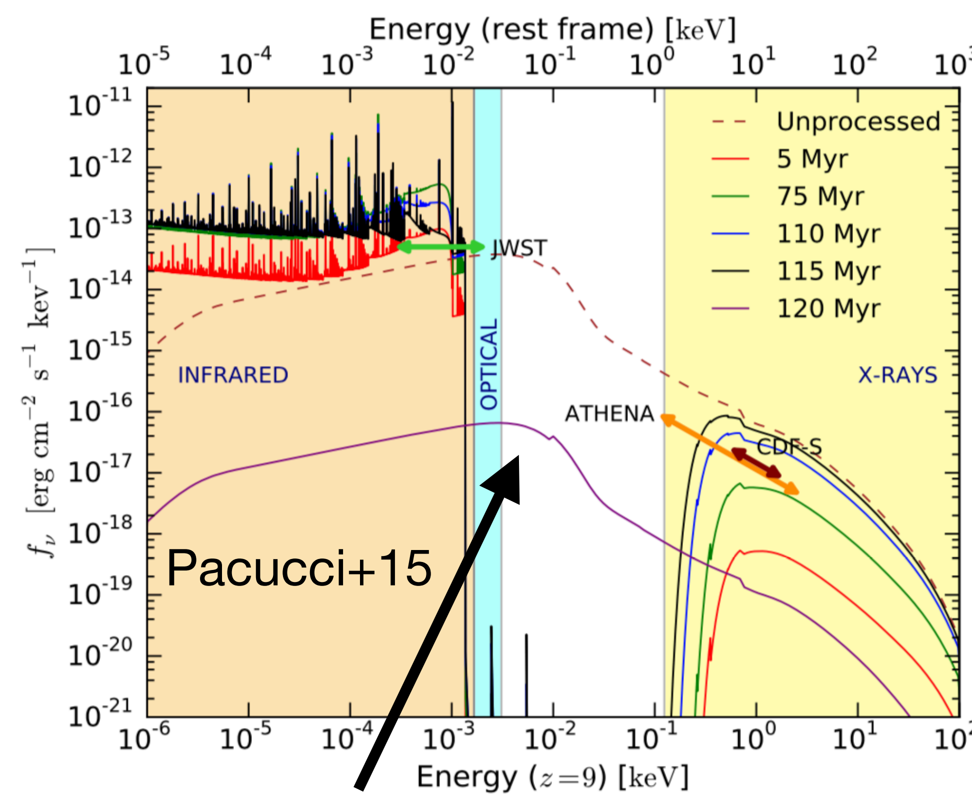
Chandra (120ks)
to confirm large N_H and
improve positional accuracy



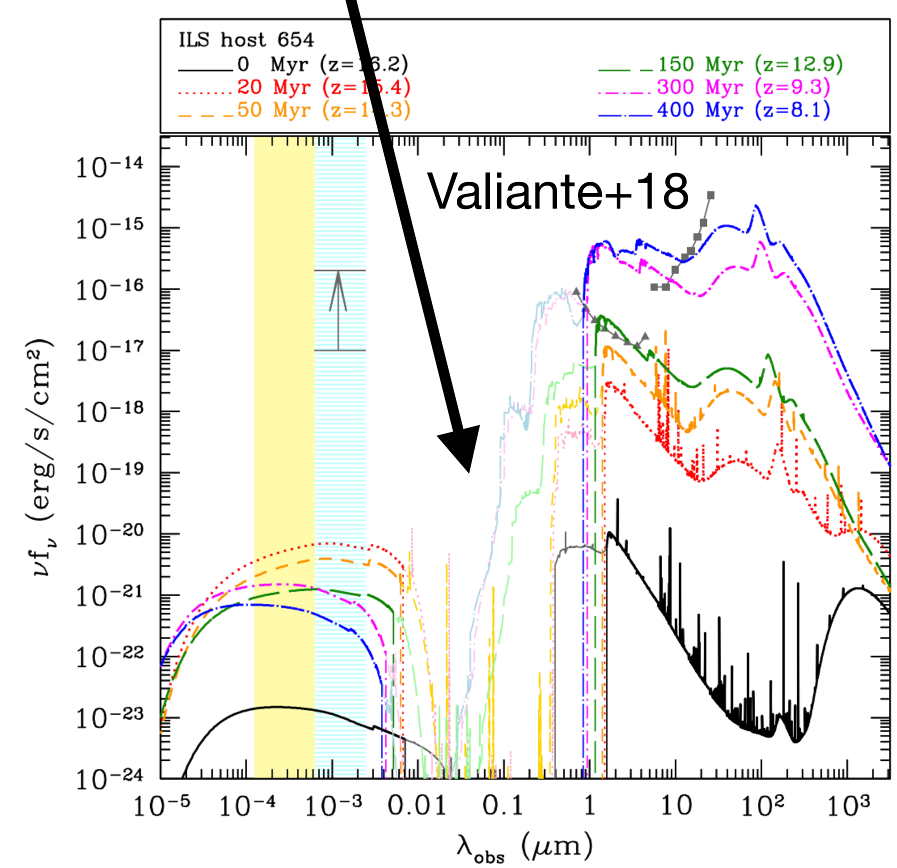


Obscured QSOs at z>6: how many are there?





Obscuration



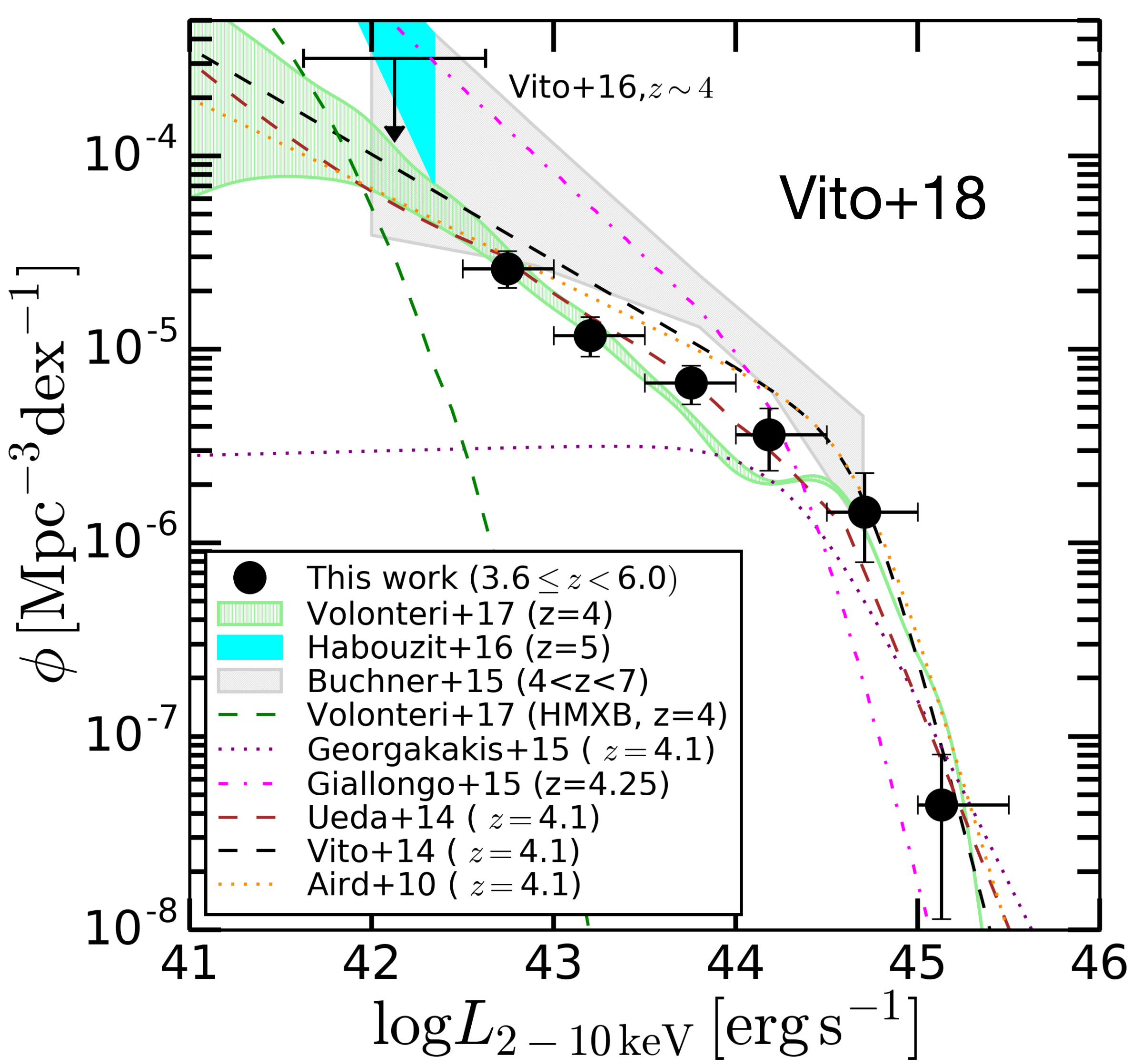
Models require fast accretion
(i.e., high Eddington ratio λ_{EDD}),
possibly in heavily obscured conditions,
to match the observed M_{BH} at z=6-7.5

Obscured QSOs at z>6: how many are there?

Extrapolate AGN X-ray LF at z~4 and compare with QSO UV LF at z~6

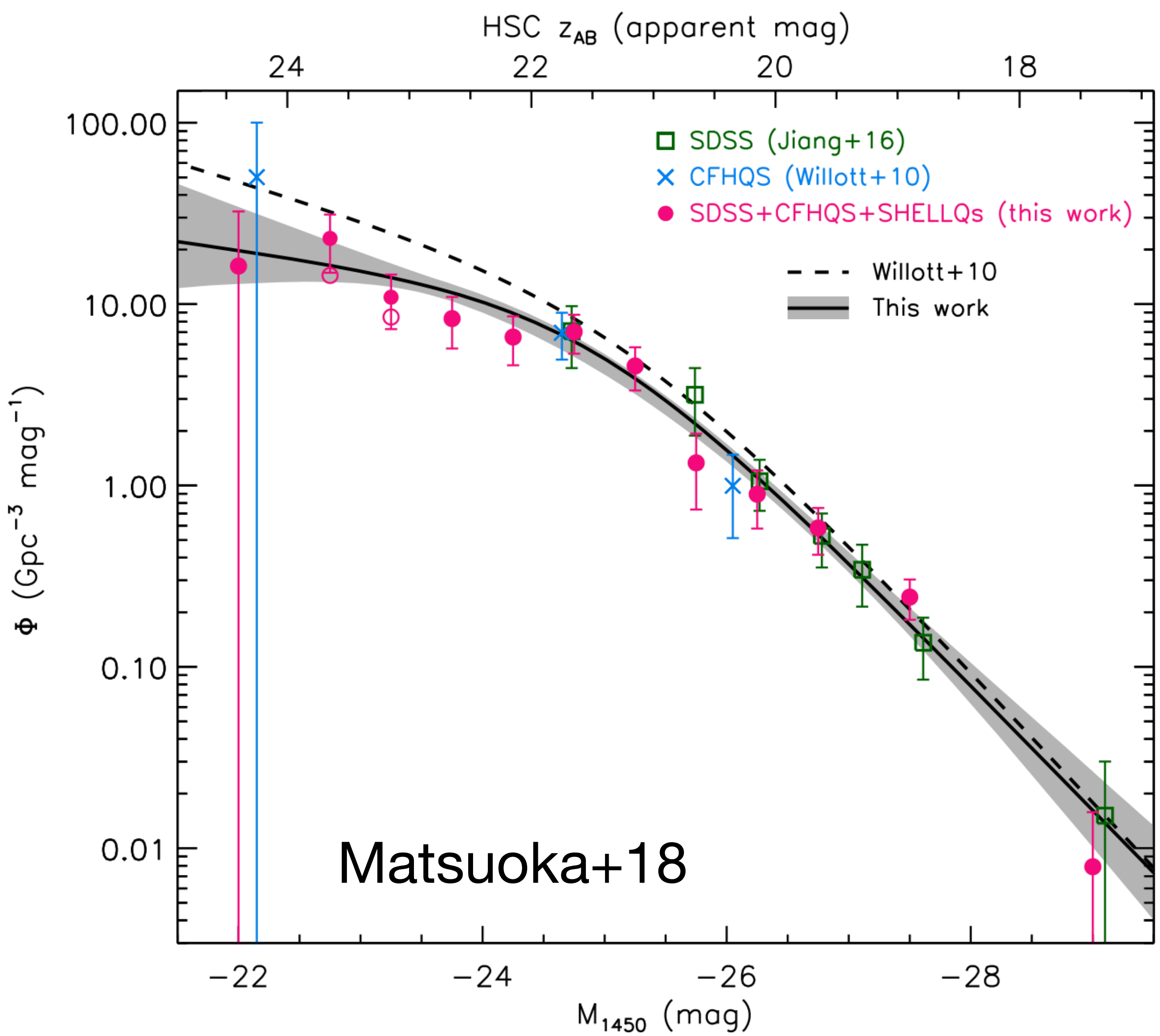
z~4 AGN XLF (Vito+14,+18)

- Includes ~all obscured AGN
- normalization $\propto (1+z)^{-6}$

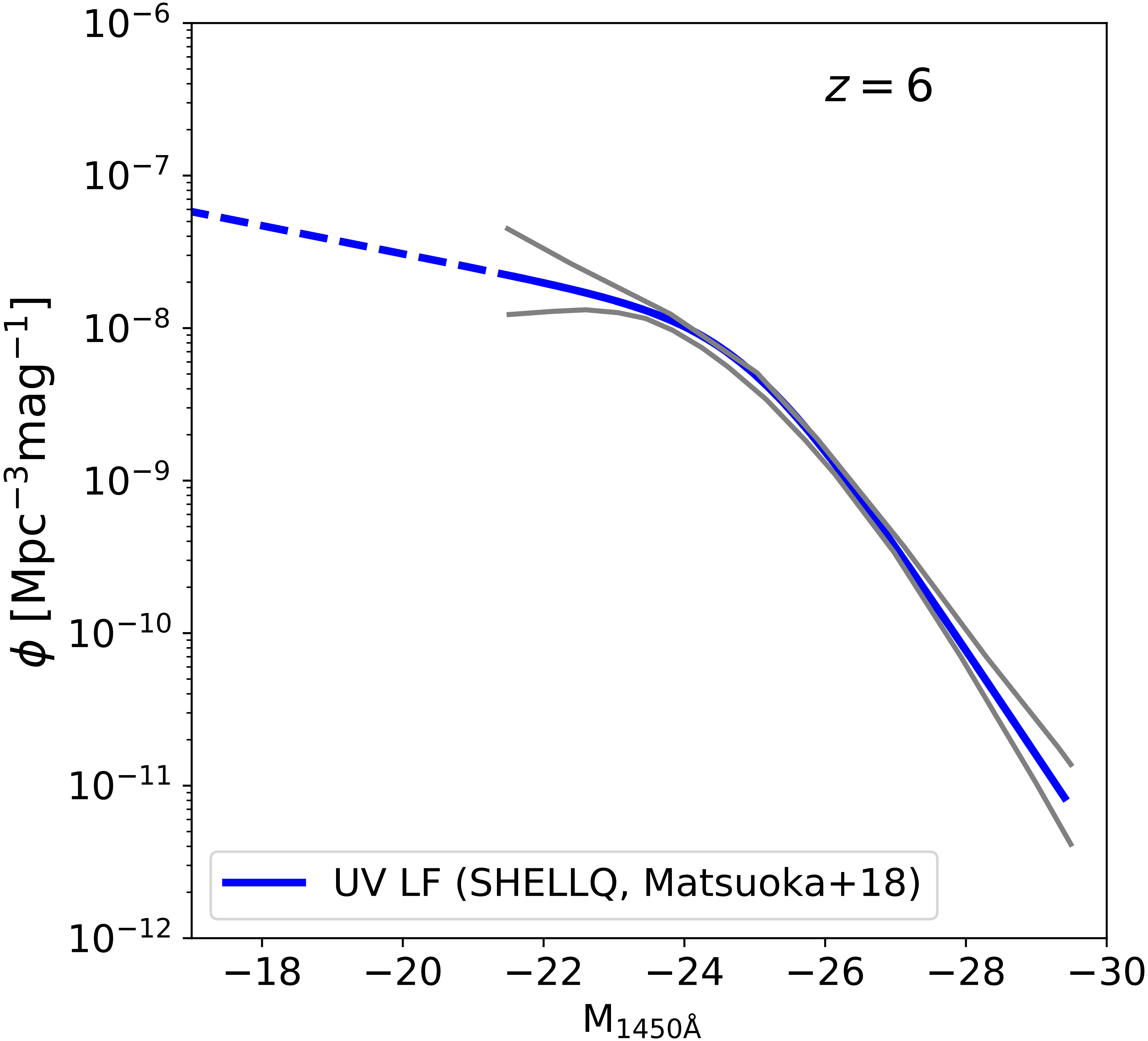


z~6 QSO UV LF (Matsuoka+18)

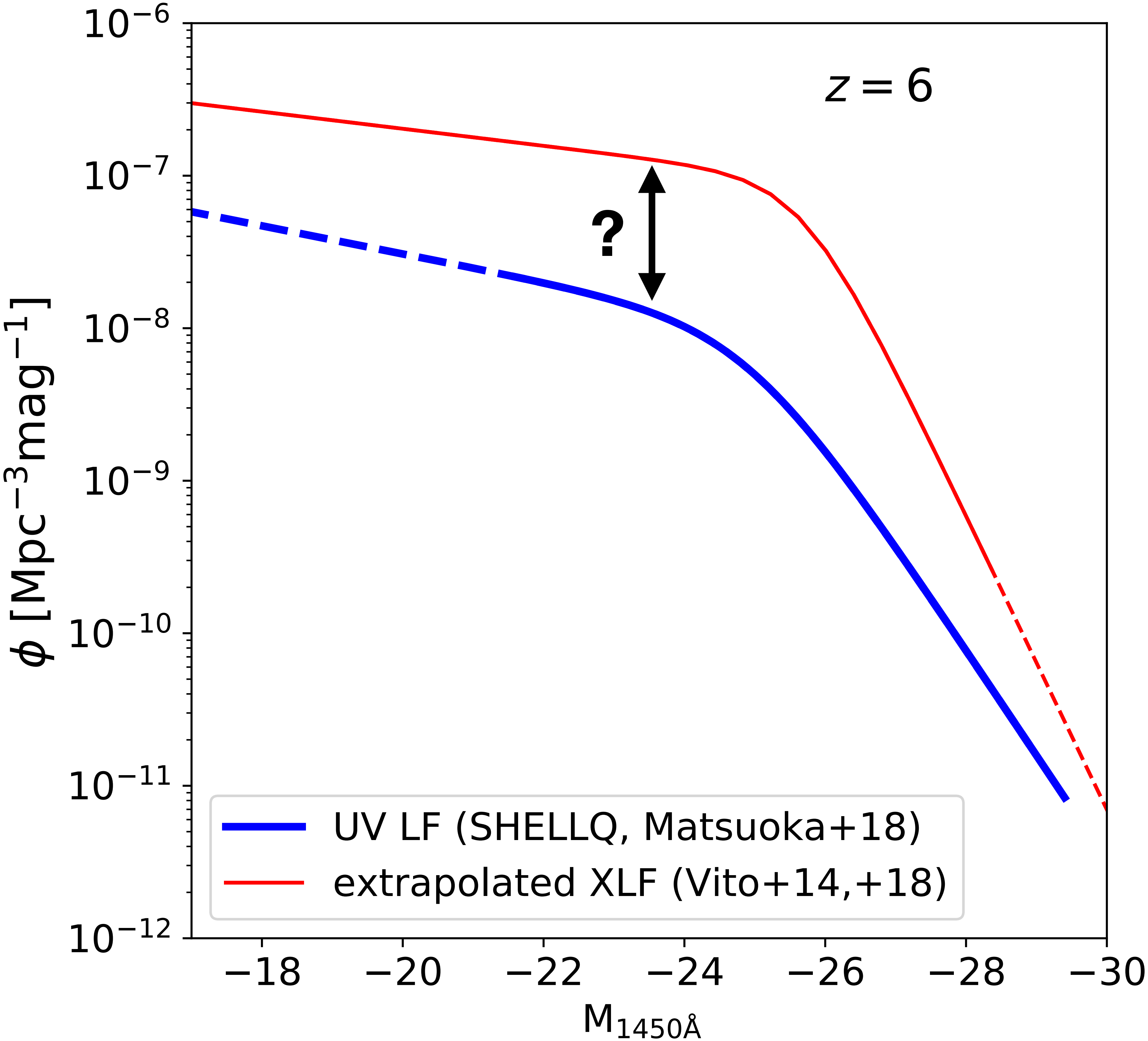
- Includes ~only unobscured QSOs



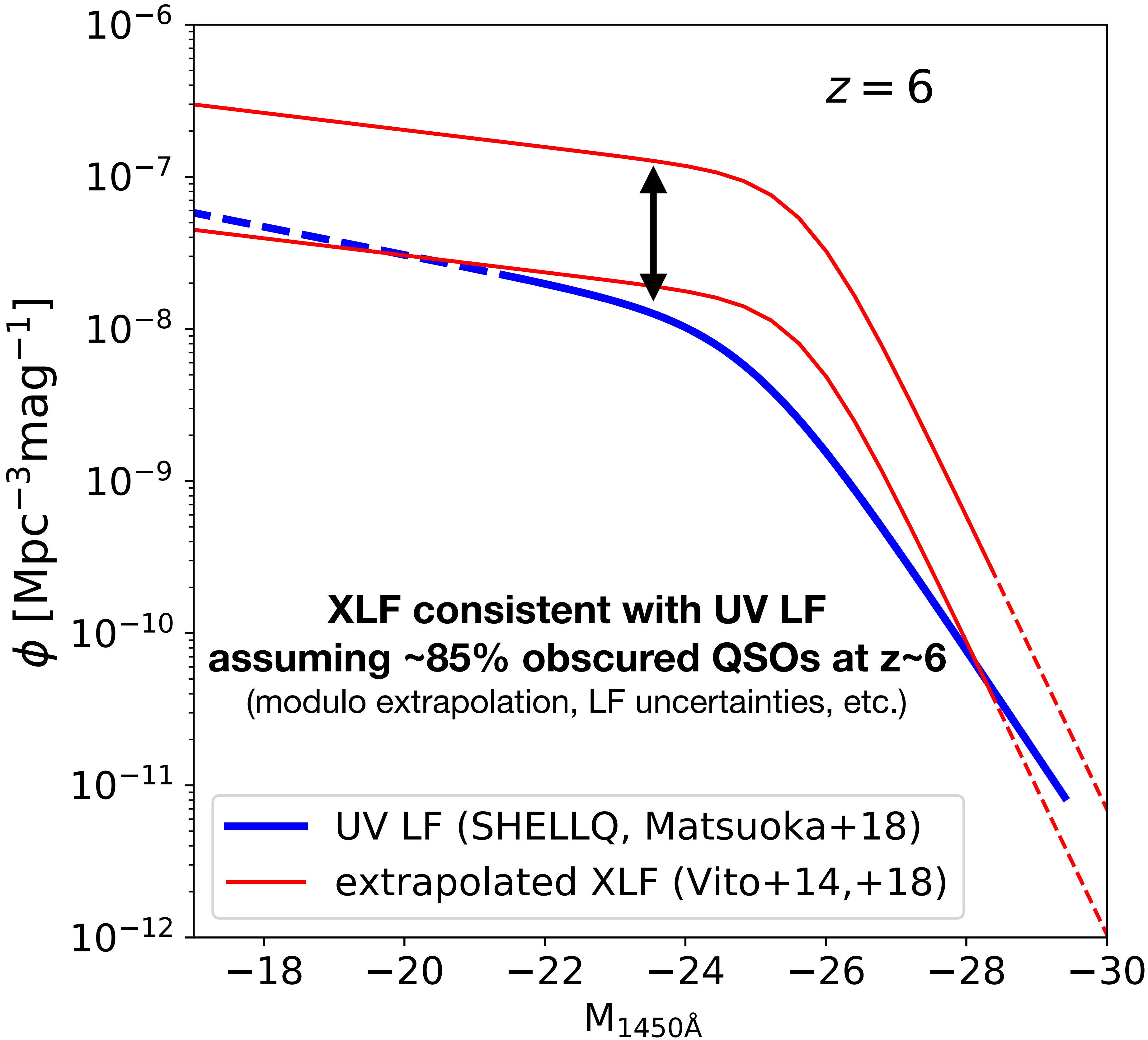
Obscured QSOs at z>6: how many are there?



Obscured QSOs at z>6: how many are there?



Obscured QSOs at z>6: how many are there?



Huge discovery space for current and future X-ray observatories!