Formation and evolution of AGN at high redshift

[In collaboration with R. Gilli, F. Vito, R. Nanni, C. Circosta, Q. D'Amato, …]

Recent review by Inayoshi et al. (2020, ARA&A) -
"The Assembly of the First Massive Black Holes"

Outline

- Where do we stand?

  Statistics on high-redshift AGN. Recent results from Pan-STARRS and SHELLQ. z>6 QSOs as massive and rare systems accreting close to Eddington, with similar properties to lower-z QSOs

- X-ray properties of high-redshift unobscured quasars

  Probing (also with X-ray spectra) luminous unobscured QSOs up to the highest redshift, challenging observations

- On the growth of SMBHs: the challenge of massive BHs in <1 Gyr

  Models vs. observations

- Obscured AGN at z>3: insights from X-ray surveys. AGN evolution. Analysis of AGN host galaxies from ALMA

  Obscured AGN fractions seems to be higher at high redshift, especially at high L_X. Can the host contribute to obscuration?

- What's next?

Part I:
Where do we stand?

Where do we stand? I. Quasar statistics

~330 QSOs at $z>5.7$ (~220 at $z>6$, ~60 at $z>6.5$, 9 at $z>7$)

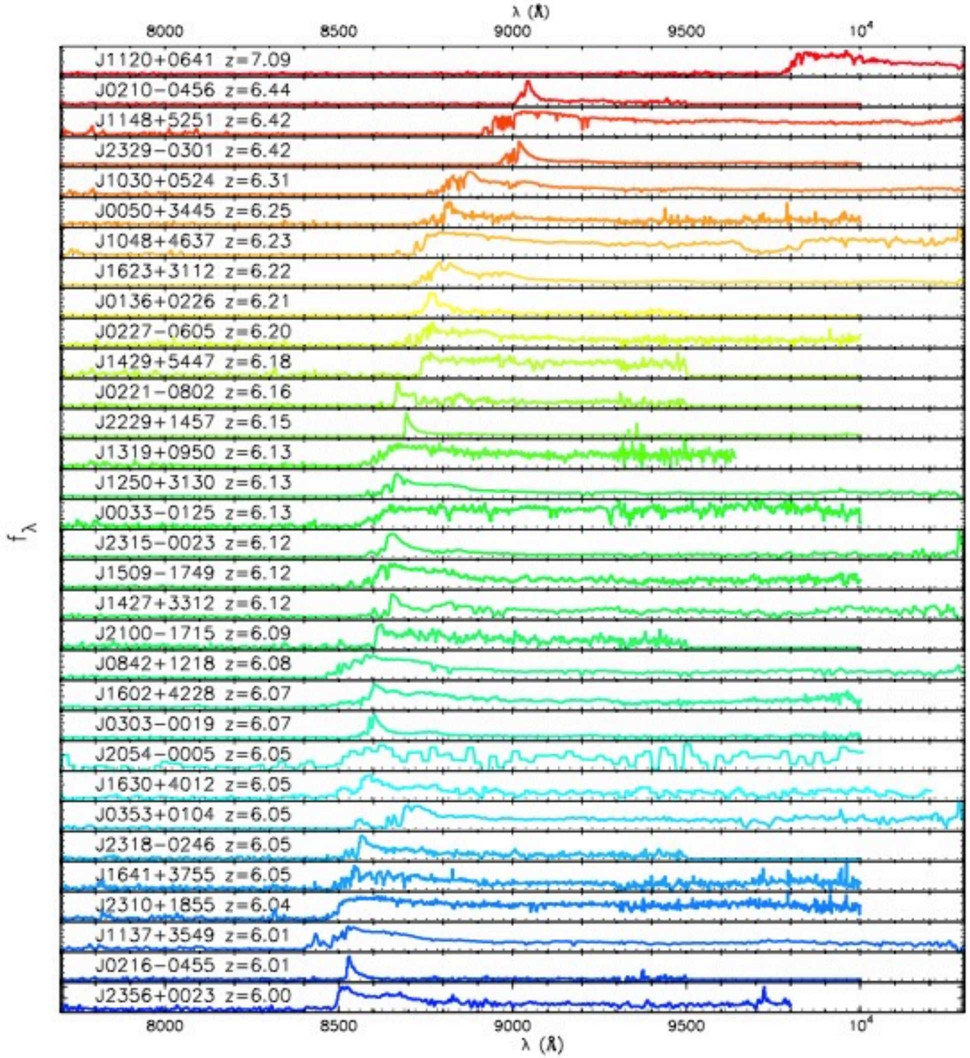
(SDSS, CFHQS, Pan-STARRS1, DES, UKIDSS, VISTA-Viking, HSC) - (Fan+00−06; Jiang+08,09; Willott+07,09,10; Banados+14,16, 18; Mortlock+11; Venemans+13, 15, Matsuoka+16,18,19)

SELECTION: Opt/NIR, several radio (McGreer+06, Zeimann+11, Belladitta+20-blazar, …), **0 X-ray**

Limited X-ray coverage

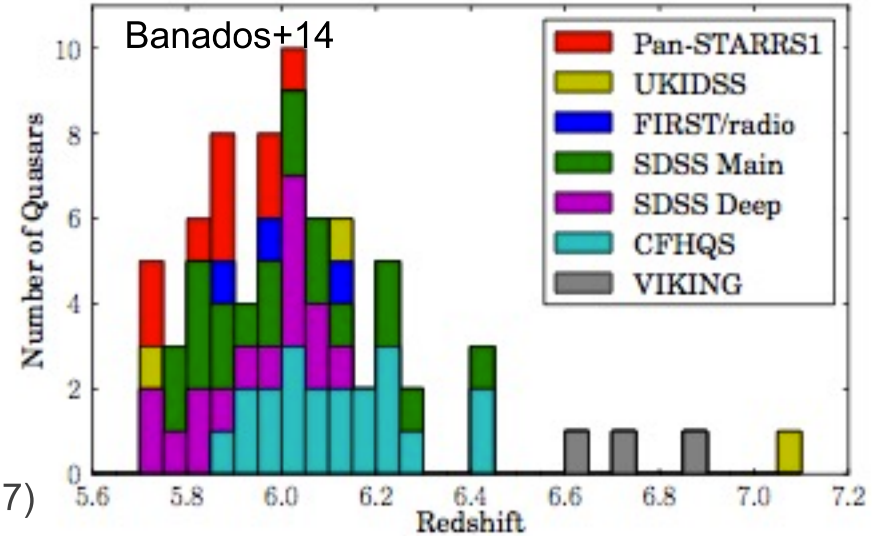
SDSS traces the most luminous QSOs ($\log L_X$~45, $\log L_{bol}$~46.5, M_{1450}=[−24,−28])

Faint end of the LF still to be achieved



Fan+12

continuous update of these numbers (e.g., Inayoshi+20, ARAA: 197 at z≥6, 6 at z>7)


Banados+14

z≥6 quasar-finder surveys

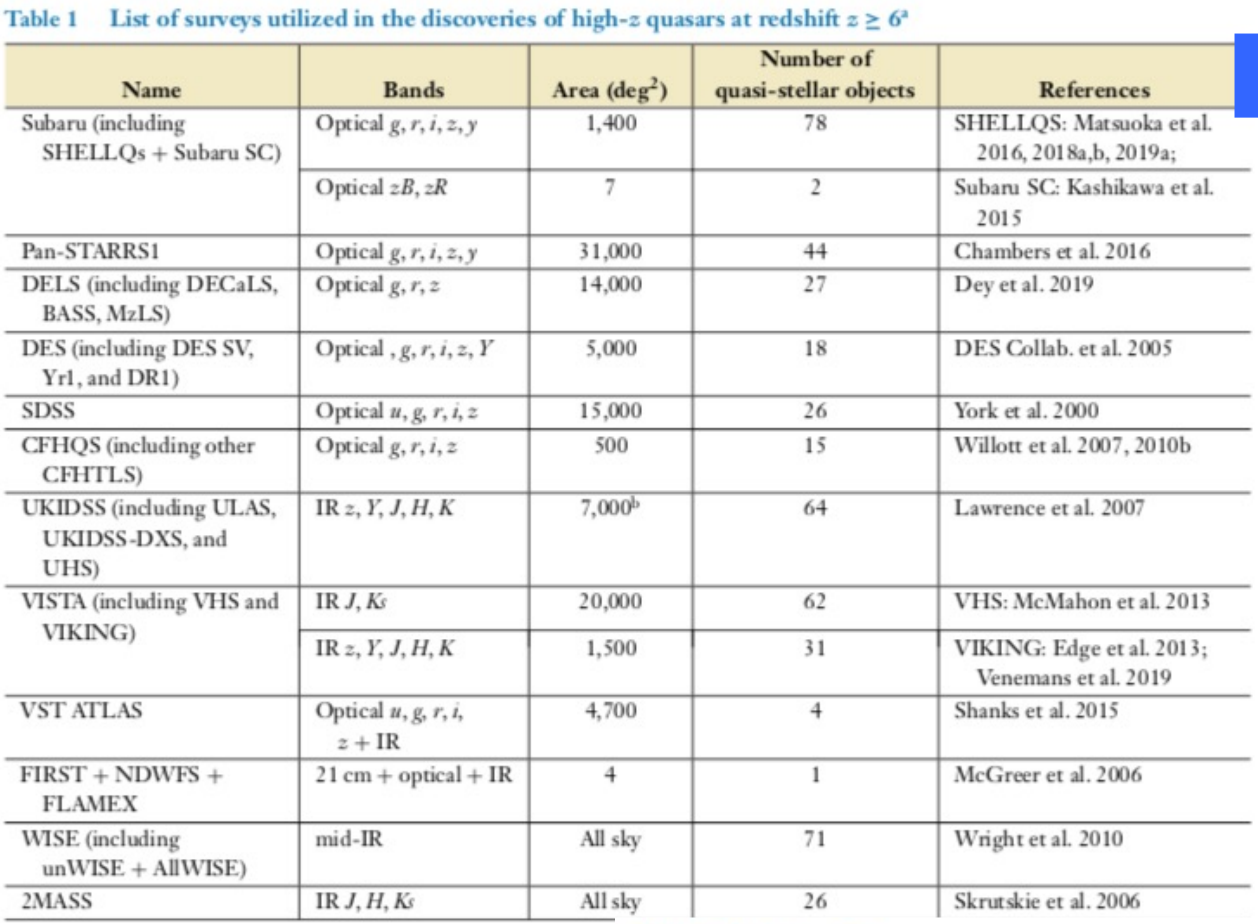


Table 1 List of surveys utilized in the discoveries of high-z quasars at redshift $z \geq 6^a$

Name	Bands	Area (deg^2)	Number of quasi-stellar objects	References
Subaru (including SHELLQs + Subaru SC)	Optical g, r, i, z, y	1,400	78	SHELLQS: Matsuoka et al. 2016, 2018a,b, 2019a;
	Optical zB, zR	7	2	Subaru SC: Kashikawa et al. 2015
Pan-STARRS1	Optical g, r, i, z, y	31,000	44	Chambers et al. 2016
DELS (including DECaLS, BASS, MzLS)	Optical g, r, z	14,000	27	Dey et al. 2019
DES (including DES SV, Yr1, and DR1)	Optical , g, r, i, z, Y	5,000	18	DES Collab. et al. 2005
SDSS	Optical u, g, r, i, z	15,000	26	York et al. 2000
CFHQS (including other CFHTLS)	Optical g, r, i, z	500	15	Willott et al. 2007, 2010b
UKIDSS (including ULAS, UKIDSS-DXS, and UHS)	IR z, Y, J, H, K	7,000^b	64	Lawrence et al. 2007
VISTA (including VHS and VIKING)	IR J, Ks	20,000	62	VHS: McMahon et al. 2013
	IR z, Y, J, H, K	1,500	31	VIKING: Edge et al. 2013; Venemans et al. 2019
VST ATLAS	Optical $u, g, r, i,$ z + IR	4,700	4	Shanks et al. 2015
FIRST + NDWFS + FLAMEX	21 cm + optical + IR	4	1	McGreer et al. 2006
WISE (including unWISE + AllWISE)	mid-IR	All sky	71	Wright et al. 2010
2MASS	IR J, H, Ks	All sky	26	Skrutskie et al. 2006

Inayoshi+20 review

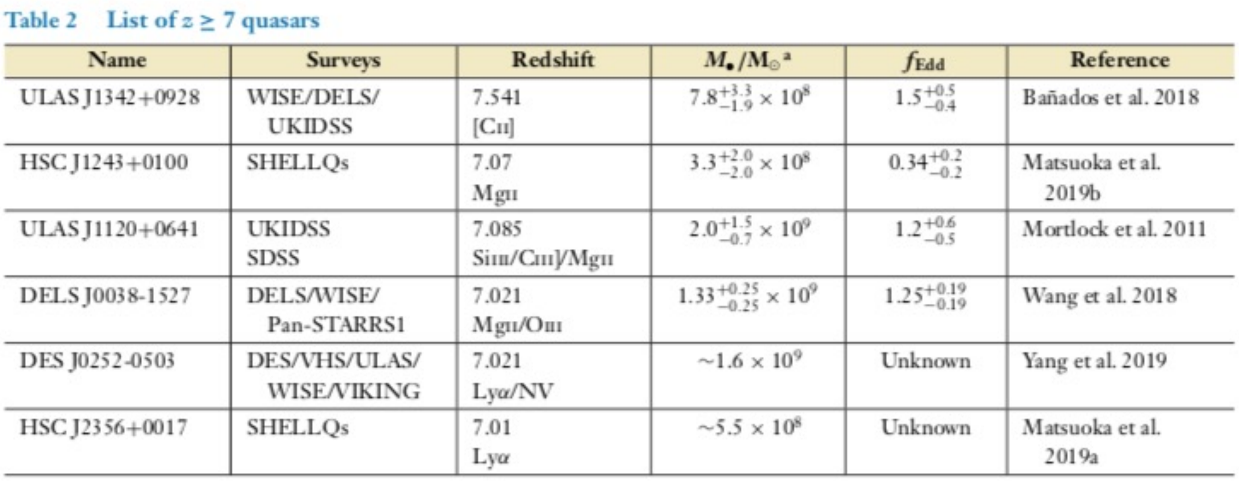


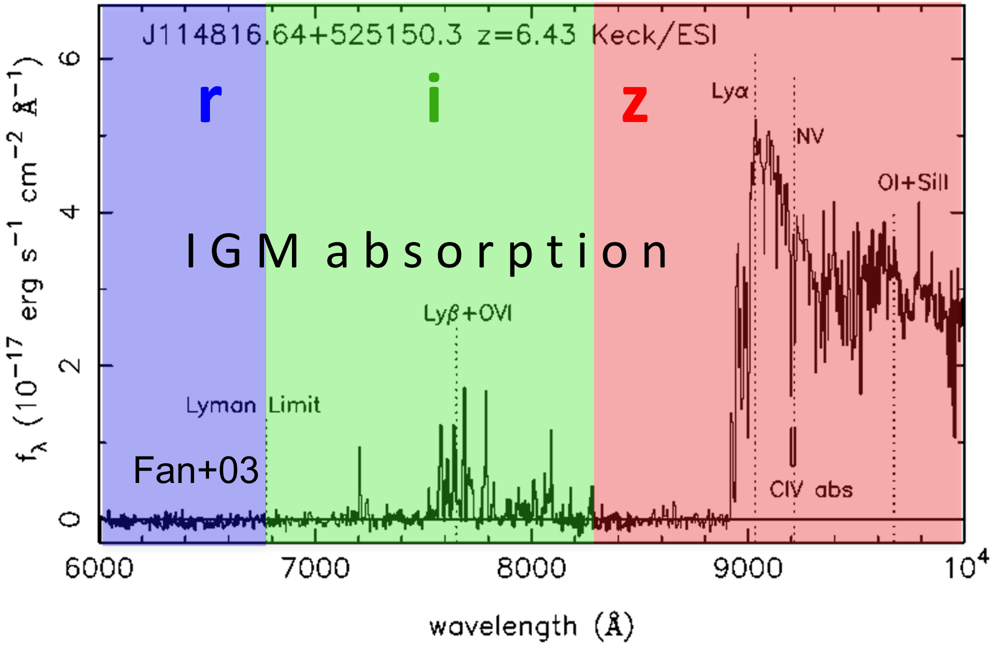
Table 2 List of $z \geq 7$ quasars

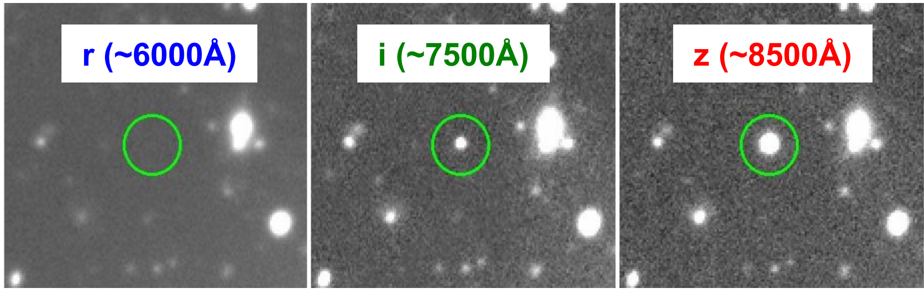
Name	Surveys	Redshift	$M_\bullet/M_\odot$ ^{a}	$f_{\rm Edd}$	Reference
ULAS J1342+0928	WISE/DELS/ UKIDSS	7.541 [C II]	$7.8^{+3.3}_{-1.9} \times 10^8$	$1.5^{+0.5}_{-0.4}$	Bañados et al. 2018
HSC J1243+0100	SHELLQs	7.07 Mg II	$3.3^{+2.0}_{-2.0} \times 10^8$	$0.34^{+0.2}_{-0.2}$	Matsuoka et al. 2019b
ULAS J1120+0641	UKIDSS SDSS	7.085 Si III/C III]/Mg II	$2.0^{+1.5}_{-0.7} \times 10^9$	$1.2^{+0.6}_{-0.5}$	Mortlock et al. 2011
DELS J0038-1527	DELS/WISE/ Pan-STARRS1	7.021 Mg II/O III	$1.33^{+0.25}_{-0.25} \times 10^9$	$1.25^{+0.19}_{-0.19}$	Wang et al. 2018
DES J0252-0503	DES/VHS/ULAS/ WISE/VIKING	7.021 Lyα/NV	$\sim 1.6 \times 10^9$	Unknown	Yang et al. 2019
HSC J2356+0017	SHELLQs	7.01 Lyα	$\sim 5.5 \times 10^8$	Unknown	Matsuoka et al. 2019a

z≥7 QSO-finder surveys

Where do we stand? II. QSO selection at z~6

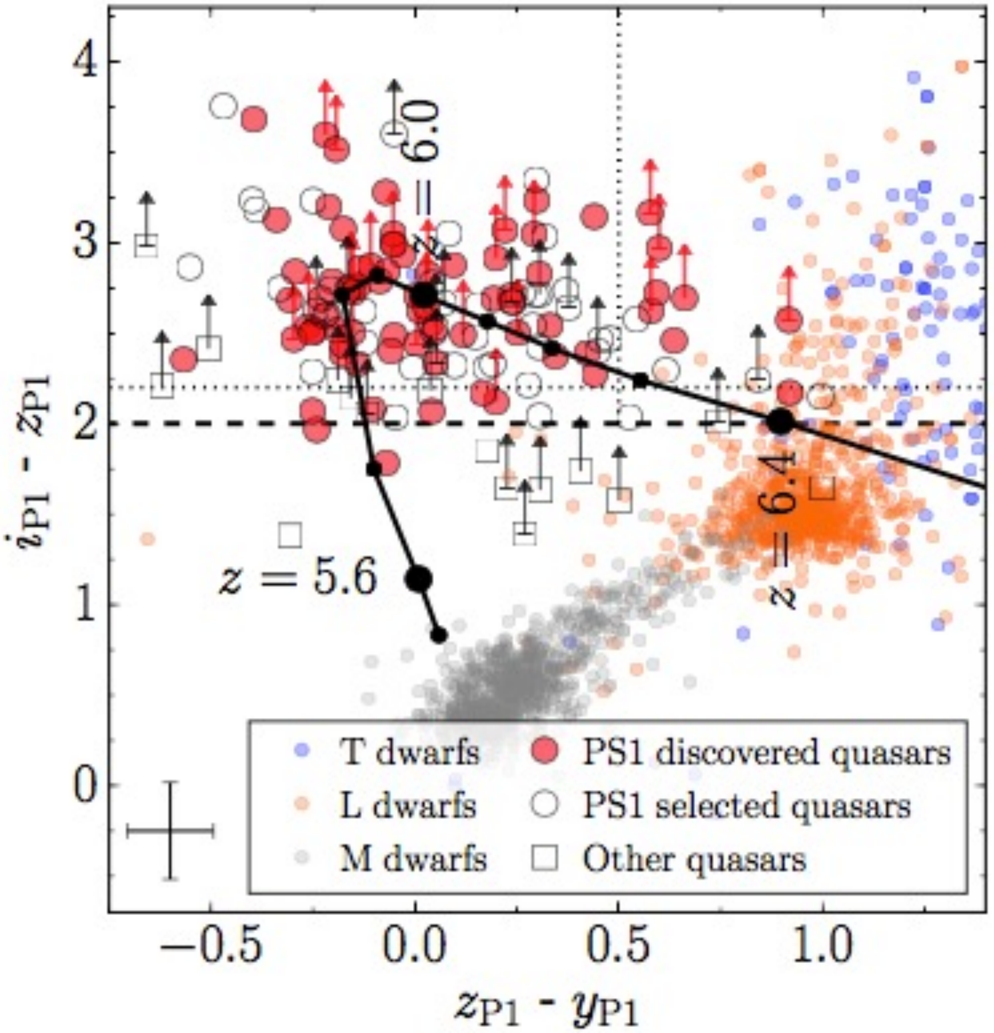
LBC/LBT color (*r,i,z*) image
of SDSS J1148 at z=6.4

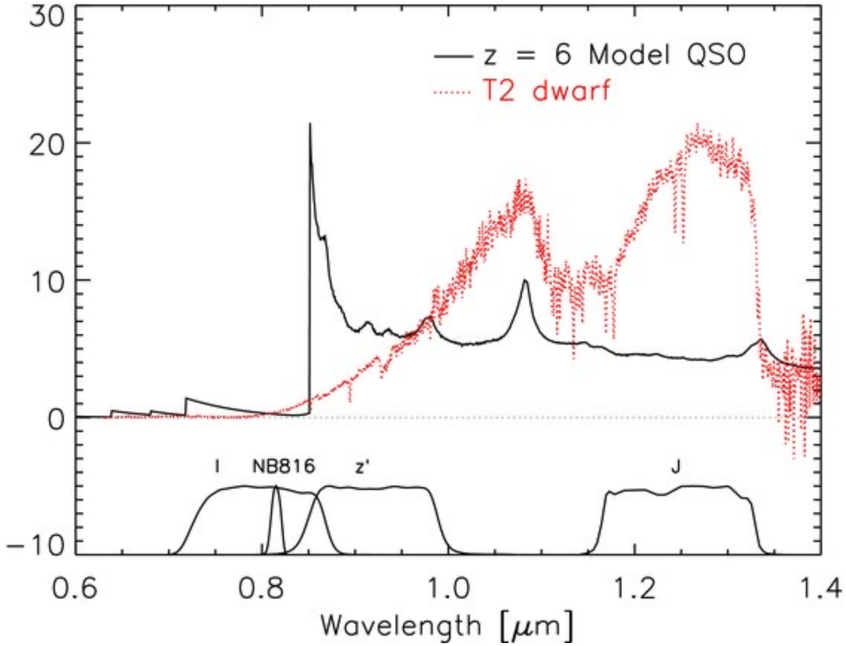




color selection (e.g. i-z>2) at bright mags returns unobscured QSOs

Drop-out technique

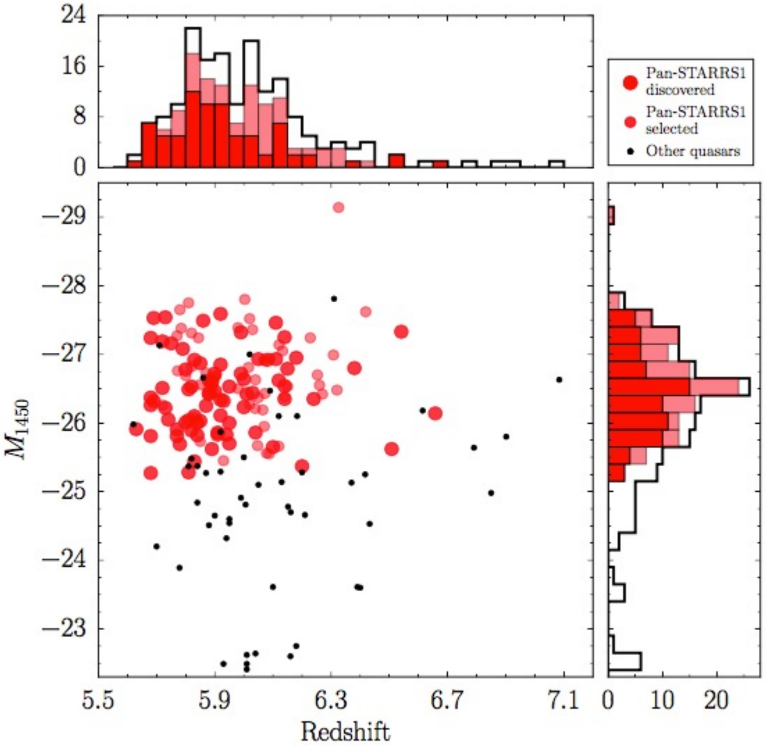


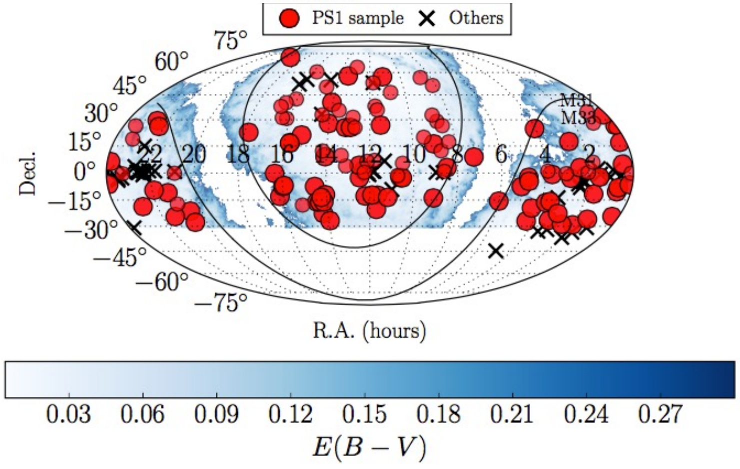


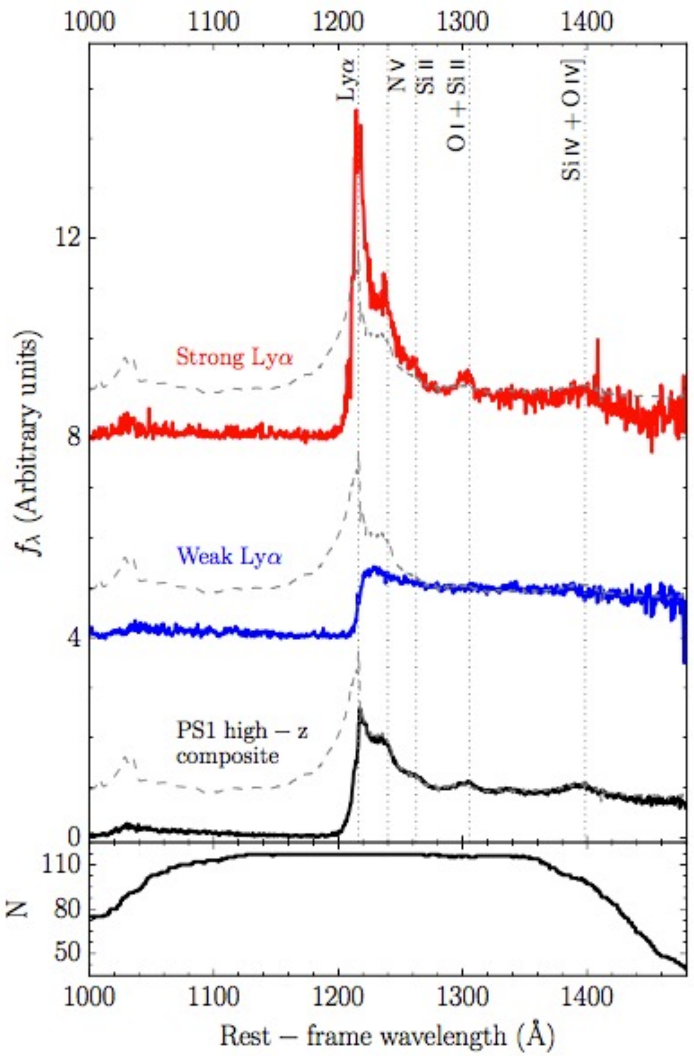
Banados+16

- Main contaminants: cool (T<3500K) dwarfs (M, L, T); surface density ~15 × that of z~6 QSOs
- Late-type stars have similar i-z colors to z~6 QSOs but much redder z-J (z-Y) colors

Where do we stand? III. PS1 results







Banados+16

Where do we stand? IV. SHELLQ results

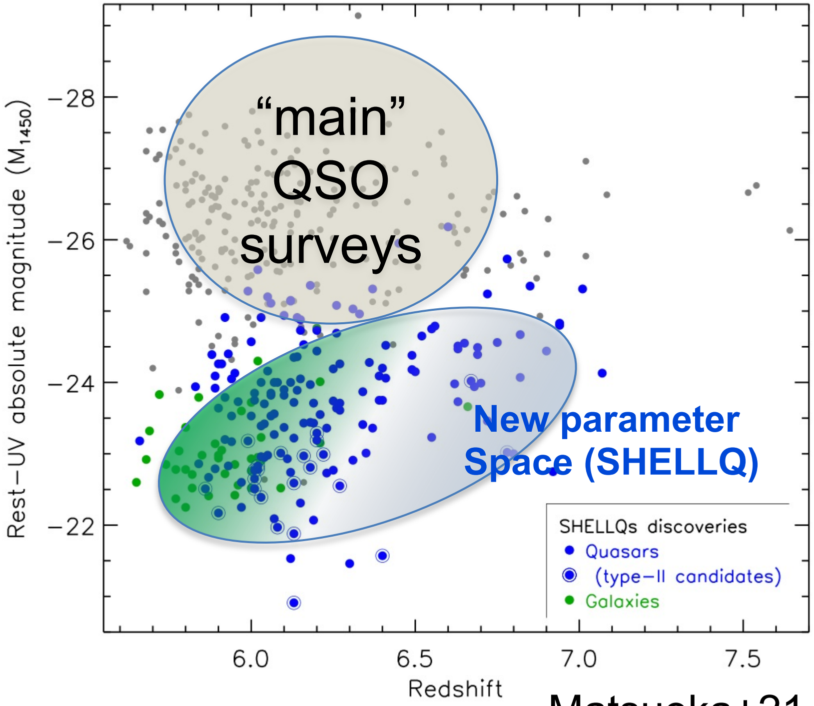
WIDE and DEEP approach

(at the end: 1400 deg^2, g~26.5, y~24.5)

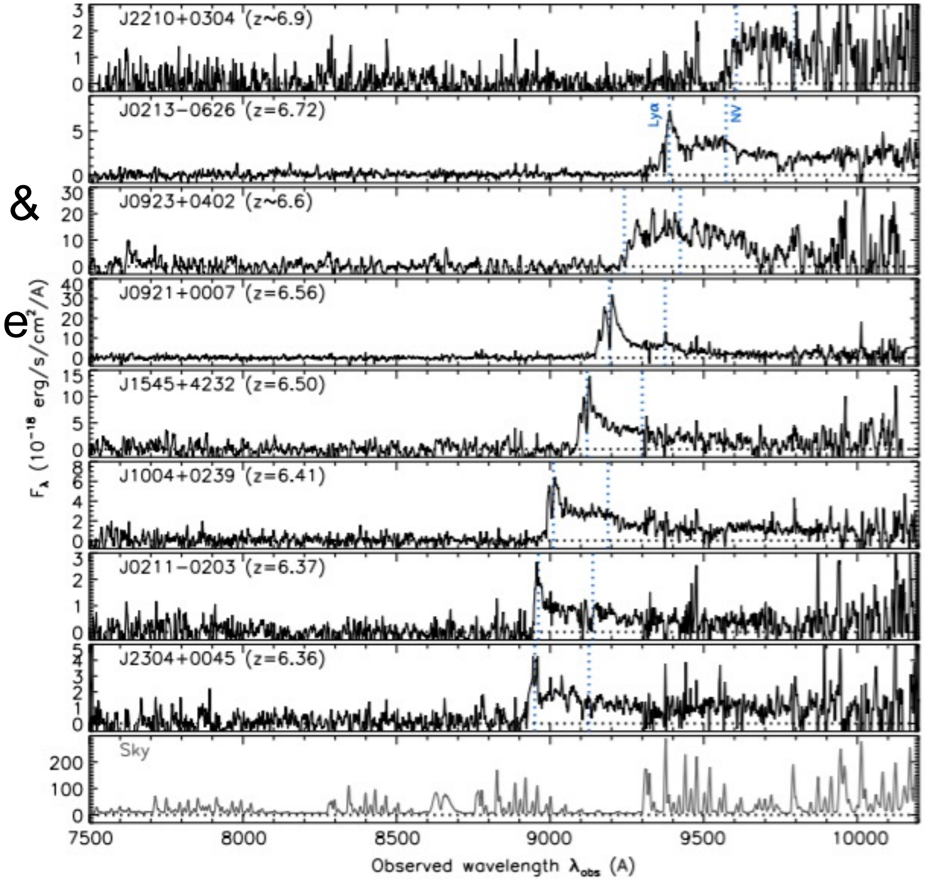
Subaru HSC: 137 red gals over 650 deg^2

(64 QSOs, z=5.7−6.9, LBGs, low-mass stars & brown dwarfs)

M_{1450}=-26÷-22 → probing the faint end of the LF (important for evolution,reionization, …)



Matsuoka+21

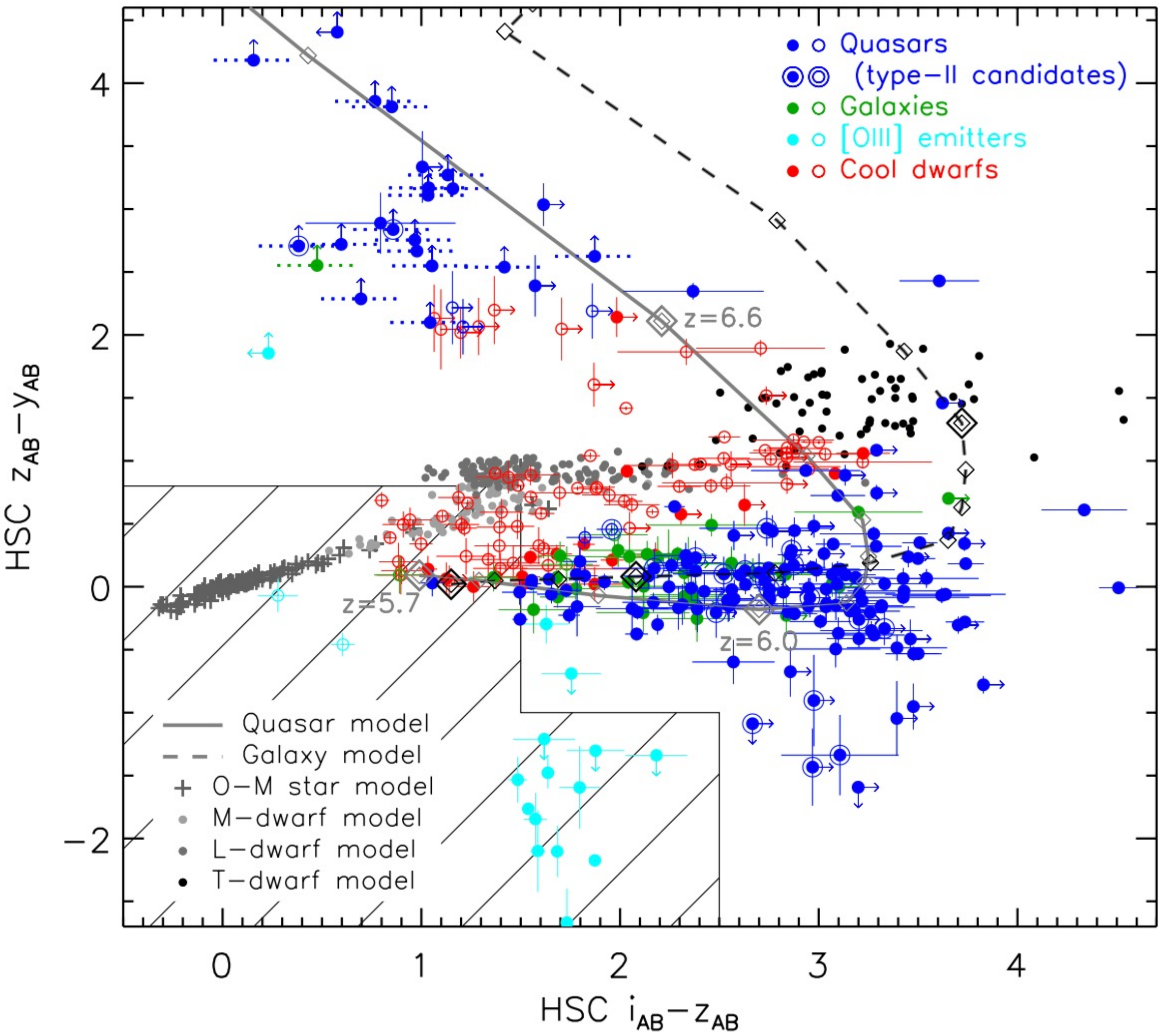


Matsuoka+18

Possibility that obscured AGN hide in bright LBGs (galaxies in the plot on the left)

Challenges

- Deep and accurate photometry for color-selection
- Discrimination of QSO candidates from other classes of sources
- Type II AGN selection (some hidden in the galaxy population?)
- Intensive spectroscopic follow-up campaigns



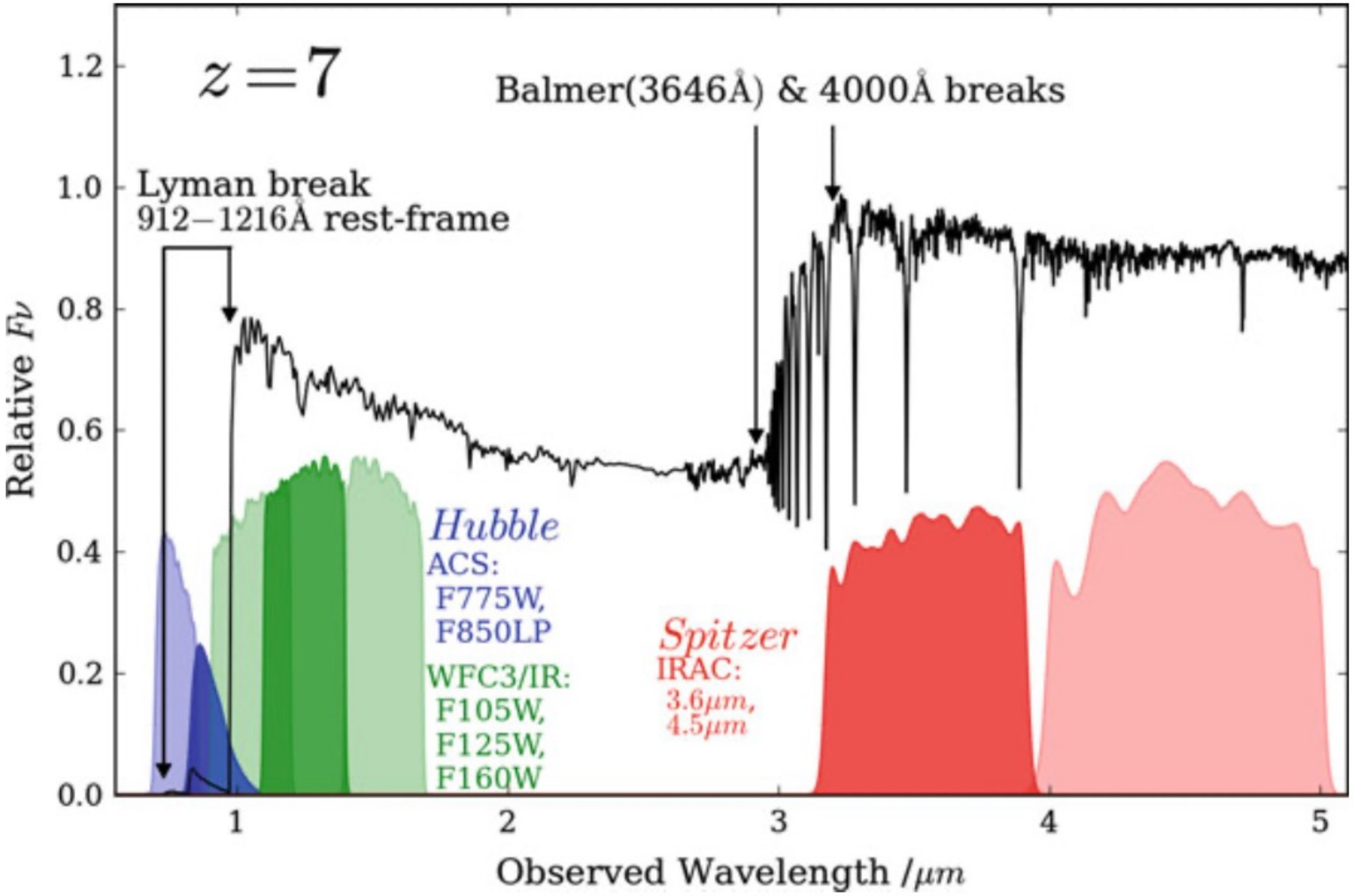
SHELLQ, Matsuoka+21

A quick introduction on high-redshift galaxies: Lyman-break Galaxies (**LBGs**) and Lyman-α emitters (**LAEs**)

Names indicates how they are selected

Photometric selection of high-z galaxies

Since LBGs were mentioned …



Dunlop (2012)

Method

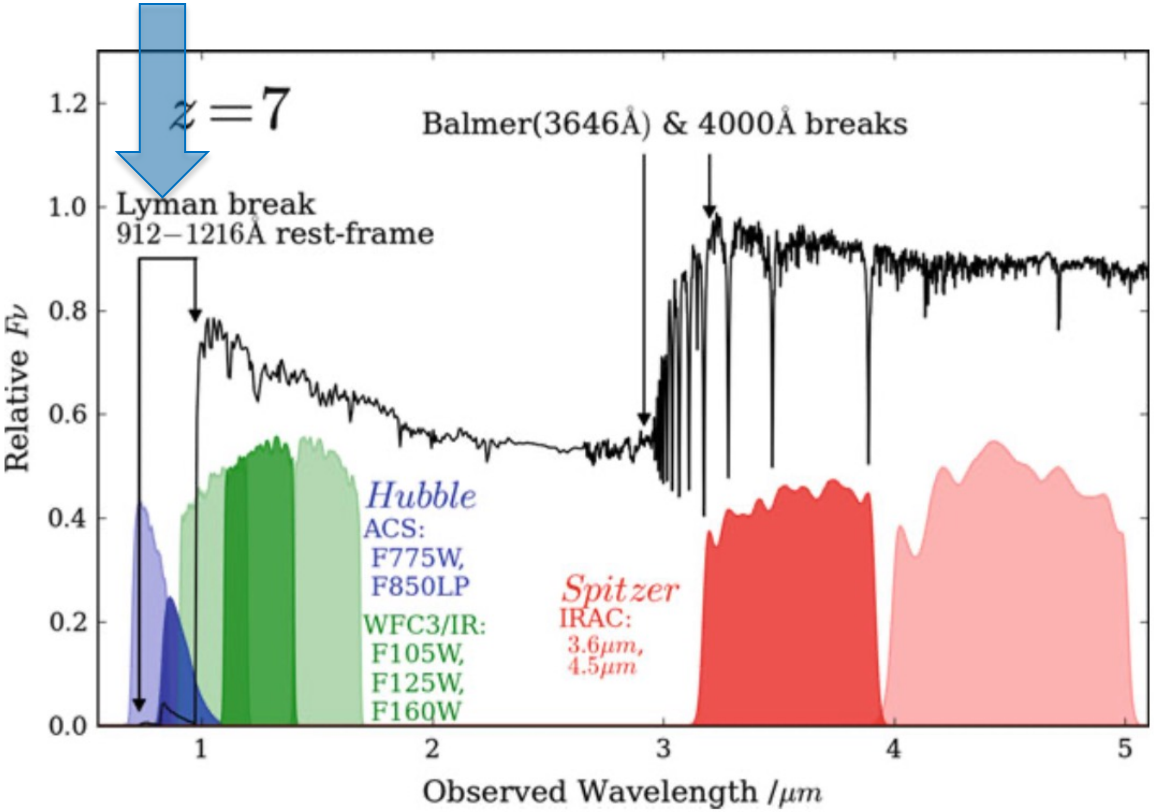
Use the observed spectral properties of galaxies to estimate the redshift in presence of *photometric data only*

Needs optical-to-near-IR observations of rest-frame UV light & relies on the presence of neutral hydrogen

Lyman-break galaxies (LBGs)

LBG

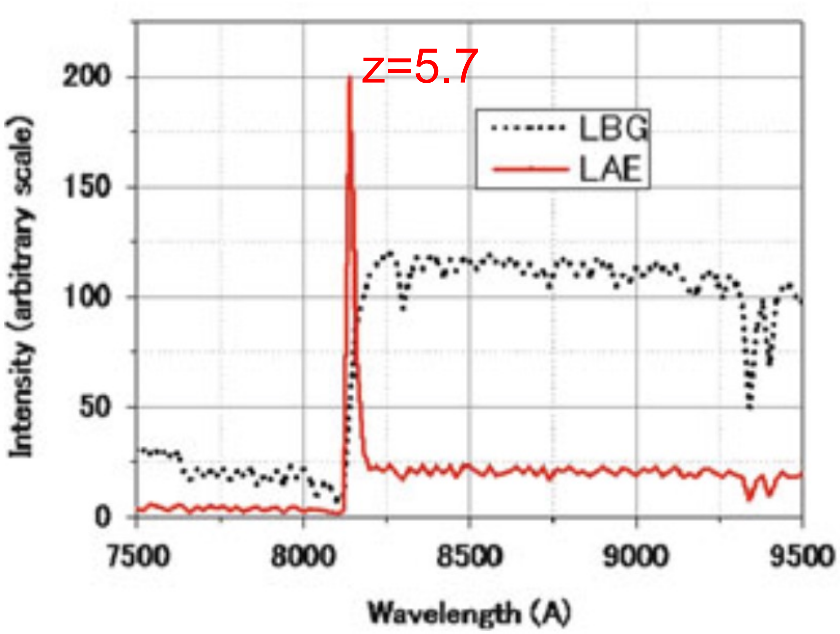
The first method, the so called **Lyman-break technique**, selects **Lyman-break galaxies** (**LBGs**) via the distinctive "step" introduced into their blue UV continuum emission by the blanketing effect of neutral hydrogen absorption (both within the galaxy itself, and by intervening clouds along the observer's line-of-sight). All of the photons at λ<912Å are absorbed by neutral hydrogen (IGM absorption increases with redshift). The method is similar to that described as "dropout" (color) selection of high-redshift AGN



Lyman-α emitters (LAEs)

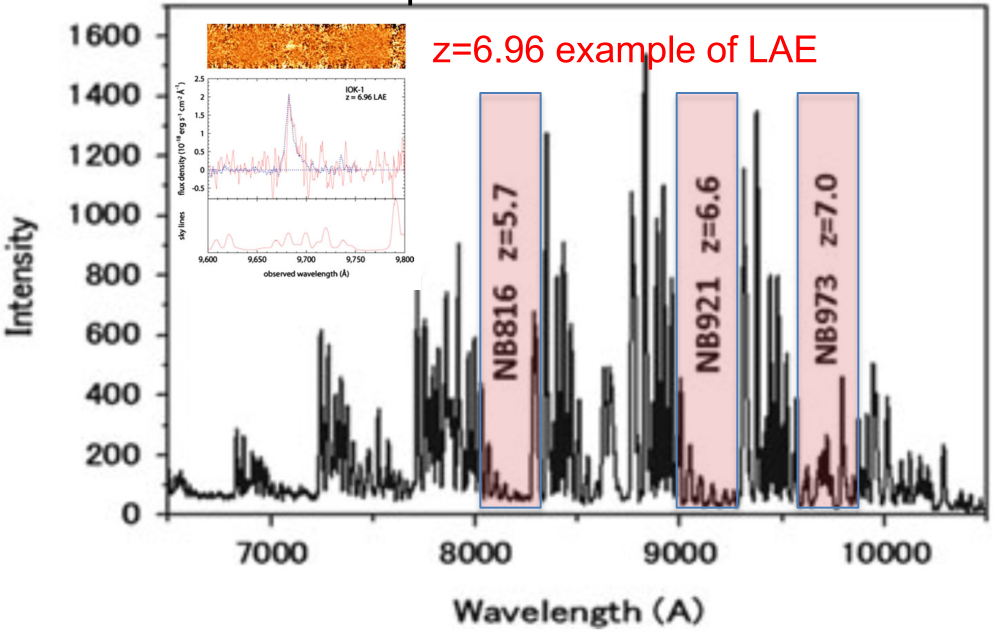
LAE

The second method selects galaxies which are **Lyman-α emitters** (**LAEs**) via their highly-redshifted Lyman-α emission lines, produced by hydrogen atoms in their interstellar media which have been excited by the ultraviolet light from young stars. Almost featureless spectrum besides the strong Lyα emission line



z=5.7

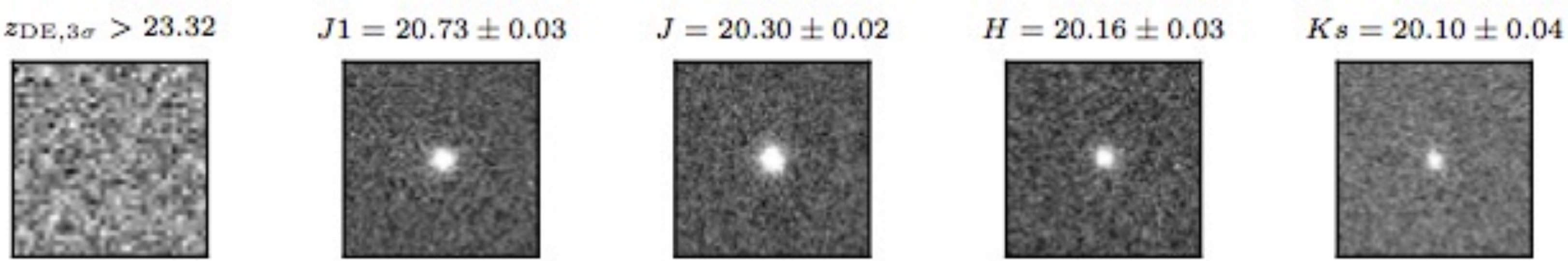
OH night-sky emission bands
In the few gaps the narrow filters
can target LAEs once their redshift has
been pre-evaluated via colors



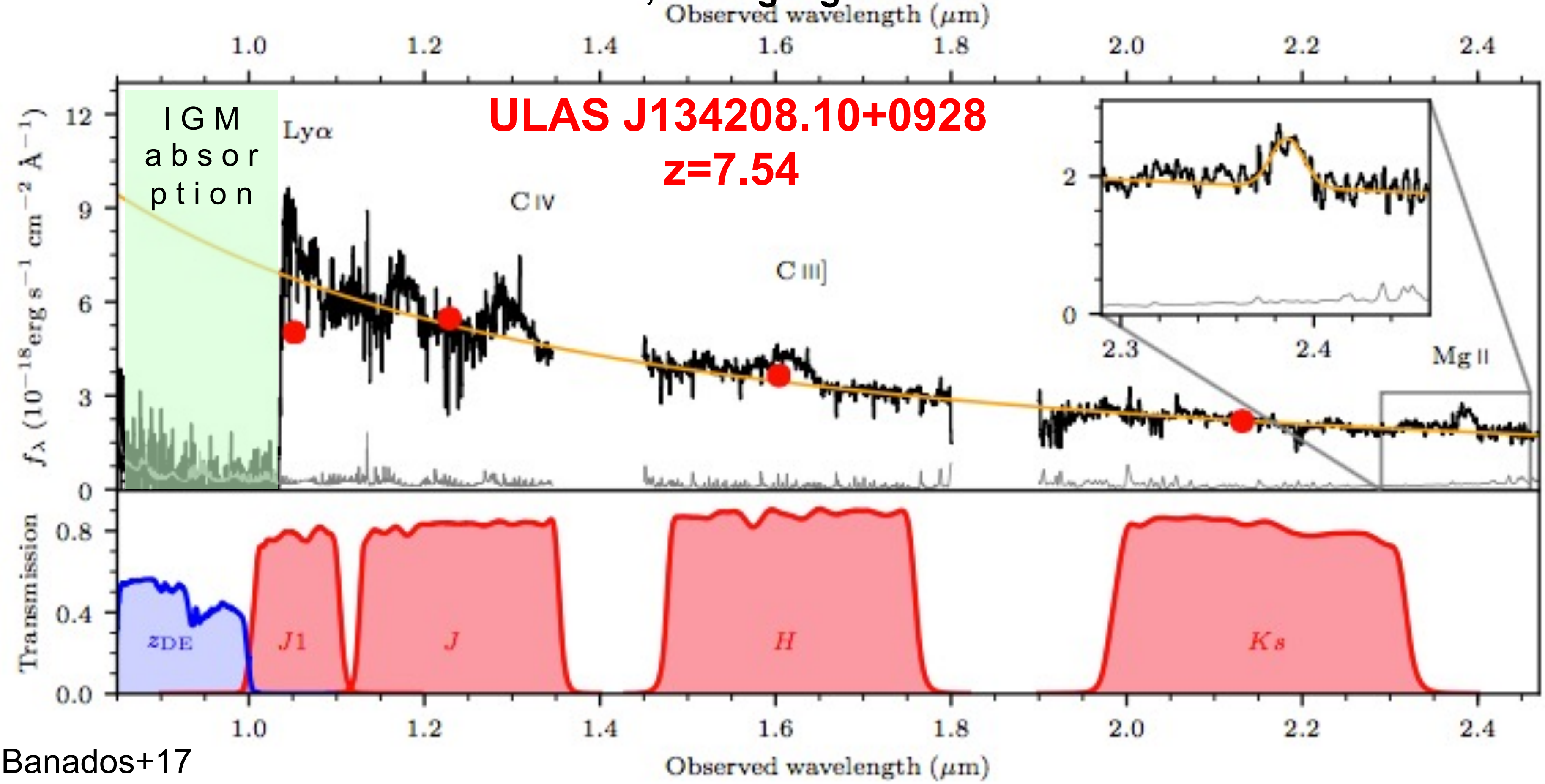
z=6.96 example of LAE

Dunlop (2012)

Where do we stand? V. One of the highest-redshift QSO

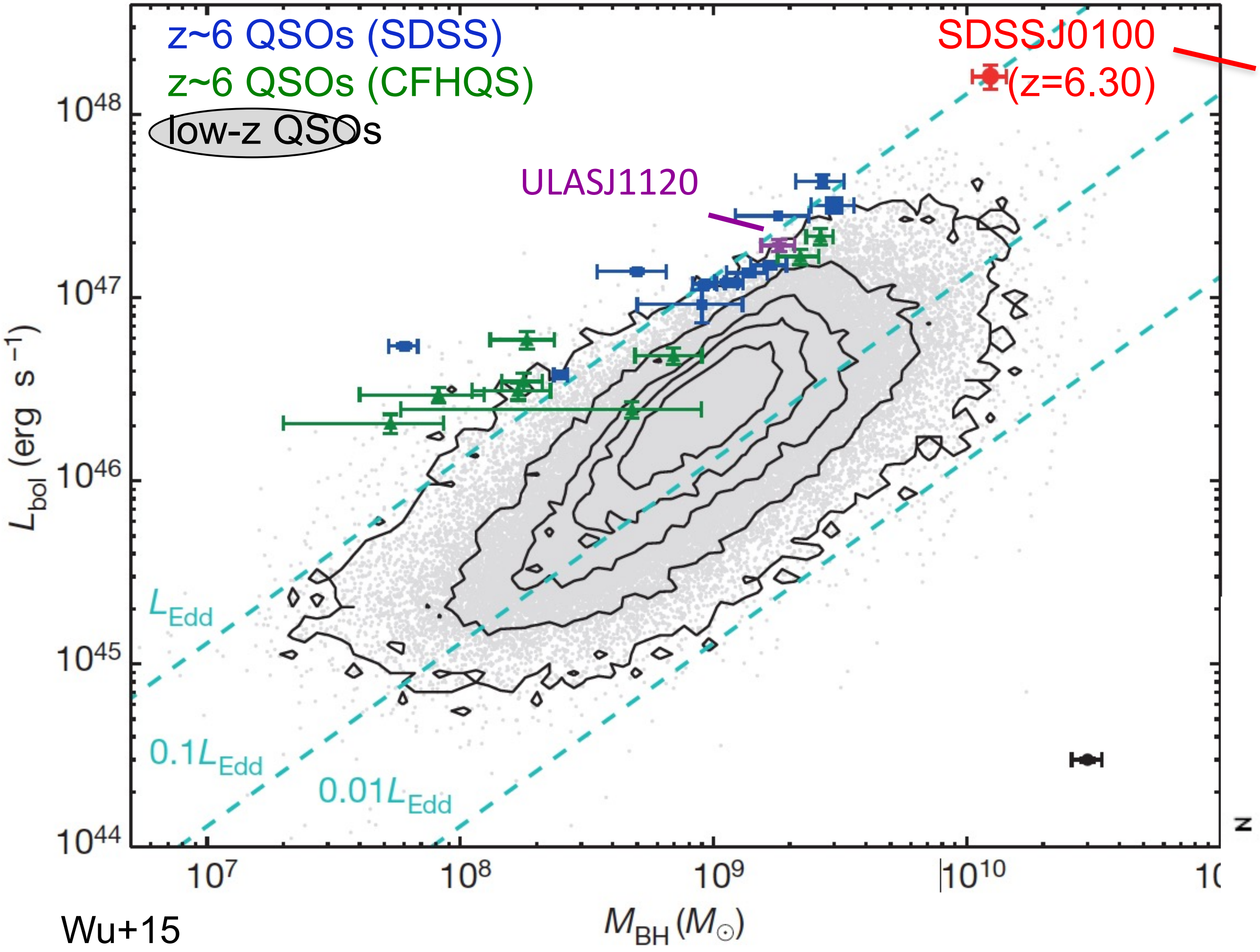


No det in DES; strong signal in UKIDSS + WISE



Banados+17

Where do we stand? VI. They are massive

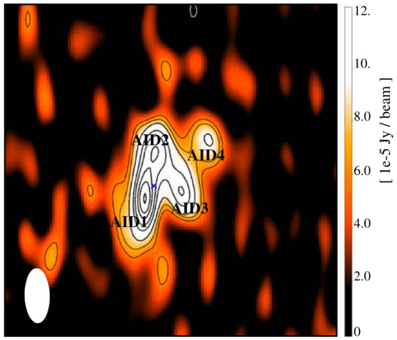


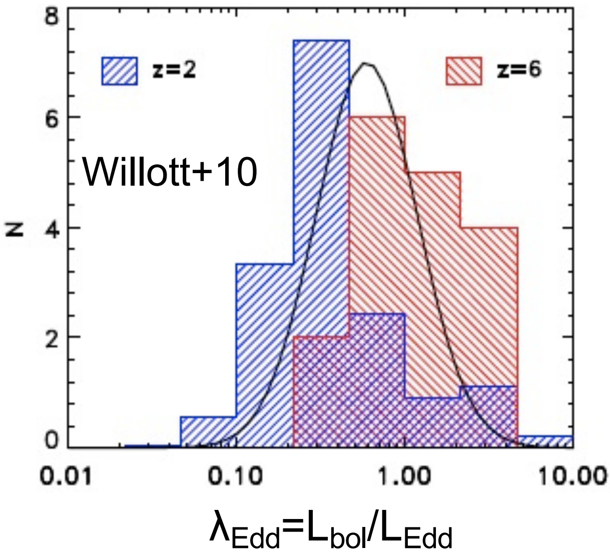
Wu+15

The most massive QSO discovered so far

Lensing is a possibility (μ~450, Fujimoto+20) – see also Connor+21

ALMA (4 comp?)





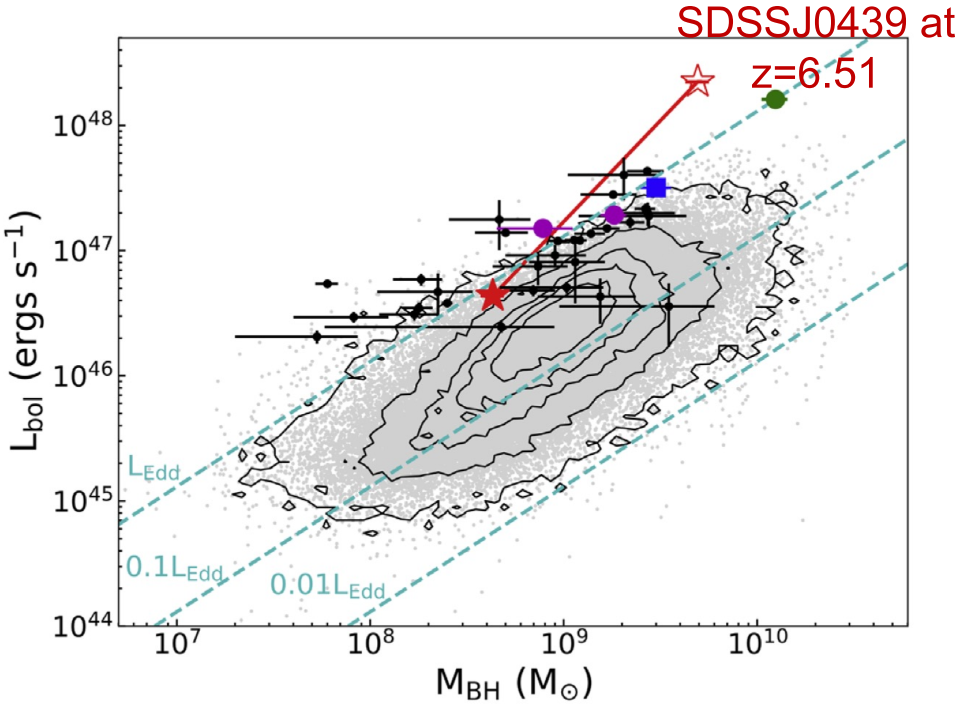
Willott+10

$M_{BH} \approx 10^{8} - 10^{10}\ M_\odot$

$L_{bol} \approx L_{Edd} > 10^{46}$ erg/s

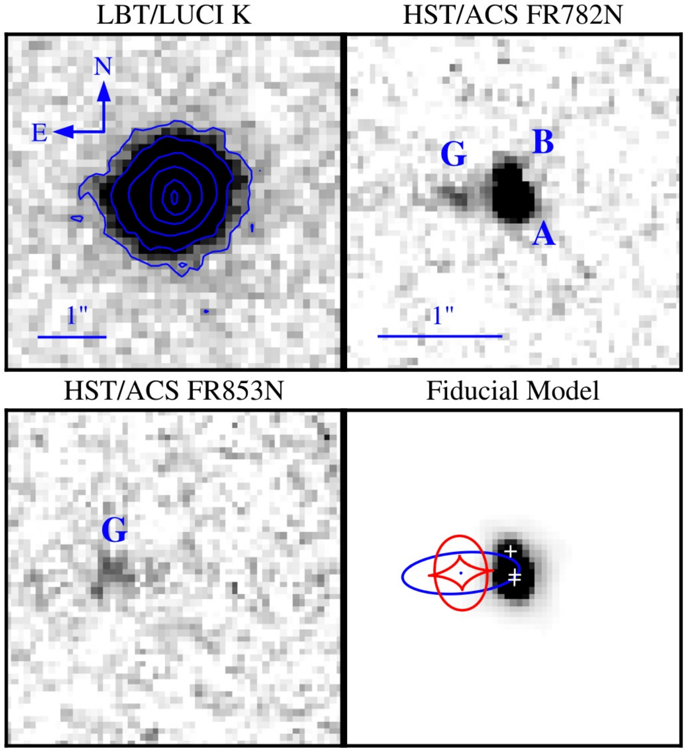
They are emitting close to the Eddington ratio

How many detected quasars at high redshift are lensed?



SDSSJ0439 at z=6.51

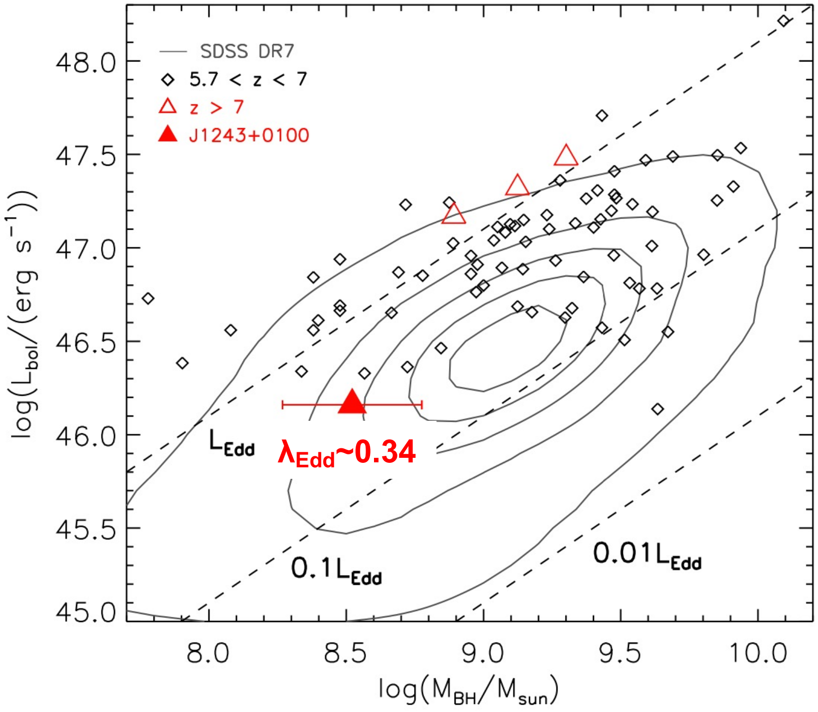
Fan+19 (see also Yue+21)

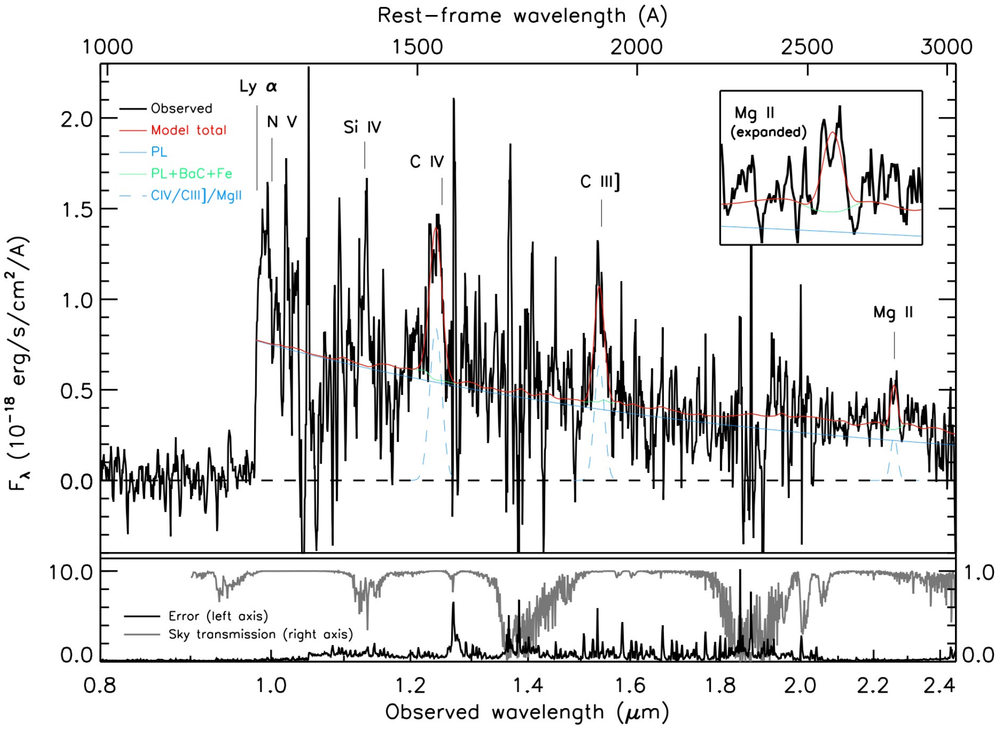


‘Unusual’ properties in ‘typical’ diagrams (‘the brighest quasar’ for J0439) can help spotting lensed systems (μ~50 in this case, z~0.7 low-luminosity galaxy as the lens)

The knowledge of the fraction of high-redshift lensed quasars would impact the QSO LF, with implications for the role of quasars in the reionization of the Universe

There are also ‘exceptions’ (lower-mass BHs, lower L_{bol} and Eddington ratio)





Matsuoka+19

Subaru HSC

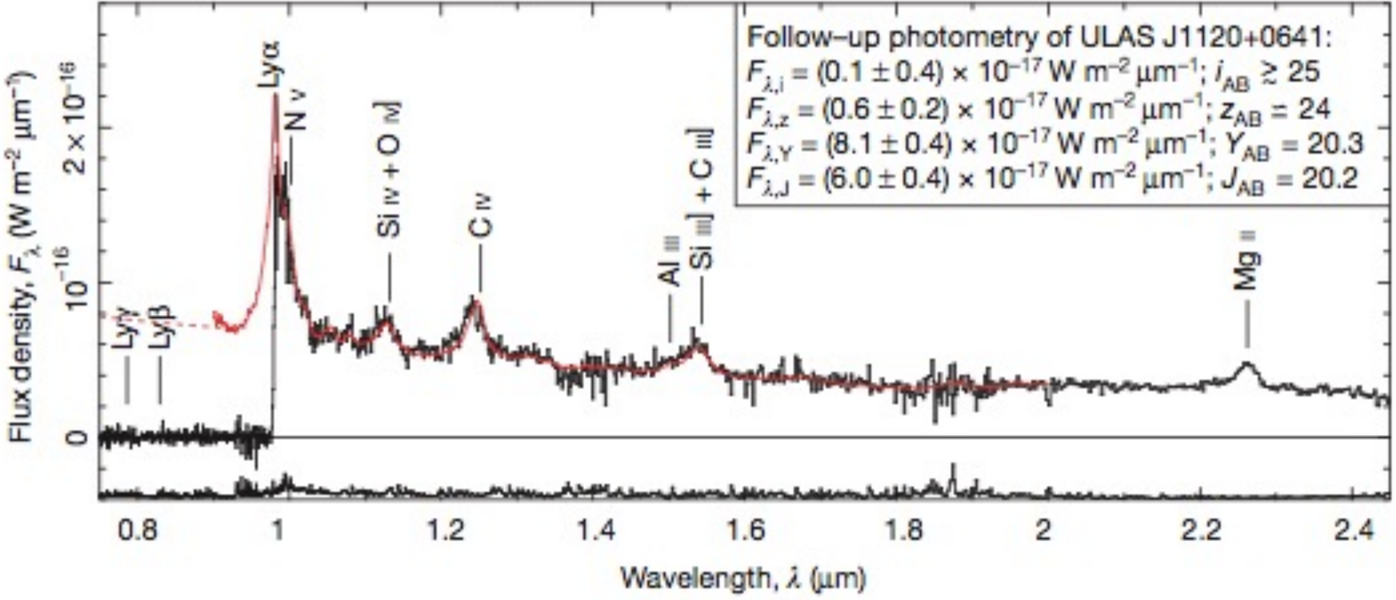
HSC1243+0100 z=7.07

$M_{1450}=-24.1$
$M_{BH}=3.3\times10^{8}\ M_{\odot}$
$L_{bol}\approx1.4\times10^{46}$ erg/s

One order of magnitude lower luminosity than the other z>7 QSOs

Where do we stand? VII. Similar spectra to low-z QSOs

Mortlock+11, GNIRS+FORS2, compared to average z~2.5 SDSS QSOs



UKIDSS

ULAS J1120 z=7.08

$M_{1450}=-26.6$
$M_{BH}=2.4 \times 10^9\ M_\odot$
$L_{bol} \approx 2.4 \times 10^{47}$ erg/s

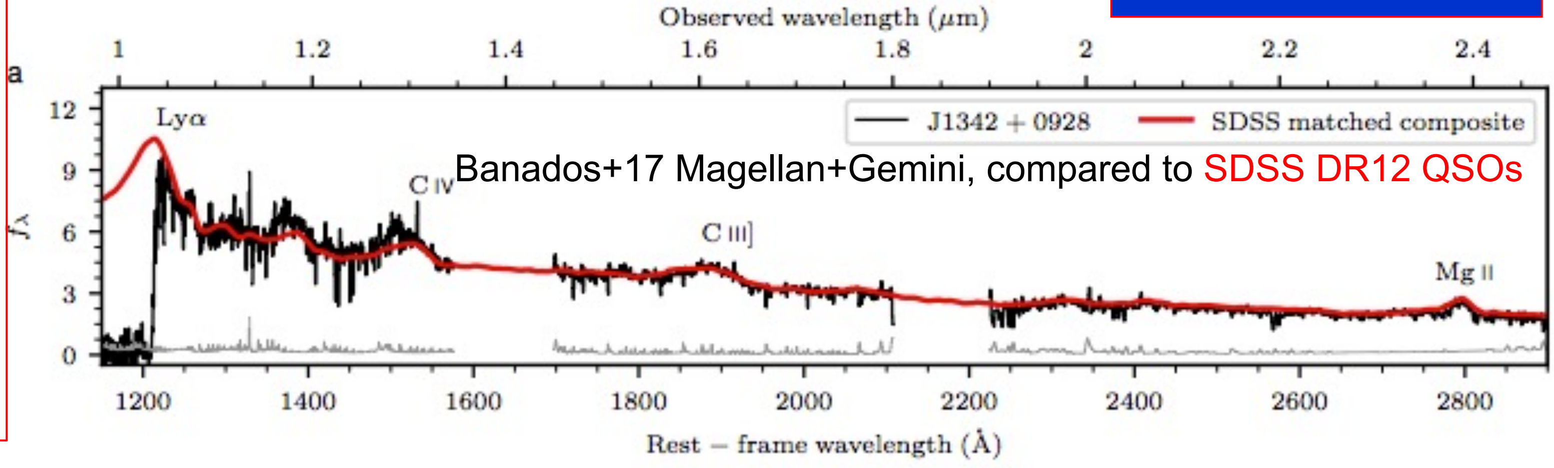
$M_{1450}=-26.8$
$M_{BH}=8.0 \times 10^8\ M_\odot$
$L_{bol} \approx 1.5 \times 10^{47}$ erg/s

ULAS J1342 z=7.54

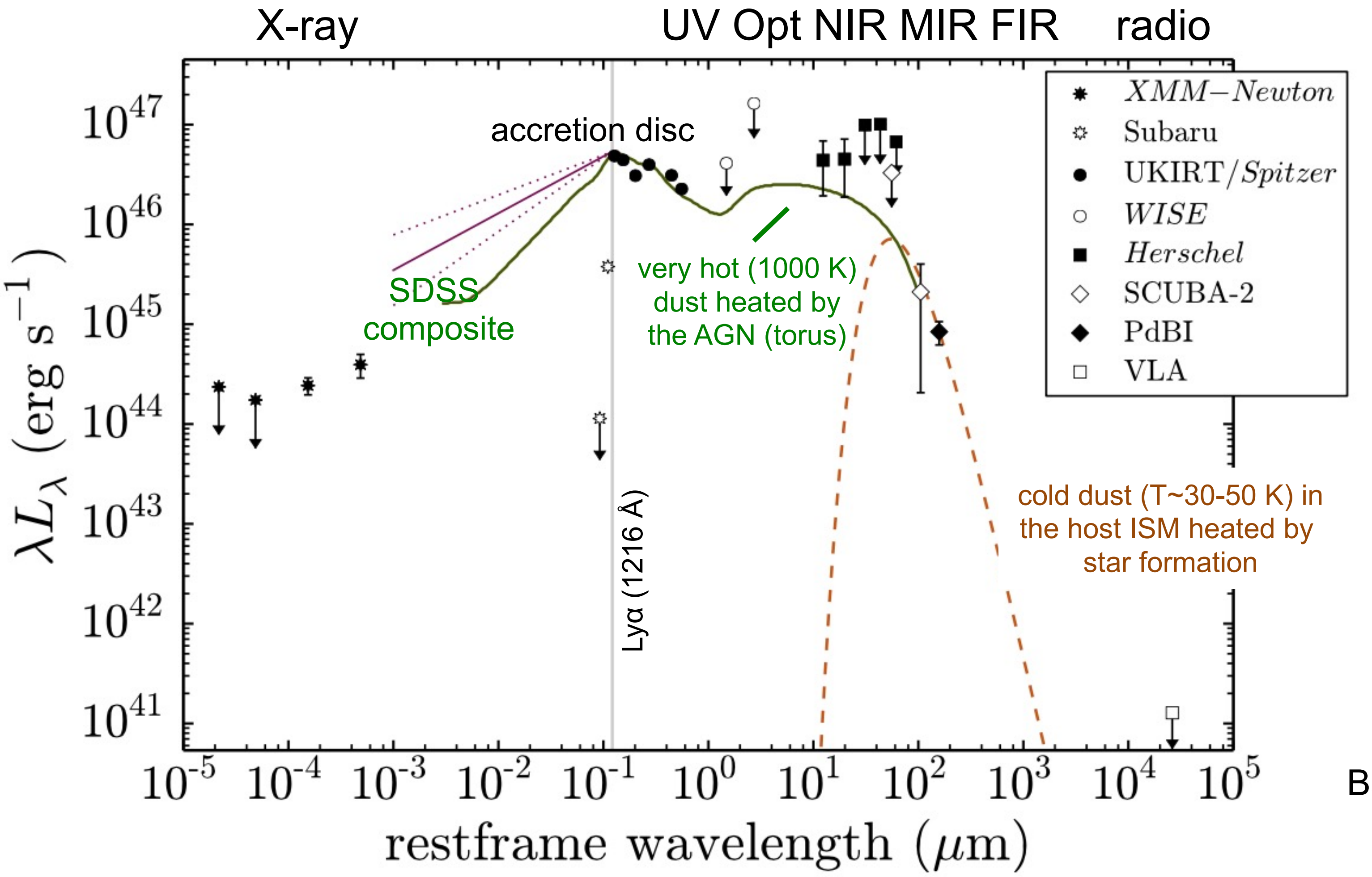
Metallicity of high-z QSOs is similar to that of low-z QSOs

→ the nuclear regions are metal rich

→ major episode of chemical enrichment in their hosts at t_U<1 Gyr


Banados+17 Magellan+Gemini, compared to SDSS DR12 QSOs

Where do we stand? VIII. Similar SEDs to low-z QSOs

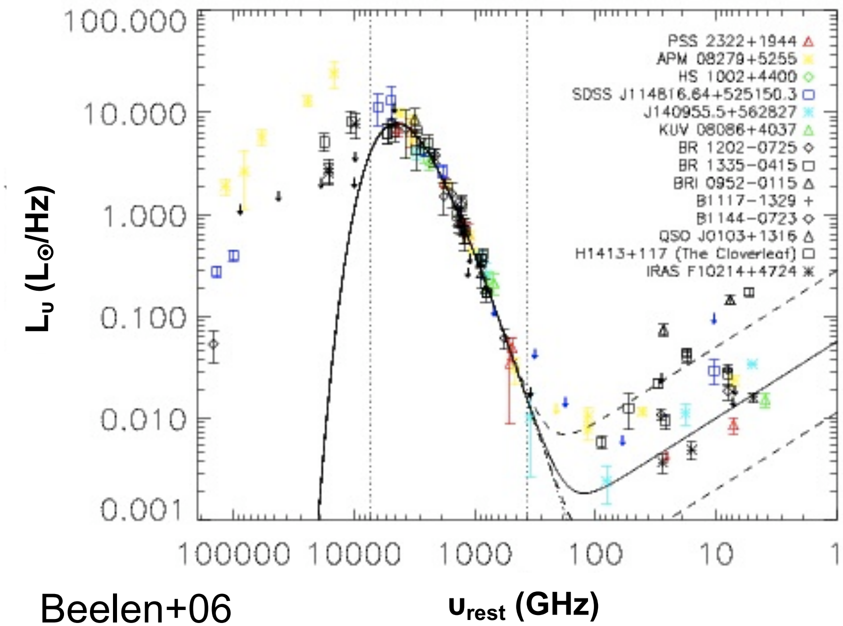


Barnett+15

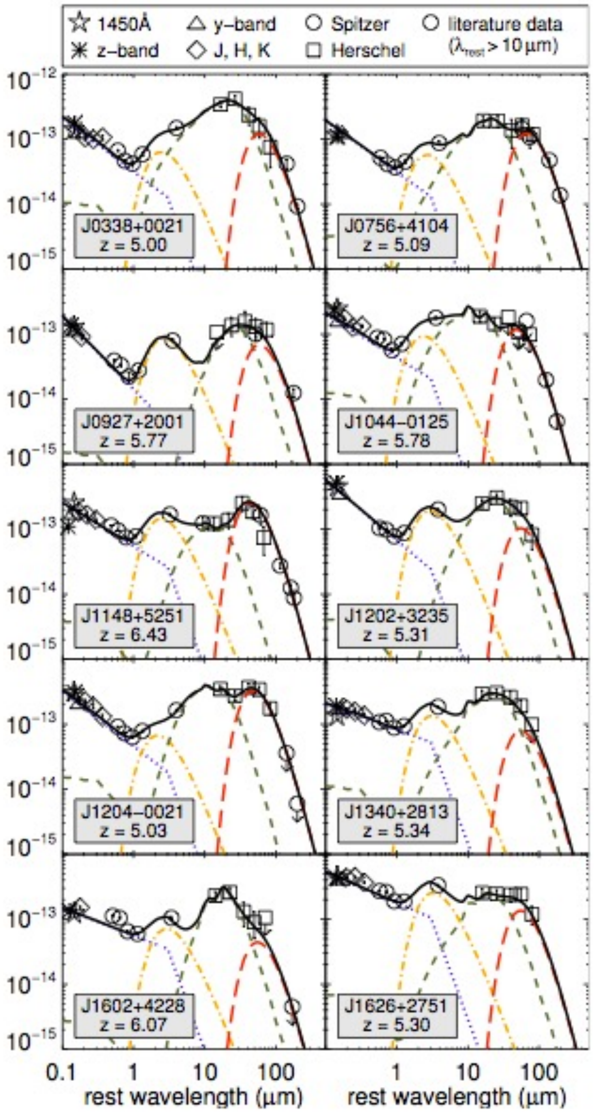
SEDs are similar to those of lower redshift QSOs
(including the presence of hot dust, likely associated to the torus)

Significant star formation at high redshift

- ≈ 30% of z≈6 QSOs detected in the sub-mm/mm − see also recent *ALMA* results (Wang+, Decarli+, etc.)
- L_{FIR}≈10^{13} $L_{\odot}$,T≈30−50 K
- SFR≈1000 $M_{\odot}$/yr (if dust heated by SB) − “Increased” AGN contribution (Schneider+14)? Mergers vs. secular processes? What about quenching SF (Mor+12)?



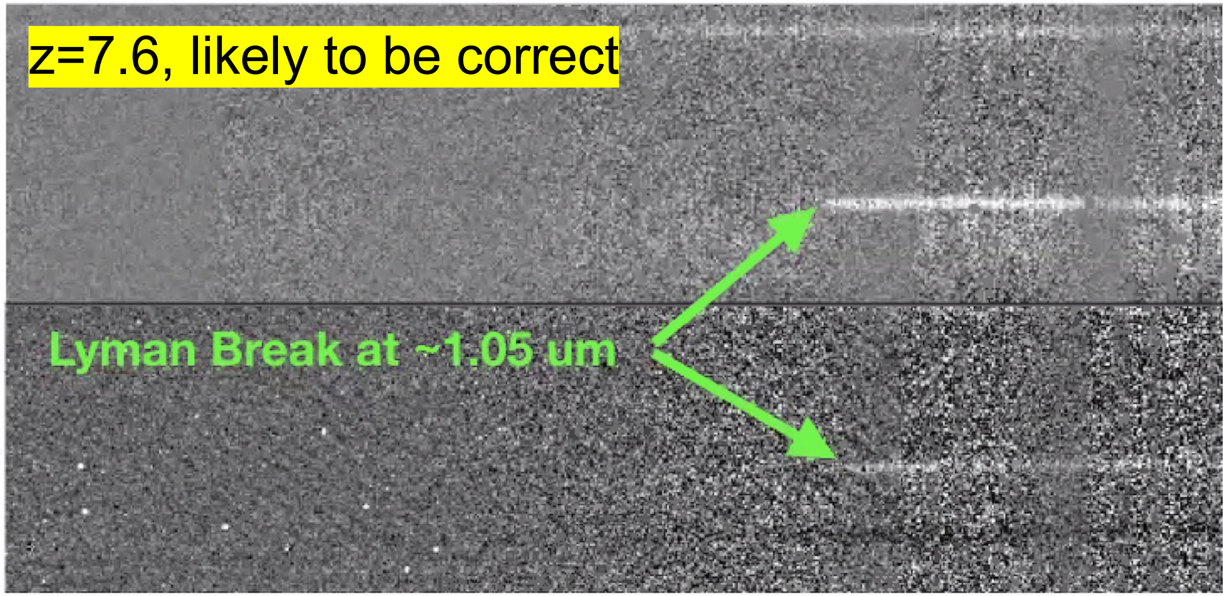
Beelen+06



Leipski+14

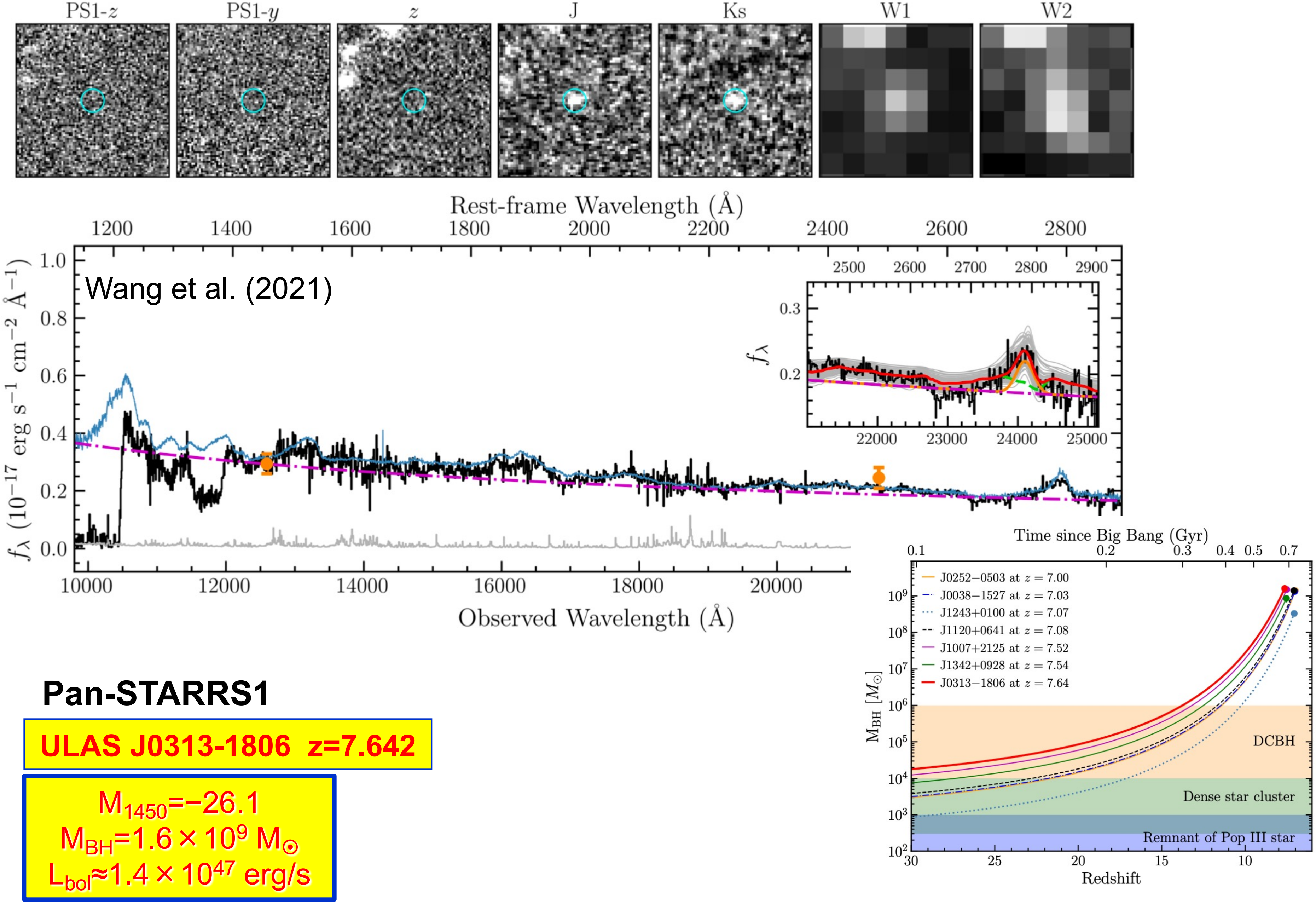
Where do we stand? IX. Very recent updates and new z>7 QSOs

New record holder: $z = 7.62$



z=7.6, likely to be correct

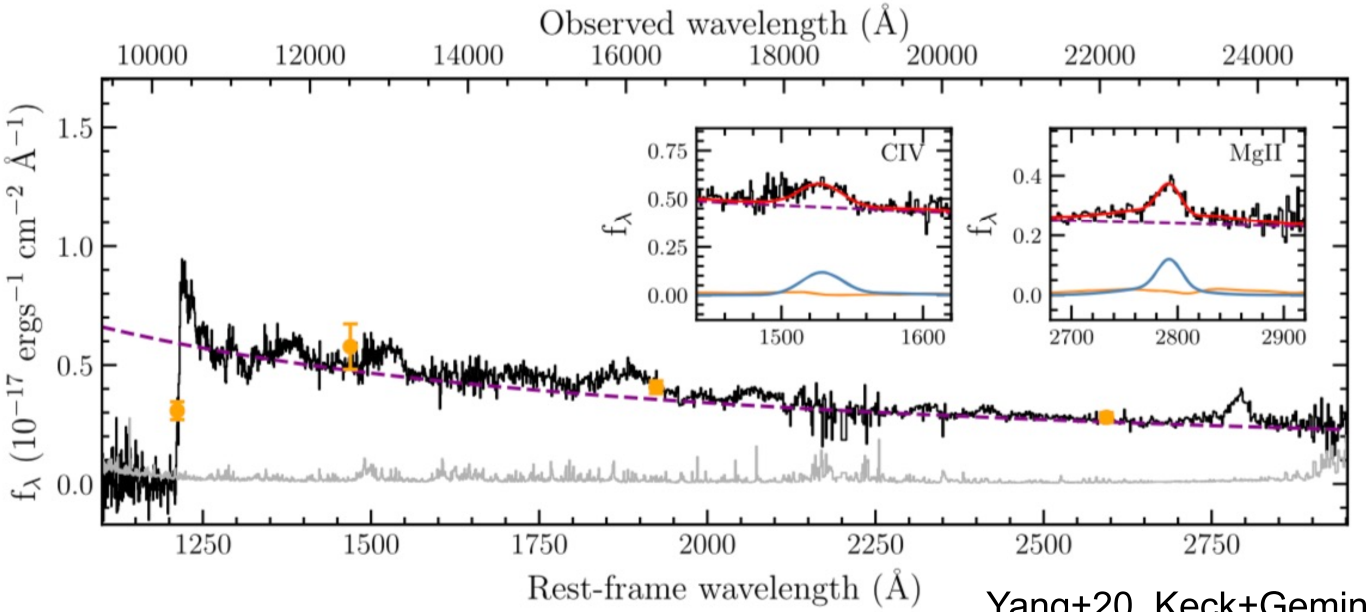
Actually …The newly discovered **highest redshift quasar**



Pan-STARRS1

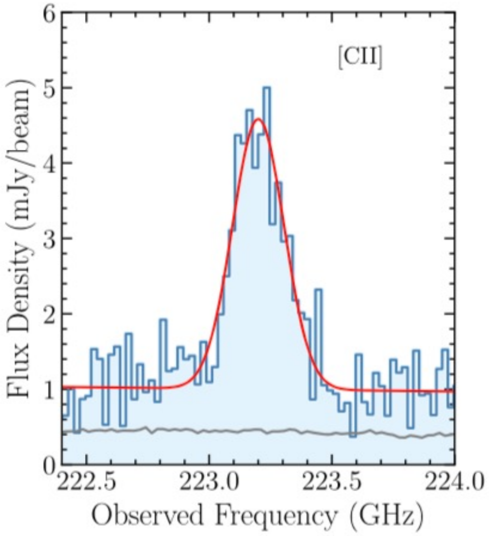
ULAS J0313-1806 z=7.642

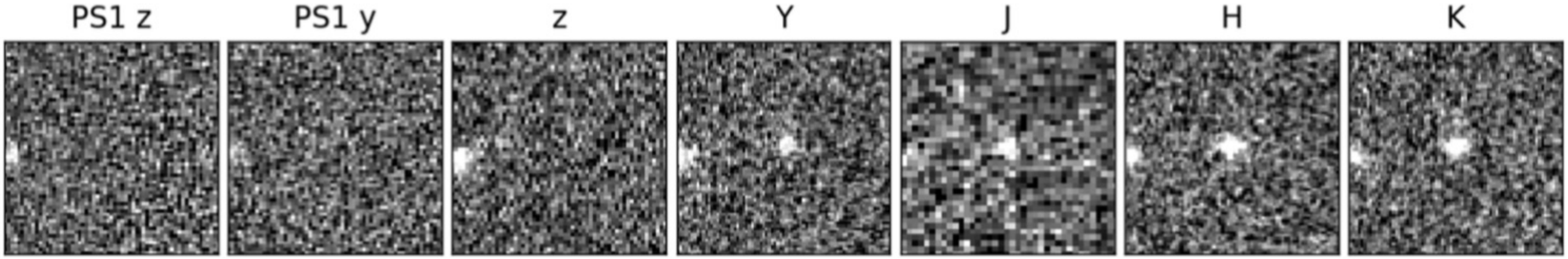
$M_{1450}=-26.1$
$M_{BH}=1.6\times10^{9}\ M_\odot$
$L_{bol}\approx1.4\times10^{47}$ erg/s



Yang+20, Keck+Gemini

Yang+20, ALMA [CII]





DESI+PS1+UKIRT+WISE

Pōniuā‘ena

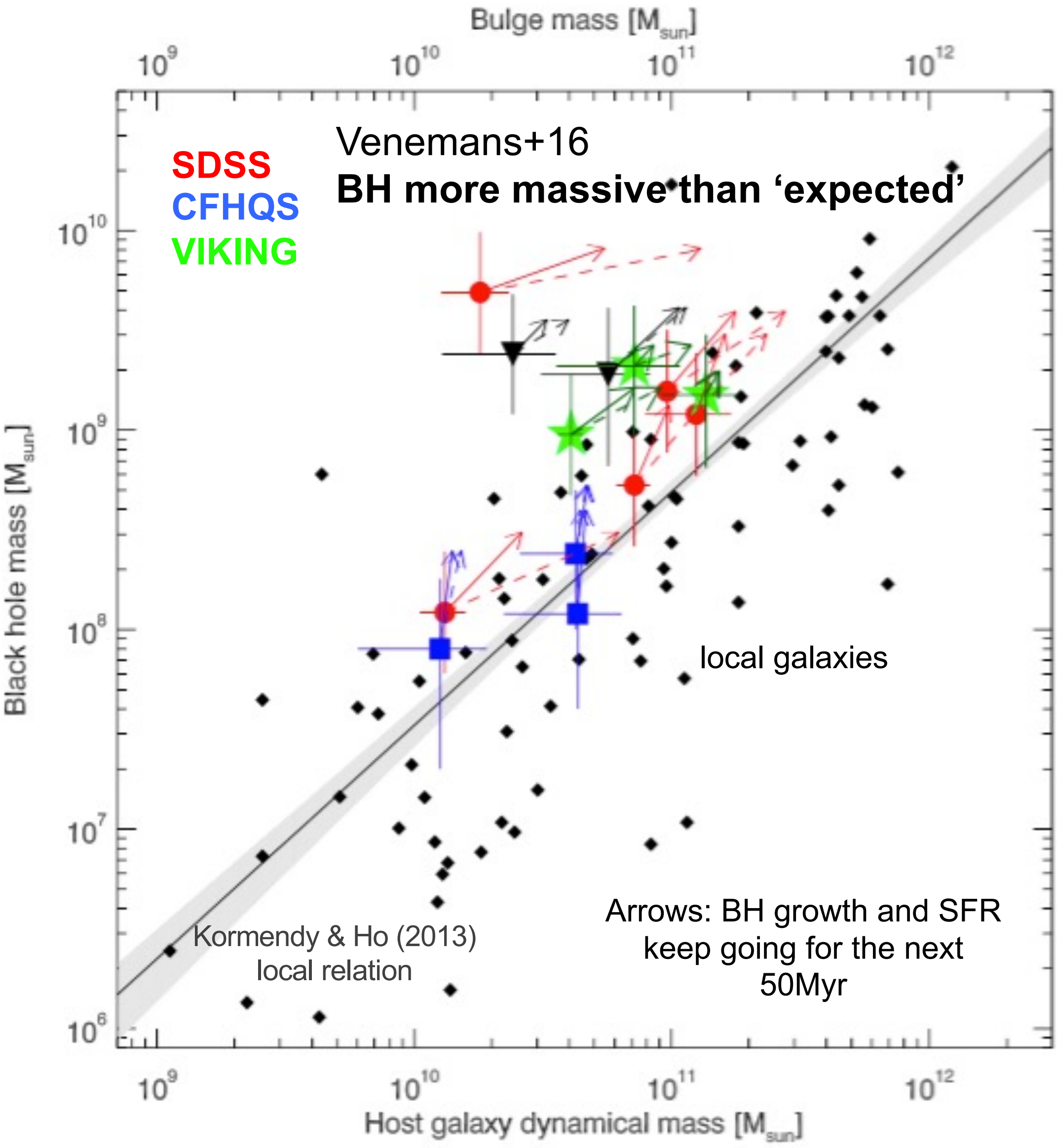
J1007+2115 z=7.52

M_{1450}=−26.7

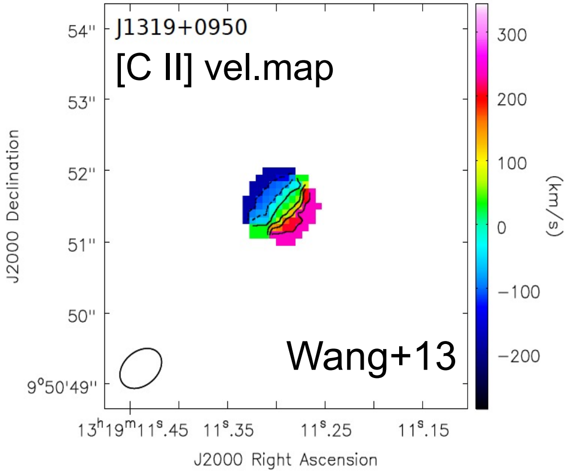
M_{BH}=1.5 × 10^9 $M_\odot$

L_{bol}≈1.9 × 10^{47} erg/s

Where do we stand? X. QSO hosts

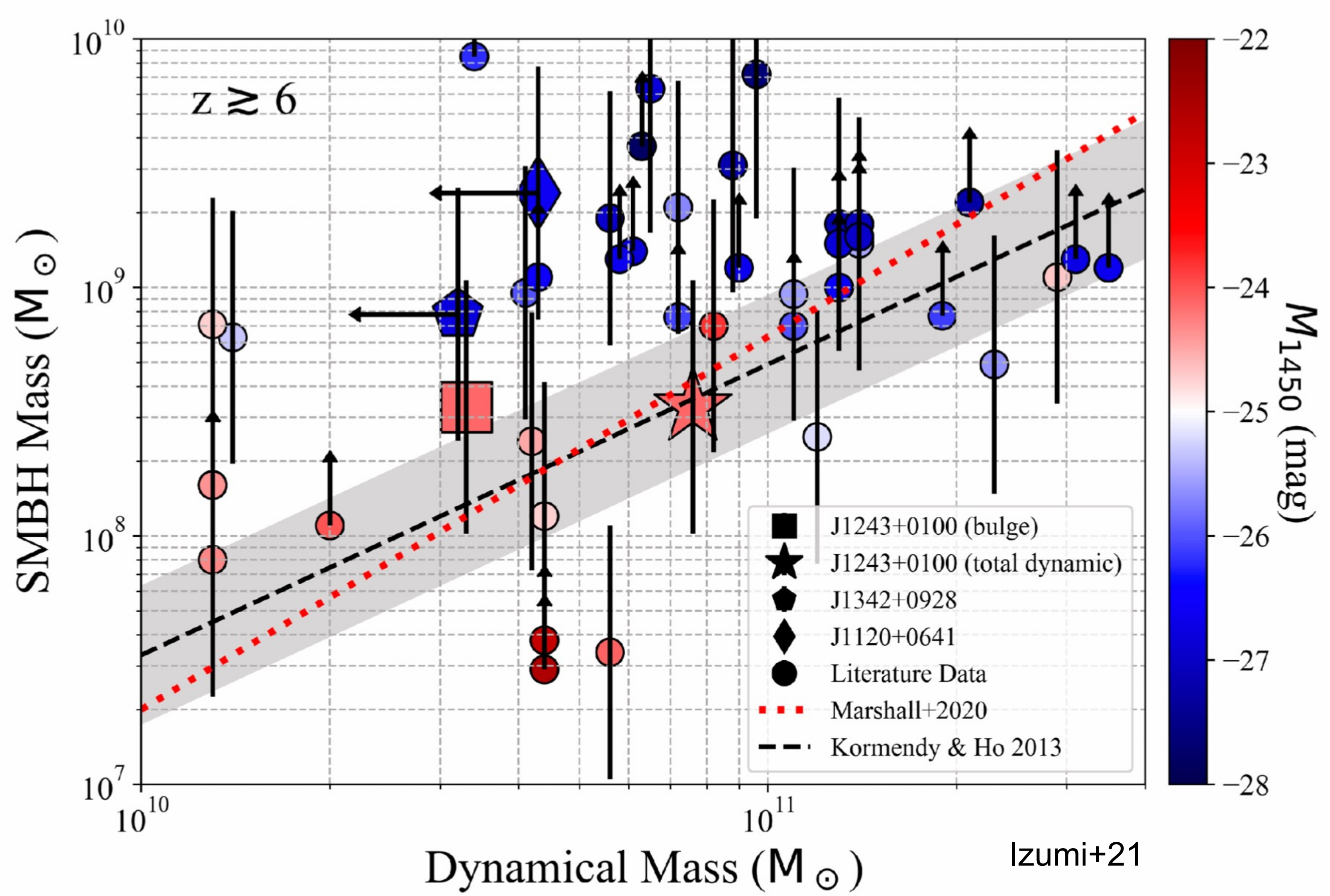


$M_{BH} \sim 10^9\, M_\odot \rightarrow M_\star \sim 10^{11}\, M_\odot \rightarrow M_{halo} >\sim 10^{12}\, M_\odot$



Dynamical studies via CO emission (ALMA breakthrough)

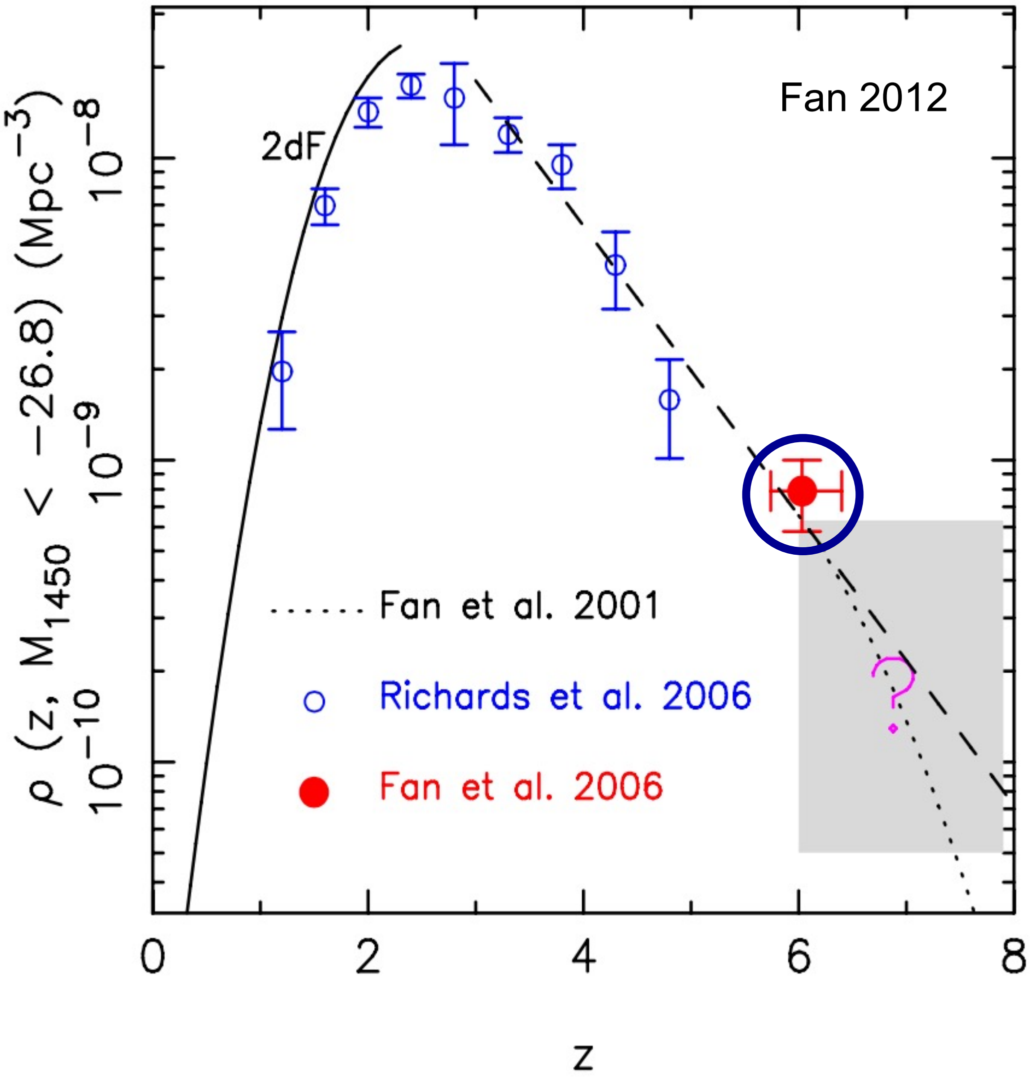
- Few-kpc sizes (from resolved CO and [CII] emissions)
- Dynamical masses ≈$10^{10-11}\, M_\odot$ (see compilation by Calura+14) − $\sin^2(i)$ uncertain in some cases
- Some $M_{dyn} - M_{dust}$ (≈$10^{8-9}\, M_\odot$) tension? (Calura+14)
- BH formed earlier than galaxy assembly finished? Selection effects (Volonteri+14)
- Signature of possible mergers


z ≳ 6
SMBH Mass (M⊙)
Dynamical Mass (M⊙)
10^10
10^9
10^8
10^7
10^10
10^11
J1243+0100 (bulge)
J1243+0100 (total dynamic)
J1342+0928
J1120+0641
Literature Data
Marshall+2020
Kormendy & Ho 2013
M1450 (mag)
−22
−23
−24
−25
−26
−27
−28

Izumi+21

Where do we stand? XI. They are rare

At z=6, density of active $10^9\ M_\odot$ SMBHs ≈ density of $10^{13}\ M_\odot$ halos ≈ 1/Gpc^3



if duty cycle = 1 → z=6 QSOs hosted by ≈ $10^{13}\ M_\odot$ halos

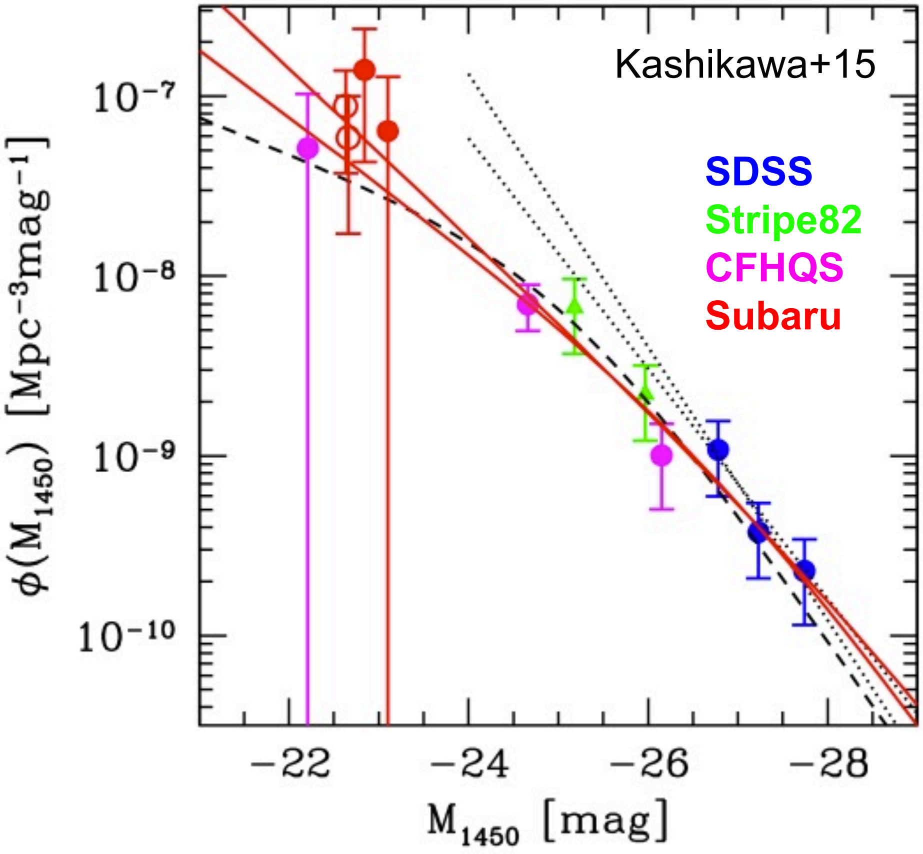
caveats!

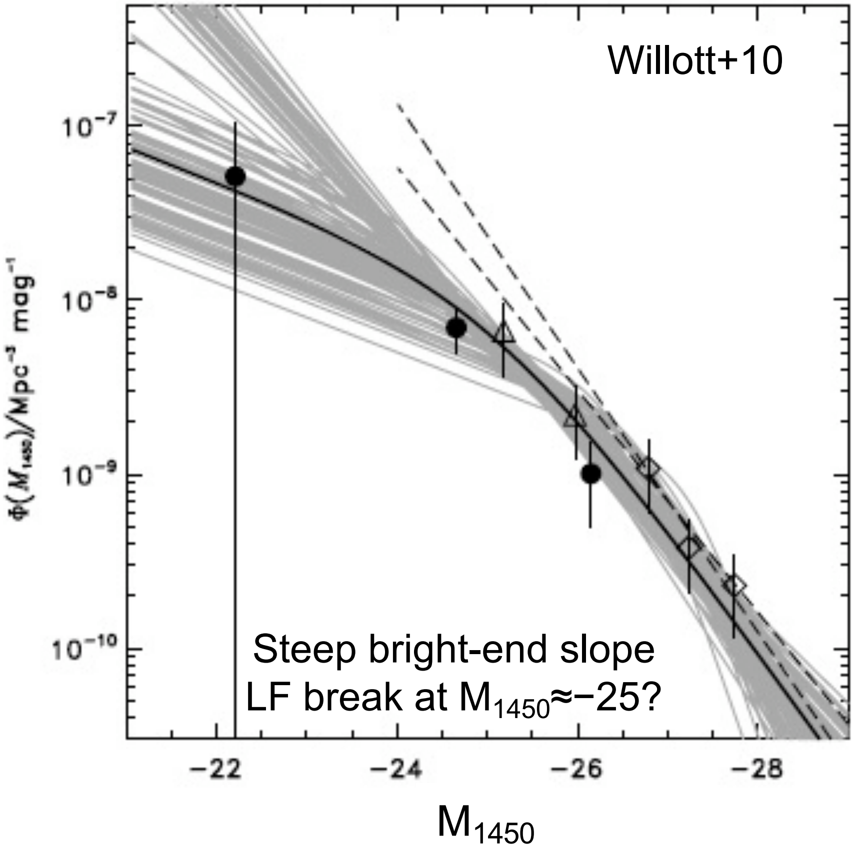
1) not all z=6 SMBHs may be active
2) still missing obscured z=6 QSOs

if BHs more abundant and duty cycle <1 → $M_h \approx 10^{11\text{-}12}\ M_\odot$

More results from X-ray surveys later

QSO luminosity functions at z~6





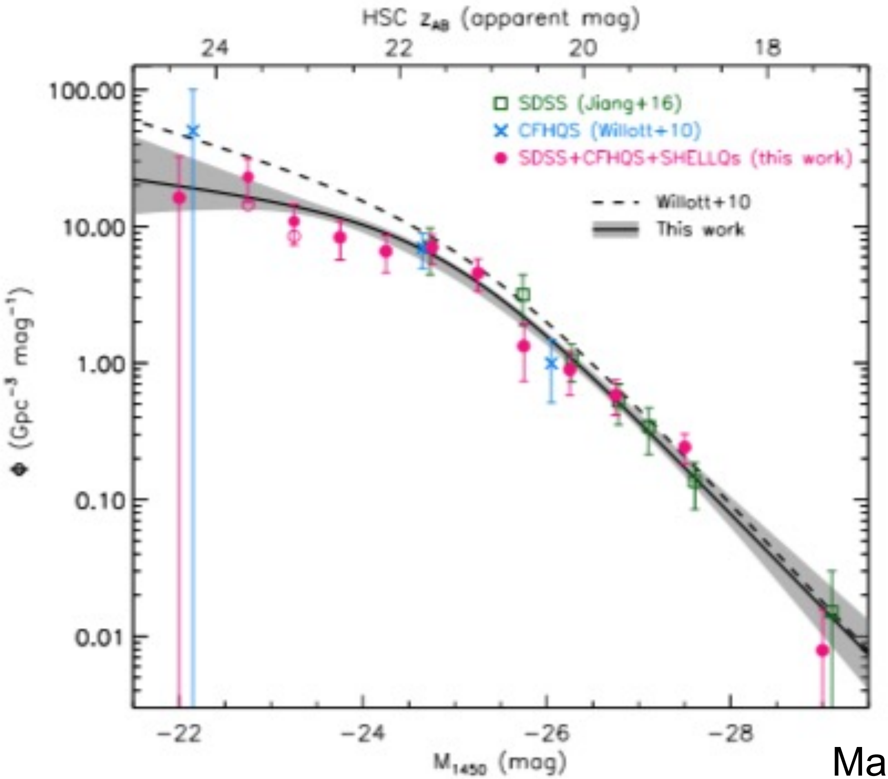
Steep bright-end slope
LF break at M_{1450}≈−25?

- Still highly uncertain faint end of the LF → if steep and high AGN f_{esc}~1, important contribution to reionization (Giallongo+15,19; see also Cappelluti+16, Ricci+17, Grazian+21)
- Luminous AGN are found to decline exponentially up to z~4−6
- Still limited is our knowledge of less luminous z≥3 AGN, i.e. the bulk of the population

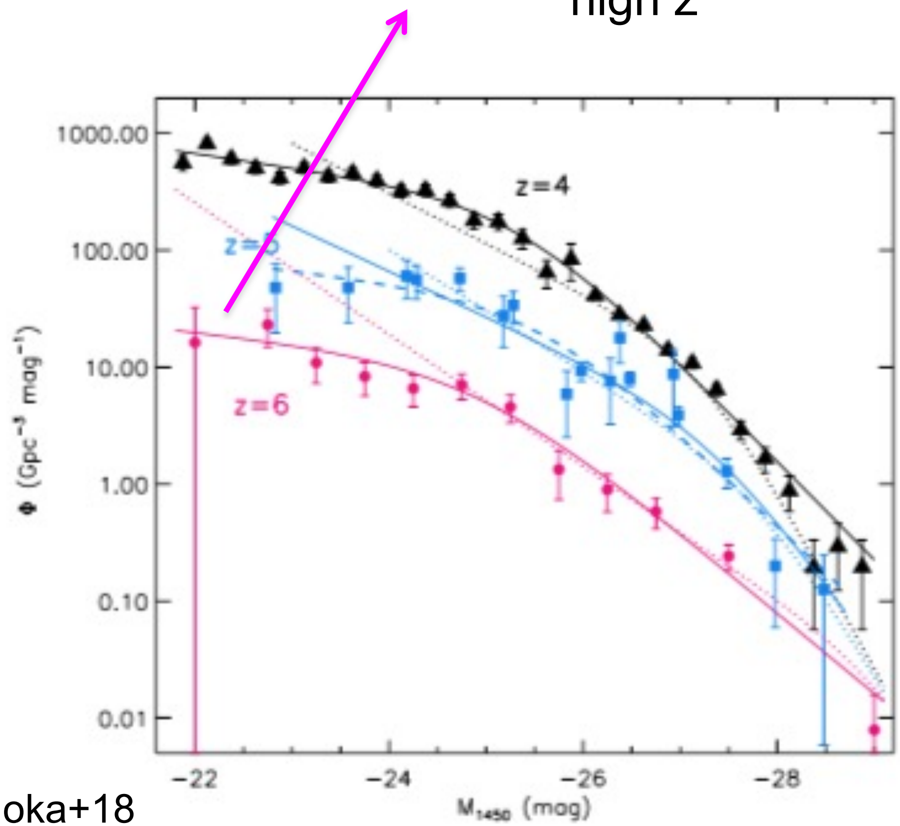
see also recent results from Vito+16,18

up to the most recent results from HSC

rapidly decreasing
number of QSOs at
high z



Matsuoka+18

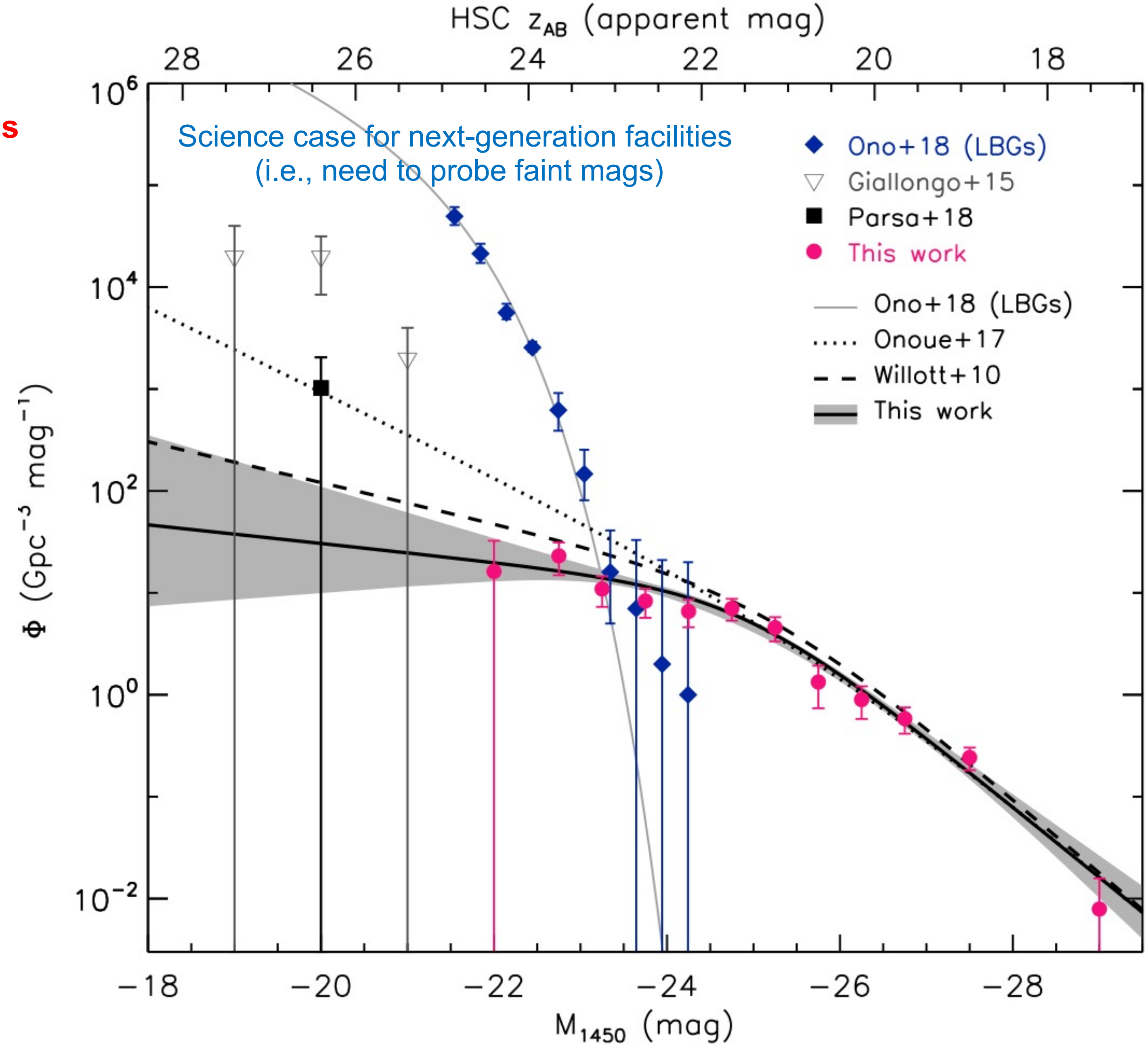


Flattening of the faint-end slope of the LF → QSOs cannot contribute significantly to the reionization (unless most of the population is missed) → needs to shed light on the obscured AGN population (X-rays favored)

AGN vs. Galaxies competition for re-ionization

Main ingredients: intensity of ionizing radiation, source (AGN, galaxies) number density (LogN-LogS, XLF), escape fraction, etc.

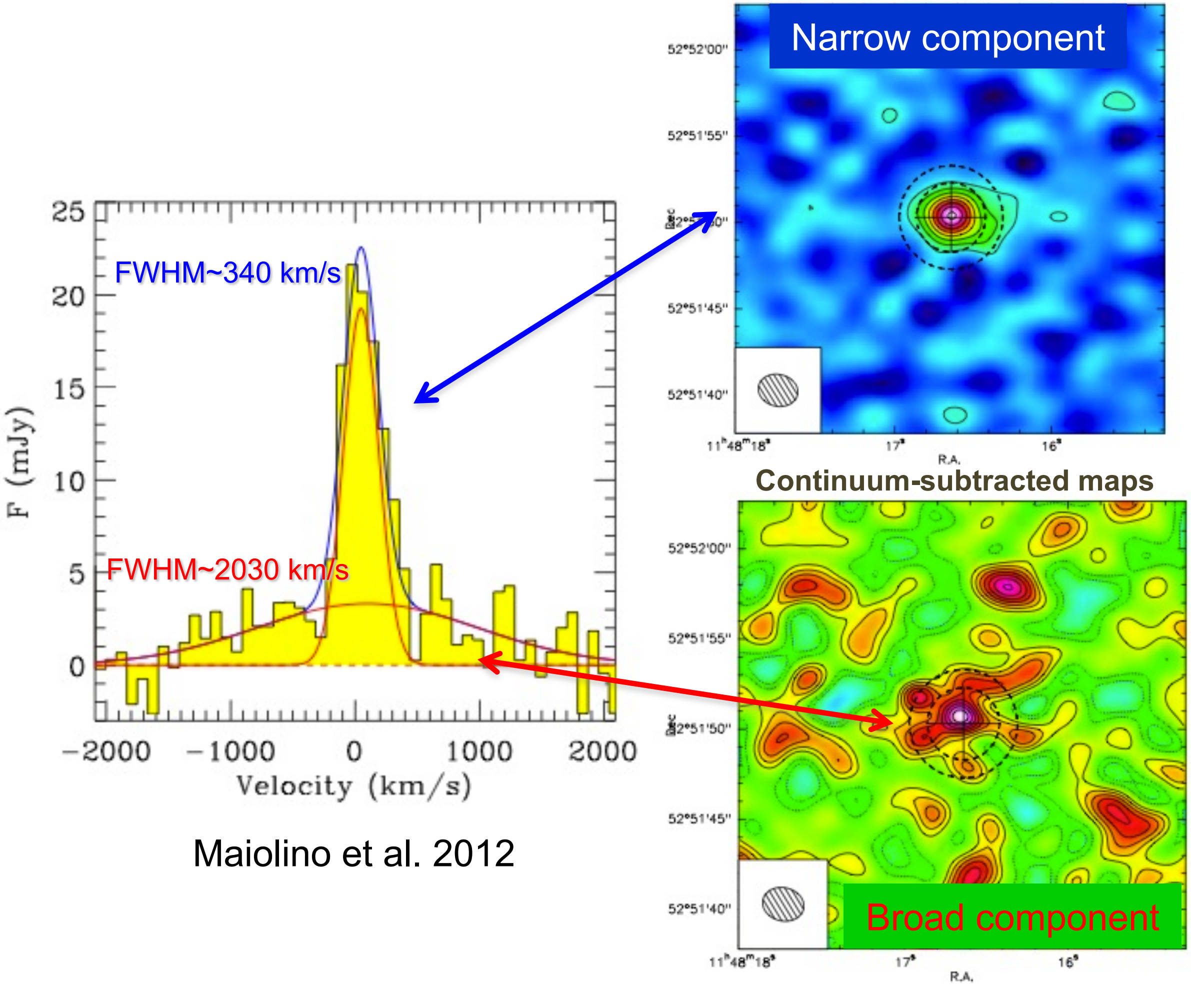
z~6 LFs



Matsuoka+18

Where do we stand? − XII. AGN feedback at high z

SDSS J1148+5251: z=6.43, [CII] obs.



Maiolino et al. 2012

Evidence of feedback at low and intermediate redshifts from neutral/ionized/mol. gas (e.g., Feruglio+10, Alexander+10, Brusa+14, Fiore+17, Bischetti+17, Vietri+18, Feruglio+18, […])

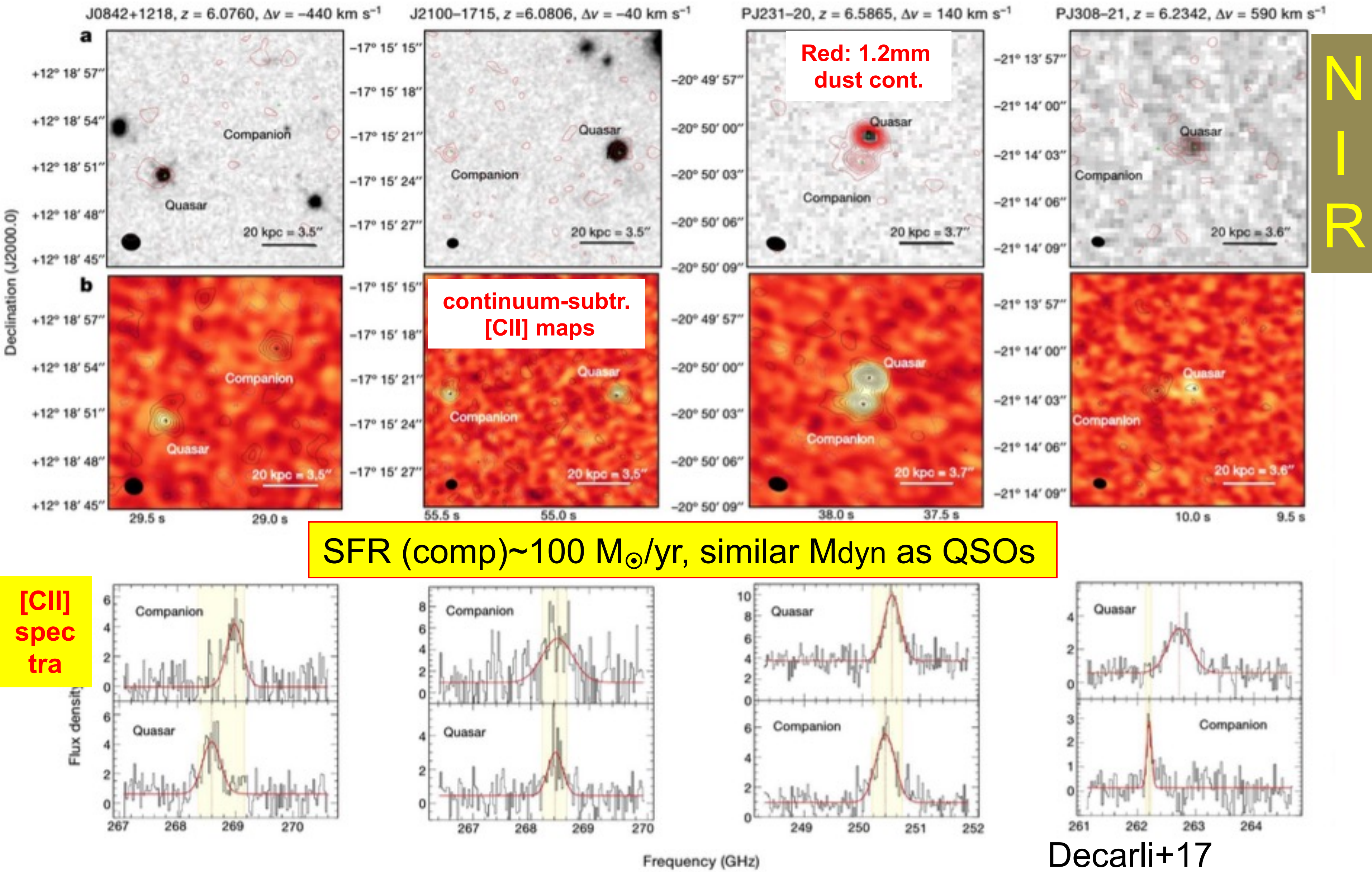
Capable of quenching SF? (e.g., Page+12, Cano-Diaz+12; see also Harrison+12, […])

see Cicone+14 ([CII]): multiple outflow events during the past 100Myr? Extension up to 30kpc

Massive outflow of $[CII]_{158\mu m}$ line, of Mdot>3500 $M_{\odot}$/yr (Maiolino+12, Valiante+12), ~SFR in the host galaxy

$P_K > 1.9 \times 10^{45}$ erg/s ≈0.6% L_{bol} (QSO) Fine with AGN Prad, barely consistent with STB-driven winds

Where do we stand? − XIII. Companions at z=6



Red: 1.2mm dust cont.

NIR

continuum-subtr. [CII] maps

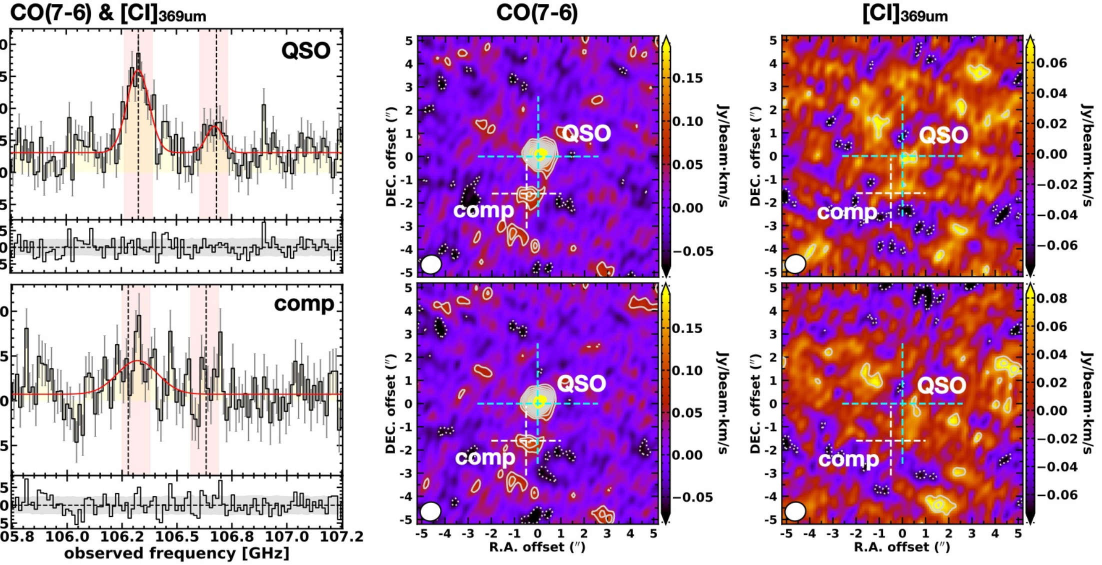
SFR (comp)~100 M$_\odot$/yr, similar Mdyn as QSOs

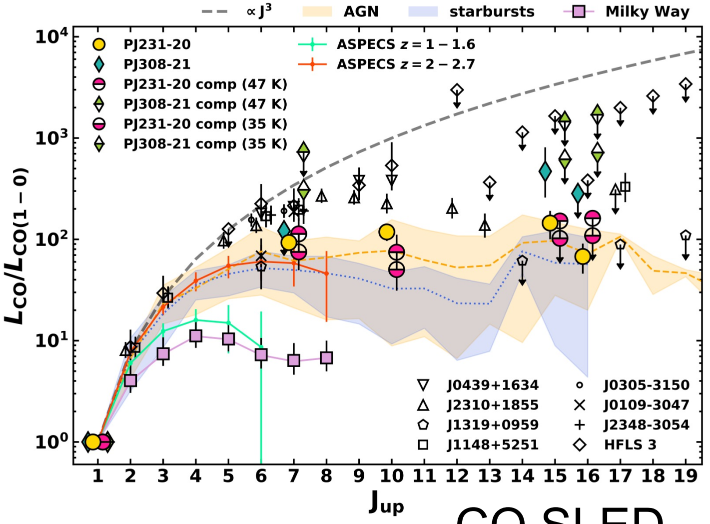
[CII] spectra

Companions – same redshift as the QSO

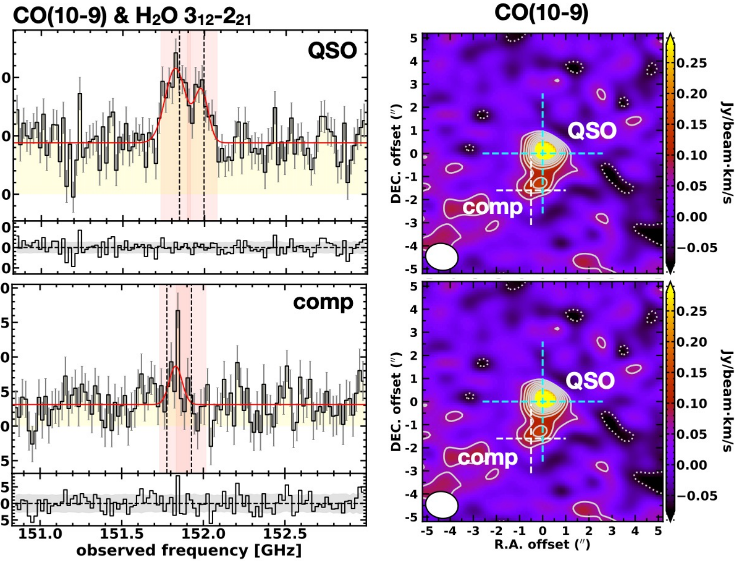
Decarli+17

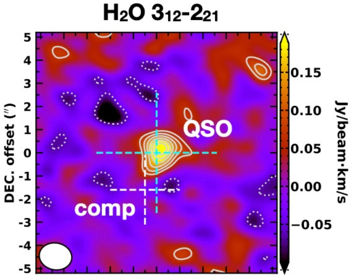
(see also Feruglio+18, Pensabene+21)



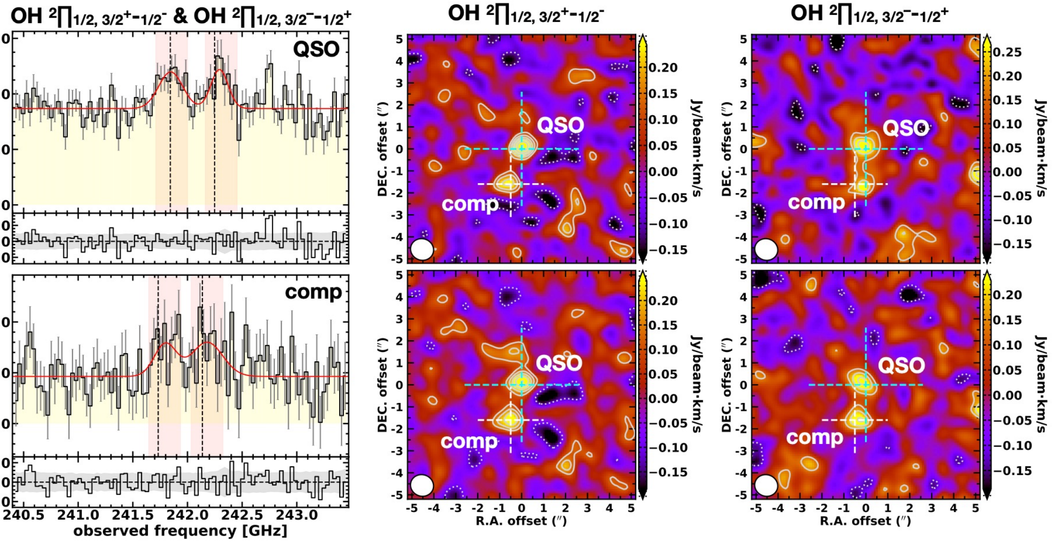


CO SLED





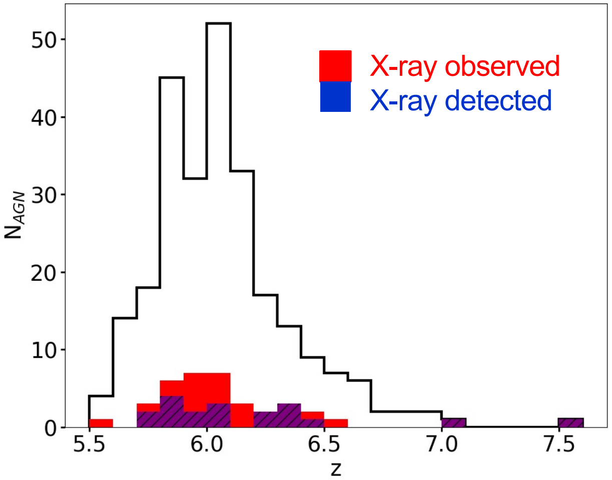
Pensabene+21



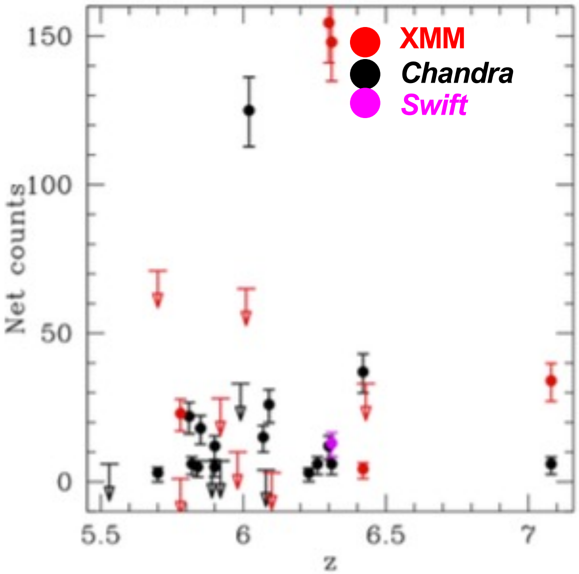
PJ231-20, z=6.59

Part II:
X-ray properties of $z>5.5$ unobscured QSOs

z~6 QSOs: the X-ray view. I. X-ray detection statistics



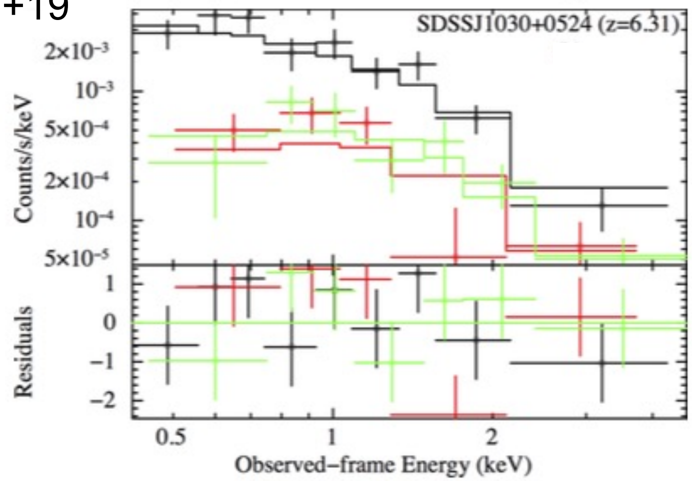
Nanni+17 (updated)
see alo Salvestrini+19

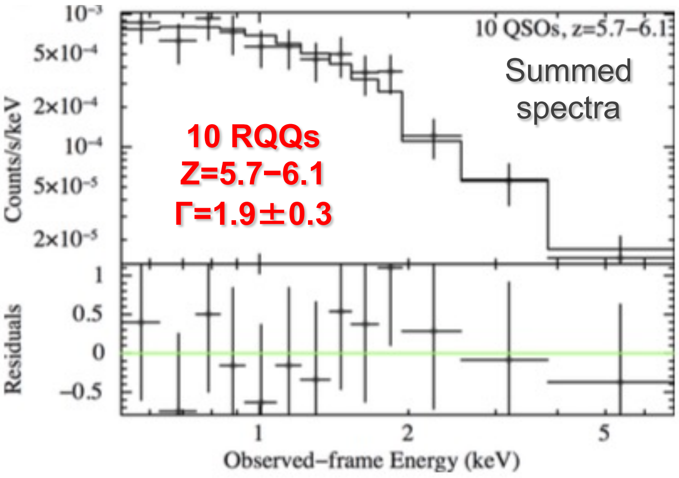


259 QSOs at z>5.5 (the majority from optical/near-IR surveys)
31 with available X-ray data
19 X-ray detections
(situation as few yrs ago)

Pushing the limit (beyond Type 1 QSO detection) is still challenging, but X-ray statistics is increasing

Γ≈1.6−2.4
see also
Farrah+04,
Moretti+14,
Page+14,
Gallerani+17



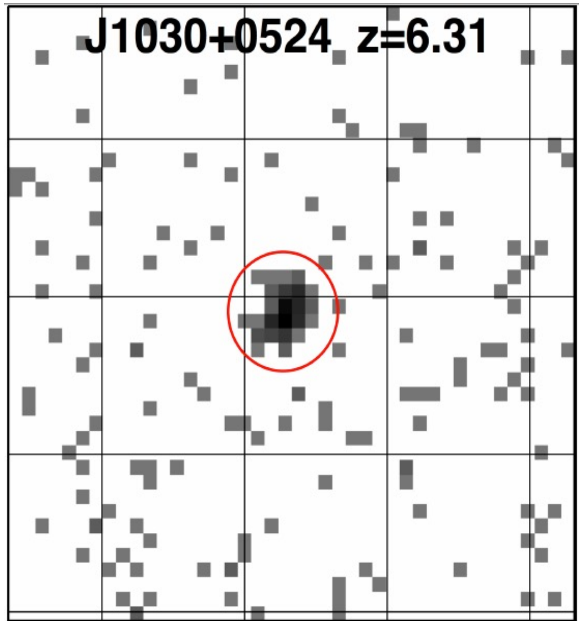


Summed spectra

10 RQQs
Z=5.7−6.1
Γ=1.9±0.3

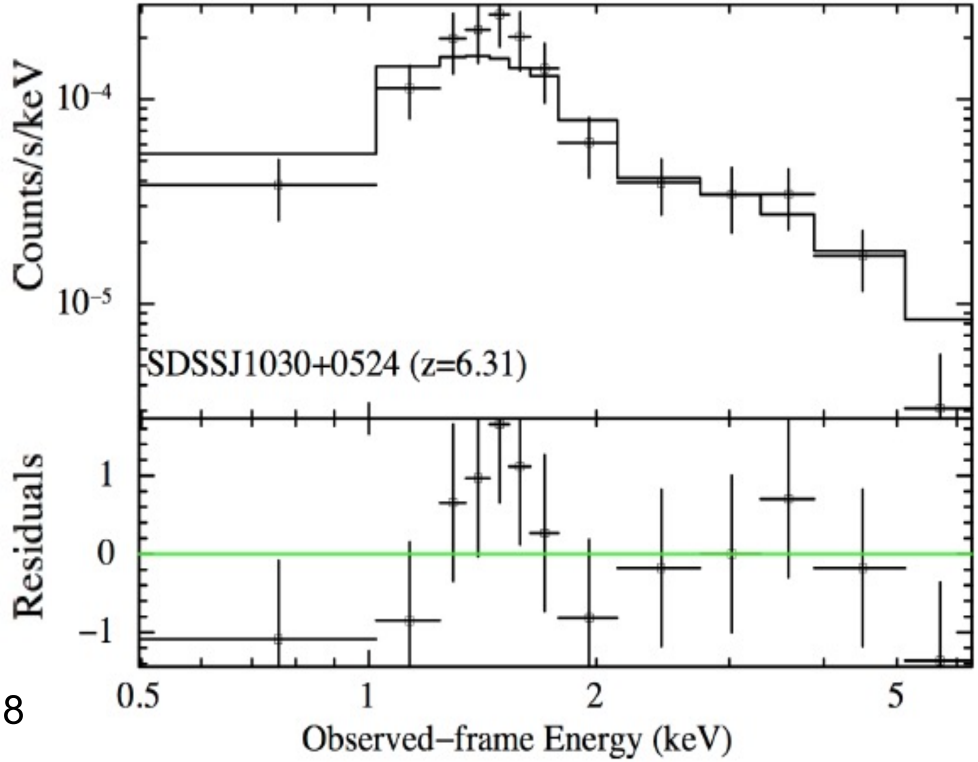
z~6 QSOs: the X-ray view. II. SDSSJ1030+0524 at z=6.3

0.5−7 keV image



20” × 20”

Chandra, $\mathbf{\Gamma}$=1.81±0.18



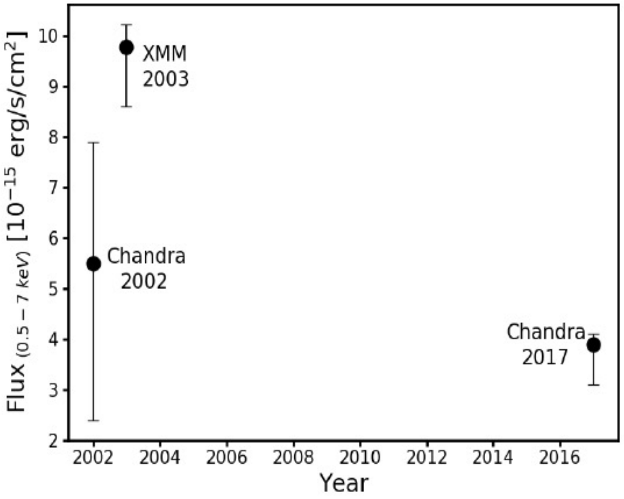
Nanni+18

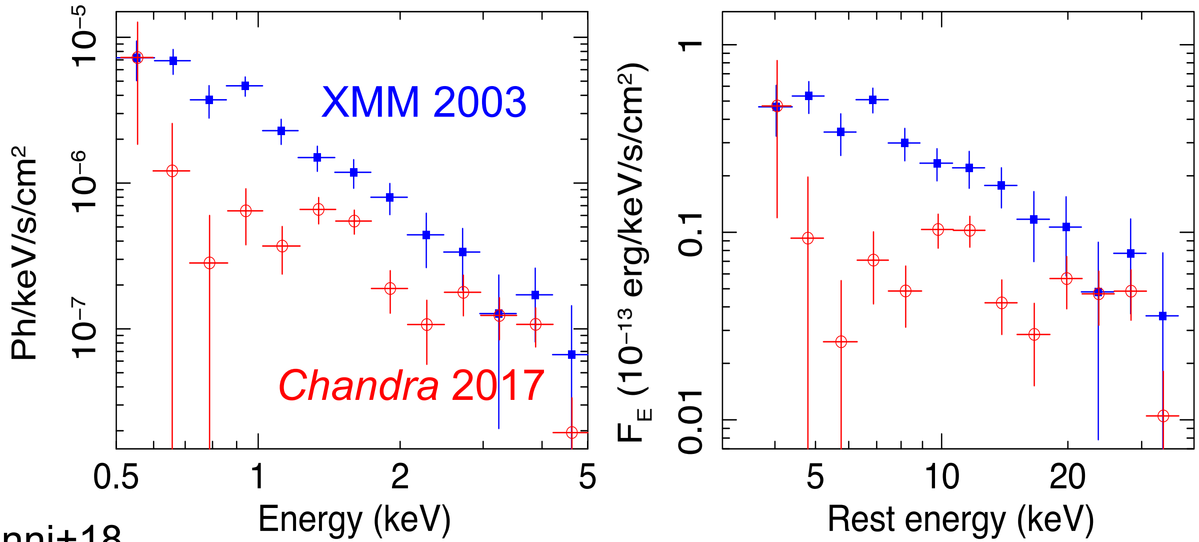
125 net counts

$F_{0.5\text{-}7keV}$=4 × 10^{-15} erg/cm^2/s

$L_{2\text{-}10keV}$ = 7 × 10^{44} erg/s

500ks *Chandra*
(PI: R. Gilli)





Nanni+18

XMM $\Gamma = 2.37 \pm 0.16$

Chandra $\Gamma = 1.81 \pm 0.18$

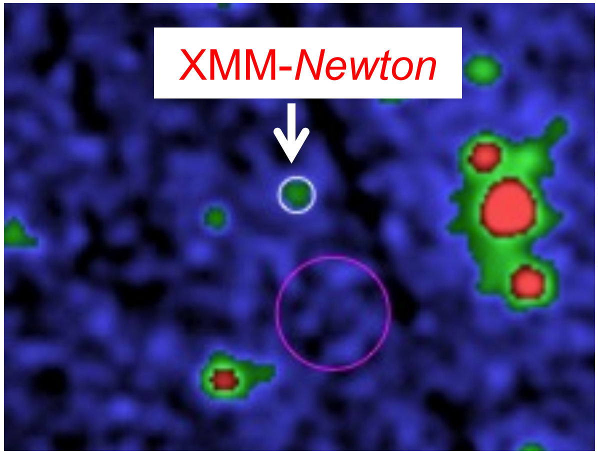
(+2.5 times fainter flux)

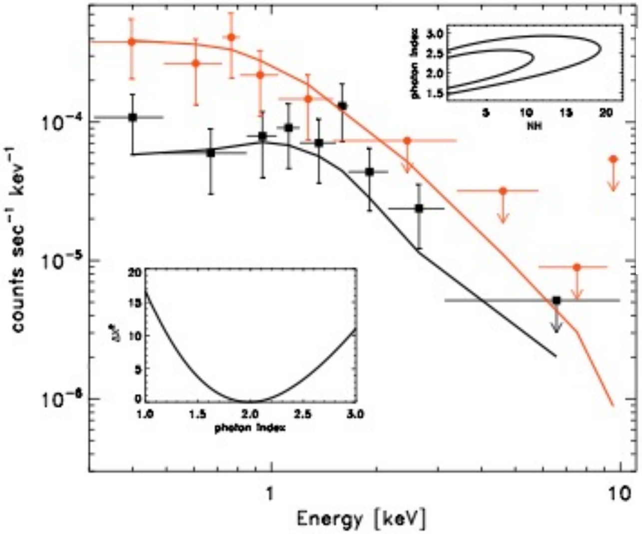
Chandra spectrum significantly harder: intrinsic hardening or increased absorption ($\approx 5 \times 10^{23}$ cm^{-2})? Likely both effects

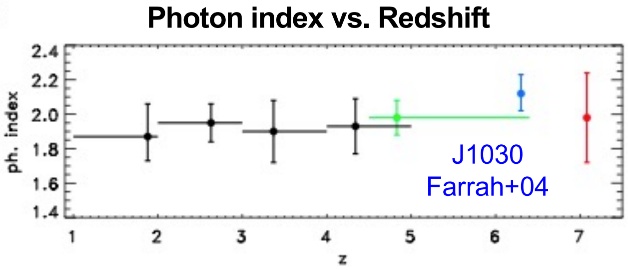
→ Possibility to extend studies X-ray variability at the highest redshift

→ From population studies to more physical studies with next-generation of X-ray instruments (i,e., *Athena*)

z~6 QSOs: the X-ray view. III. ULASJ1120 at z=7.08







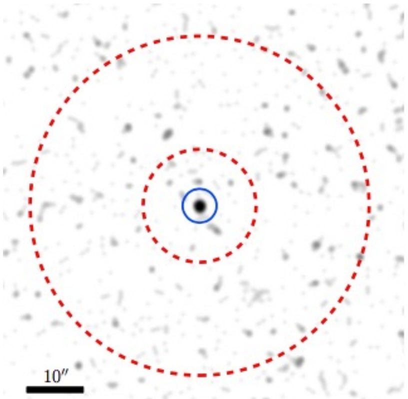
Moretti+14
(see also Page+14)

T≈340 ks obs.
150 net counts
$\Gamma=2.0\pm0.3$
$L_{2-10\mathrm{keV}}\approx 7\times10^{44}$ erg/s

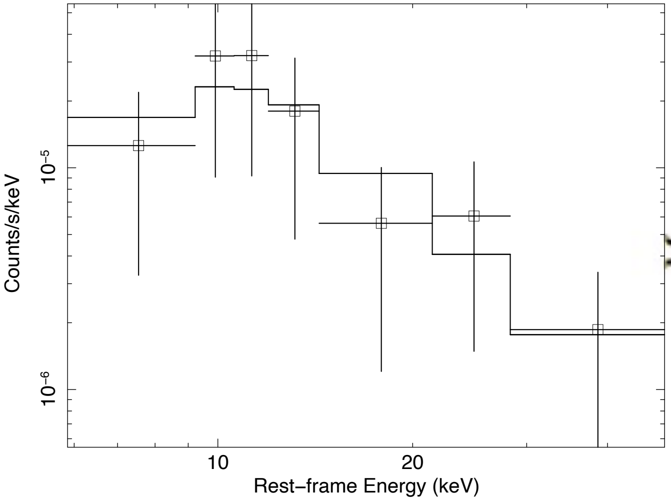
challenging observations to obtain good-quality X-ray spectra (sometimes, even a good detection) for current facilities

QSO accreting at Eddington

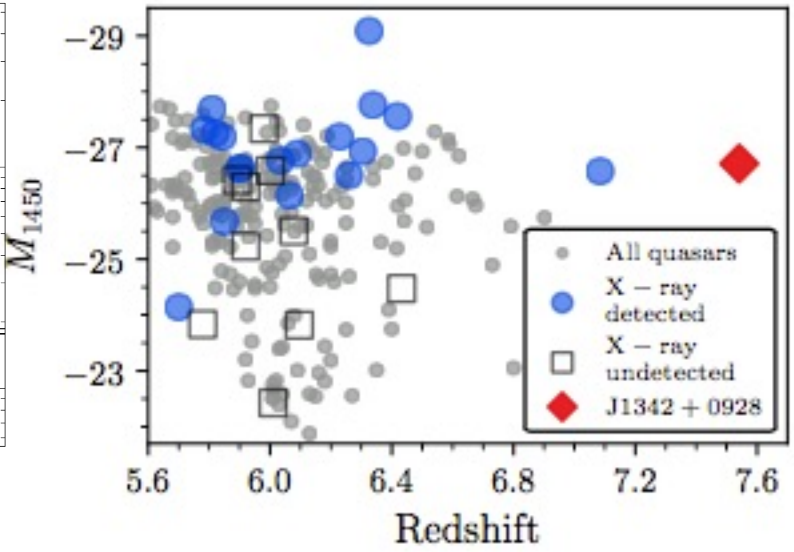
z~6 QSOs: the X-ray view. IV. ULASJ1342 at z=7.54



Banados+18



CV+; Banados+18

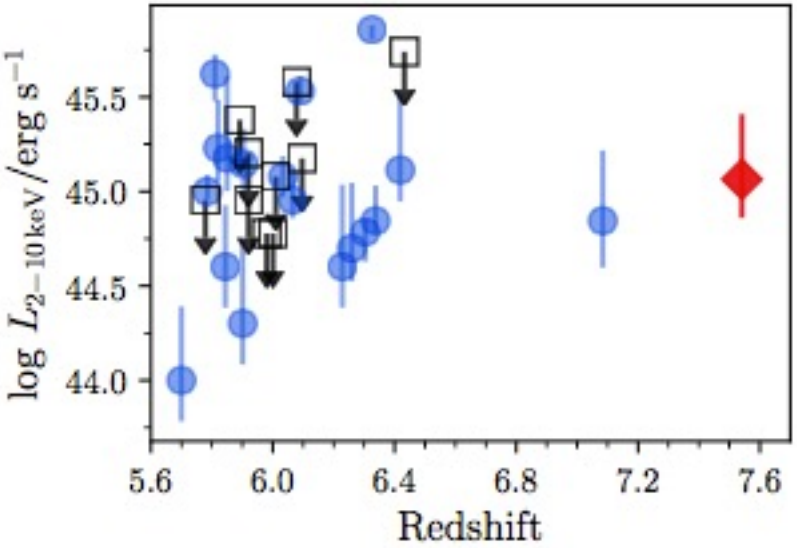


T≈45 ks *Chandra*

14 net counts

Γ=2.0±0.5

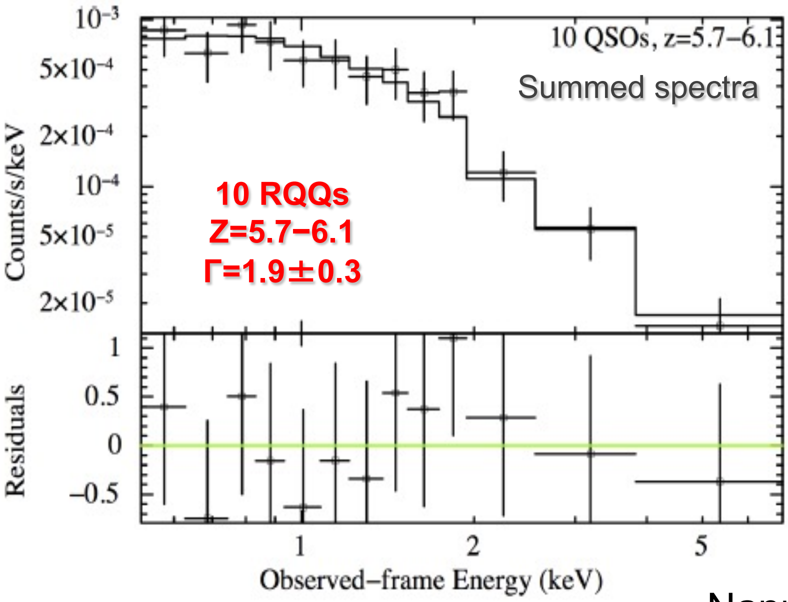
$L_{2-10keV}$≈1.2 × 10^{45} erg/s

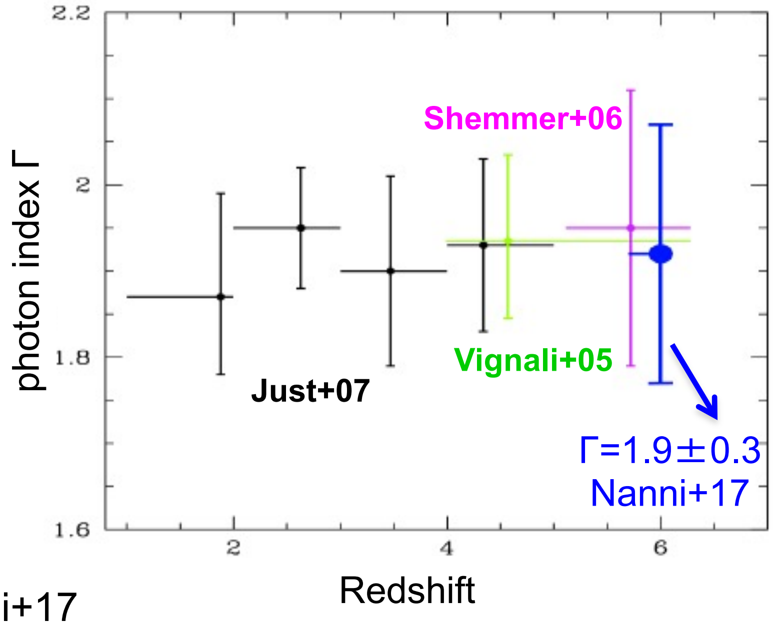


Banados+18

z~6 QSOs: the X-ray view. V. Average X-ray spectrum

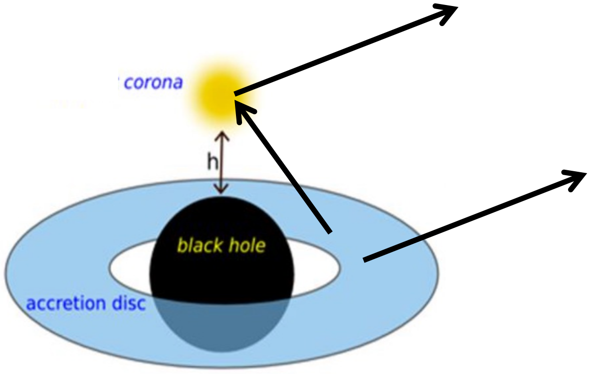
Sum of 10 QSOs at z>5.6 detected with *Chandra*





Nanni+17

$$f_\nu \approx \nu^{-\alpha} = \nu^{\Gamma-1}$$

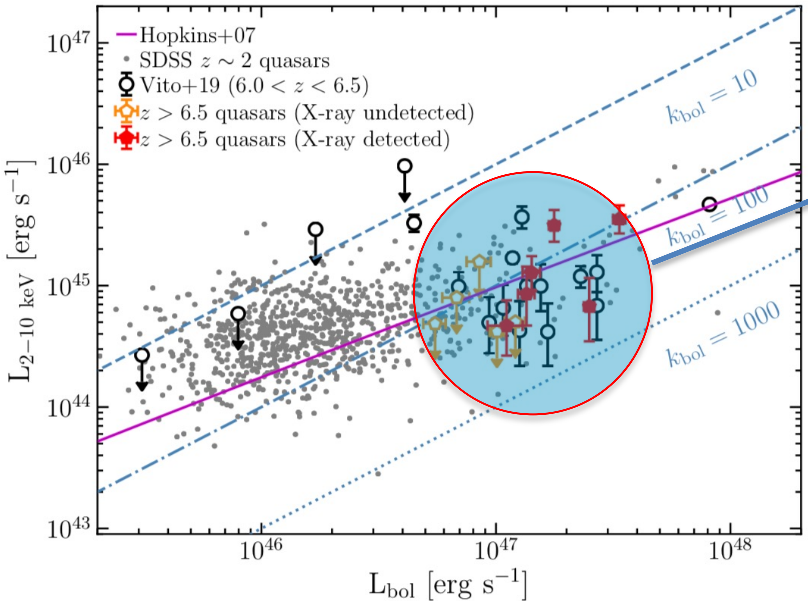


basic AGN inner structure (accretion disk + hot e^- corona) in place in t<<1 Gyr

(the small-scale X-ray emission regions of AGN appear to be insensitive to the significant changes occurring at z≈0−6)

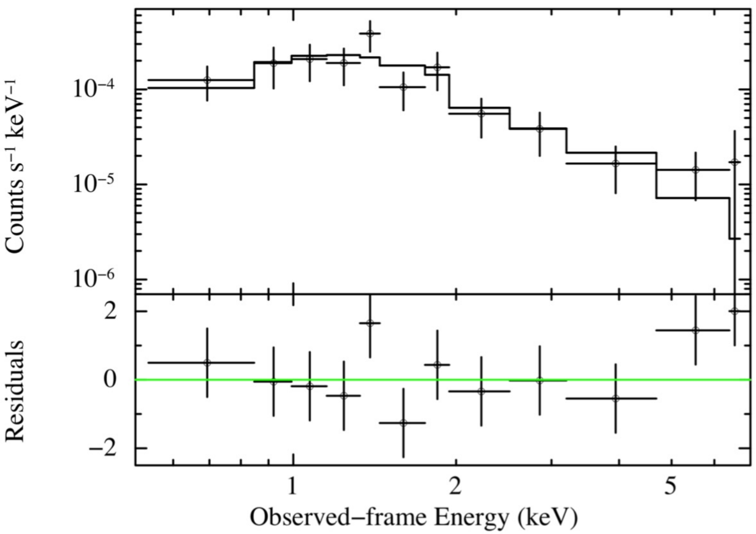
z~6 QSOs: the X-ray view. VI. Γ vs. λ_{Edd}

Sample of QSOs observed by *Chandra* (Wang+20)

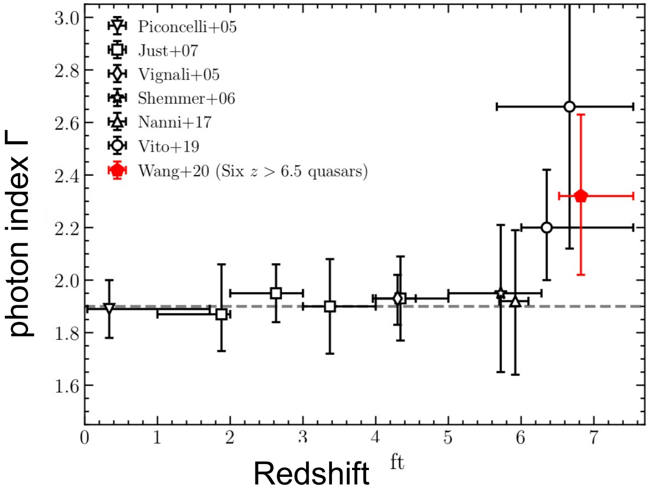


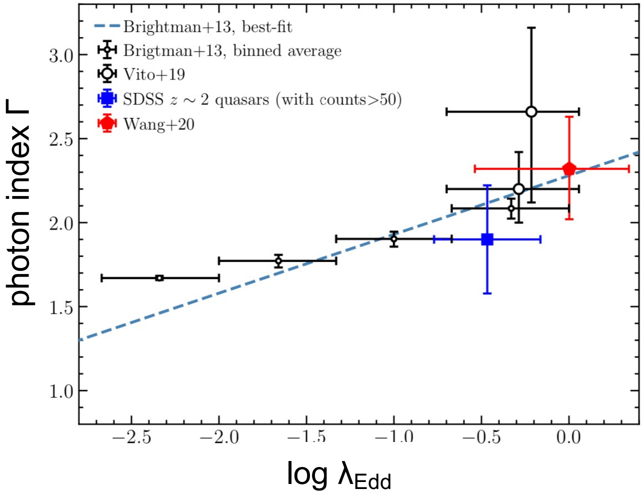
X-ray~1/100 of the bolometric accretion luminosity (which resides in the Big Blue Bump in Type 1 QSOs)

Joint spectral analysis Γ=2.3±0.3



Wang+20

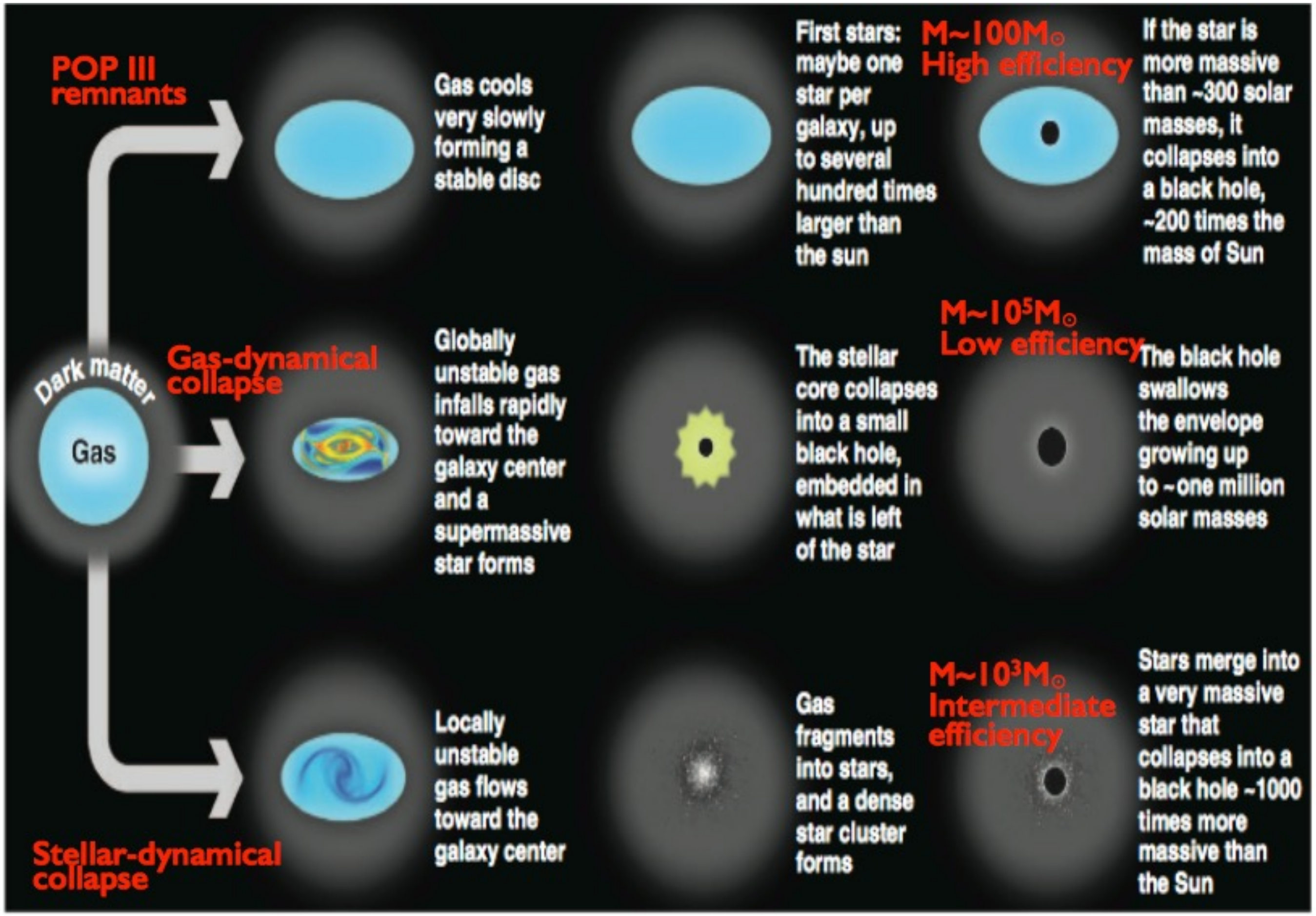




A steeper photon index (but errors are large) can be related to the on-average higher Eddington ratios probed at high redshift (Shemmer+08, Brightman+13; see also Trakhtenbrot et al. 2017)

Part III:
The challenge of BH growth

BH growth at high z. I. Which BH seeds?



Gas cools very slowly forming a stable disc

First stars: maybe one star per galaxy, up to several hundred times larger than the sun

If the star is more massive than ~300 solar masses, it collapses into a black hole, ~200 times the mass of Sun

Globally unstable gas infalls rapidly toward the galaxy center and a supermassive star forms

The stellar core collapses into a small black hole, embedded in what is left of the star

The black hole swallows the envelope growing up to ~one million solar masses

Locally unstable gas flows toward the galaxy center

Gas fragments into stars, and a dense star cluster forms

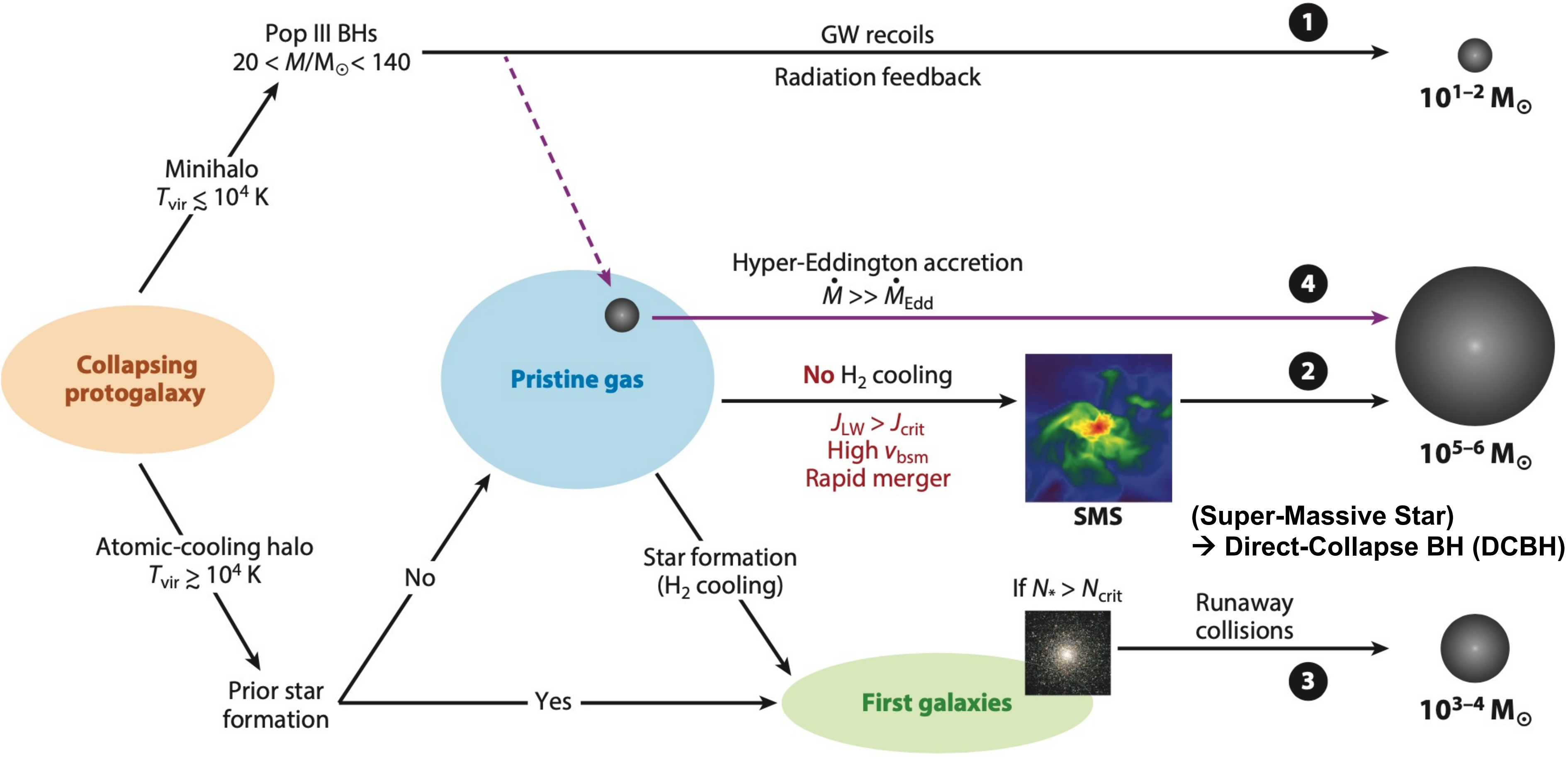
Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

Volonteri10 review

“light” seeds
(pop III star remnants)
$M_{BH} \approx 100-600\ M_\odot$
$z \approx 20-50$
Madau & Rees 01
Volonteri+03

“heavy” seeds
DCBHs
$M_{BH} \approx 10^4-10^6\ M_\odot$
$z \approx 5-10$
Volonteri+08,
Agarwal+13, Yue+13

intermediate seeds
$M_{BH} \approx 10^3\ M_\odot$, $z \approx 10-15$
Runaway stellar mergers in high-z clusters
Devecchi & Volonteri09



(Super-Massive Star)
→ Direct-Collapse BH (DCBH)

Inayoshi+20 review

Information about seed initial properties lost at high redshift (partly inferred from their number)
Limit imposed by the Soltan (1982) argument (comparison of AGN at all z with local population of dormant SMBHs)

BH growth at high z. III. The challenge

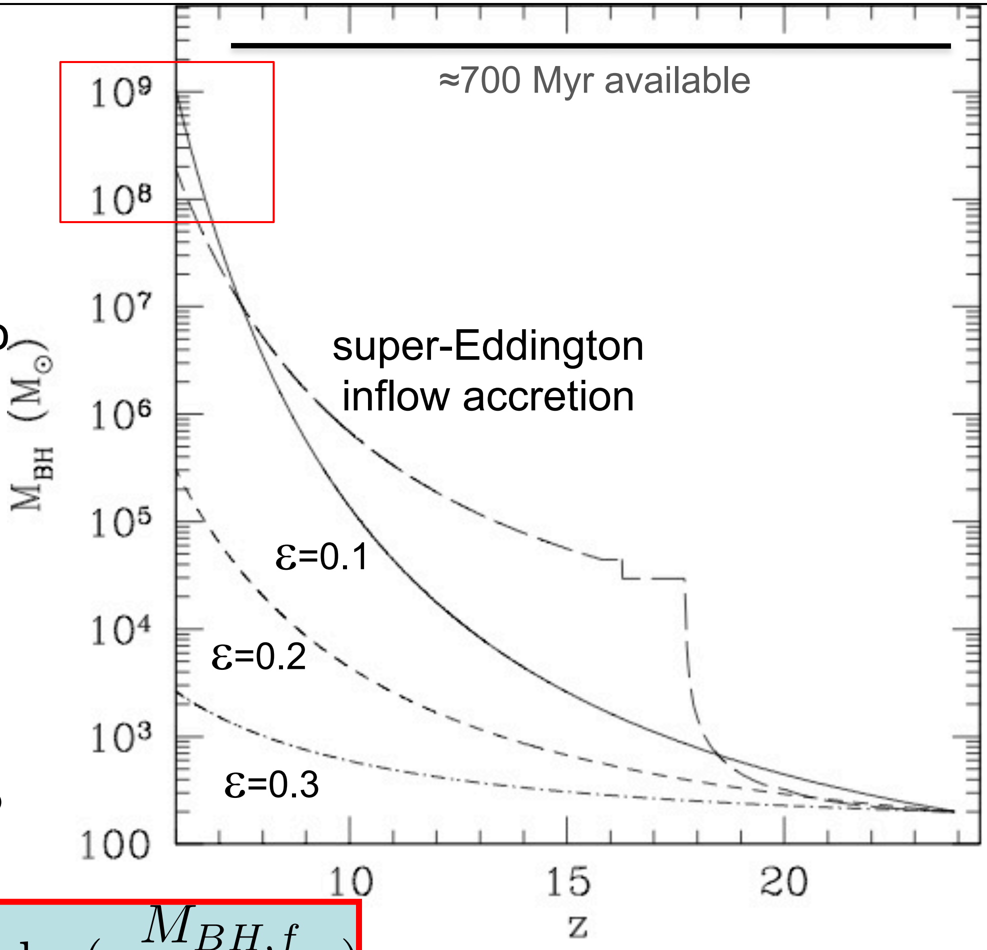
“Light” BH seeds require continuous accretion at λ_{Edd}=1 for long (z>20) periods
Most likely: unstable and episodic accretion flow (Ciotti & Ostriker 07, Dubois+13)

$$M(t) = M_0\, e^{\left(\frac{1-\varepsilon}{\varepsilon}\frac{t}{t_{\mathrm{Edd}}}\right)}$$

Larger radiation efficiency ε (η in previous slides) means longer times to achieve a given mass
[t_{Edd}=0.45 Gyr for ε=0.1]

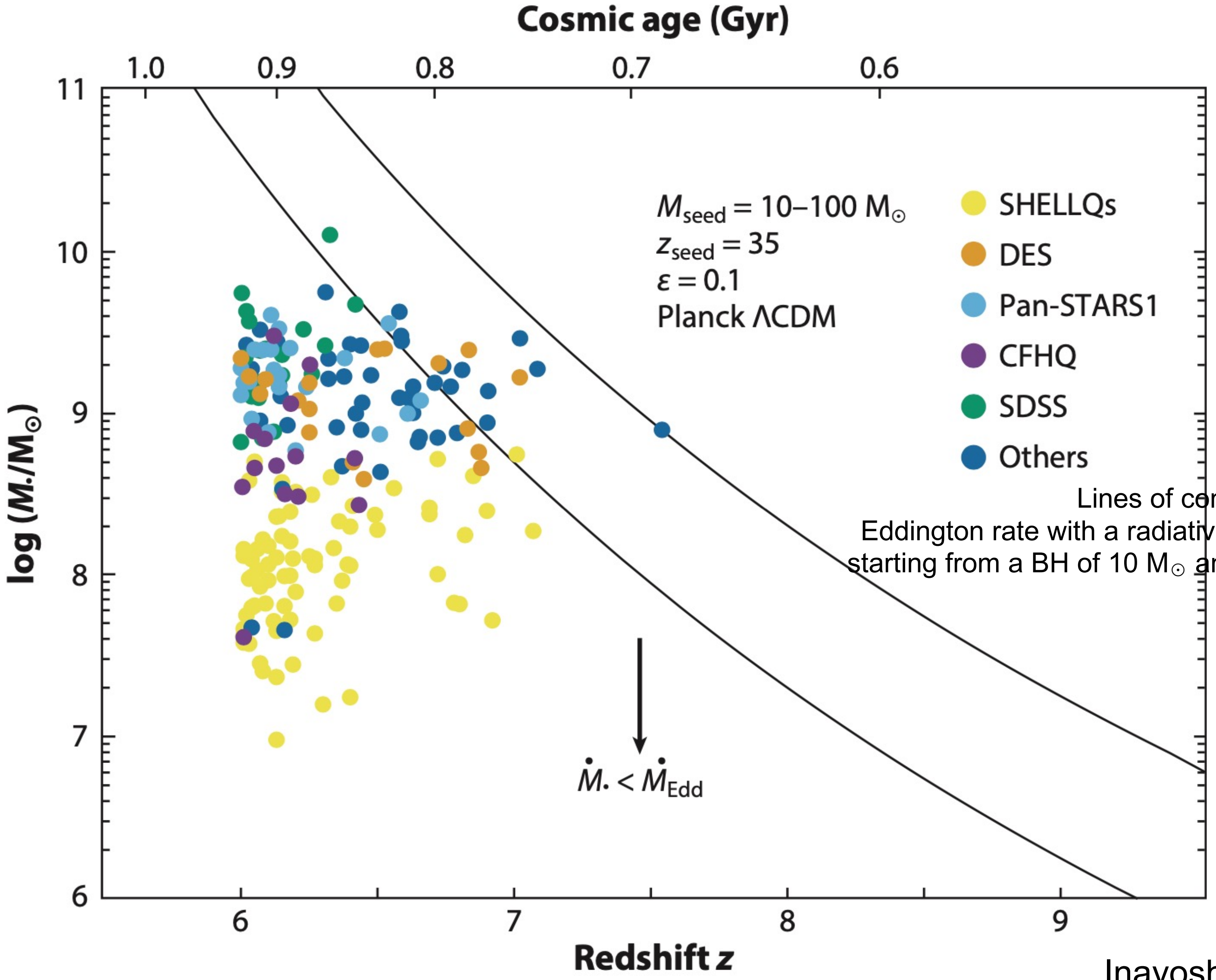
Rapidly spinning BHs might have problems because of a larger ε

Highest-redshift QSOs: $M_{BH} \approx 10^9\ M_\odot$



Volonteri & Rees 2006

$$t/Gyr = 0.45 \times \frac{\epsilon}{1-\epsilon} \times \frac{L_{Edd}}{L_{bol}} \times \ln\left(\frac{M_{BH,f}}{M_{BH,seed}}\right)$$

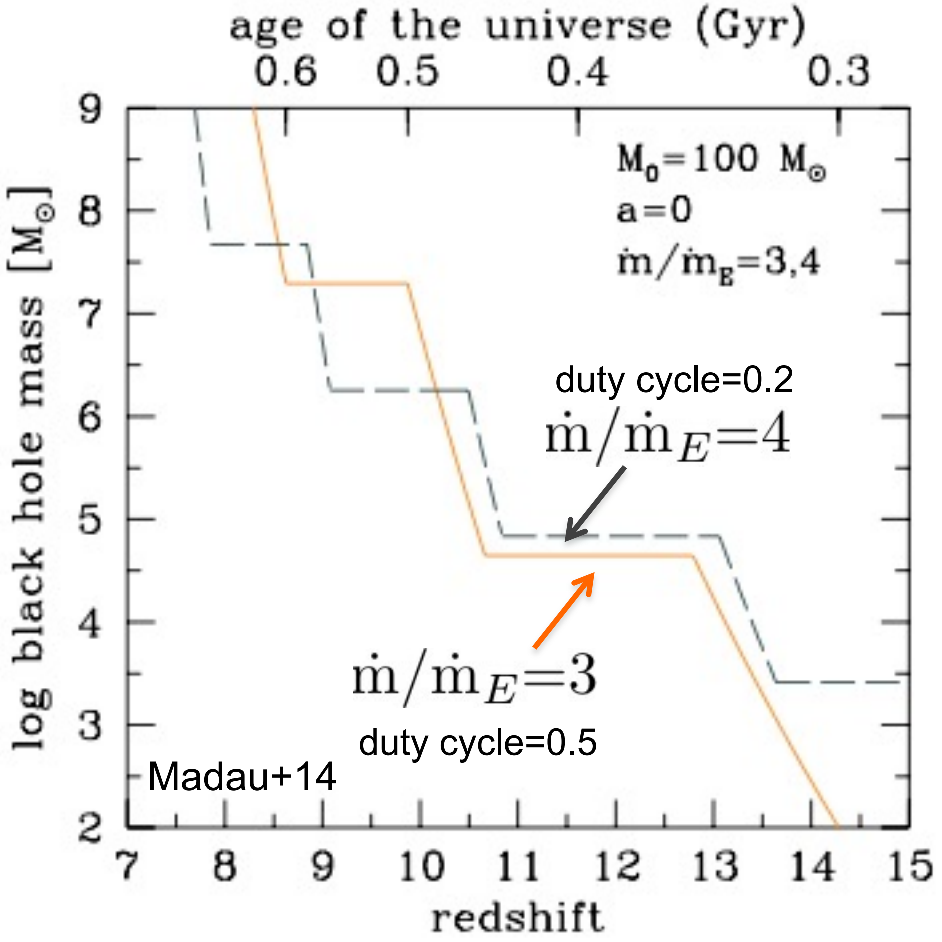


Lines of continuous growth at Eddington rate with a radiative efficiency ε=0.1, starting from a BH of 10 $M_\odot$ and 100 $M_\odot$ at z=35

Inayoshi et al. (2020)

BH growth needs that gas is retained in the host to provide high $f_{\rm acc,duty}$ → limited feedback/quenching, large gas reservoir

BH growth at high z. IV. Super-Eddington growth



$$t/Gyr = 0.45 \times \frac{\epsilon}{1-\epsilon} \times \frac{L_{Edd}}{L_{bol}} \times \ln\left(\frac{M_{BH,f}}{M_{BH,seed}}\right)$$

Non-rotating BH with seed mass=100 $M_\odot$

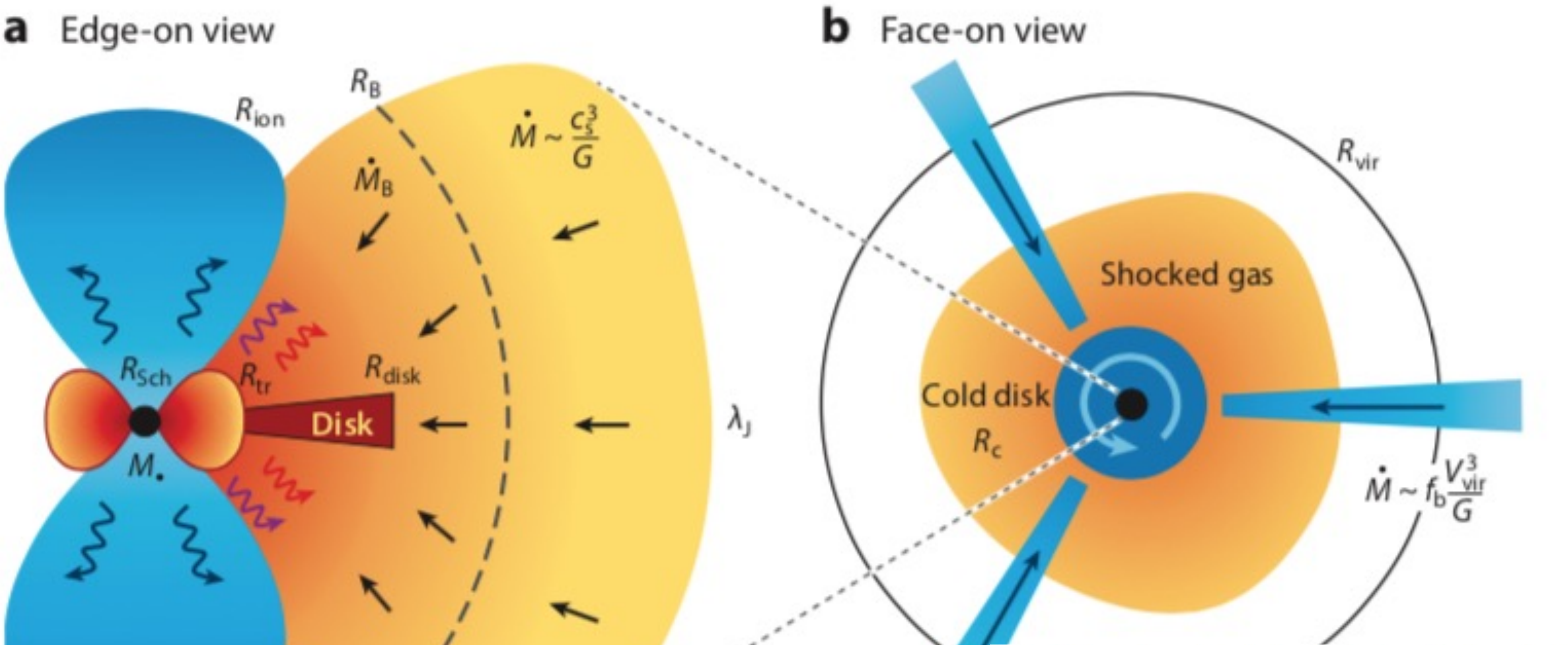
Intermediate (tq=100 Myr) *Super-Eddington accretion* can be the answer (e.g, Madau+14, Volonteri & Silk14, Pezzulli+17)

Radiatively inefficient highly accreting BH (slim disk) provide fast growth. Slim disks remain only moderately luminous ($L \geq L_{Edd}$) as a large fraction of the viscosity-generated heat is advected inward and released closer to the hole or not released at all

Likely DCBHs is the “easiest” scenario for SMBH accretion in short timescales

While in ADAF the low radiative efficiency is due to the low accretion rate, in **slim discs** (geometrically and optically thick) the accretion rate and the gas density are high → the flow is opt. thick, the BH may accrete well above the Eddington critical rate, *yet producing limited luminosity* because the emitted radiation is mostly ‘trapped'

BH growth at high z. V. Super-Eddington growth



Inayoshi+20

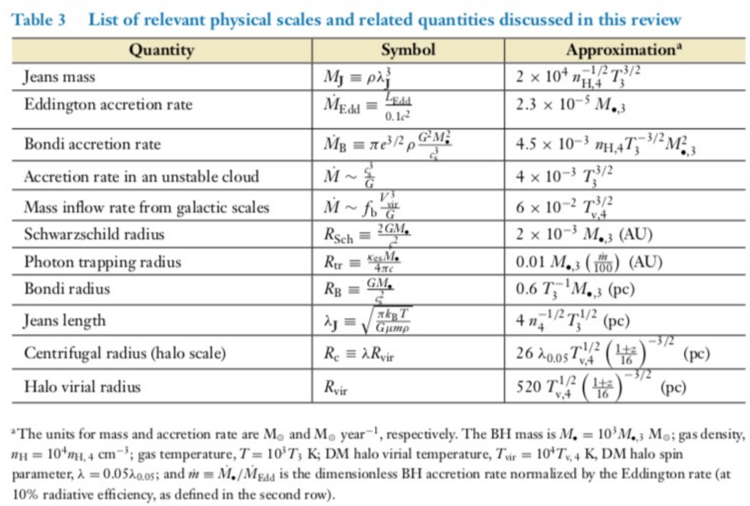


Table 3 List of relevant physical scales and related quantities discussed in this review

Quantity	Symbol	Approximation[a]
Jeans mass	$M_J \equiv \rho\lambda_J^3$	$2 \times 10^4\, n_{\rm H,4}^{-1/2} T_3^{3/2}$
Eddington accretion rate	$\dot{M}_{\rm Edd} \equiv \frac{L_{\rm Edd}}{0.1c^2}$	$2.3 \times 10^{-5}\, M_{\bullet,3}$
Bondi accretion rate	$\dot{M}_{\rm B} \equiv \pi e^{3/2} \rho \frac{G^2 M_\bullet^2}{c_s^3}$	$4.5 \times 10^{-3}\, n_{\rm H,4} T_3^{-3/2} M_{\bullet,3}^2$
Accretion rate in an unstable cloud	$\dot{M} \sim \frac{c_s^3}{G}$	$4 \times 10^{-3}\, T_3^{3/2}$
Mass inflow rate from galactic scales	$\dot{M} \sim f_{\rm b} \frac{V_{\rm vir}^3}{G}$	$6 \times 10^{-2}\, T_{\rm v,4}^{3/2}$
Schwarzschild radius	$R_{\rm Sch} \equiv \frac{2GM_\bullet}{c^2}$	$2 \times 10^{-3}\, M_{\bullet,3}$ (AU)
Photon trapping radius	$R_{\rm tr} \equiv \frac{\kappa_{\rm es} \dot{M}_\bullet}{4\pi c}$	$0.01\, M_{\bullet,3} \left(\frac{\dot{m}}{100}\right)$ (AU)
Bondi radius	$R_{\rm B} \equiv \frac{GM_\bullet}{c_s^2}$	$0.6\, T_3^{-1} M_{\bullet,3}$ (pc)
Jeans length	$\lambda_{\rm J} \equiv \sqrt{\frac{\pi k_{\rm B} T}{G \mu m \rho}}$	$4\, n_4^{-1/2} T_3^{1/2}$ (pc)
Centrifugal radius (halo scale)	$R_{\rm c} \equiv \lambda R_{\rm vir}$	$26\, \lambda_{0.05} T_{\rm v,4}^{1/2} \left(\frac{1+z}{16}\right)^{-3/2}$ (pc)
Halo virial radius	$R_{\rm vir}$	$520\, T_{\rm v,4}^{1/2} \left(\frac{1+z}{16}\right)^{-3/2}$ (pc)

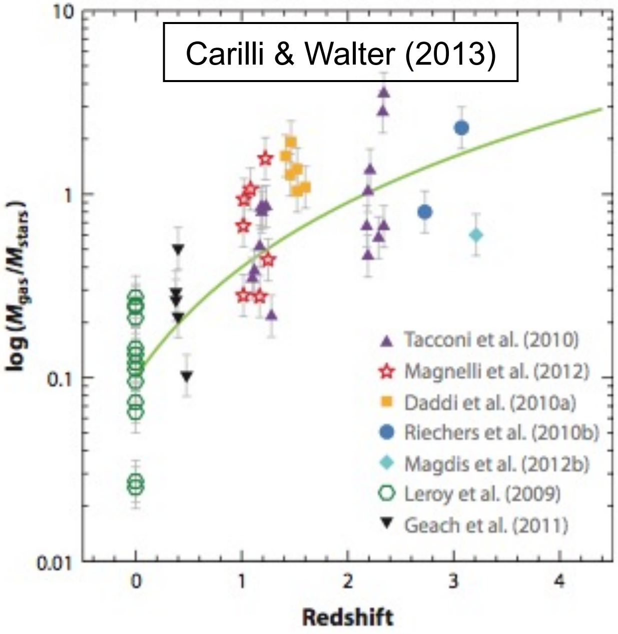
[a] The units for mass and accretion rate are $M_\odot$ and $M_\odot$ year^{-1}, respectively. The BH mass is $M_\bullet = 10^3 M_{\bullet,3}\, M_\odot$; gas density, $n_{\rm H} = 10^4 n_{\rm H,4}$ cm^{-3}; gas temperature, $T = 10^3 T_3$ K; DM halo virial temperature, $T_{\rm vir} = 10^4 T_{\rm v,4}$ K, DM halo spin parameter, $\lambda = 0.05\lambda_{0.05}$; and $\dot{m} \equiv \dot{M}_\bullet / \dot{M}_{\rm Edd}$ is the dimensionless BH accretion rate normalized by the Eddington rate (at 10% radiative efficiency, as defined in the second row).

structure of the accretion flow
onto a BH embedded in a protogalaxy

Part IV:
Obscured AGN at z>3:
insights from X-ray surveys

(but not only…)

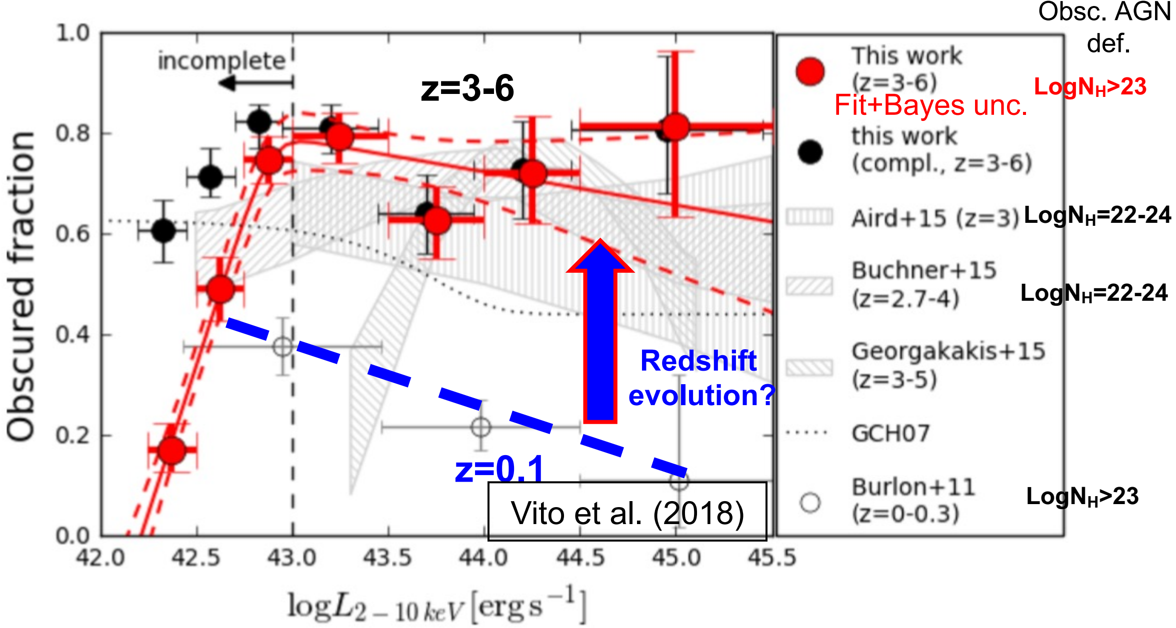
Obscured AGN at z>3. I. Evolution of obscured AGN fraction



Large quantity of gas available at high redshift

Deep X-ray observations now start probing obscured AGN systems beyond the local Universe

CDF-S (7Ms) + CDF-N (2Ms) analysis
(N~102 X-ray selected AGN, ~28 spec-z)



z>3 AGN: ≈70−80% with N_H>10^{23} cm^{-2}

see also Iwasawa et al. (2012) – CDFS, 3Ms, z=1.7−3.7

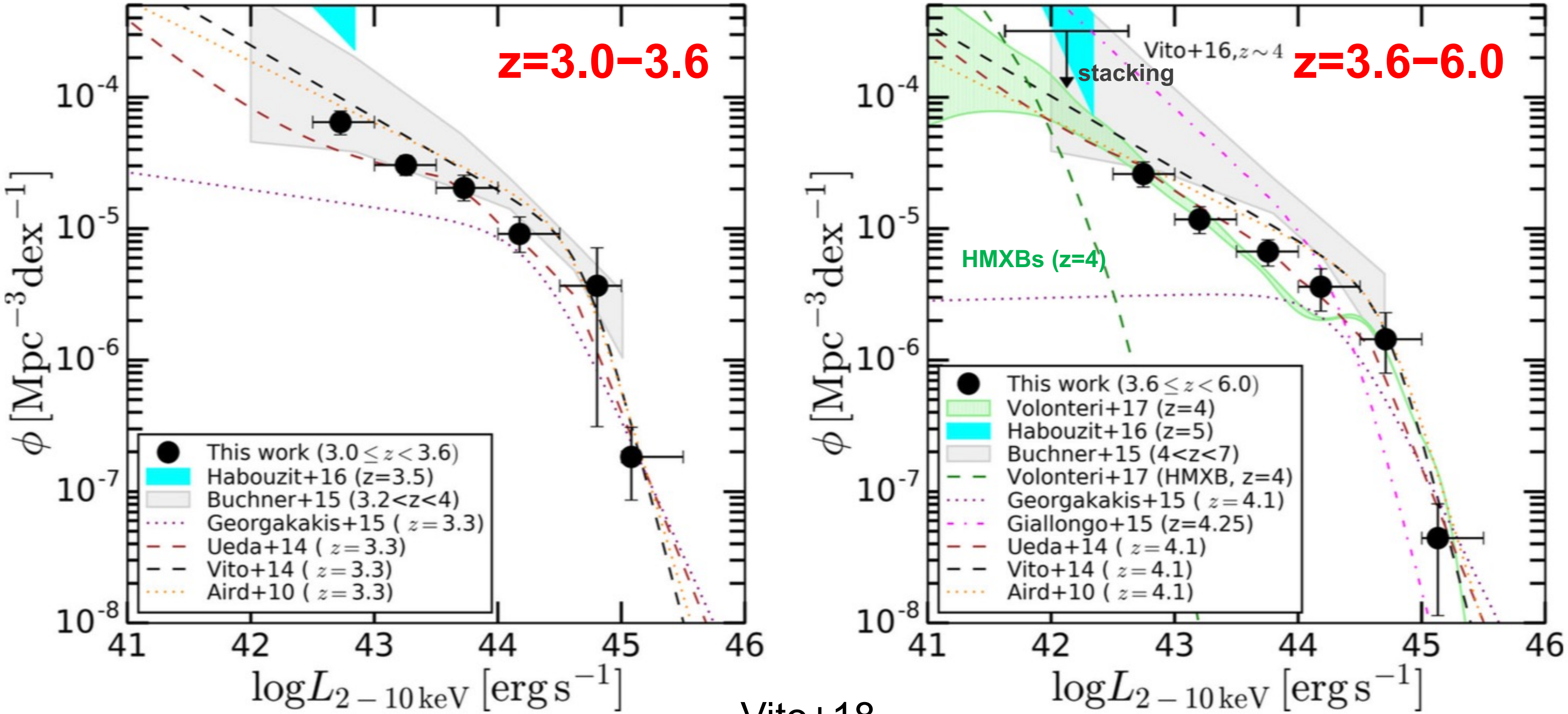
Obscured AGN fraction increases with redshift, especially at high luminosity

Higher merger rate and more gas available for the accreting SMBHs at high redshift; larger covering factors?

The same gas sustaining strong SF at high redshift may be responsible for the obscuration (Gilli+14)

X-ray spectral analysis and stacking are fundamental tools, but we need photons and low background

AGN at z>3. II. Luminosity function



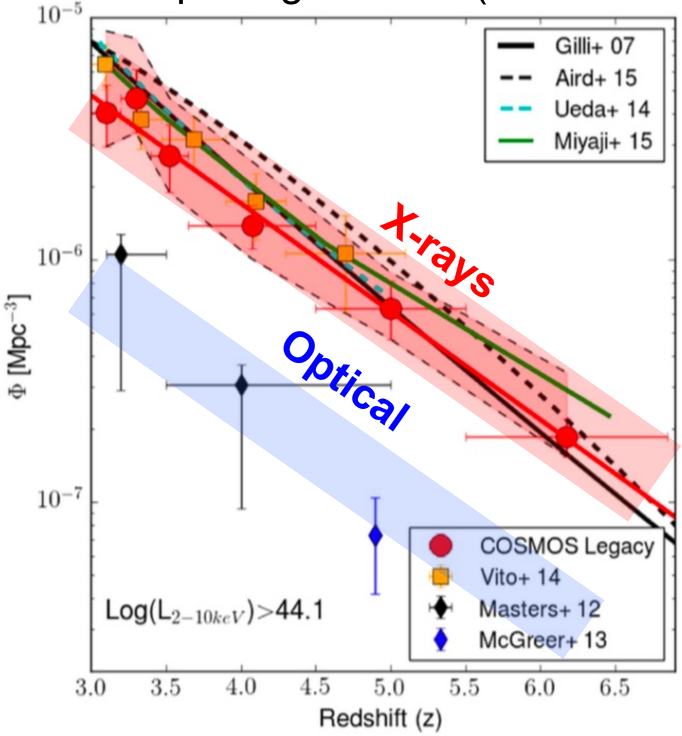
Vito+18

Probably not so steep AGN XLF required at high redshift
(see also Marchesi+16)

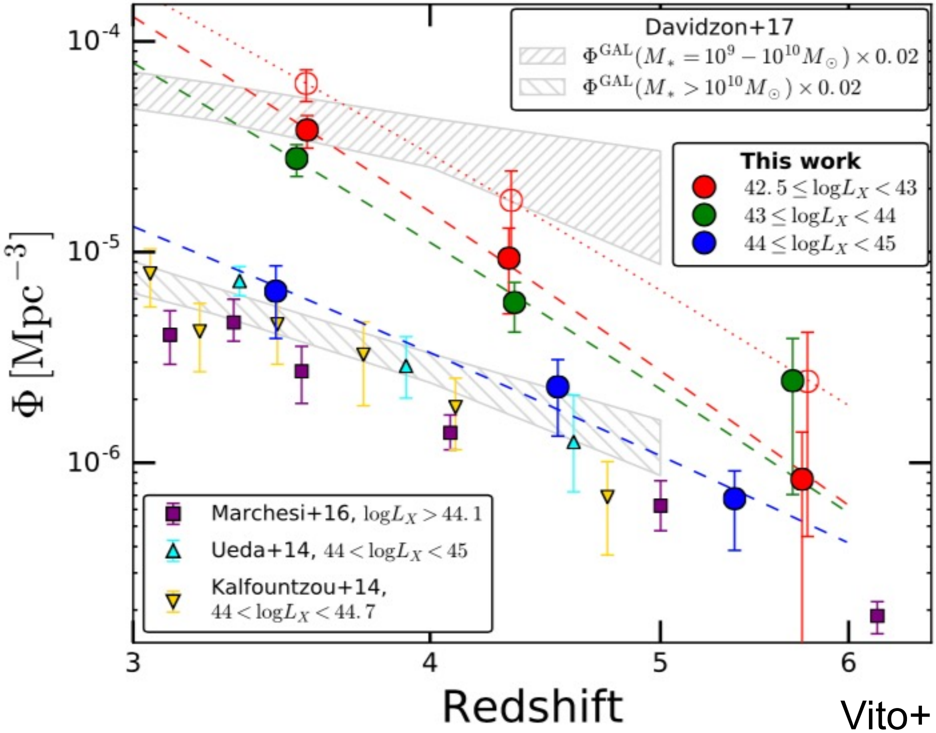
Caveats in considering these results to estimate AGN contribution to reionization: UV to X-ray conversions, Eddington bias, contribution of X-ray binaries at the low luminosities probed by the deepest X-ray fields

AGN at z>3. III. Space density

Decline at high L driven by the evolution of number of massive galaxies?
Hints of steepening at low L (not matched by low-mass gals.): change in accretion parameters?



Marchesi+16
Chandra COSMOS-Legacy
(2.2 deg^2, N=174, 50% spec-z)

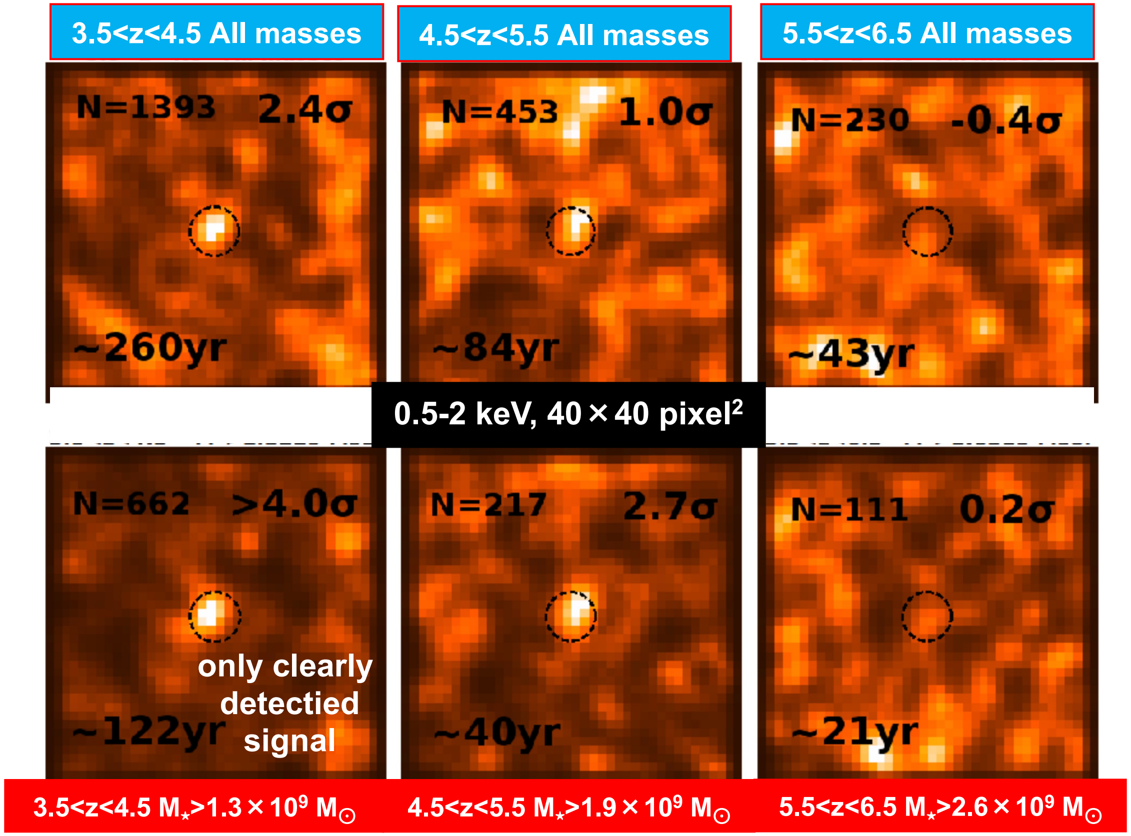


Vito+18
deep fields

[see also Brusa+09, Civano+11, Hiroi+12, Vito+13,14, Kalfountzou+14, Georgakakis+15, […], and recent eROSITA results (few sources so far)]

X-ray surveys trace the bulk of active SMBHs
Space density of high-L AGN declines as (1+z)$^{-6}$, similarly to optical QSOs (McGreer+13)

AGN at z>3. IV. The power of X-ray stacking



3.5<z<4.5 All masses

4.5<z<5.5 All masses

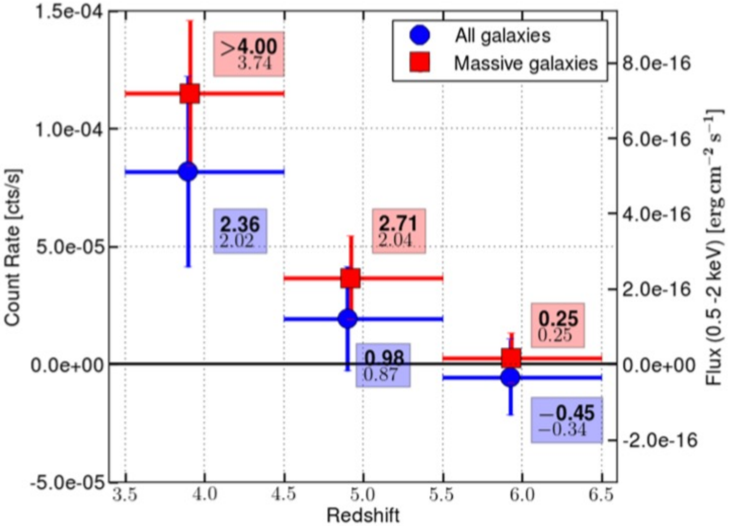
5.5<z<6.5 All masses

0.5-2 keV, 40 × 40 pixel^2

3.5<z<4.5 $M_* > 1.3 \times 10^9\ M_\odot$

4.5<z<5.5 $M_* > 1.9 \times 10^9\ M_\odot$

5.5<z<6.5 $M_* > 2.6 \times 10^9\ M_\odot$



Vito+16

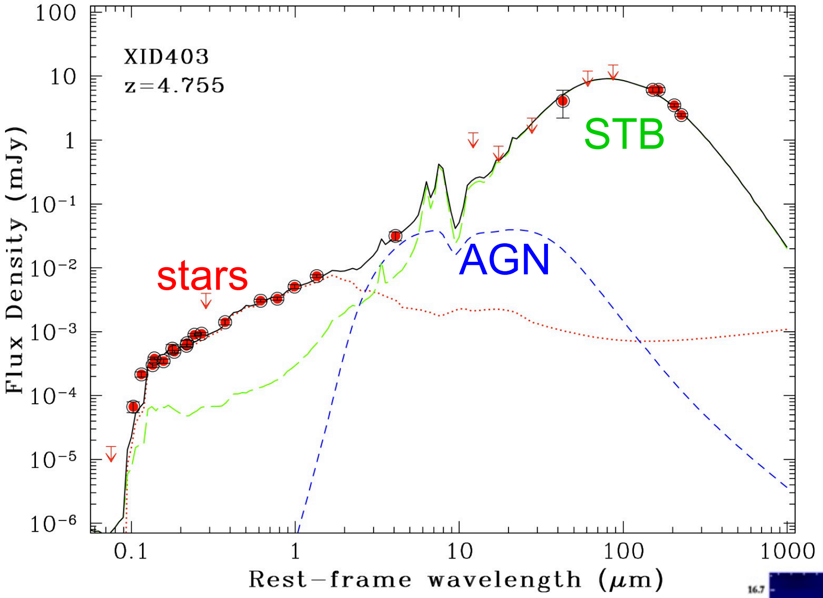
Pushing the X-ray analysis at its extreme (differences wrt. Giallongo and Cappelluti works) – Caveats: optical association, assumed photo-z, stacking tools, Eddington bias

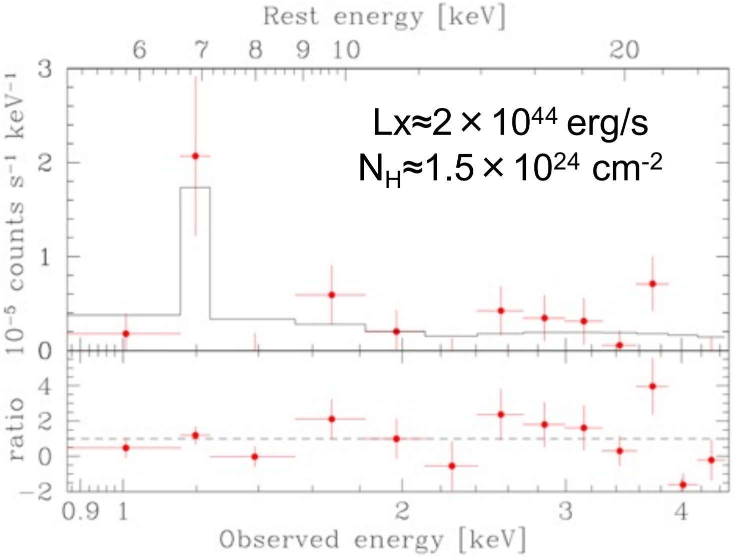
X-ray stacking in the CDF-S (7Ms) at the positions of CANDELS galaxies at z=3.5−6.5 (H<28)

- X-ray emission at the faintest fluxes dominated by processes related to star formation
- Low-mass accretion onto SMBHs in individually X-ray undetected galaxies is negligible compared to BHAD in X-ray selected AGN at high redshift

AGN at z>3. V. Compton-thick obscuration at z=4.75

Facts: high-z galaxies are more compact (Bouwens+04, Oesch+10) and gas-rich (Carilli & Walter 2013)
→ denser ISM responsible for the increasing obscured AGN fraction?

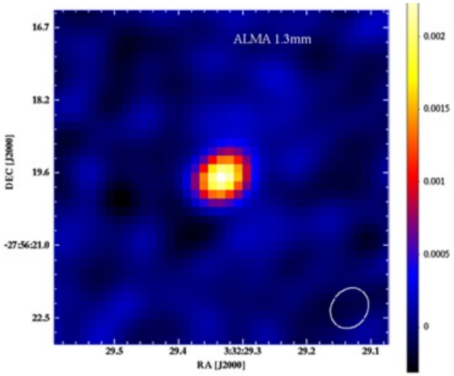




SFR≈1000 $M_\odot$/yr
Σ_{SFR}> 26 $M_\odot$/yr/kpc^2

Compact starburst, possibly responsible for the X-ray obscuration

Progenitor of compact quiescent massive galaxies at z≈3



Gilli et al. 2011, 2014

$R_{half, dust}$=(0.9±0.3)kpc
$M_{dust} \approx 5 \times 10^8$ $M_\odot$ ($T_{dust} \approx 60K$)
$M_{H2+HI} \sim 1.6 \times 10^{10}$ $M_\odot$

see also Coppin+10, Nagao+12, De Breuck+14

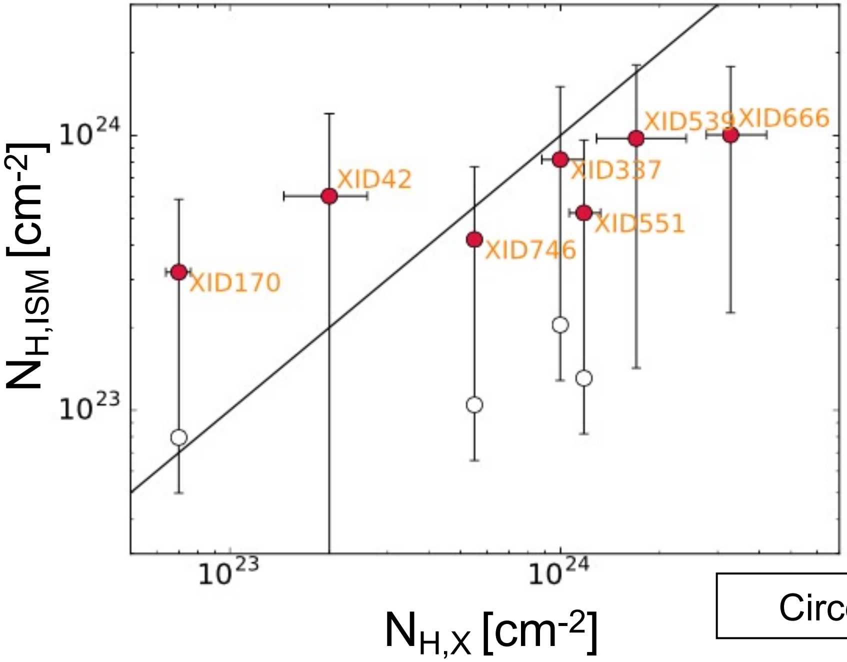
ISM in the host of obscured AGN likely responsible for at least part of the X-ray obscuration

(see Gilli+14, Gallerani+17, Circosta+19, D'Amato+20; see also Buchner+17 for GRB hosts; Trebitsch+19 from the simulation side)

AGN at z>3. VI. Testing obscuration by ISM

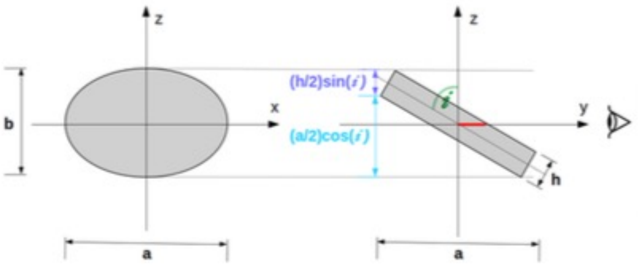
$N_{H,X}$ from X-ray spectra (using appropriate torus models and 7Ms CDF-S spectra)

$N_{H,ISM}$ from Scoville+16 (using $L_{850\mu m}$ → L'_{CO} → M_{H2} + empirical relations and spherical + uniform geometry; sizes from available ALMA and CANDELS data)



Circosta et al. (2019)

Next step: using more realistic (but poorly constrained) geometry, and velocity-map info (rotating disk)

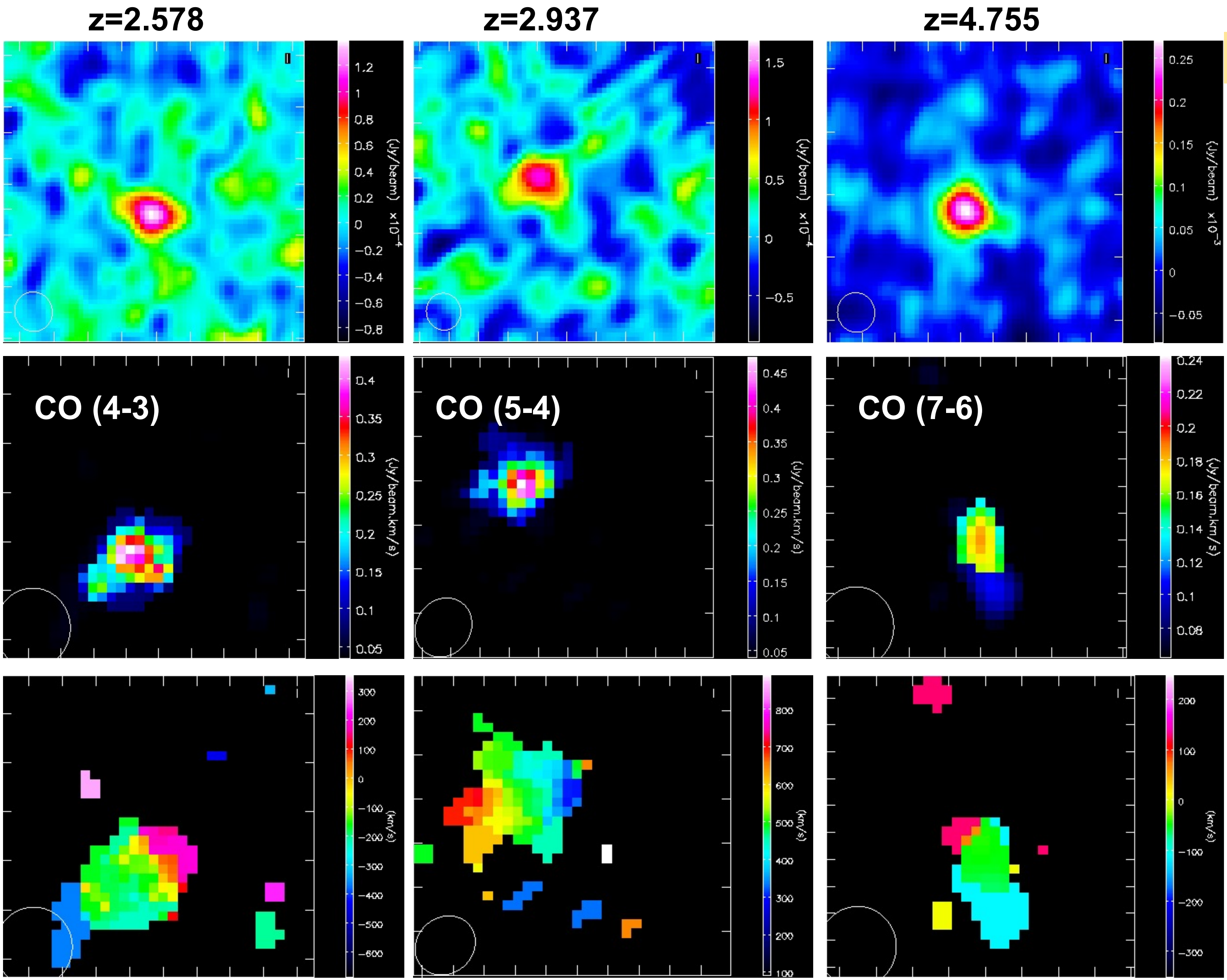


D'Amato et al. (2020)

The dust-enriched gas in the galaxy center can obscure highly accreting BHs (see also Trebitsch+2019) → the host galaxy contributes to the obscuration at least at high z

AGN at z>3. VII. The host of z>2.5 QSOs as seen by ALMA

D'Amato+20



Continuum

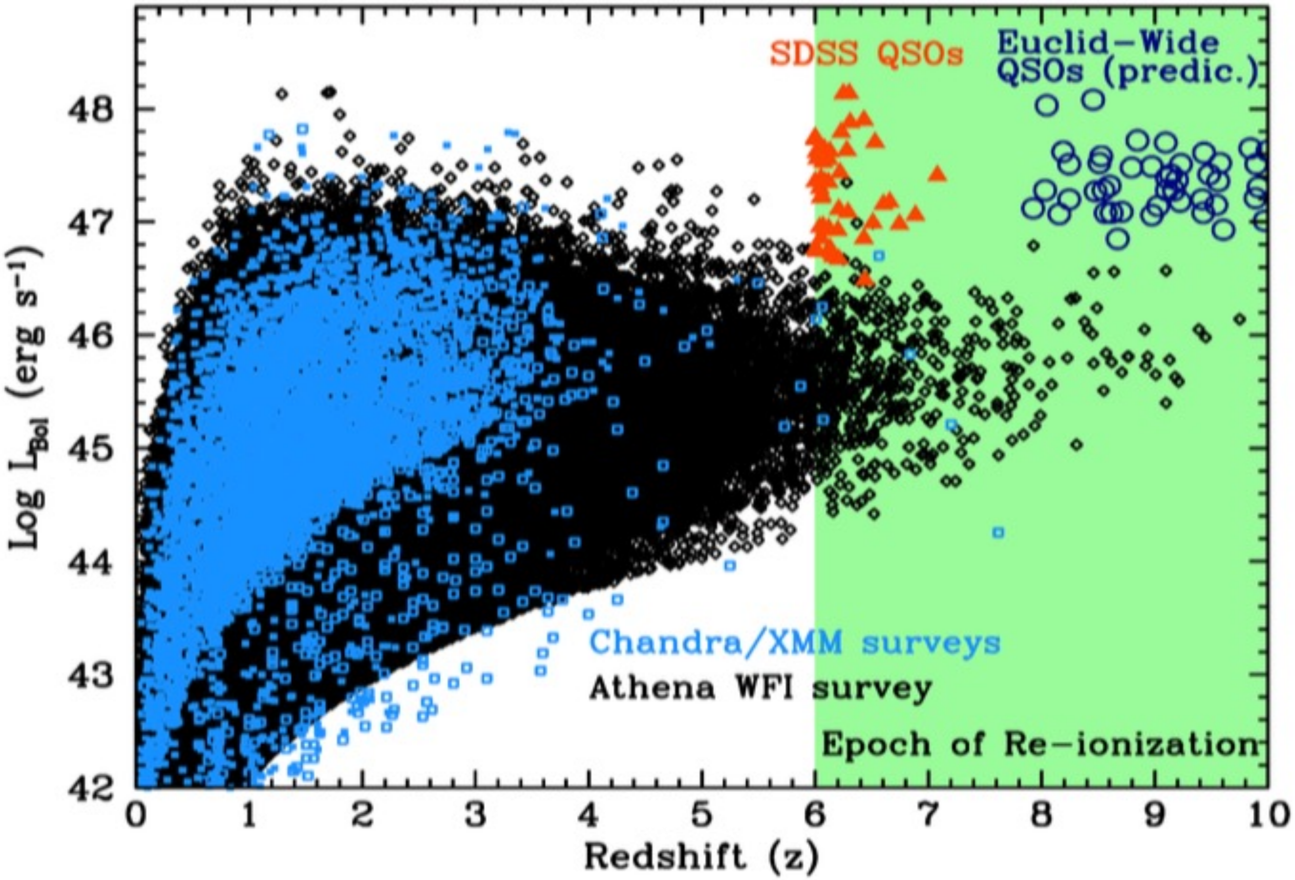
CO
emission

CO
Velocity
M_{H2}~a
few × 10^{10} $M_\odot$
Size~kpc

What’s next:
Hunting BHs at high redshift

What’s next. Hunting BHs at high redshift. I

Athena, eROSITA, LSST, Euclid, JWST… then, hopefully, Lynx

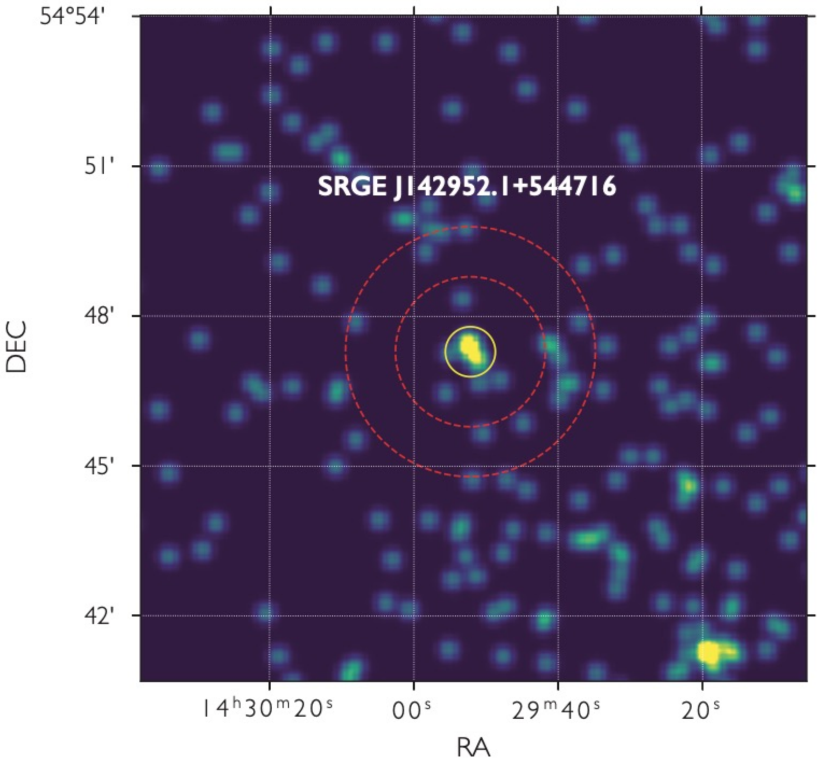


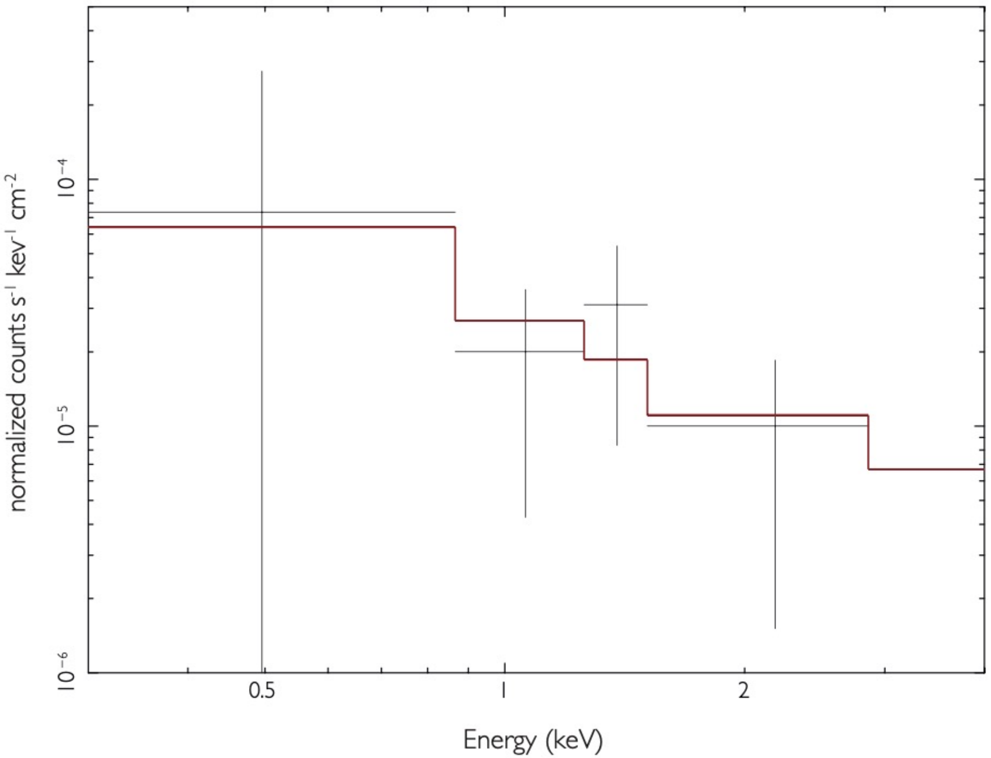
see Aird+13,
Reynes & Comastri 16

Athena (~2032): 400 QSOs at z>6 (half likely obscured)

What’s next. Hunting BHs at high redshift. II

We are already in the future (with the mentioned German/Russian *eROSITA* mission)

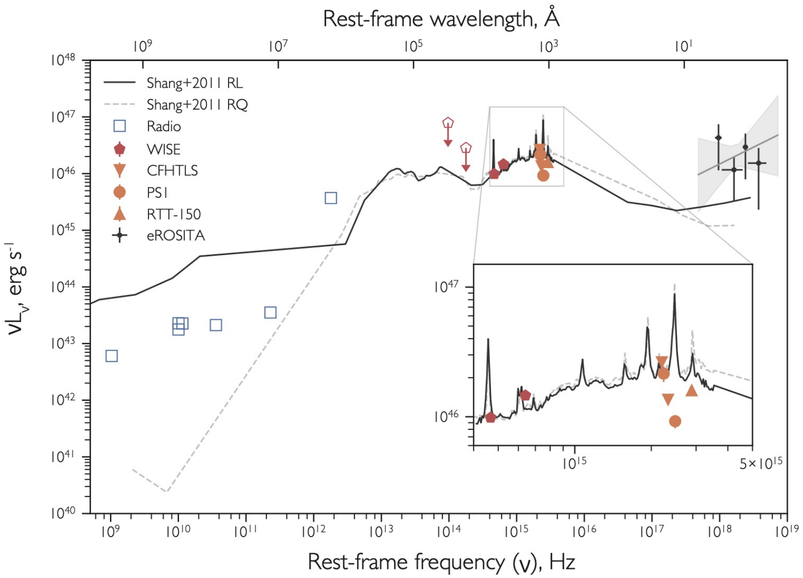


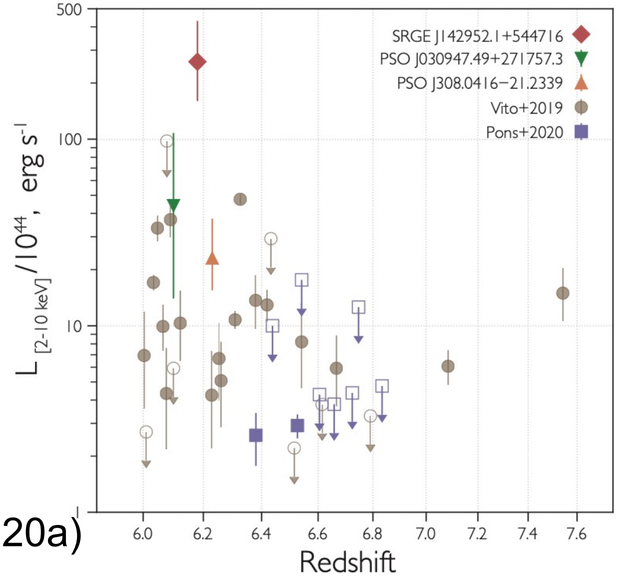


Medvedev et al. (2020a)

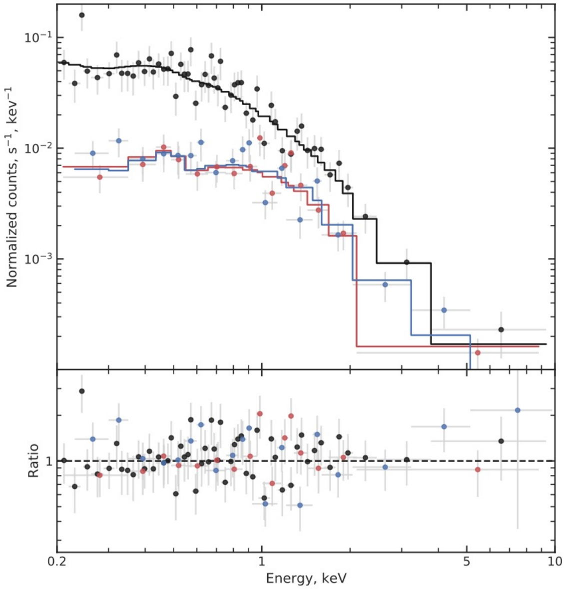
z=6.18, radio loud, L_{BOL}~a few 10^{47} erg/s, ‘enhanced’ X-ray due to IC/CMB of jet electrons?

What’s next. Hunting BHs at high redshift. III

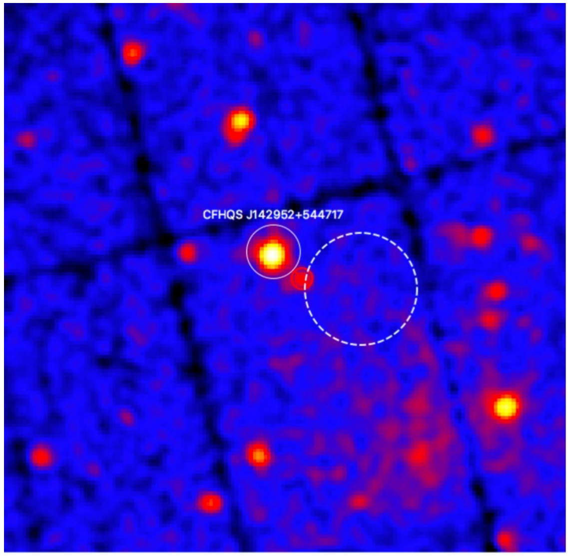




Medvedev et al. (2020a)

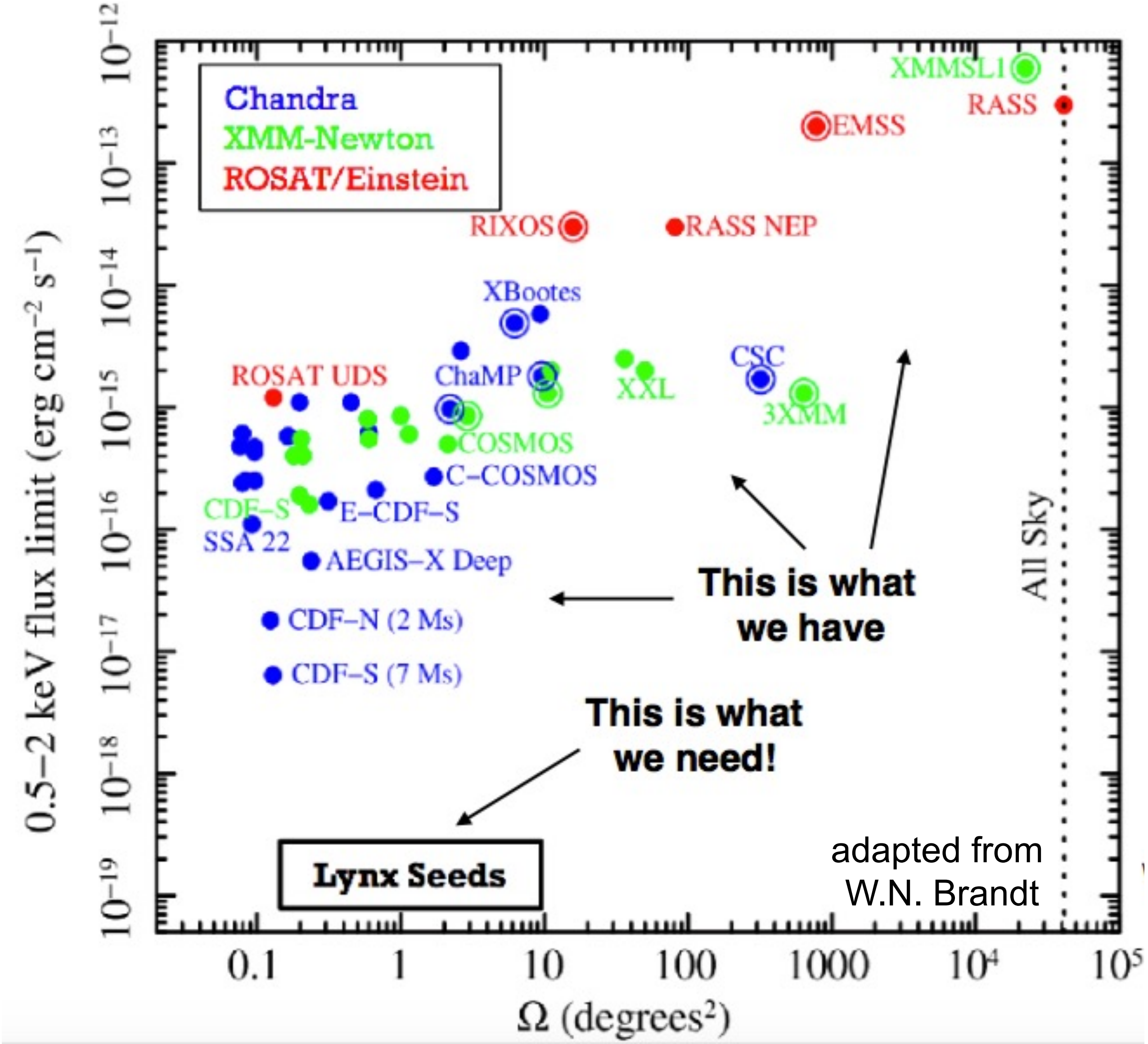


Followed-up by
XMM-*Newton*
(up to ~70 keV
r.f.)



Medvedev et al. (2020b)

What's next. Hunting BHs at high redshift. IV



This is what we have

This is what we need!

adapted from W.N. Brandt

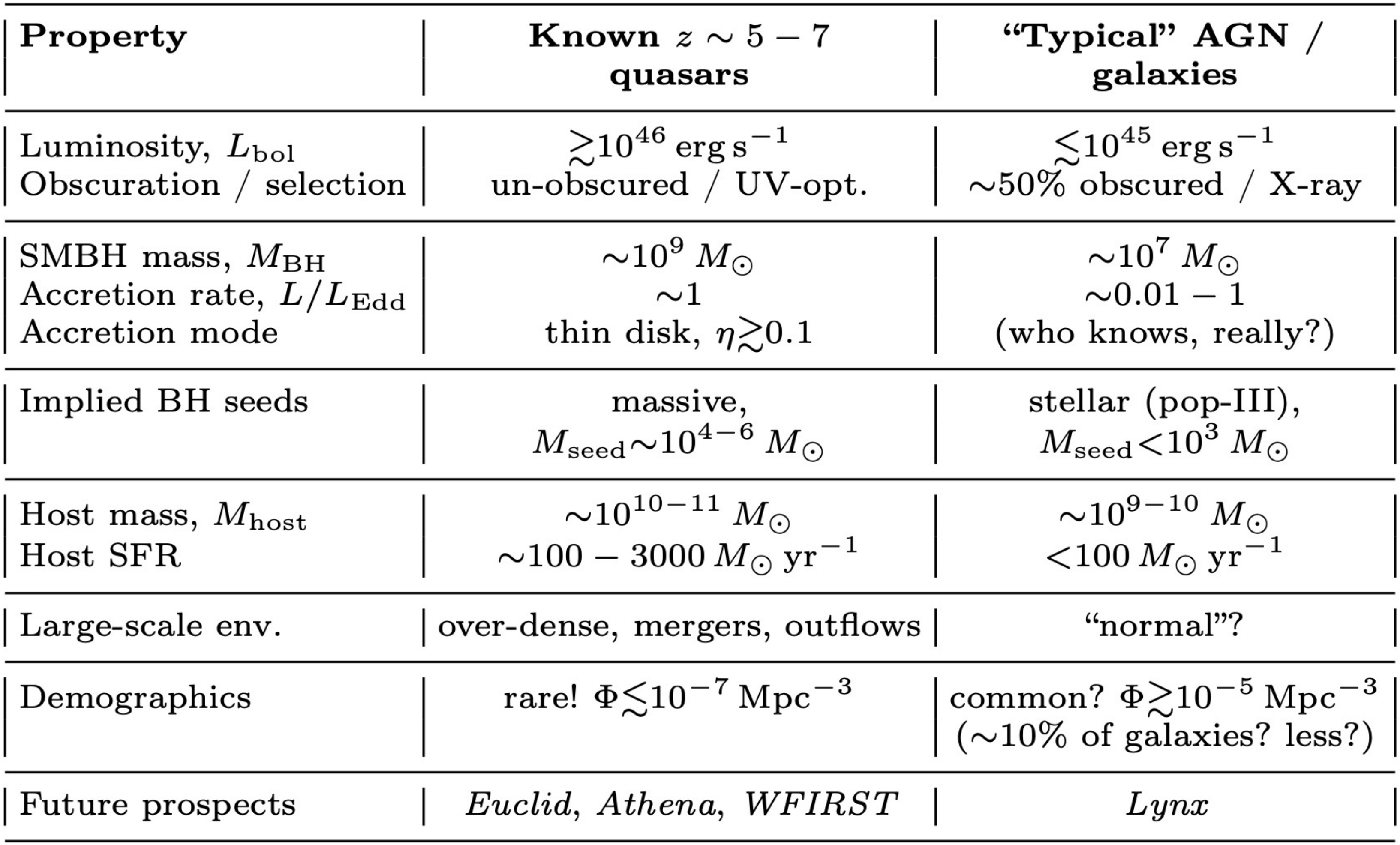
Lynx:
down to Lbol≈4 × 10^{42} erg/s at z=10 (assuming kbol=10)

Probing faint/obscured accretion at z>6

needs to go down to ≈10^5 $M_\odot$ at high z (but contamination from galaxies and 4Ms exposures needed, besides near-IR identifications)

What’s next. Hunting BHs at high redshift. V

Known properties and expectations



Property	**Known $z \sim 5-7$ quasars**	**“Typical” AGN / galaxies**
Luminosity, $L_{\rm bol}$ Obscuration / selection	$\gtrsim 10^{46}$ erg s^{-1} un-obscured / UV-opt.	$\lesssim 10^{45}$ erg s^{-1} $\sim$50% obscured / X-ray
SMBH mass, $M_{\rm BH}$ Accretion rate, $L/L_{\rm Edd}$ Accretion mode	$\sim 10^9\ M_\odot$ ~ 1 thin disk, $\eta \gtrsim 0.1$	$\sim 10^7\ M_\odot$ $\sim 0.01-1$ (who knows, really?)
Implied BH seeds	massive, $M_{\rm seed} \sim 10^{4-6}\ M_\odot$	stellar (pop-III), $M_{\rm seed} < 10^3\ M_\odot$
Host mass, $M_{\rm host}$ Host SFR	$\sim 10^{10-11}\ M_\odot$ $\sim 100-3000\ M_\odot$ yr^{-1}	$\sim 10^{9-10}\ M_\odot$ $<100\ M_\odot$ yr^{-1}
Large-scale env.	over-dense, mergers, outflows	“normal”?
Demographics	rare! $\Phi \lesssim 10^{-7}$ Mpc^{-3}	common? $\Phi \gtrsim 10^{-5}$ Mpc^{-3} ($\sim$10% of galaxies? less?)
Future prospects	*Euclid*, *Athena*, *WFIRST*	*Lynx*

Trakhtenbrot+20

On the realm of high-redshift AGN: a summary

- ➢ Where do we stand?
- ☐ Detection and identification of z≈6 QSOs is challenging because they are rare
- ☐ Luminous unobscured QSO properties currently known: SED, X-ray emission, metallicity and M_{BH} similar to lower-z QSOs
- ☐ Still missing the heavily obscured AGN at the highest redshift. Deep X-ray stacking limits the contribution of accretion in low-mass galaxies. Huge discovery field for next-generation facilities (but SHELLQ is promising)
- ☐ ALMA and NOEMA fundamental to place constraints to neutral/molecular gas, and the occurrence of feedback/outflows. Role of molecular gas in obscuration
- ➢ What are the progenitors (seeds) of high-redshift AGN? Where and when did they form? How z=6 SMBH preceded galaxy formation?
- ☐ We need large number of AGN to constrain models (beyond degeneracies) and physics at high redshift, and good photon statistics to characterize them

Discovery space for z>5−6 AGN and QSOs is huge