Active Galactic Nuclei – V

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"

Outiline

- 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

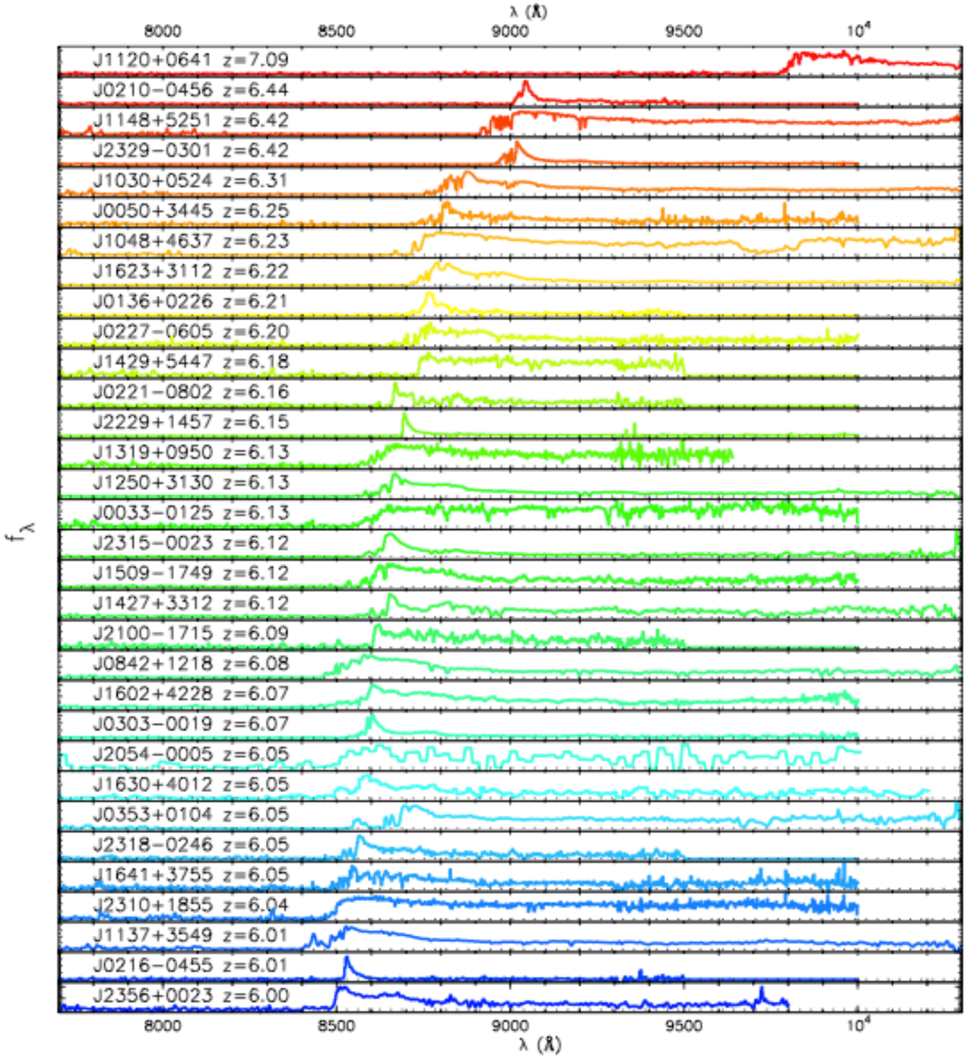
- Obscured AGN at z>3: insights from X-ray surveys. AGN evolution. Analysis of AGN host galaxies from ALMA

  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



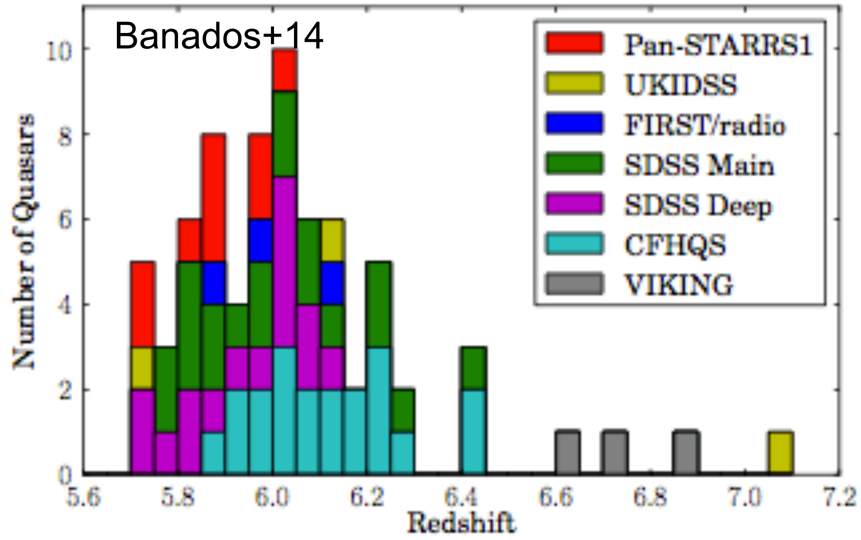
Fan+12

259 QSOs at z>5.5 (145 at z>6, 21 at z>6.5)
(SDSS, CFHQS, Pan-STARRS1, DES, UKIDSS, VISTA-Viking, HSC) - (Fan+00−06; Jiang+08,09; Willott+07,09,10; Banados+14-16; Mortlock+11; Venemans+13, 15, Matsuoka+16,18)

SELECTION: O/NIR, 2 radio (McGreer+06, Zeimann+11)**, 0 X-ray**
About 1/10 with X-ray coverage, 19 X-ray det.

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

Faint end of the LF still to be achieved



continuous update of these numbers
Inayoshi+20, ARAA: 197 at z≥6, 6 at z>7

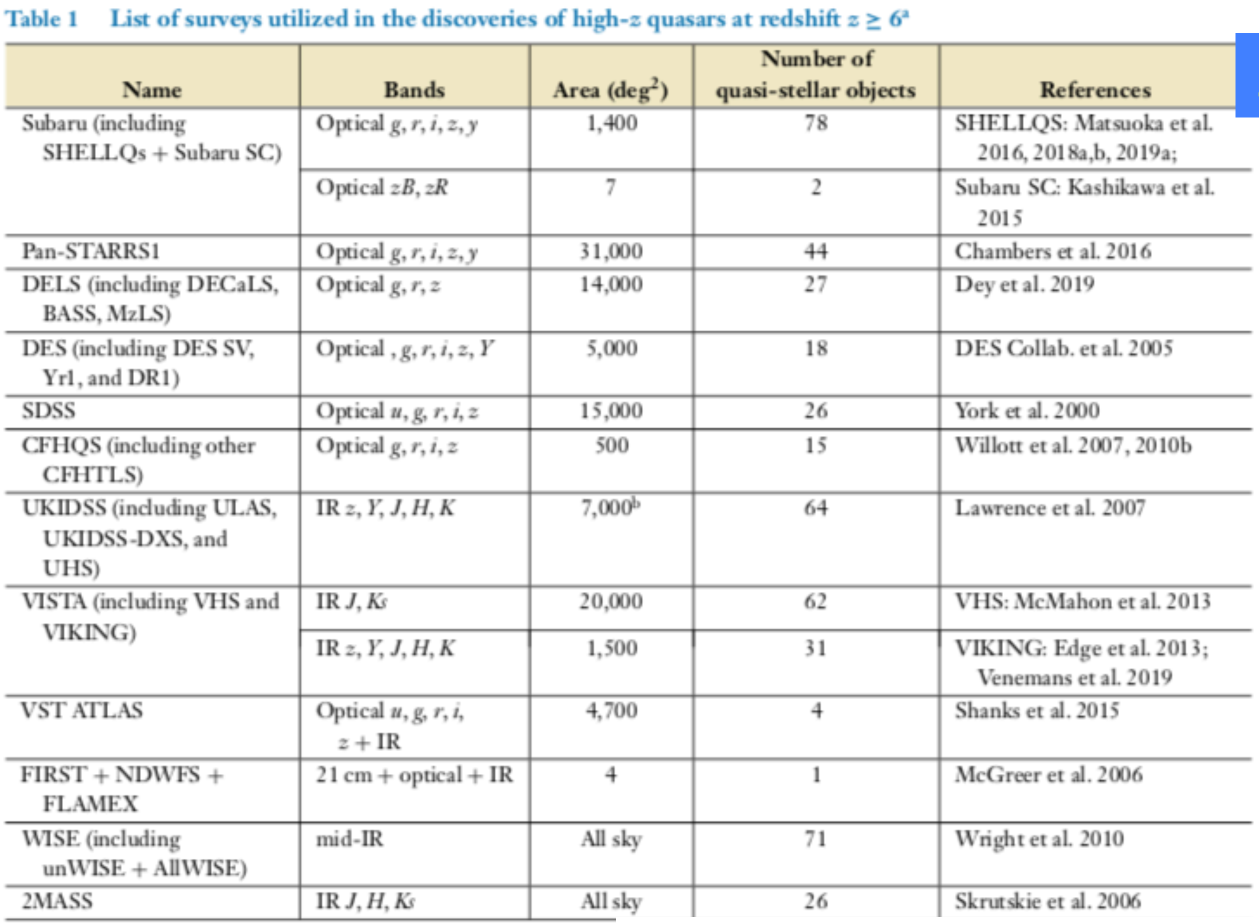


Table 1 List of surveys utilized in the discoveries of high-z quasars at redshift $z \geq 6$[a]

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

z≥6 quasar-finder surveys

Inayoshi+20 review

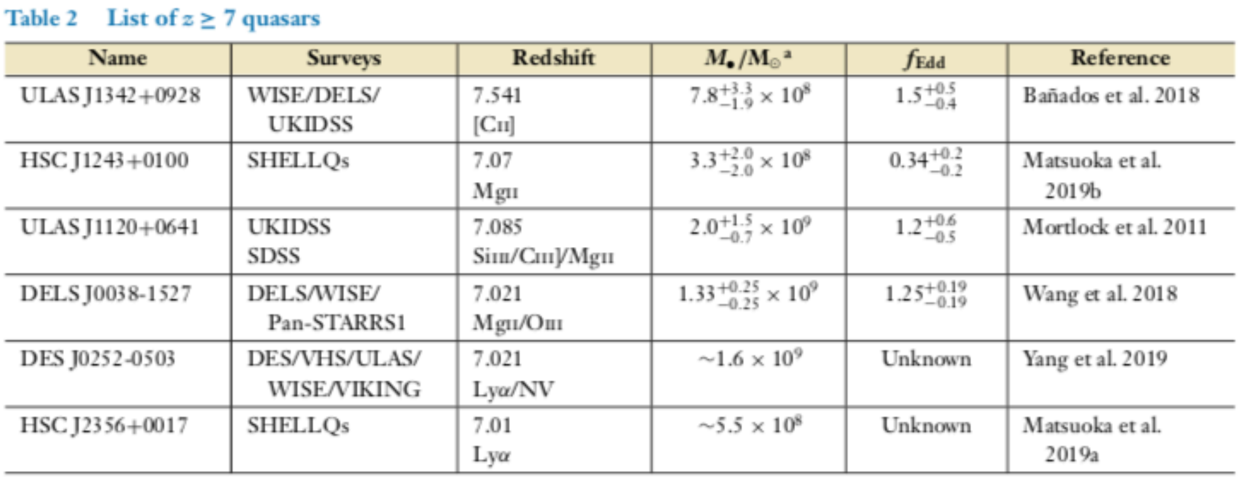


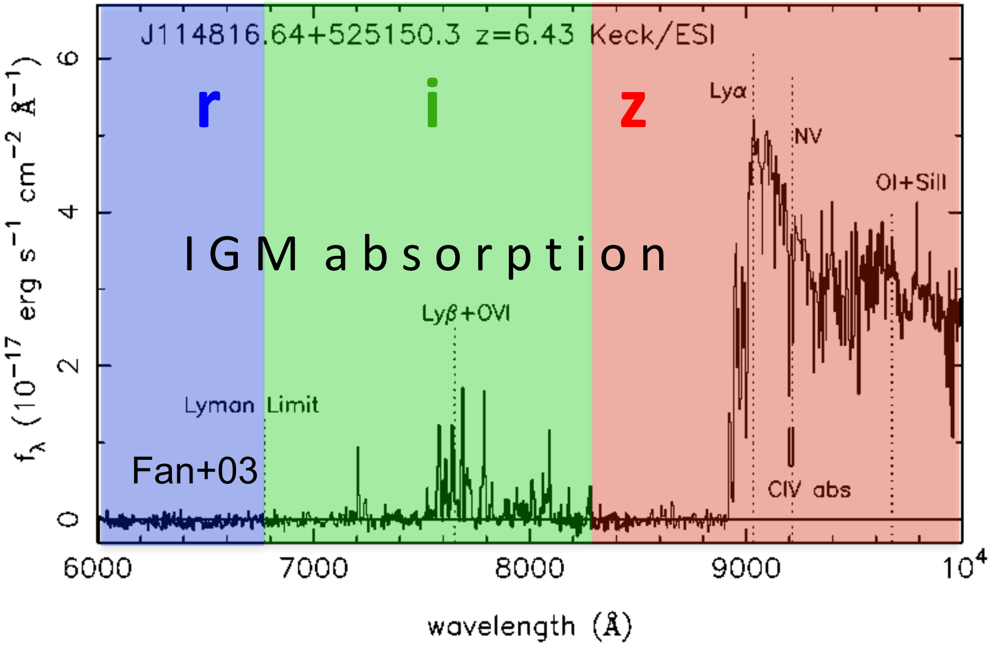
Table 2 List of $z \geq 7$ quasars

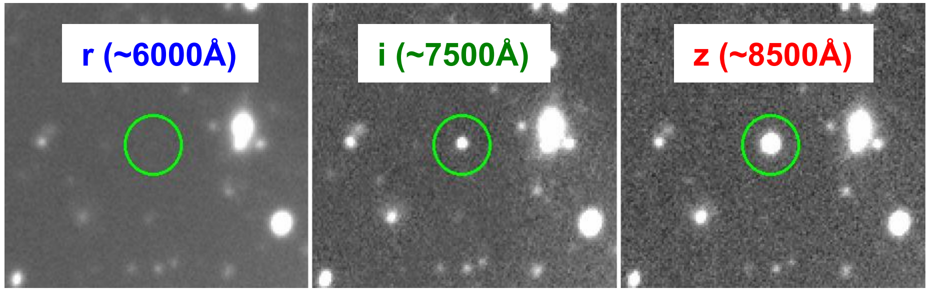
Name	Surveys	Redshift	$M_\bullet/M_\odot$[a]	$f_{\rm Edd}$	Reference
ULAS J1342+0928	WISE/DELS/ UKIDSS	7.541 [CII]	$7.8^{+3.3}_{-1.9} \times 10^8$	$1.5^{+0.5}_{-0.4}$	Bañados et al. 2018
HSC J1243+0100	SHELLQs	7.07 MgII	$3.3^{+2.0}_{-2.0} \times 10^8$	$0.34^{+0.2}_{-0.2}$	Matsuoka et al. 2019b
ULAS J1120+0641	UKIDSS SDSS	7.085 SiIII/CIII]/MgII	$2.0^{+1.5}_{-0.7} \times 10^9$	$1.2^{+0.6}_{-0.5}$	Mortlock et al. 2011
DELS J0038-1527	DELS/WISE/ Pan-STARRS1	7.021 MgII/OIII	$1.33^{+0.25}_{-0.25} \times 10^9$	$1.25^{+0.19}_{-0.19}$	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

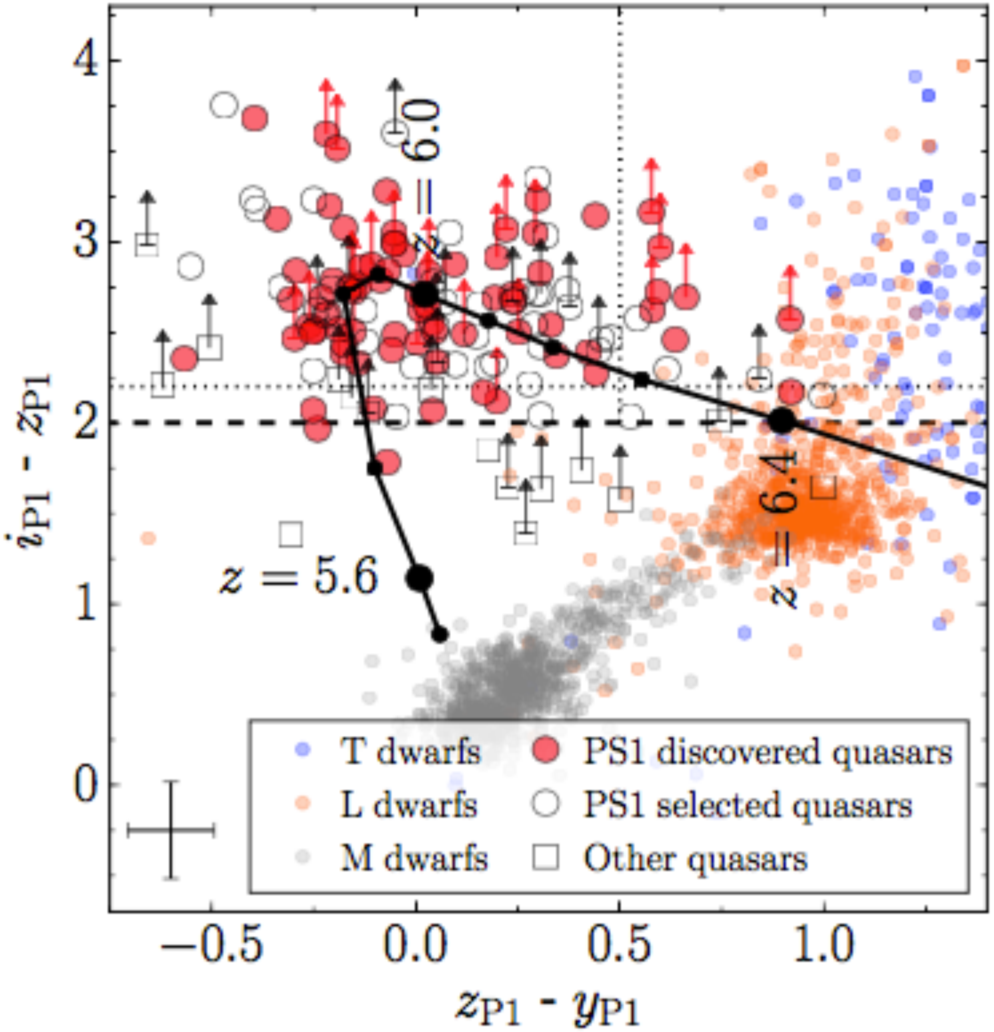
Where do we stand? II. QSO selection at z~6

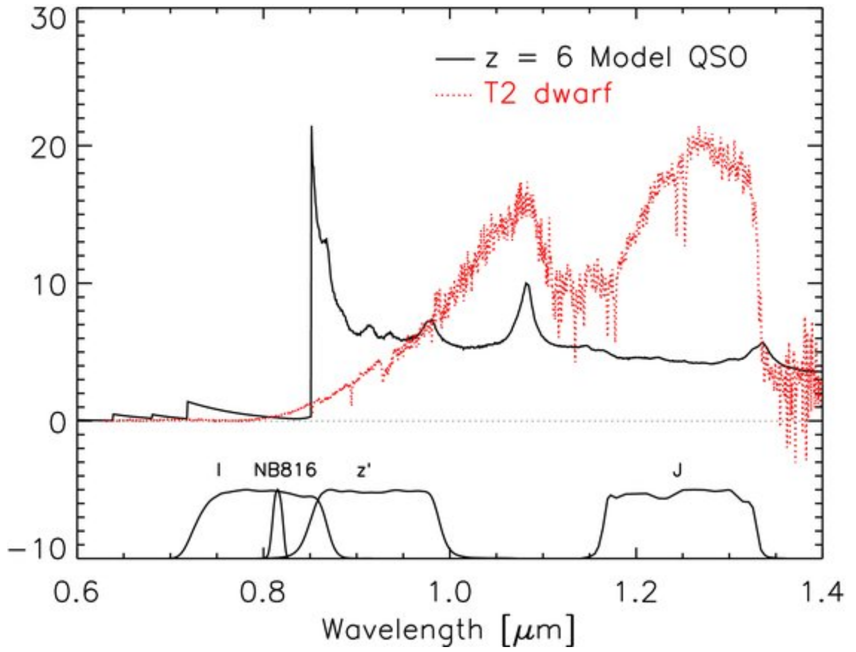
LBC/LBT color (*r,i,z*) image
of SDSS J1148 at z=6.4





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

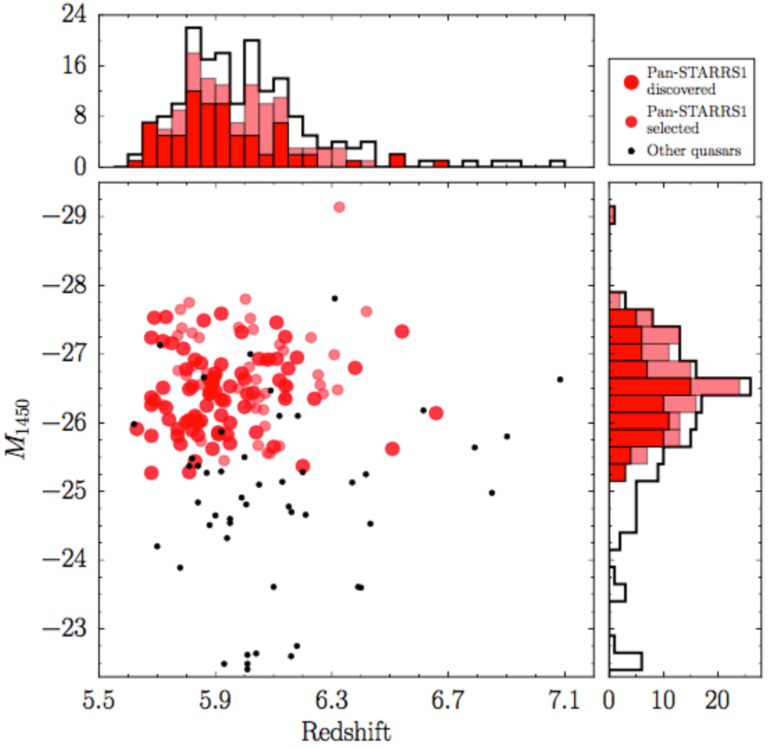


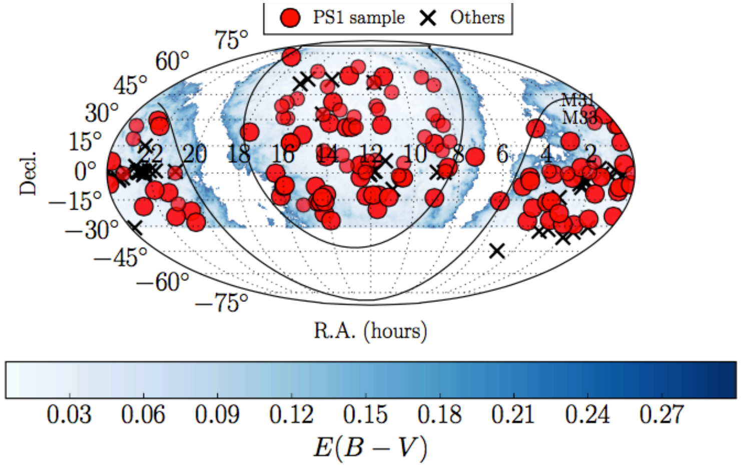


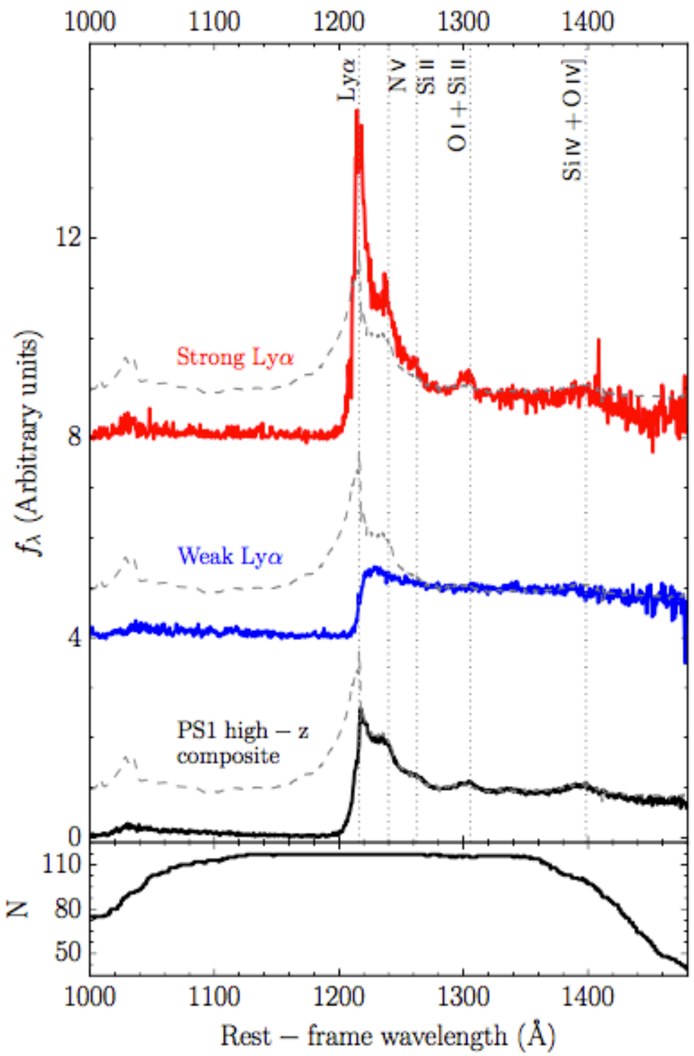
Banados+16

- 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

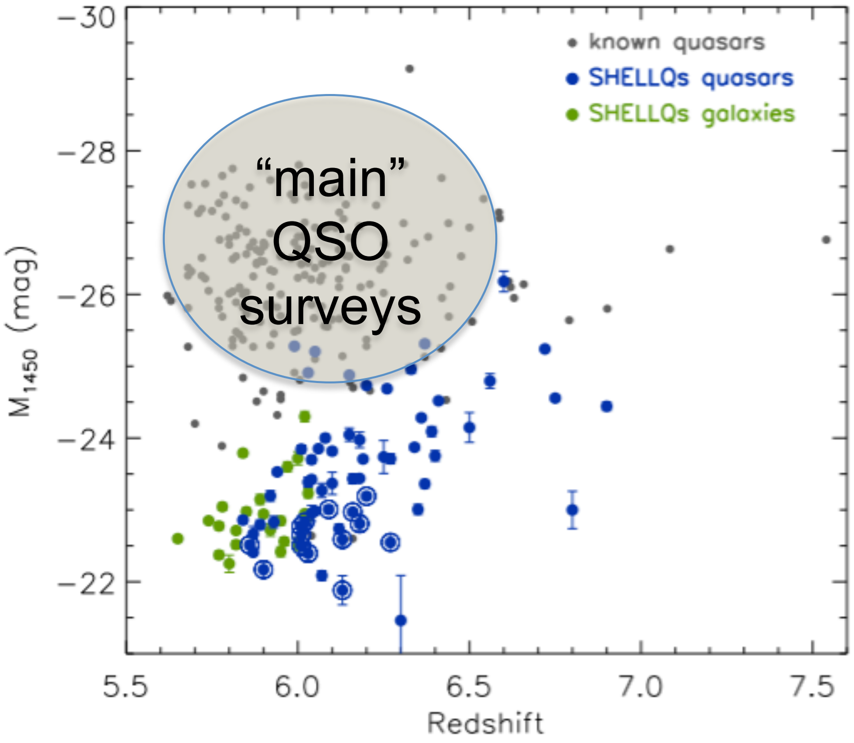
WIDE and DEEP approach

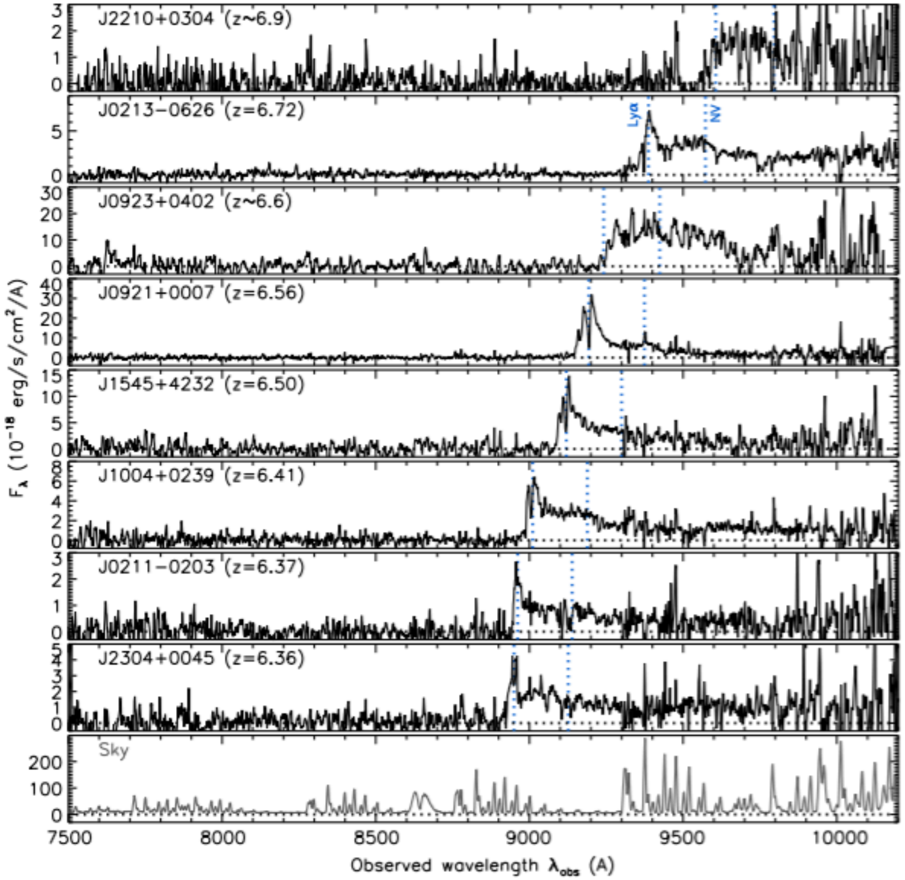
(at the end: 1400 deg^2, g~26.5, y~24.5)

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, …)

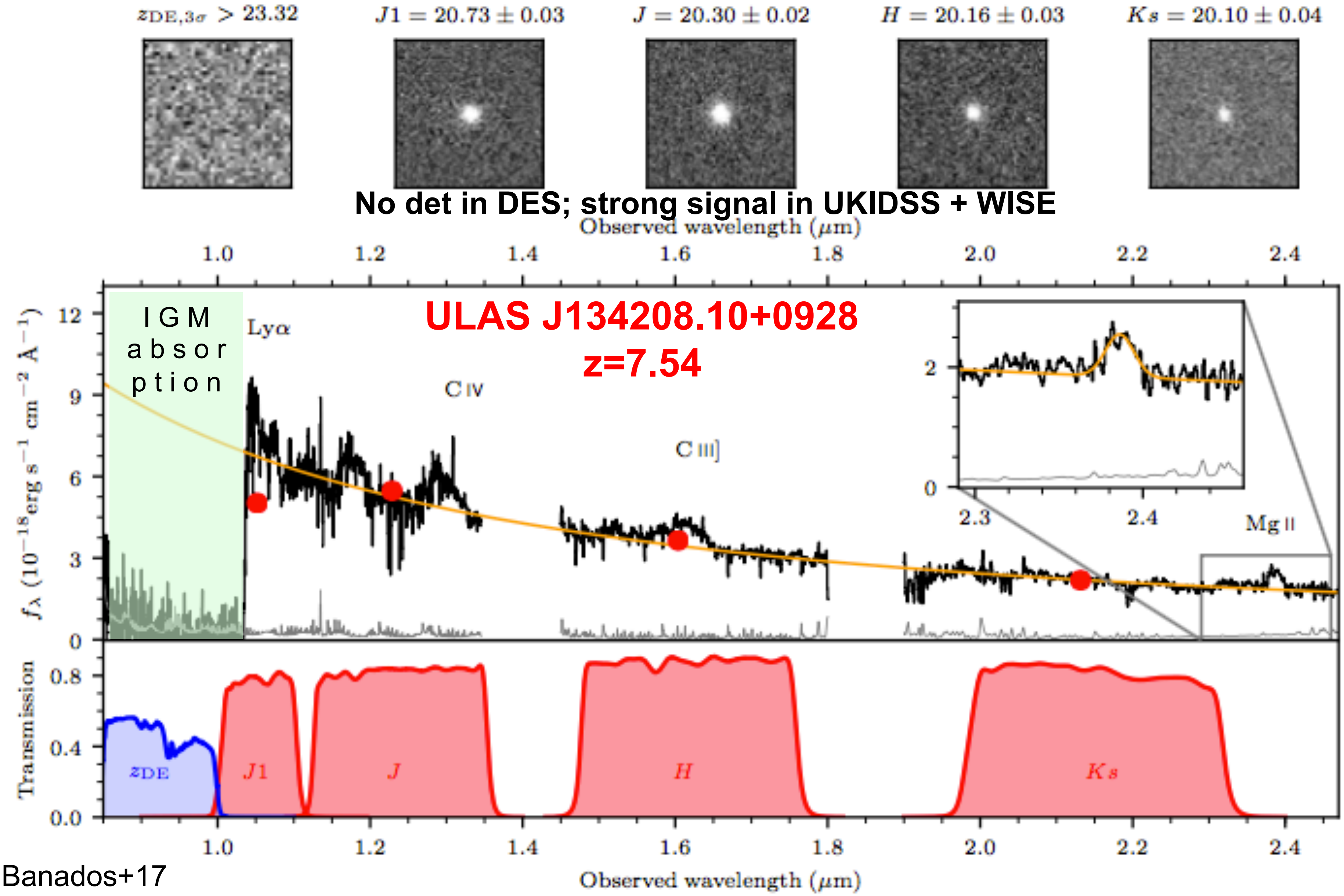




Matsuoka+18

Possibility that obscured AGN hide in bright LBGs

Where do we stand? V. The highest-redshift QSO



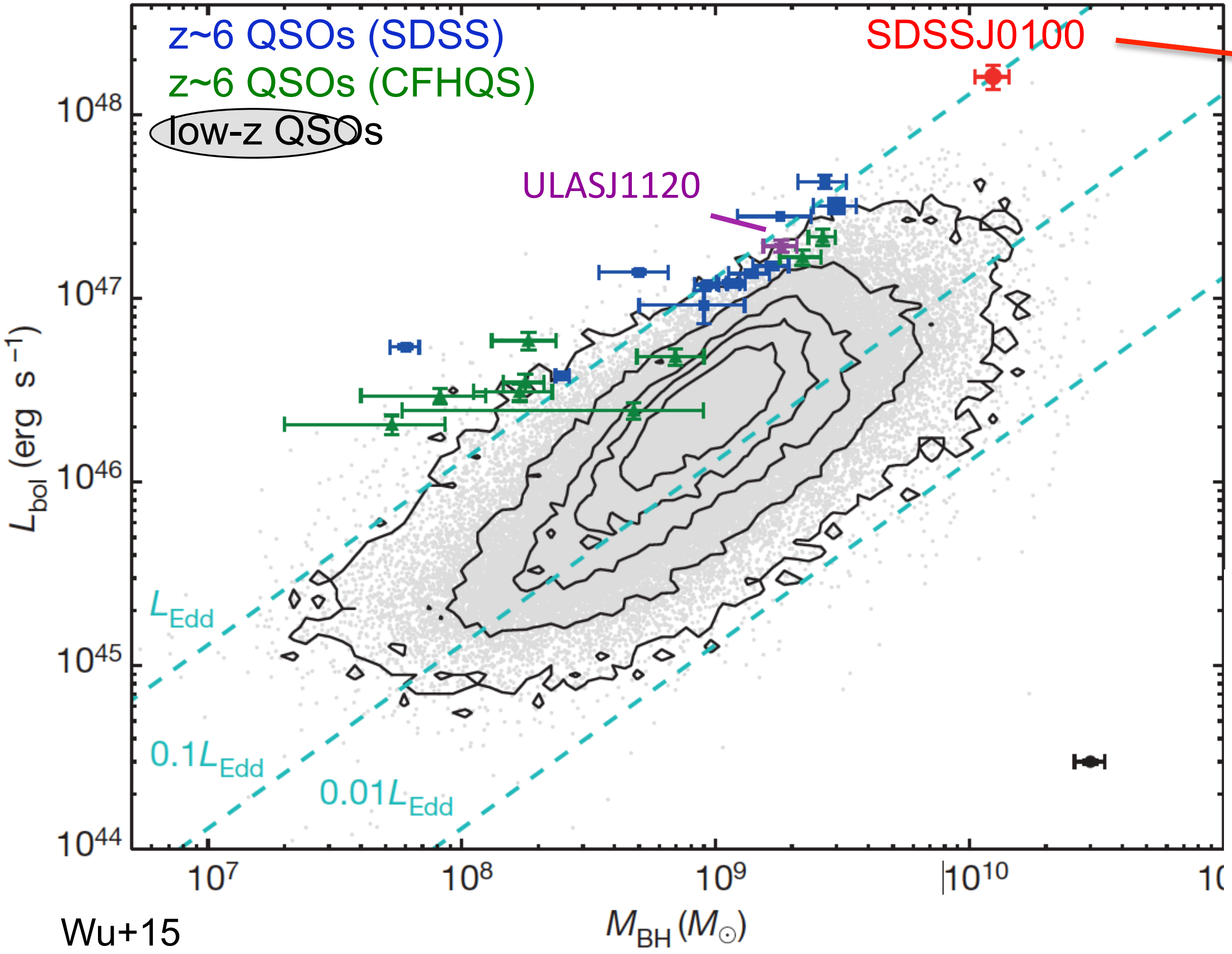
No det in DES; strong signal in UKIDSS + WISE

IGM absorption

ULAS J134208.10+0928
z=7.54

Banados+17

Where do we stand? VI. They are massive

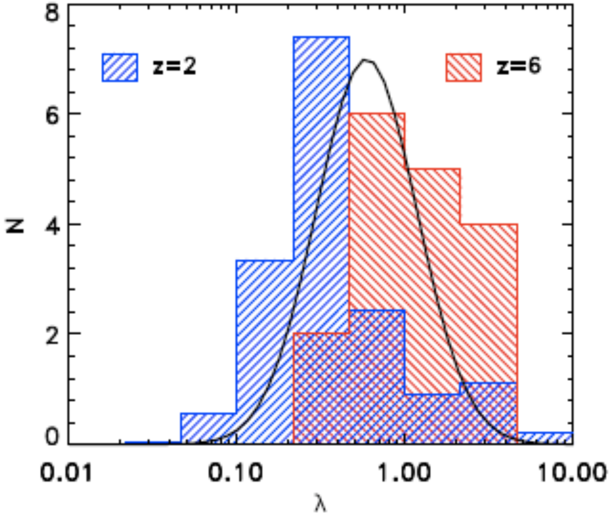


Wu+15

The most massive QSO discovered so far (z=6.30) lensed? a possibility

$M_{BH} \approx 10^8 - 10^{10}\ M_{\odot}$
$L_{bol} \approx L_{Edd} > 10^{46}$ erg/s

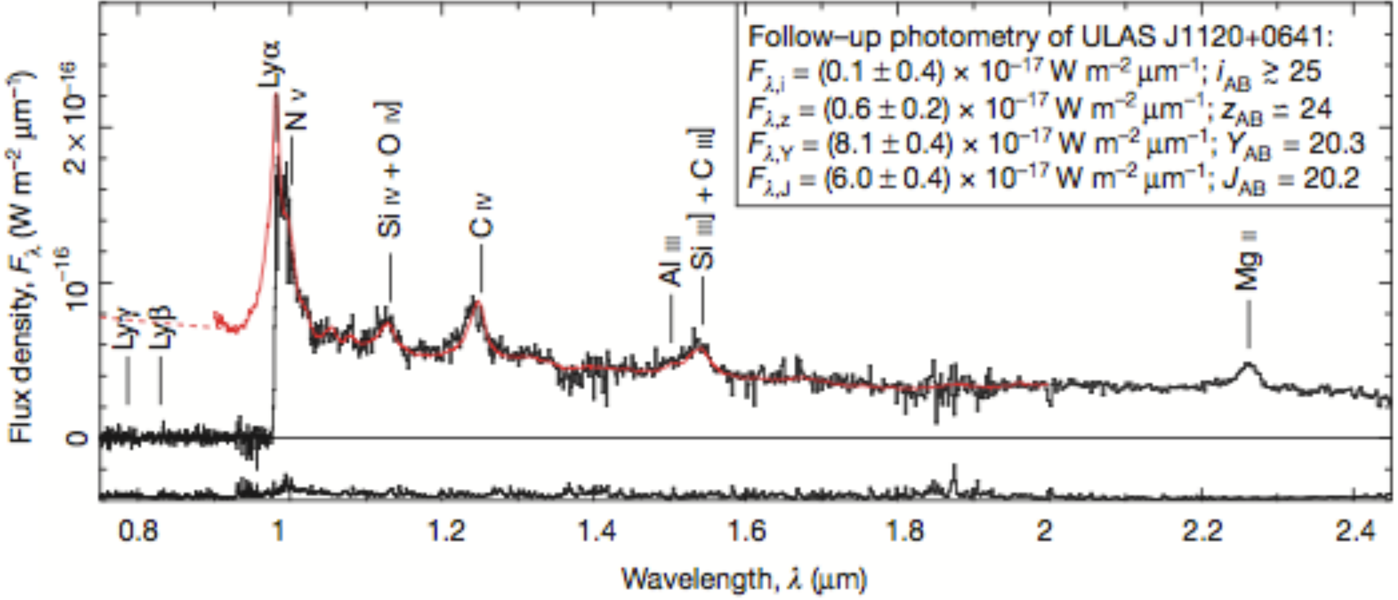
They are emitting close to the Eddington ratio



Willott+10

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

$M_{1450}=-26.6$
$M_{BH}=2.4\times10^9\ M_\odot$
$L_{bol}\approx2.4\times10^{47}$ erg/s

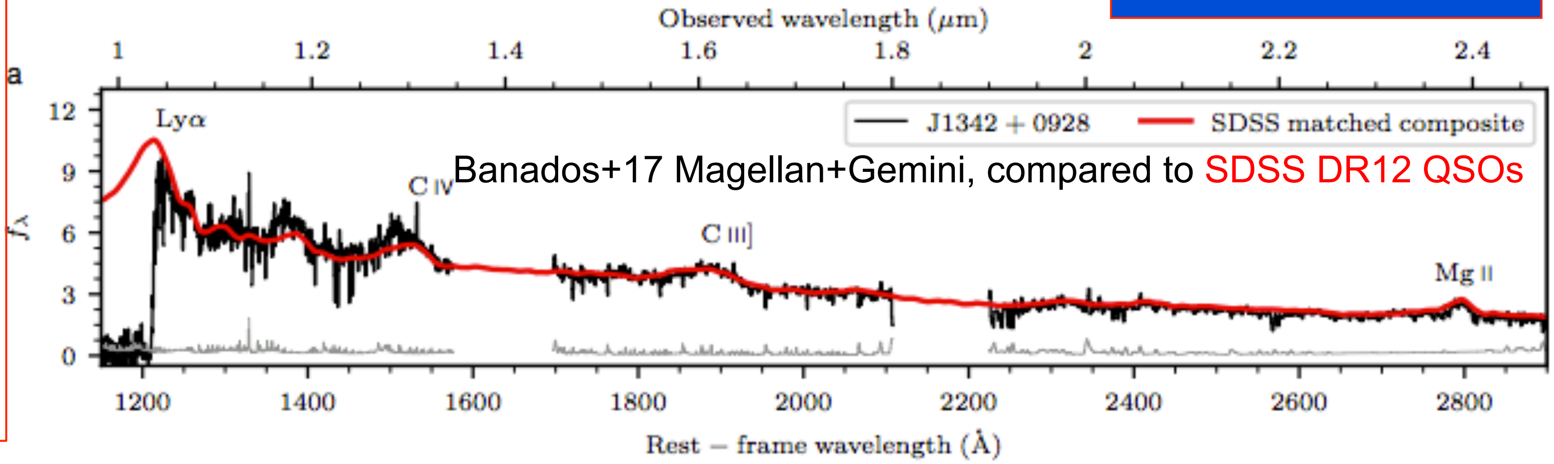
$M_{1450}=-26.8$
$M_{BH}=8.0\times10^8\ M_\odot$
$L_{bol}\approx1.5\times10^{47}$ erg/s

ULAS J1342 z=7.54

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

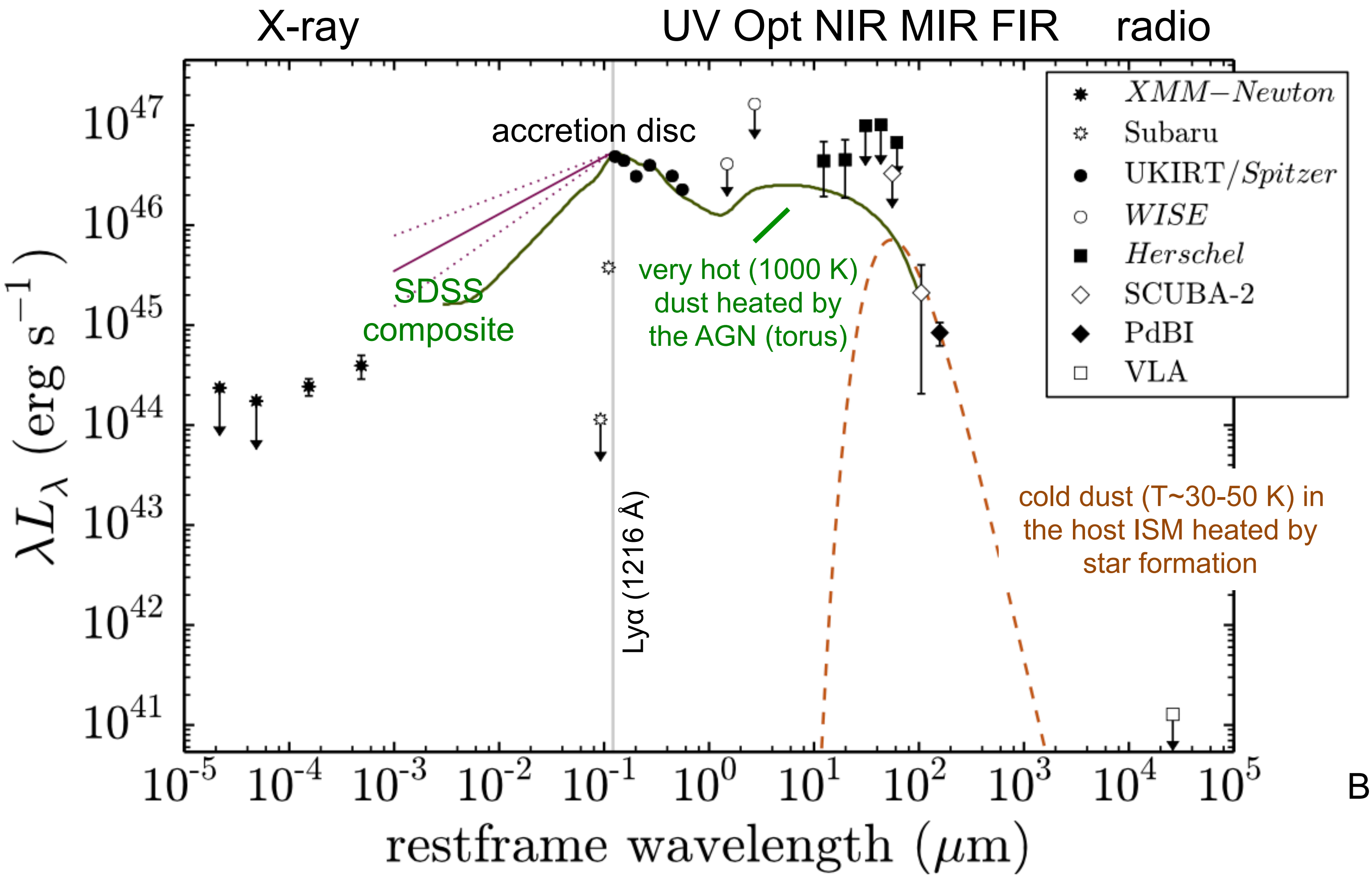
→ the nuclear regions are metal rich

→ 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

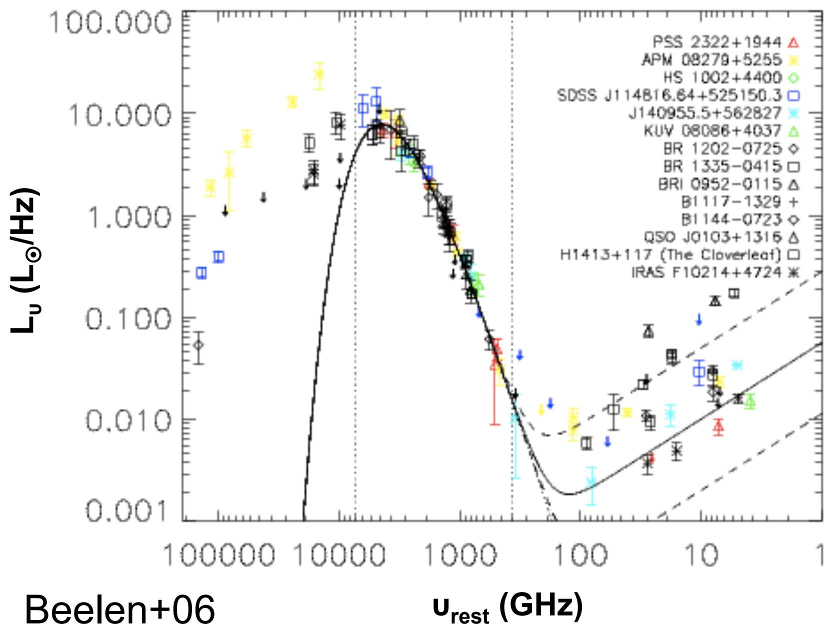


Barnett+15

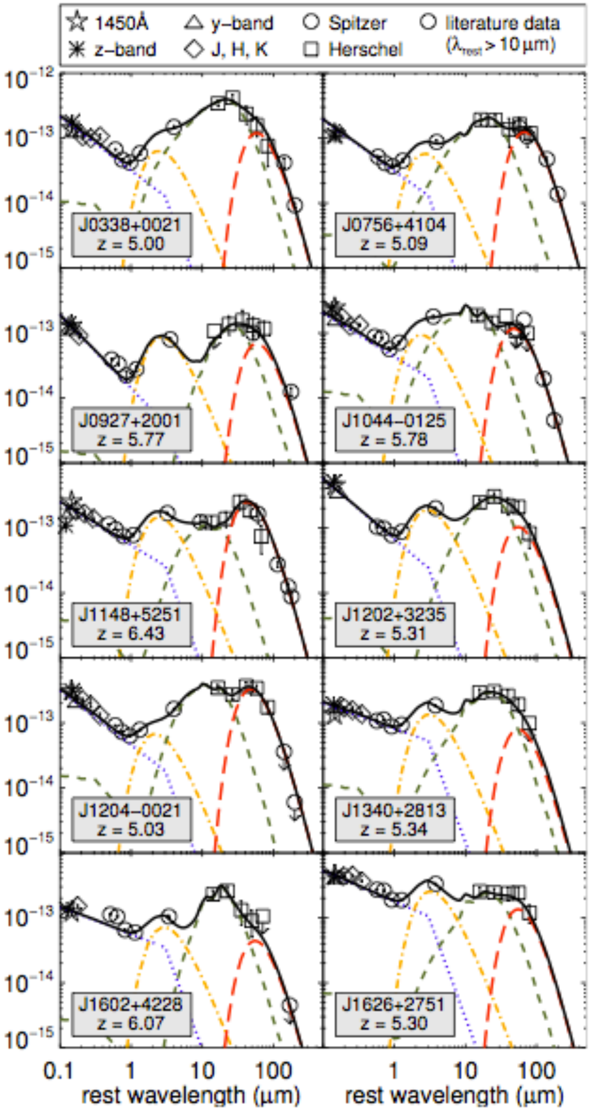
SEDs are similar to those of lower redshift QSOs
(including the presence of hot dust, likely associated to the torus)

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.)
- $L_{FIR} \approx 10^{13}\ L_{\odot}$, $T \approx 30-50$ 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)?

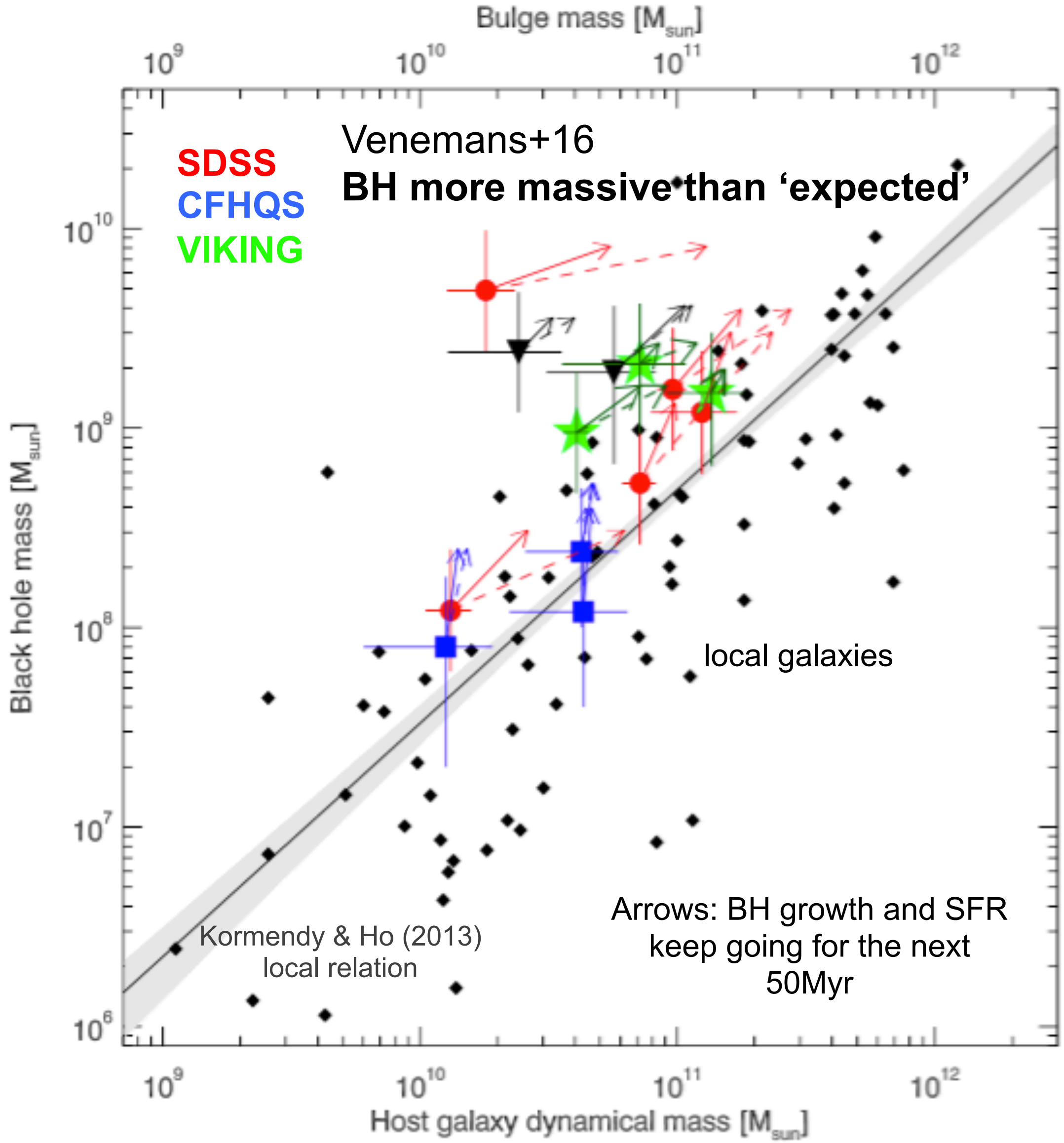


Beelen+06



Leipski+14

Where do we stand? IX. QSO hosts



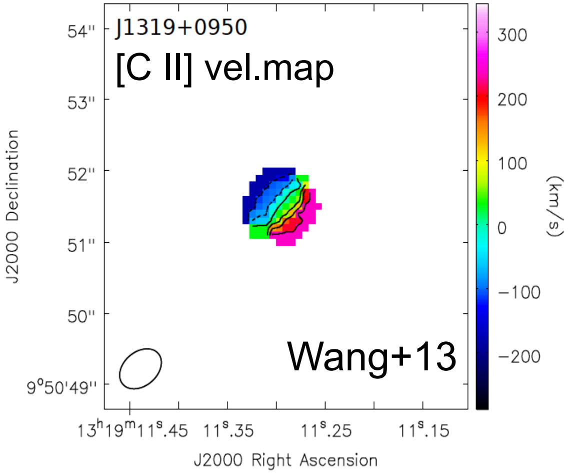
Venemans+16

BH more massive than ‘expected’

Kormendy & Ho (2013) local relation

Arrows: BH growth and SFR keep going for the next 50Myr

$M_{BH}\sim10^9\ M_\odot \rightarrow M_\star\sim10^{11}\ M_\odot \rightarrow M_{halo}>\sim10^{12}\ M_\odot$



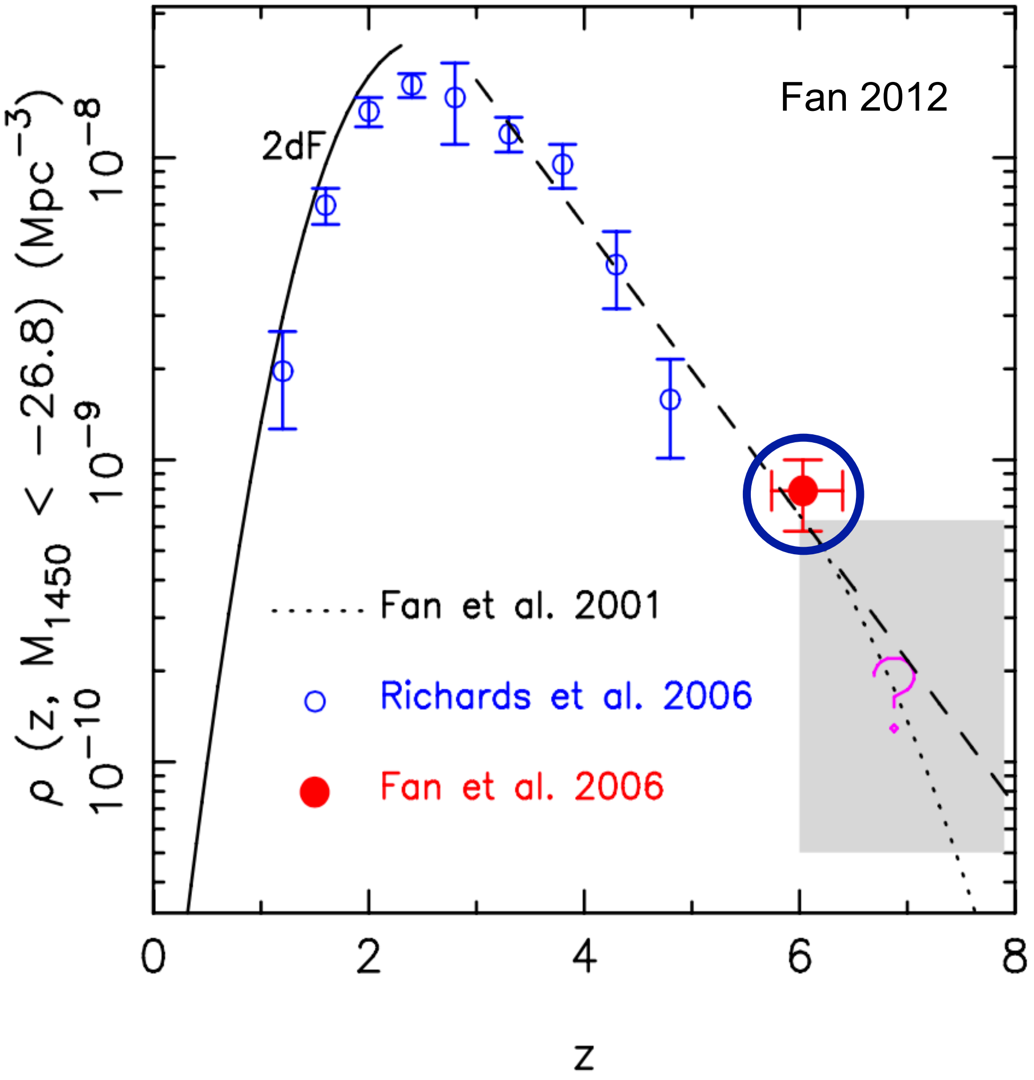
Wang+13

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

Where do we stand? X. 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

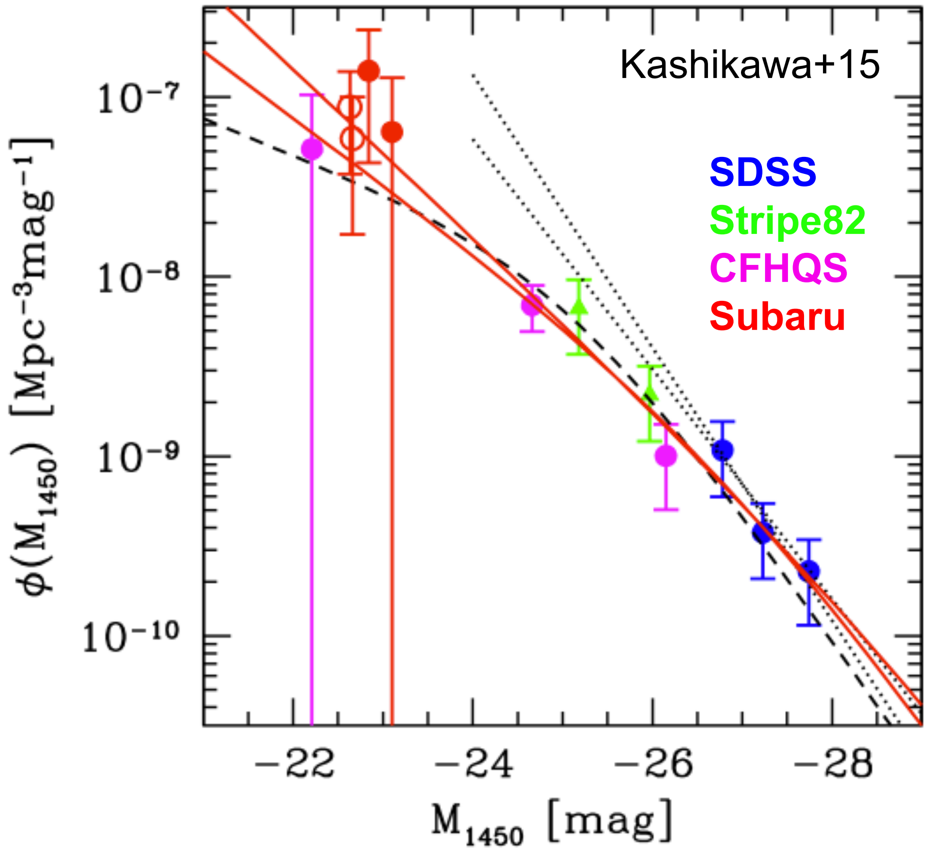
caveats!

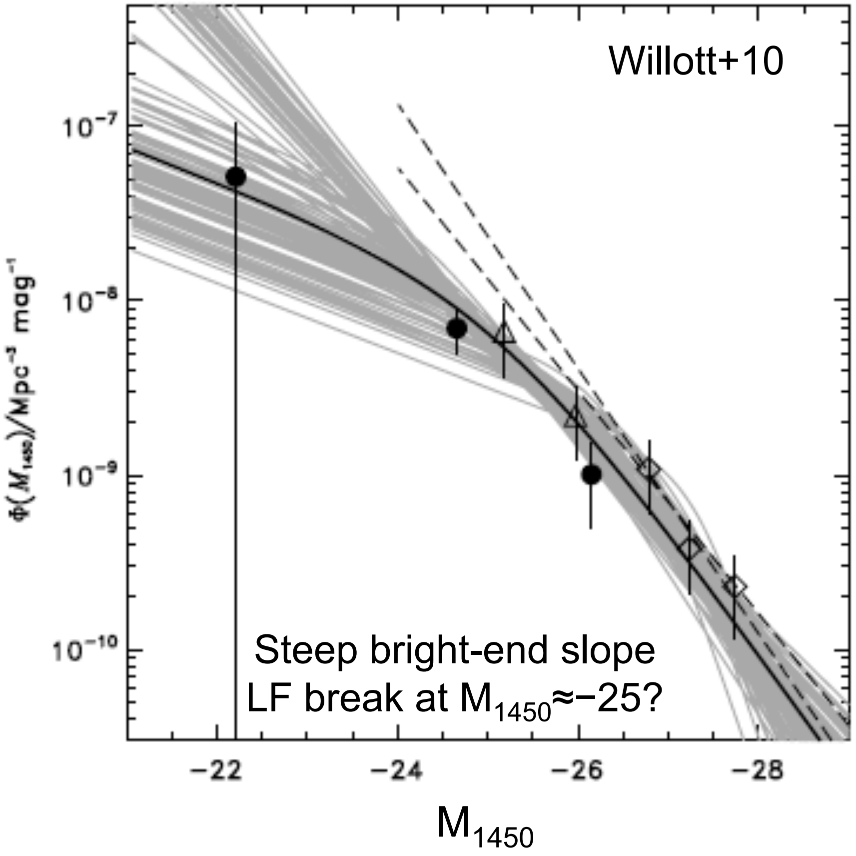
1) not all z=6 SMBHs may be active
2) still missing obscured z=6 QSOs

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





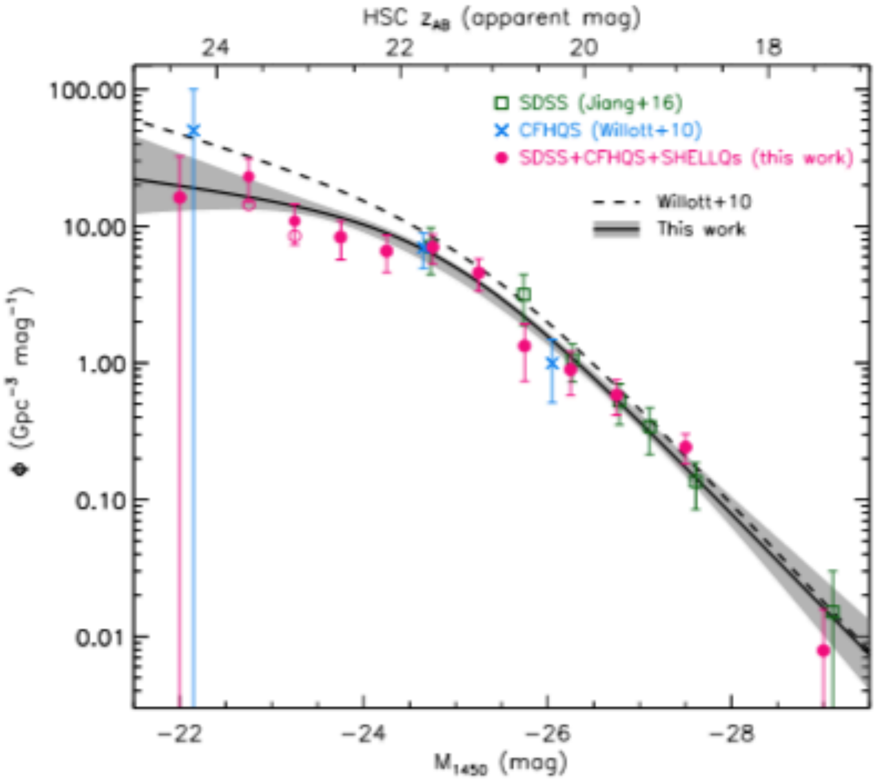
Steep bright-end slope
LF break at M_{1450}≈−25?

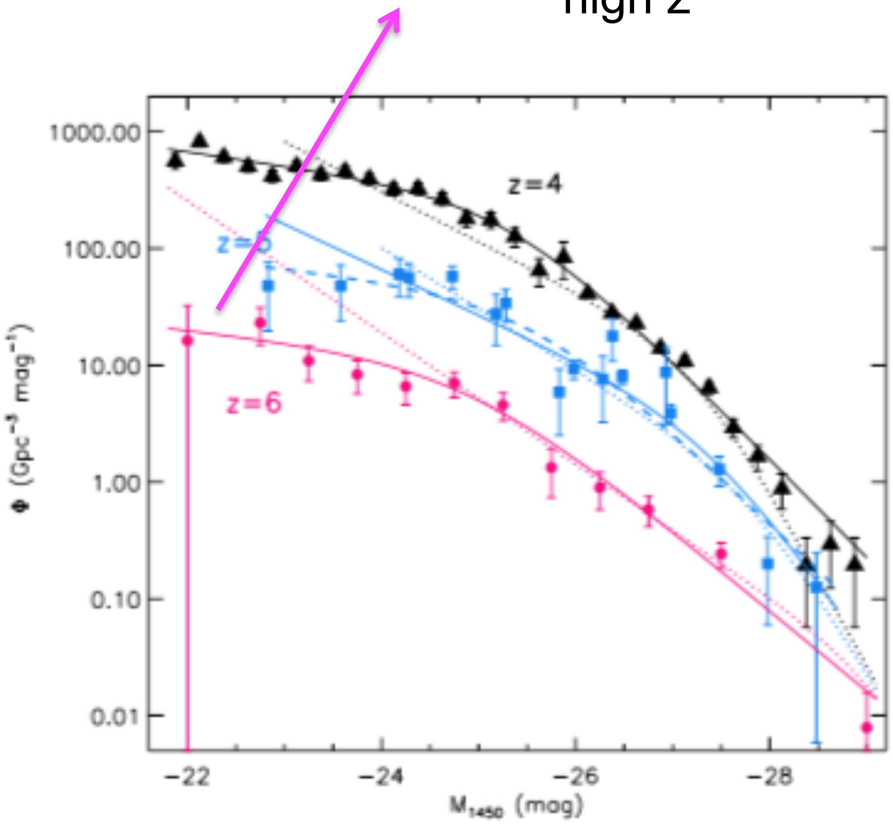
- Highly uncertain faint end of the LF → if steep and high AGN f_{esc}~1, important contribution to reionization (Giallongo+15,19; see also Cappelluti+16, Ricci+17)
- Luminous AGN are found to decline exponentially up to z~4−6
- Still limited is our knowledge of less luminous z≥3 AGN, i.e. the bulk of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

see recent results from Vito+16,18

up to the most recent results from HSC

rapidly decreasing
number of QSOs at
high z

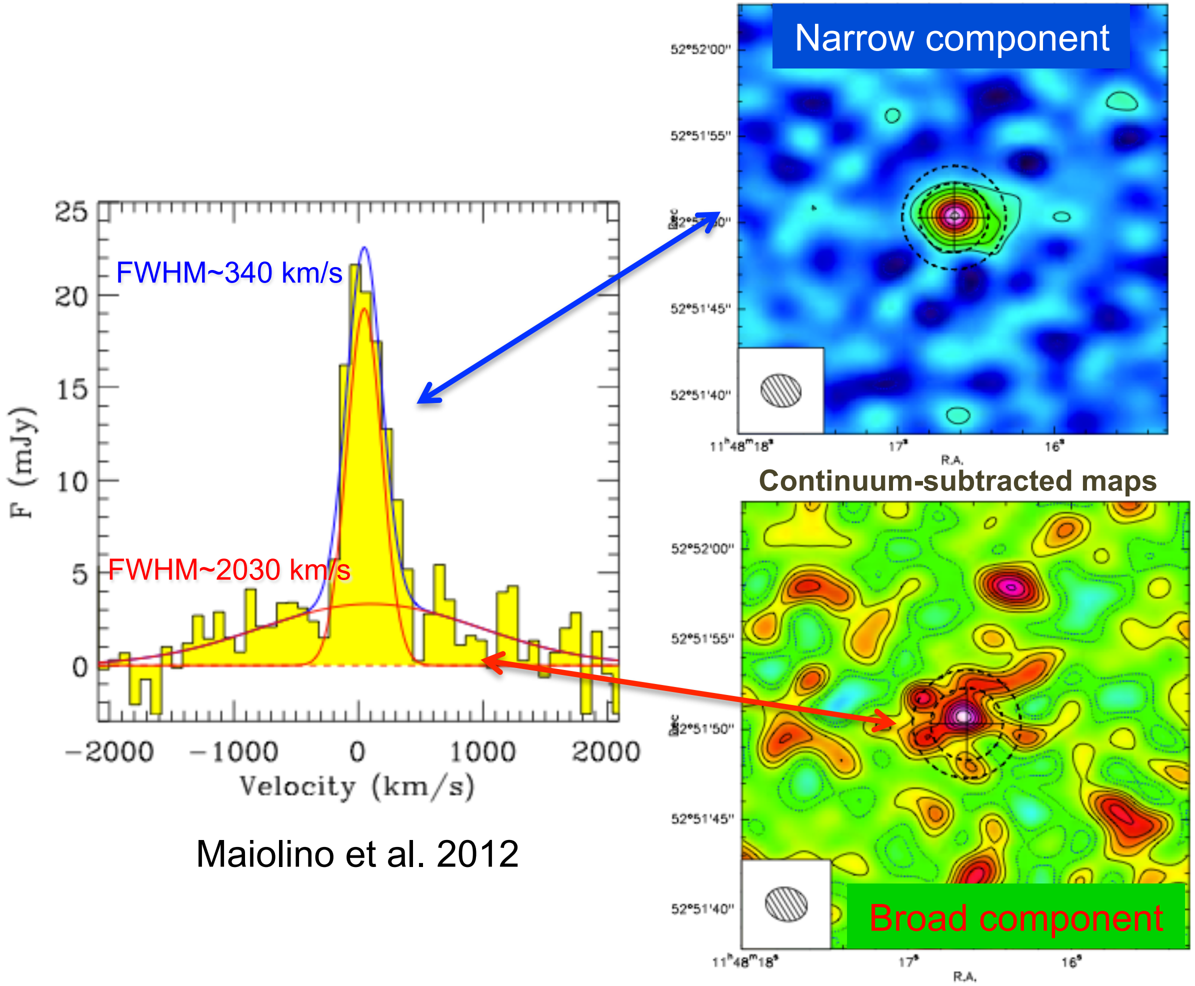




Flattening of the faint-end slope of the LF → QSOs cannot contribute significantly to the reionization (unless most of the population is missed) → needs to shed light on the obscured AGN population (X-rays favored)

Where do we stand? – XI. 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)

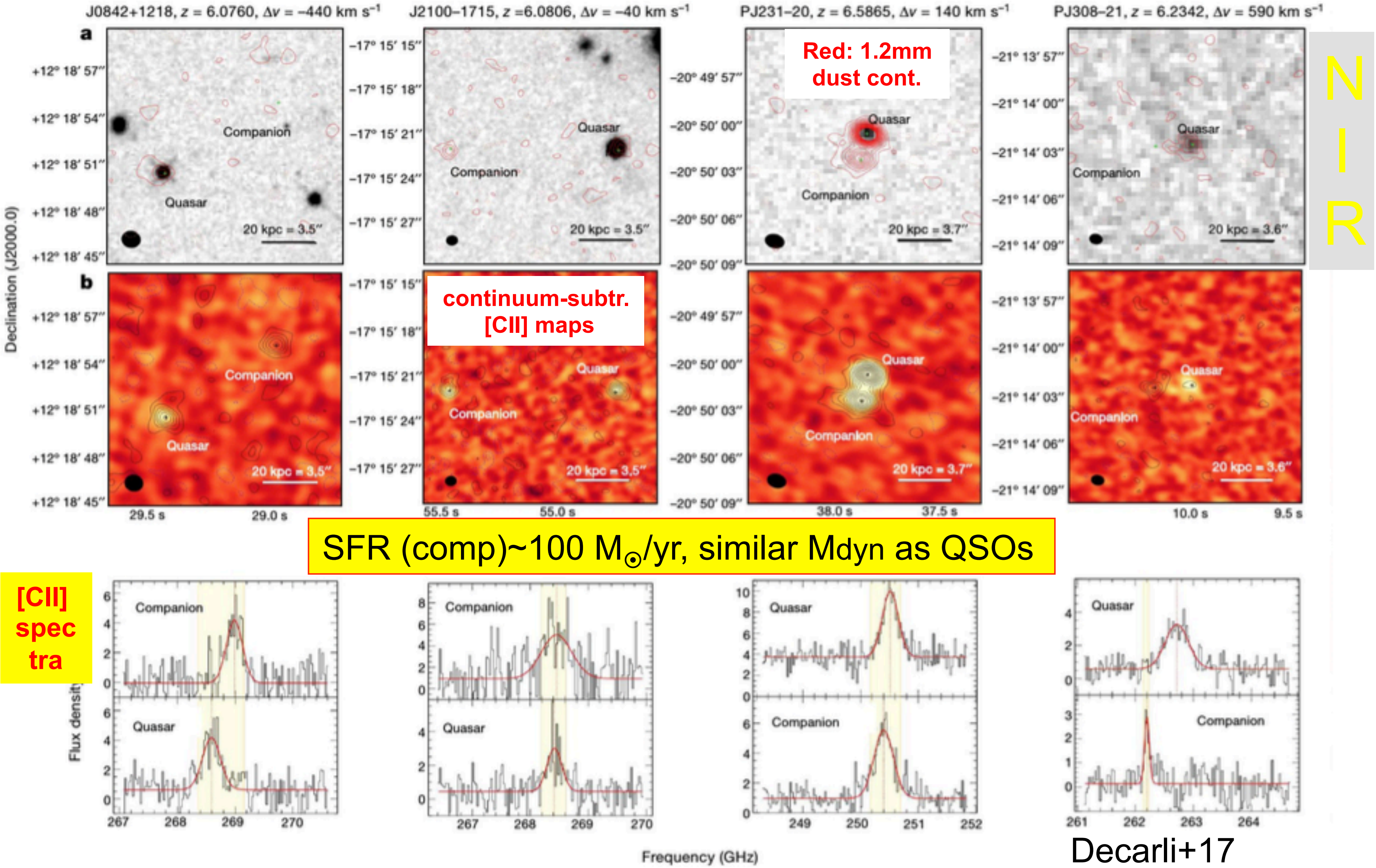
Capable of quenching SF? (e.g., Page+12, Cano-Diaz+12; see also Harrison+12, […])

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

$P_K>1.9\times10^{45}$ erg/s ≈0.6% L_{bol} (QSO) OK with AGN Prad, barely consistent with STB-driven winds

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



Red: 1.2mm dust cont.

N I R

continuum-subtr. [CII] maps

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

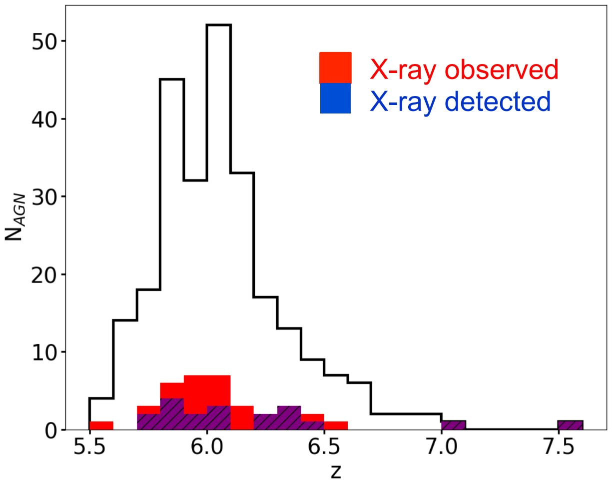
[CII] spec tra

Decarli+17

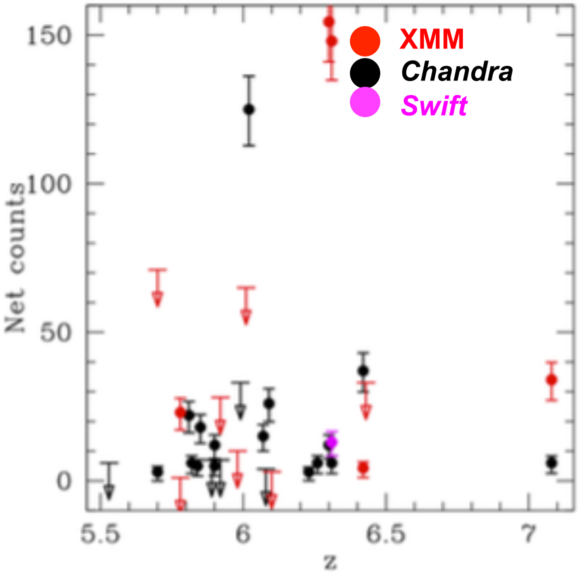
(see also Feruglio+18)

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)



259 QSOs at z>5.5 (the majority from optical/near-IR surveys)

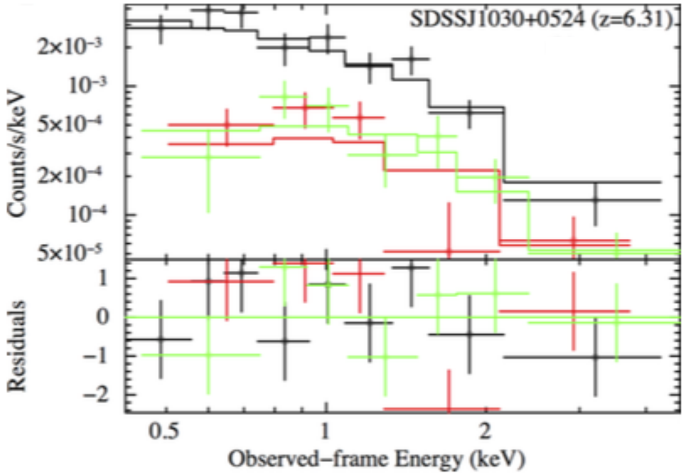
31 with available X-ray data

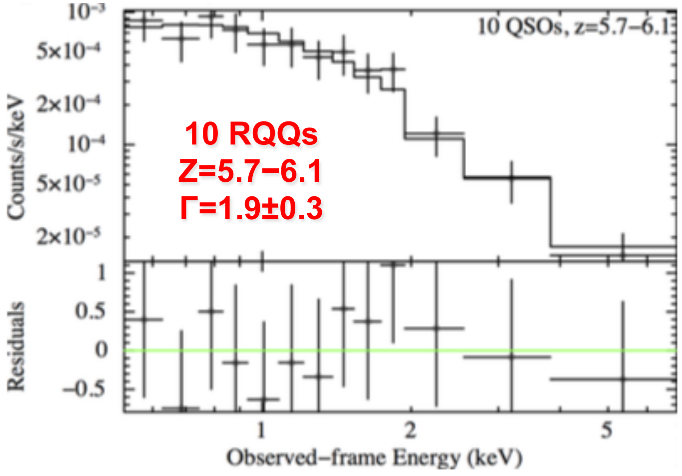
19 X-ray detections

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

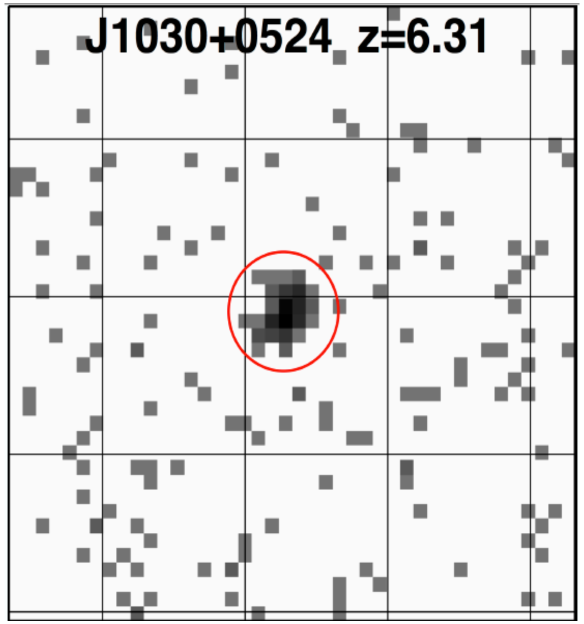




10 RQQs
Z=5.7−6.1
Γ=1.9±0.3

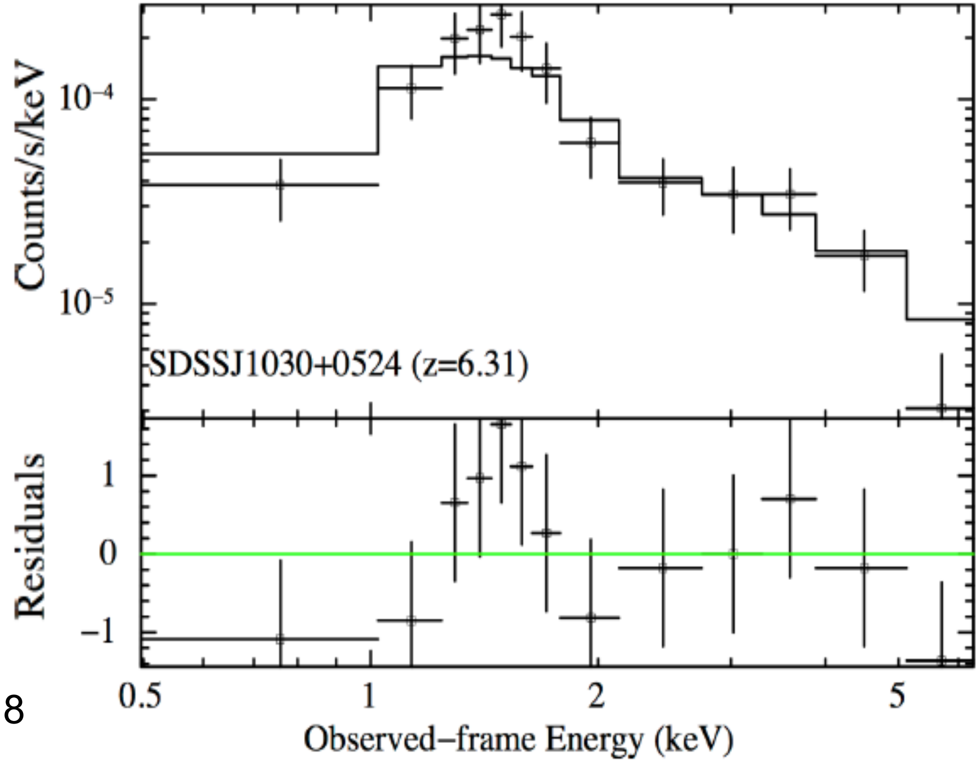
z~6 QSOs: the X-ray view. II. SDSSJ1030+0524 at z=6.3

0.5−7 keV image



20”×20”

Chandra, **Γ**=1.81±0.18



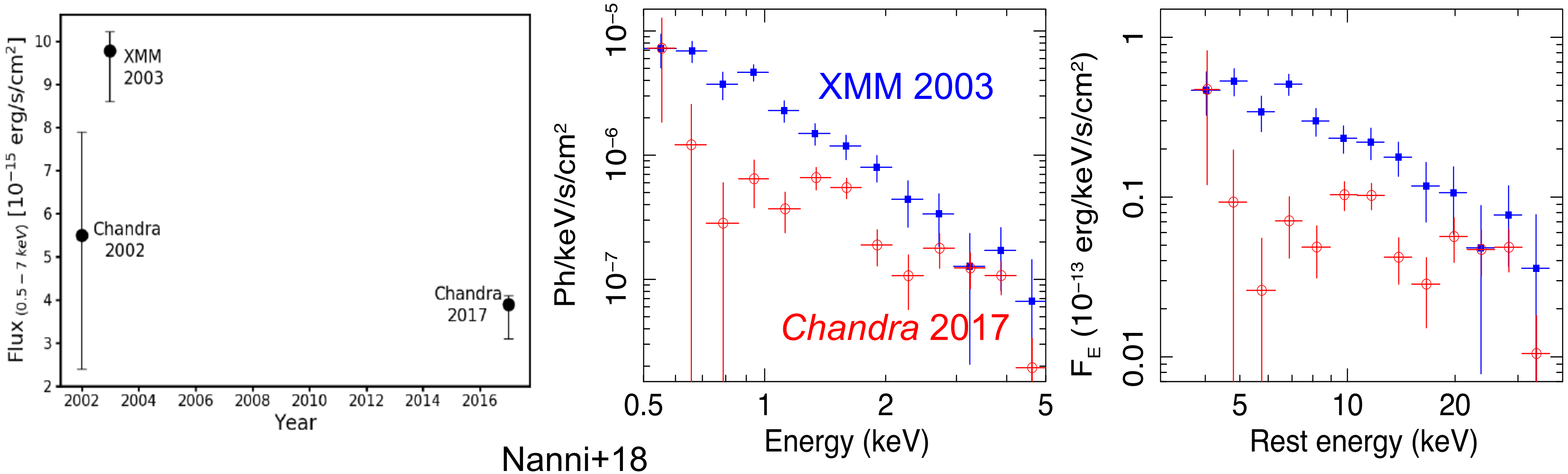
Nanni+18

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 $\Gamma = 2.37\pm0.16$

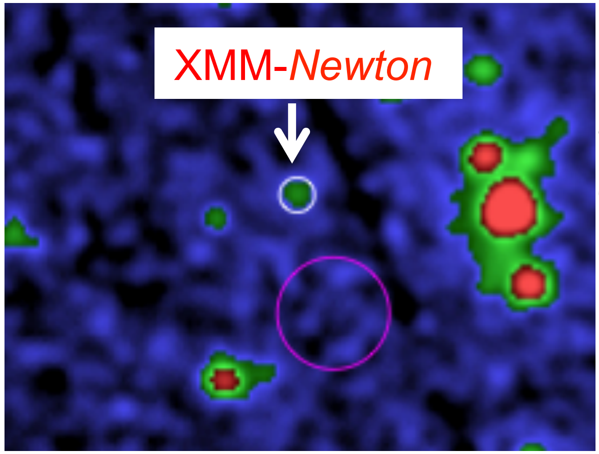
Chandra $\Gamma = 1.81\pm0.18$

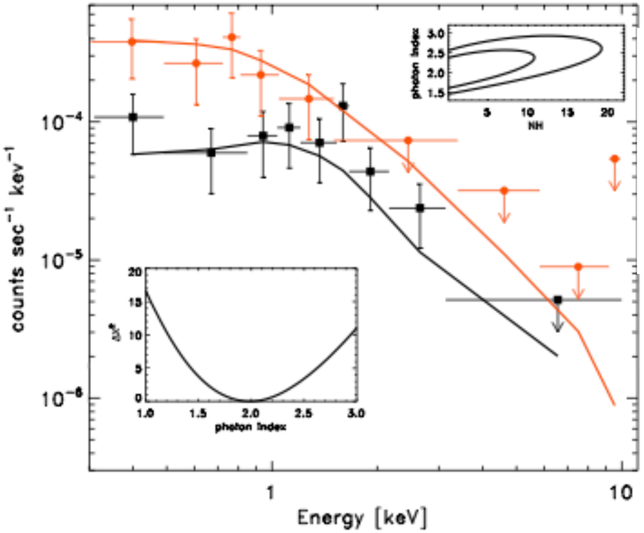
(+2.5 times fainter flux)

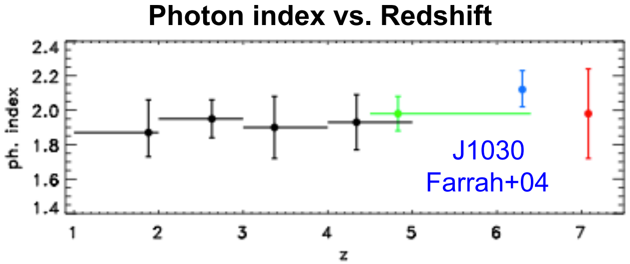
Chandra spectrum significantly harder: intrinsic hardening or increased absorption ($\approx 5\times10^{23}$ cm^{-2})? Likely both effects

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

z~6 QSOs: the X-ray view. III. ULASJ1120 at z=7.1







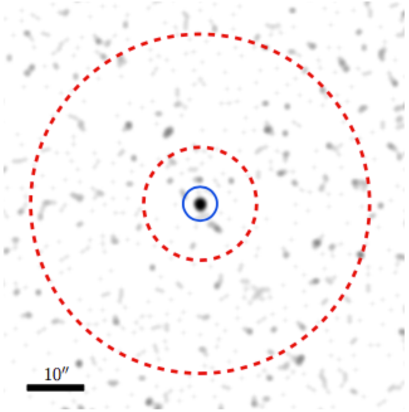
Moretti+14
(see also Page+14)

T≈340 ks obs.
150 net counts
Γ=2.0±0.3
$L_{2-10keV}$≈7×10^{44} erg/s

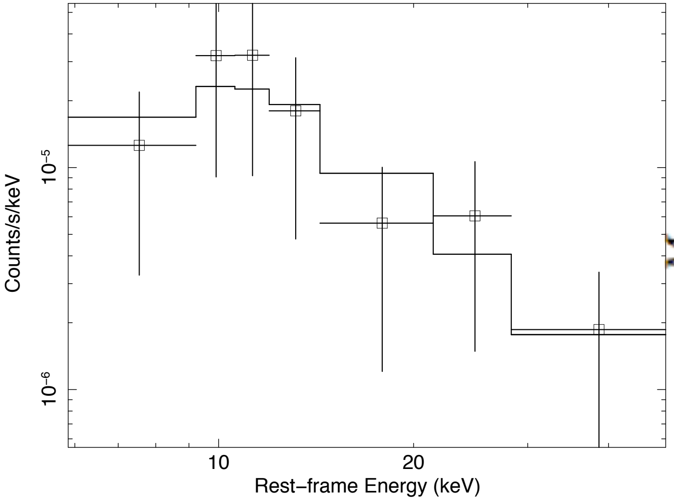
challenging observations to obtain good-quality X-ray spectra (sometimes, even a good detection) for current facilities

QSO accreting at Eddington

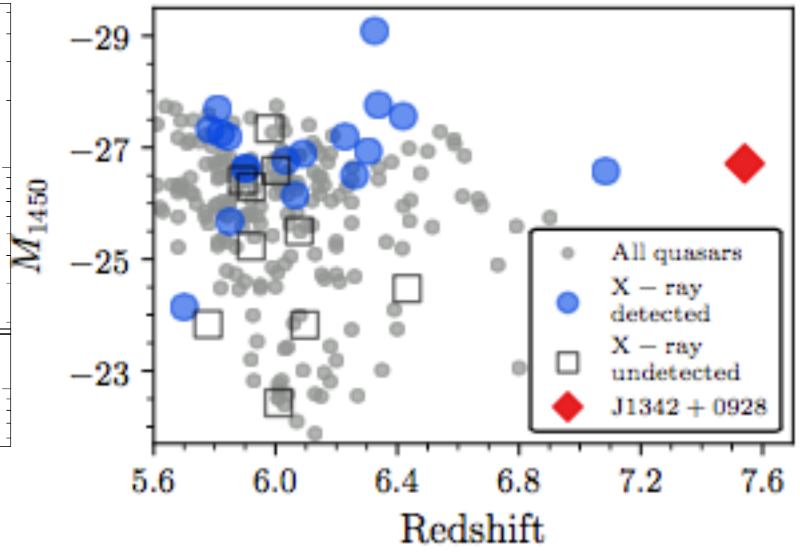
z~6 QSOs: the X-ray view. IV. ULASJ1342 at z=7.5



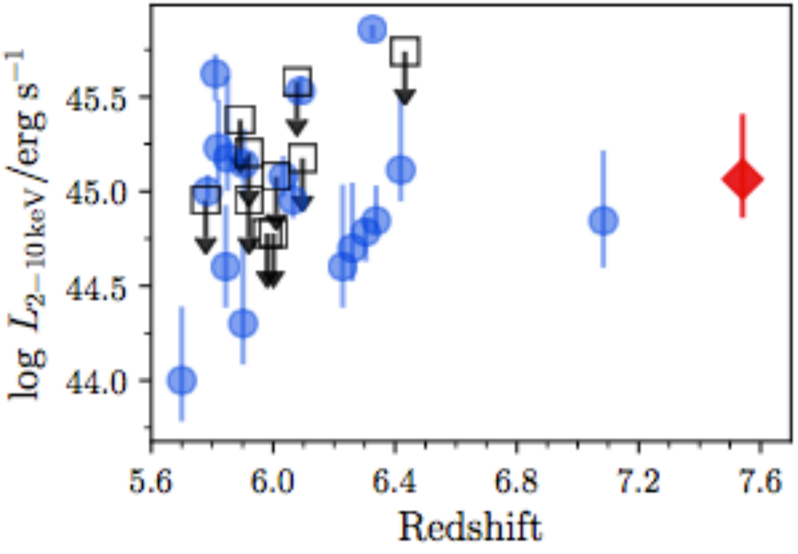
Banados+18



CV+;
Banados+18



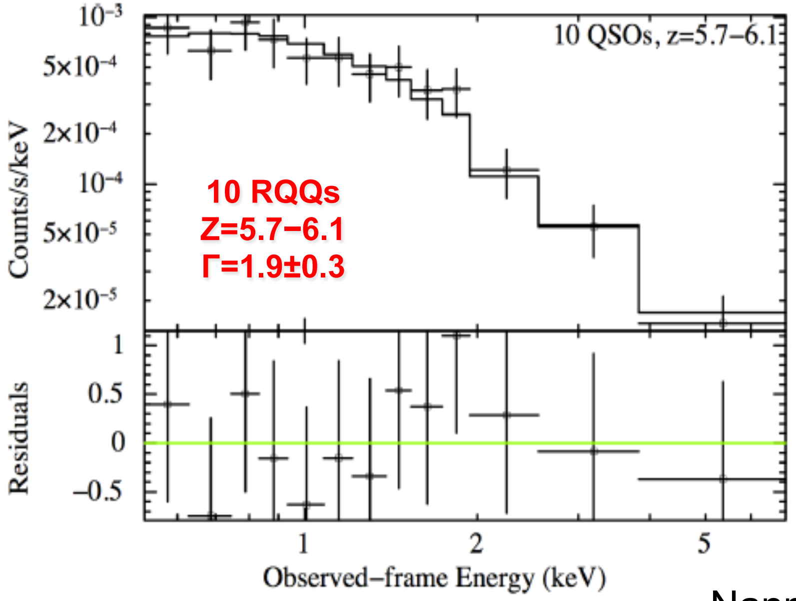
T≈45 ks *Chandra*
14 net counts
Γ=2.0±0.5
$L_{2-10keV}$≈1.2×10^{45} erg/s



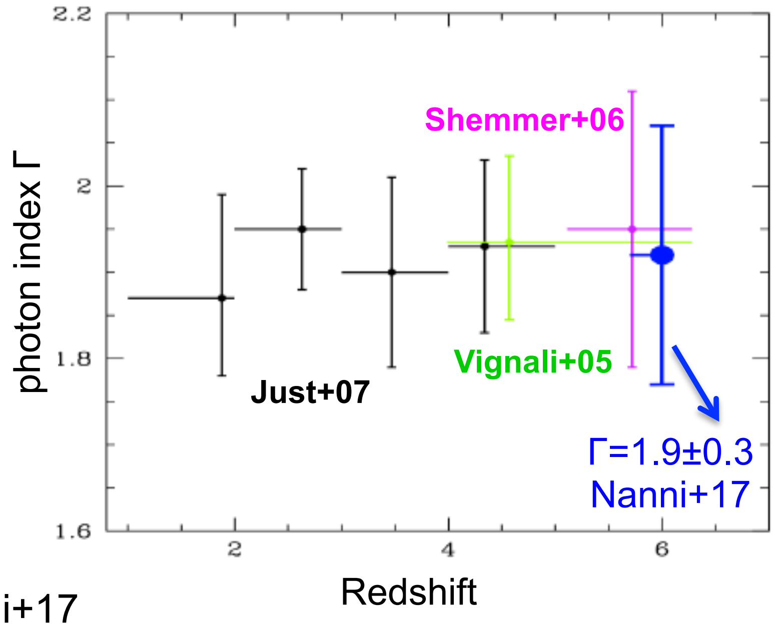
Banados+18

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

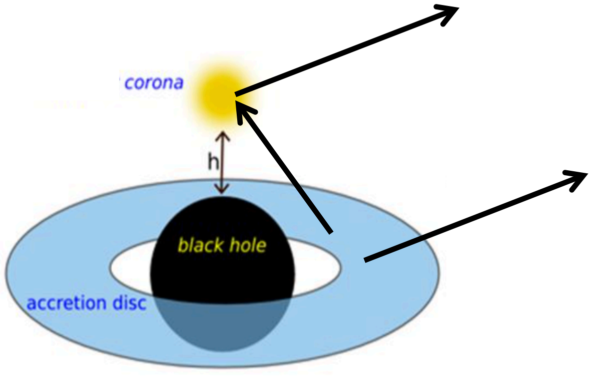
Stack of 10 QSOs at z>5.6 detected with *Chandra*



Nanni+17



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

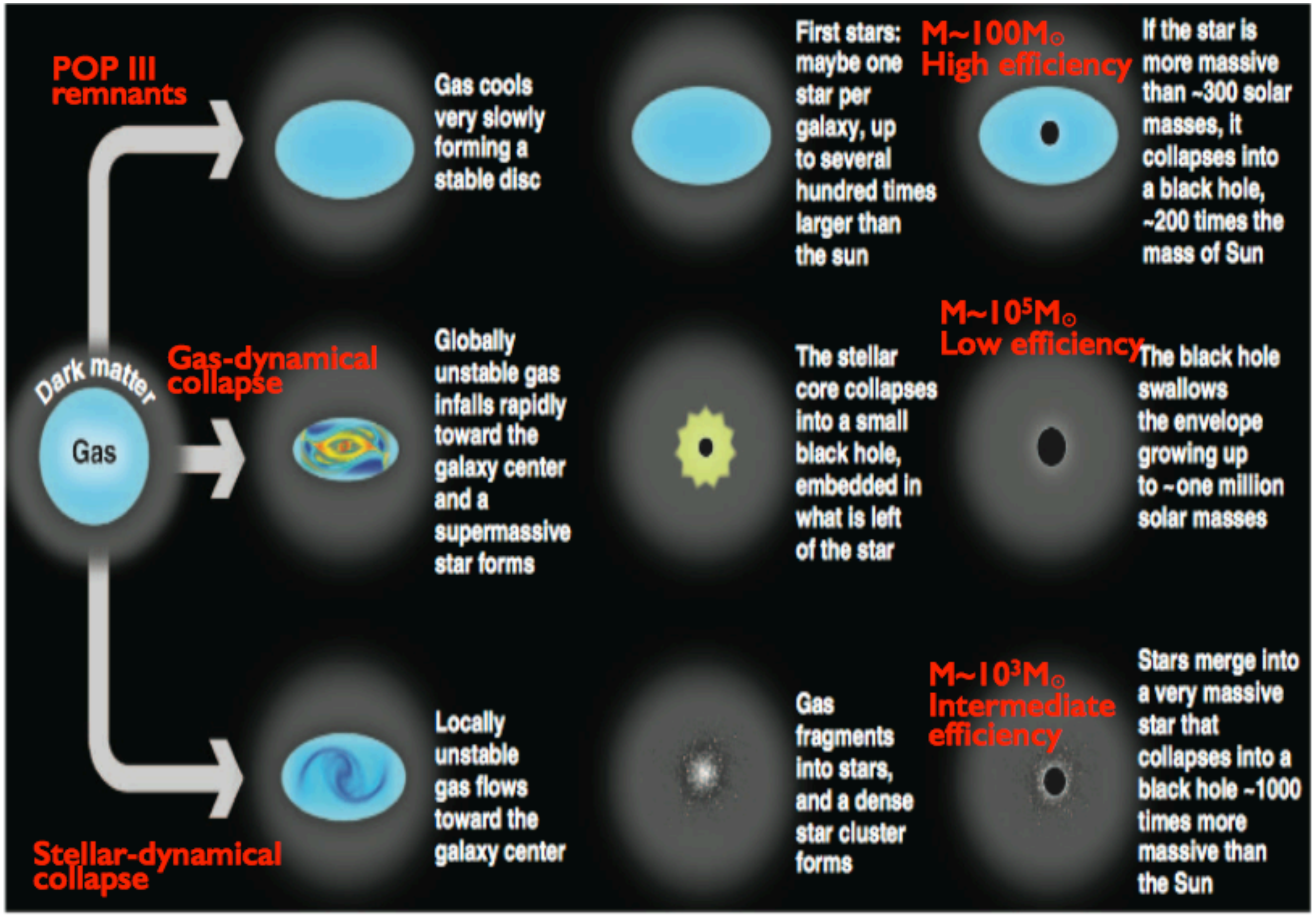


basic AGN inner structure (accretion disk + hot e^- corona) in place in t<<1 Gyr

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

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

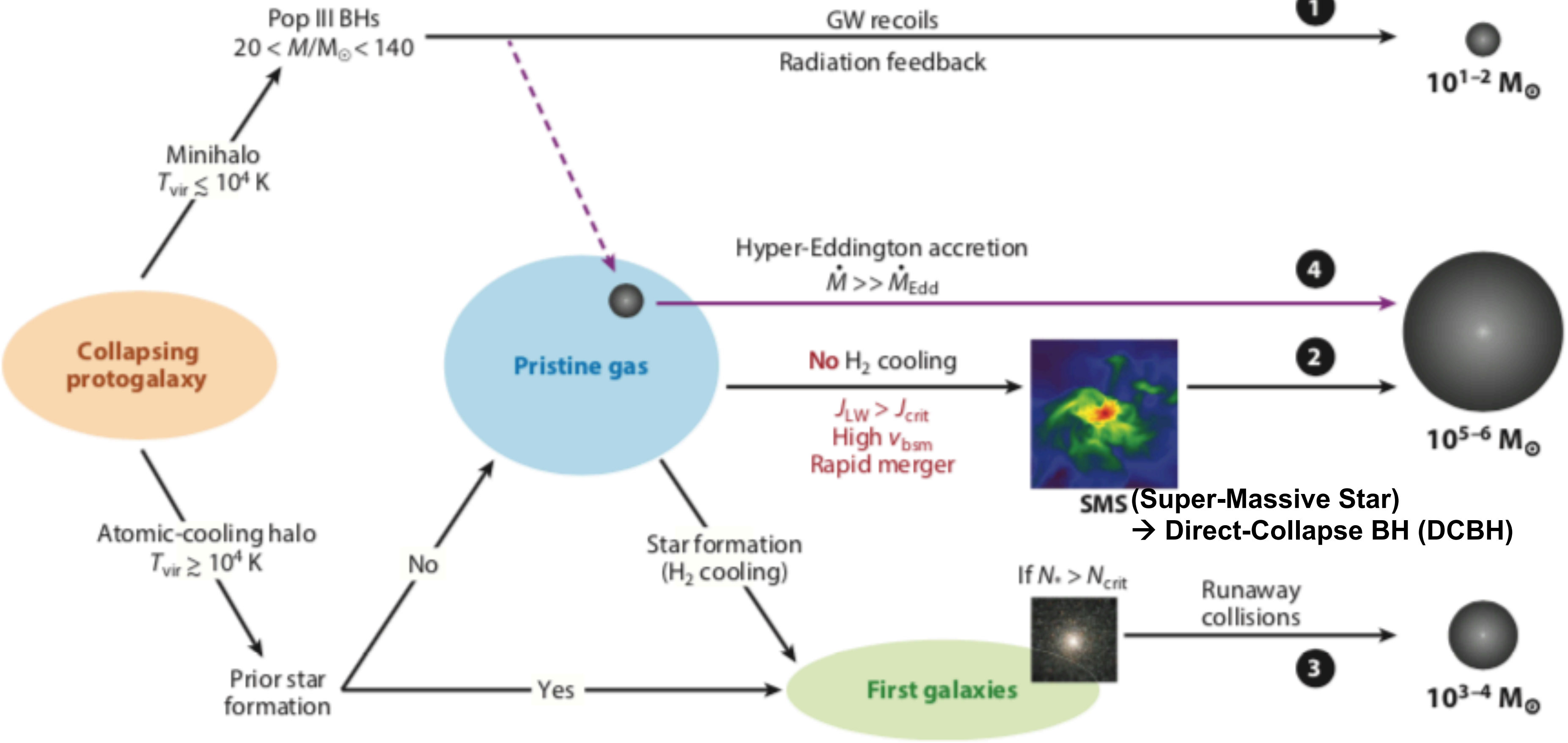
Stars merge into a very massive star that collapses into a black hole ~1000 times more massive than the Sun

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

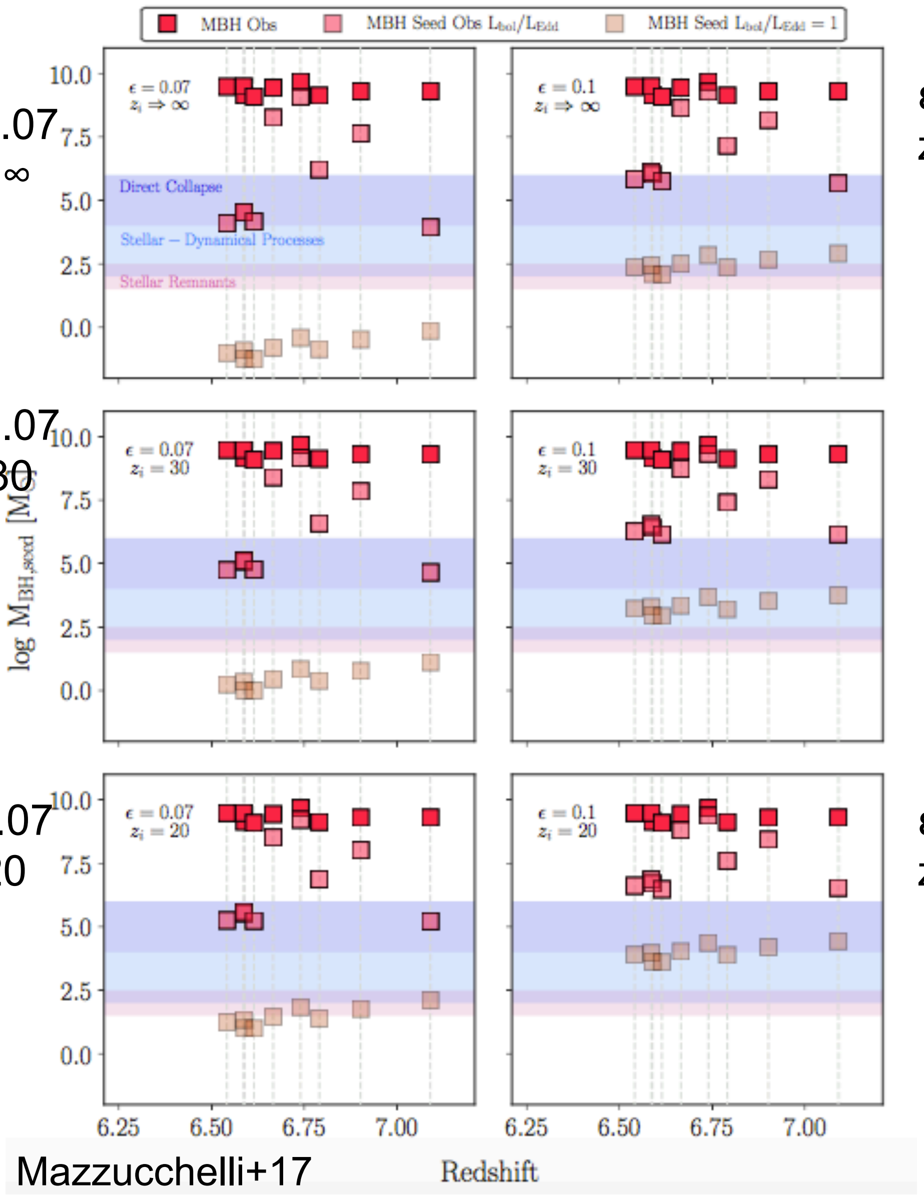


Inayoshi+20 review

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. II. Model degeneracy



ε=0.07 z_i→∞

ε=0.1 z_i→∞

ε=0.07 z_i=30

ε=0.1 z_i=30

ε=0.07 z_i=20

ε=0.1 z_i=20

Mazzucchelli+17

$M_{BH,seeds}$ needed to obtain the observed QSO BH masses (dark red squares)

Assumption: sources accrete constantly with the observed Eddington ratio (light red squares) and at Eddington rate=1 (yellow squares)

→In all cases with ε=0.07 and L_{bol}/L_{Edd}=1 and in case of [ε=0.1, L_{bol}/L_{Edd}=1 and z_i→∞], the calculated seed masses (>100 $M_\odot$) are consistent with being formed by stellar remnants. Alternatively, higher efficiency (ε=0.1) and later seed birth (z_i=30,20) at L_{bol}/L_{Edd}=1 would require ≈10^{3-4} $M_\odot$ seed BHs as progenitors of z~6.5 QSOs

$$\boxed{M_{seed} = M_0 = \frac{M_{QSO}(t)}{\frac{1-\epsilon}{\epsilon} \quad \frac{t}{t_{Edd}}}}$$

BH growth at high z. III. The challenge

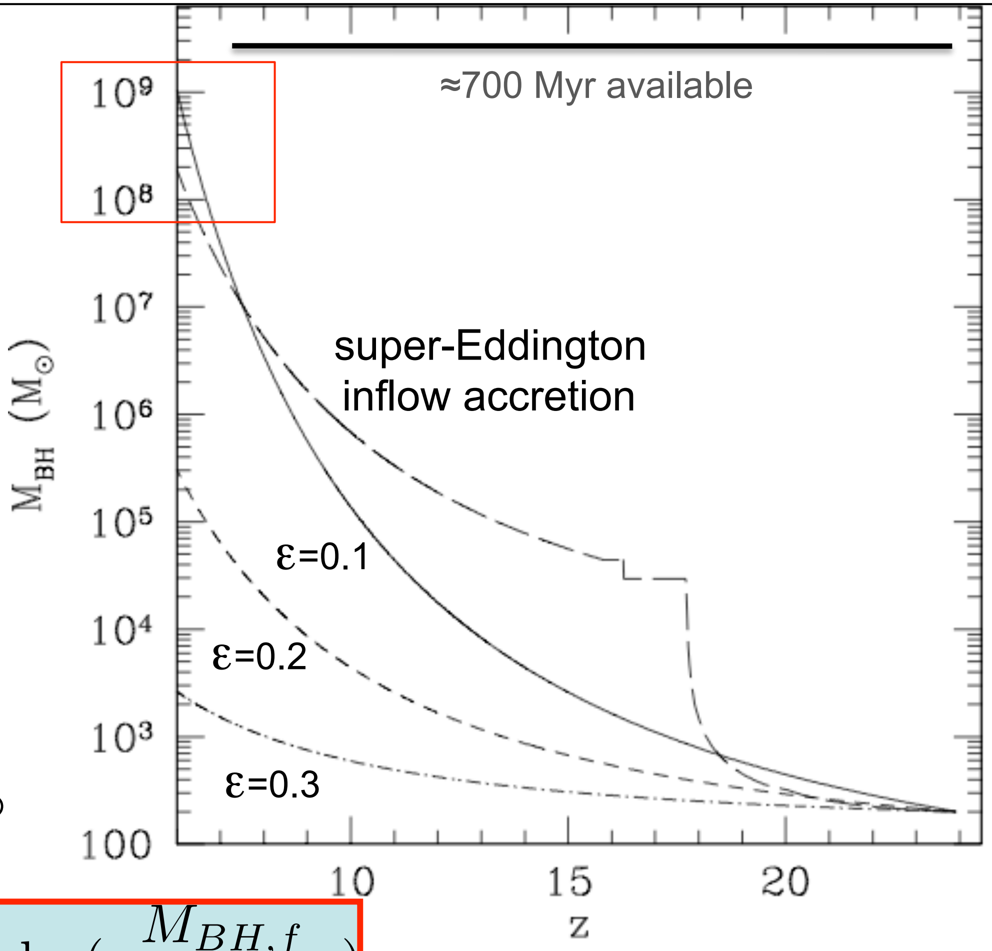
“Light” BH seeds require continuous accretion at $\lambda_{Edd}=1$ for long (z>20) periods
Most likely: unstable and episodic accretion flow (Ciotti & Ostriker 07, Dubois+13)

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

Larger radiation efficiency ε means longer times to achieve a given mass
[t_{Edd}=0.45 Gyr for ε=0.1]

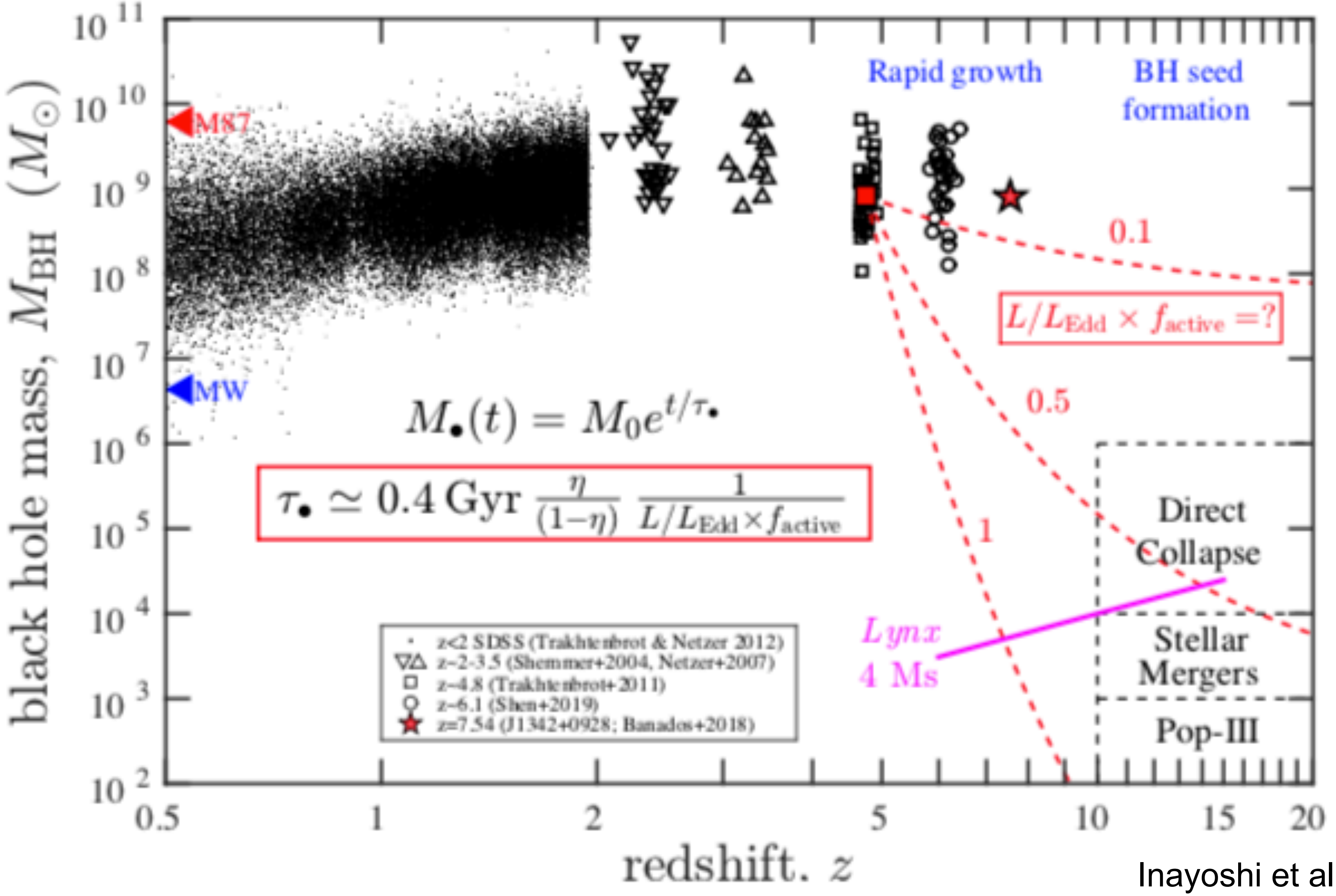
Rapidly spinning BHs might have problems because of a larger ε

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



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

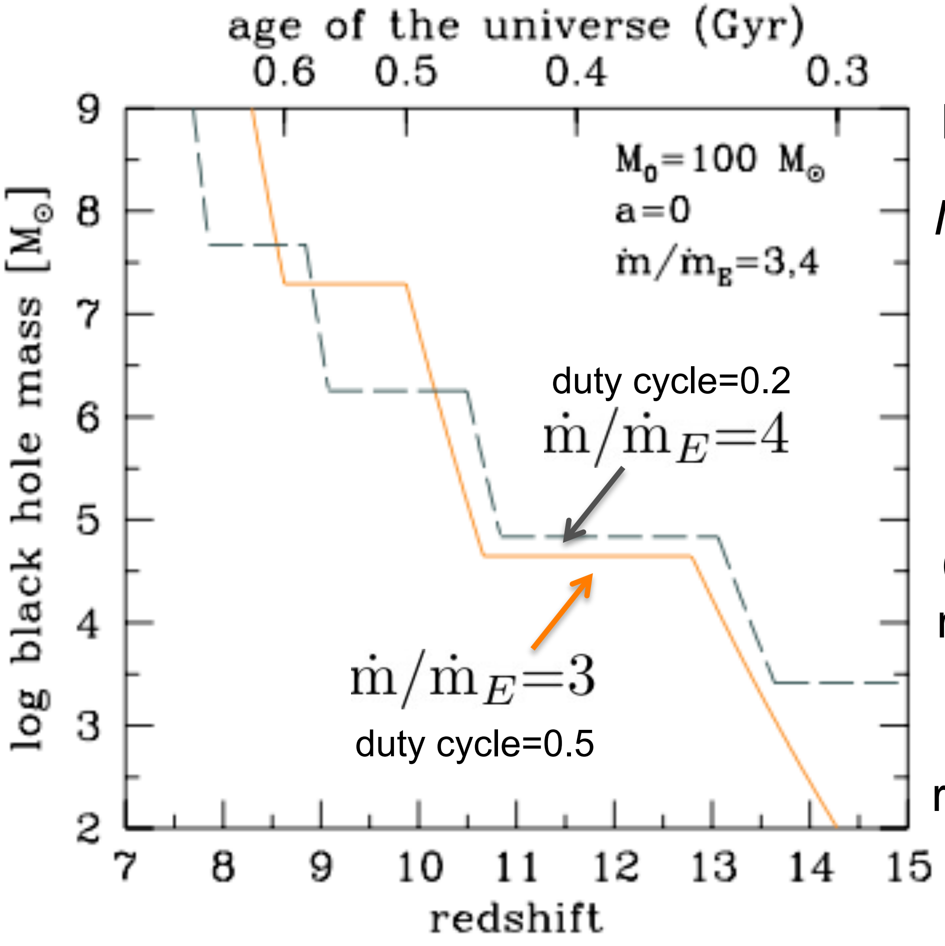
Volonteri & Rees 2006



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



Madau+14

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

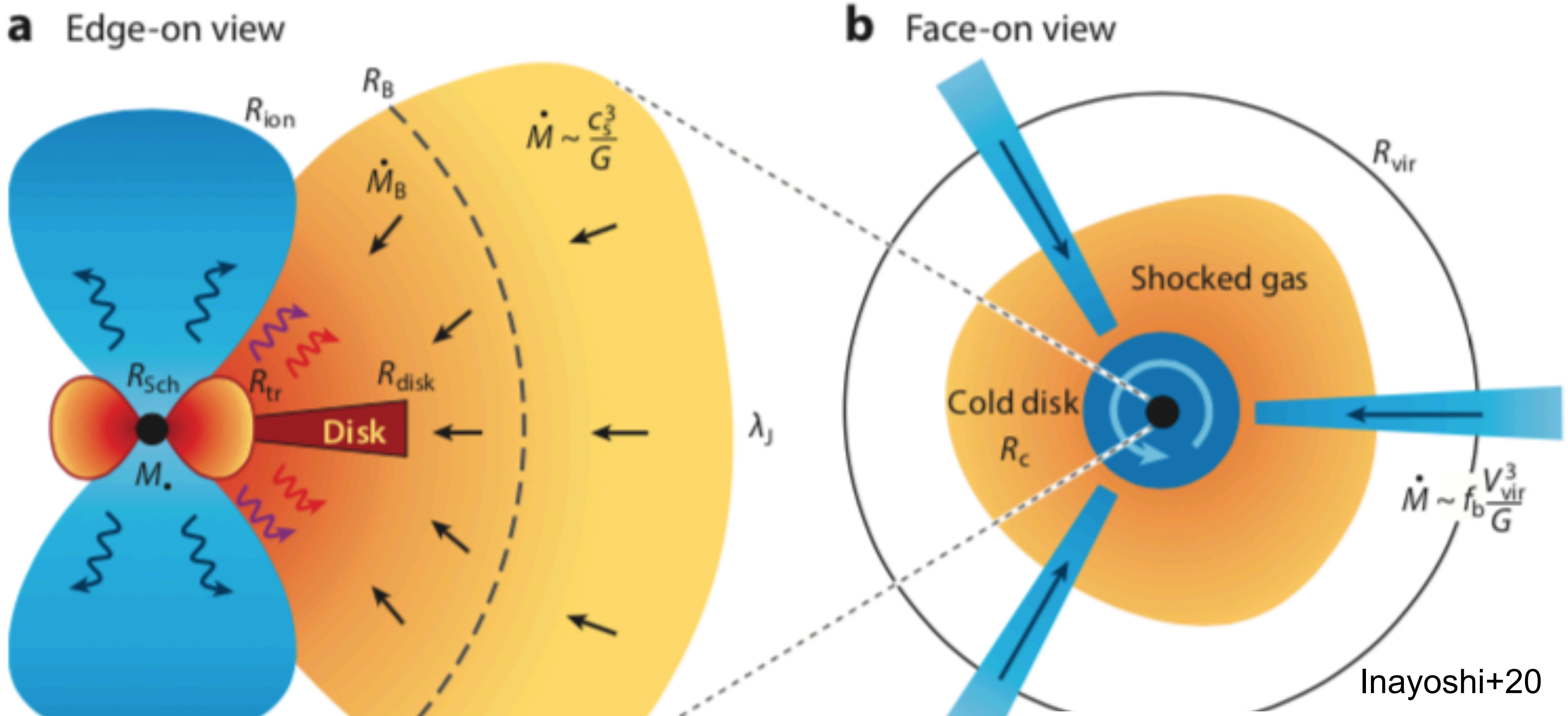
Non-rotating BH with seed mass=100 $M_\odot$

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

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



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

Inayoshi+20

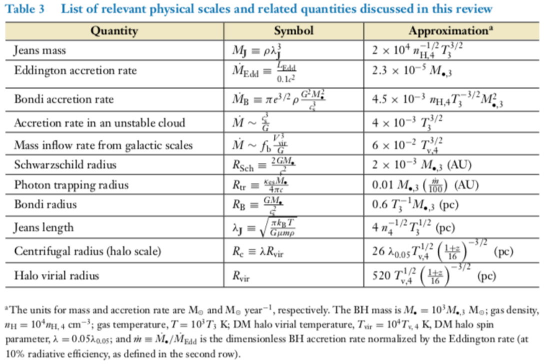


Table 3 List of relevant physical scales and related quantities discussed in this review

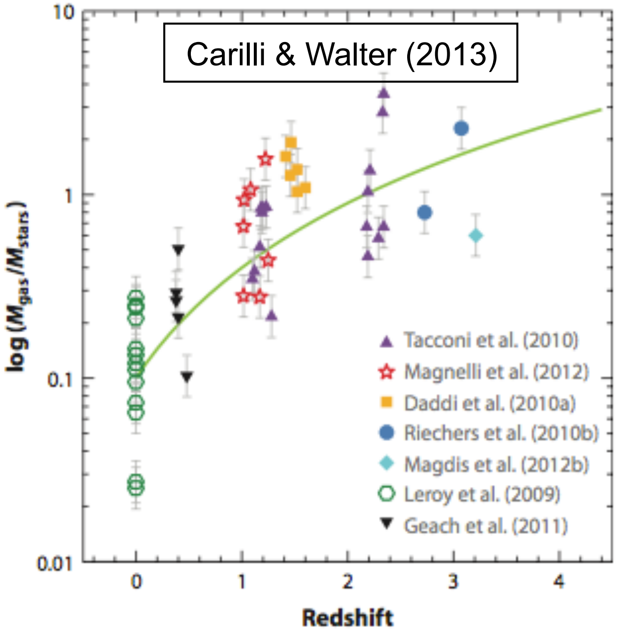
Quantity	Symbol	Approximation[a]
Jeans mass	$M_J \equiv \rho \lambda_J^3$	$2 \times 10^4\, n_{H,4}^{-1/2} T_3^{3/2}$
Eddington accretion rate	$\dot{M}_{Edd} \equiv \frac{L_{Edd}}{0.1c^2}$	$2.3 \times 10^{-5}\, M_{\bullet,3}$
Bondi accretion rate	$\dot{M}_B \equiv \pi e^{3/2} \rho \frac{G^2 M_\bullet^2}{c_s^3}$	$4.5 \times 10^{-3}\, n_{H,4} T_3^{-3/2} M_{\bullet,3}^2$
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	$\dot{M} \sim f_b \frac{V_{vir}^3}{G}$	$6 \times 10^{-2}\, T_{v,4}^{3/2}$
Schwarzschild radius	$R_{Sch} \equiv \frac{2GM_\bullet}{c^2}$	$2 \times 10^{-3}\, M_{\bullet,3}$ (AU)
Photon trapping radius	$R_{tr} \equiv \frac{\kappa_{es} \dot{M}_\bullet}{4\pi c}$	$0.01\, M_{\bullet,3} \left(\frac{\dot{m}}{100}\right)$ (AU)
Bondi radius	$R_B \equiv \frac{GM_\bullet}{c_s^2}$	$0.6\, T_3^{-1} M_{\bullet,3}$ (pc)
Jeans length	$\lambda_J \equiv \sqrt{\frac{\pi k_B T}{G \mu m_p \rho}}$	$4\, n_4^{-1/2} T_3^{1/2}$ (pc)
Centrifugal radius (halo scale)	$R_c \equiv \lambda R_{vir}$	$26\, \lambda_{0.05} T_{v,4}^{1/2} \left(\frac{1+z}{16}\right)^{-3/2}$ (pc)
Halo virial radius	R_{vir}	$520\, T_{v,4}^{1/2} \left(\frac{1+z}{16}\right)^{-3/2}$ (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, $n_H = 10^4 n_{H,4}$ cm^{-3}; gas temperature, $T = 10^3 T_3$ K; DM halo virial temperature, $T_{vir} = 10^4 T_{v,4}$ K, DM halo spin parameter, $\lambda = 0.05\lambda_{0.05}$; and $\dot{m} \equiv \dot{M}_\bullet / \dot{M}_{Edd}$ is the dimensionless BH accretion rate normalized by the Eddington rate (at 10% radiative efficiency, as defined in the second row).

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

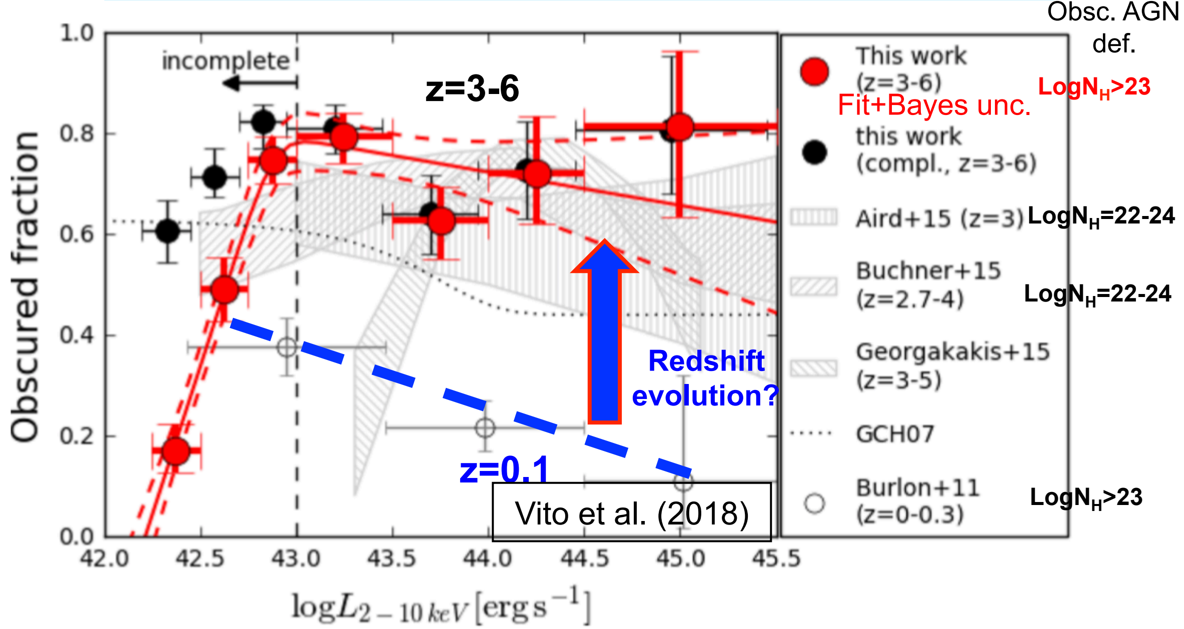

Carilli & Walter (2013)

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)


Vito et al. (2018)

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

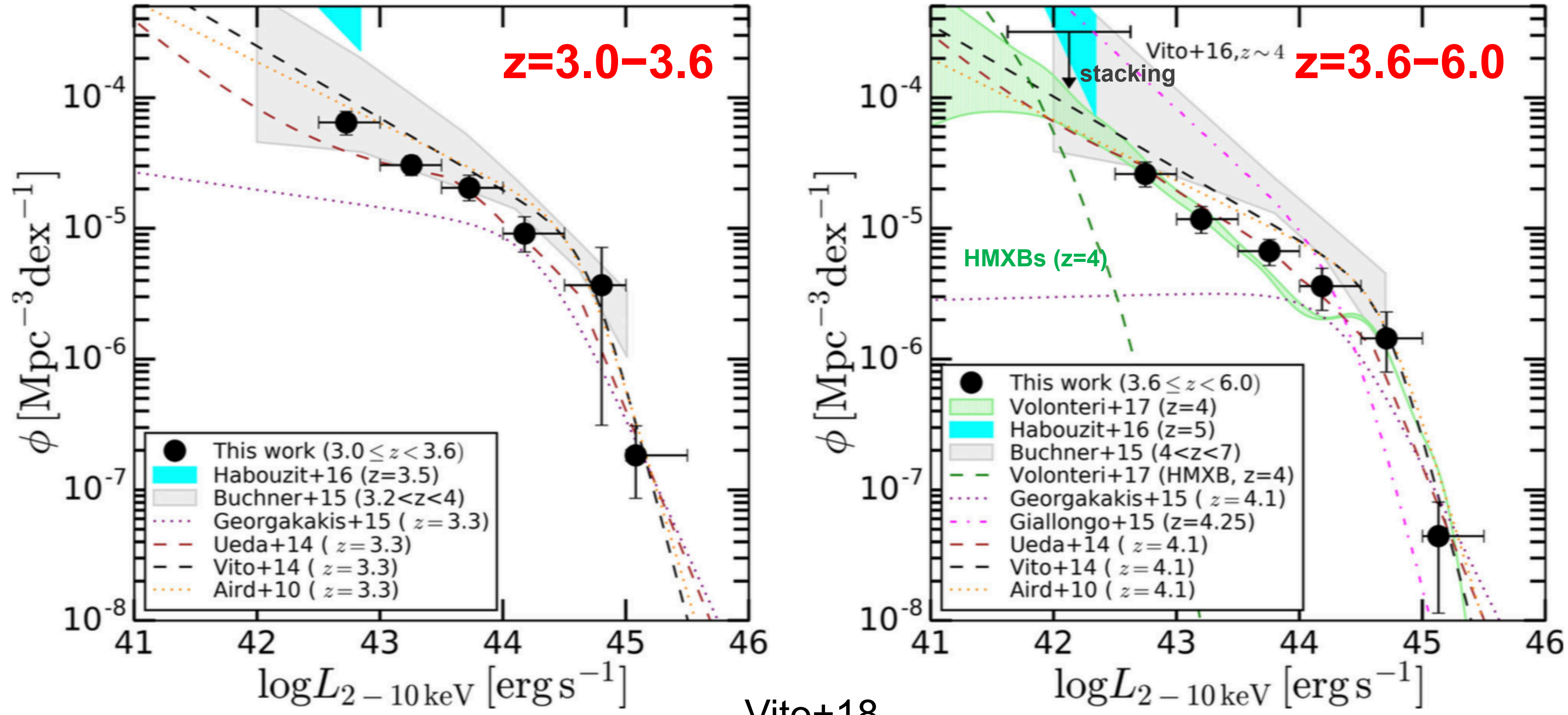
Obscured AGN fraction increases with redshift, especially at high luminosity

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

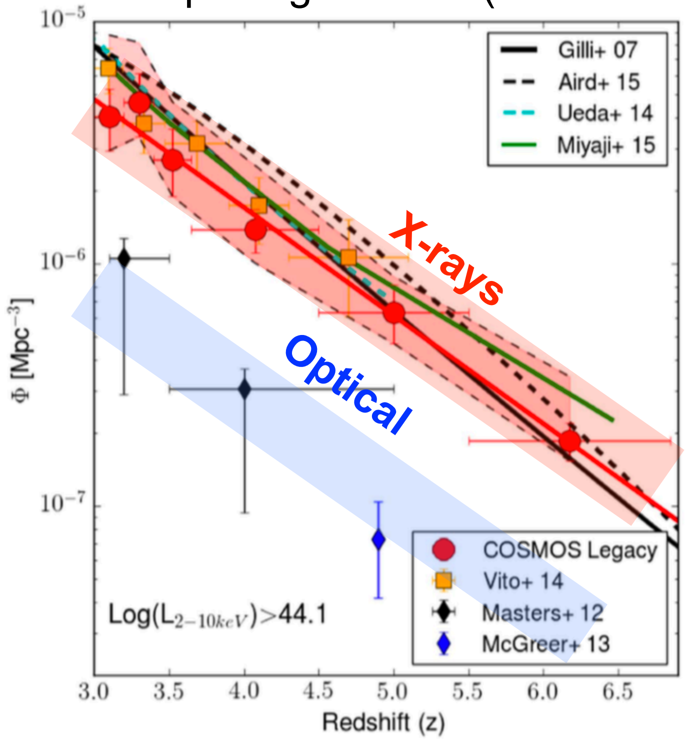


Vito+18

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

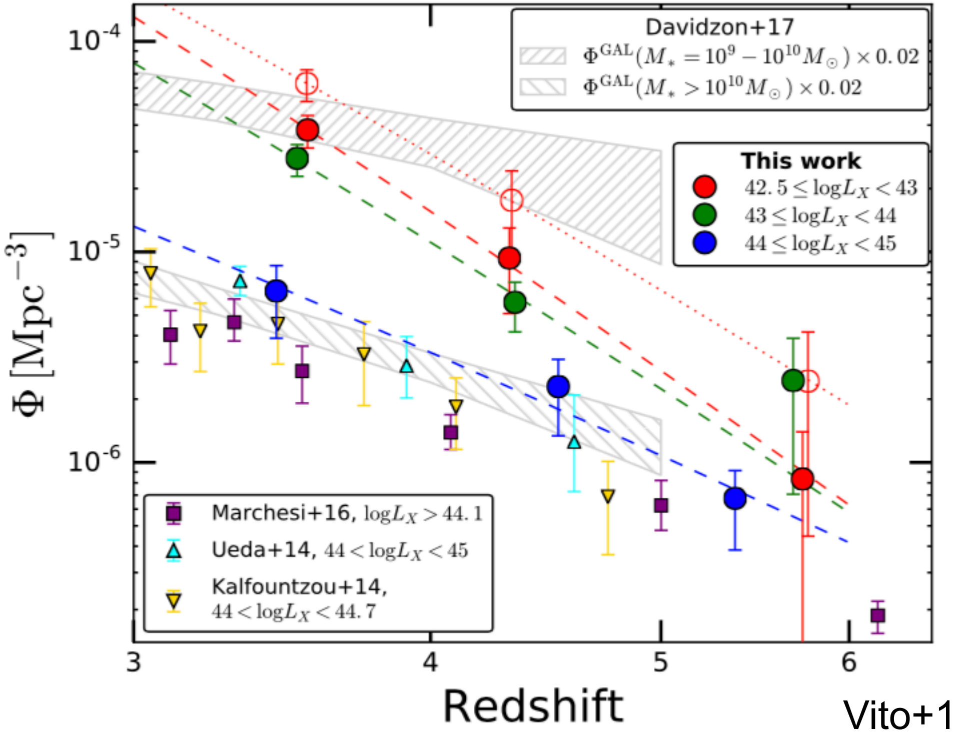
AGN at z>3. III. Space density

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)

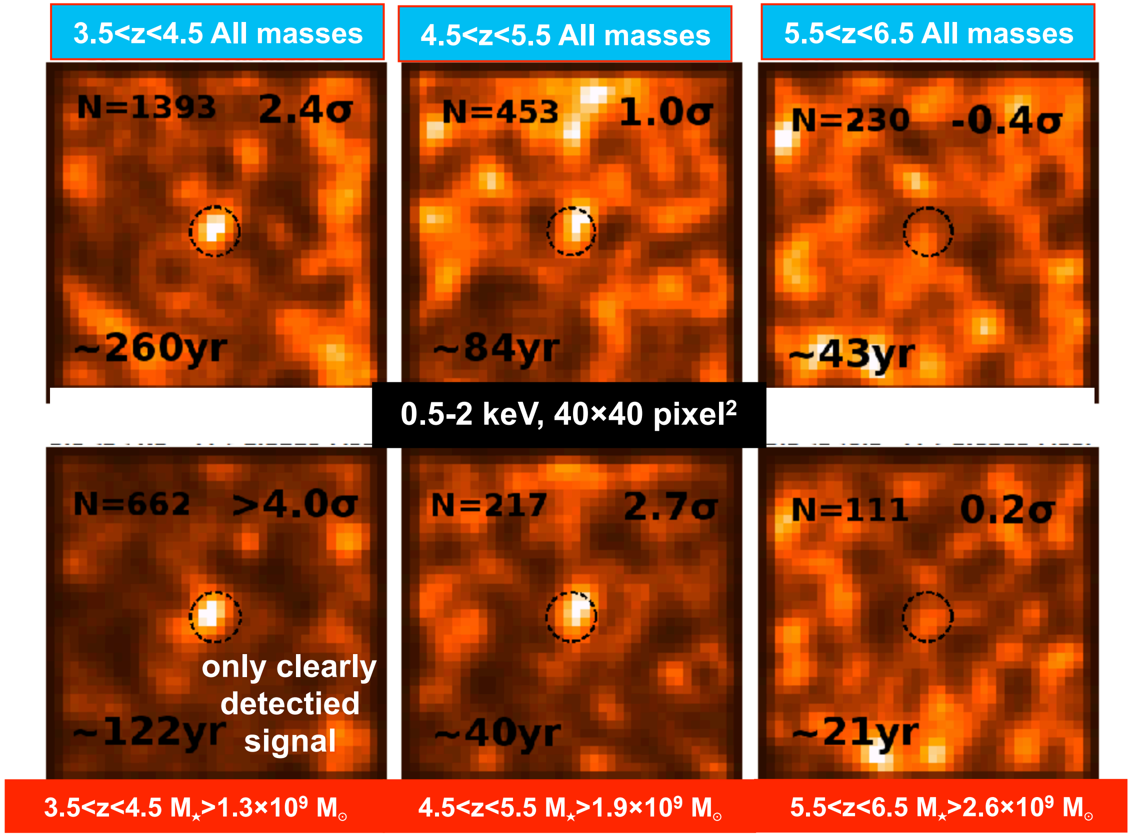
(see also Brusa+09, Civano+11, Hiroi+12, Vito+13,14, Kalfountzou+14, Georgakakis+15)

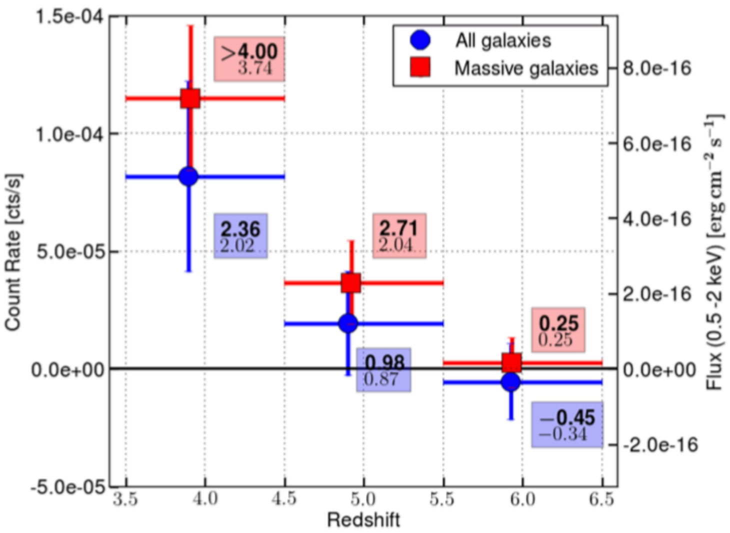


Vito+18
deep fields

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





Vito+16

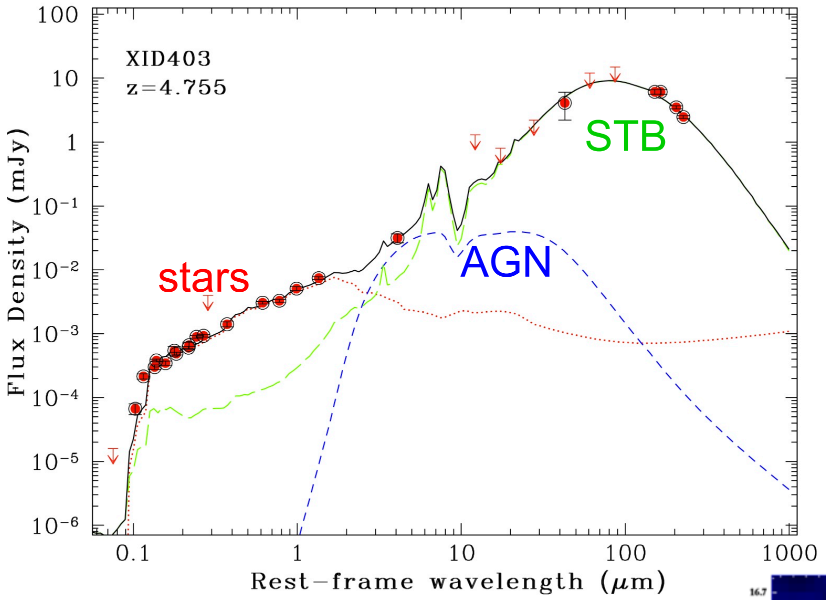
Pushing the X-ray analysis at its extreme (differences wrt. Giallongo and Cappelluti works) – Caveats: optical association, assumed photo-z, stacking tools, Eddington bias

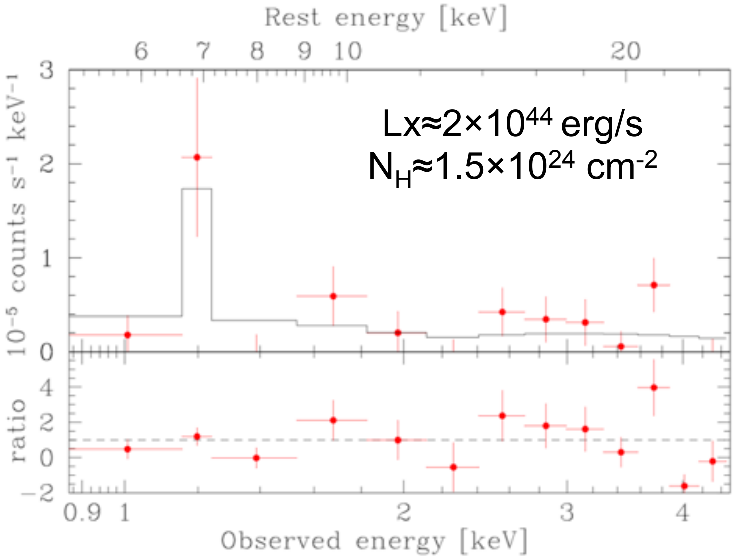
X-ray stacking in the CDF-S (7Ms) at the positions of CANDELS galaxies at z=3.5−6.5 (H<28)

- 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

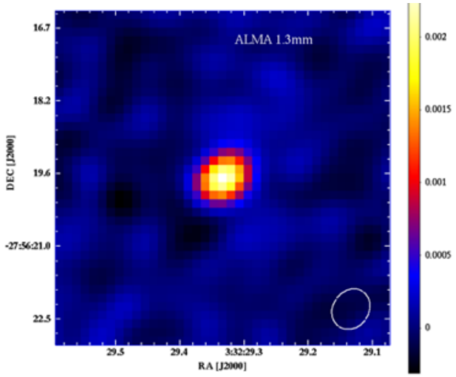
AGN at $z>3$. V. Compton-thick obscuration at $z=4.75$

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?





$L_X \approx 2\times10^{44}$ erg/s
$N_H \approx 1.5\times10^{24}$ cm^{-2}



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

$R_{half,\ dust}=(0.9\pm0.3)$kpc
$M_{dust}\approx5\times10^8\ M_\odot$ ($T_{dust}\approx60$K)
$M_{H2+HI}\sim1.6\times10^{10}\ M_\odot$

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

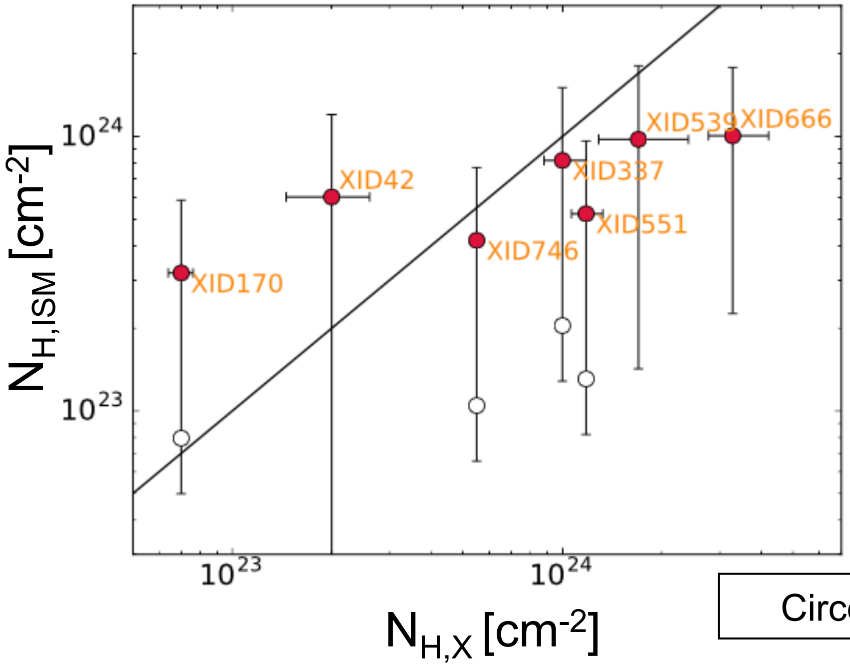
ISM in the host of obscured AGN likely responsible for at least part of the X-ray obscuration

(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

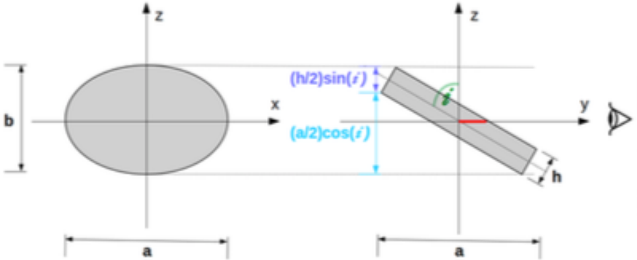
$N_{H,X}$ from X-ray spectra (using appropriate torus models and 7Ms CDF-S spectra)

$N_{H,ISM}$ 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)

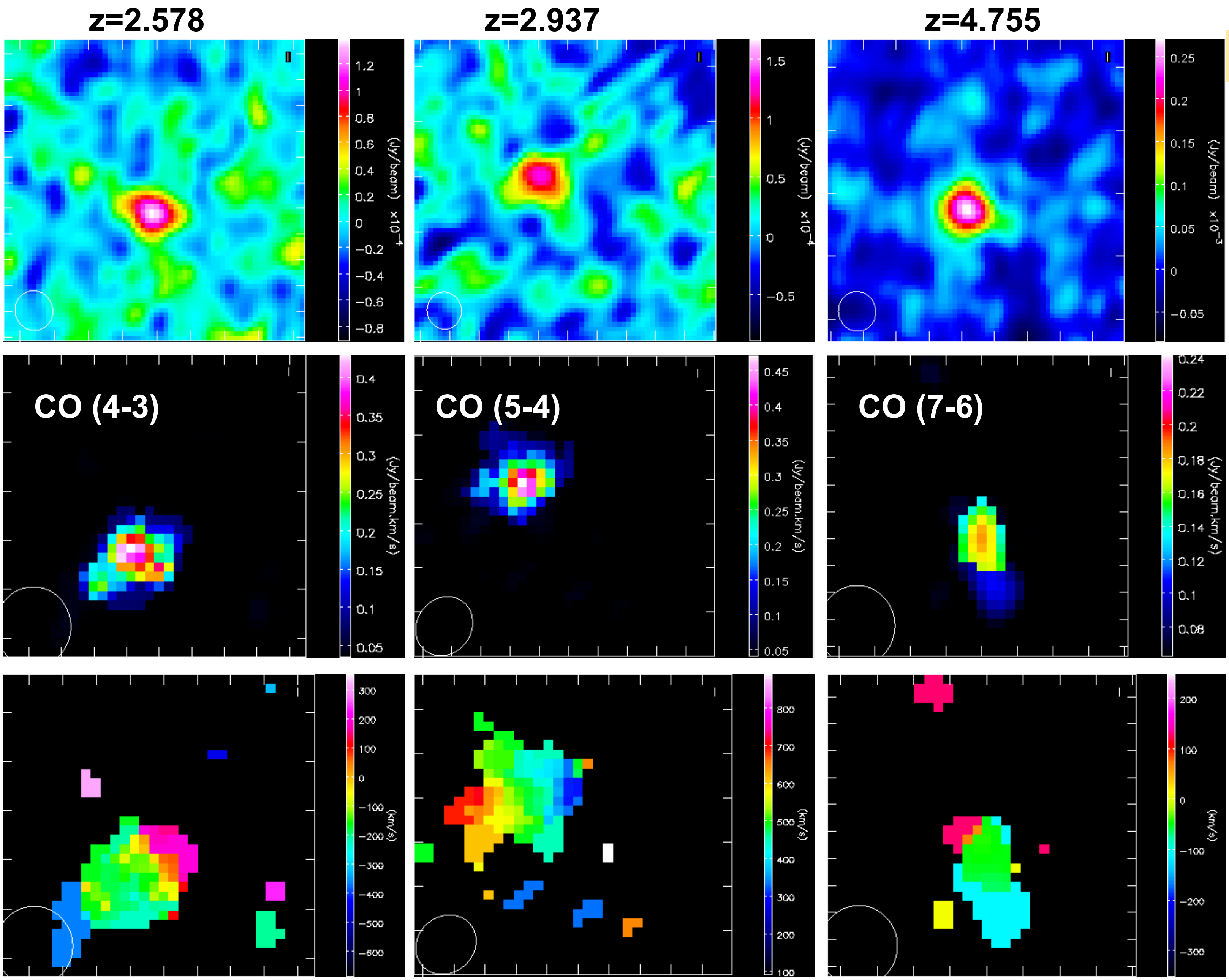


D'Amato et al. (2020)

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


z=2.578

z=2.937

z=4.755

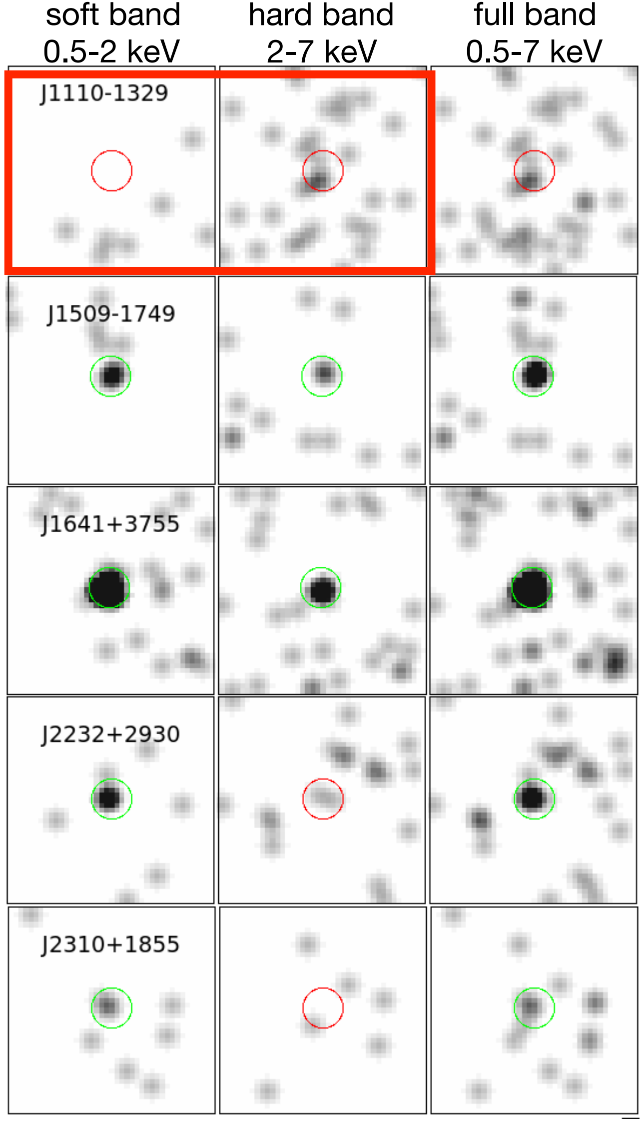
Continuum

CO
emission

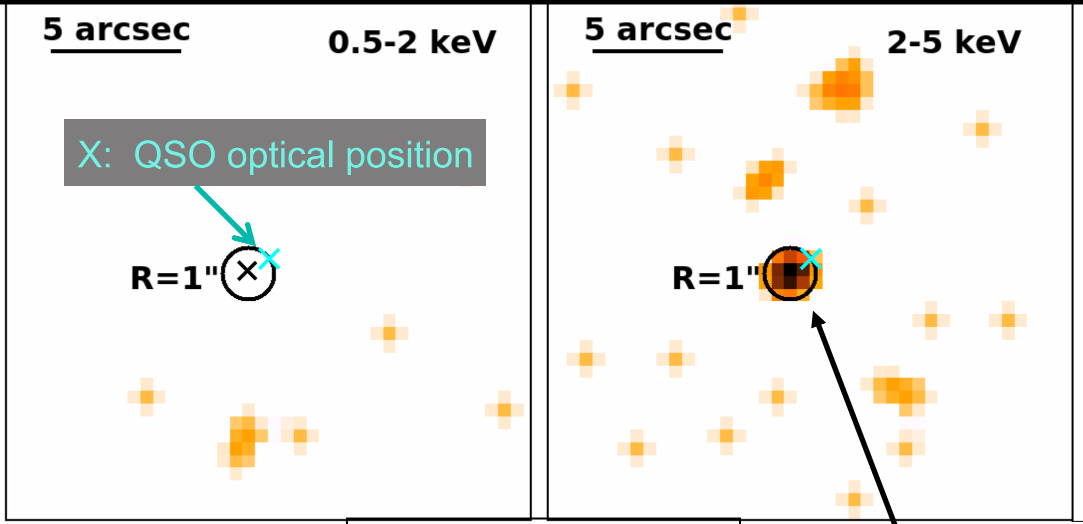
CO
Velocity
M_{H2}~a
few×10^{10} $M_\odot$
Size~kpc

AGN at z>3. VIII. Obscured AGN at z~6?

The case of PSO167-13 at z=6.515

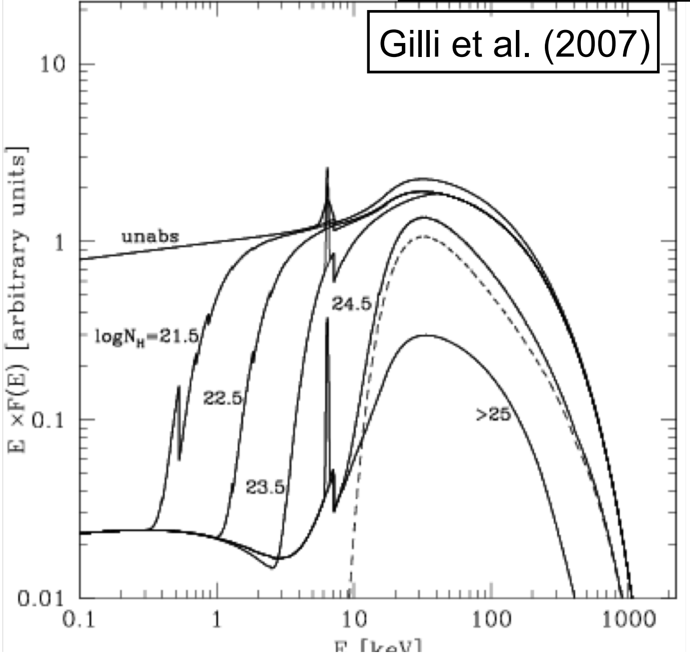


Vito et al. (2019b)



Vito et al. (2019a)

3 photons (59ks; P=0.9996, Weisskopf+07)

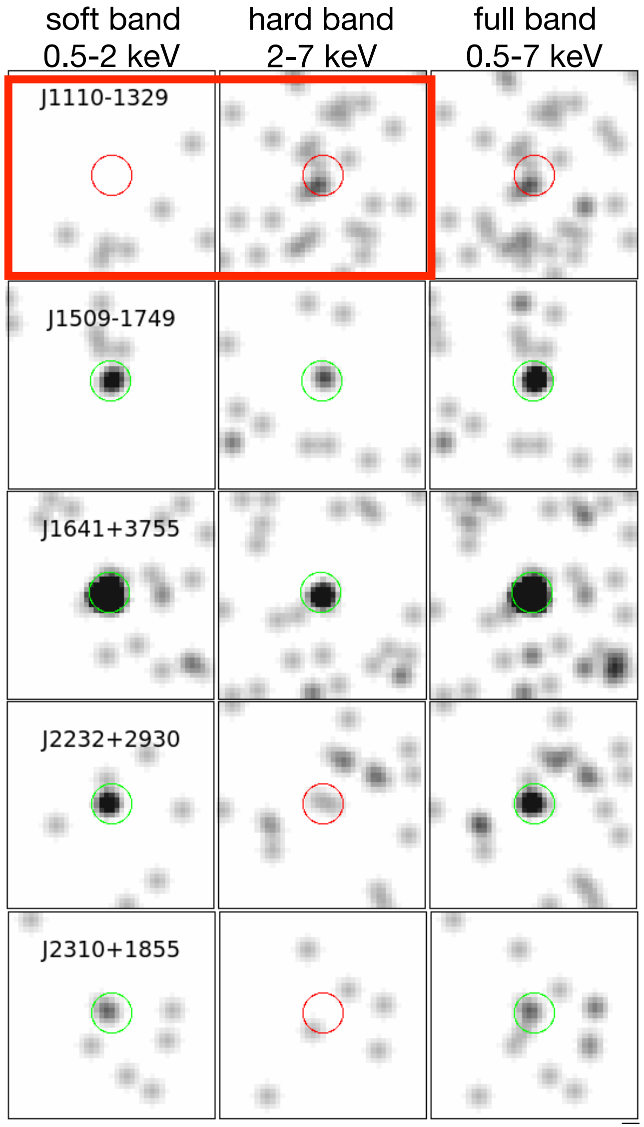


Gilli et al. (2007)

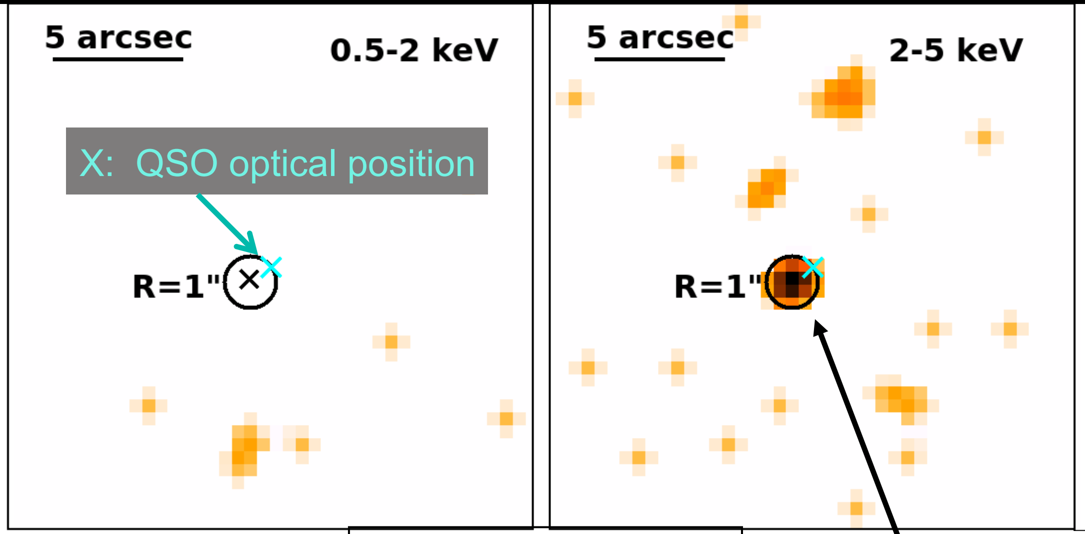
Relative emission
in soft and hard bands
gives indications
of absorption level

AGN at z>3. IX. Obscured AGN at z~6?

The case of PSO167-13 at z=6.515



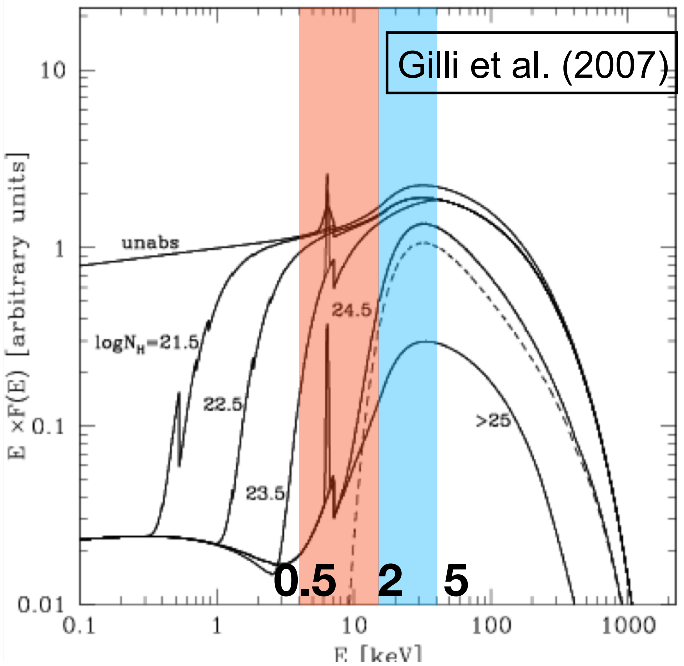
Vito et al. (2019b)



X: QSO optical position

Vito et al. (2019a)

3 photons (59ks; P=0.9996, Weisskopf+07)



Gilli et al. (2007)

$N_H > 2 \times 10^{24}$ cm^{-2}
at 68% confidence level

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

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

see also Connor et al. (2019)

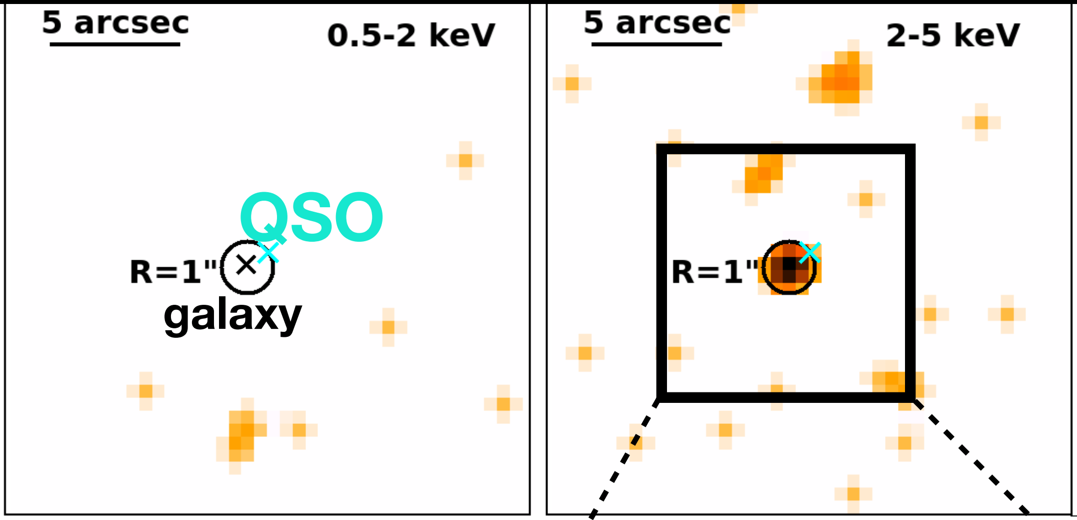
AGN at z>3. X. Obscured AGN at z~6?

The case of PSO167-13 at z=6.515

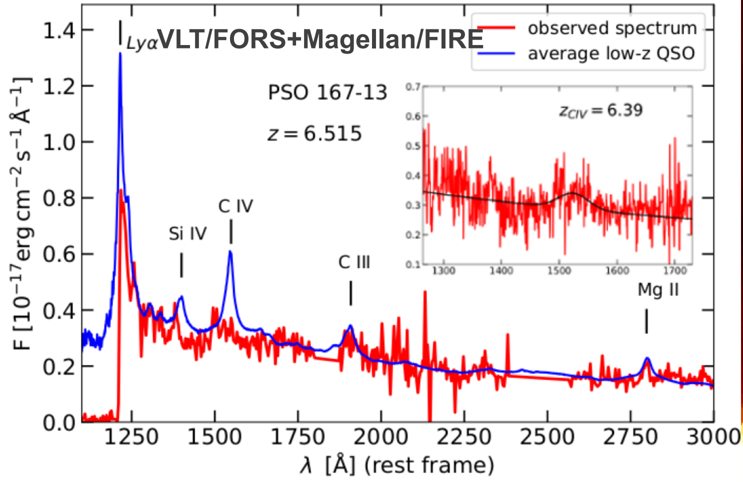
X-ray to optical/sub-mm offset of ~1 arcsec, but significant positional uncertainty

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

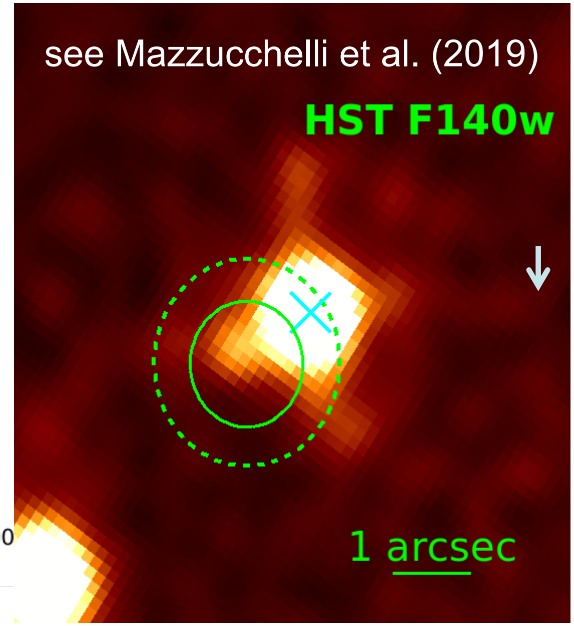
- WLQ?
- BALQSO?
- Changing look QSO?



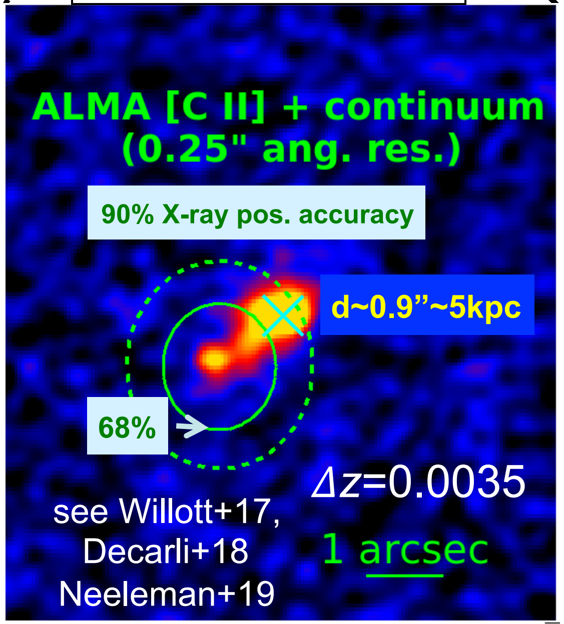
Vito et al. (2019a)



see also Venemans et al. (2015)



see Mazzucchelli et al. (2019)

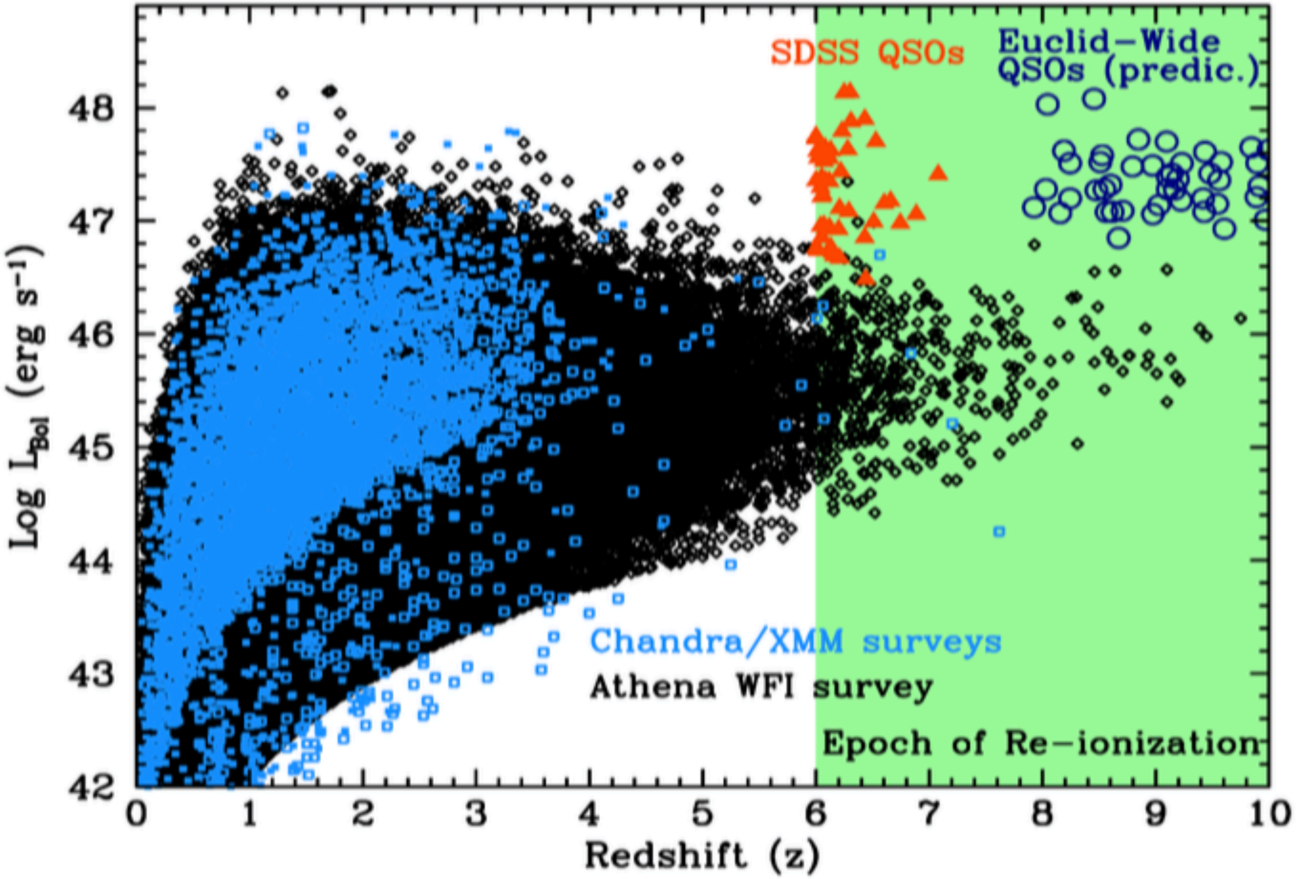


see Willott+17, Decarli+18 Neeleman+19

What’s next:
Hunting BHs at high redshift

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

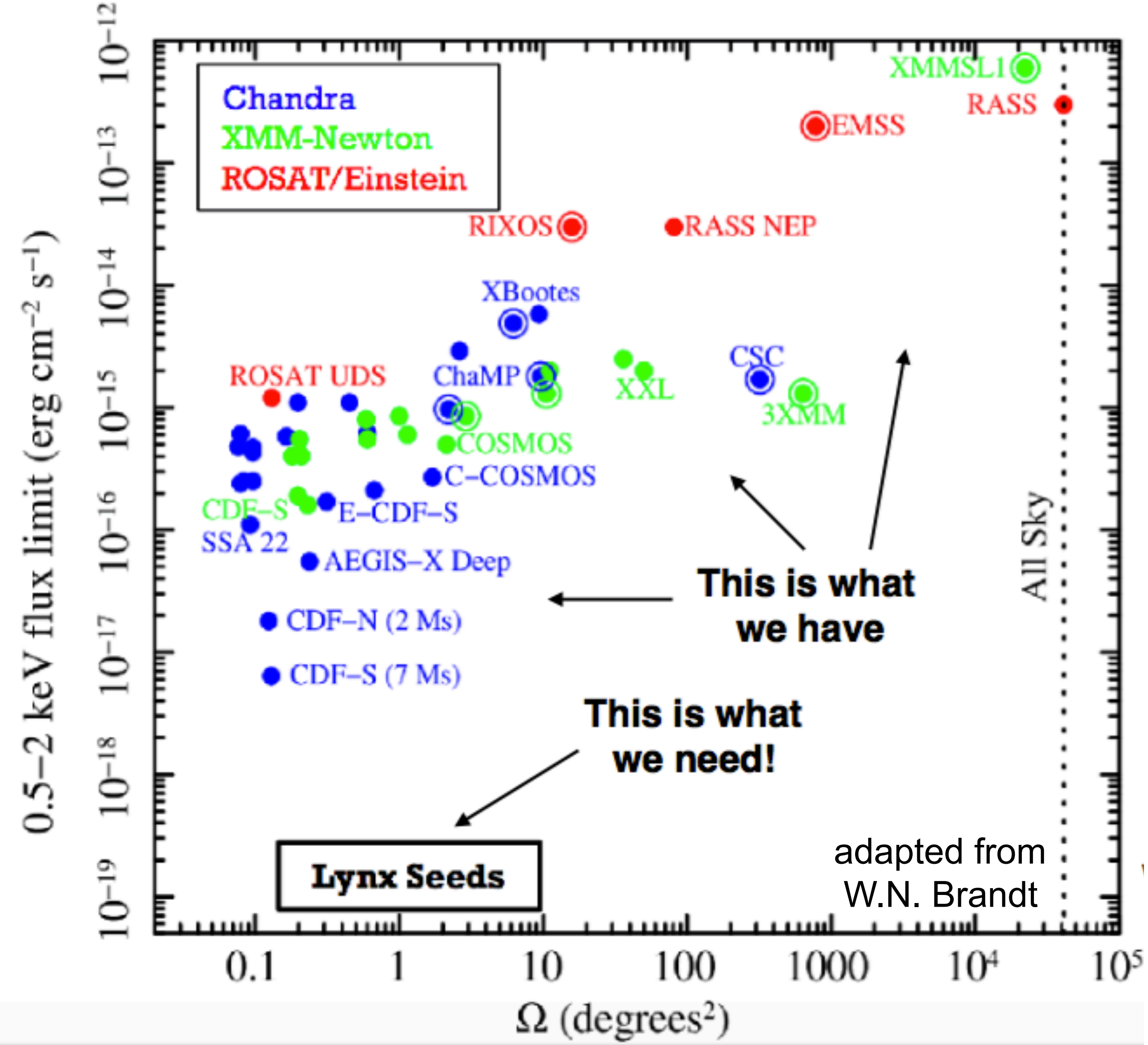
Athena, eROSITA, LSST, Euclid, JWST… then, hopefully, Lynx



see Aird+13,
Reynes & Comastri 16

Athena (~2030): 400 QSOs at z>6 (half likely obscured)

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



adapted from W.N. Brandt

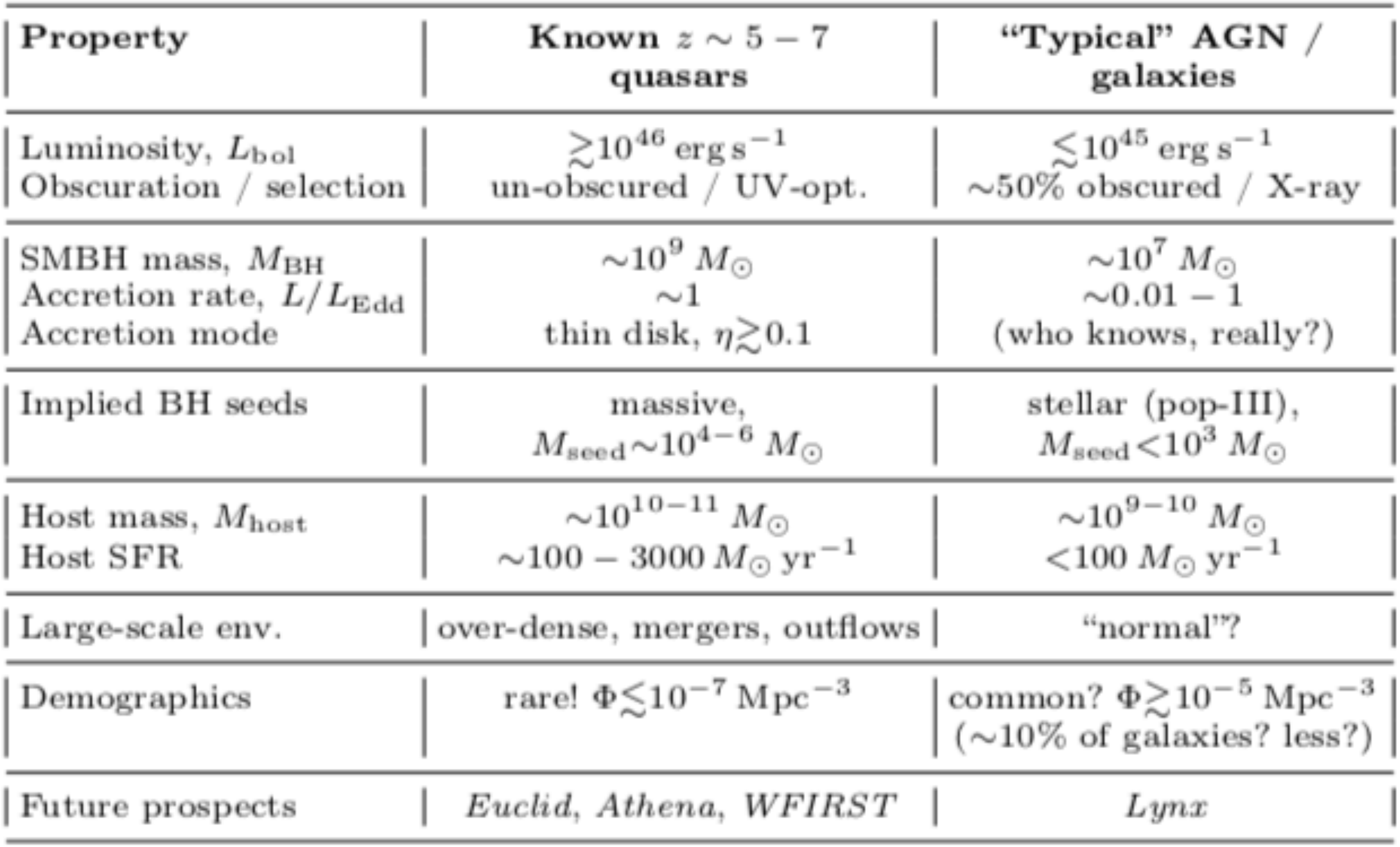
Lynx:
down to Lbol≈4×10^{42} erg/s at z=10 (assuming kbol=10)

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 ID)

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

Known properties and expectations



Property	**Known $z \sim 5-7$ quasars**	**“Typical” AGN / galaxies**
Luminosity, $L_{\rm bol}$	$\gtrsim 10^{46}$ erg s^{-1}	$\lesssim 10^{45}$ erg s^{-1}
Obscuration / selection	un-obscured / UV-opt.	~50% obscured / X-ray
SMBH mass, $M_{\rm BH}$	$\sim 10^{9}\,M_{\odot}$	$\sim 10^{7}\,M_{\odot}$
Accretion rate, $L/L_{\rm Edd}$	~1	~0.01 – 1
Accretion mode	thin disk, $\eta \gtrsim 0.1$	(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, $M_{\rm host}$	$\sim 10^{10-11}\,M_{\odot}$	$\sim 10^{9-10}\,M_{\odot}$
Host SFR	$\sim 100 - 3000\,M_{\odot}\,{\rm yr}^{-1}$	$< 100\,M_{\odot}\,{\rm yr}^{-1}$
Large-scale env.	over-dense, mergers, outflows	“normal”?
Demographics	rare! $\Phi \lesssim 10^{-7}$ Mpc^{-3}	common? $\Phi \gtrsim 10^{-5}$ Mpc^{-3} (~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 $z \approx 6$ 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
- ❑ 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