What observations tell us about the first black holes and AGN in the Universe

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In collaboration with many people …

Some open issues in early BH growth

- Formation and growth of $10^9\ M_{\odot}$ SMBH in less than 1 Gyr

  What are the BH seeds? (Cappelluti) Super-Eddington accretion? (Haardt) Role of mergers

- Are black holes too massive at high redshift wrt. their hosts? BHs seem to lead the formation of the bulge

  Dynamical masses still uncertain (Valiante), ALMA needed (Gallerani)

- Role of feedback at high redshift?

  Increasing observational evidence (Feruglio, Carniani, Gallerani)

- The obscured AGN fraction at high redshift

  Deep X-ray surveys are a powerful tool to unveil the obscured z=3−4 AGN population (Vito). Very limited information at z>5. Matter for *eROSITA* (Brusa) and *Athena* (Cappi)

- AGN content in HST-discovered high-redshift galaxies (candidates)?

  X-ray stacking, no signal yet, 7Ms CDF-S data soon

- Do bright high-redshift QSOs trace high-density fields?

  Promising results with LBT

- How did interactions between galaxies, AGN and the IGM at the end of the "Dark Age" shape the Universe we observe at later times?

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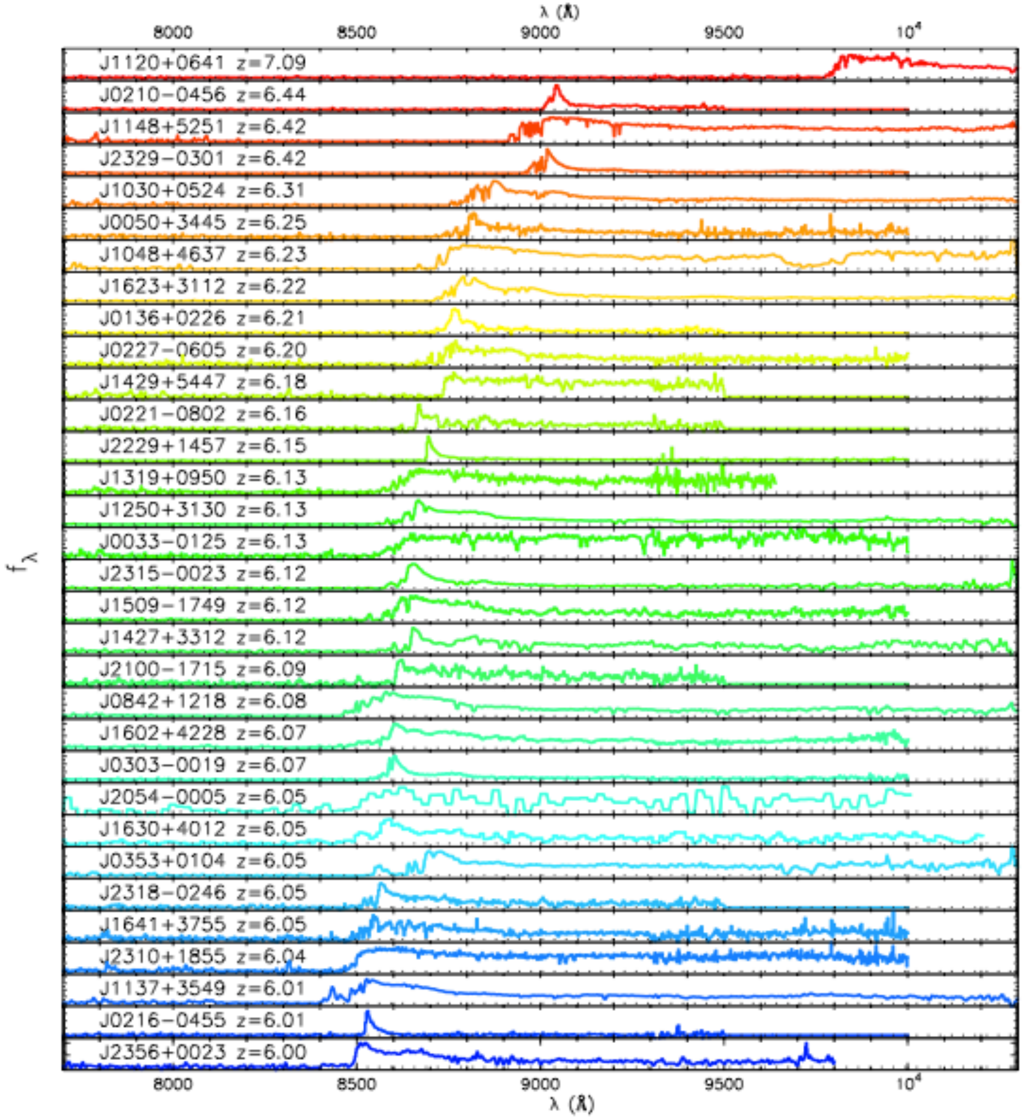
Are current theoretical models and simulations able to explain the observed AGN and galaxy properties at high z?

Part I:
Where do we stand?

Where do we stand. I. Quasar statistics



Fan+12

About **80 QSOs at z>5.7**

(SDSS, CFHQS, Pan-STARRS1)

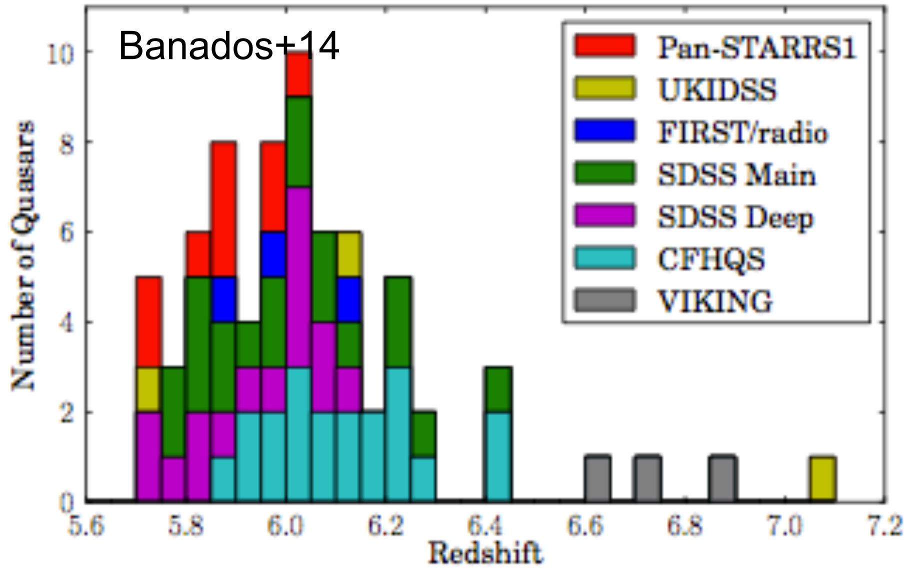
(Fan+00−06; Jiang+08,09; Willott+07,09,10; Banados+14)

including UKIDSS/VISTA (Mortlock+11; Venemans+13)

Less than one quarter with X-ray detections

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

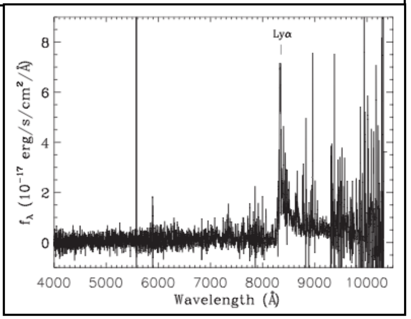
Faint end of the LF still to be achieved



Where do we stand? – II. Quasar statistics

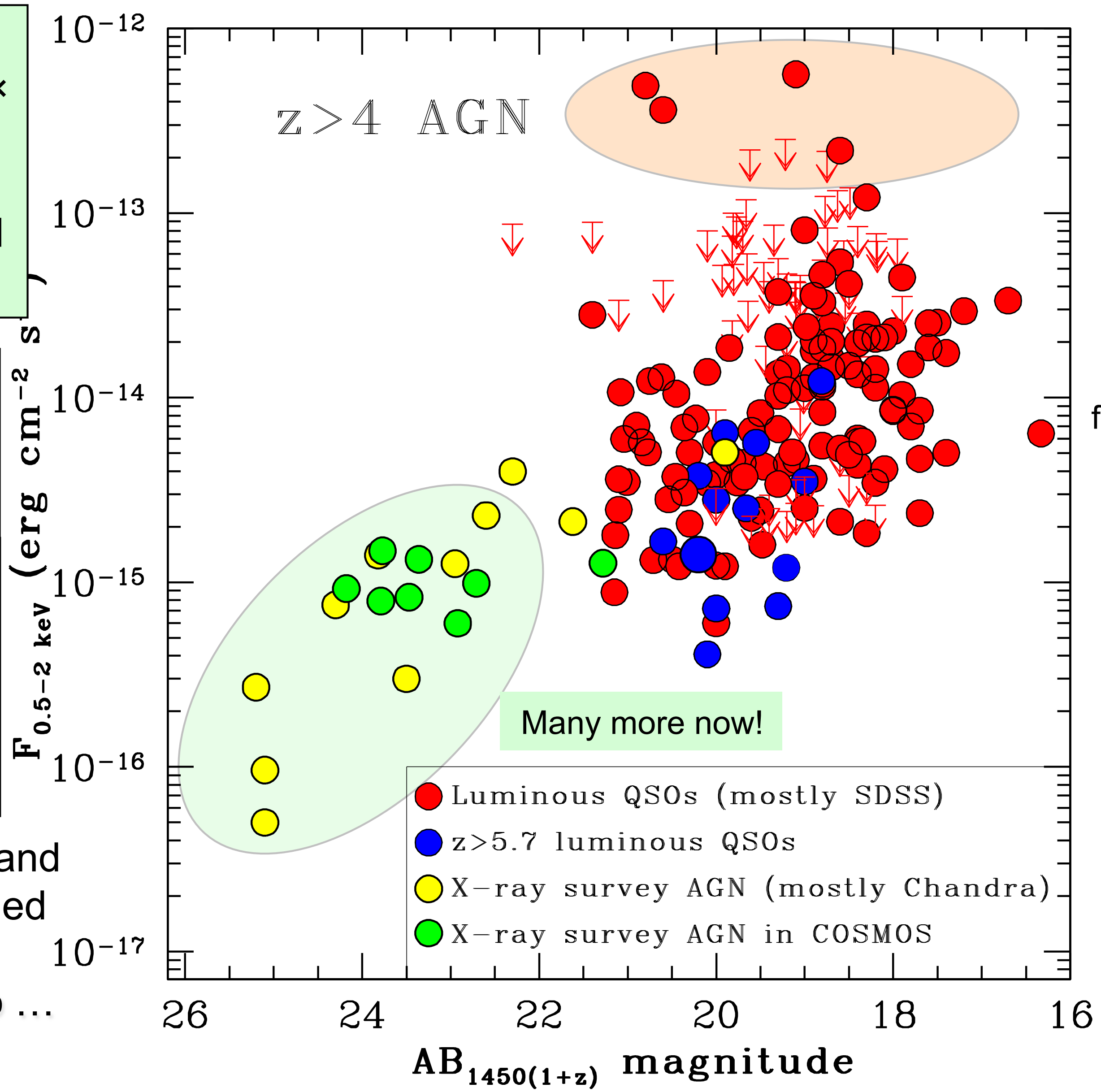
X-ray surveys still limited by sensitivity × solid angle.
Required to extend selection to obscured AGN

Highest-z QSO with X-ray identification: z=5.86 (LaMassa+13 – Stripe 82)



Deep optical/near-IR and X-ray coverage needed

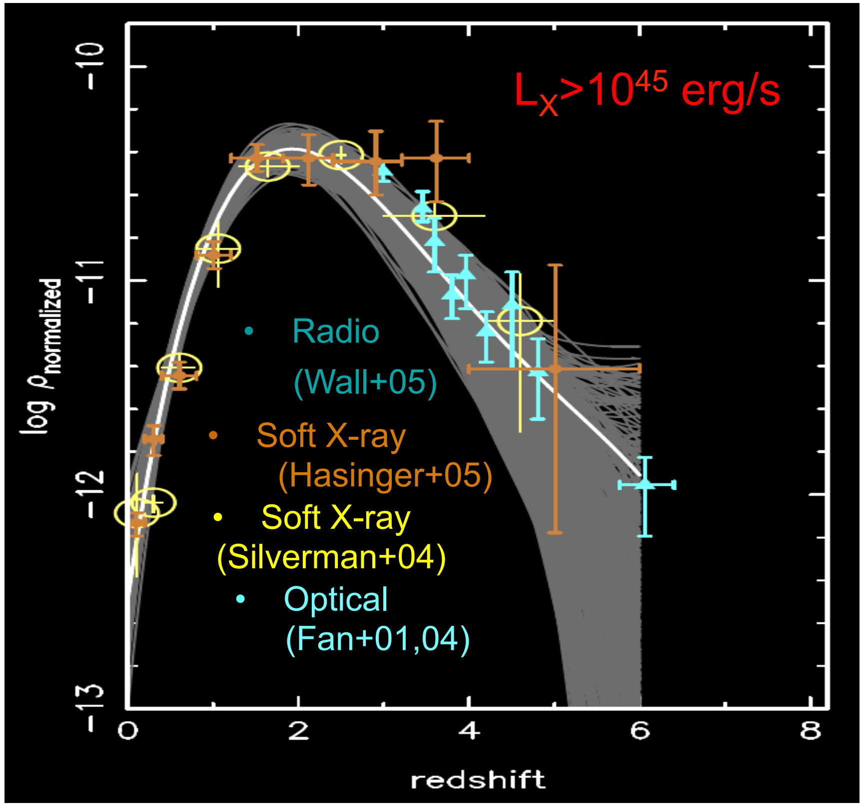
Where we need to go …

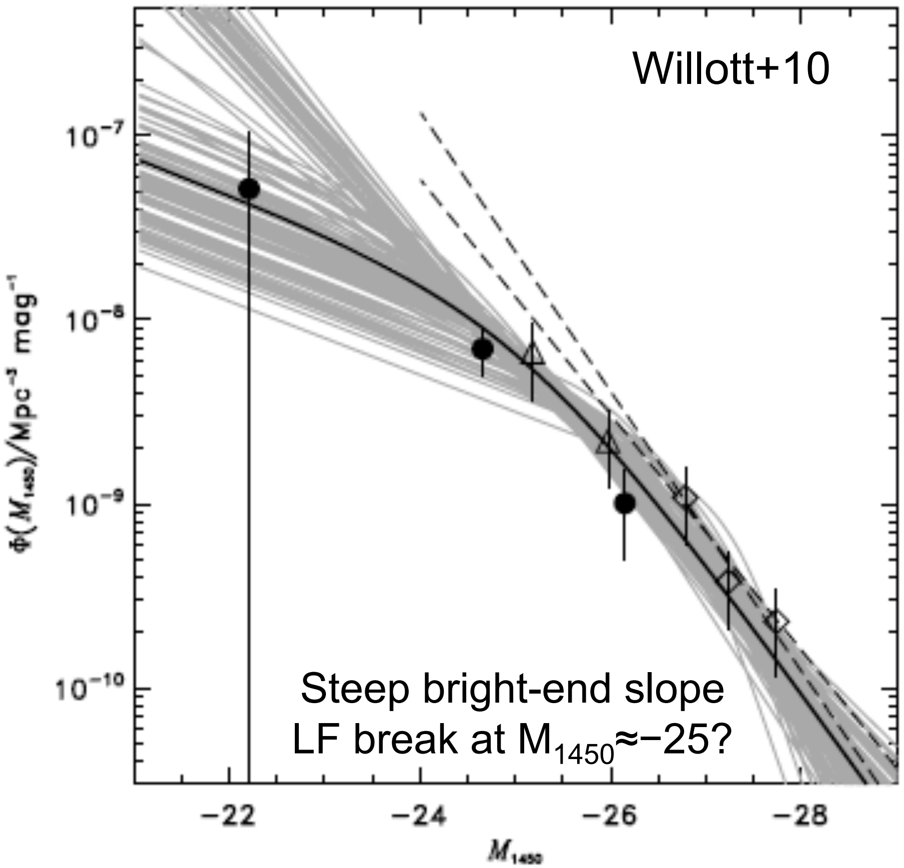


Kaspi et al. 2000
ROSAT

SDSS-like QSOs: few thousand at z>4

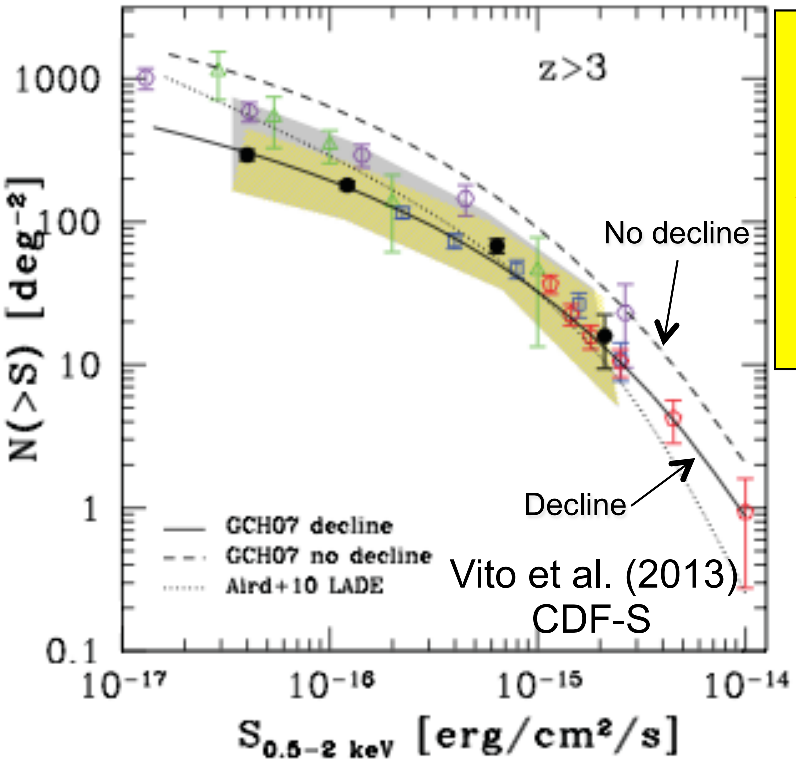
Where do we stand? − III. AGN evolution





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. Promising results from X-ray surveys

Where do we stand? – IV. AGN evolution



CDF-S 4Ms: Vito+13

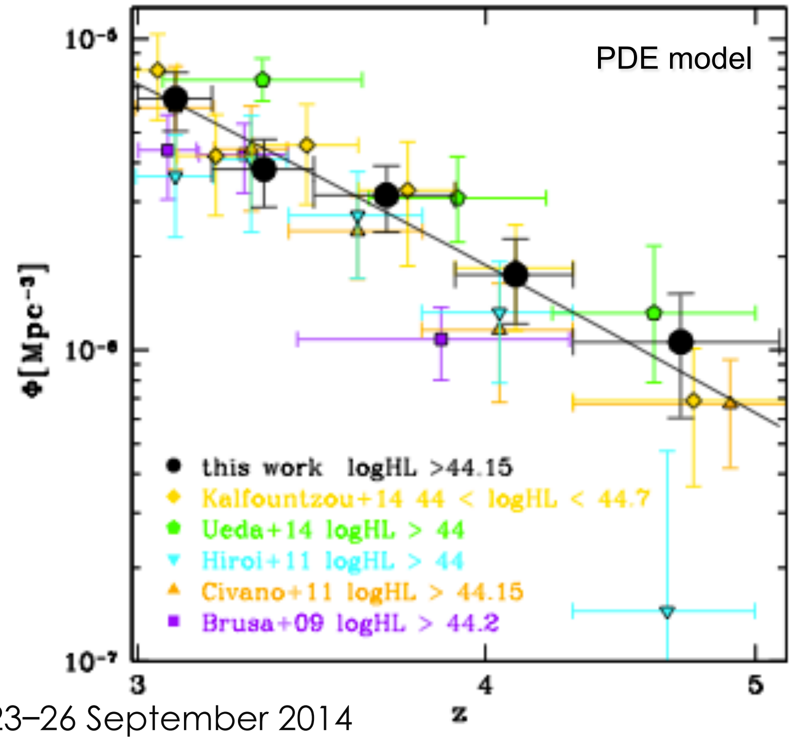
CDF-S 4Ms: Fiore+12

XMM-COSMOS: Brusa+09

C-COSMOS: Civano+11

CDF-S 4Ms: Lehmer+12

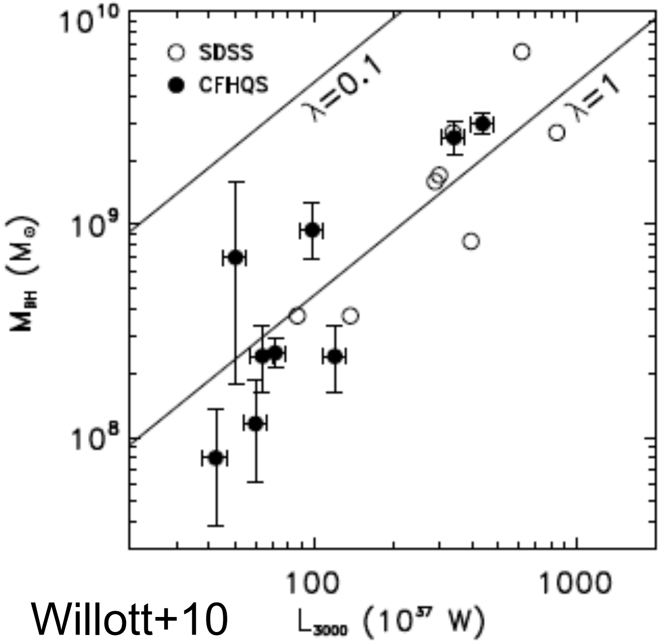
Vito et al. (2014)
CDF-S+COSMOS+SXDF
Log L_X≈43−45



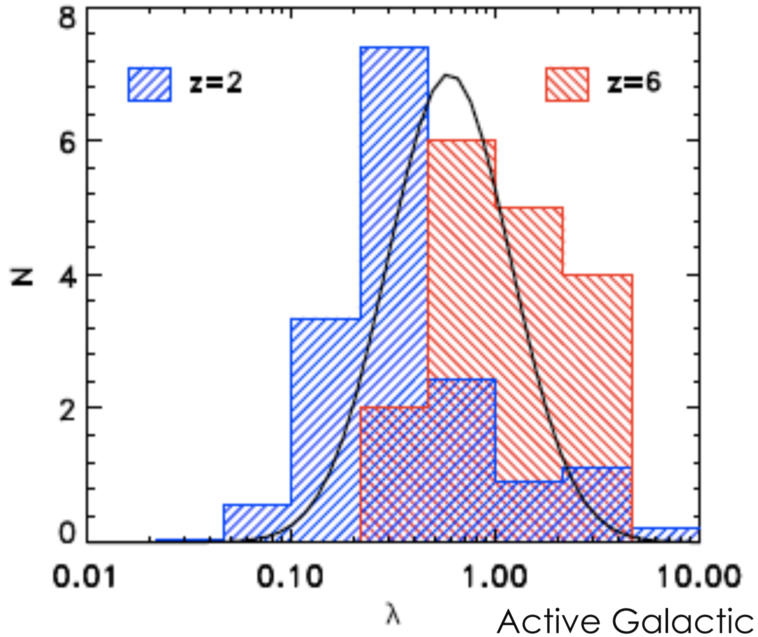
XMM/*Chandra*-COSMOS + CDF-S data consistent with the AGN decline scenario (see also Kalfountzou+14) – **Vito talk**

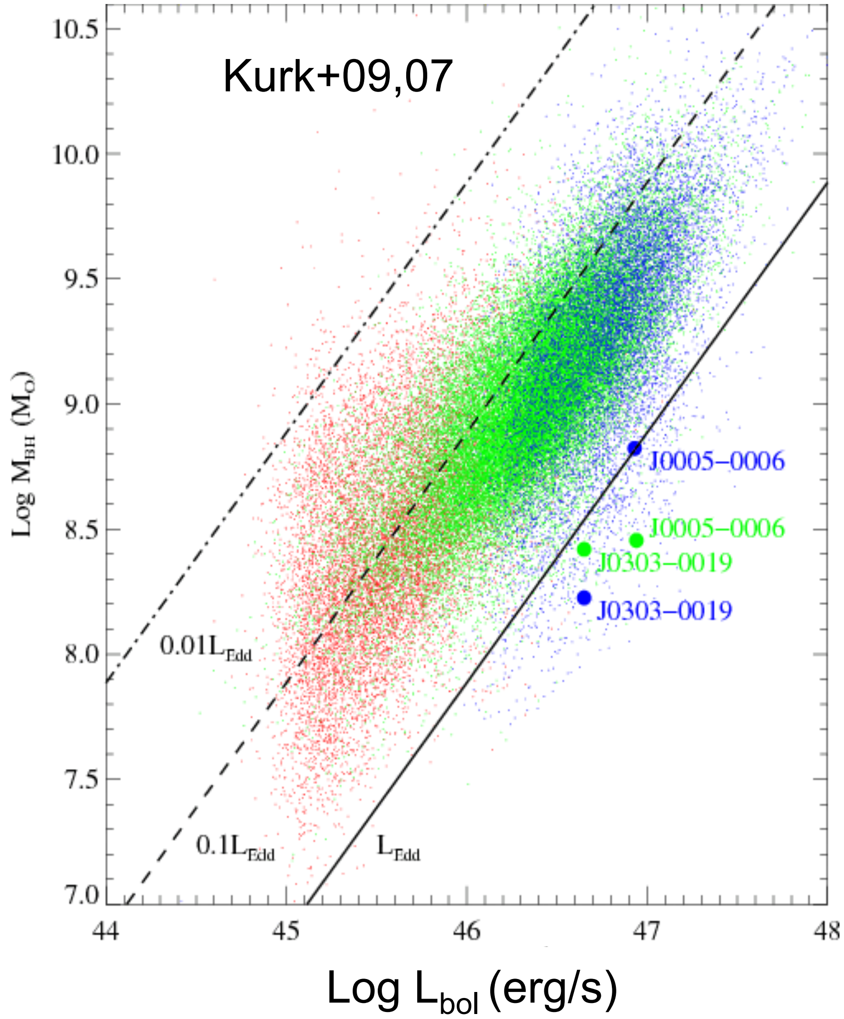
CDF-S allows probing the obscured (N_H≥10^{23} cm^{-2}) AGN population at z>3

Where do we stand? − V. Eddington ratios



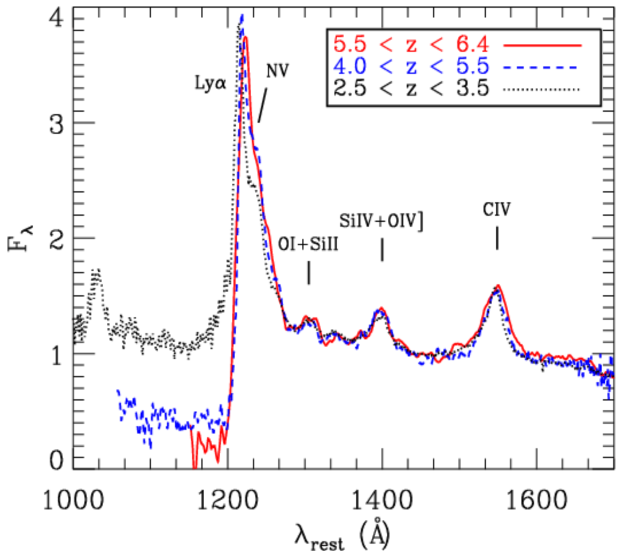
Willott+10





Large Eddington ratios in high-z QSOs

Where do we stand? – VI. Fast metal enrichment



BLR enrichment

(Juarez+09; see also Dietrich+; […])

High metallicities at very high redshift

➔ early chemical enrichment: the host galaxy has undergone a vigorous star formation

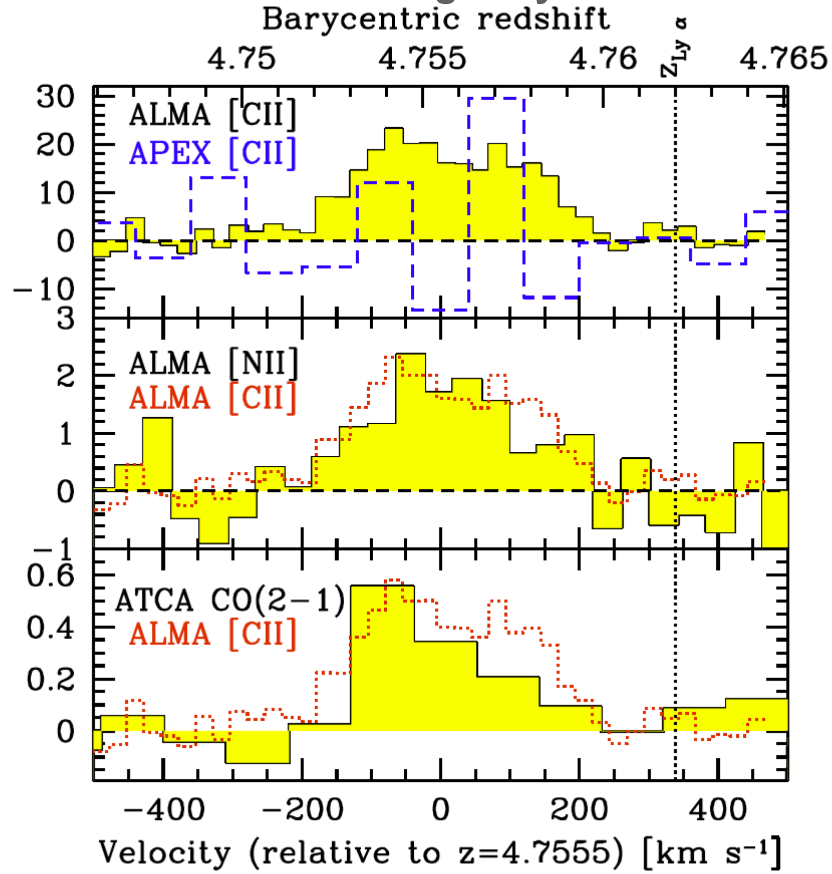
BUT BH-to-galaxy mass ratio at least one order of magnitude larger than observed locally
The ISM has already reached super-solar metallicities but >90% of the final stellar mass has still to be formed to reach the local $M_{BH}/M_\star$ relation
(***BHs grow 'faster' than their host galaxies***)

First galaxy with both $[CII]_{158\mu m}$ and $[NII]_{205\mu m}$ detections at very high redshift
➔ physical properties of the gas (e.g., metallicity) in a dusty environment

De Breuck+13

host-galaxy enrichment

ALMA, IRAM, VLA
atomic/molecular results

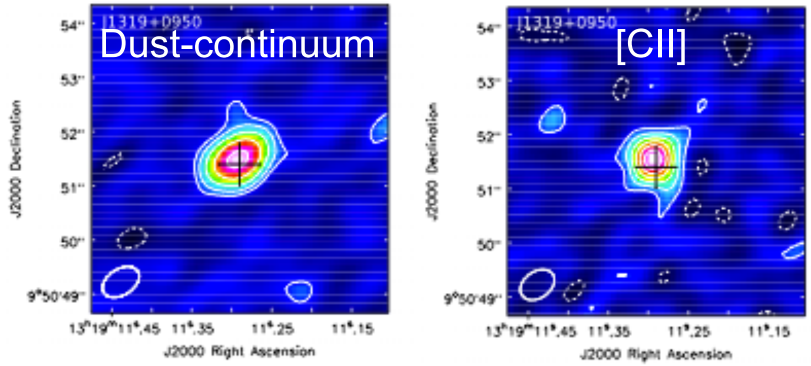


Where do we stand? – VII. QSO vs. galaxy growth (a)

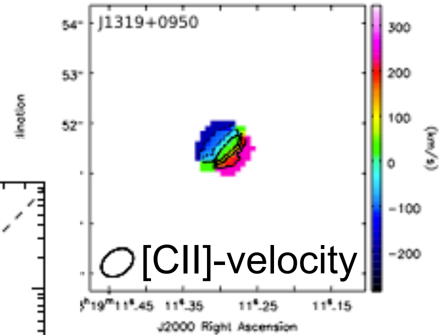
Dynamical studies via CO emission

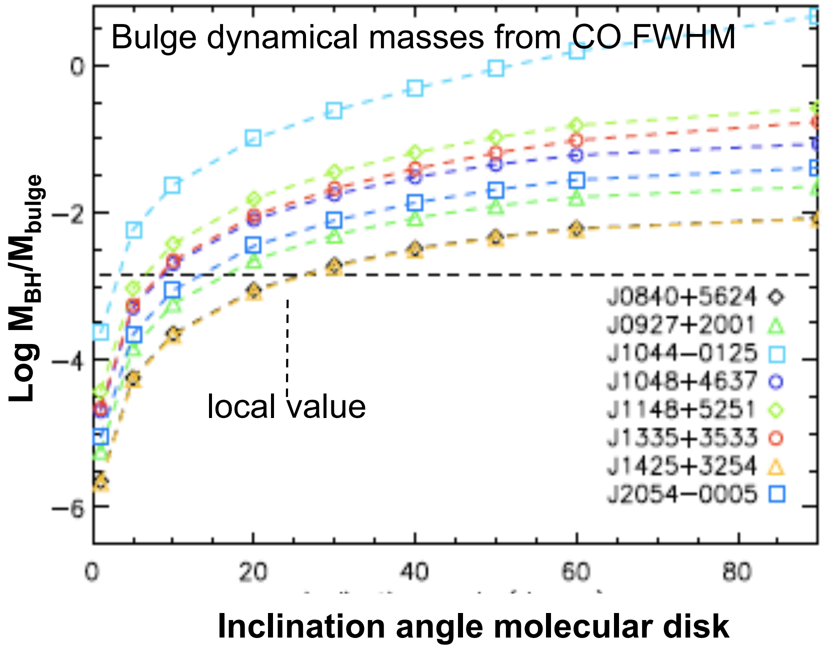
see talks by Gallerani, Valiante

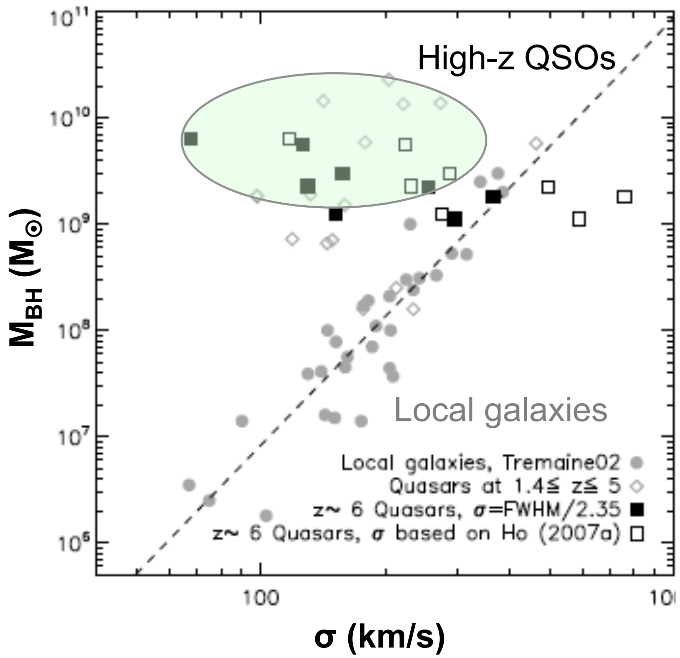
- Few kpc sizes (from resolved CO and [CII] emissions)
- Dynamical masses ≈10^{10-11} $M_\odot$ (see compilation by Calura+14) – BUT $\sin^2(i)$ uncertain
- BH formed earlier than galaxy assembly finished?
- Signature of possible mergers

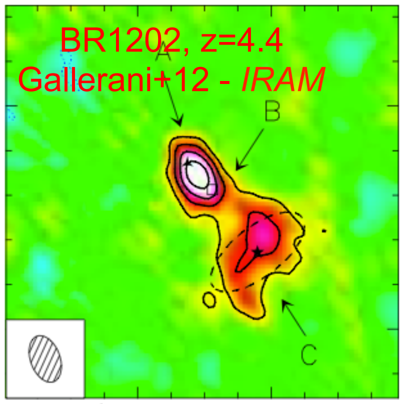


ULAS 1319: z=6.13 (Wang+13) – *ALMA*









Where do we stand? – VII. QSO vs. galaxy growth (b)

Outflows predicted by some models of early BH/galaxy co-evolution. Provide feedback on host, quenching SF in SDSS J1148 (e.g. Valiante+11,12). May be ubiquitous features

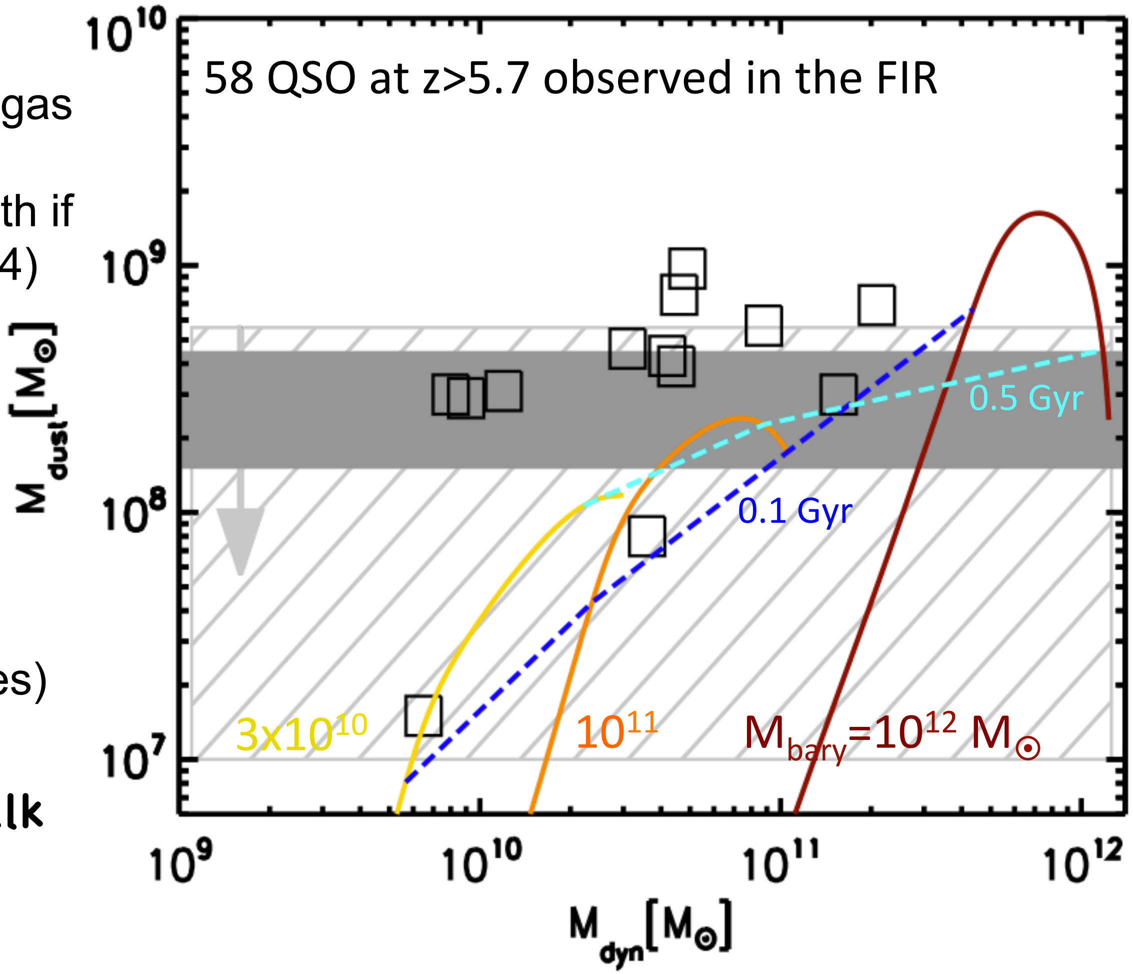
Chemical evolution models for forming protospheroids successfully explain SFR, gas and dust content of hosts for standard assumptions on IMF, SFE, and grain growth if $M_\star > 10^{11}$ $M_\odot$ (e.g., Valiante+11,Calura+14)

In some systems tension between M_{dust} and M_{dyn} unless changing IMF (top-heavy), SFE (higher), grain growth (enhanced)

Can M_{dyn} be underestimated?
(would bring $M_{BH}/M_\star$ closer to local values)

See also Valiante+14 and ***Valiante's talk***

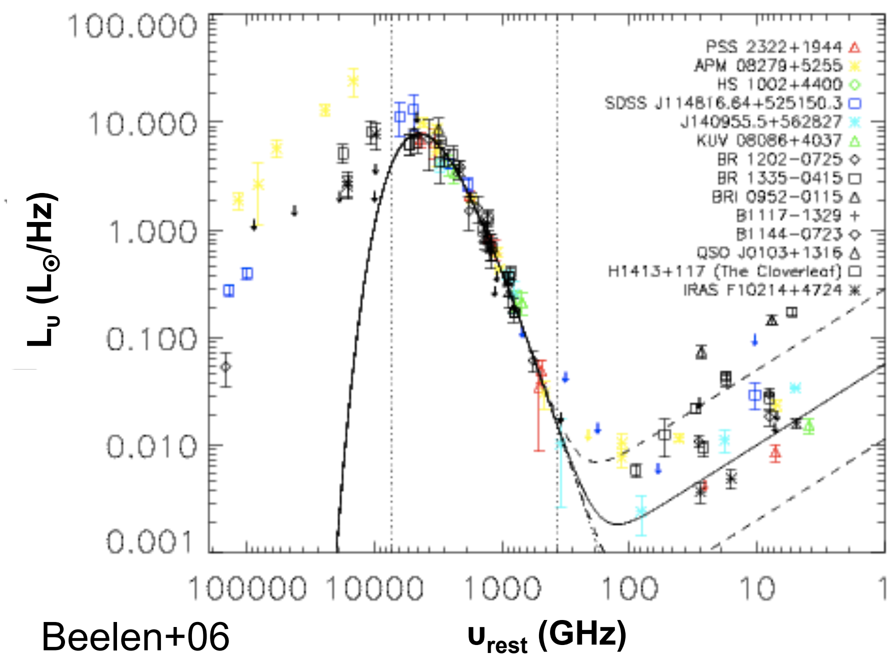
Calura+14



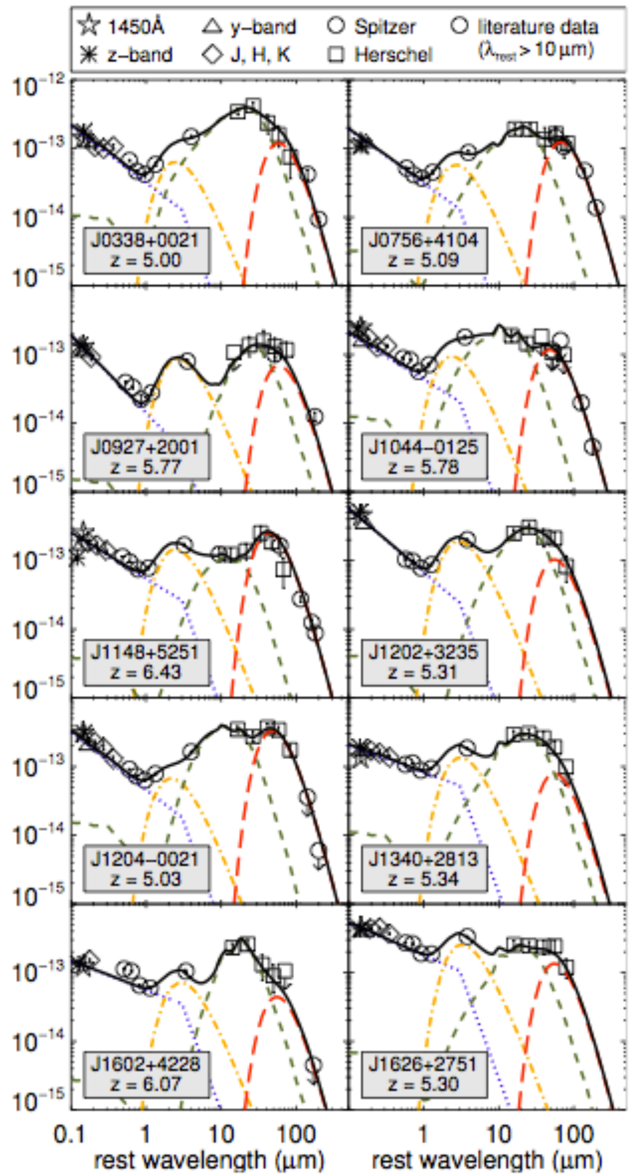
Where do we stand? − VIII. High star-formation activity

Significant star formation at high redshift

- ≈ 30% of z≈6 QSOs detected in the sub-mm/mm (down to 1 mJy level) − see also recent *ALMA* results
- L_{FIR}≈10^{13} $L_{\odot}$,T≈40−60 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)?



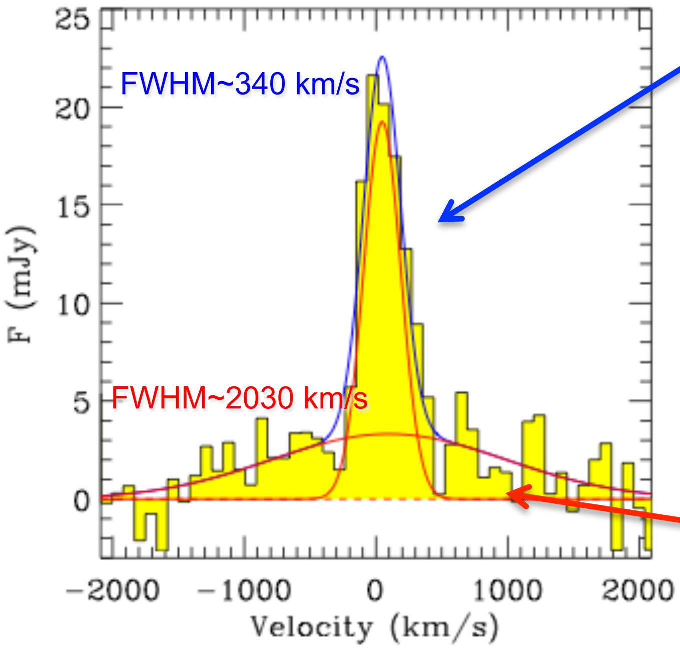
Beelen+06



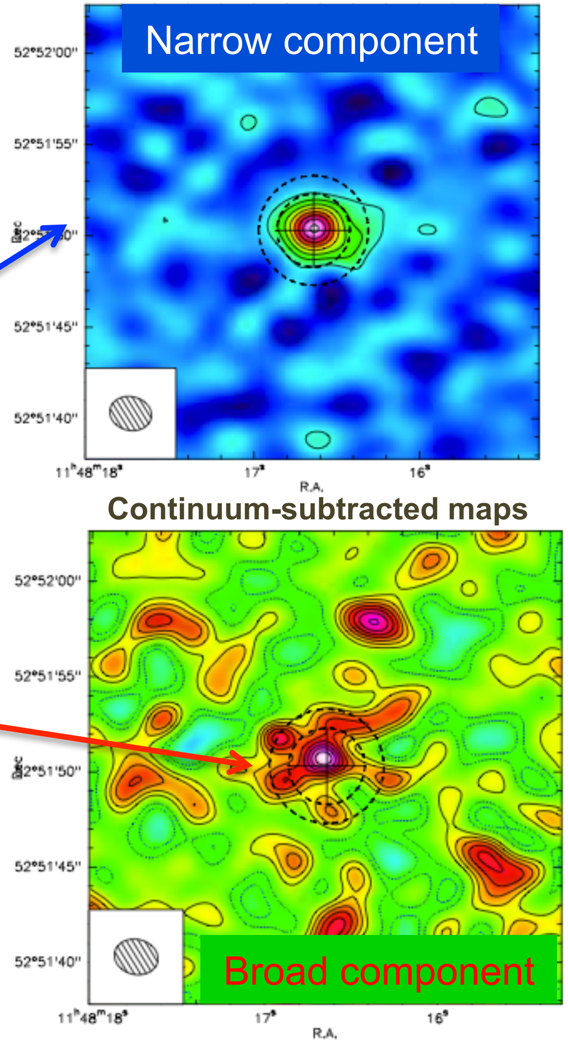
Leipski+14

Where do we stand? – IX. The role of AGN feedback

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



Maiolino et al. 2012



Evidence of feedback at low and intermediate redshifts from neutral/ ionized gas (e.g., Feruglio+10, Alexander+10, Brusa+14)

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

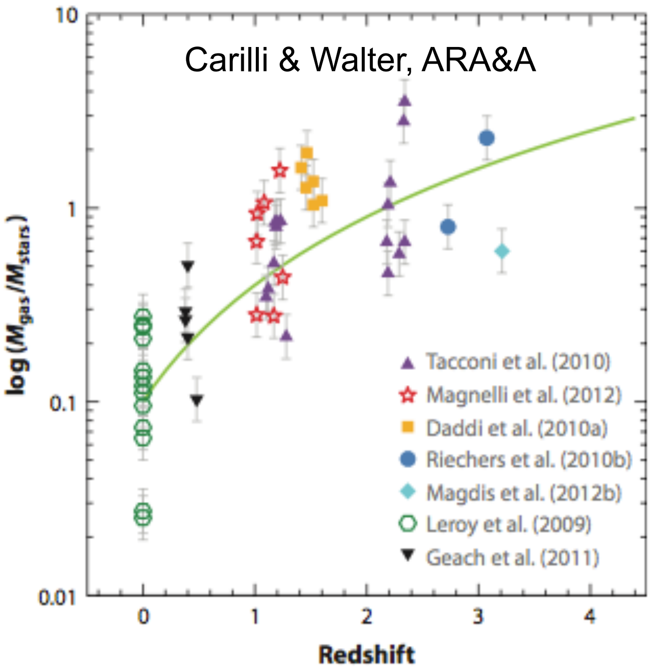
see Cicone+14 ([CII]): multiple outflow events during the past 100Myr? Extension up to 30kpc

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

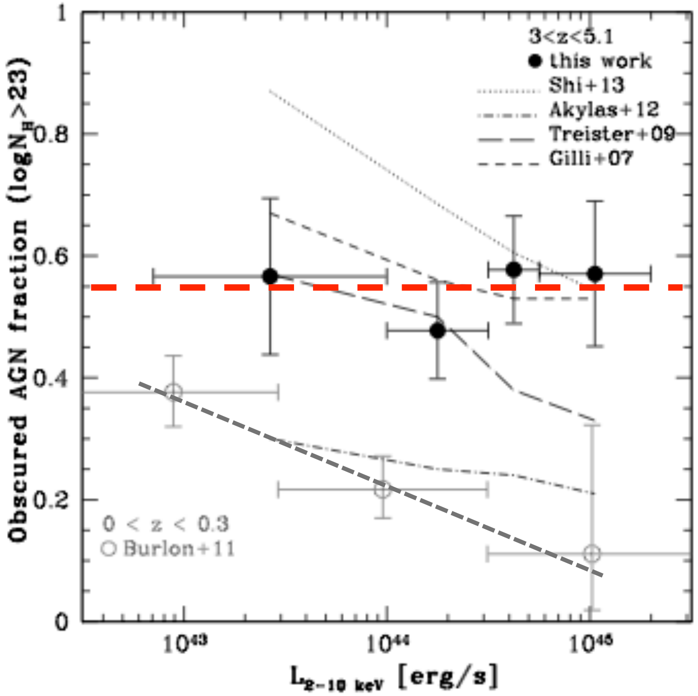
Where do we stand? − X. Obscuration

The evolution of the obscured AGN fraction over cosmic time has been a debated issue since almost a decade (Ueda, La Franca, Gilli, Hasinger, Treister, …) − see also Merloni+14



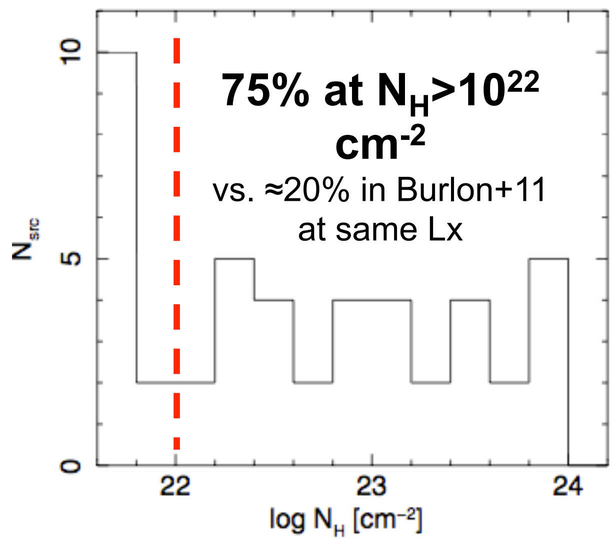
Large quantity of gas available at high redshift

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



z>3 AGN: 54% with $N_H>10^{23}$ cm^{-2}

Vito+14



XMM-CDFS, 3Ms, **z=1.7−3.7**

Iwasawa+12

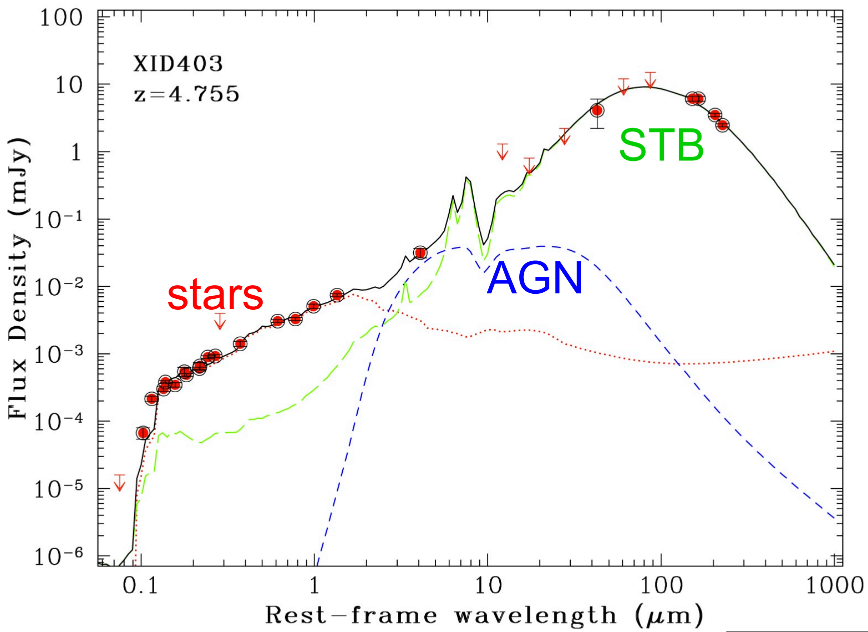
Higher merger rate and more gas available for the accreting SMBHs at high redshift

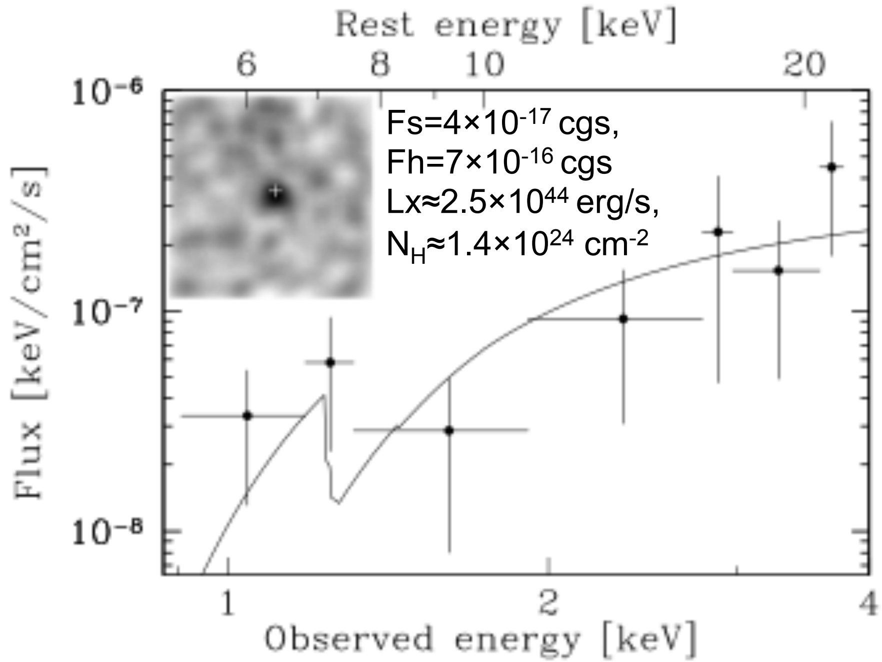
The same gas sustaining strong SF at high redshift may be responsible for the obscuration (Gilli+14)

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

Part II:
Intriguing cases at high redshift

Compton-thick accretion and star formation at high z: The case of LESS73 at z=4.75





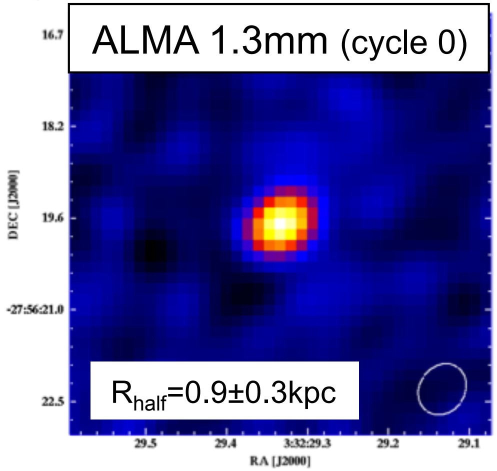
Gilli et al. 2011, 2014

$L_{STB} \approx 2\times10^{46}$ erg/s – $L_{AGN} \approx 7\times10^{45}$ erg/s
$M_\star \approx 1.1\times10^{11}\ M_\odot$ – $M_{H2} = 1.6\times10^{10}\ M_\odot$;
$M_{dust} \approx 5\times10^{8}\ M_\odot$ – $T_{dust} \approx 60K$
see also De Breuck+14, Coppin+10, Nagao+12

$SFR \approx 1000\ M_\odot$/yr
$\Sigma_{SFR} > 26\ M_\odot/yr/kpc^2$

Compact starburst, possibly responsible for the X-ray obscuration

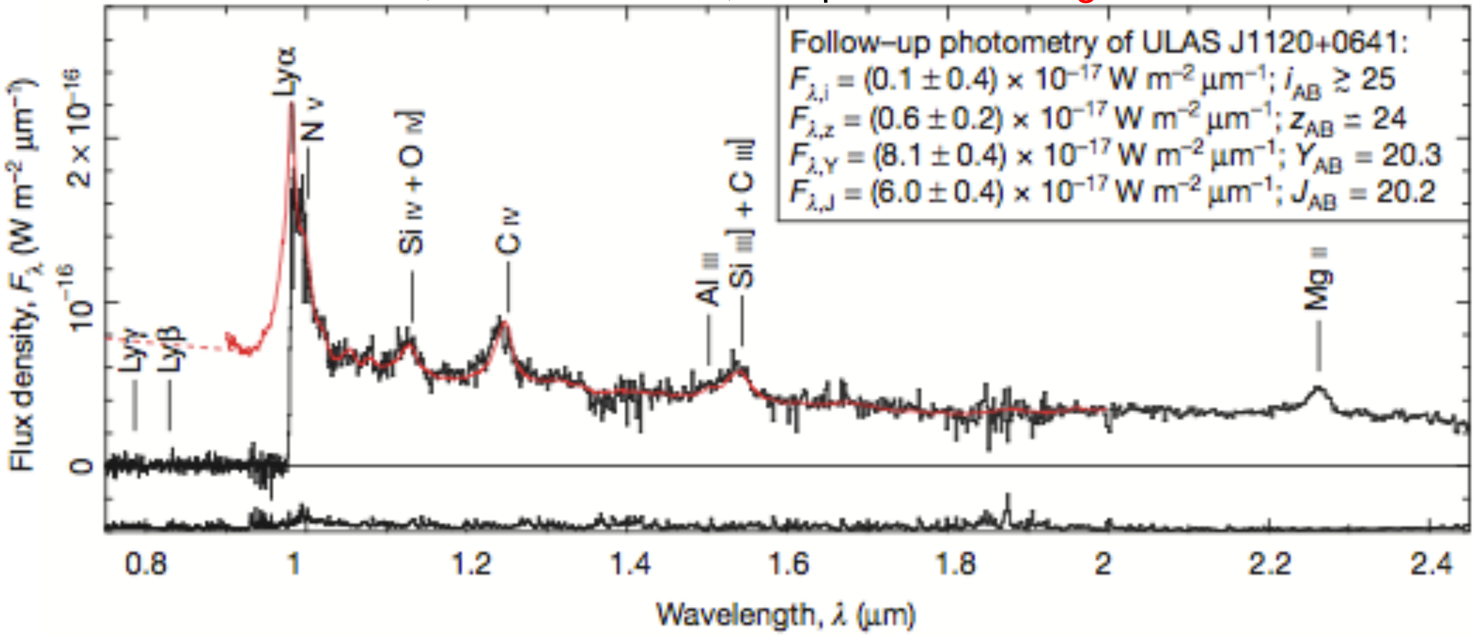
Progenitor of compact quiescent massive galaxies at z≈3



Challenging and time-consuming
Need >Ms exposures
4Ms → 7Ms soon in the CDFS

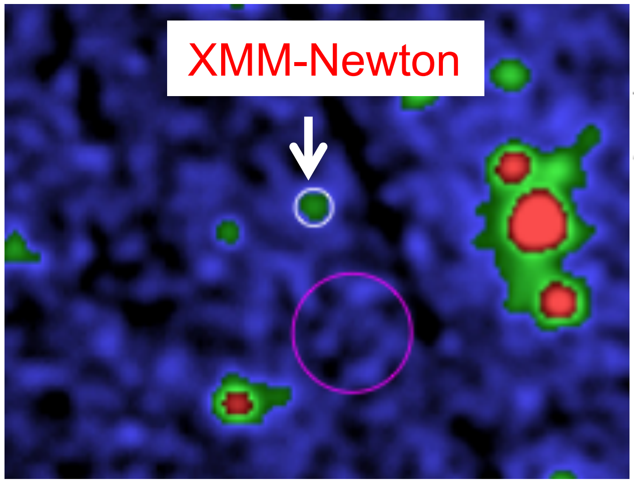
The highest redshift quasar known: ULAS J1120 at z=7.08

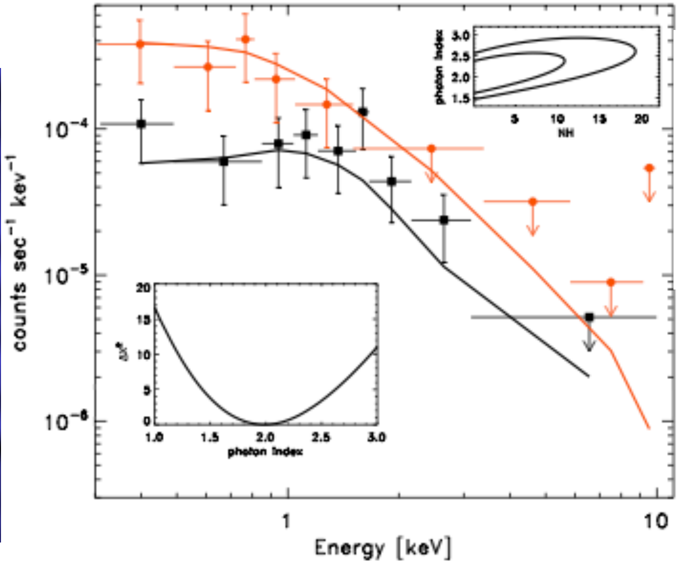
Mortlock et al. 2011, GNIRS+FORS2, compared to average z~2.5 SDSS QSOs

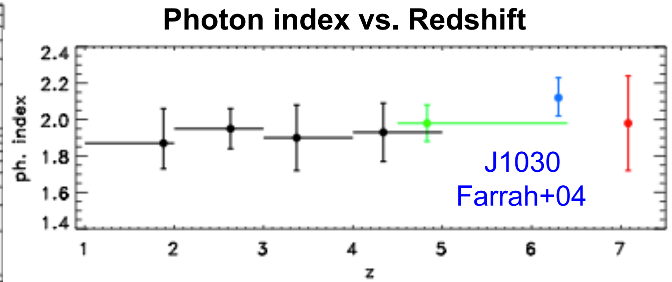


UKIDSS

M_{1450}=−26.6
M_{BH}=2.4×10^9 $M_\odot$
L_{bol}≈2.4×10^{47} erg/s
Already "mature" QSO







$L_{2\text{-}10keV}$≈6.7×10^{44} erg/s
QSO accreting at Eddington

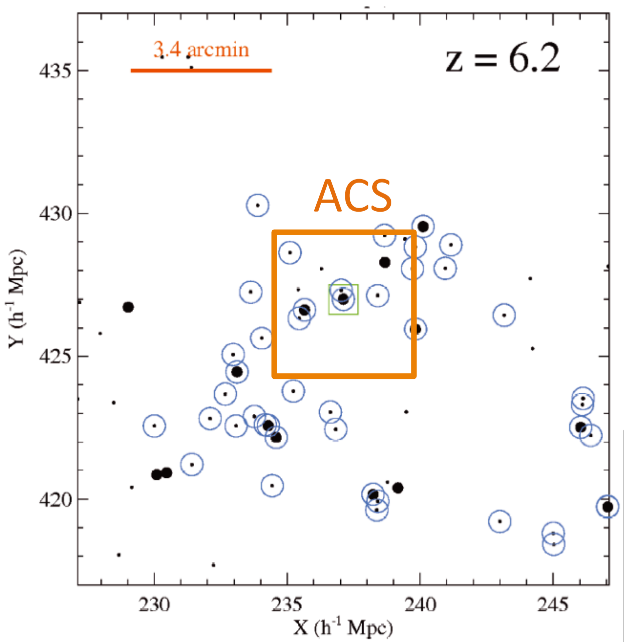
Moretti+14
(see also Page+14)

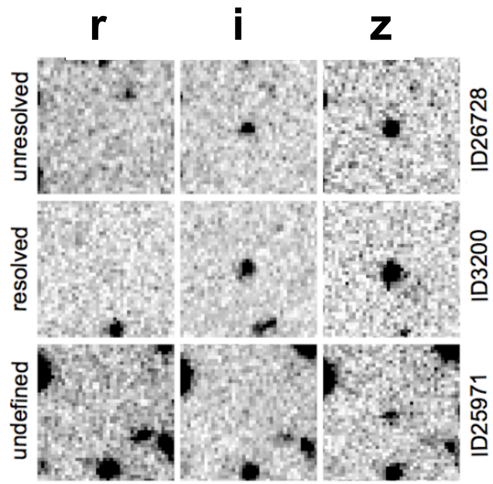
Part III:
The environment of z~6 QSOs

Where do high-z QSO live? – II. Need for large-scale observations

Search for source overdensities around z~6 QSO is inconclusive (Stiavelli+05, Kim +09, Husband+13, Banados+13, Simpson+14) BUT small FoV. ACS/HST = 3×3 arcmin^2 = 1x1 Mpc^2 at z=6

- Overdensities might extend up to 30 arcmin, i.e., 10 physical Mpc (Overzier+09)
- Feedback may limit galaxy formation in the QSO vicinity (e.g. Stroemgren radius ≈2−4 Mpc) − stellar wind feedback?





i-z drop-out selection

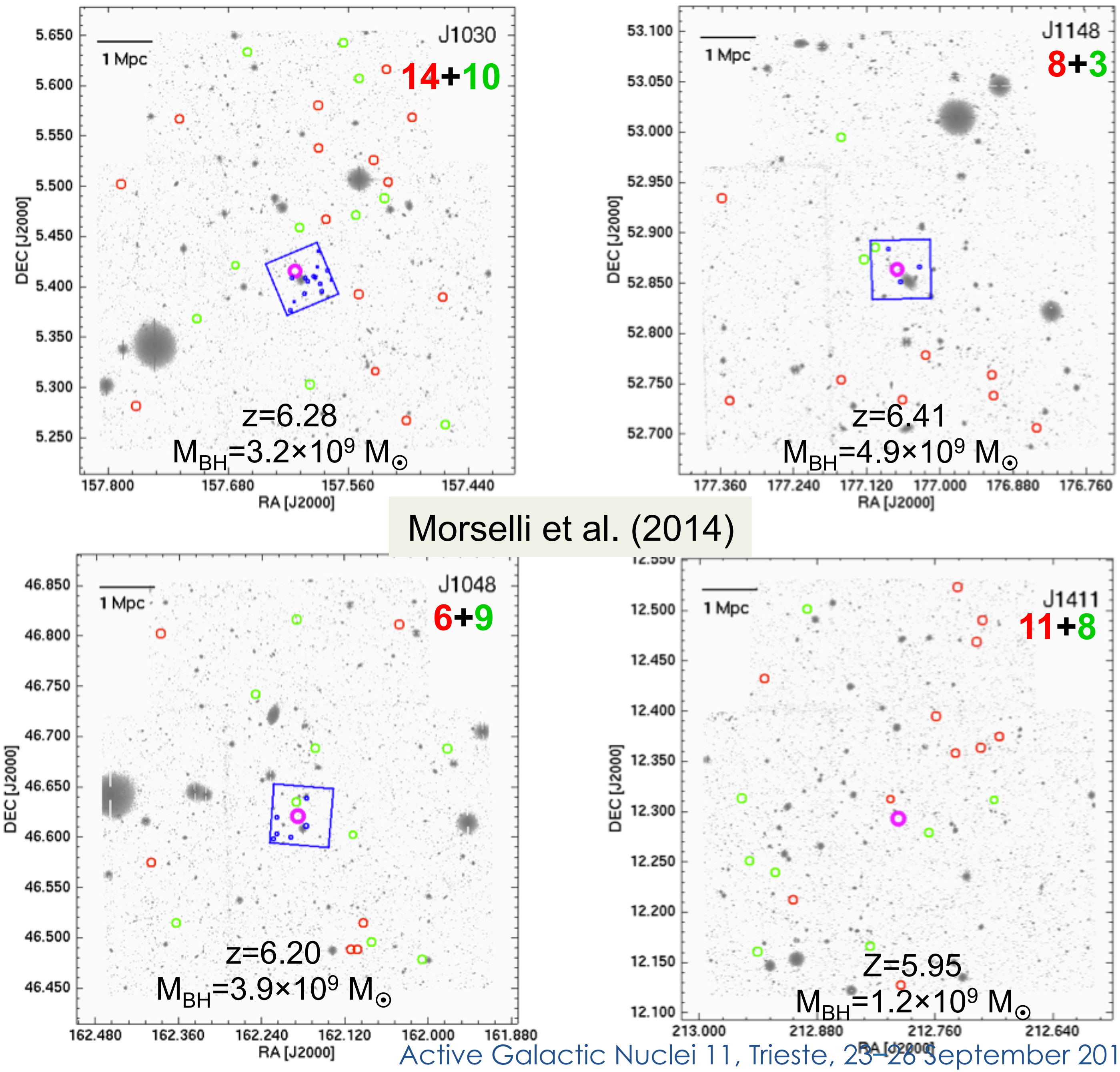
Primary: $(i-z)-\sigma_{(i-z)}>1.3$

Secondary: $1.1<(i-z)-\sigma_{(i-z)}<1.3$

"Pioneering" work: Utsumi+10 34'x27' Suprime-cam 3s overdensity of i-band dropouts around a z=6.43 QSO

Use LBC@LBT: FoV ≈23'×25' (8×8 phys. Mpc): 4 QSO fields at z≈6.0−6.4, deep imaging (z≈25.2, 5σ, 50% compl.; i≈27; r≈28)

Where do high-z QSO live? – III. LBT results



Morselli et al. (2014)

Primary
Secondary
HST/ACS
QSO

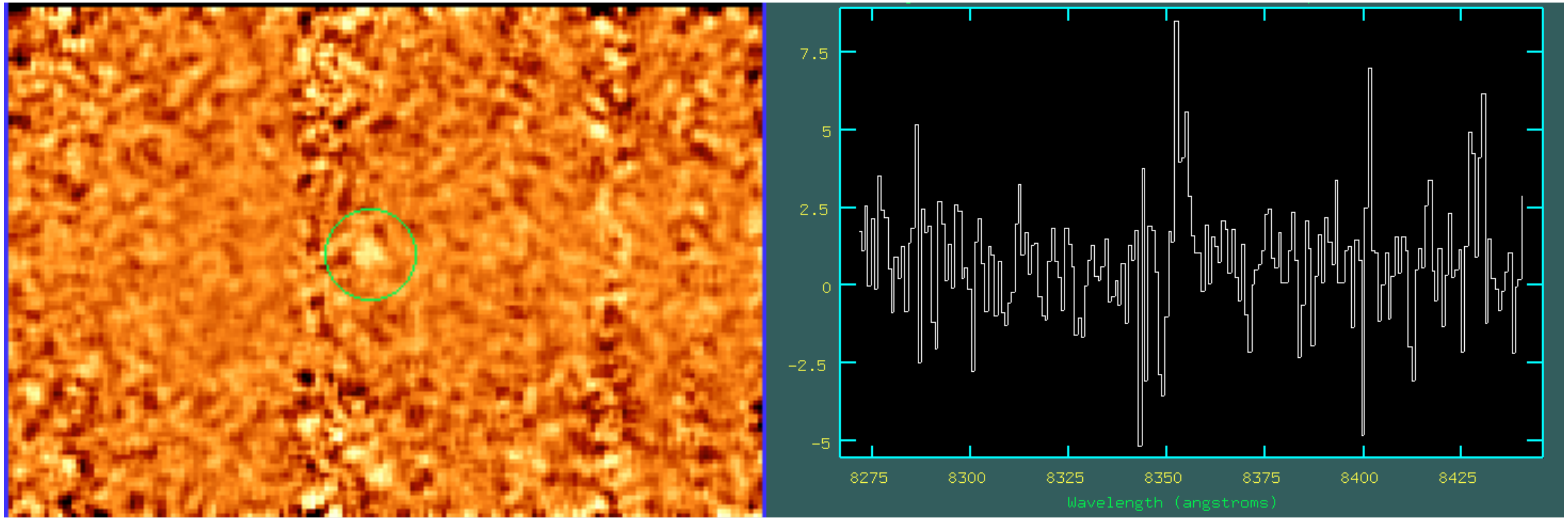
Asymmetric src distribution in most fields

Significance 1.7σ−3.3σ (combined=3.7σ)

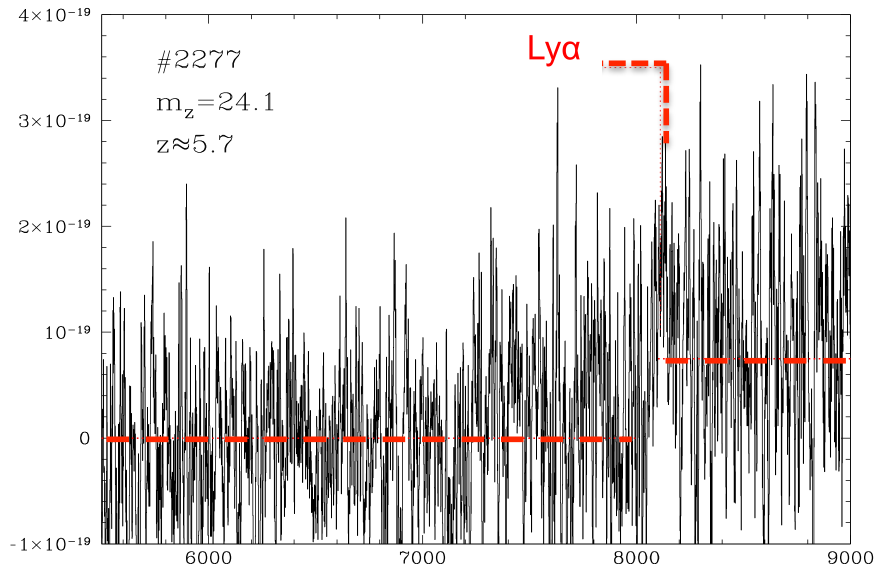
vs.
the deep 1 deg^2 *Subaru* X-ray Deep Survey, SXDS, Furusawa+08)

2.4σ evidence for drop-out deficit at d<2.5 Mpc: AGN/SNe feedback? (Costa+14 simulations)

Where do high-z QSO live? – IV. Follow-ups



primary dropout at z=6.3 (LBT/MODS in J1048): Lyα emission line (5σ) – Δz=0.1 ➔5.7 Mpc

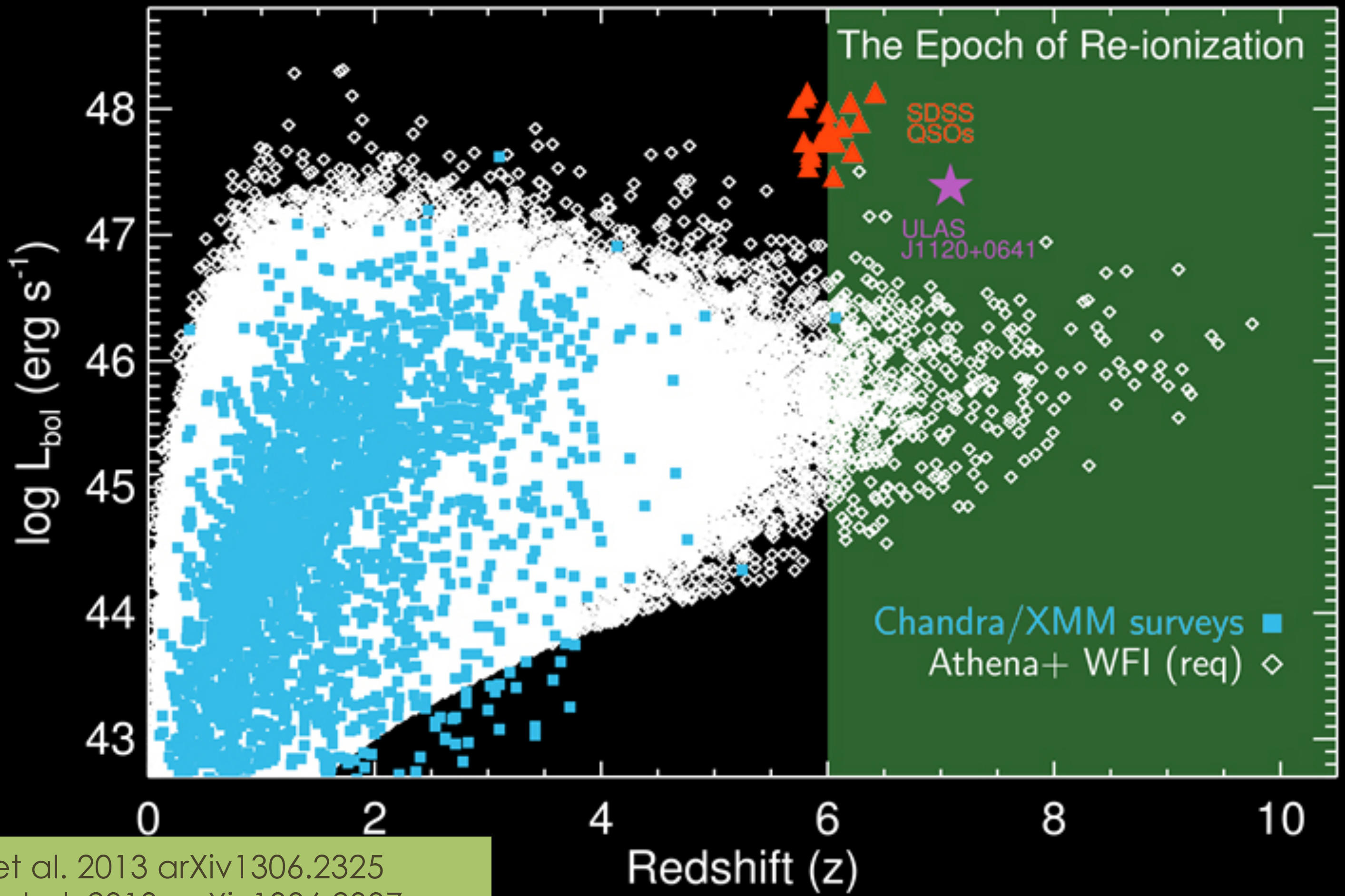


secondary dropout at z=5.7

Part IV:
New perspectives in high-z AGN detection and identification

Black hole growth in the early Universe

What was the growth history of black holes in the epoch of reionization?



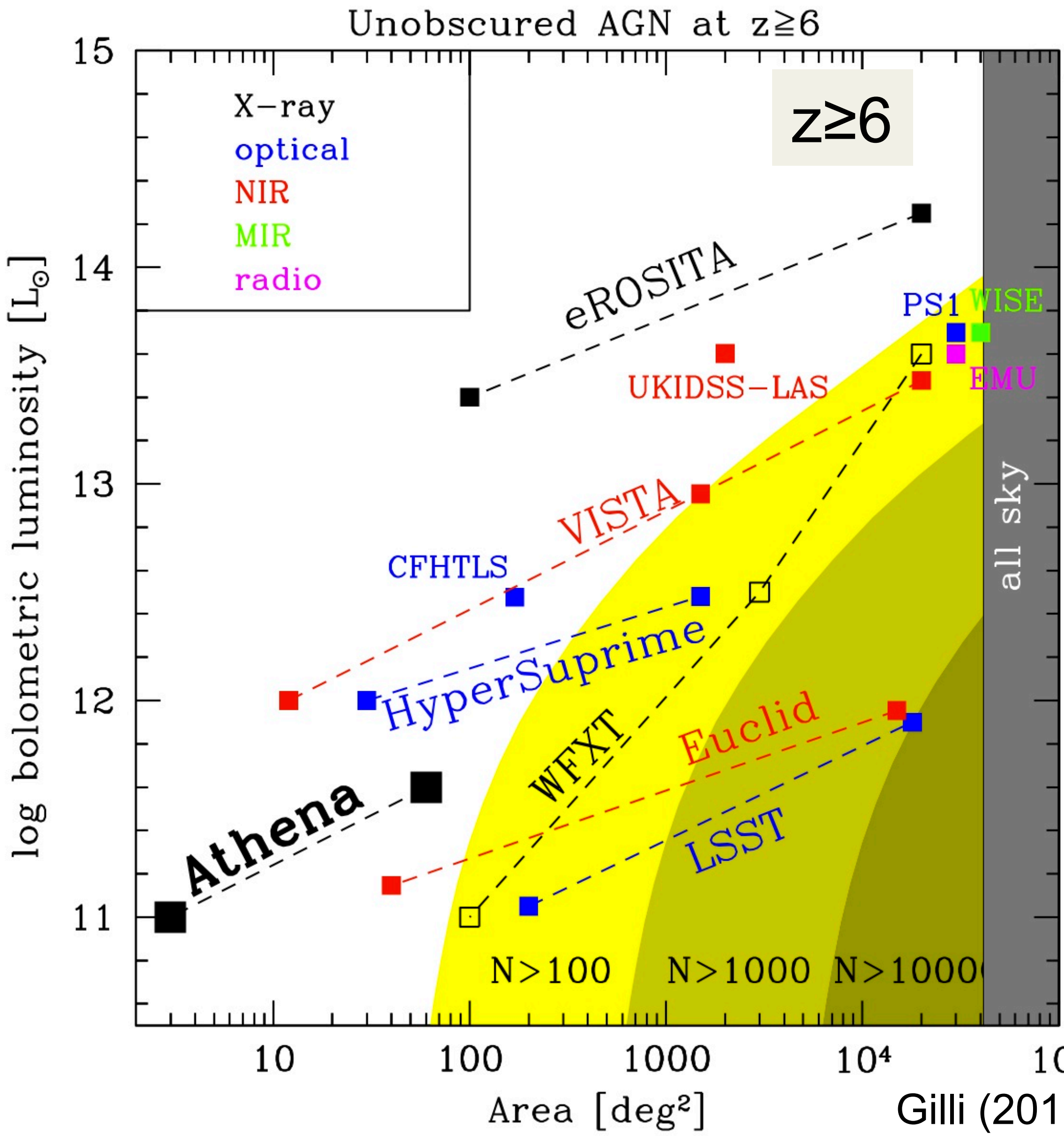
Aird, Comastri et al. 2013 arXiv1306.2325
Nandra, Barret et al. 2013, arXiv1306.2307
http://www.the-athena-x-ray-observatory.eu/

see Cappi's talk on Thursday

Multi-wavelength synergies needed for source identification

X-rays and radio:
"easier" Type 2 AGN detections

Identification will rely in photo-z and multi-slit facilities



Gilli (2013)

Open issues and future opportunities

- Where do we stand?

  Detection and identification of z>5−6 QSOs is difficult (rare objects); mostly are unobscured QSOs. Deep X-ray surveys promising to reveal Type 2 AGN

  ALMA and IRAM fundamental to place constraints to neutral/molecular gas, and the occurrence of feedback/outflows

- 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 and physics at high redshift, and good photon statistics to characterize them

- Do high-redshift QSOs trace the densest peaks of the matter distribution?

  Likely yes, models and observations still controversial; need to observe large field-of-views and proper follow-up observations. LBT observations quite promising

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