The high-redshift Universe and the role of galaxies and AGN to cosmic reionization

Lecture 2
• Selection techniques of high-redshift AGN
• The census of early SMBHs: what we know and what we miss
• Nuclear obscuration at high redshift

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Optical and near-IR selection:
the “dropout” technique
Reionization and IGM transmission

Moving back in time the fraction of neutral hydrogen increases and the IGM becomes progressively more opaque to photons with $\lambda_{\text{rest}} < 1216 \, \text{Å}$

average HI fraction is $< 10^{-4}$ at $z \sim 6$

Trac & Cen 2007
The Lyman alpha forest


1216Å x (1+z_{cloud})  λ -->  1216Å x (1+z_{QSO})
QSOs at \( z \sim 6 \) appear as “i-band dropouts”

LBC/LBT color \((r,i,z)\) image of SDSS J1148 at \( z = 6.42 \)

Color selection: \( i-z > 2.0 \) \((\sim f_{8500}/f_{7500} > 6)\)

no detection blueward of i-band
late type stars are the most abundant pointlike sources in the sky

Fan et al. 2001
Contaminants: cool (T<~3500K) dwarfs (M, L, T)

Late type stars have similar i-z colors to z~6 QSOs but much redder z-J colors
Removing stellar contaminants with near-IR (e.g. J-band) imaging

Fan et al. 2001
The SDSS breakthrough

>14,000 deg$^2$ ugriz imaging in SDSS DR12 selection of bright ($z_{AB}<20$) QSOs up to $z\sim6.5$ (i-band dropouts) possible over ~1/3 of the sky
Beyond redshift 6.5: near-IR imaging and z-band dropouts

VIKING survey: zYJHKs 1500 deg² selects QSO candidates with 6.5<z<7.4 and $\text{Y}_{\text{AB}}$<21.3

Venemans et al. 2013, 2015
3 QSOs at $z>6.5$ discovered in VIKING

A total of 7 QSOs at $z>6.5$ known to date including:

1. (ULASJ1120 at $z=7.085$) from UKIDSS LAS:
   4000 deg$^2$, YJHK, z-band dropouts down to $Y_{AB} \approx 20.2$

3. (Venemans et al. 2015) from Pan-STARRS:
   20000 deg$^2$, grizY, z-band dropouts down to $Y_{AB} \approx 20.5$

Venemans et al. 2013
Demography of high-z QSOs

About **80 QSOs known at z>5.7** from wide area optical (SDSS, CFHQs, Pan-STARRS1) and near-IR (UKIDSS, VISTA) surveys

SDSS main and PS1 trace the brightest QSOs: \( M_{1450} \sim -27, \ L_{\text{bol}} \sim 3 \times 10^{47} \ L_{\odot} \)

SDSS-Stripe82 and CFHQs \sim 2 \text{ mag deeper}

Banados et al. 2014
\[ \sim 1 \text{ every } 500 \text{ deg}^2 \text{ at } z_{AB}<20 \quad (\Rightarrow \text{ only } \sim 80 \text{ in the whole Universe}) \]

\[ \sim 1 \text{ every } 40 \text{ deg}^2 \text{ at } z_{AB}<22 \]
Evolution of luminous QSOs

\[ M_{1450} < -26.8 \]
i.e.
\[ L_{\text{bol}} > 3 \times 10^{47} \text{ erg/s} \]
\[ L_{\text{bol}} > 7.5 \times 10^{13} L_{\odot} \]
\[ M_{\text{BH}} > 2 \times 10^9 \lambda_{\text{Edd}}^{-1} M_{\odot} \]
\[ \lambda_{\text{Edd}} = \frac{L_{\text{bol}}}{L_{\text{Edd}}} \]
\[ \sim 1 \text{ per Gpc}^3 \text{ (rare)} \]

Fan 2012
Luminosity Function of $z\sim 6$ QSOs

less than 3 AGN with $M_{1450} > -23$ known at $z\sim 6$
($M_{BH} > 4\times 10^7 \lambda_{Edd}^{-1} M_{\text{sun}}$)

none with $M_{1450} > -22$
($M_{BH} > 1.5\times 10^7 \lambda_{Edd}^{-1} M_{\text{sun}}$)

Kashikawa et al. 2014
Are we just seeing the tip of the iceberg?

How many low-lum (small BHs) and distant AGN do we miss?

How do we detect them and distinguish among the various seeding and fueling models?

What if the nucleus is hidden?
How many obscured and distant AGN do we miss?
The largest AGN population: hidden accreting SMBHs
AGN types: (type 1) unobscured vs (type 2) obscured

Mignoli et al. 2013

![Spectral line diagram](MgII, [NeV], [OII], Hγ, [OIII])

- **type 1**: accretion disc
- **type 2**: host galaxy

**Broad Line Region (BLR)** (grav. bound, fast rotating gas clouds)

dust and gas in the pc-scale obscuring torus* completely block the UV/optical radiation of the accretion disc and BL clouds

* obsolete??
ACS i-band images of AGN at z=1.6 $\rightarrow$ 3000Å rest-frame

type 1 (direct view of the nucleus: pointlike)  

optical imaging not efficient to select obscured AGN  
$\rightarrow$ use X-rays: largely free from absorption (especially at high-z) and galaxy dilution

Courtesy M. Mignoli
Examples of X-ray spectra of nearby AGN

\[ \alpha = 0.7 \]

Unabsorbed

Absorbed
Examples of X-ray spectra of nearby AGN

Unabsorbed (intrinsic)
$I_{\text{Int}}(E) \approx E^{-\alpha}$ \quad $\alpha = 0.7 - 1.0$
$(N_{\text{Int}}(E) \approx E^{-\Gamma} \quad \Gamma = 1.7 - 2.0)$

Absorbed
$I_{\text{Abs}}(E) \approx I_{\text{Int}}(E) \ e^{-\tau}$

$\tau = N_H \sigma_E$

Fe K$\alpha$ ($@ 6.4$ keV for neutral iron) fluorescence within “torus”

Adapted from Comastri et al. 2010
Cross sections

\[ \sigma_E = \text{cross section for photoelectric absorption} \]
\[ \sigma_T = \text{cross section for Thomson scattering} \]

\[ N_H = \text{hydrogen equivalent column density} \]
units: cm\(^{-2}\)

\[ I_{\text{obs}}(E)/I_{\text{int}}(E) \approx e^{-\tau} \]
\[ \tau = N_H \sigma_E \]
\[ \sigma_E \approx E^{-2.5} \]

Nuclear emission is transparent at high energies

Absorption of X-ray photons is produced by metals

\[ \sigma_T > \sigma_E \text{ at } E > 10 \text{ keV} \]

example: for \( N_H = 10^{23} \text{ cm}^{-2} \), absorption at 2 keV by gas with cosmic abundance of metals is 90 times more efficient than by metal-free gas
Photoelectric absorption + scattering

\[ \frac{I_{\text{obs}}(E)}{I_{\text{int}}(E)} \approx e^{-\tau} \]
\[ \tau = N_H \sigma \]

For \( N_H > \sigma_T^{-1} \approx 1.5 \times 10^{24} \text{ cm}^{-2} \), \( \tau_T > 1 \)

Compton-scattering brings high-E photons to lower E where absorption is effective

medium opaque even at \( E > 10 \text{ keV} \)

These objects are called Compton-thick
AGN X-ray spectral templates with different $N_H$

Unabsorbed: 
$logN_H<21$

Compton-Thin: 
$21<logN_H<24$

Compton-Thick:
- Mildly ($log N_H = 24-25$)
- Heavily ($log N_H > 25$)

As $N_H$ increases, the spectrum is absorbed towards higher and higher energies.
Examples of local Compton-thick AGN

- A prominent (EW >~1 keV) Fe Kα line is the blue print of a Compton-thick nuclei

How abundant are they?
The cosmic X-ray background

$N_{\text{abs,thin}} \sim N_{\text{abs,thick}} \sim 3 \times N_{\text{unabs}}$

- 80-90% of SMBH growth is obscured
- 40% is heavily obscured (Compton-thick)

At $z>6$ only unabsorbed QSOs discovered so far

$\Rightarrow$ we still miss most of the early SMBH growth
K-correction is favorable for obscured AGN at high-z

\[ 0.5-7 \text{ keV rest} \]

Chandra/XMM bandpass

- \( z=0 \)
- \( \log N_H = 21.5 \)
- \( \log N_H = 22.5 \)
- \( \log N_H = 23.5 \)
- \( \log N_H > 25 \)
K-correction is favorable for obscured AGN at high-z

2.0-28 keV rest
K-correction is favorable for obscured AGN at high-z

Nonetheless, deep X-ray exposures needed to get good spectra

4.0-56 keV rest

N(E)~ E^2

Nonetheless, deep X-ray exposures needed to get good spectra
Extragalactic X-ray surveys

3Ms XMM XXL-South, 23.6 deg$^2$
Pierre et al. (2015)

4.6 Ms COSMOS-Legacy, 2.2 deg$^2$ (Civano et al. 2015)

4 Ms CDFS, 0.14 deg$^2$
(Xue et al. 2011)

sensitive X-ray surveys still limited to small (~0.1-10 deg$^2$) areas (see last lecture)

the most distant X-ray selected AGN is at z=5.4 (Steffen et al. 2004)
The deepest X-ray image of the Universe

the 4Ms (1.5 months) Chandra Deep Field South (will reach 7Ms by Dec 2015)

Xue et al. 2011
Examples of X-ray selected AGN at high-z

\[ N_H = 10^{24} \text{ cm}^{-2}, \quad L_x = 6 \times 10^{44} \text{ erg/s} \]

Comastri et al. 2011
(from 3Ms XMM exposure of CDFS)

Norman et al. 2002
Examples of X-ray selected AGN at high-z

$N_H = 2 \times 10^{23} \text{ cm}^{-2}$
$L_x = 2.5 \times 10^{43} \text{ erg/s}$  
Compton-thin

Ly$\alpha$

$\Gamma = 2.0$

Barger et al. 2002

Vignali et al. 2002
(from 2Ms CDFN)
Examples of X-ray selected AGN at high-z

Many candidates rely on photometric redshifts

\[ N_H < 10^{23} \text{ cm}^{-2} \]
\[ L_x = 10^{45} \text{ erg/s} \]

From 4.6 Ms Chandra COSMOS-Legacy

Courtesy of S. Marchesi & G. Lanzuisi
The most distant Compton-thick AGN known to date

LESS 73 = ALESS 73.1 = XID403

4Ms Chandra spectrum

\[ L_X \sim 2 \times 10^{44} \text{ erg/s} \]
\[ N_H \sim 1.4 \times 10^{24} \text{ cm}^{-2} \quad \Rightarrow \text{Compton-thick QSO} \]

\( z = 4.75 \)

(from both optical and submm spectroscopy)
M_{HI+H_2} \sim 2 \times 10^{10} M_{\odot} \\
(De Breuck et al. 2014)

If gas and dust co-spatial:
N_{HI+H_2} = 0.3-1.1 \times 10^{24} \, \text{cm}^2
comparable with X-rays

\rightarrow \text{obscuration by host ISM?}
Z = Z_{\odot} \ (Nagao et al. 2012)
Dynamical mass

\[ M_{\text{dyn}} = 3 \times 10^{10} \, M_\odot \]

\[ M_* = 1 \times 10^{10} \, M_\odot \]

(1 dex smaller than from SED fitting!)
Dust and stellar mass

Calura et al. 2014

$M_{\text{dust}}$ is ok with $M_*$ from SED-fitting

again, tension between $M_{\text{dust}}$ (and $M_*$) vs $M_{\text{dyn}}$, as for $z \sim 6$ QSOs
The X-ray luminosity function

Limit of current AGN XLFs: \( \log L_x > 44 \) at \( z > 4 \)

\( (L_{\text{bol}} > 10^{12} L_{\odot} \Rightarrow M_{\text{BH}} > 3 \times 10^7 \lambda_{\text{Edd}}^{-1} M_{\odot}) \)

Vito et al. 2014

see also Kalfountzou et al. 2014, Georgakakis et al. 2015
Space density of X-ray AGN at $z>3$

141 AGN (obscured+unobscured) at $z>3$ in deep X-ray fields
55% spec-z, 45% phot-z

$\phi(z) \sim (1+z)^{-6} \Rightarrow$

~1 dex decrease from $z=3$ to $z=5$

exactly like brighter SDSS QSOs
Obscured AGN fraction at $z>3$

The fraction of luminous obscured AGN increases significantly with redshift (La Franca et al. 2005, Treister et al. 2006, Ueda et al. 2014, ...)

Half of $z>3$ AGN are obscured by $\log N_H > 23$

Possibly due to higher gas fraction and merger rate at high-$z$? (Menci et al. 2008, Lamastra et al. 2010)

Increasing absorption contribution from host ISM, as in XID403?

Vito et al. 2014
Pushing AGN detection to the faintest limits

X-ray photometry at the position of optical dropouts in CANDELS

\[ \log L_x = 42.6 - 44 \text{ at } z > 4 \]
\[ M_{BH} > 10^6 \lambda_{Edd}^{-1} M_{\odot} \]

Giallongo et al. 2015
AGN contribution to cosmic reionization

$$\epsilon_{\text{ion}}(z) = \langle f \rangle \epsilon_{912} =$$

$$\langle f \rangle \int \phi(L_{1450}, z) L_{1450} \left( \frac{1200}{1450} \right)^{0.44} \left( \frac{912}{1200} \right)^{1.57} dL_{1450}$$

$$\epsilon_{912} = \frac{\text{total emissivity at the Lyman limit}}{L_{\text{esc}}/L_{\text{int}} @ 912\text{Å}} = \text{escape fraction}$$

$$\epsilon_{\text{ion}} = \text{AGN hydrogen ionizing emissivity}$$

AGN can provide a significant contribution to cosmic reionization (provided $f_{\text{esc}} \sim 1$)

_is this reasonable? See lectures by E. Vanzella_
some LyC

rest wav. (Å)

no LyC

obs wav. (Å)

L_x \sim a few \times 10^{44} \text{ erg/s}

z > 3 \text{ AGN in the CDFS}
Pushing AGN detection to the faintest limits

SFR $\sim 6 \ M_{\text{sun}}/\text{yr}$

How many are real AGN?
faint end of the AGN LF still uncertain
Pushing even beyond individual detections: cosmic backgrounds

X-ray background fluctuations correlate with near-IR bkg fluctuations at $>3\mu m$ but NOT with optical bkg fluctuations

→ population of X-ray emitting IR dropouts

→ high-z ($z>7$) accreting BHs

Helgason et al. 2014
Background fluctuations from Direct Collapse Black Holes?

DCBHs ($10^4$-$10^6$ M$_{\odot}$)

\[ \rho_{\text{DCBH}} = \text{mass density of DCBHs} \]
\[ \rho_{\text{BH,local}} = \text{mass density of local SMBHs} \]

\[ \rho_{\text{DCBH}} > \rho_{\text{BH,local}} \rightarrow \]

at \( z=0 \) there should be 100-1000 dormant DCBHs per galaxy: too many?

\[ \rho_{\text{BH,local}} \]

Yue et al. 2014
Are we just seeing the tip of the iceberg?  
most likely yes

How many low-lum (small BHs) and distant AGN do we miss?  
No BH with $M<10^7 \, M_{\odot}$ discovered when $t_U < 1$ Gyr

How many obscured and distant AGN do we miss?  
we miss all hidden SMBHs at $z>6$, i.e. the largest population

How do we detect them and distinguish among the various seeding and fueling models?  
deep multi-\lambda fields, cosmic bkgs, future facilities (see last lecture)