[CII] outflows in $z = 6$ QSOs are there: investigating AGN feedback and host galaxy properties in luminous high-redshift QSOs

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In this talk: Luminous + Hyper-luminous QSOs ($L_{\text{Bol}} > 10^{46}$ erg/s)

Theory: “strength” of an outflow increases as $L_{\text{Bol}}^{0.5}$
(e.g. Menci+08, Faucher-Giguère+12, Zubovas & King+12)

Observations: Large-scale outflow momentum rate is $\sim 20-50 \times L_{\text{Bol}}$
(e.g. Cicone+14, Feruglio+15)

The most luminous QSOs are primary targets to hunt for powerful AGN-driven outflows

ALMA [CII] 158 µm observations

- Cold outflows in $z>4.5$ QSOs
- Early SMBH and host galaxy assembly
Multiphase outflows in APM08279

Hyper-luminous ($L_{\text{Bol}} \sim 10^{48}$ erg/s) lensed QSO at $z = 3.91$

**UFO in X-rays**

![Image of X-ray spectrum with Fe XXV Kα peaks at 0.2c and 0.4c]

**BAL in UV**

![Image of UV spectrum with C IV blueshifted absorption]

Srianand+2000

Chartas+002
Multiphase outflows in APM08279

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**UFO in X-rays**

Chartas+02

- Fe XXV Kα
- Velocity shift [km/s]: $0.2c$, $0.4c$

**BLR winds in UV**

- $H\beta$
- MgII
- CIV

**Molecular outflow**

- $M \gtrsim 3000 \text{M} \odot /\text{yr}$

**BAL in UV**

Srianand+2000

- C IVλ1550
- C IVλ1548

**Srianand+2000**

Relative Velocity $10^3 \text{km/s}$

- C IVλ1550
- C IVλ1548

- CO(4-3) blueshifted absorption

- Flux [$\text{mJy}$]

- Velocity [km s$^{-1}$]
Ubiquitous presence of galaxy-wide \([\text{OIII}]\) outflows

**WISE-SDSS selected hyper-luminous (WISSH) QSOs**

\[ \dot{M} \text{ up to 8000 } M_\odot/\text{yr} \]

\[ \text{Flux} \left[ 10^{-15} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \right] \]

Rest frame lambda [Å]

**COSMOS QSO XID2028 at } z = 1.59**

\[ \text{Flux} \left[ 10^{-11} \text{erg s}^{-1} \text{cm}^{-2} \text{Å}^{-1} \right] \]

Wavelength [micron]

contours: [OIII] core
map: [OIII] broad

\[ 13 \text{ kpc} \]

\[ 7 \text{ kpc} \]

\[ 7 \text{ kpc} \]

\[ 1 \text{D spectrum [pixels interval]} \]

see talks by G. Vietri, A. Travascio, F. Duras
QSO-driven outflows (un)detected in the early-Universe

Massive [CII] outflow detected in J1148+5251 at $z = 6.4$ on kpc scale ($L_{\text{Bol}} \sim 2 \times 10^{47} \text{ erg/s}$)

But….only clear detection of broad wings despite tens of QSOs targeted in [CII]!
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Maiolino+2012  
Cicone+2015

But….only clear detection of broad wings despite tens of QSOs targeted in [CII]!

Stacking analysis:  
Investigate the presence of faint, broad [CII] wings

SAMPLE: 48 high -redshift QSOs observed with ALMA

- [CII] 158 μm ALMA detection at $\gtrsim 5\sigma$ significance
- $45.9 < \text{Log}(L_{\text{bol}} \text{ /erg s}^{-1}) < 47.7$
- $4.6 < z < 7.1$
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Discussion about new tentative detections in individual $z \sim 6$ QSOs
see talk by Stefano Carniani
Cold outflows in the early Universe are there

Variance-weighted stack analysis

\[ W'_k = \sum_{j=1}^{n} w_{j,k} = \sum_{j=1}^{n} \frac{1}{\sigma_{j,k}^2} = \frac{1}{\sigma_k^2} \]

\[ I'_k = \frac{\sum_{j=1}^{n} (i_{j,k} \cdot w_{j,k})}{W'_k} \]

48 QSOs = 34h on source
>10x improved sensitivity
than J1148+5251
Cold outflows in the early Universe are there

Variance-weighted stack analysis

\[ W'_k = \sum_{j=1}^{n} w_{j,k} = \sum_{j=1}^{n} \frac{1}{\sigma^2_{j,k}} = \frac{1}{\sigma^2_k} \]

\[ I'_k = \frac{\sum_{j=1}^{n} (i_{j,k} \cdot w_{j,k})}{W'_k} \]

48 QSOs = 34h on source

>10x improved sensitivity than J1148+5251

Wings: peak ~ 1:20

\[ \text{FWHM}_{\text{broad}} \sim 1700 \text{ km/s} \]

\[ \Delta v_{\text{broad}} \sim -100 \text{ km/s} \]

Optically thick [CII]?
AGN-driven [CII] outflows in high-z QSOs

Stack in bins of FWHM and $L_{\text{AGN}}$:

$\text{FWHM} < 400 \text{ km s}^{-1}$ $L_{\text{AGN}} < 10^{46.8}$

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18 sources
$L_{\text{broad}} = 8.81$
AGN-driven [CII] outflows in high-z QSOs

Stack in bins of FWHM and $L_{\text{AGN}}$:

Increasing $L_{\text{AGN}}$

$\text{FWHM} < 400 \text{ km s}^{-1}$ $L_{\text{AGN}} < 10^{46.8}$

$\text{FWHM} < 400 \text{ km s}^{-1}$ $L_{\text{AGN}} > 10^{46.8}$

The luminosity of the [CII] broad wings correlates with $L_{\text{AGN}}$

$\text{FWHM} > 400 \text{ km s}^{-1}$ $L_{\text{AGN}} > 10^{46.8}$

18 sources

$L_{\text{broad}} = 8.81$

The diagram shows the relationship between the FWHM of the [CII] narrow line and the luminosity of the AGN. The luminosity of the [CII] broad wings correlates with the luminosity of the AGN.
Energetics of [CII] outflows in high-z QSOs

Stacked ALMA cube

contours = [2, 3, 4, ...]σ

|v| > 400 km/s

Dec [arcsec]

Ra [arcsec]

10 kpc

Blue wing

Red wing

[CII] core

L_{[CII]} [10^8 L_⊙]

beam-corrected half-light radius ~ 3.5kpc
Energetics of \([\text{CII}]\) outflows in high-z QSOs

\[
L_{\text{broad}} + \frac{M_{\text{out}}}{M_\odot} = 0.77 \left( \frac{0.7 L_{\text{CII}}}{L_\odot} \right) \left( \frac{1.4 \times 10^{-4}}{X_{\text{C}^+}} \right) \left( 1 + 2e^{-9K/T} + n_{\text{crit}}/n \right) \text{ Hailey-Dunsheath} + 2000 \]

\[\text{half light radius} \sim 3.5 \text{ kpc}\]

(we might be losing a significant fraction of extended flux)

\[v_{\text{out}} = |\Delta v_{\text{broad}}| + \text{FWHM}_{\text{broad}}/2\]

Mass outflow rate of the \([\text{CII}]\) outflows (atomic phase)
Energetics of [CII] outflows in high-z QSOs

\[ L_{\text{broad}} + M_{\text{out}}/M_\odot = 0.77 \left( \frac{0.7L_{\text{CII}}}{L_\odot} \right) \left( \frac{1.4 \times 10^{-4}}{X_{\text{C}_2^+}} \right) \frac{1 + 2e^{-91K/T} + n_{\text{crit}}/n}{2e^{-91K/T}} \]

Hailey-Dunsheath+2000

Mass outflow rate of the [CII] outflows (atomic phase)

\[ v_{\text{out}} = |\Delta v_{\text{broad}}| + \text{FWHM}_{\text{broad}}/2 \]

Half light radius \(~ 3.5 \text{ kpc}\) (we might be losing a significant fraction of extended flux)

Whole sample: \( \dot{M} \sim 100 M_\odot/\text{yr} \)

High L_{\text{Bol}}: \( \dot{M} \sim 200 M_\odot/\text{yr} \)

Comparable to local, lower luminosity AGN

[B] high-z QSOs (stacks)
- [CII] local galaxies
- molecular
- ionised
- J1148+5251

Bischetti+18b, arXiv1806.00786
Energetics of [CII] outflows in high-z QSOs

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Half light radius
\[ \sim 3.5 \text{ kpc} \]
(we might be losing a significant fraction of extended flux)

Whole sample: \( \dot{M} \sim 100 M_\odot/\text{yr} \)
High \( L_{\text{Bol}} \): \( \dot{M} \sim 200 M_\odot/\text{yr} \)
Comparative to local, lower luminosity AGN

Cold outflows at high-z might be less effective in removing gas than in local AGN

However:
- Possible flux losses
- Range of \( L_{\text{Bol}} \) unexplored so far for molecular and neutral outflows in local AGN

except … see talk by E. Piconcelli
The WISSH QSOs project: the ALMA view

SAMPLE: 86 WISE/SDSS Selected Hyper-luminous (WISSH) QSOs
- $\log(L_{\text{bol}}/\text{erg s}^{-1}) > 47.2$
- $1.5 < z < 4.5$

The most luminous broad-line IR-loud AGN at cosmic noon
- available BH mass
- SED-based SFR
- evidence for nuclear and galaxy-wide outflows
  (Bischetti+17, Duras+17, Vietri+18, Bruni+18, Travascio+18 in prep.)

ALMA pilot follow-up program:
high-res [CII] 158$\mu$m map of a $z=4.4$ WISSH QSO

GOAL: study the SMBH and host galaxy growth at early epochs when both processes are maximised

see talks by G. Vietri, A. Travascio, F. Duras
The early assembly of a giant galaxy

Exceptional overdensity over 20 kpc
Discovery of the closest (2 kpc!) companion of a high-z QSO

• 3 [CII]-detected companions + 2 physically-associated continuum emitters

(Bischetti+2018a DOI:10.1038/s41550-018-0261-2)
The early assembly of a giant galaxy

SDSSJ1015+0020 
\( z = 4.4 \)

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Merging systems

(Bischetti+2018a DOI201833249)
The early assembly of a giant galaxy

Most of stellar mass assembly occurs outside of the QSO host galaxy!

- SFR(QSO) $\sim 100 \, M_{\odot}/yr$
- SFR(Total) $\sim 1000 \, M_{\odot}/yr$

(Bischetti+2018a DOI201833249)
see also Duras+17
Single epoch $M_{\text{BH}} \sim 5 \times 10^9 \, M_\odot$

$\lambda_{\text{Edd}} \sim 0.25$

$M_{\text{BH}} : M_{\text{dyn}} = 1:7$

*Two orders of magnitude smaller than local relations!*

Local relations: $M_{\text{dyn}} \sim 10^{12}$ at $z = 0$

*We are observing the cradle of a giant galaxy at $z = 0$*

$M_{\text{dyn}} \sim 10^{11.3}$ already in place

at $z = 4.4$ adding up QSO and [CII] emitters

(Venemans+16,17, Willott+15,17, Trakhtenbrot+17, Kimball+15, Wang+16)
Stack of 48 luminous QSOs with ALMA [CII] detection

cold outflows are there!

The outflow luminosity and \( \dot{M} \) increase with \( L_{\text{AGN}} \)

High-z QSO-driven outflows may be less efficient in removing gas than local AGN
Summary and Conclusions:

Stack of 48 luminous QSOs with ALMA [CII] detection

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Early assembly of giant galaxies: the case of J1015+0020

Overdense region around the QSO

Merging companion at only 2 kpc!

Bulk of SFR outside of the QSO host galaxy
**Summary and Conclusions:**

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**To do next:**

Cold outflows in high-z QSO: the search for outflow in the early Universe has just begun!

- deeper [CII] and CO observations $\rightarrow$ statistics of detected outflows (in individual sources or by stacking larger samples), energetics, morphology, driving mechanism, impact on the host

Assembly of high-z QSO hosts

- High res [CII] and CO $\rightarrow$ location and scatter of the $M_{\text{BH}}$-$M_{\text{dyn}}$ correlation at high z. Molecular vs neutral gas fraction