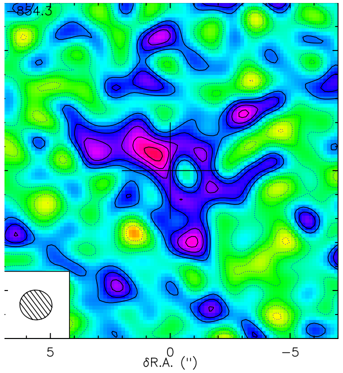
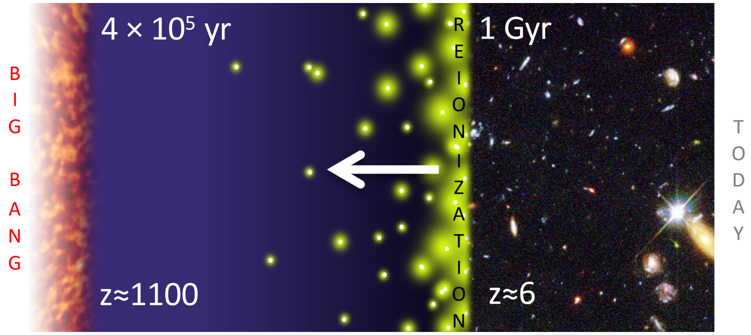
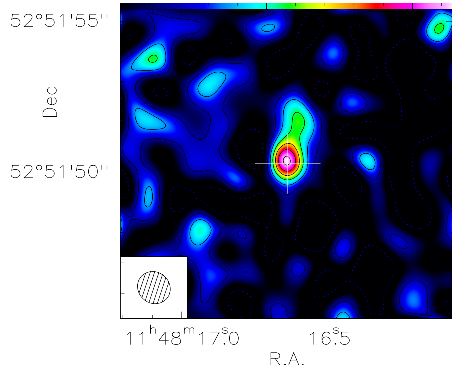






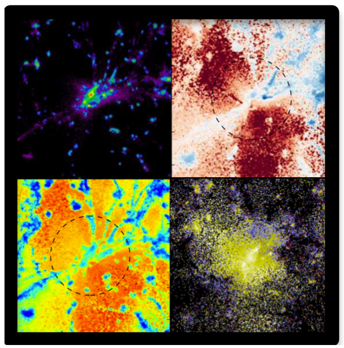
Physical Properties of z ≈ 6 Quasars

Simona Gallerani

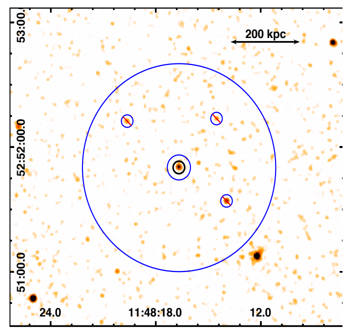
SCUOLA NORMALE SUPERIORE

in collaboration with:

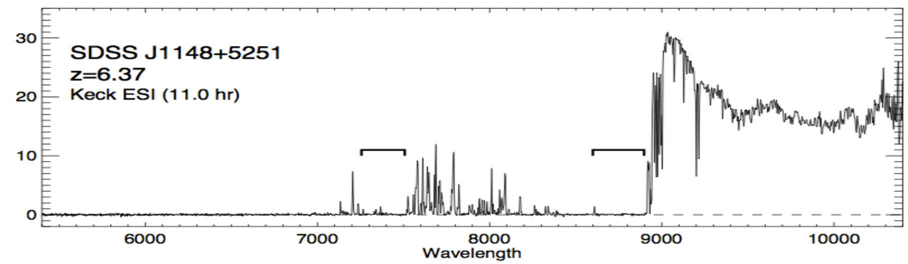
Paramita Barai, Stefano Carniani, Claudia Cicone, Davide Decataldo, Valentina D'Odorico, Andrea Ferrara, Chiara Feruglio, Roberto Maiolino, Andrea Pallottini, Livia Vallini



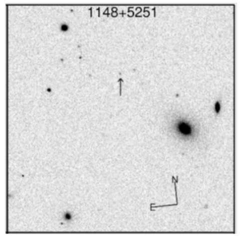
Bologna Joint Astrophysical Colloquium (JAC)
9th January 2019

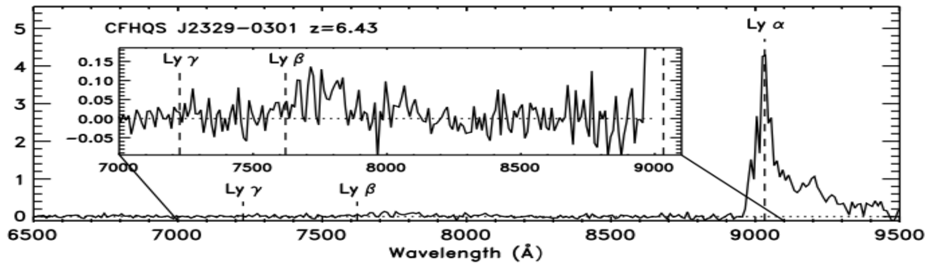


Observations of more than 100 z ≈ 6 quasars

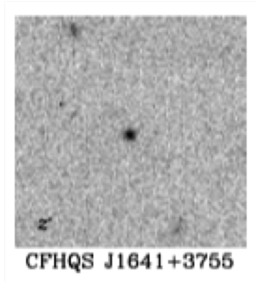


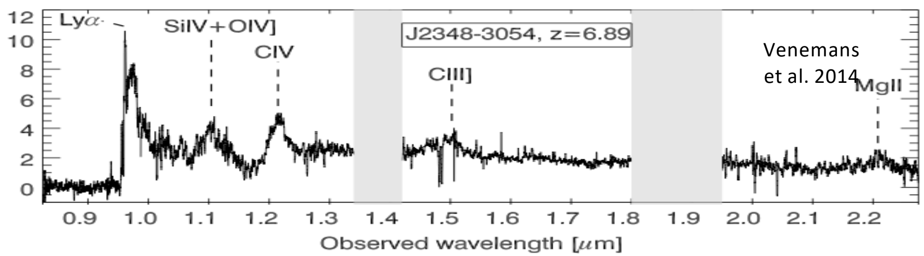
Sloan Digital Sky Survey
(SDSS, Fan et al. 2001,2003,2006)



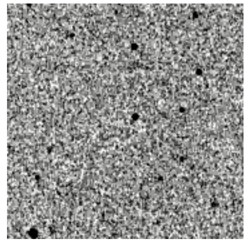


Canada-France High-z Quasar Survey
(CFHQS, Willott et al. 2005,2009,2010)

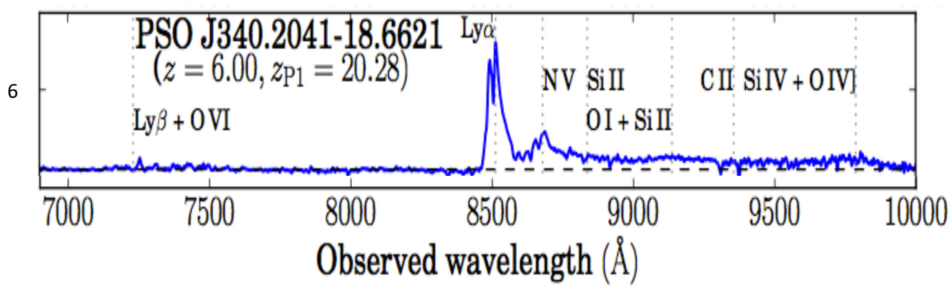




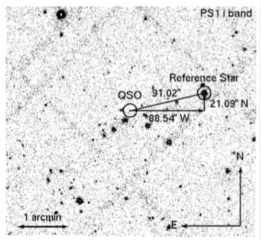
Visible and Infrared Survey Telescope
for Astronomy Kilo-degree INfrared Galaxy
(VIKING, Venemans et al. 2013, 2015)



ULAS J1120

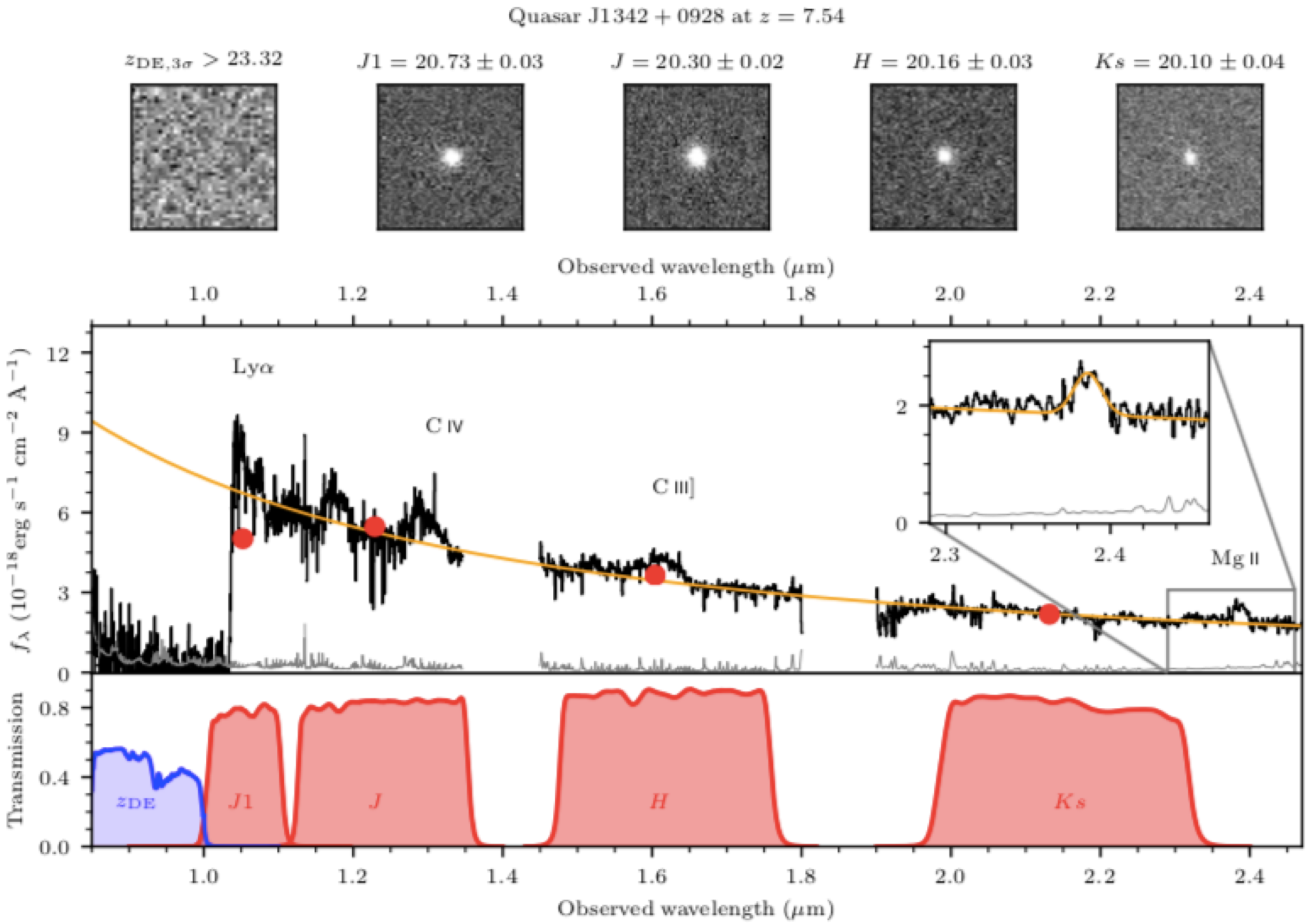


Panoramic Survey Telescope
And Rapid Response System 1
(PanSTARRS1, Banados et al. 2016)



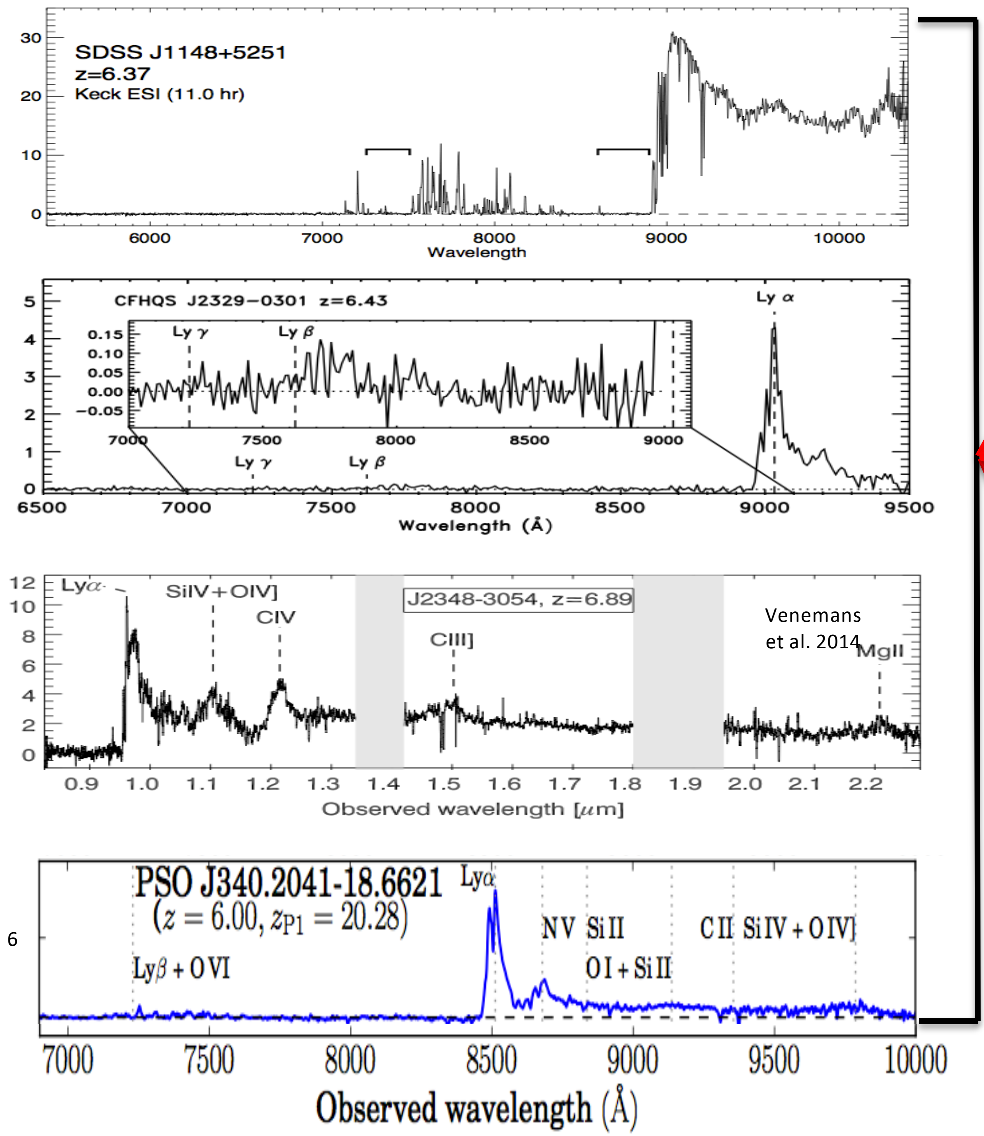
PSO J215

Current record holder



Banados et al. (2018)

Observations of more than 100 z ≈ 6 quasars



Cosmic reionization

Fan et al. 2006, Gallerani et al. 2006, 2008a,b, Mesinger et al. 2010, Greig et al. 2017

Metal enrichment

D'Odorico et al. 2013, Pallottini et al. 2014

Quasar environment

Kim et al. 2006, Banados et al. 2013, Morselli et al. 2014, Balmaverde et al. 2017

High-z dust properties

Maiolino et al. 2004, Gallerani et al. 2010

BH and host galaxy properties

Maiolino et al. 2006, Gallerani et al. 2012, Riechers et al. 2007, Gallerani et al. 2014, Venemans et al. 2017

Galaxy-BH co-evolution

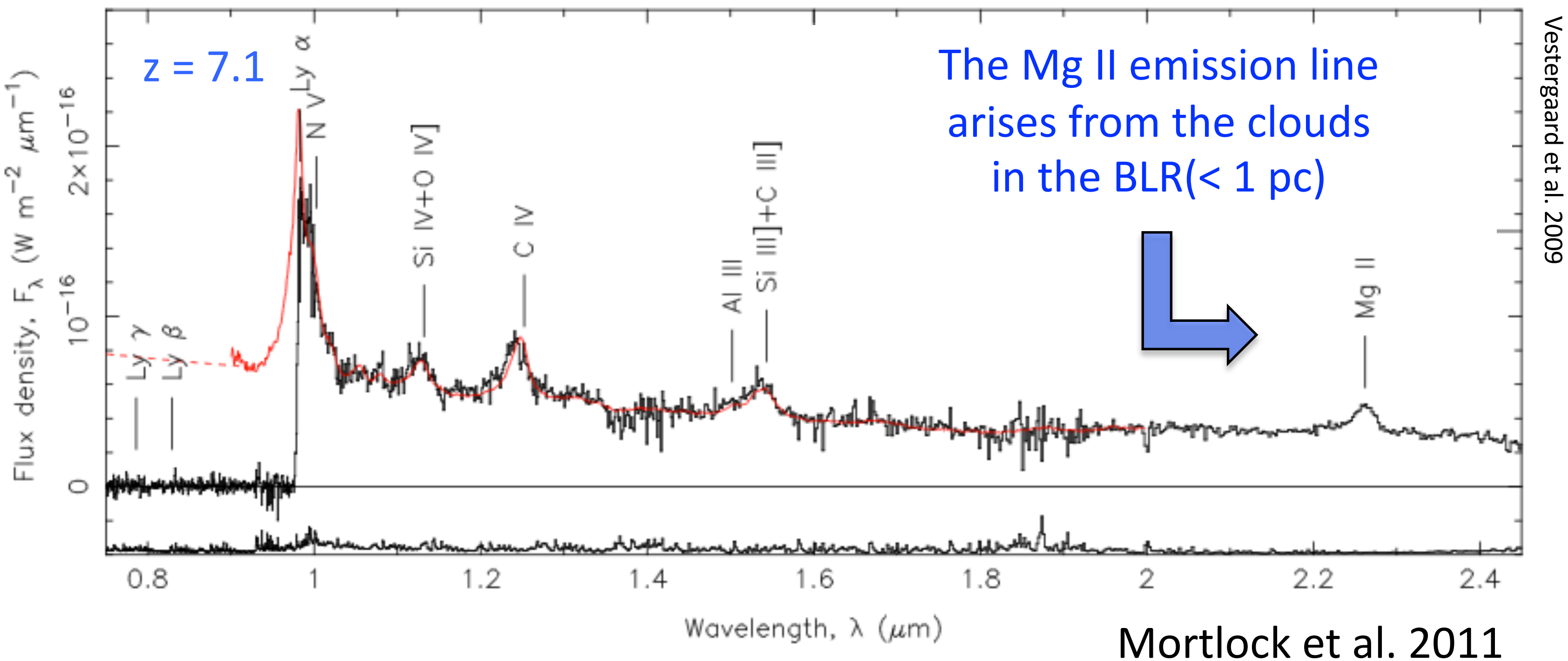
Maiolino et al. 2012, Cicone et al. 2015, Barai et al. 2017

Cosmological scales (1-100 Mpc)

Galactic scales (10 pc-10 kpc)

See Gallerani, Fan, Maiolino, Pacucci (2017) for a recent review, arXiv:1702.06123

Black hole mass measurements in z ≈ 6 quasars

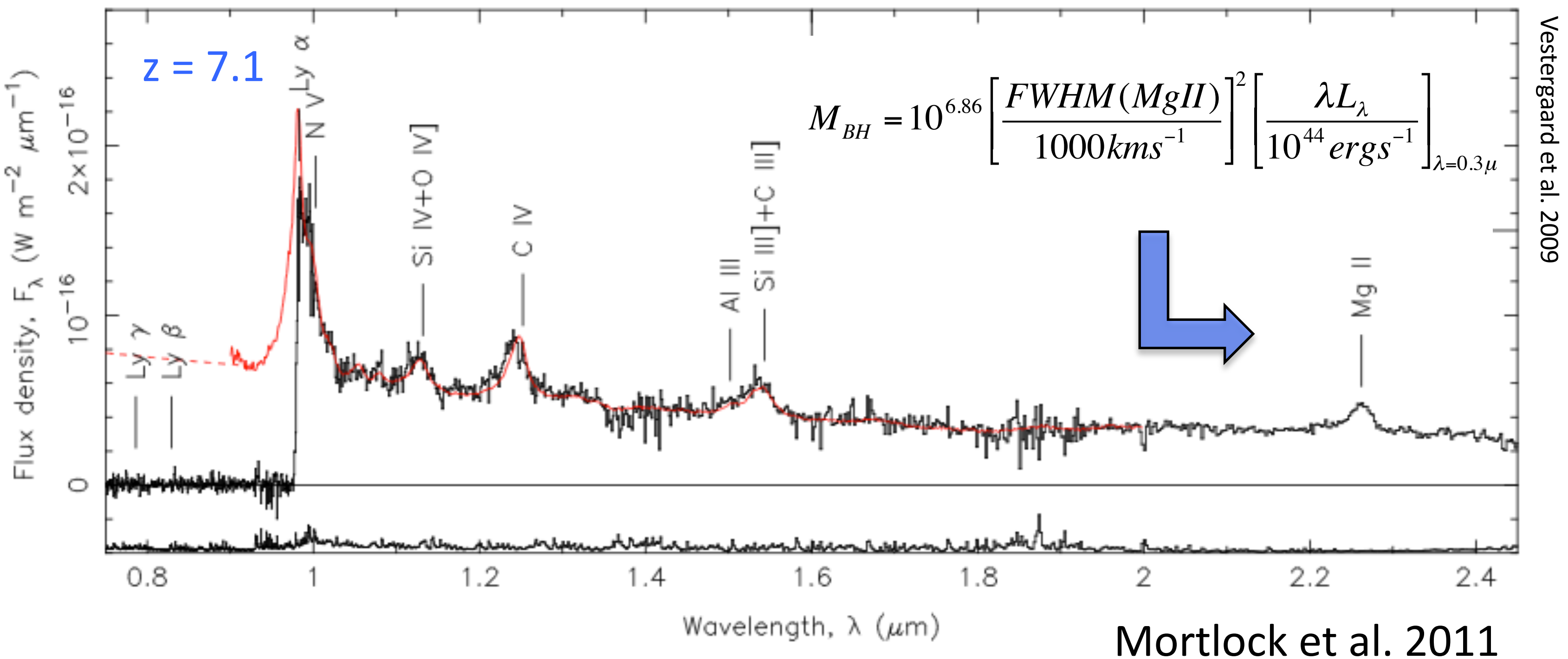


Mortlock et al. 2011

$$M_{BH} = 10^{6.86}\left[\frac{FWHM(MgII)}{1000kms^{-1}}\right]^2\left[\frac{\lambda L_\lambda}{10^{44}ergs^{-1}}\right]_{\lambda=0.3\mu}$$

$$M_{BH} = 2\times10^9 M_{sun}$$

Black hole mass measurements in z ≈ 6 quasars



Mortlock et al. 2011

Tens of z ≈ 6 quasars

(e.g. Barth et al. 2003; Jiang et al. 2007; Wang et al. 2010; Wu et al. 2015)

$$M_{BH} = (0.02 - 1.10) \times 10^{10} M_{sun}$$

How SMBHs have formed in less than 1 Gyr?

Possible pathways for the origin of SMBH seeds

(1) PopIII remnants

collapse of primordial stars
(M_{PopIII}>100 M_{sun})
in DM minihalos
(M_{DM}≈10^6 M_{sun})

z≈20-30

(2) Compact nuclear star clusters

Star collisions
can lead
to the formation of VMSs

z ≈10-20

(3) Direct Collapse Black Holes

Primordial gas
irradiated by LW radiation
in atomic-cooling halos

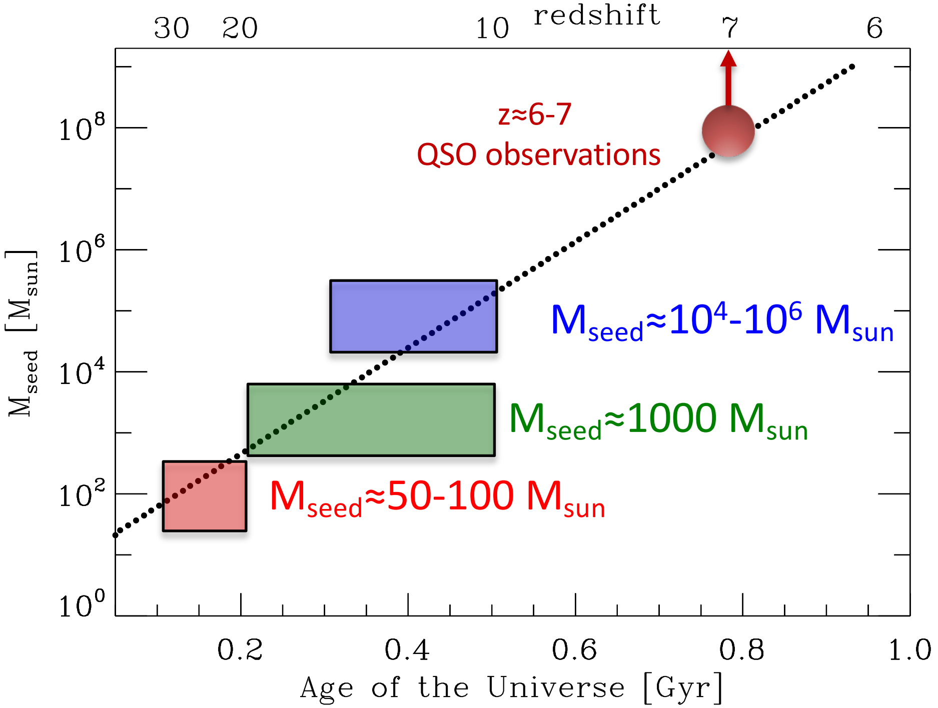
z > 10

z ≈ 3300 ← …

(4) Primordial Black Holes

Direct collapse of
primordial density
inhomogeneities

z > 2.3 x $10^4 h^2 \Omega_m$
(radiation-dominated era)



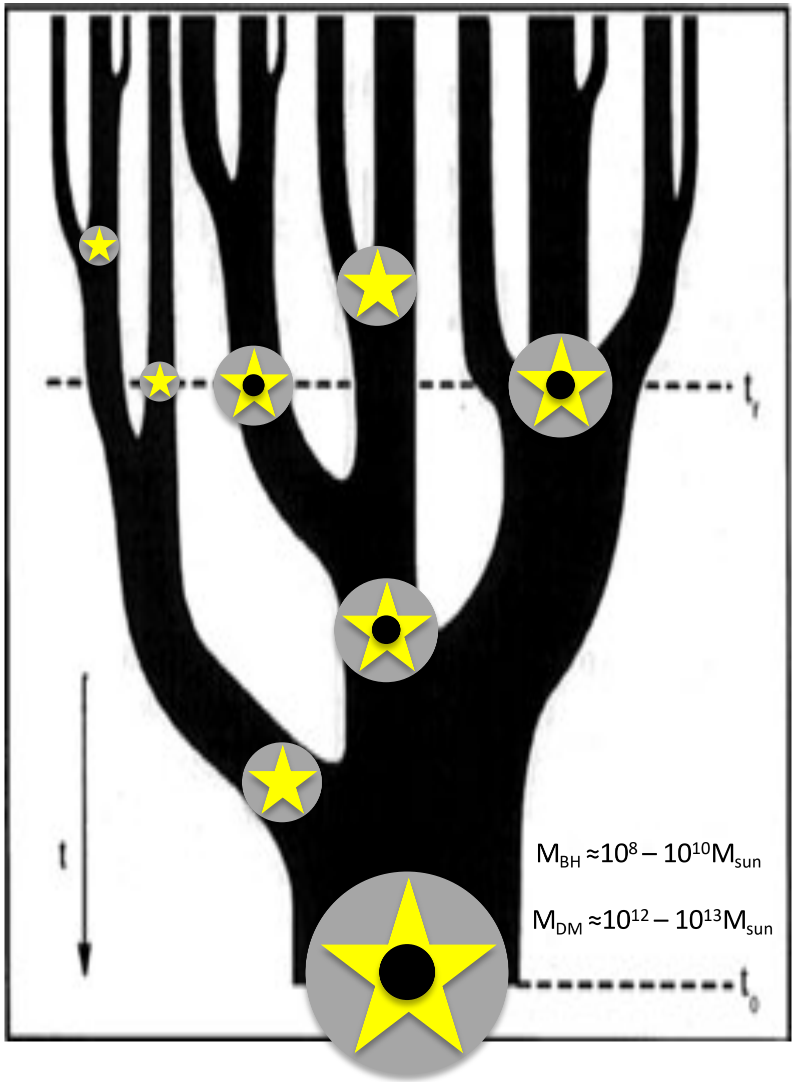
(e.g. Zel'dovich & Novikov 1967; Hawking 1971; Chapline et al. 1975; Bernal et al. 2017)

(e.g. Haehnelt & Rees 1993; Yue et al. 2013; Pallottini et al. 2017; Pacucci et al. 2017)

(e.g. Schneider et al. 2006; Clark et al. 2008; Devecchi et al. 2012)

(e.g. Tegmark et al. 1997; Madau & Rees 2001; Bromm et al. 2002)

Searching for SMBH progenitors



Lacey & Cole (1993)

STEP 3

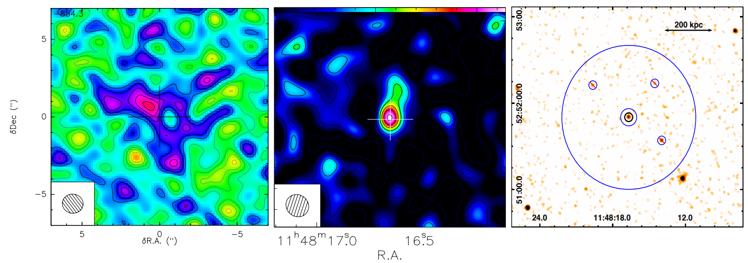
Predictions for observational signatures of SMBH progenitors (ALMA, JWST, Lynx)

STEP 2

Numerical simulations of quasars (100 < z < 6) constrained by means of z≈6 observations

STEP 1

Multi-wavelength observations of z≈6 quasars

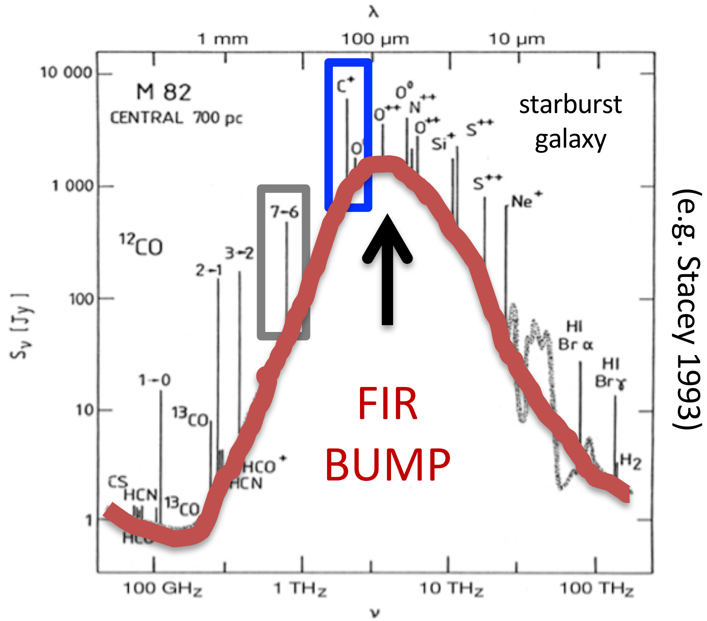


Sinergy between multi-wavelength data & cosmological simulations

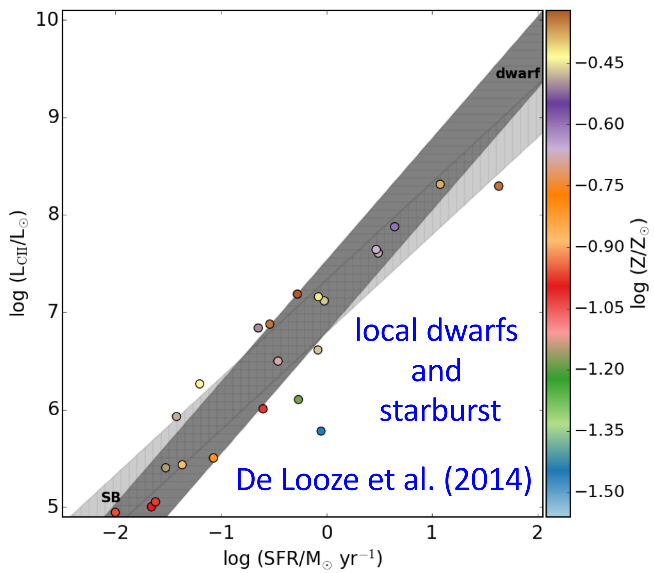
Far infrared emission lines: tracers of the ISM

$$L_{FIR} = 4\pi M_{dust} \int k(\nu) B_\nu(T_{dust}) d\nu$$

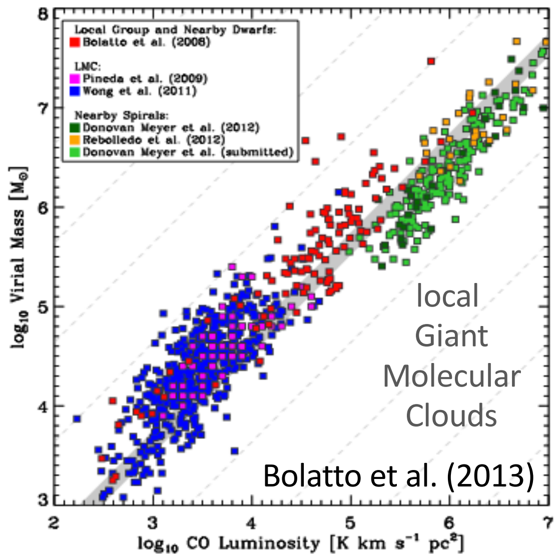
Fine structure transitions from heavy elements
(e.g. **[CII] ($^2P_{3/2}$-$^2P_{1/2}$) @158 μm**)
and rotational transitions from molecules
(e.g. **CO (J-J-1) @ J × 115 GHz**)
on the top of the **FIR BUMP**



L_{CII}-SFR relation



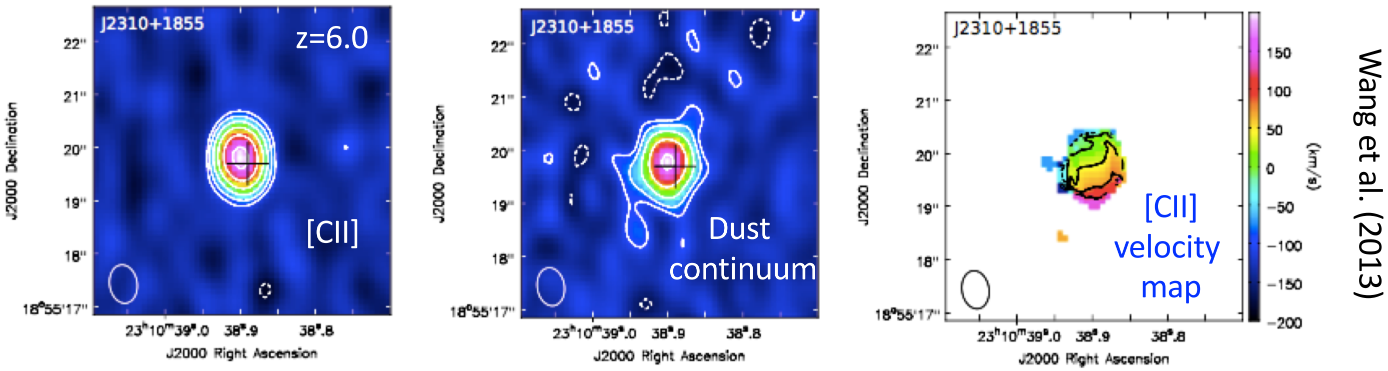
L_{CO}-M_{H2} relation

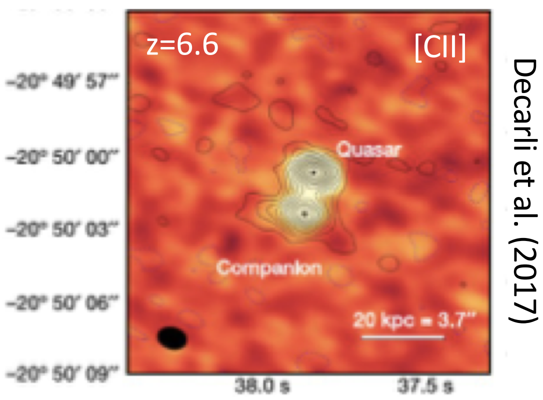


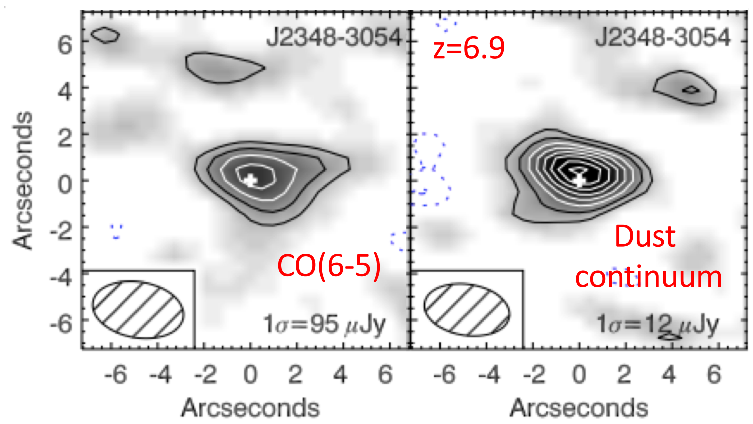
Detectable with ALMA/NOEMA at z>4

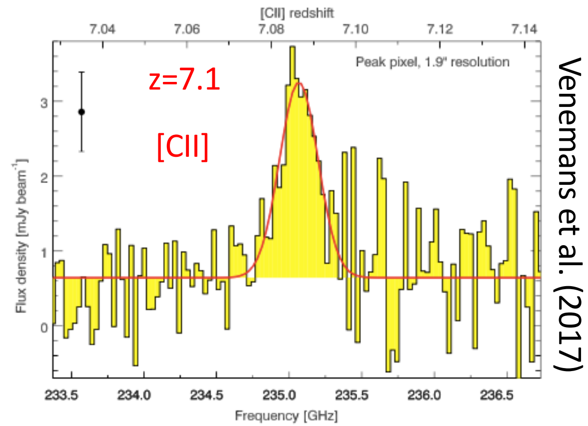
Sub-mm observations of z ≈ 6 quasar host galaxies

See also
Walter et al. (2003/2004);
Riechers et al. (2009);
Wang et al. (2010);
Bañados et al. (2015);
Willott et al. (2015)









Quasar host galaxies harbor intense starbursts

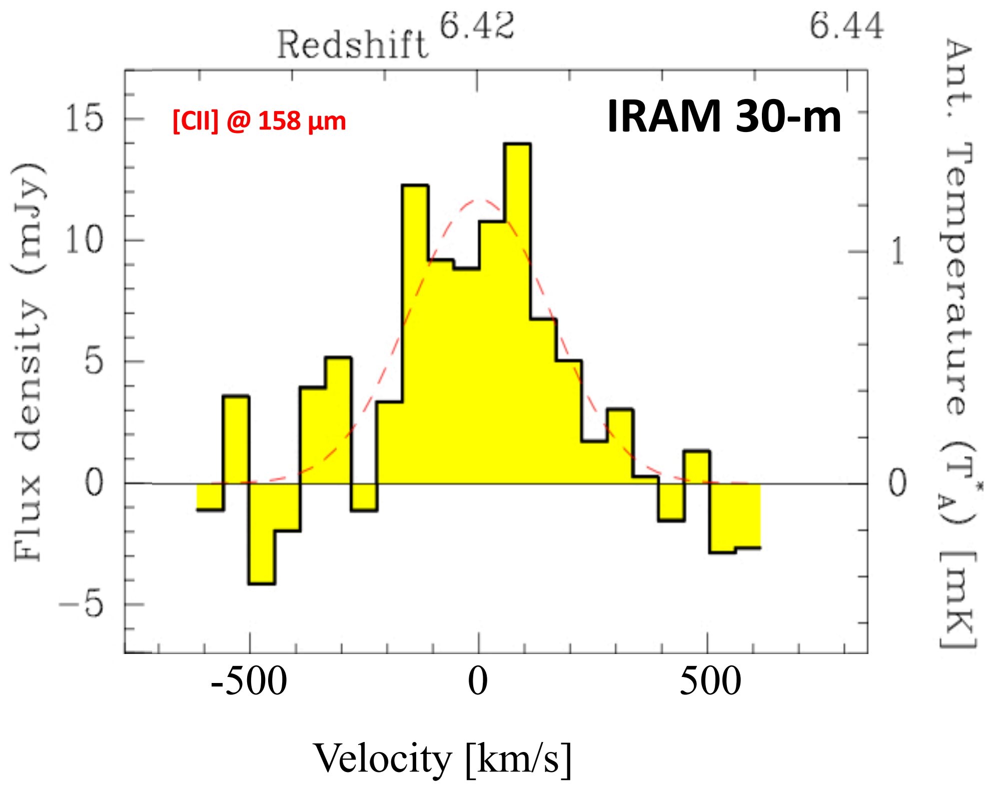
SFR ~ 10^2-10^3 M_{sun} yr^{-1}

M_{H2} ~ 10^9-10^{10} M_{sun}

M_{dust} ~ 10^7-10^8 M_{sun}

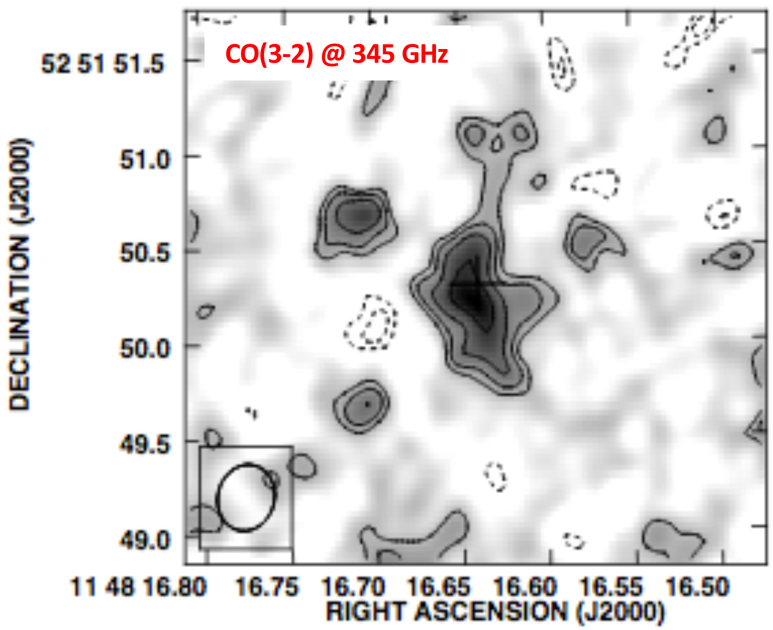
See Gallerani, Fan, Maiolino, Pacucci (2017) for a recent review, arXiv:1702.06123

The case of SDSS J1148 + 5251 at z ≈ 6.4



FIRST [CII] EVER DETECTED AT HIGH-z

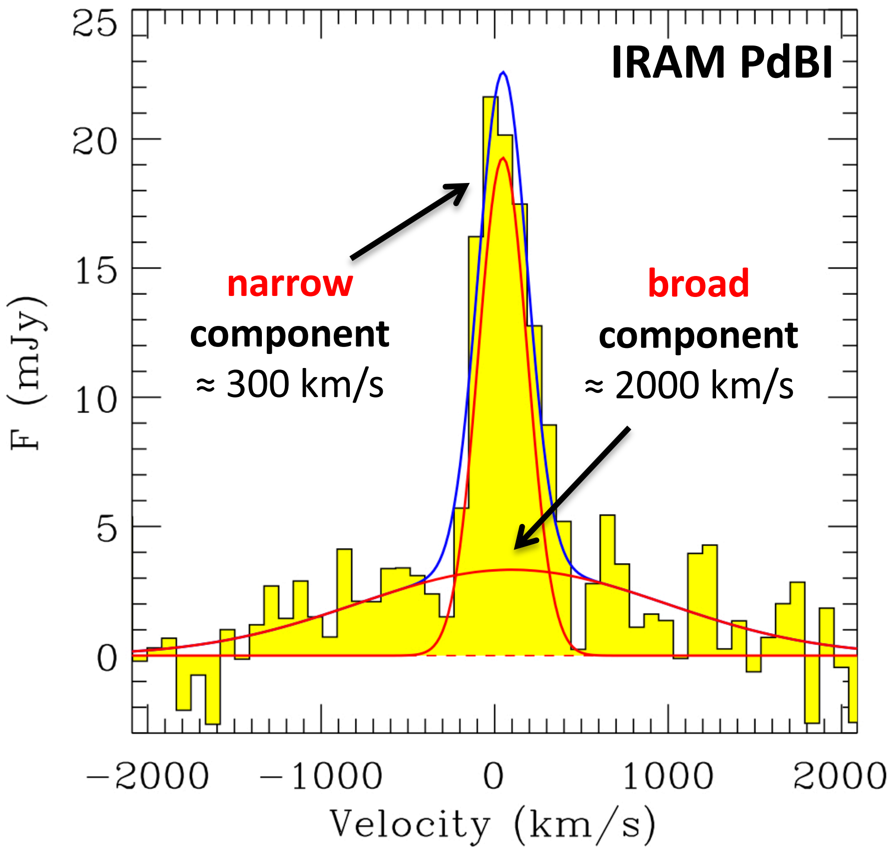
(Maiolino et al. 2005)



FIRST RESOLVED CO MAP AT HIGH-z

(Walter et al. 2009)

(PdBI) [CII] emission in J1148 at z ≈ 6.4



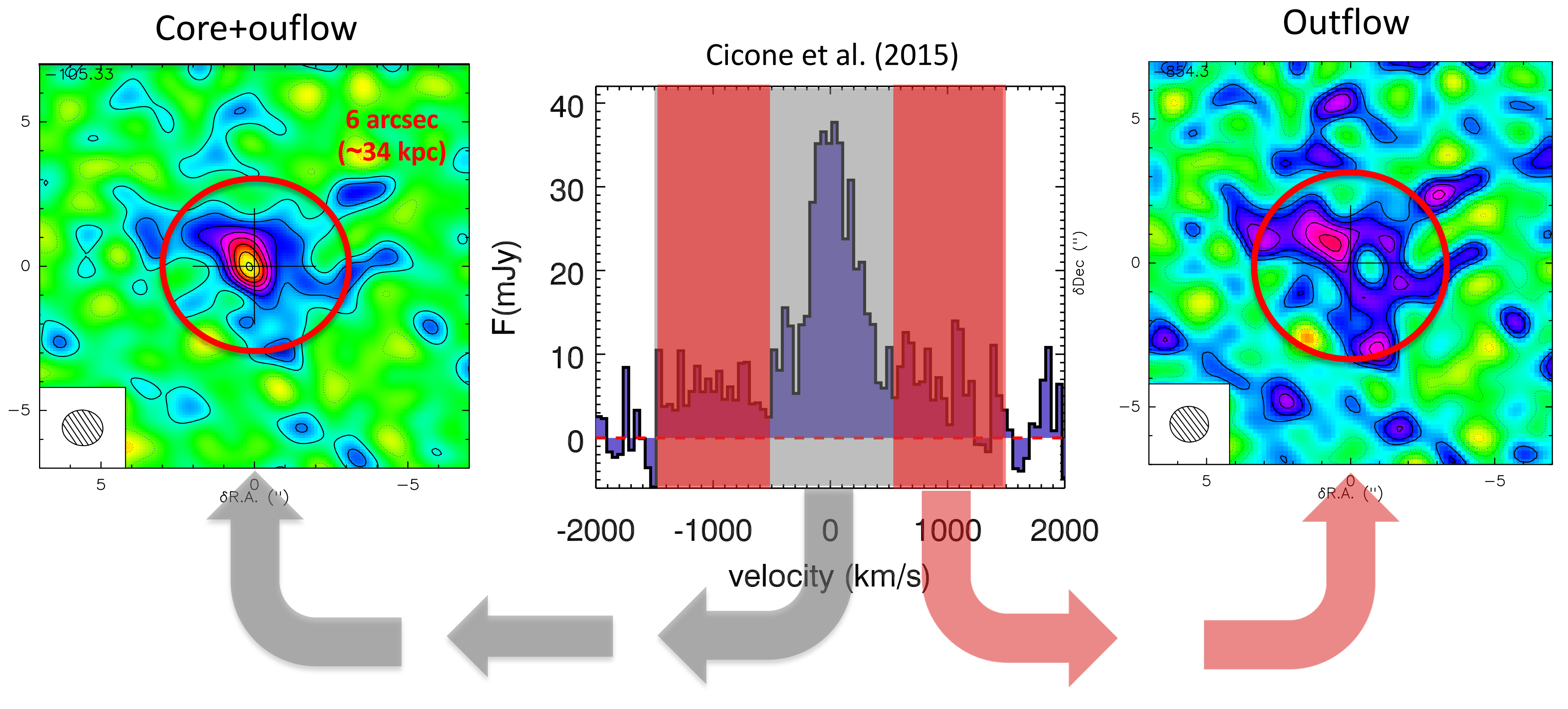
Broad wings
extended up to
± 1300 km/s

indication of a
powerful outflow

Maiolino et al. (2012)

Evidence of strong quasar feedback at z≈6

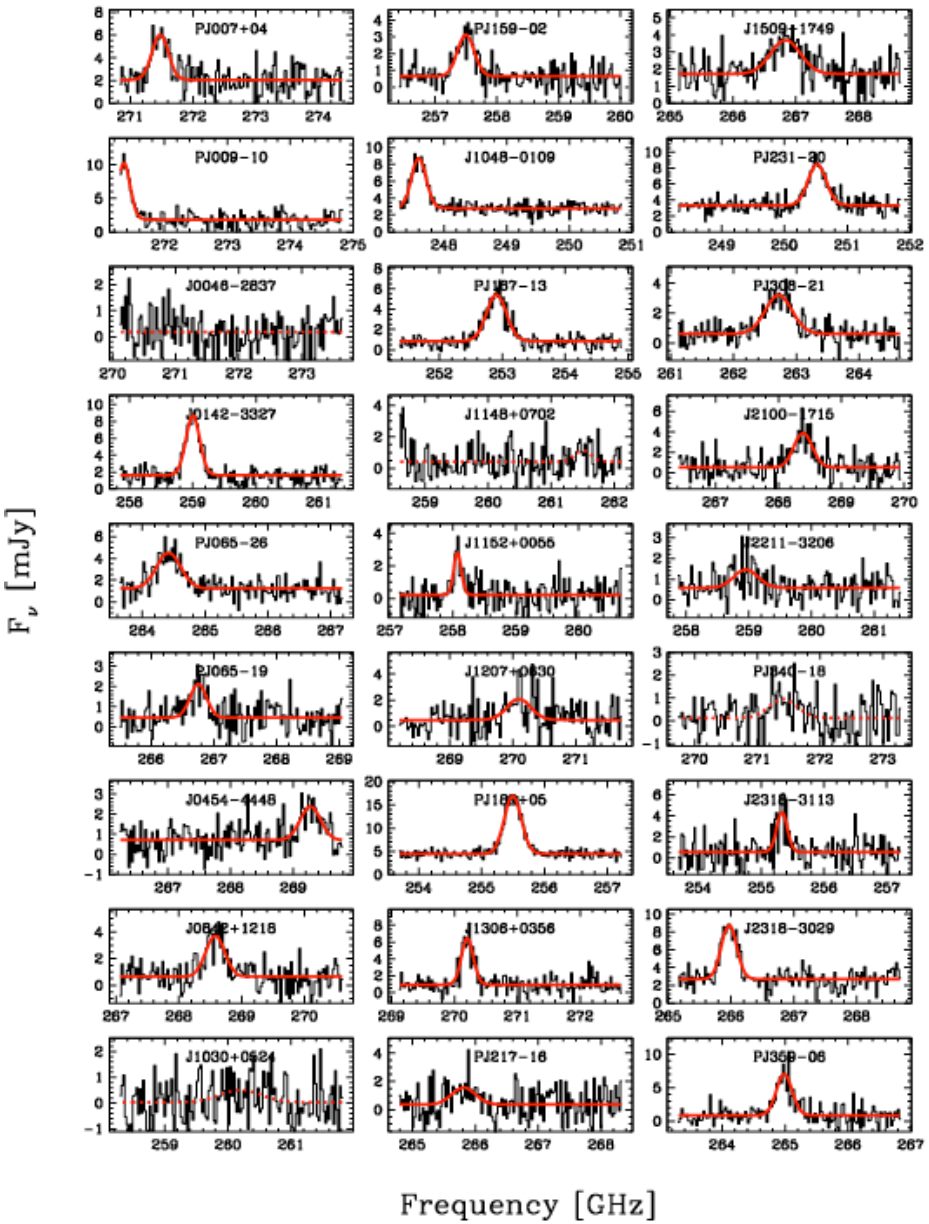
[CII] emission in a quasar at z ≈ 6.4



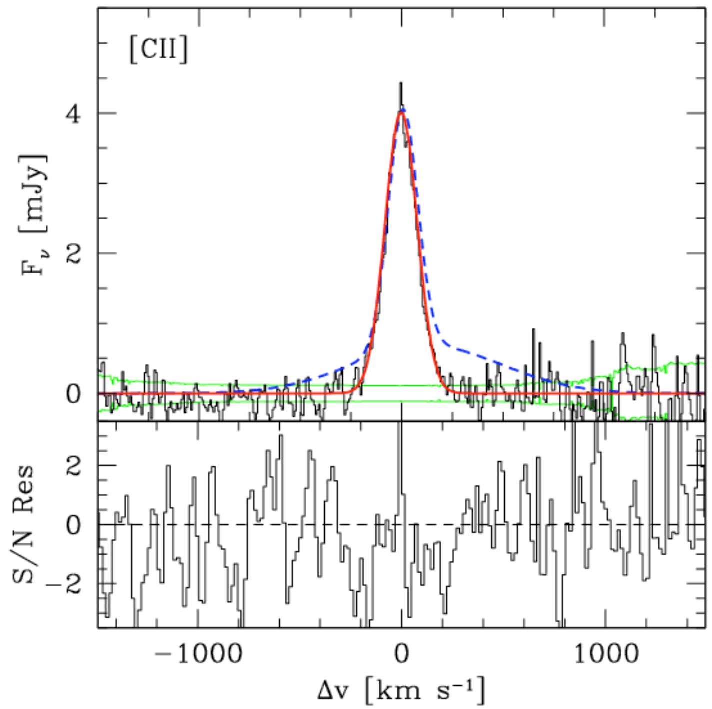
Metals and outflowing gas
are distributed on scales ≥ 20 - 30 kpc

What about other z ≈ 6 quasars?

AN ALMA [CII] SURVEY OF 27 QUASARS AT z > 5.94



No detection of outflows either in individual sources (23 detected in [CII]) or in the stacked spectrum

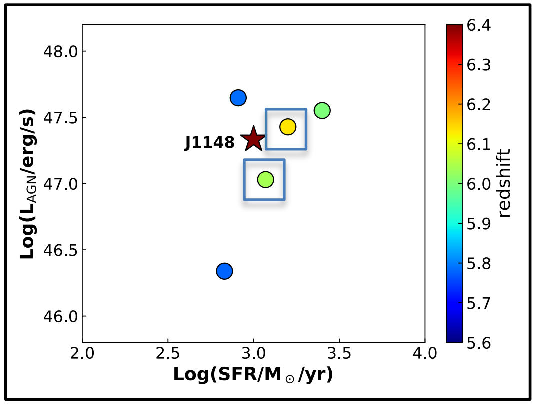


S/N ratio? Orientation effects?

Decarli et al. (2018)

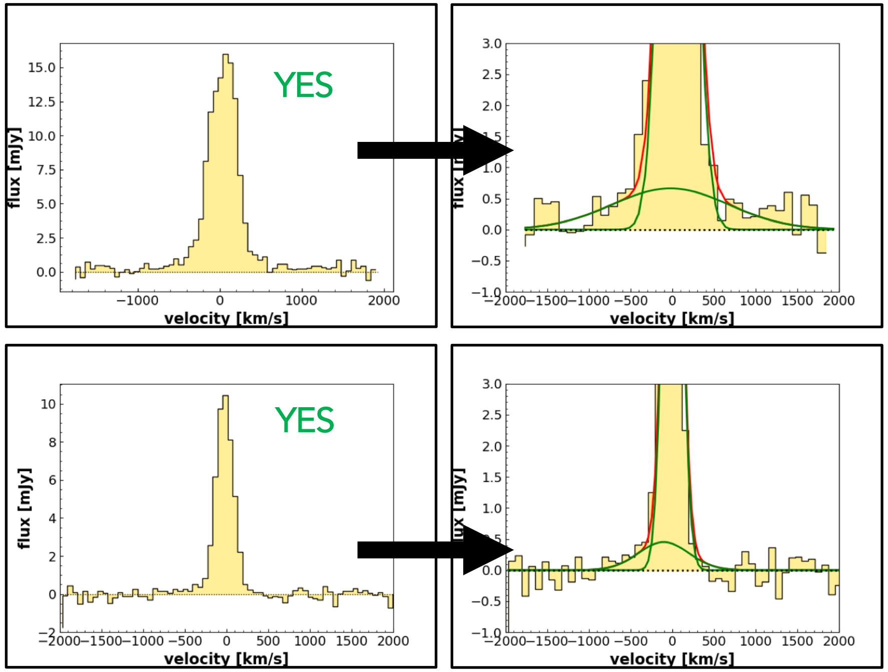
What about other z ≈ 6 quasars?

ALMA [CII] observations
of 5 quasars at z ≈ 6

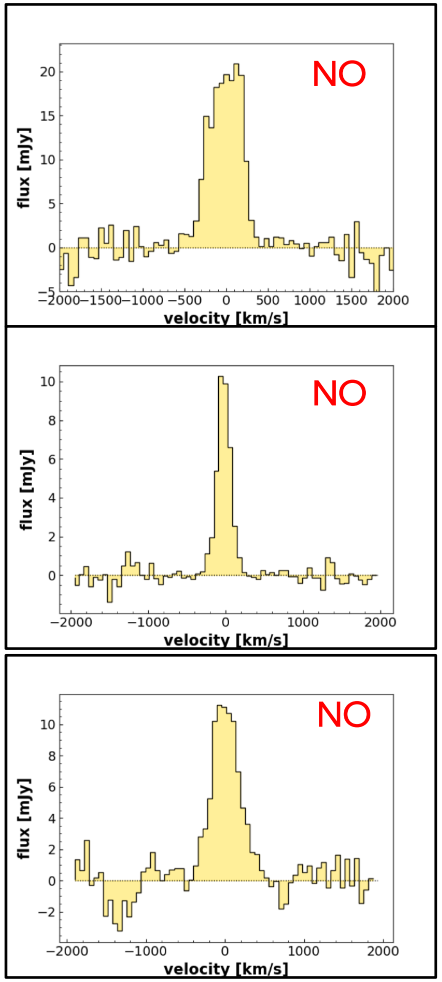


physical properties
and sensitivities
similar to J1148

10 times fainter than J1148



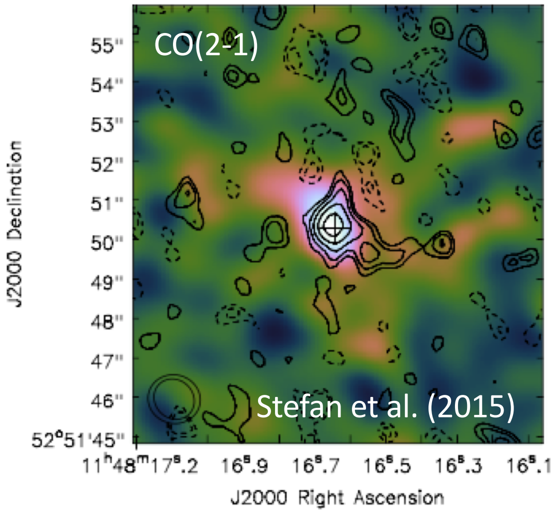
Broad components detected in 2 quasars

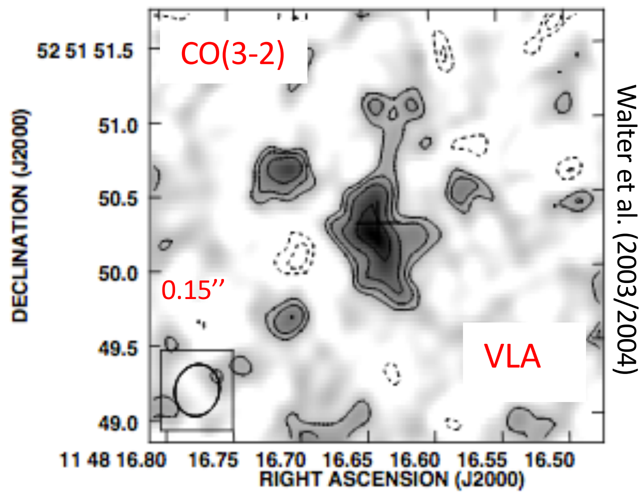


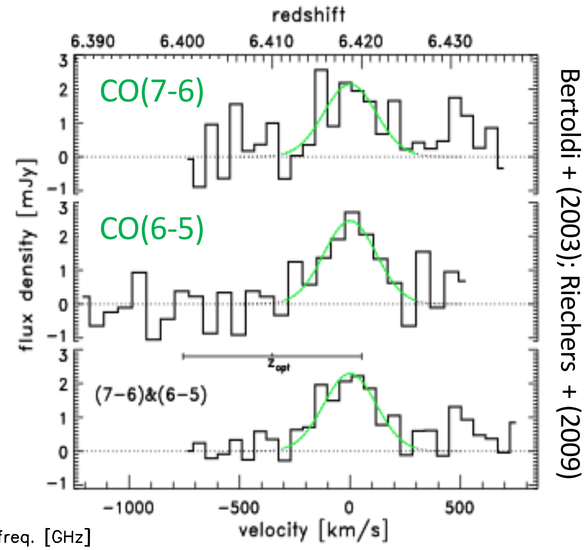
6 times less extended than J1148

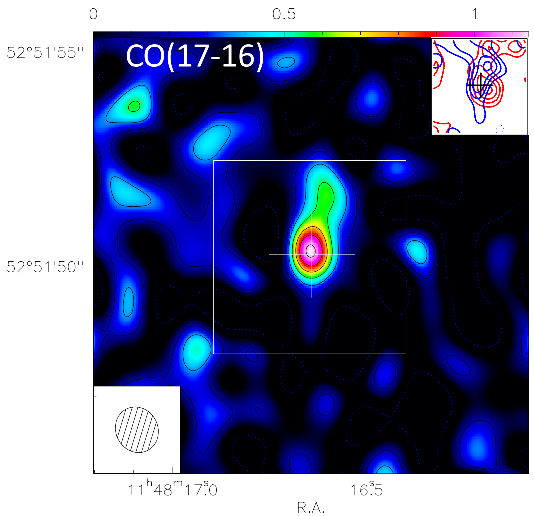
Carniani et al. in prep.

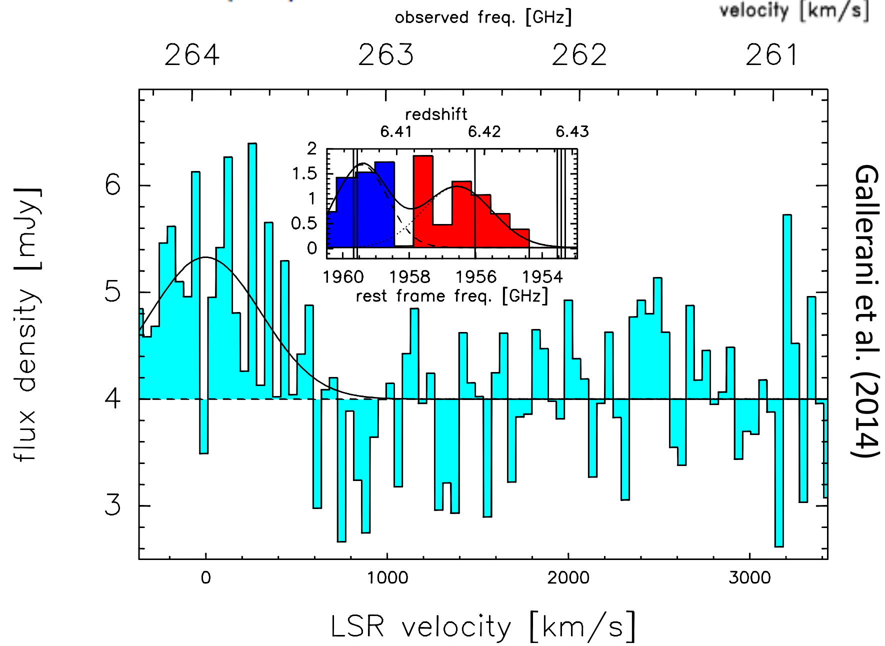
CO emission in J1148 at z ≈ 6.4







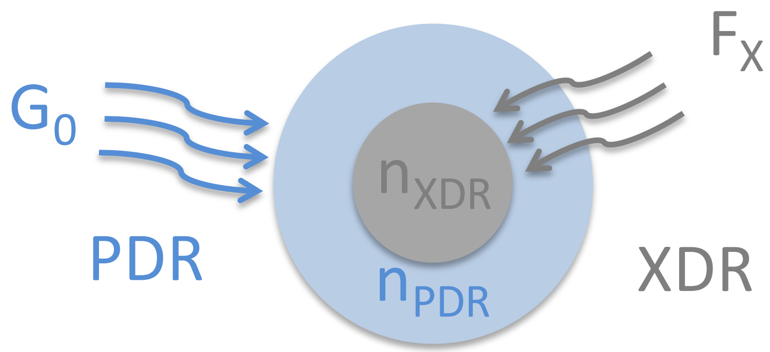




The CO(17-16) is the most excited CO line found in z ≈ 6 quasars

CO Spectral Line Energy Distribution in J1148

PDR/XDR model by
Meijerink et al. (2005/2006)



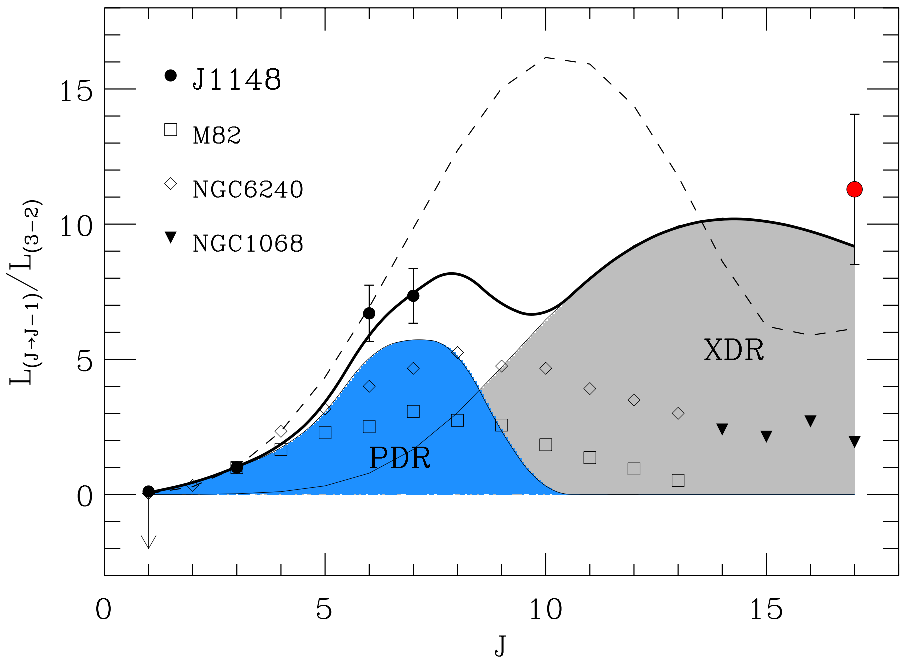
Molecular
Cloud

PDR

Photo-dissociation regions

$n_{PDR}= 10^{4.25}$ [cm^{-3}]

$G_0=10^5$



Gallerani et al. (2014)

XDR

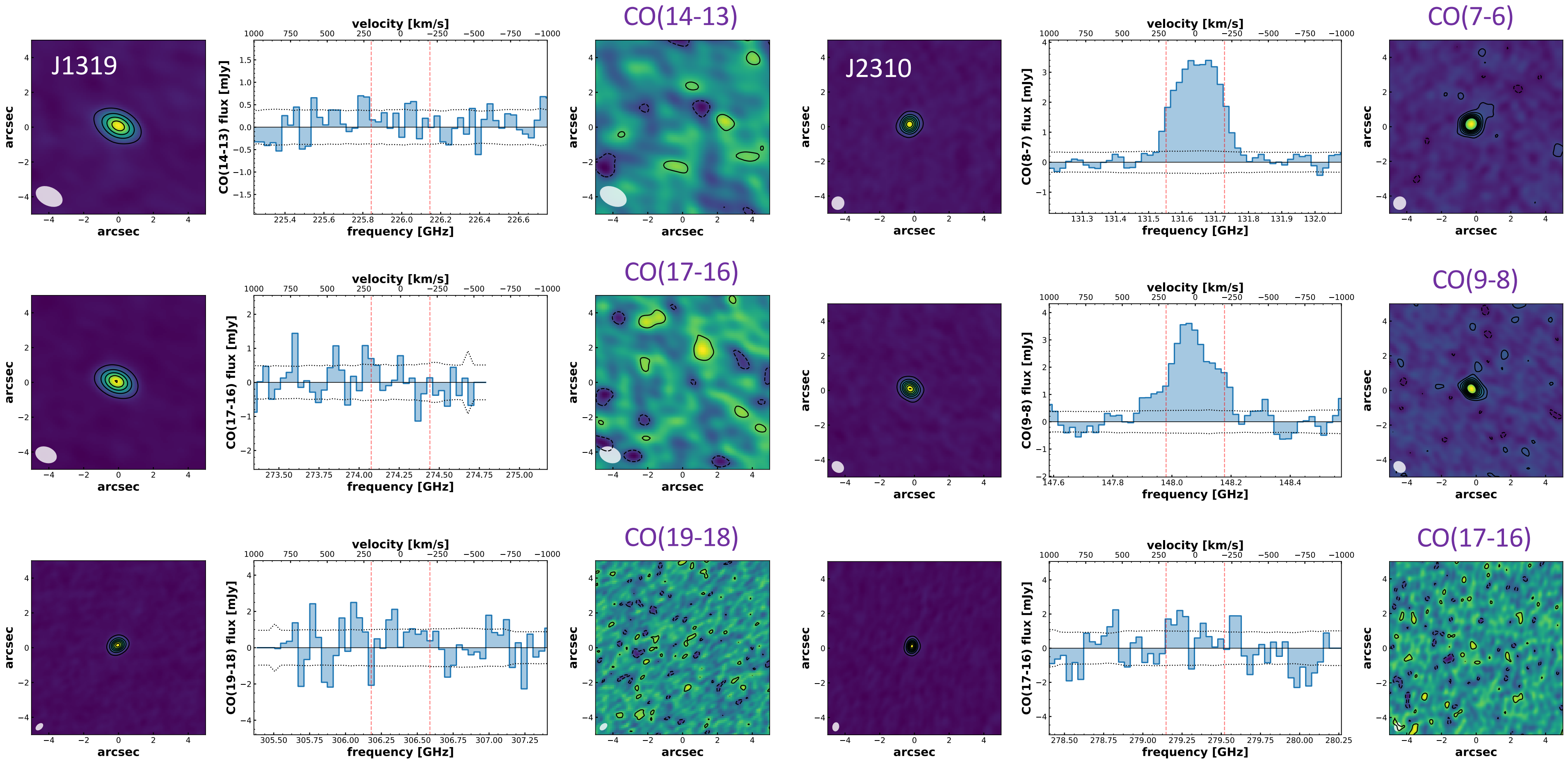
X-ray dominated regions

$n_{XDR} = 10^{4.5}$ [cm^{-3}]

F_X = 160 [erg s^{-1} cm^{-2}]

The XDR contribution is required
to explain the detection of the CO(17-16) line

ALMA observations of high-J CO lines in z ≈ 6 quasars



PI: Ran Wang

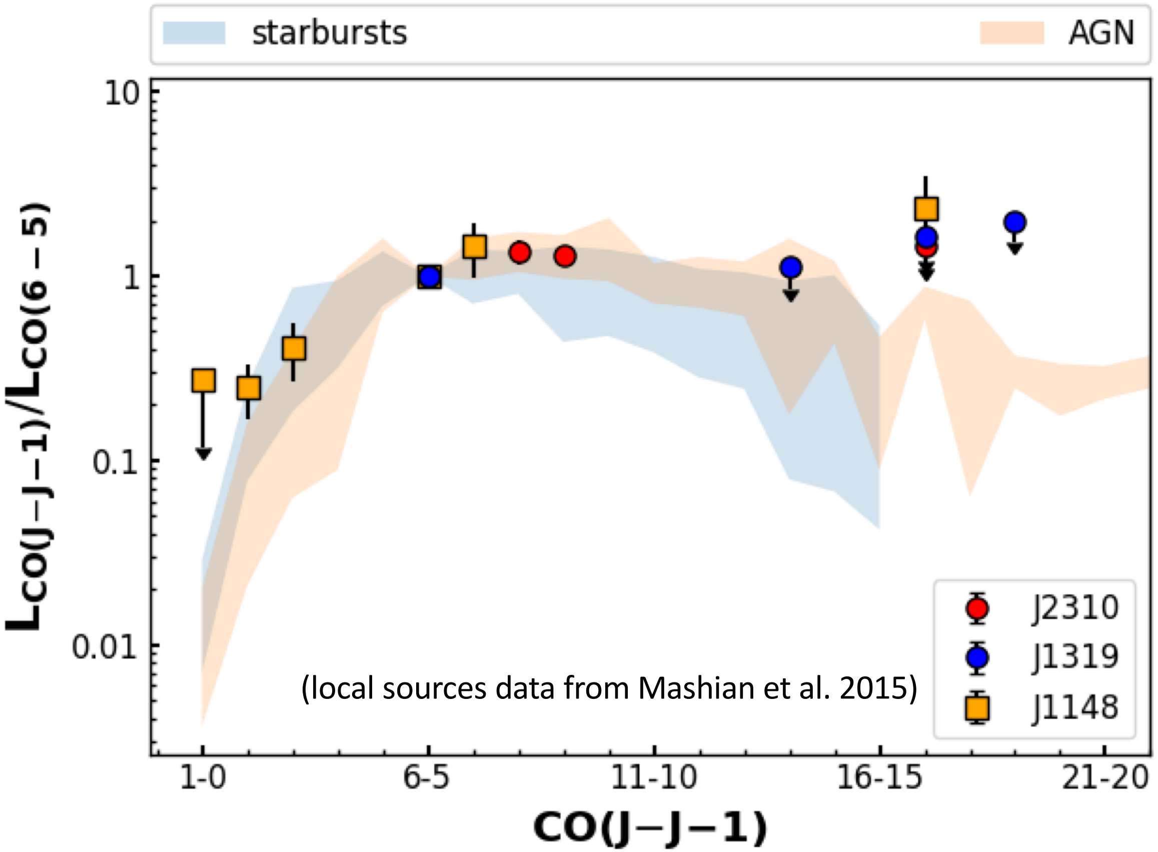
Dust continuum detected in both quasars at all frequencies

No detection of high-J (J≥10) CO lines in both quasars

Detection of CO(8-7) and CO(9-8) in J2310

Carniani et al. in prep.

Comparison with COSLEDs observed in the local Universe and in J1148



- Results for **J2310** and **J1319** are consistent with local sources observations
- The CO(17-16) emission line of **J1148** is > 3σ brighter than the averaged CO SLED of local sources

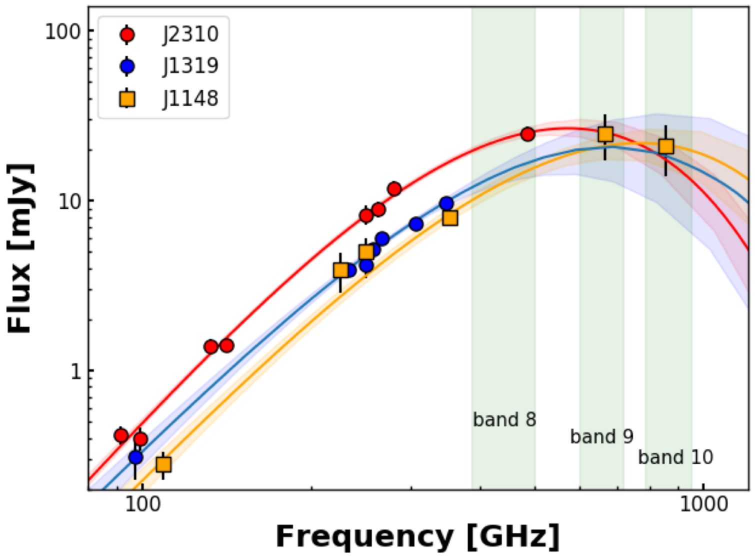
What is the origin of these differences?

Carniani et al. in prep.

Mechanisms responsible for molecular gas excitation:

Star formation, AGN activity, Shocks

- **Star formation**: The properties of J1148, J2310, and J1310 are quite similar in terms of FIR emission (SFRs). If high-J CO lines are predominantly excited by star formation activity, we should have observed in J2310 and J1319 high-J CO lines as luminous as in J1148.



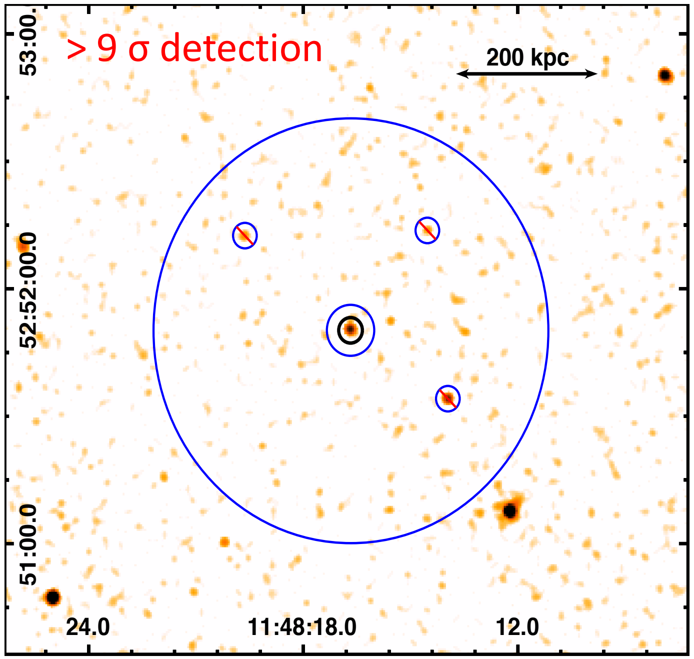
	J2310	J1319	J1148
$\mathrm{Log(SFR_{FIR}/M_\odot\ yr^{-1})^{(1)}}$	$3.45^{+0.11}_{-0.09}$	3.6 ± 0.3	3.51 ± 0.14
$\mathrm{L_{C\,II}}^{(2)}$ [10[illegible] $\mathrm{L_\odot}$]	8.7 ± 1.4	4.4 ± 0.9	37 ± 9
$\mathrm{\dot{M}_{outflow}}^{(3)}$ $[\mathrm{M_\odot\ yr^{-1}}]$	No outflow	∼10 x lower	∼3000
$\mathrm{L_{X-ray}}^{(4)}$ $[10^{45}\ \mathrm{erg\ s^{-1}}]$	-	-	$1.4^{+0.4}_{-0.3}$
$\mathrm{M_{BH}}^{(5)}$ $[10^9\ \mathrm{M_\odot}]$	2.8	2.1	3

Carniani et al. in prep.

Mechanisms responsible for molecular gas excitation:

Star formation, AGN activity, Shocks

- **AGN activity**: Strong high-J CO lines can be excited in X-ray dominated regiong. J1148 is the only quasar among the three for which X-ray observations are available.



	J2310	J1319	J1148
$\mathrm{Log(SFR_{FIR}/M_\odot\ yr^{-1})}$ (1)	$3.45^{+0.11}_{-0.09}$	3.6 ± 0.3	3.51 ± 0.14
$L_{C\,II}$ (2) $[10^9\ L_\odot]$	8.7 ± 1.4	4.4 ± 0.9	37 ± 9
$\dot{M}_{outflow}$ (3) $[M_\odot\ yr^{-1}]$	No outflow	~10 x lower	~3000
L_{X-ray} (4) $[10^{45}\ erg\ s^{-1}]$	-	-	$1.4^{+0.4}_{-0.3}$
M_{BH} (5) $[10^9\ M_\odot]$	2.8	2.1	3

$L_X \approx 1.5 \times 10^{45}$ erg s^{-1}

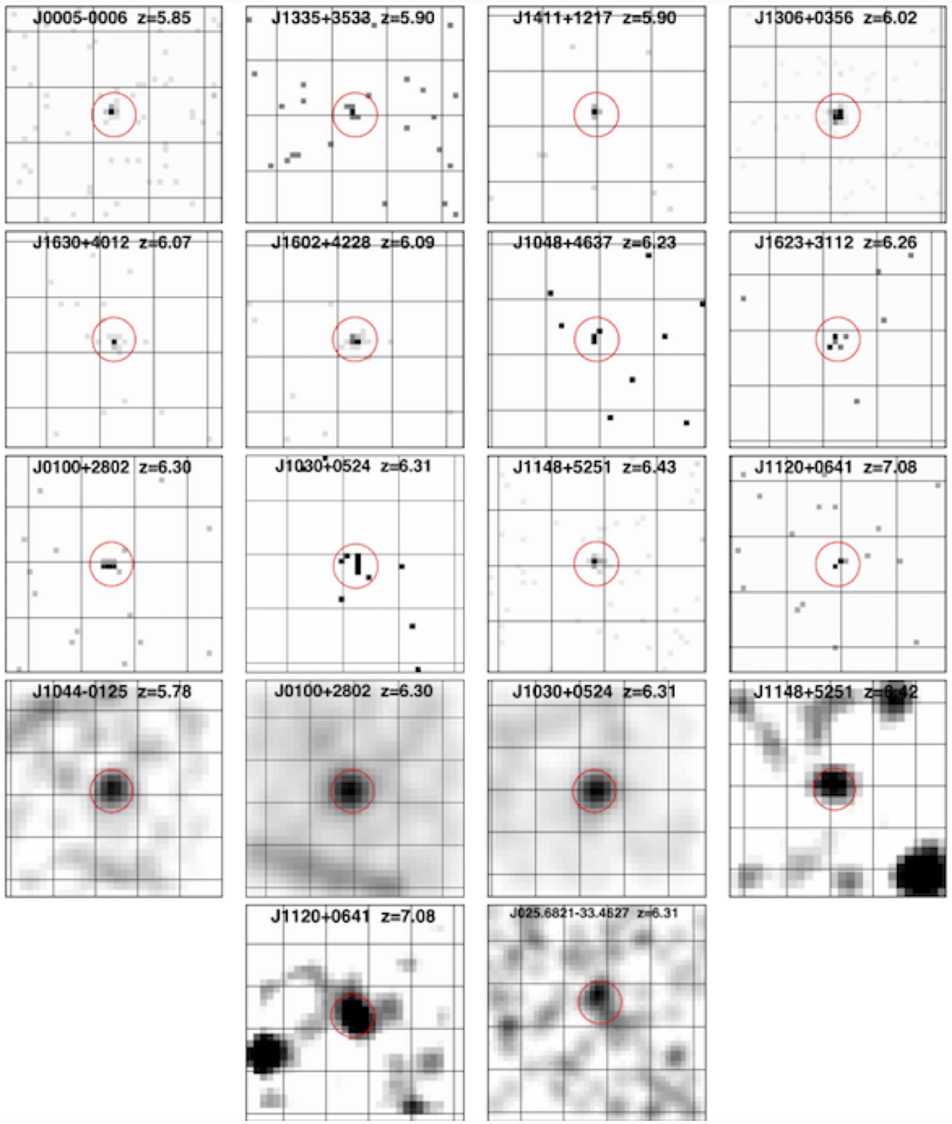
$\alpha_{OX} = -1.76 \pm 0.14$

$\Gamma = 1.6 \pm 0.3$

X-ray properties consistent both with low-z high-luminosity AGN

X-ray properties of z ≈ 6 luminous quasars

Nanni et al. (2017)



AVERAGE VALUES

$L_X = (0.1\text{-}4.2) \times 10^{45}$ erg s^{-1}

$\alpha_{ox} = -1.75$

$\Gamma = 1.92_{-0.27}^{+0.28}$

J1148

$L_X \approx 1.5 \times 10^{45}$ erg s^{-1}

$\alpha_{OX} = -1.76 \pm 0.14$

$\Gamma = 1.6 \pm 0.3$

From the best-fit relation α_{ox} - $L_{2500\,Å}$

$\alpha_{ox} = (-0.155 \pm 0.003) \log(L_{2500Å}) + (3.206 \pm 0.103)$

$L_{2500\,Å} = 10^{32}$ erg s^{-1} Å^{-1} → $\alpha_{ox} = -1.75$

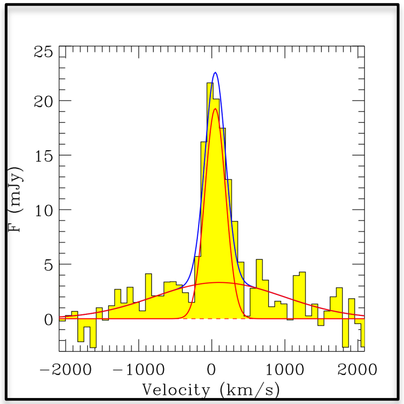
(see also Farrah et al. 2004, Moretti et al. 2014, Page et al. 2014, Moretti et al. 2018)

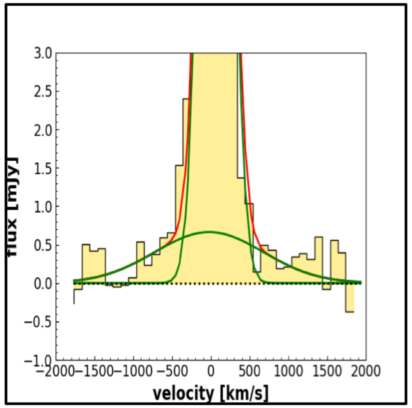
X-ray properties consistent both with low-z high-luminosity AGN and other z ≈ 6 quasars

Mechanisms responsible for molecular gas excitation:

Star formation, AGN activity, Shocks

- **Shocks**: High temperatures associated to shocks can also be responsible for boosting the luminosity of high-J CO lines. In this context, it is remarkable that, while J1148 exhibits a massive, powerful outflow, in the other sources no such strong outflows have been found. Indeed, broad wings in the [CII] profile have been observed only in J1319, yielding an outflow rate ∼10 times smaller than that found in J1148.



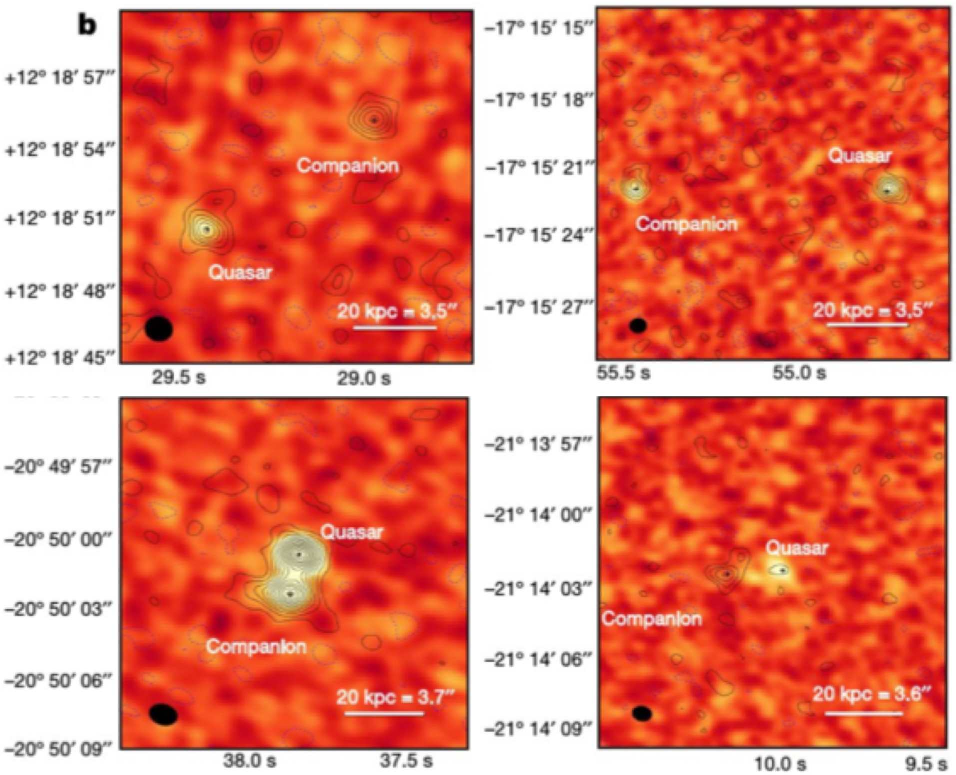


	J2310	J1319	J1148
$\mathrm{Log(SFR_{FIR}/M_{\odot}\ yr^{-1})^{(1)}}$	$3.45^{+0.11}_{-0.09}$	3.6 ± 0.3	3.51 ± 0.14
$\mathrm{L_{CII}}^{(2)}\ [10^9\ \mathrm{L_{\odot}}]$	8.7 ± 1.4	4.4 ± 0.9	37 ± 9
$\dot{\mathrm{M}}_{\mathrm{outflow}}{}^{(3)}\ [\mathrm{M_{\odot}\ yr^{-1}}]$	No outflow	∼10 x lower	∼3000
$\mathrm{L_{X-ray}}^{(4)}\ [10^{45}\ \mathrm{erg\ s^{-1}}]$	-	-	$1.4^{+0.4}_{-0.3}$
$\mathrm{M_{BH}}^{(5)}\ [10^9\ \mathrm{M_{\odot}}]$	2.8	2.1	3

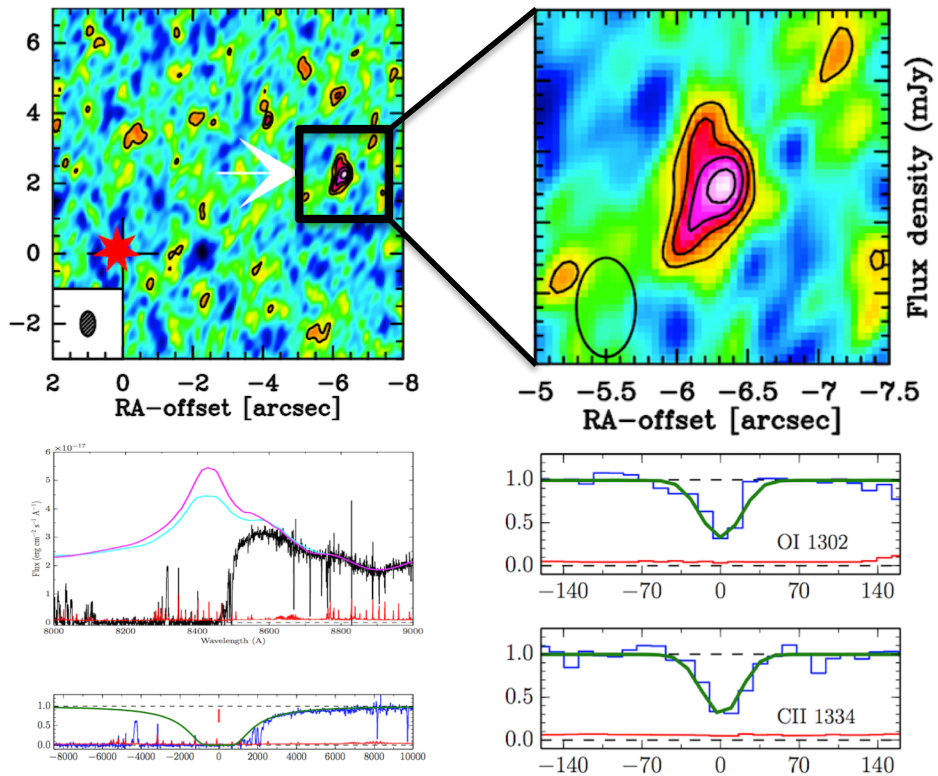
The broad component of J1148 is more than 10 times the one detected in J1319

Carniani et al. in prep.

[CII] and CO(6-5) emission from field galaxies



Decarli et al. (2017)

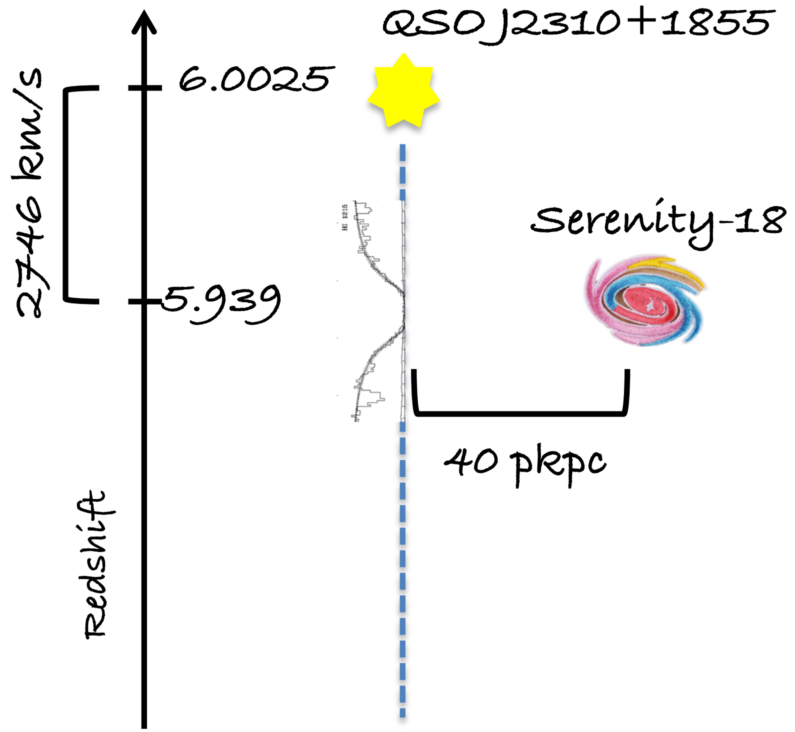


D'Odorico et al. (2018)

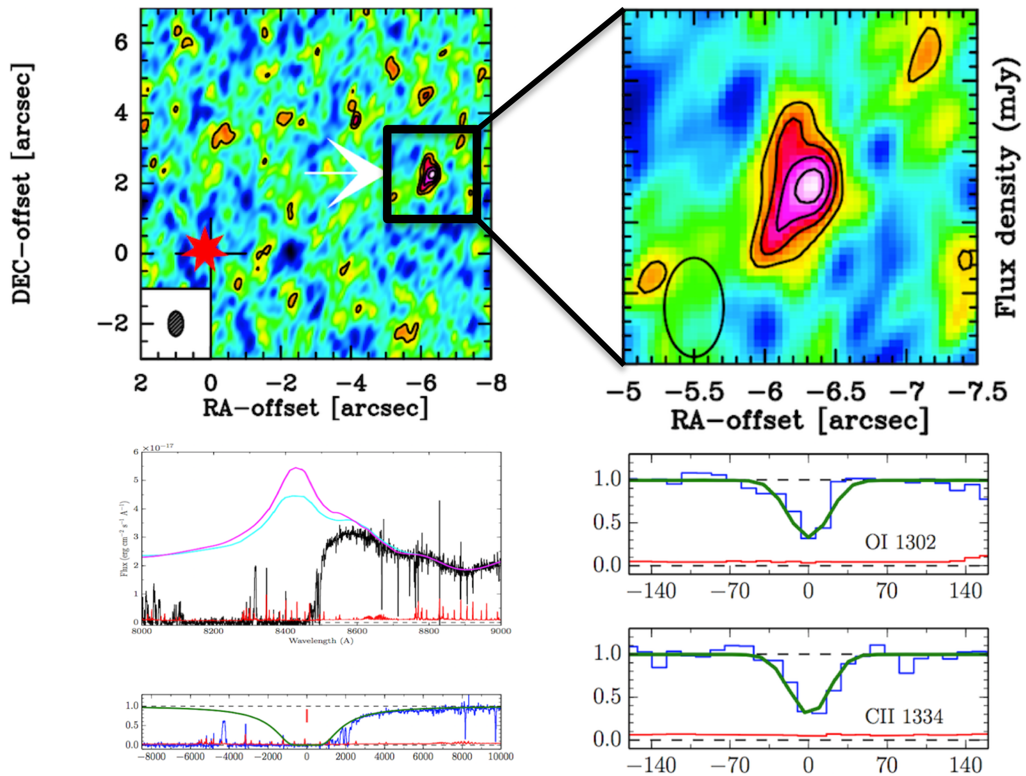
Serendipitous discovery of galaxy companions in z≈ 6 quasars

(see also e.g. Gallerani et al. 2012, Trakhtenbrot et al. 2017 for z≈ 4-5 quasars)

[CII] and CO(6-5) emission from field galaxies



QSO J2310+1855 z_{em} = 6.0025
X-shooter observations
Associated DLA at z=5.939



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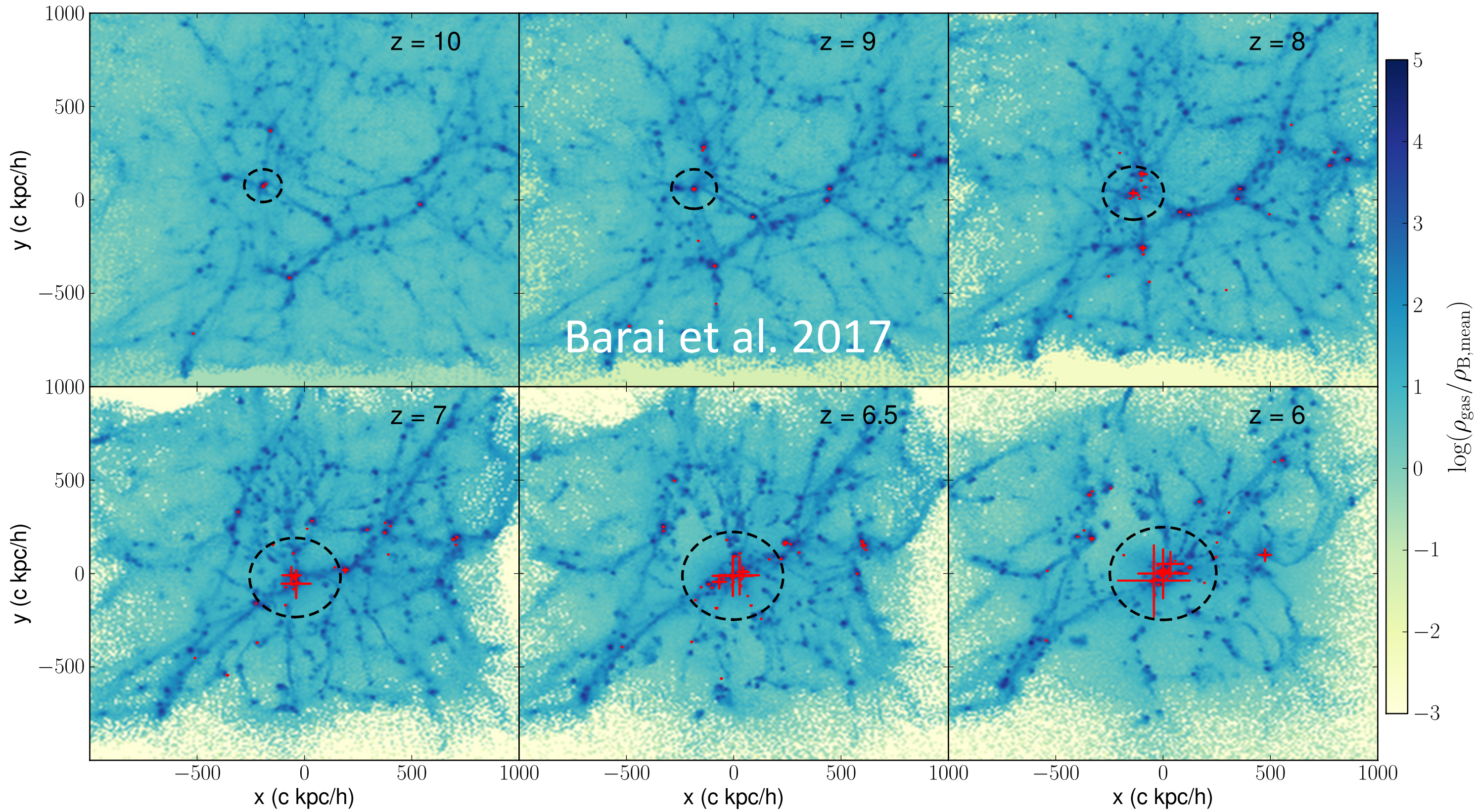
Cosmological simulations of a z ≈ 6 quasar



GADGET-3 (Springel 2005)

100 > z > 6

$L_{box} \approx 1\ h^{-1}$ c Mpc

$m_{DM}^{res} = 4 \times 10^{6}\ M_{sun}$

$\lambda_{smooth} = 1\ h^{-1}$ c kpc

$M_{DM}^{tot} \approx 4 \times 10^{12}\ M_{sun}$

STAR FORMATION: ($n > 0.1$ cm^{-3}) - **SN FEEDBACK**

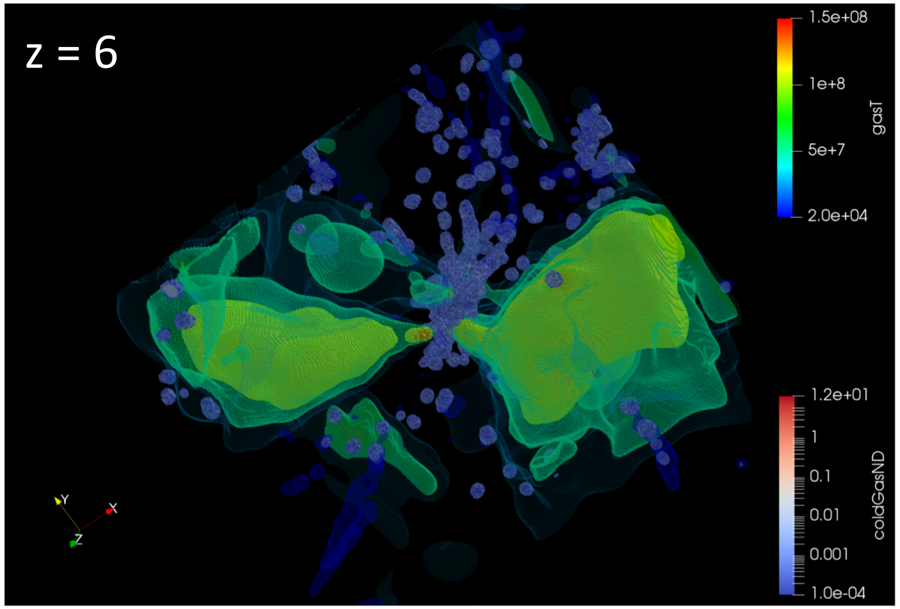
BLACK HOLE SEEDING: $10^5\ M_{sun}$ BH in $M_{DM} > 10^9 M_{sun}$

BLACK HOLE GROWTH: Gas accretion and galaxy merging

$$\dot{M}_{Bondi} = \alpha \frac{4\pi G^2 {M_{BH}}^2 \rho_{gas}}{(c^2 + {v_{BH-gas}}^2)^{3/2}}$$

(Bondi & Hoyle 1944; Hoyle & Lyttleton 1939)

Cosmological simulations of a z ≈ 6 quasar



QUASAR FEEDBACK

Quasar feedback energy is distributed as kinetic energy

We have assumed a bi-conical and spherical geometry

Surrounding ***gas is driven outward***

$(v_{outflow}, \dot{M}_{outflow}) \qquad v_{outflow} = 10^4\, km/s$

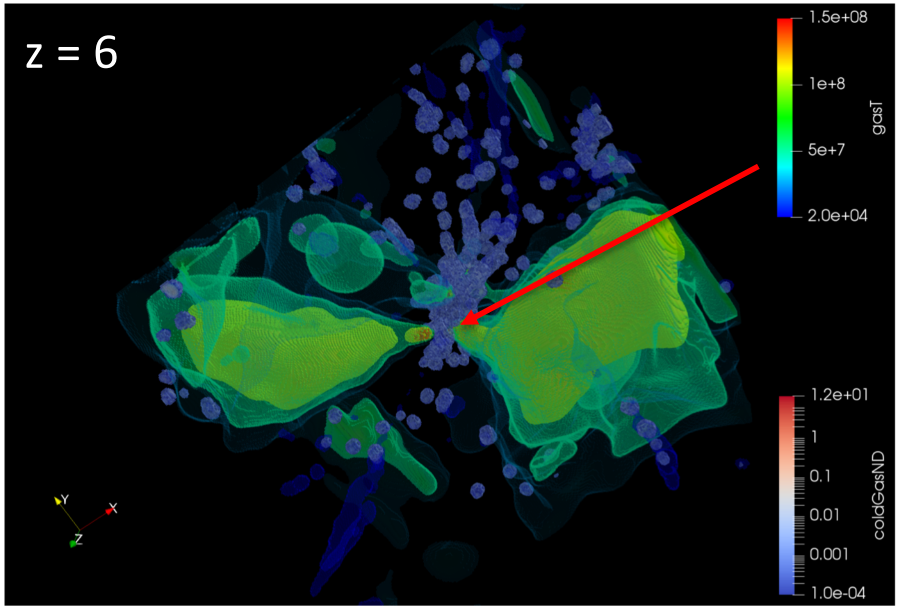
$$\frac{1}{2}\dot{M}_{ouflow} v_{outflow}{}^2 = \dot{E}_{feed}$$

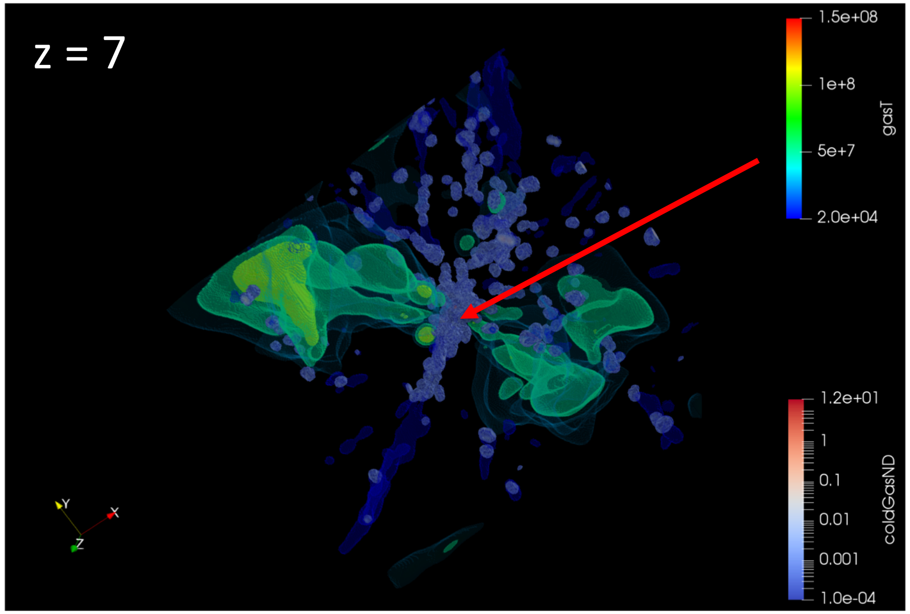
↓

$$\dot{M}_{outflow} = 2\, \varepsilon_{feed}\, \varepsilon_{rad}\, \dot{M}_{BH} \left(\frac{c}{v_{outflow}}\right)^2$$

Although a powerful outflow is in place,
fast-moving gas would be detectable only along directions
intercepting the outflow orientation.

Cosmological simulations of a z ≈ 6 quasar





QUASAR FEEDBACK

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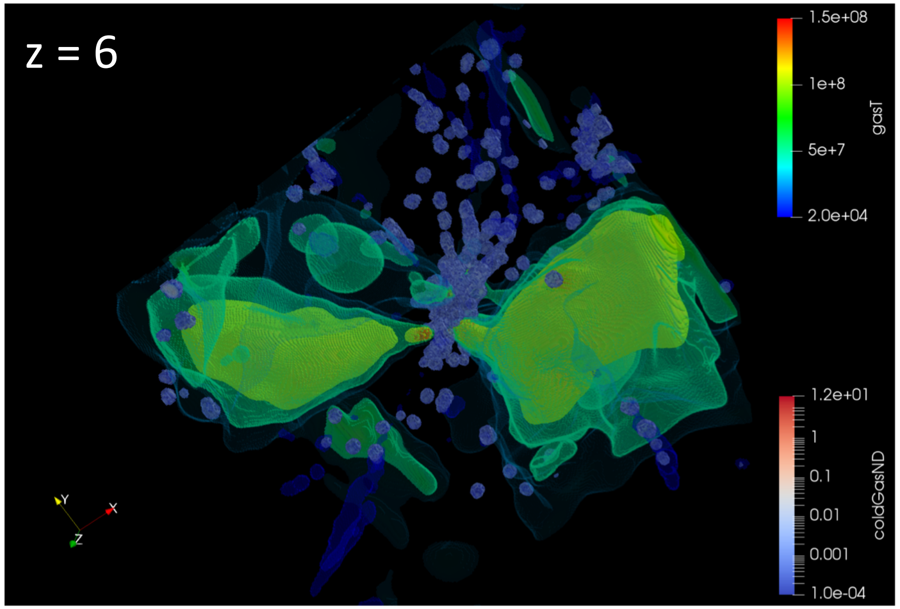
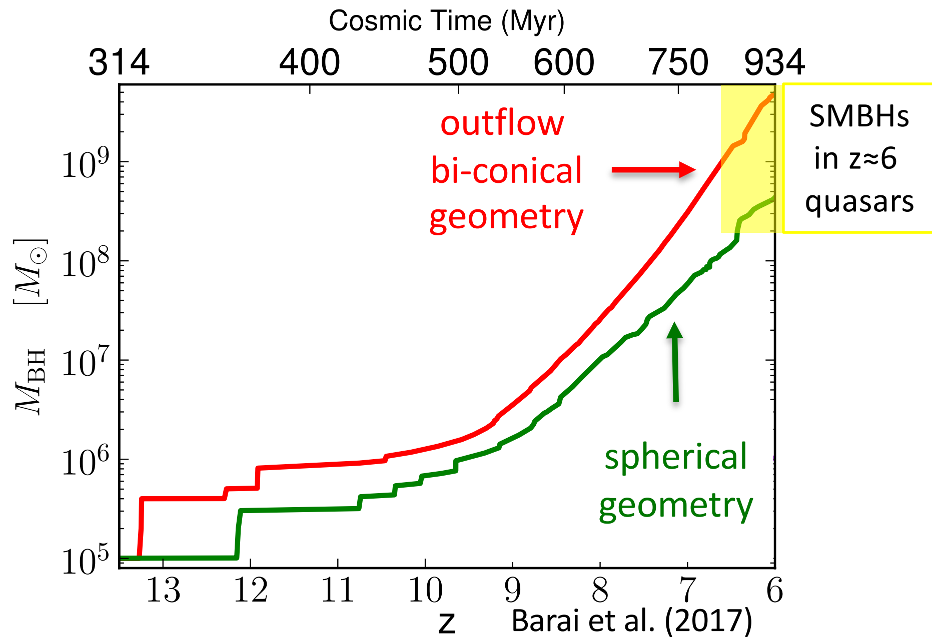


QUASAR FEEDBACK



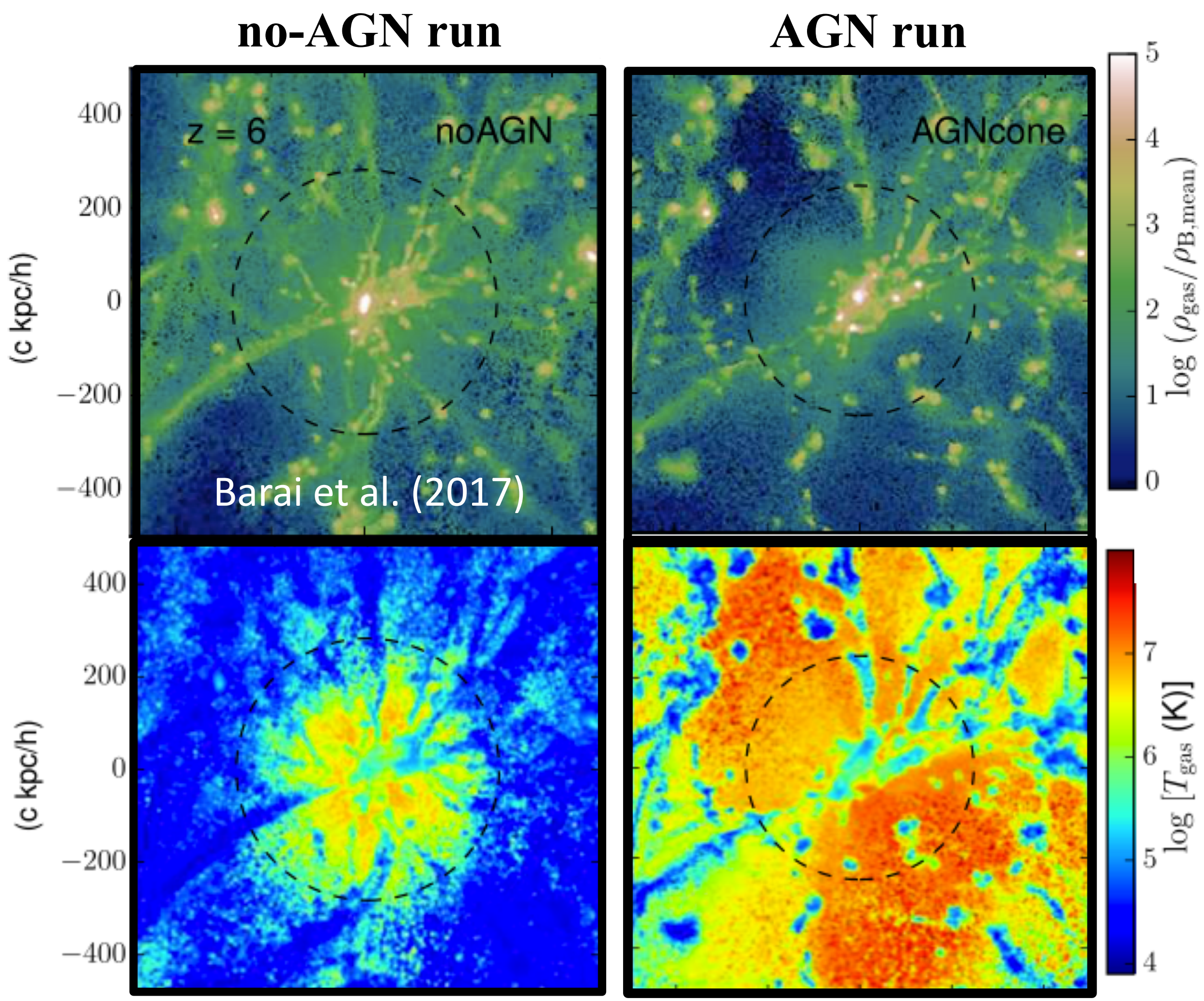
BLACK HOLE MASS EVOLUTION

At z ≈ 6 a SMBH with M_{BH} ≈ 10^8-10^9 M_{sun} is formed, in agreement with BH mass measurements obtained from the Mg II emission line.

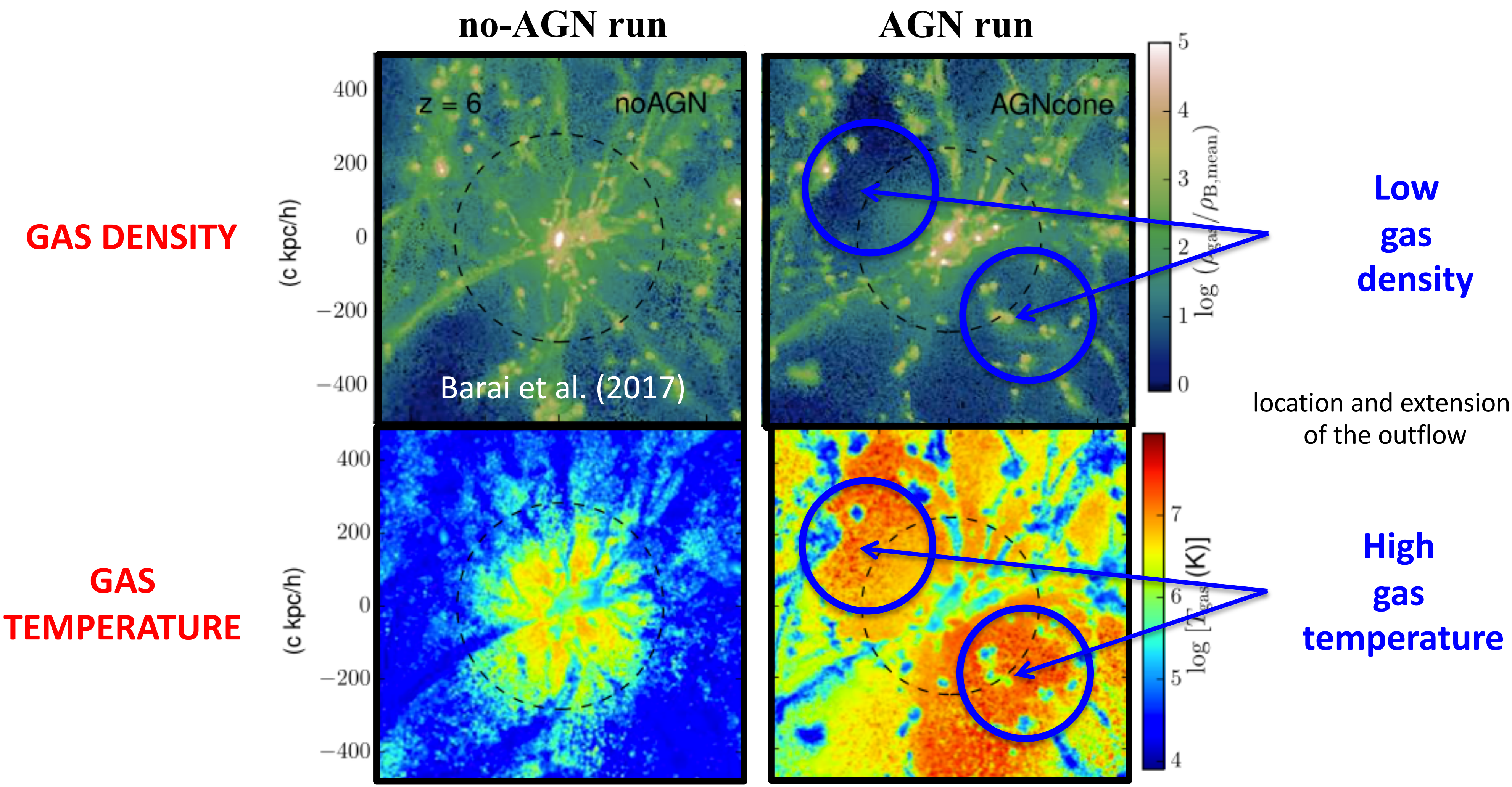
Quasar feedback effects on the host galaxy

GAS DENSITY

GAS TEMPERATURE

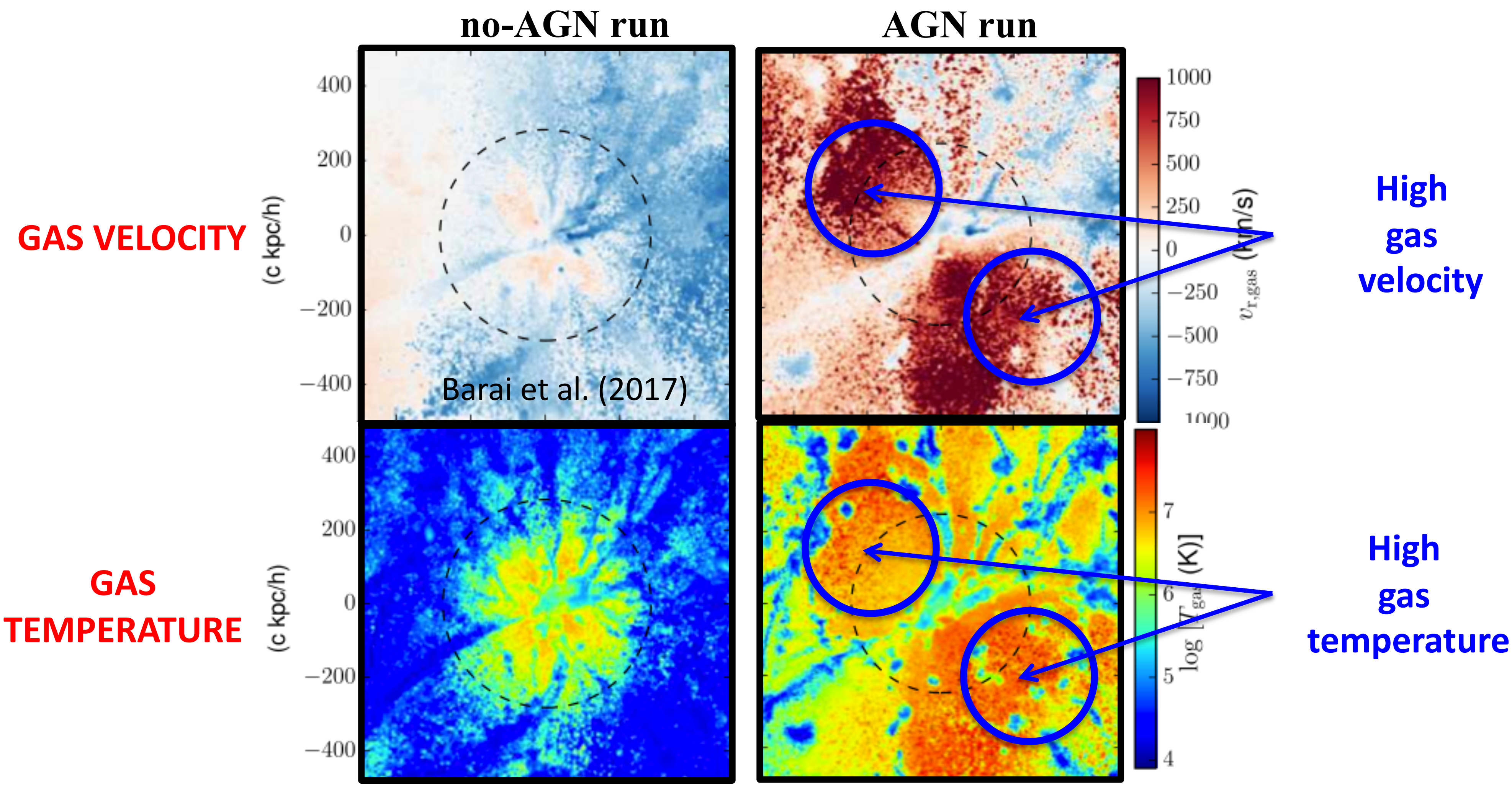


Quasar feedback effects on the host galaxy



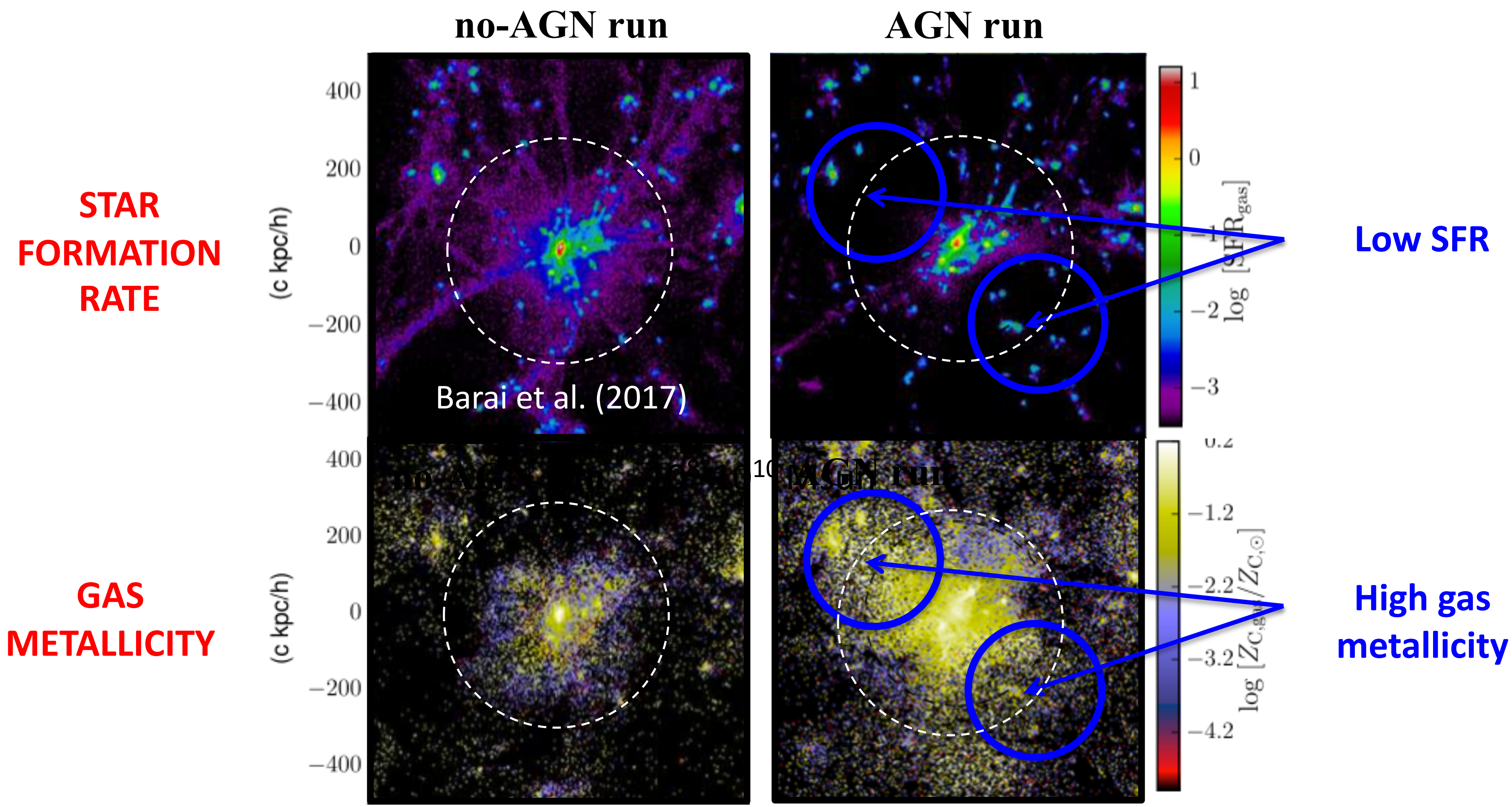
The gas density and temperature maps shows the location and extension of the outflowing gas

Quasar feedback effects on the host galaxy



In the AGN run, particles reach very large velocities (up to 1000 km s^{-1}) in agreement with the outflow velocities as inferred from the broad wings of the [CII] line observations

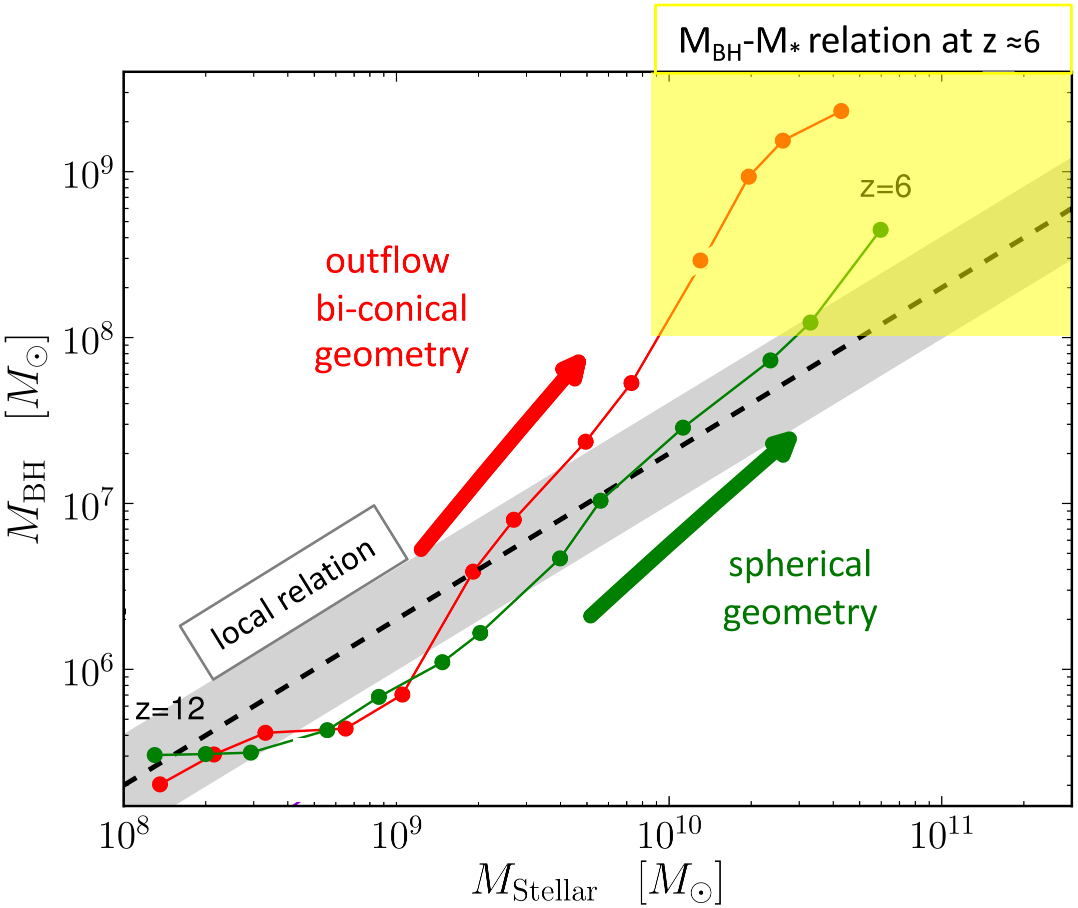
Quasar feedback effects on the host galaxy



Star formation is quenched due to the shock-heated low density gas

Fast outflowing metals are distributed on large scales (≥ virial radius) possibly being ejected in the surrounding intergalactic medium.

The M_{BH}-M_* relation at high redshift



$M_{BH}=10^9$ M_{sun}

Deviation from the local M_{BH}-M_* relation

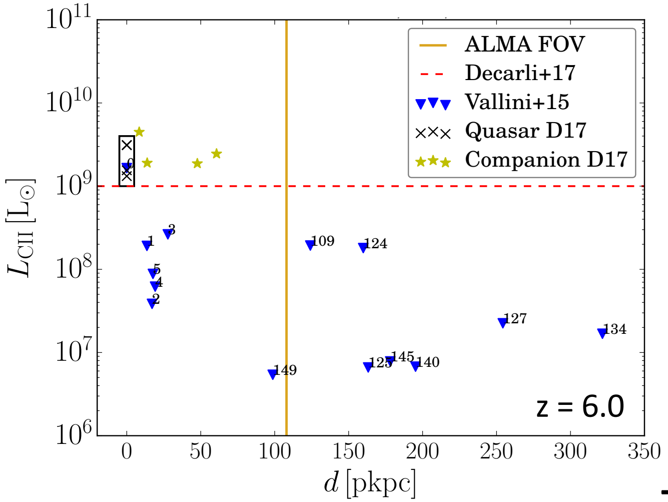
$M_{BH}=10^8$ M_{sun}

Agreement with the local M_{BH}-M_* relation

$M_{BH}=10^7$ M_{sun}

More observations of z ≈ 6 quasars are required to put tighter constraints on the M_{BH}-M_* relation at high-z

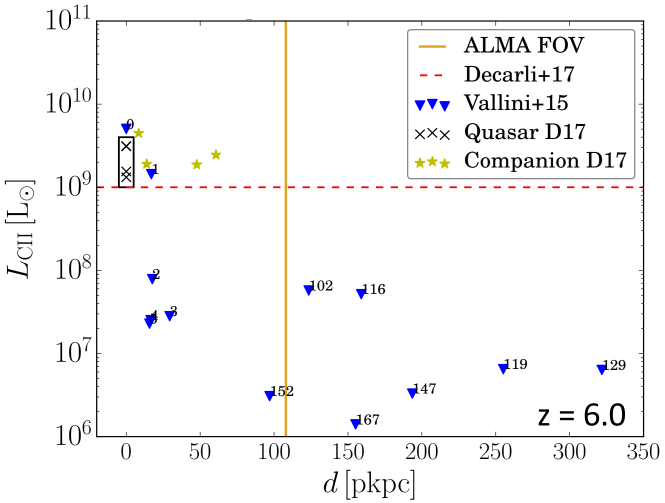
[CII] emission from field galaxies



Bi-Conical

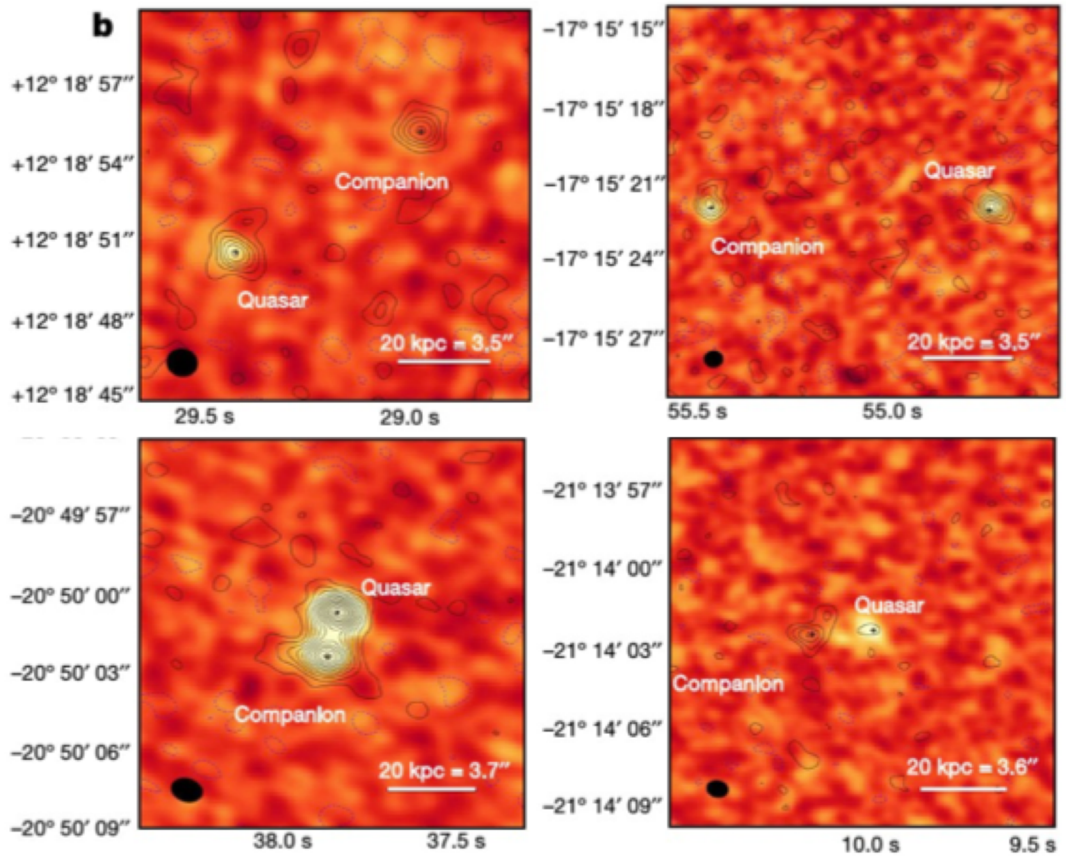
feedback

[CII] emission computed as in Vallini et al (2015, 2017)



Spherical

Comparison with [CII] observations

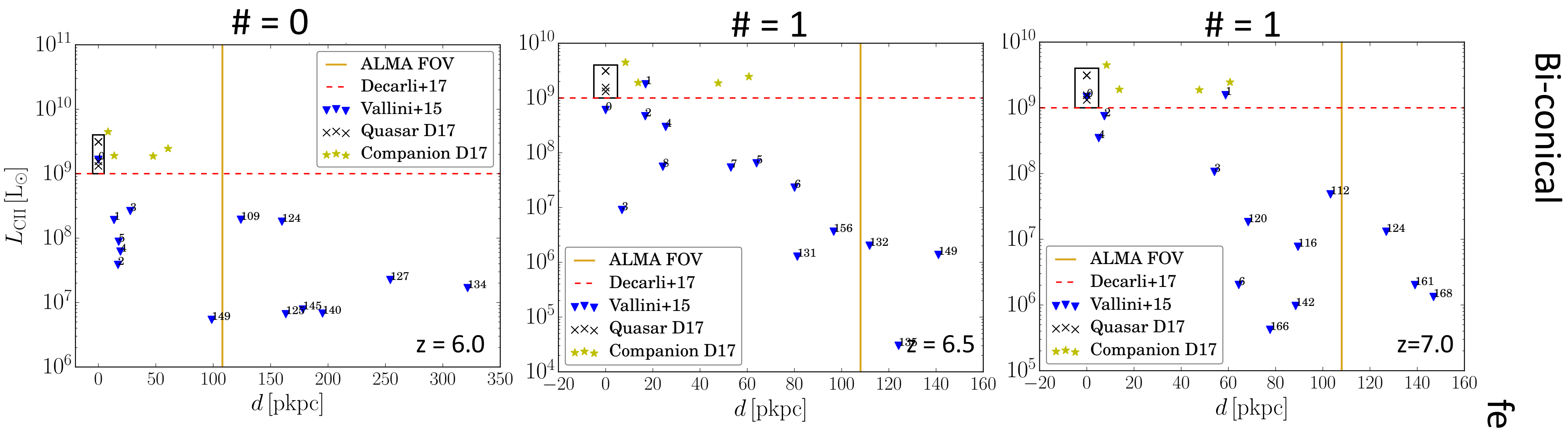


Decarli et al. (2017)

Serendipitous discovery of galaxy companions in 4 out of 25 quasars at z > 6

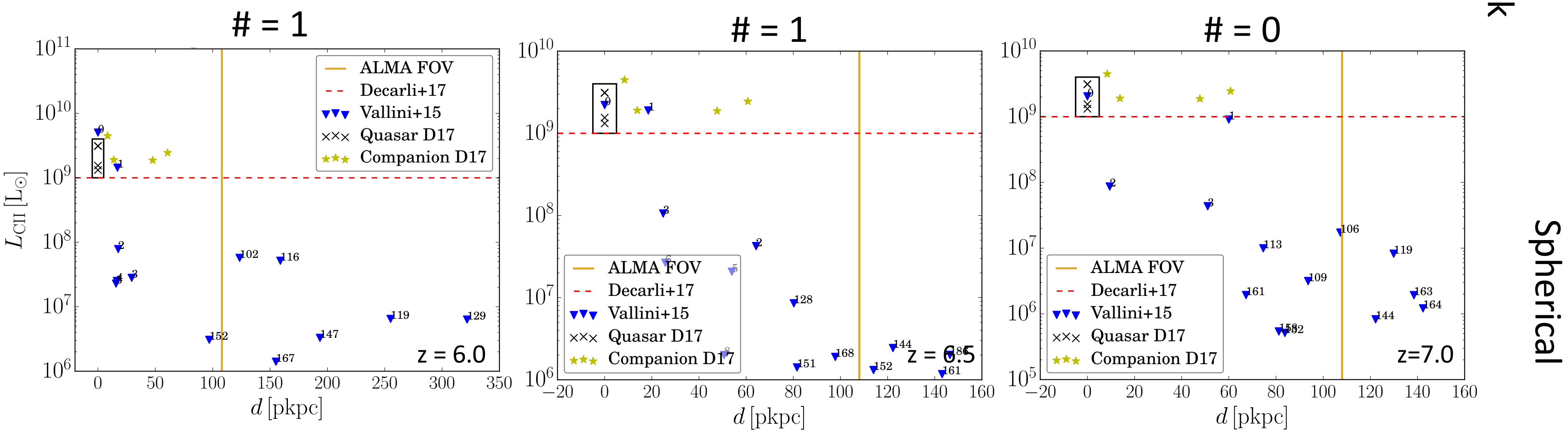
[CII] emission from field galaxies

= Number of galaxies with $L_{[CII]} > 10^9\ L_{sun}$



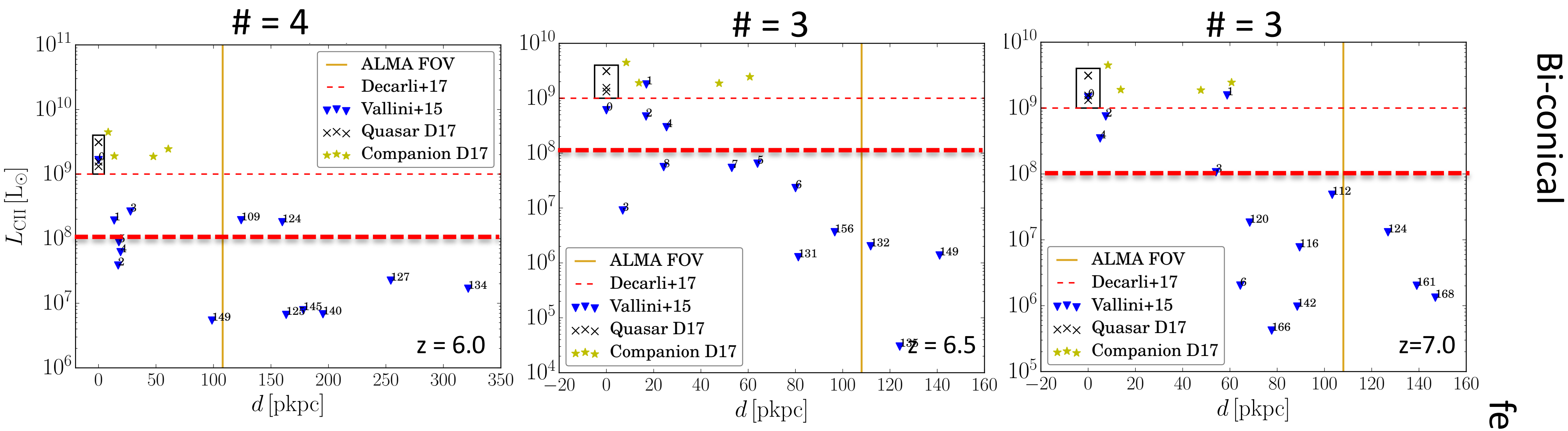
Consistent with [CII] observations → more stringent constraints from deeper observations

feedback



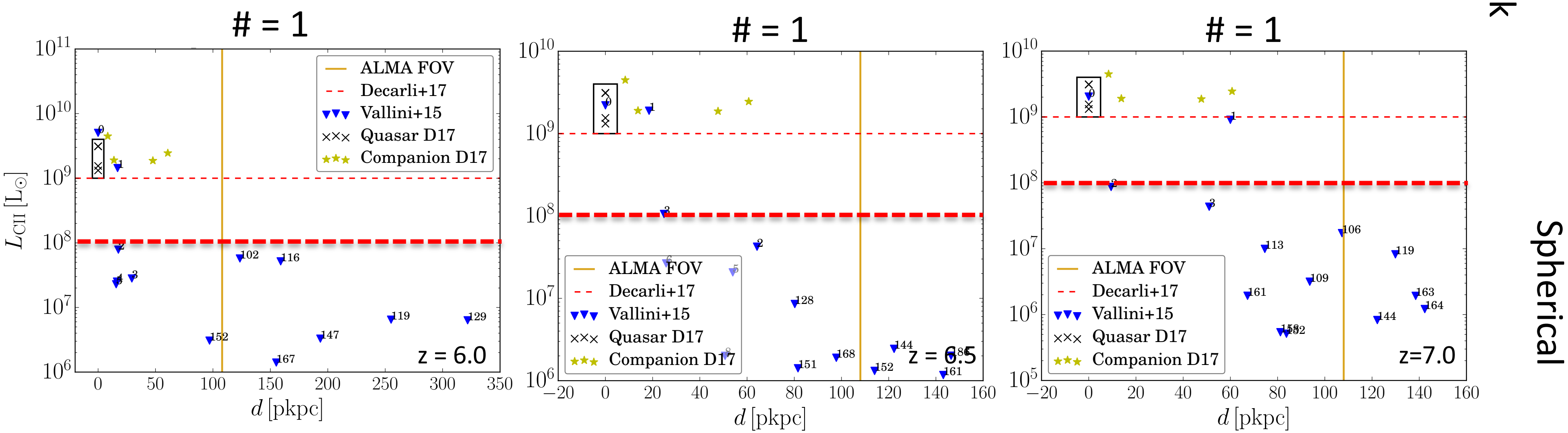
[CII] emission from field galaxies

= Number of galaxies with $L_{[CII]} > 10^8 L_{sun}$



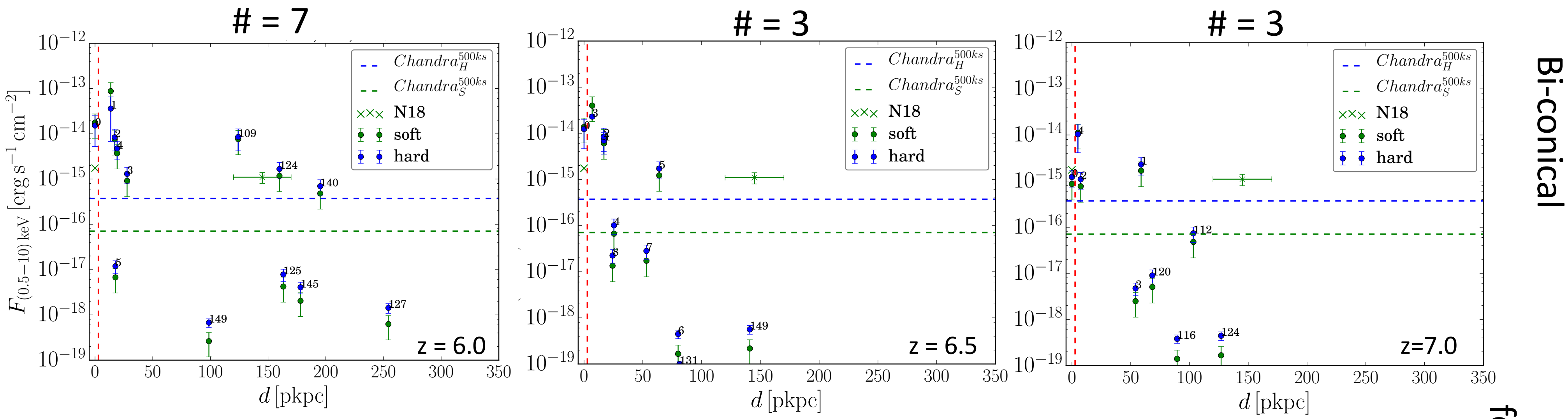
Spherical feedback is more efficient in quenching star formation in field galaxies

feedback

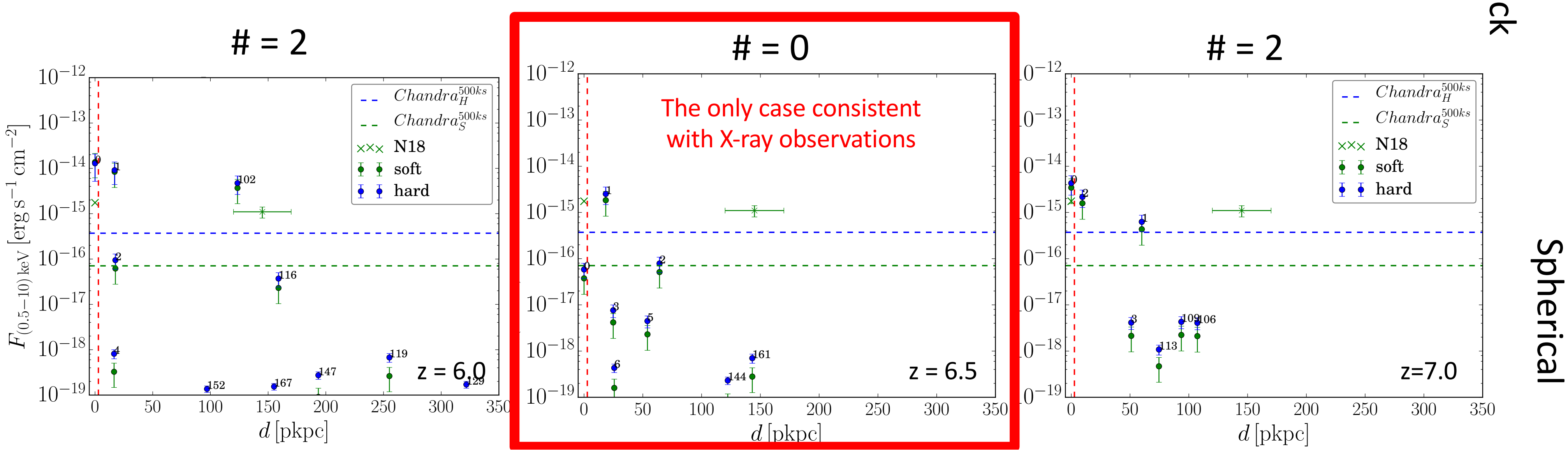


X-ray emission from field galaxies

\# = Number of galaxies with $F_X > 5 \times 10^{-16}$ erg s^{-1} cm^{-2}



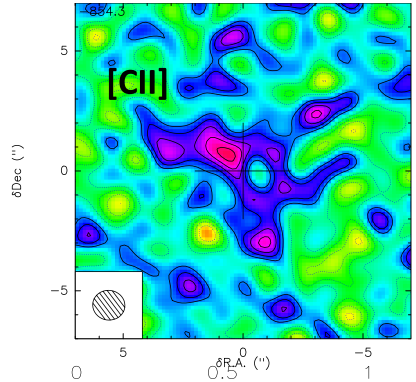
Spherical feedback is more efficient in removing the gas surrounding the quasar

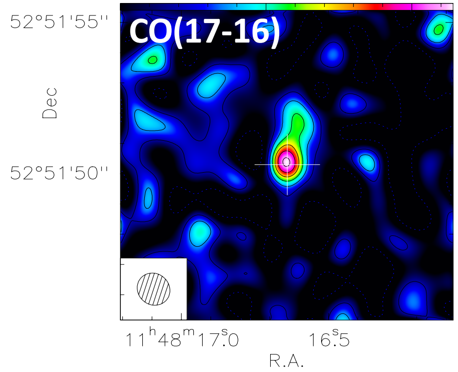


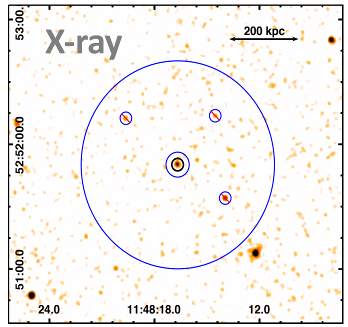
Physical Properties of z ≈ 6 Quasars

OBSERVATIONS

- z ≈ 6 quasars are powered by SMBH (masses ≈ 10^8-10^{10} M_{sun})
- Quasar host galaxies harbor intense starbursts ($SFR \sim 10^2$-10^3 $M_{sun}\,yr^{-1}$; $M_{H2} \sim 10^{10}$ M_{sun}; $M_{dust} \sim 10^8$ M_{sun})
- Quasar feedback are in place at high-z ($v_{outflow} \approx 1000$ km/s; $R_{outflow} \approx 10$-30 kpc)
- CO(17-16) line detected only in J1148 (undetected in J2310 and J1319)
- X-ray emission properties similar to low-z high luminosity AGNs







SIMULATIONS

- Cosmological simulations can reproduce the BH observed masses starting from massive seeds (M_{seed}= 10^5 Msun)
- Quasar feedback quenches star formation by expelling the surrounding gas out of the host galaxy
- Metals are distributed on scales larger than the virial radius