Quasars in the epoch of reionization

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Carnegie-Princeton Fellow

Illuminating the Dark Ages
June 27, Heidelberg, Germany

Quasars and galaxies in the reionization epoch

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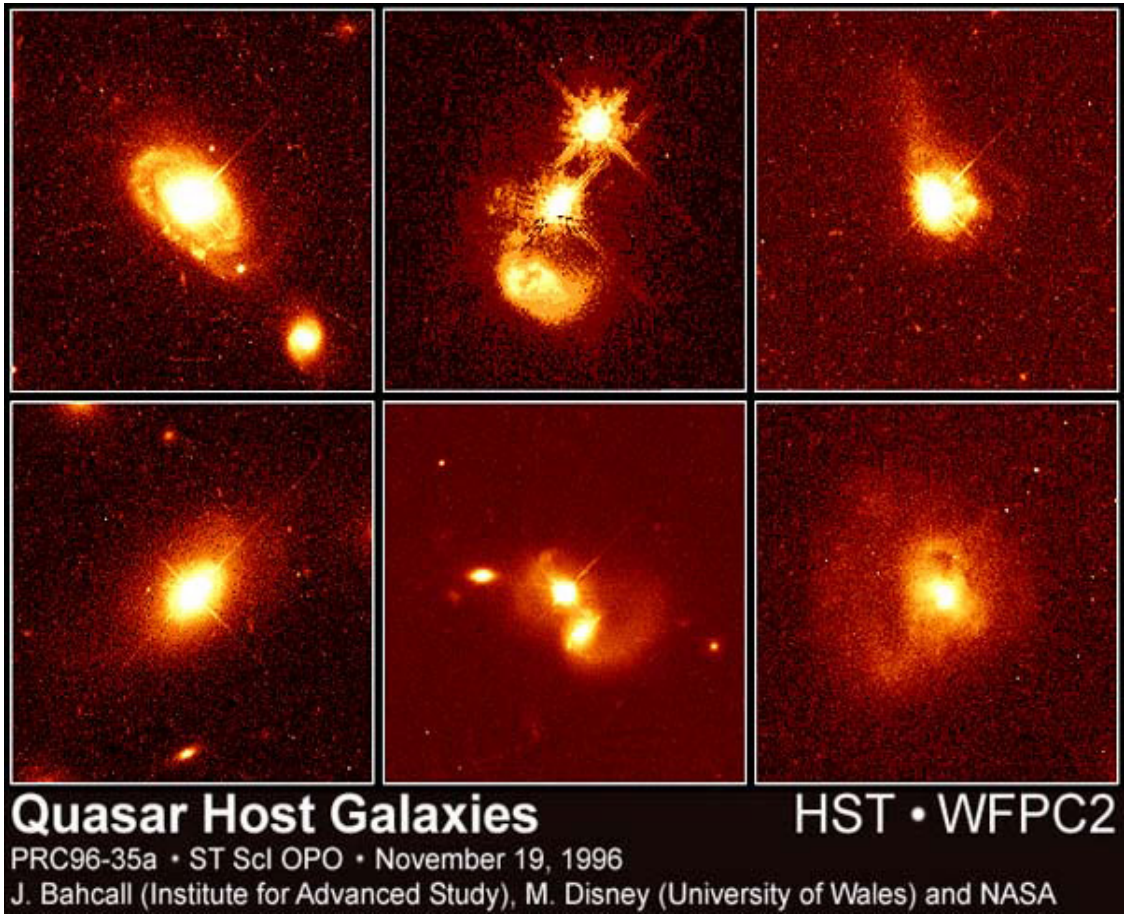
Quasars as a phase of a galaxy



Outline

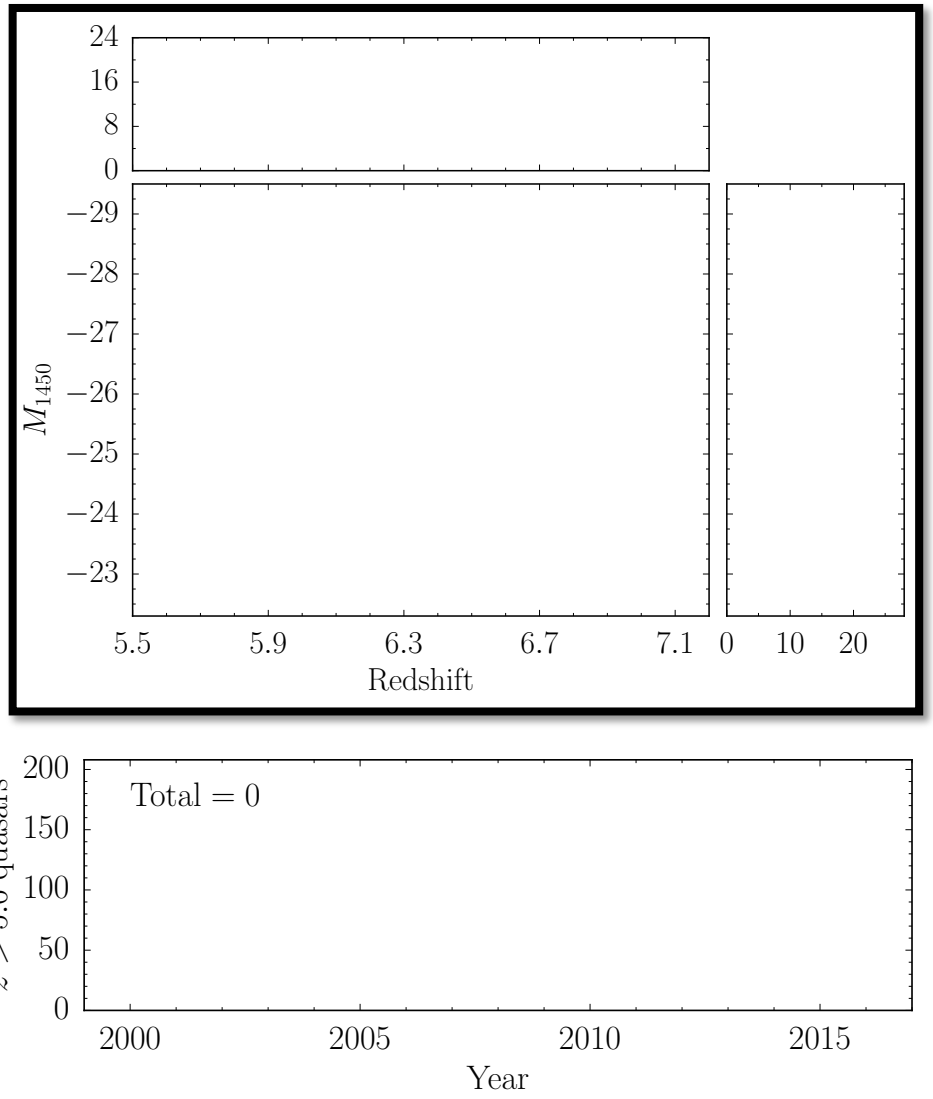
- The search of the most distant quasars (z>5.5)
- Quasars as probes of the intergalactic medium
- Quasar host galaxies

The search for distant quasars

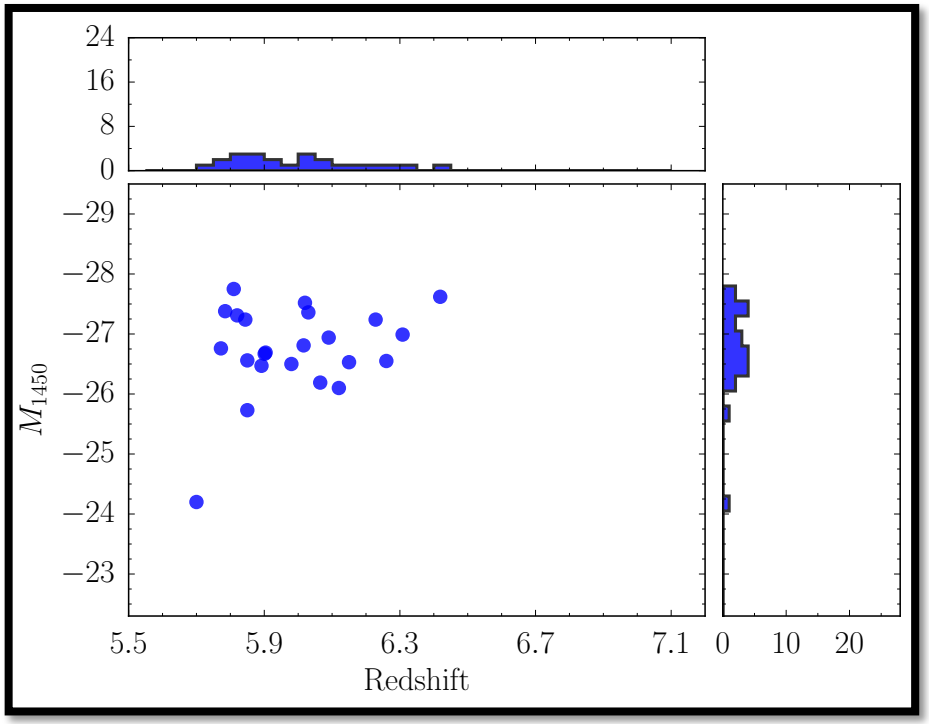
- The challenge:
  - Quasars at z>5.5 are **very** rare
  - Not found in deep HST blank fields

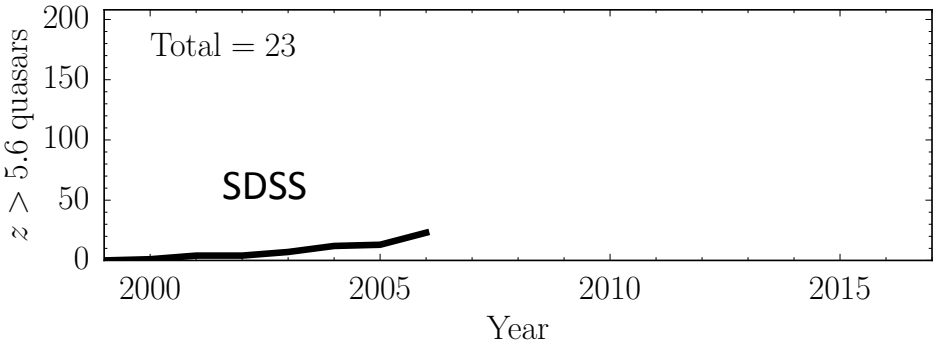
- Requirement:
  - Large area multi-color surveys

The search for distant quasars



The search for distant quasars

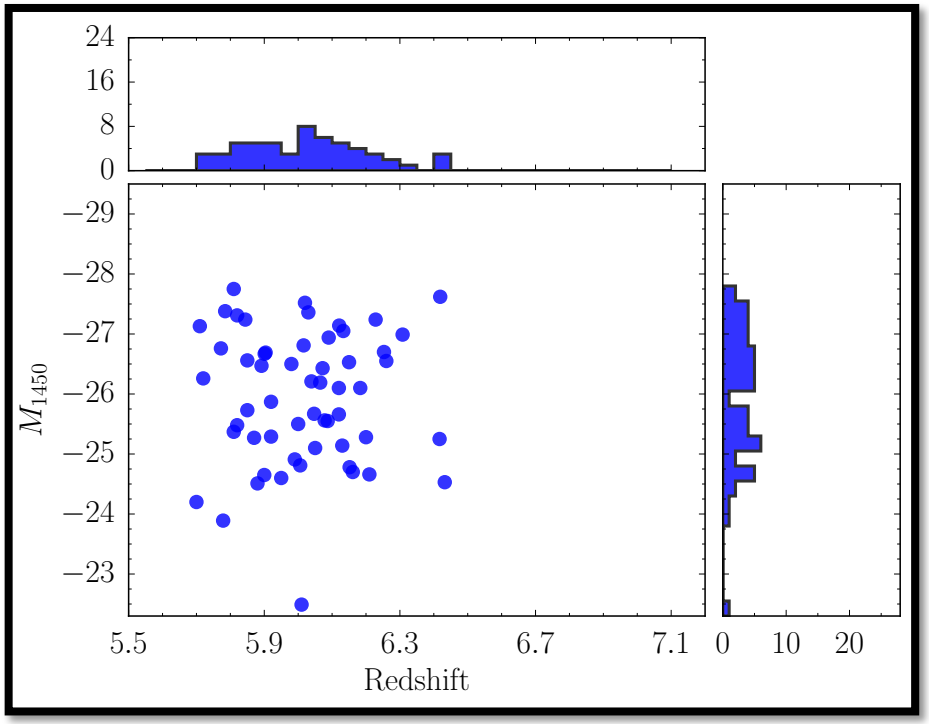


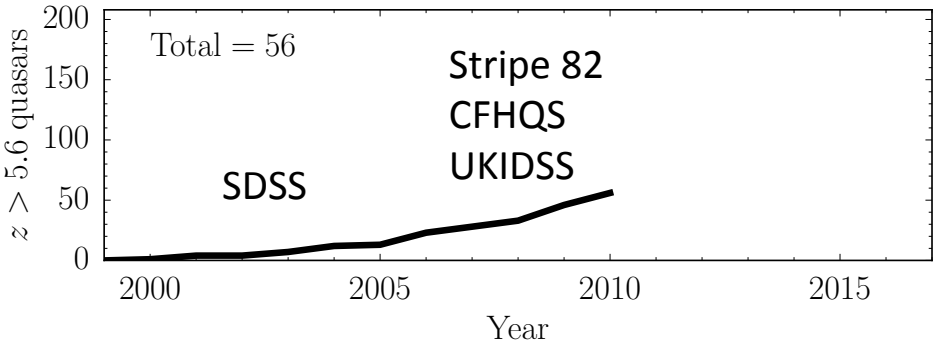


Fan+ 2000-2006

See talk by Linhua Jiang

The search for distant quasars

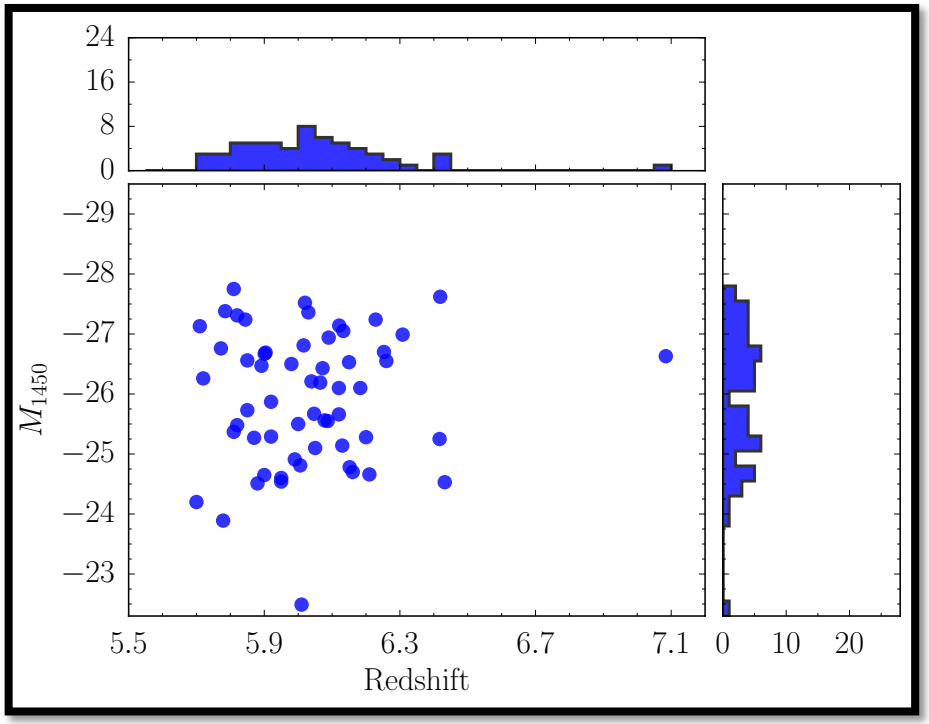


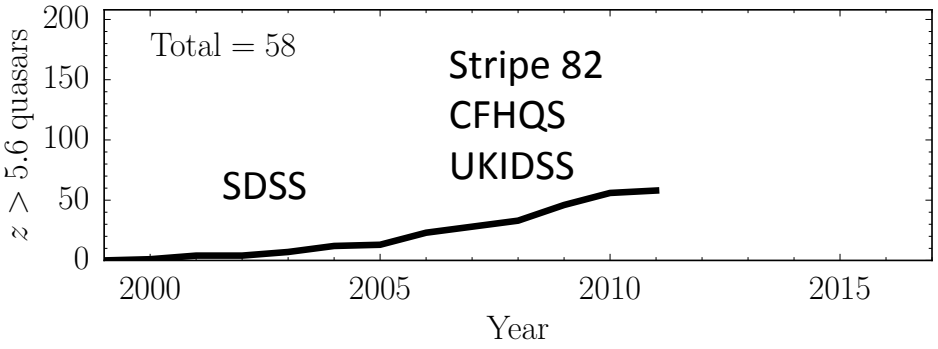


Fan+ 2000-2006
Jiang+ 2008-2009
Willott+ 2007-2010

See talk by
Linhua Jiang

The search for distant quasars





Fan+ 2000-2006
Jiang+ 2008-2009
Willott+ 2007-2010
Mortlock+ 2011

See talk by
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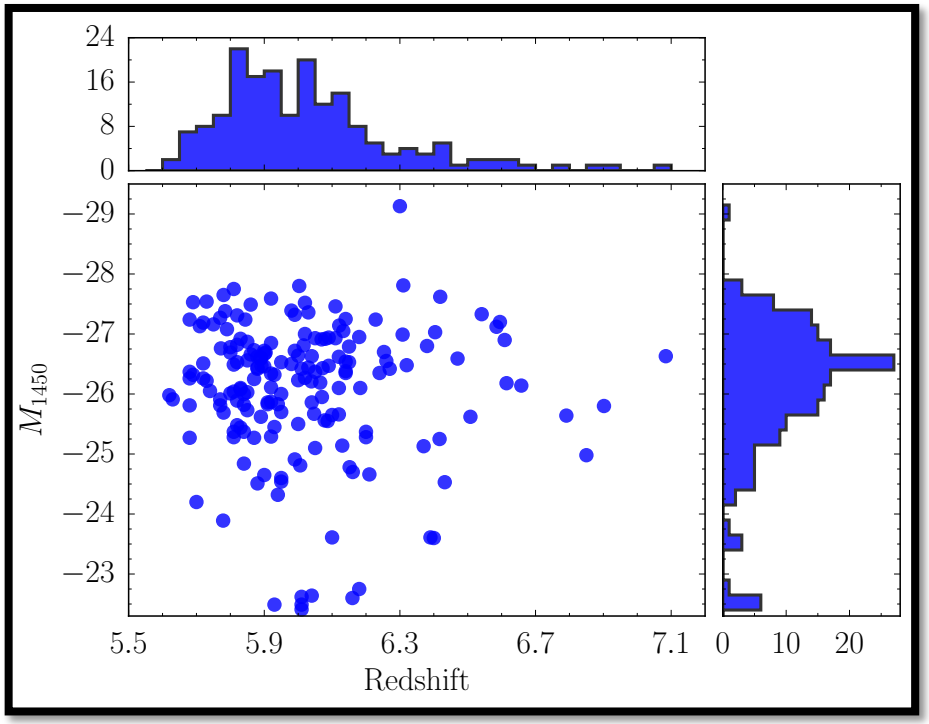
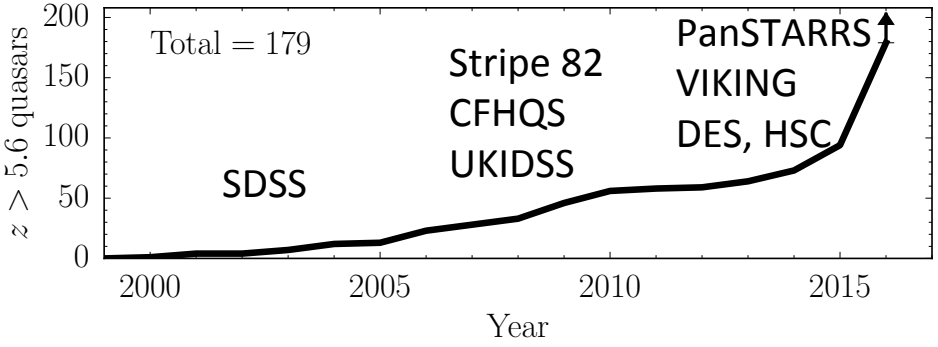
The search for distant quasars

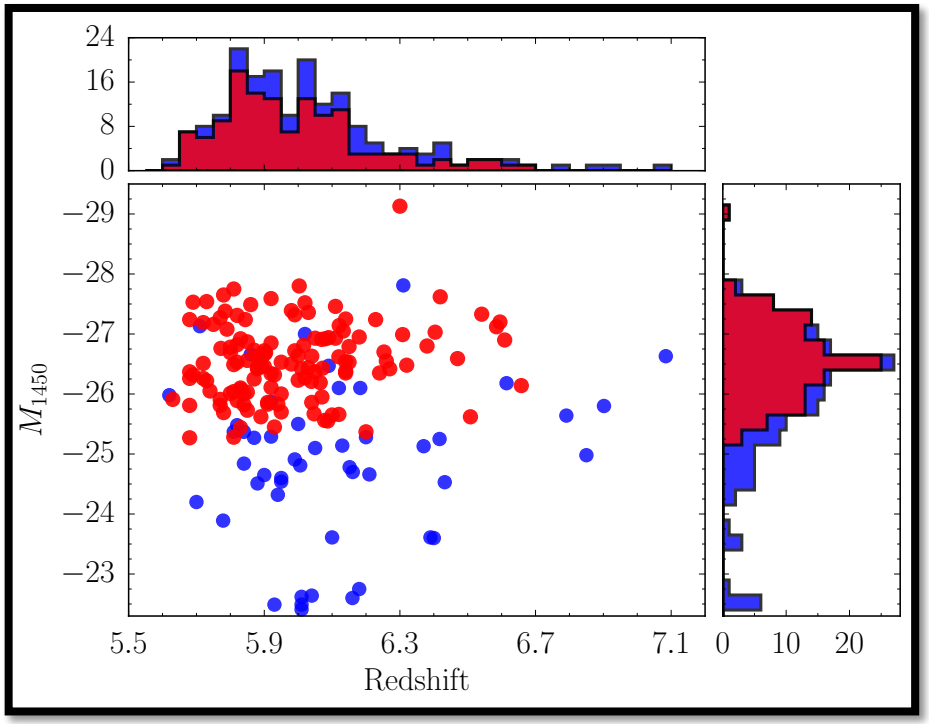




See talks by
Chiara Mazzucchelli,
Sophie Reed, and
Yoshiki Matsuoka

Bañados+ 2014-2016
Jiang+ 2015
Venemans+2013,2015
Reed+ 2015
Matsuoka+2016
…

The search for distant quasars



Pan-STARRS Sample

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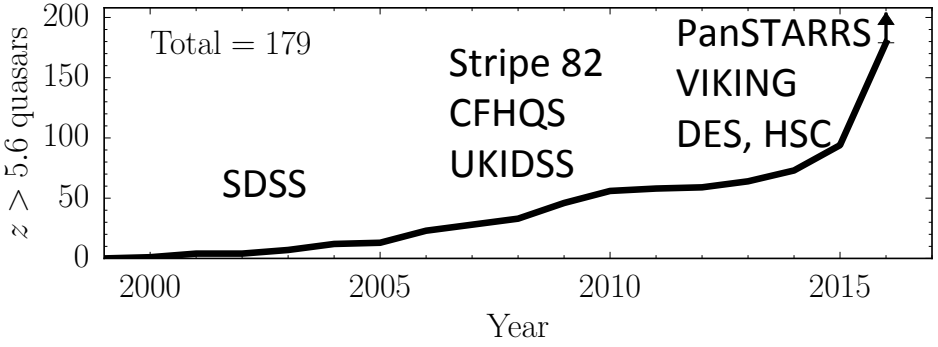
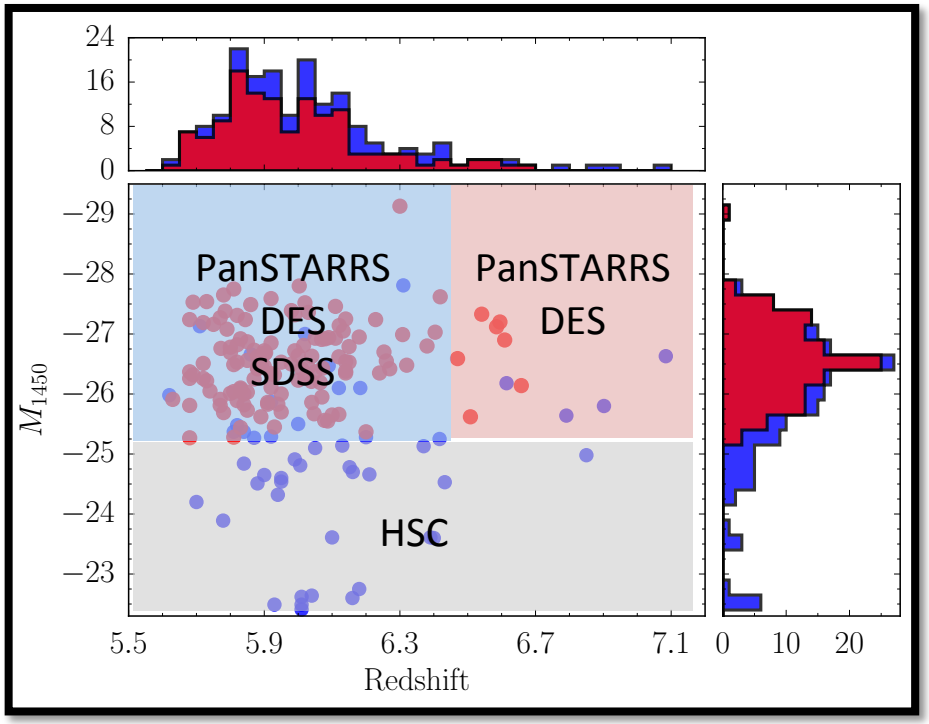
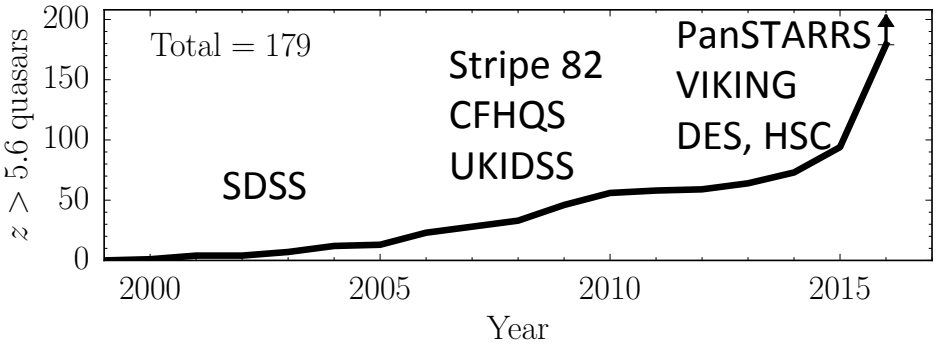
Chiara Mazzucchelli,
Sophie Reed, and
Yoshiki Matsuoka



Bañados+ 2014,2015,2016
Venemans, Bañados+ 2015
Mazzucchelli+ in prep.

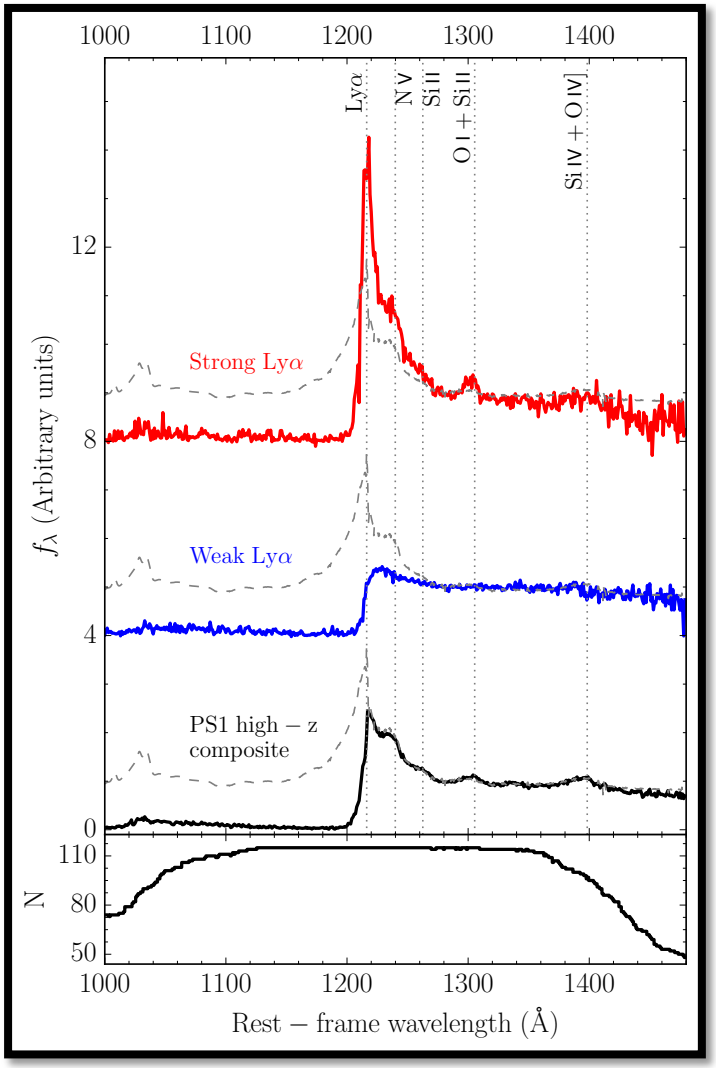
The search for distant quasars





See talks by Chiara Mazzucchelli, Sophie Reed, and Yoshiki Matsuoka

Variety of spectral properties



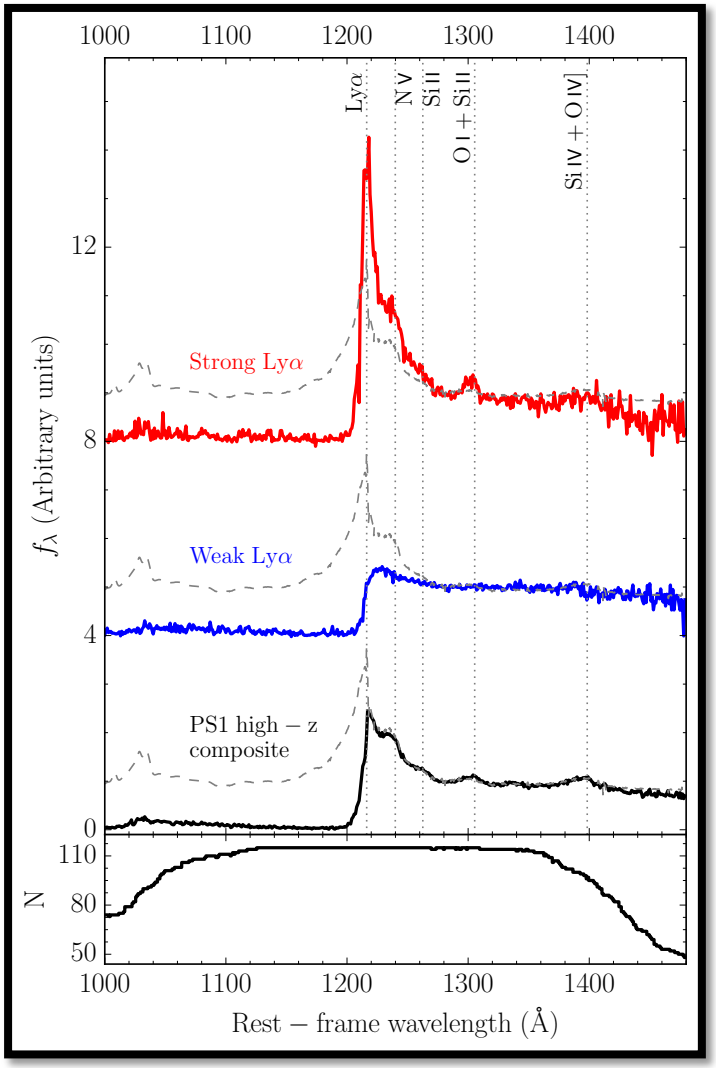
Bañados+ subm.

Variety of spectral properties

Weak-line quasars:

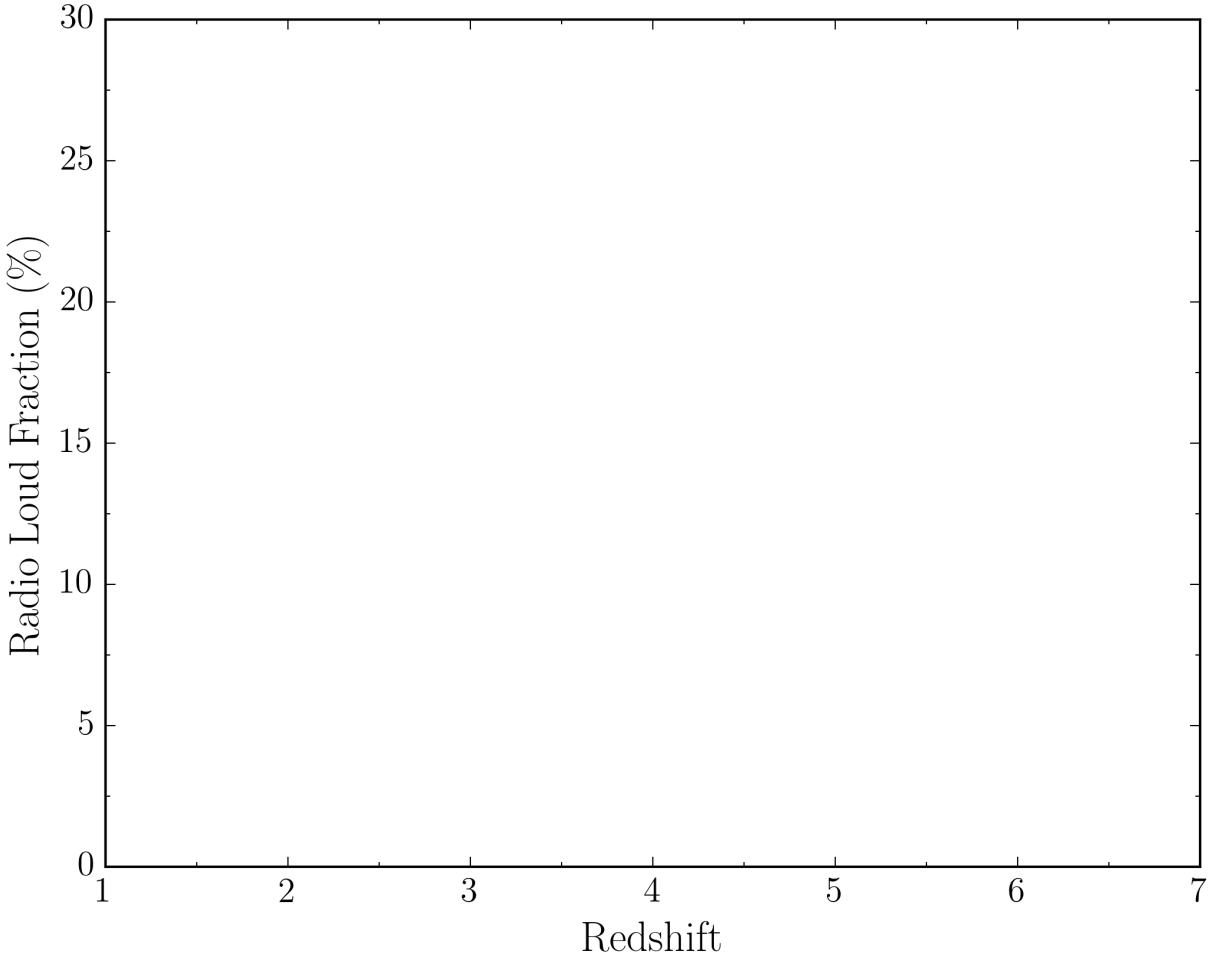
- 14% at z=6
- 1-6% at z=2-4

Diamond-Stanic+ 2009
Bañados+ 2014, 2016 subm.



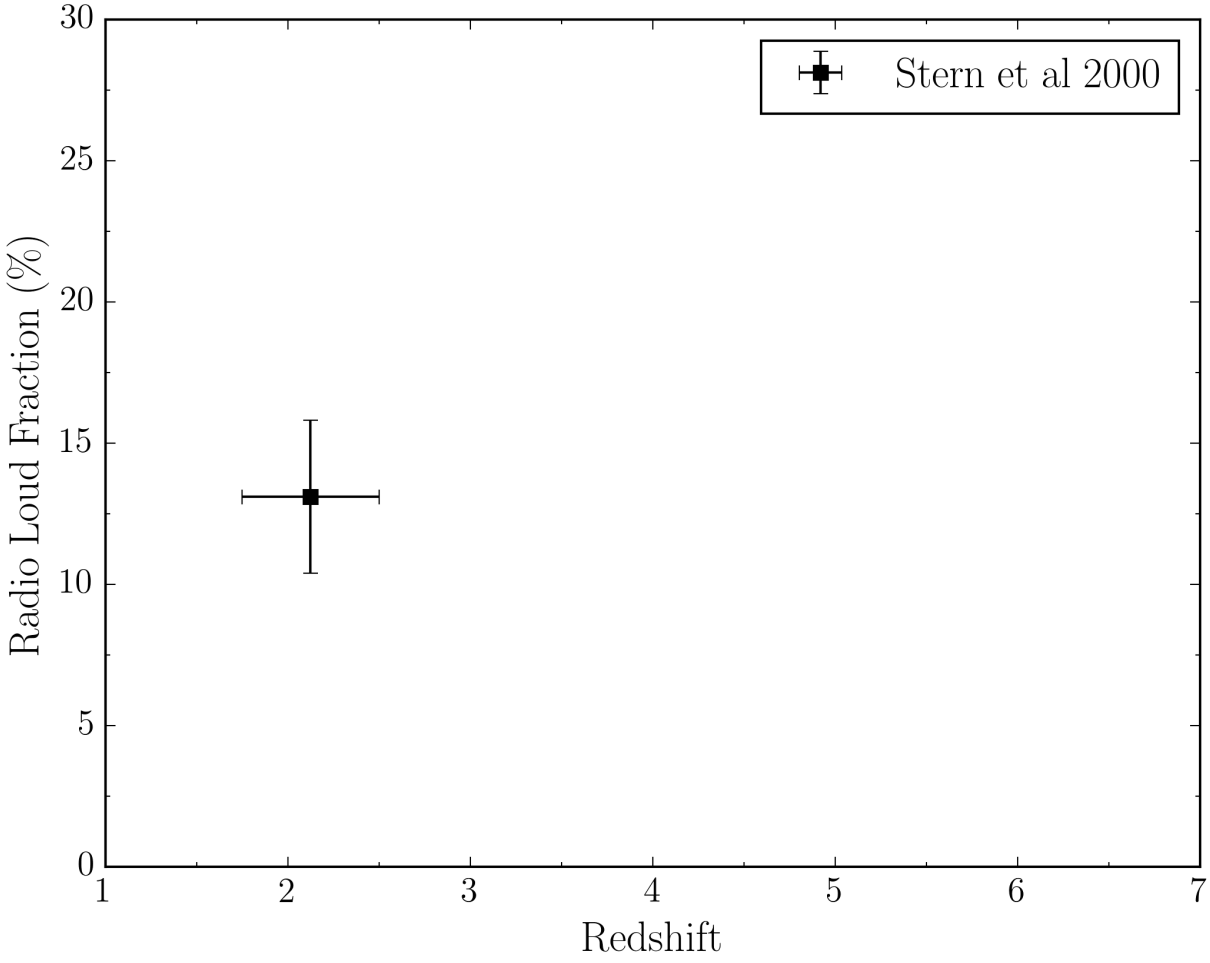
Bañados+ subm.

Radio-loud fraction



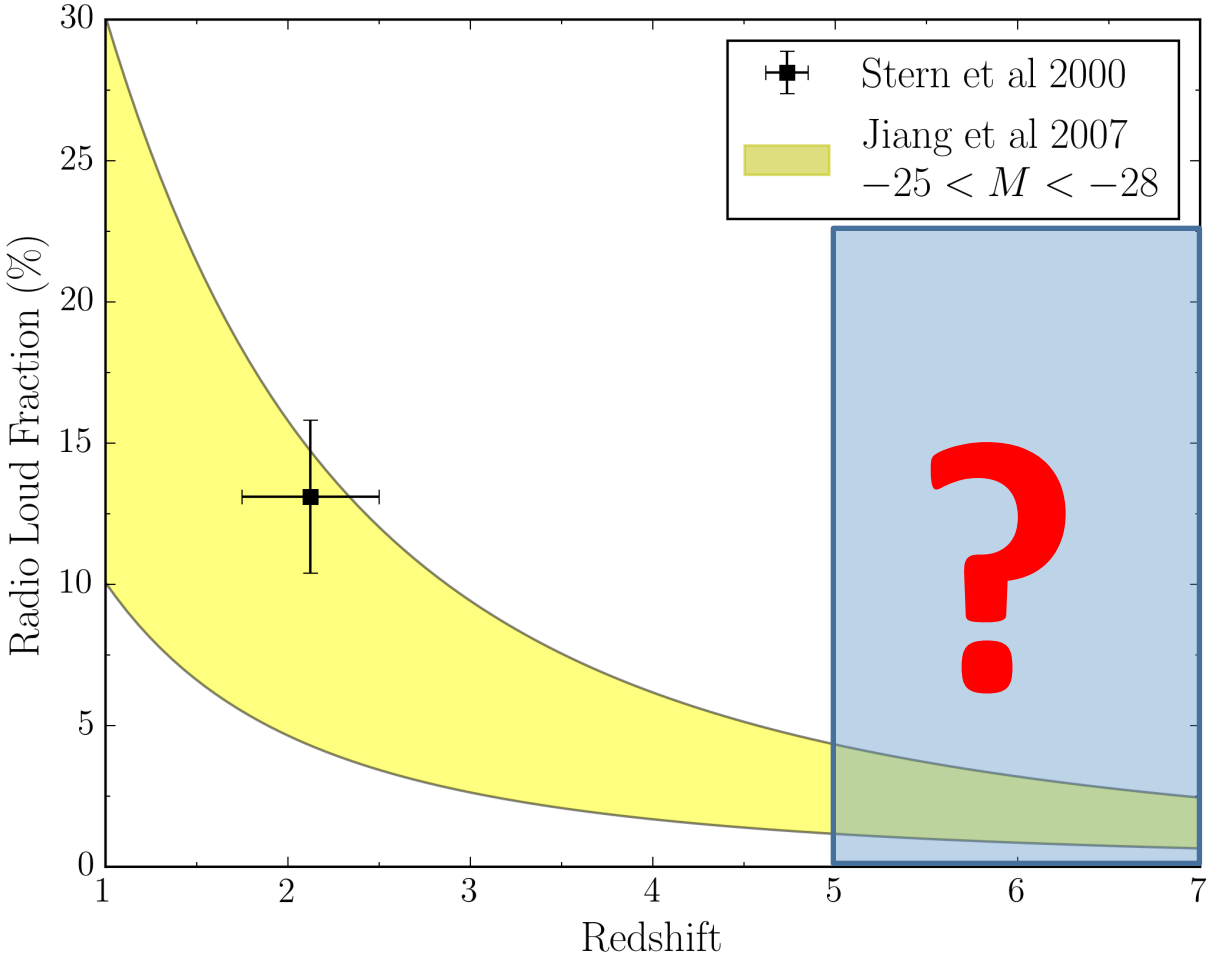
Bañados+ 2015a

Radio-loud fraction



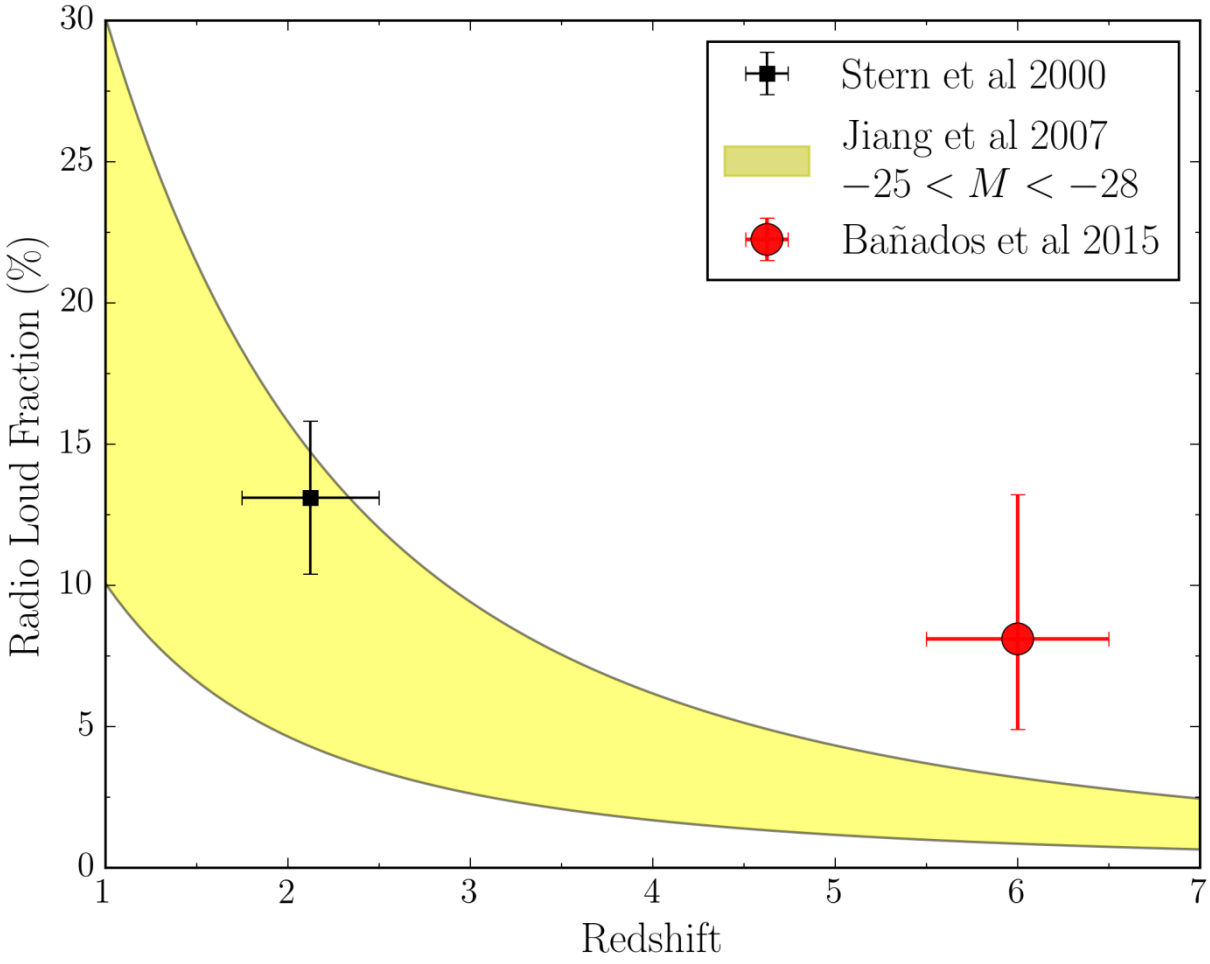
Bañados+ 2015a

Does it evolve with redshift?



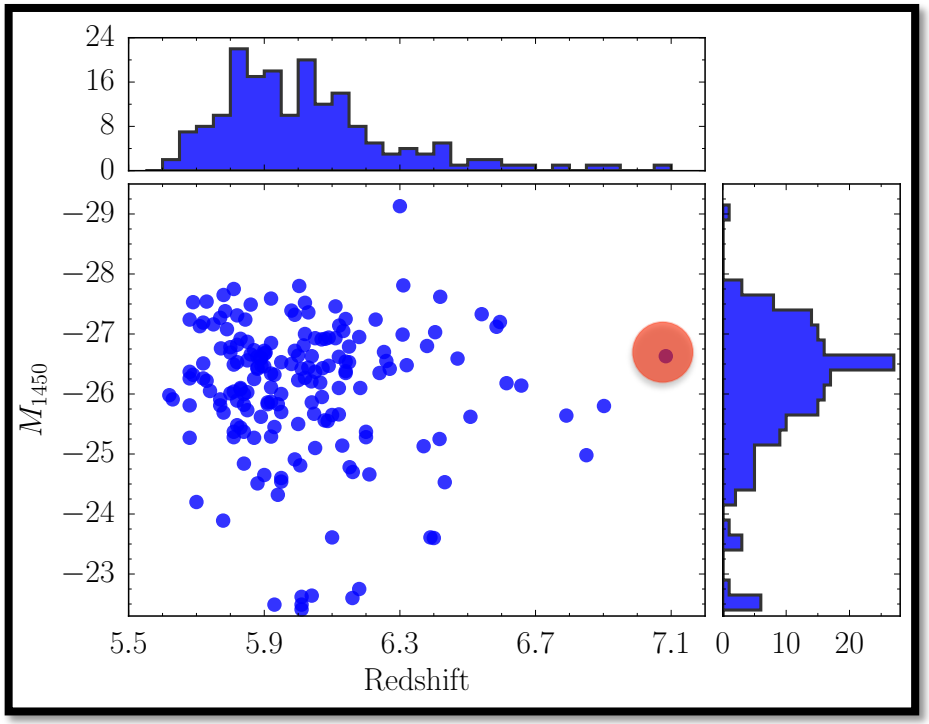
Bañados+ 2015a

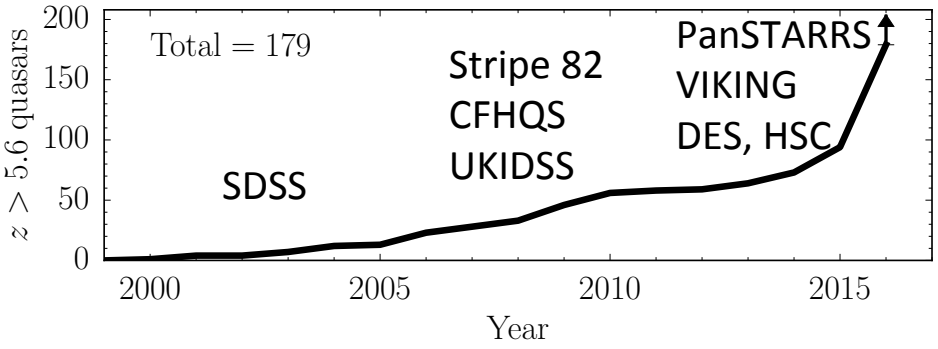
No evolution up to z=6



Bañados+ 2015a

The most distant quasar

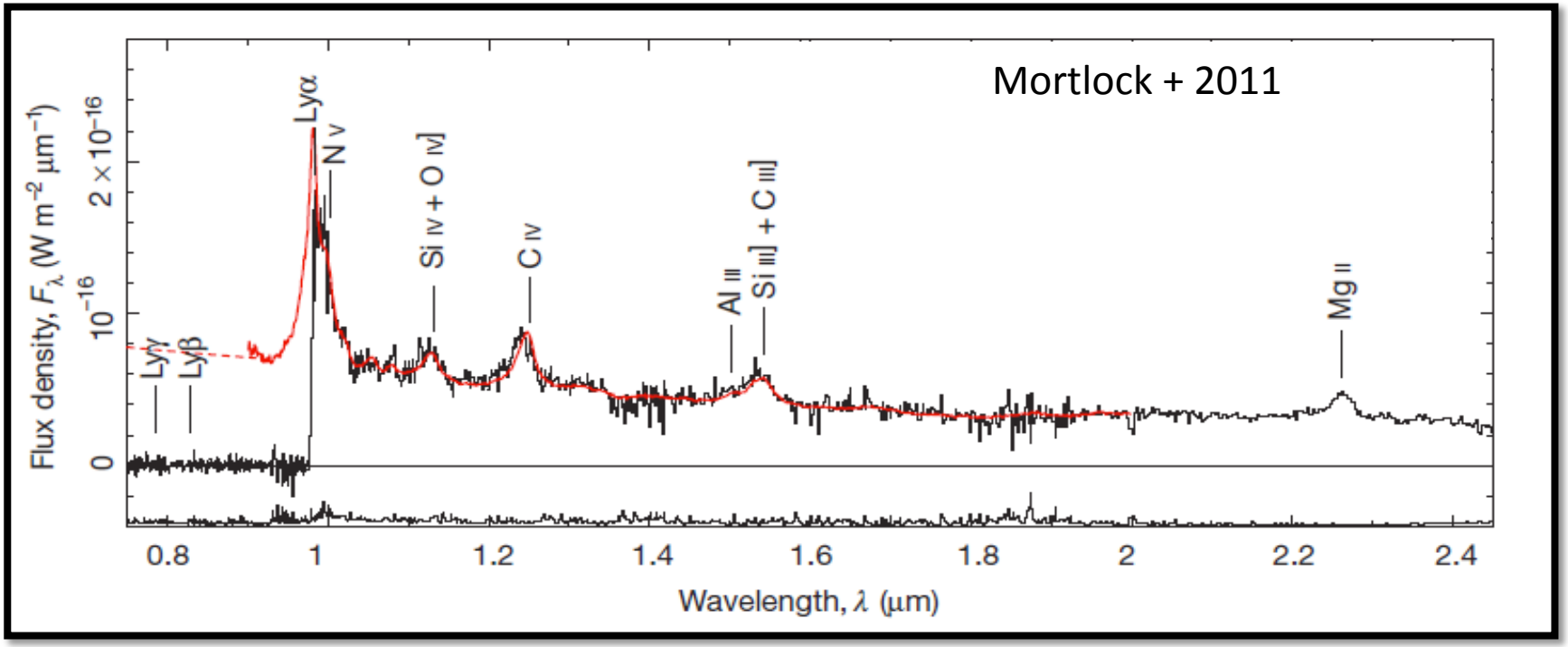




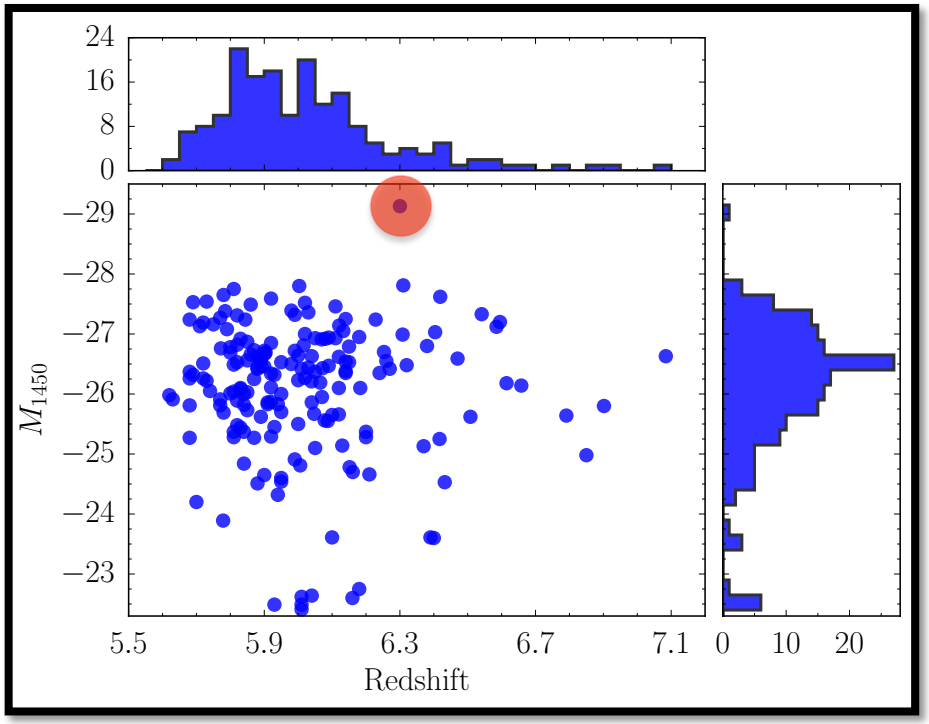
See talks by Chiara Mazzucchelli, Sophie Reed, and Yoshiki Matsuoka

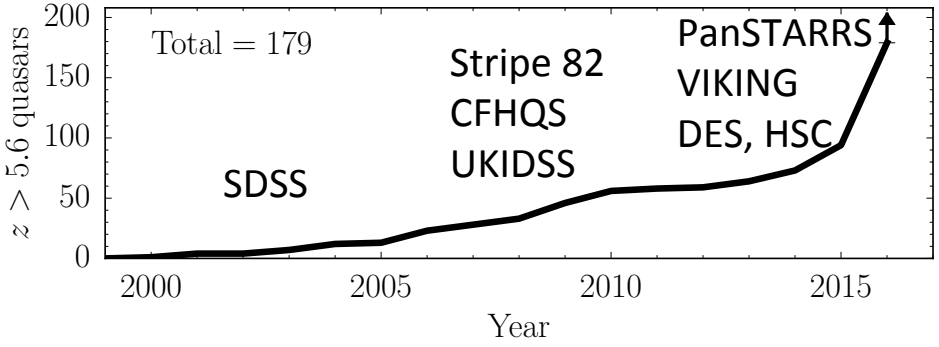
The most distant quasar

Quasar at z=7.1 (Age of Universe: 0.75 Gyr)
Black hole mass: 2 x 10^9 $M_\odot$
M_{1450} = -26.6 J_{AB} = 20.4

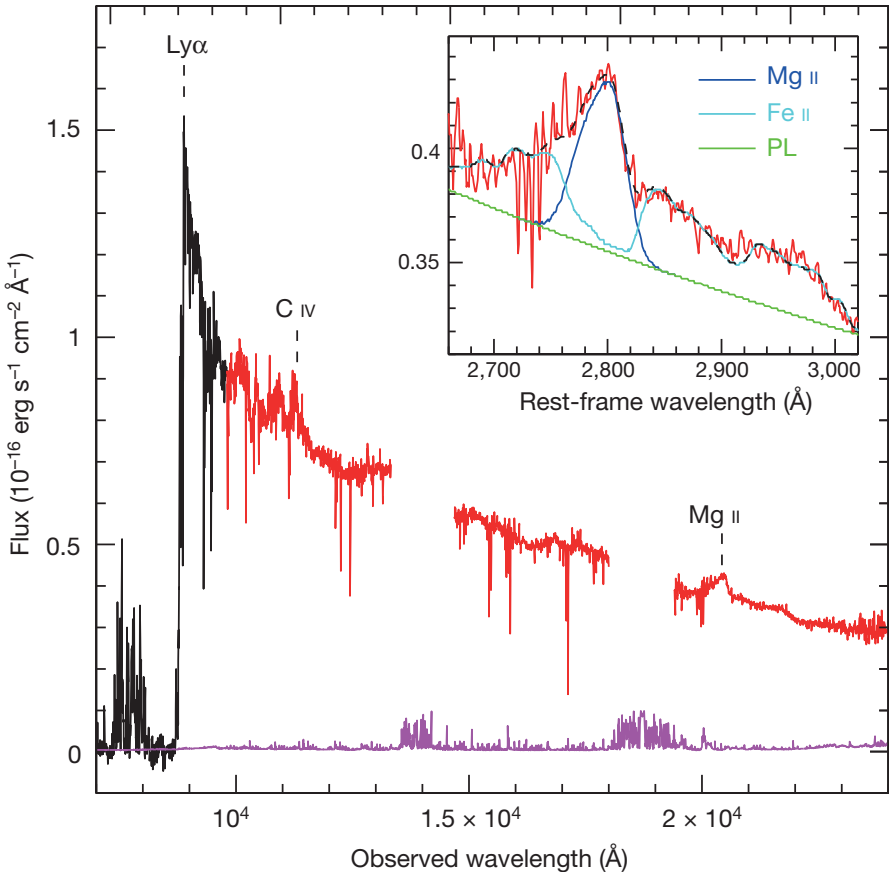


The most luminous and massive quasar





The most luminous and massive quasar



z=6.3 (Age of Universe: 0.88 Gyr)

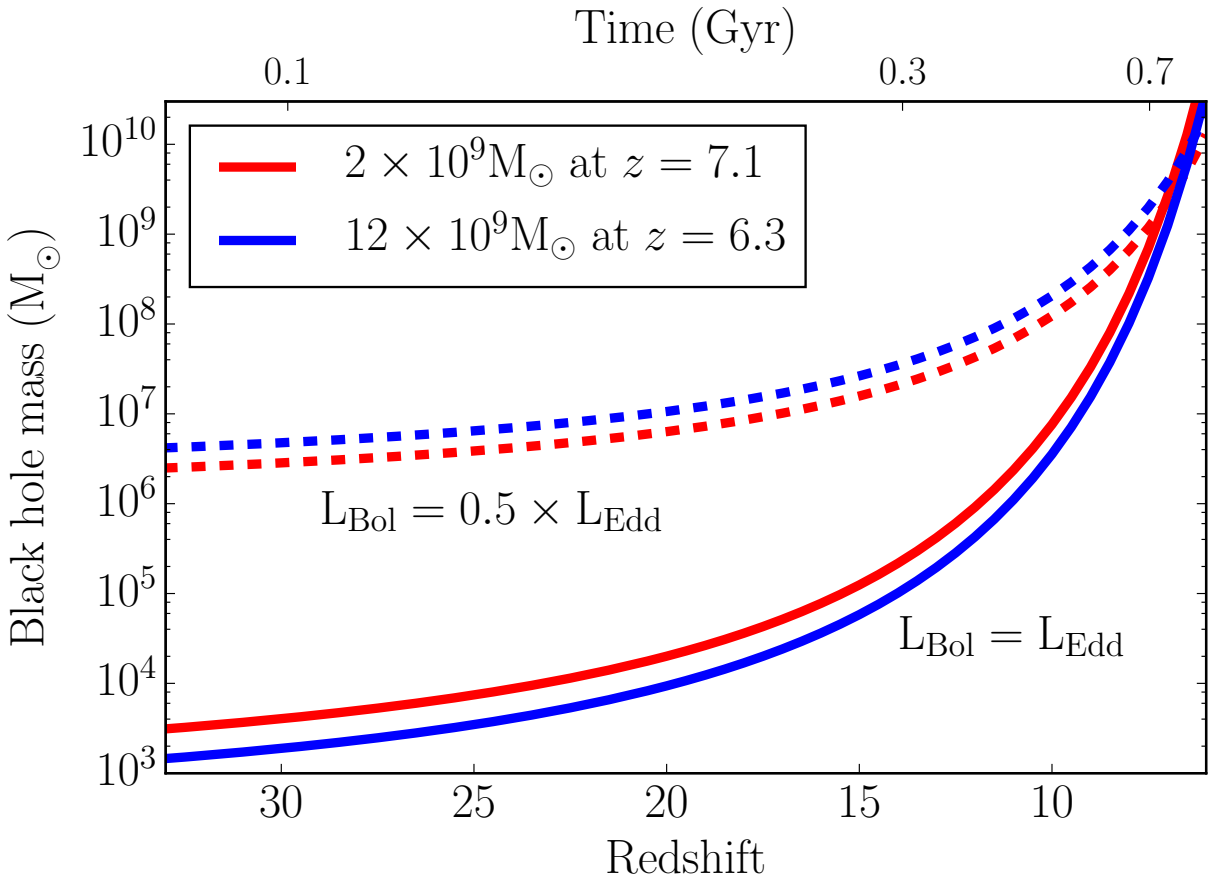
Black hole mass: 12 x 10^9 $M_\odot$

M_{1450} = -29.1

J_{AB} = 17.6

Wu+ 2015

Constraints on black hole growth



But see also Volonteri+ 2015, Latif+ 2016, Li+ 2007, Inayoshi+ 2016 …

Quasars as probes of the IGM

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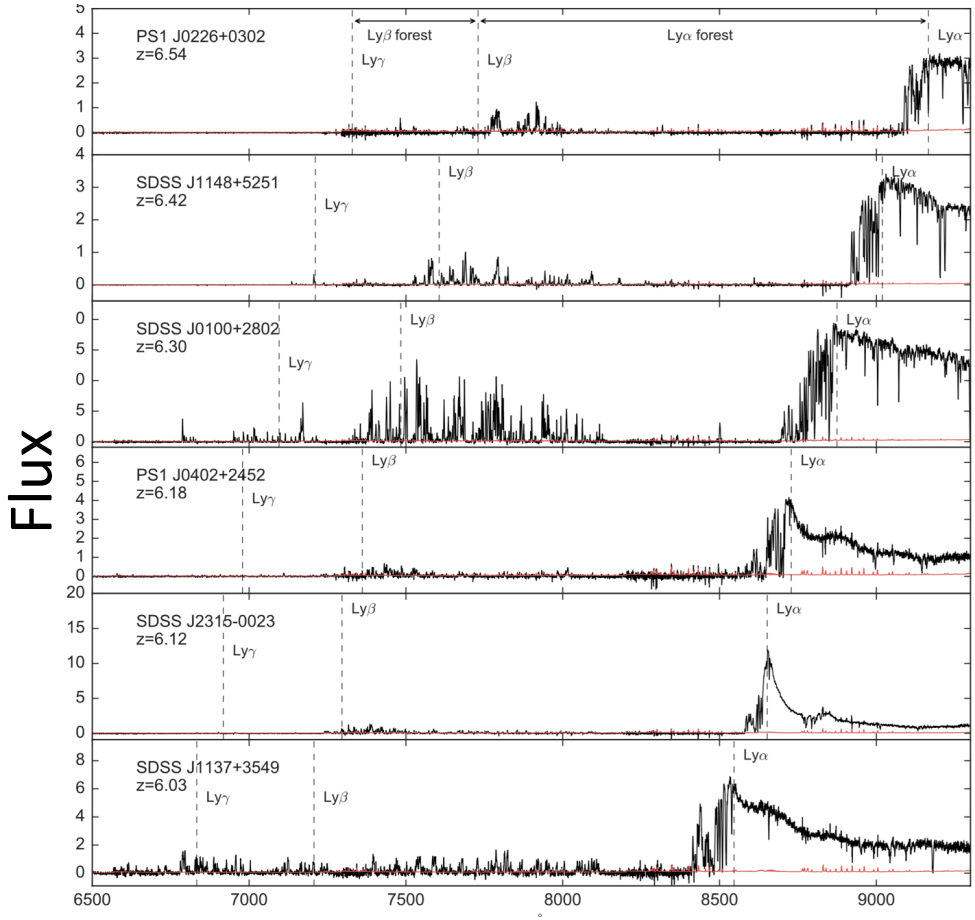
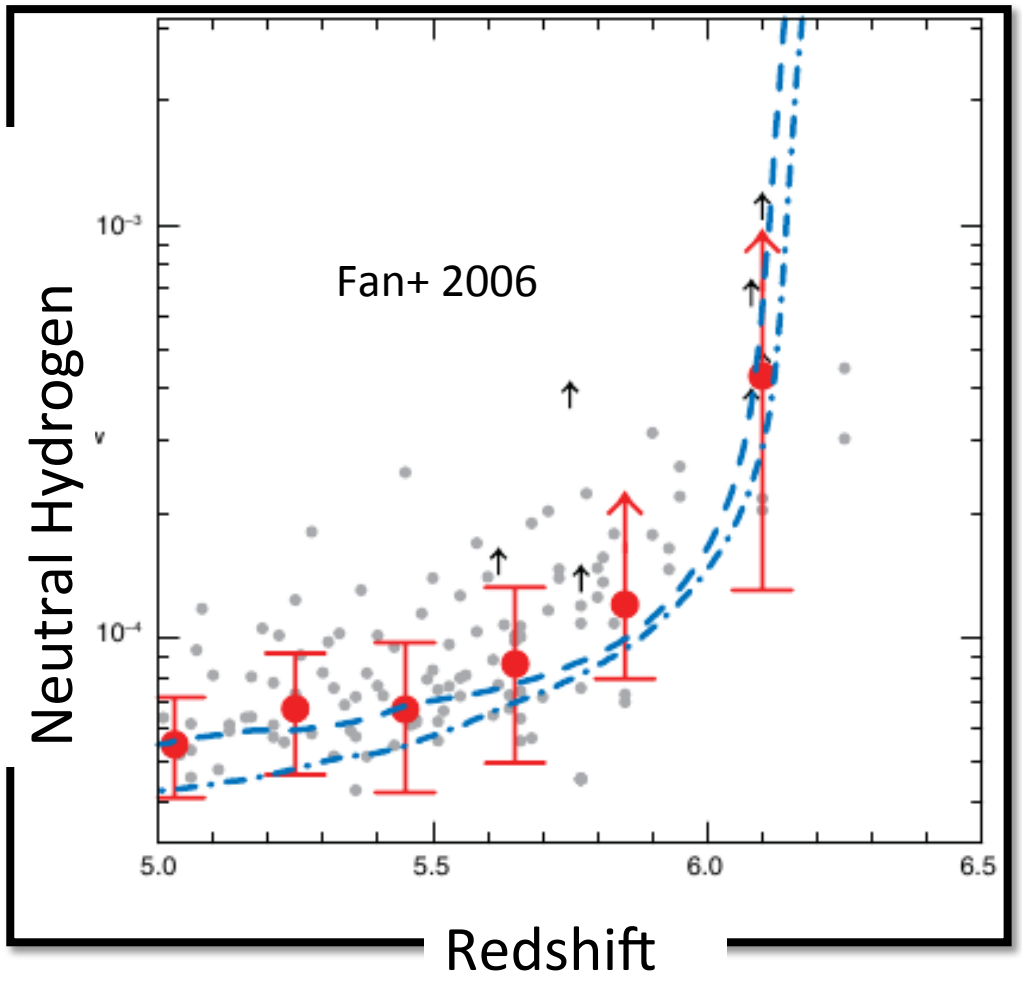


Eilers+ in prep.

End of reionization at z~6



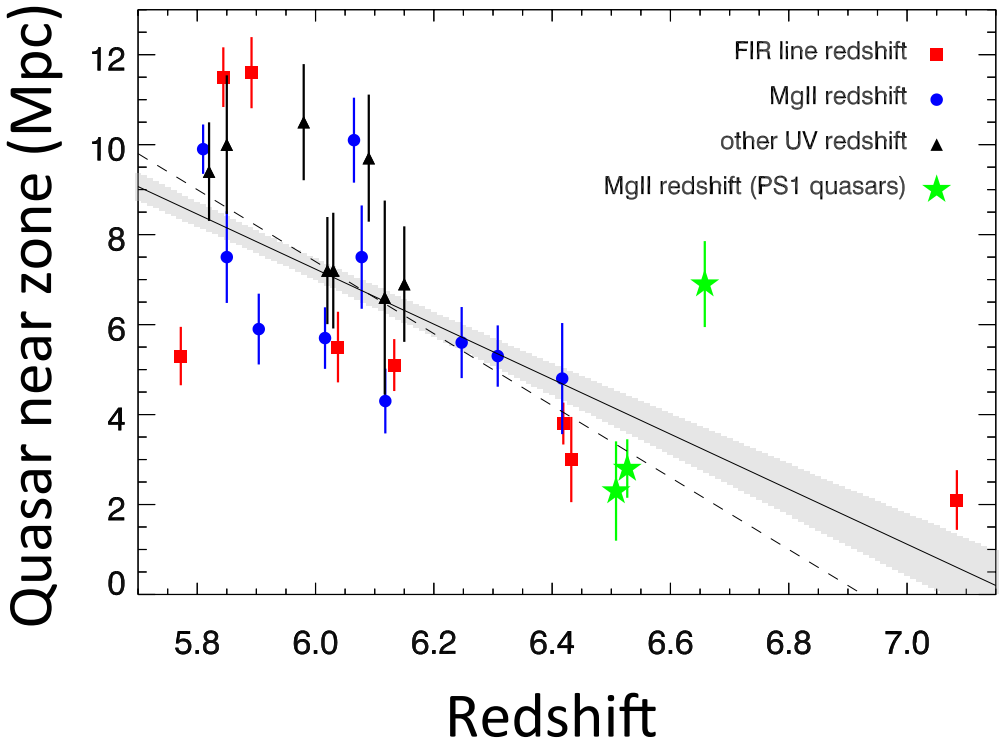
Gunn-Peterson effect saturates at low neutral fraction

$$x_{HI} < 10^{-4}$$

See also Becker+ 2015 and McGreer+ 2015

Quasar ionization regions

Near zone size: $R \sim x_{HI}^{-1/3}$ (Fan+ 2006, Carilli+ 2010)

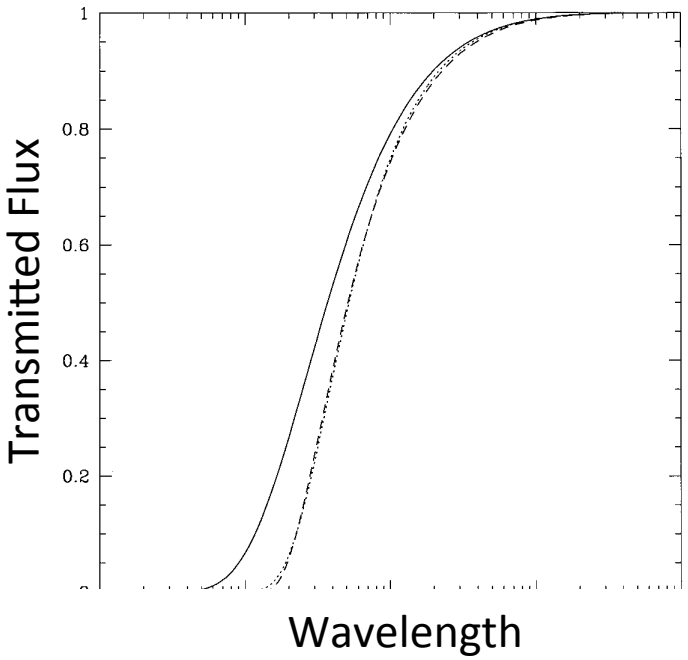


But see also:
Anna-Christina Eilers'talk
Bolton & Haehnelt 2007
Keating+ 2015

Venemans, Bañados+ 2015

IGM damping wing

IGM absorption profile



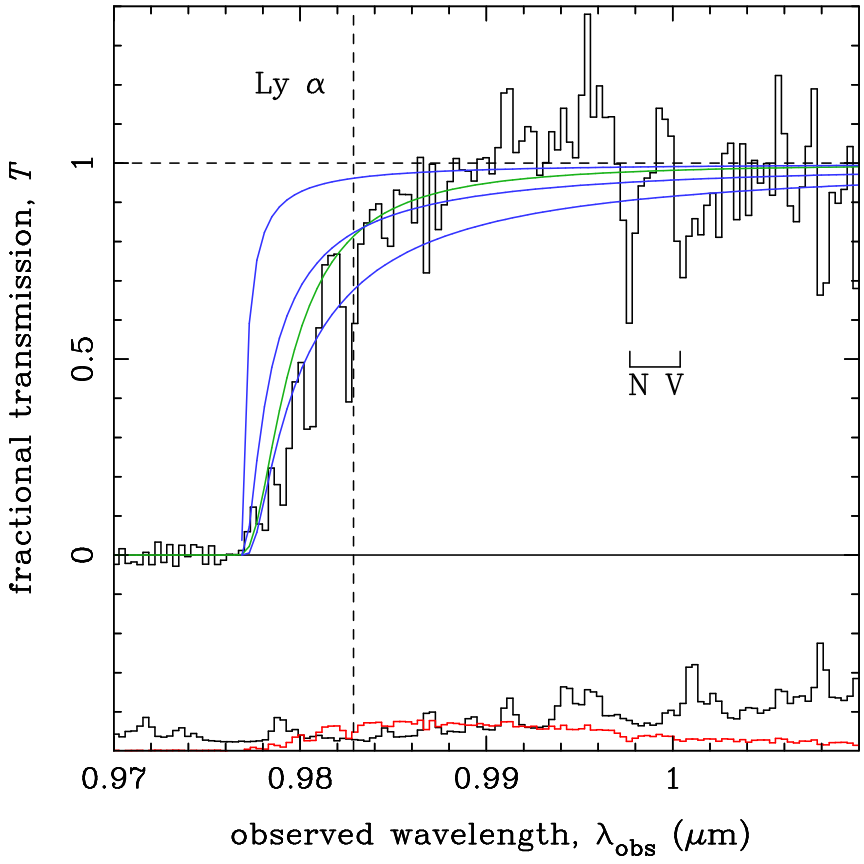
Miralda-Escude 1998

Sensitive to neutral IGM:

$$x_{HI} > 0.1$$

First IGM damping wing at z~7?

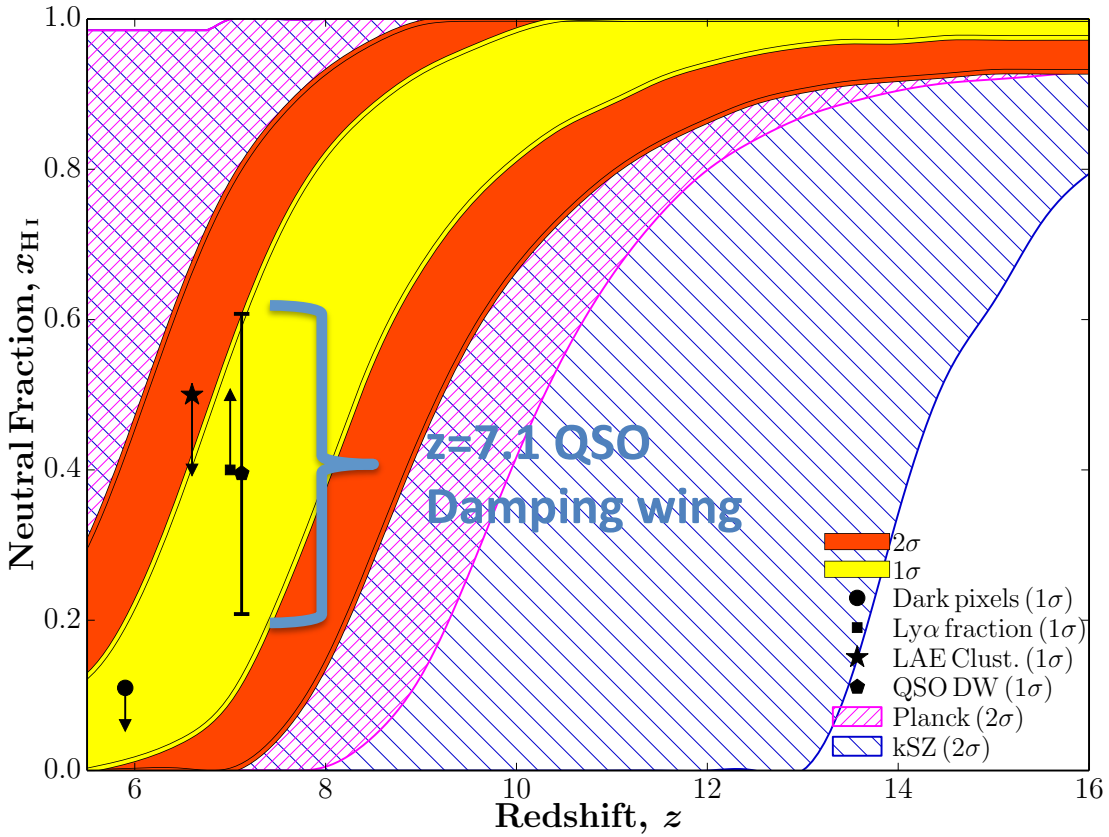
z=7.1 quasar (Mortlock+ 2011)



See also:
Bradley Greig's talk
Simcoe+ 2012
Schroeder+ 2013
Greig+ 2016

No consensus on IGM absorption nature:
e.g., Bosman & Becker 2015

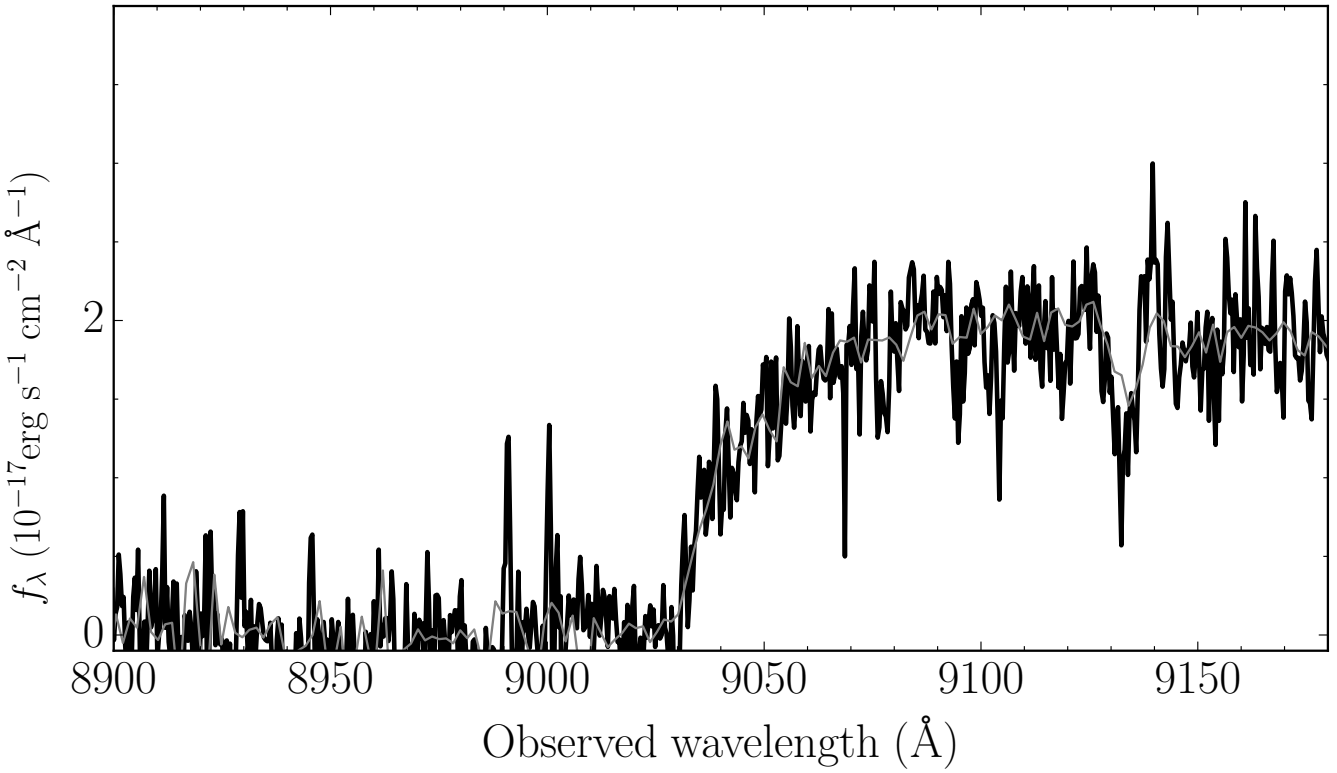
IGM damping wing



But see also
Bosman & Becker 2015

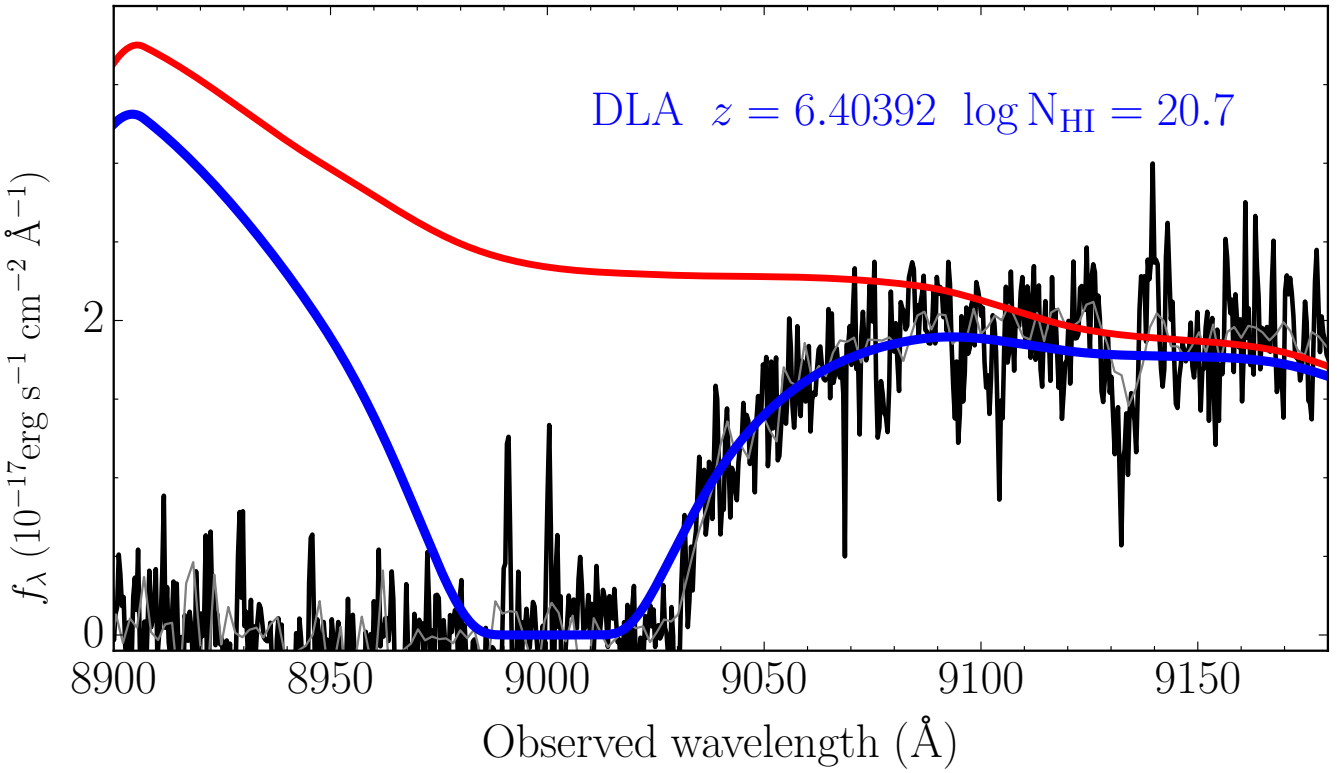
Greig & Mesinger 2016
Greig+ 2016

IGM damping wing at z=6.4?



Bañados+ in prep.

Proximate DLA at z=6.4



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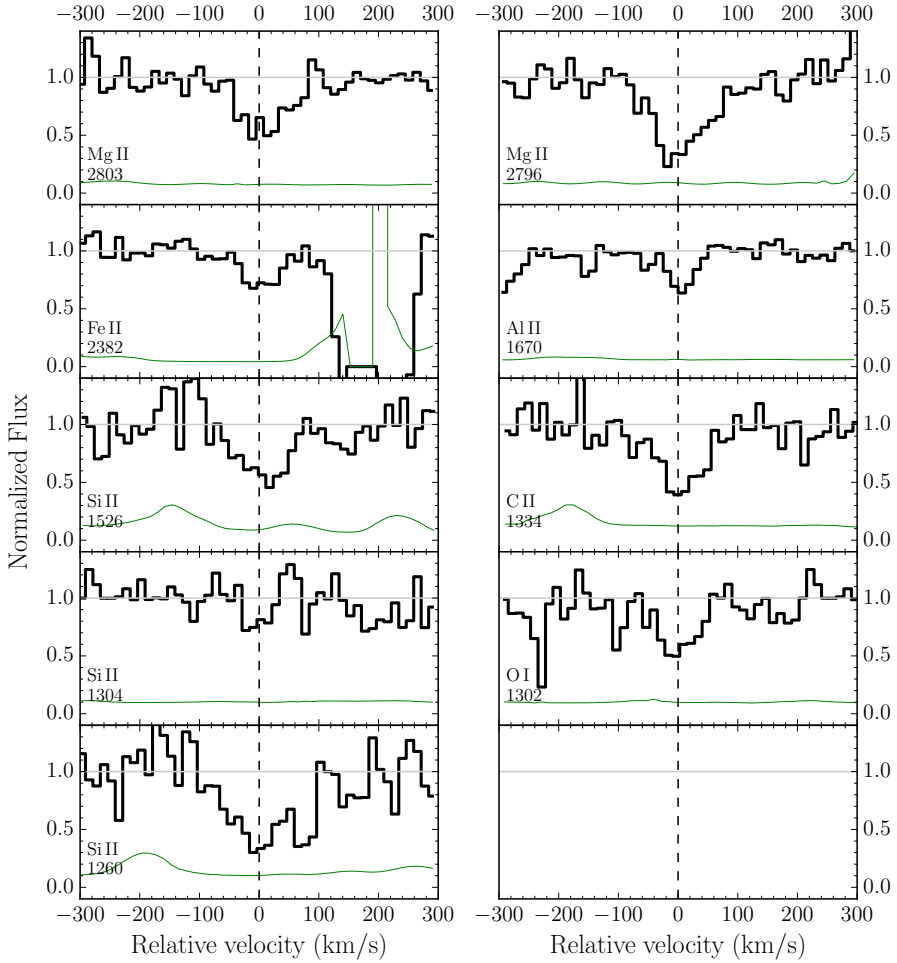
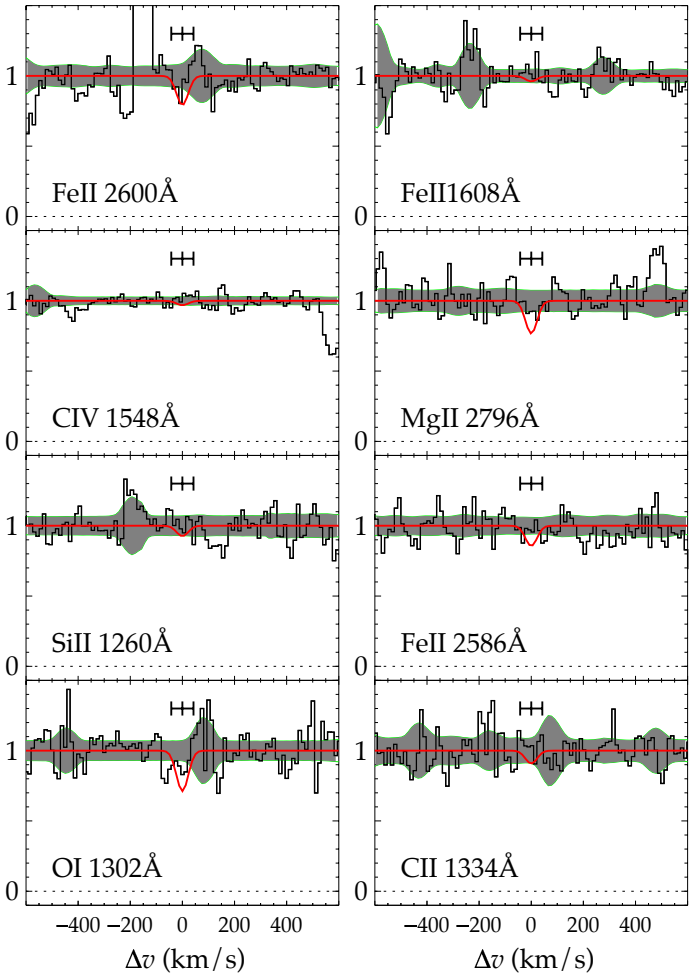
Proximate DLA at z=6.4





Bañados+ in prep.

z=7.1 quasar, Simcoe+ 2012

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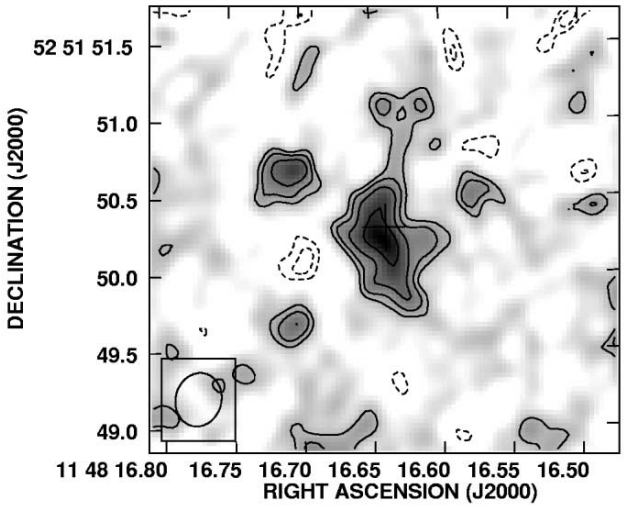
Quasar host galaxies

Quasar host galaxies

- Really hard (impossible?) in the UV/Optical
  (e.g., Decarli+ 2012, Mechtley+ 2012, Emanuele Farina's talk)

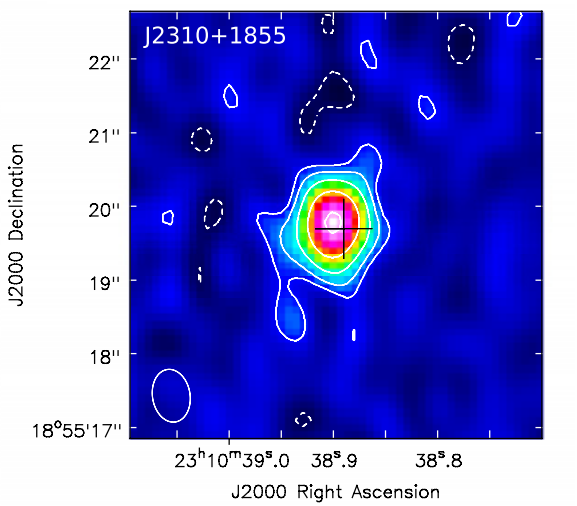
- Possible in the sub-mm/radio
  (e.g., see talks by Ran Wang, Bram Venemans, and Roberto Decarli)

CO at z=6.4



Walter+ 2004

[CII] at z=6.0



Wang+ 2013

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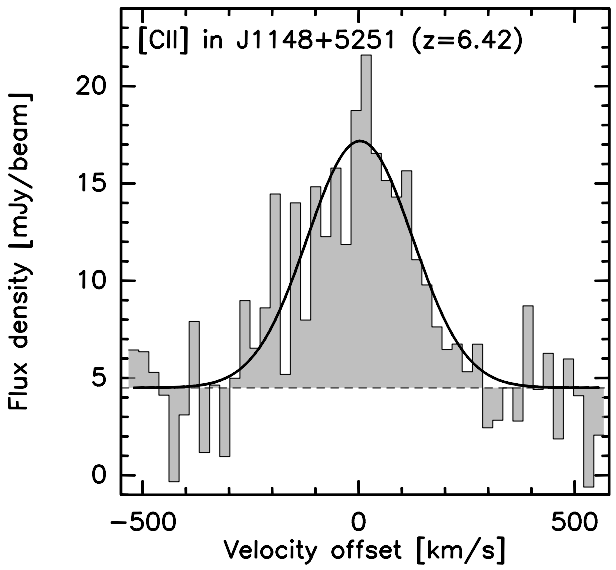
Quasar host galaxies

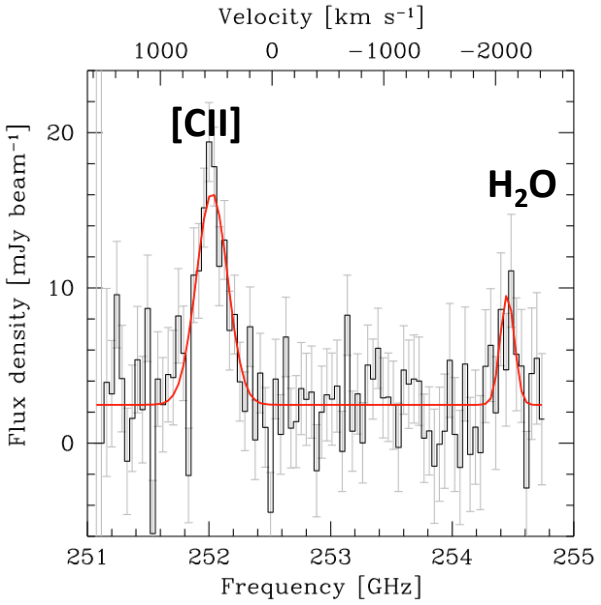
- [CII] 158um fine structure line:
  - Principal ISM coolant
  - Traces regions of active star formation
  - One of the brightest lines in star-forming galaxies
  - z > 5 → redshift to mm bands

J1148+5251 at z=6.42



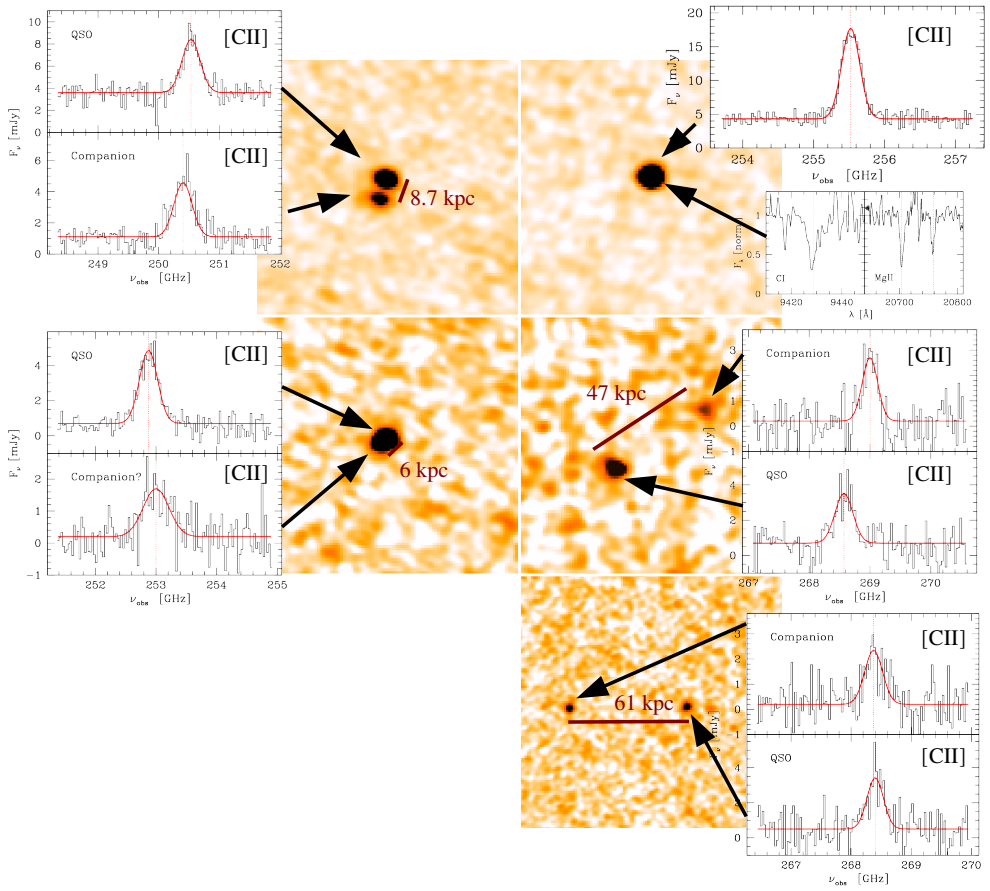
Walter+ 2009

P036+03 at z=6.54



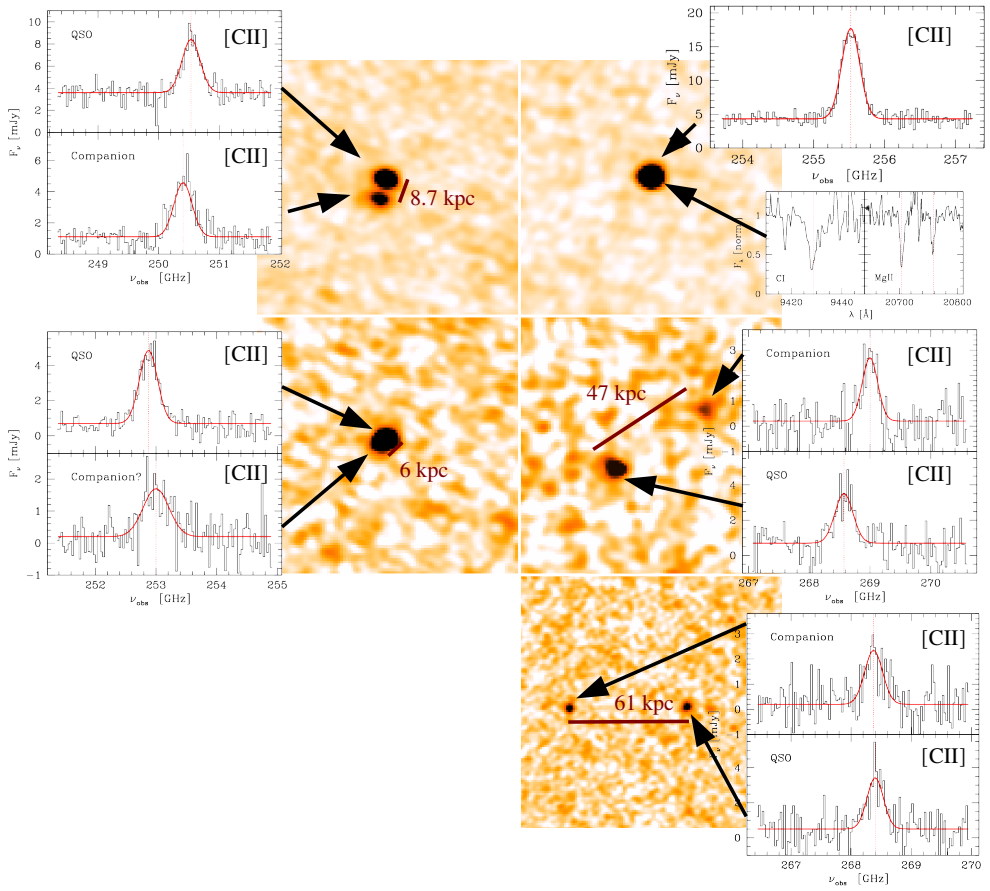
Bañados+ 2015b

ALMA [CII] survey



More in
Roberto Decarli's talk

Bright ALMA companions ...



See also Bañados+ 2013

More in
Roberto Decarli's talk

Summary & Outlook

Summary

- Quasars are ideal targets to study the early universe
- Sample of ~200 quasars and increasing
- Multiwavelength characterization on-going
  ALMA, VLA, HST, Spitzer, Muse, Optical/NIR spectroscopy

Outlook

- Push the redshift barrier (Euclid, WFIRST, LSST, …)
- QSO host galaxies and environments with ALMA
- Rest-frame optical properties with JWST (BH masses)
- Radio-loud quasars for 21cm forest with SKA