Quasars in the Epoch of Reionization

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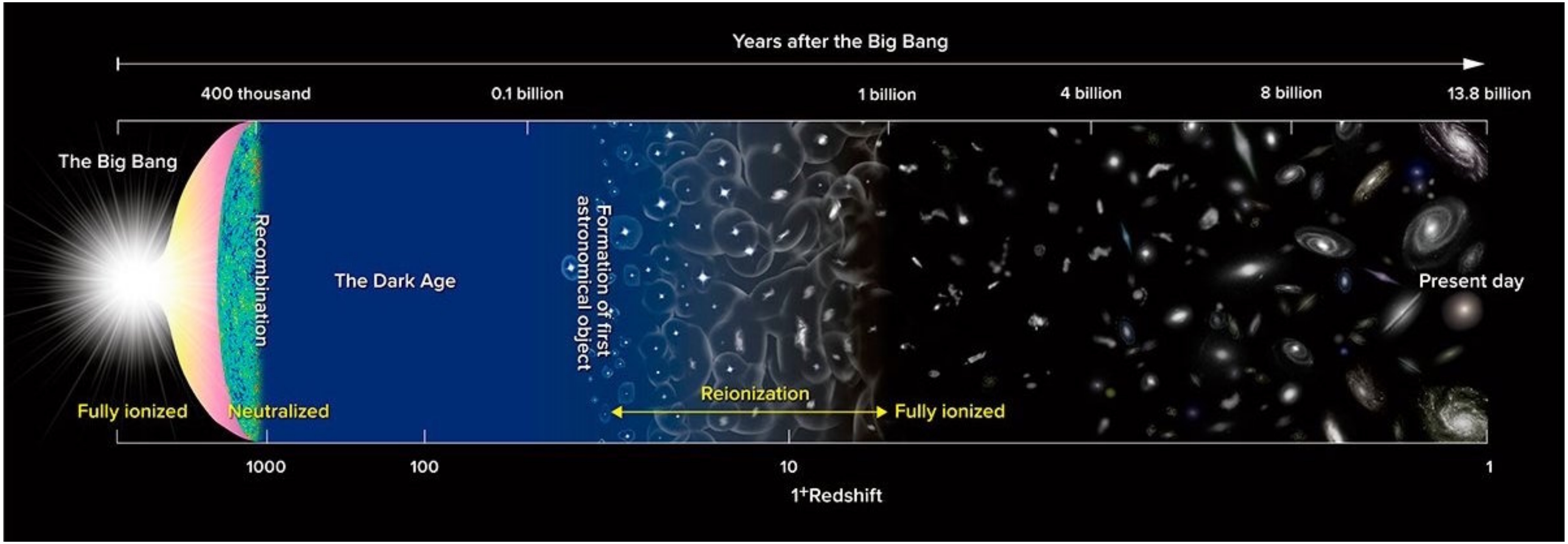
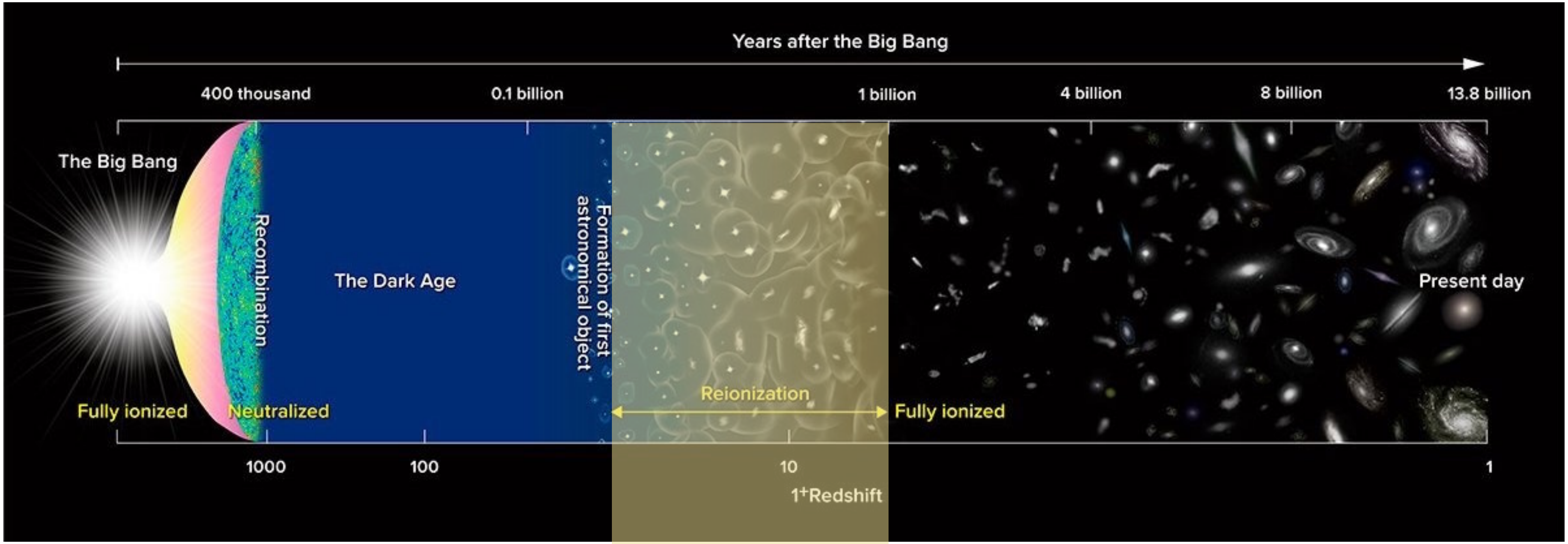
cosmic history



cosmic history

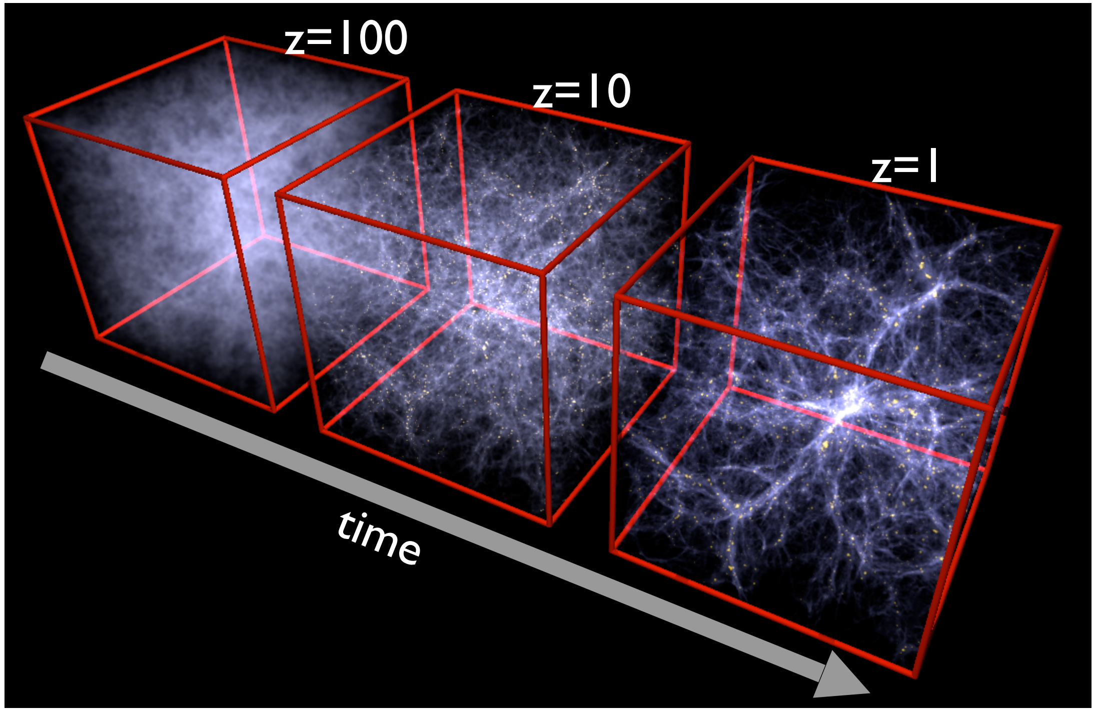


Reionization

Last major phase change of our universe

theoretical framework

hydrodyn. simulations of structure formation

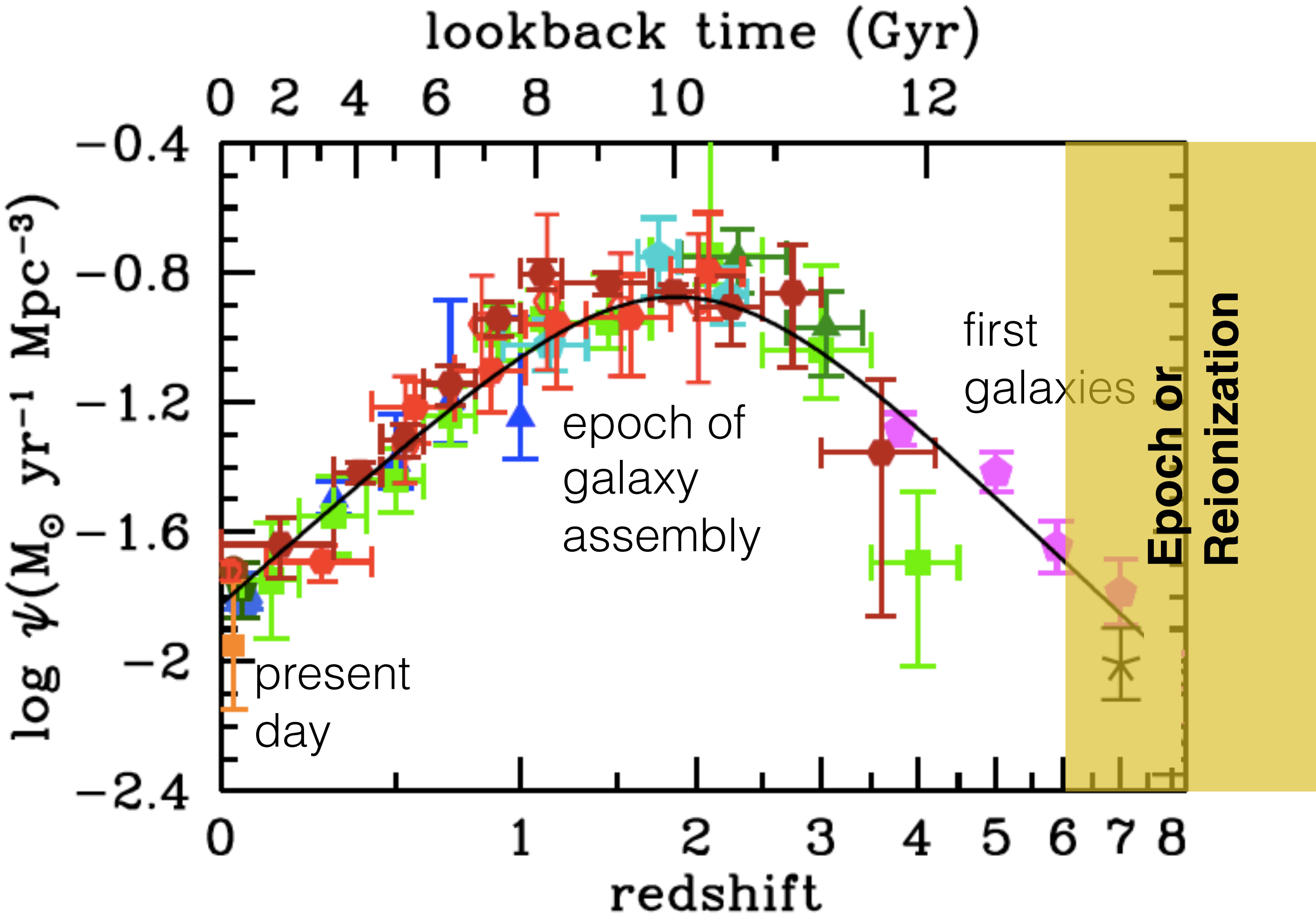


e.g. Springel et al.

galaxies and black holes grow through gas accretion…

cosmic star formation

Volume density of star formation in galaxies as f(cosmic time)

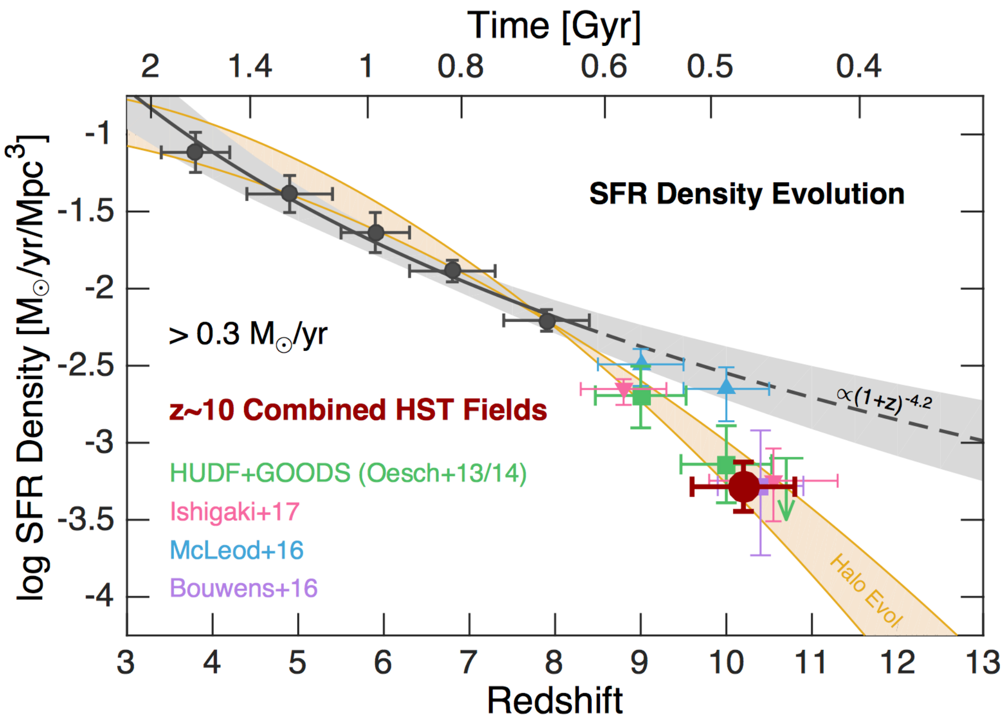


z>6 = ‘the first Gyr of the Universe’

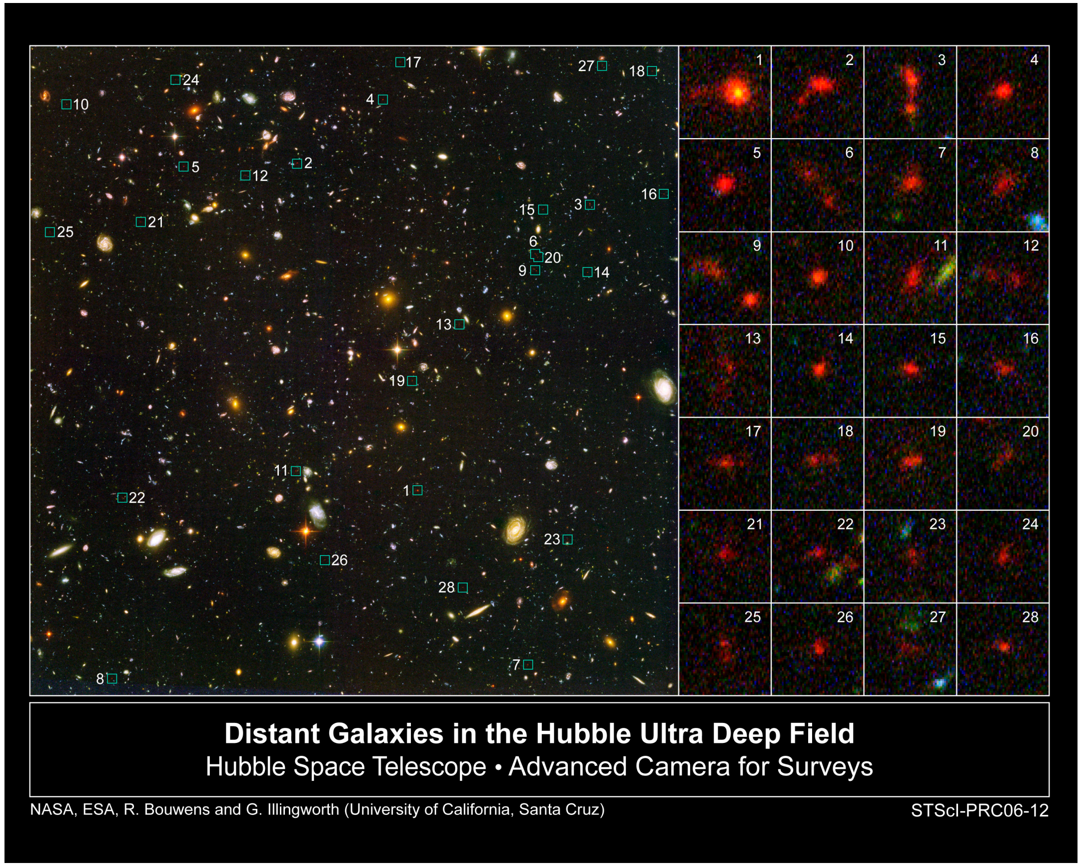
Madau & Dickinson 2014

the earliest galaxies

Bouwens et al.



Oesch et al. 2017

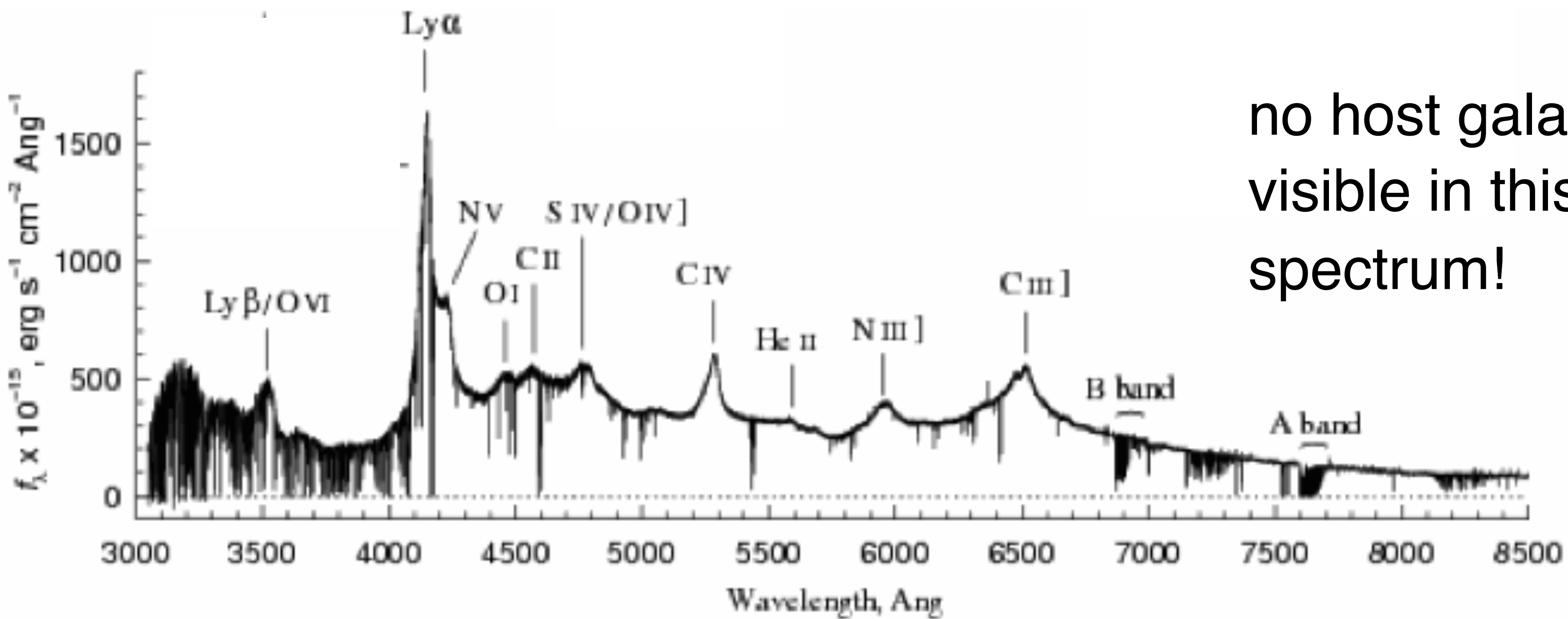


these galaxy candidates are very faint!

…often impossible to confirm spectroscopically

quasars to the rescue!

- powered by accreting black holes
- brightest sources in universe
- UV/optical spectrum:
  - power-law cont. by accretion disk + broad emission lines
- line width+continuum≈black hole mass



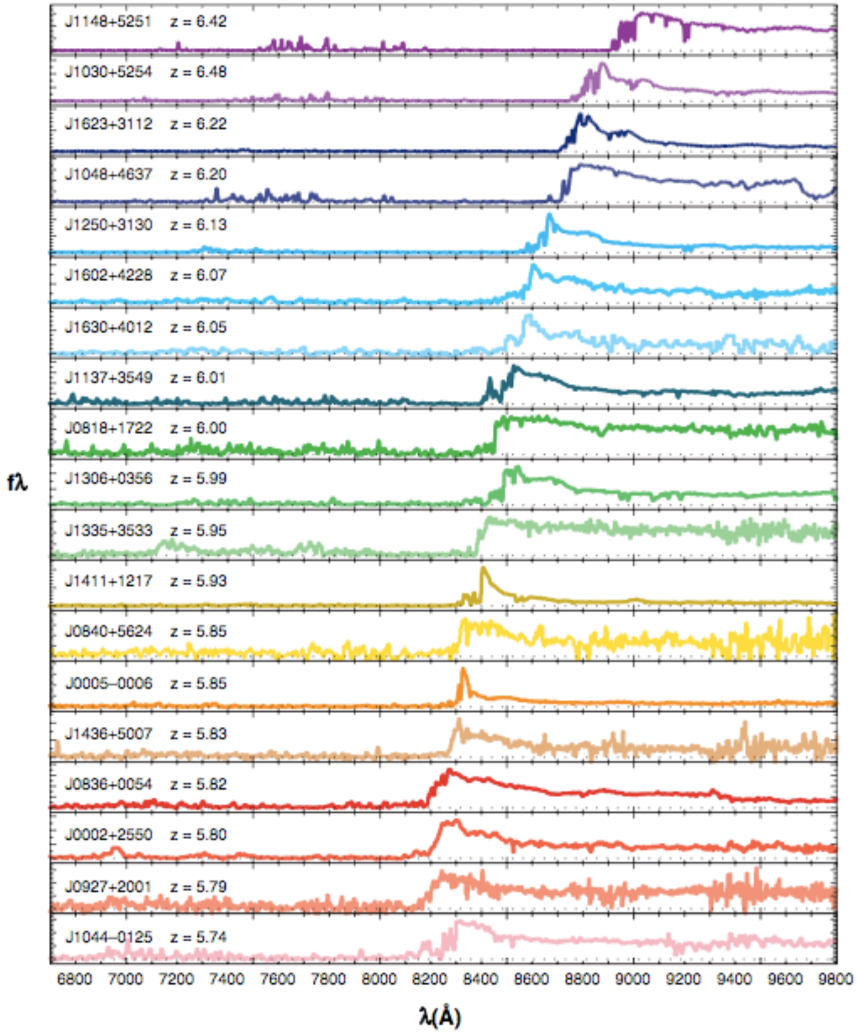
no host galaxy visible in this spectrum!

quasars: seen out to z~6 already a decade ago

…using SDSS:

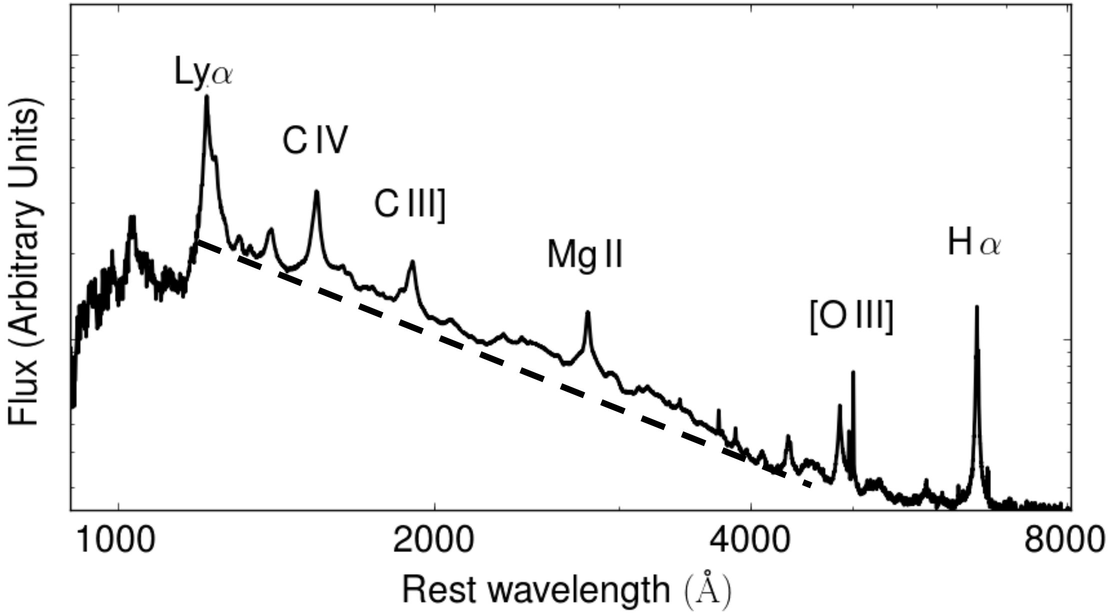
supermassive black holes ($>10^9$ M_{sun}) already exist within 1 Gyr after Big Bang

challenging for black hole formation models

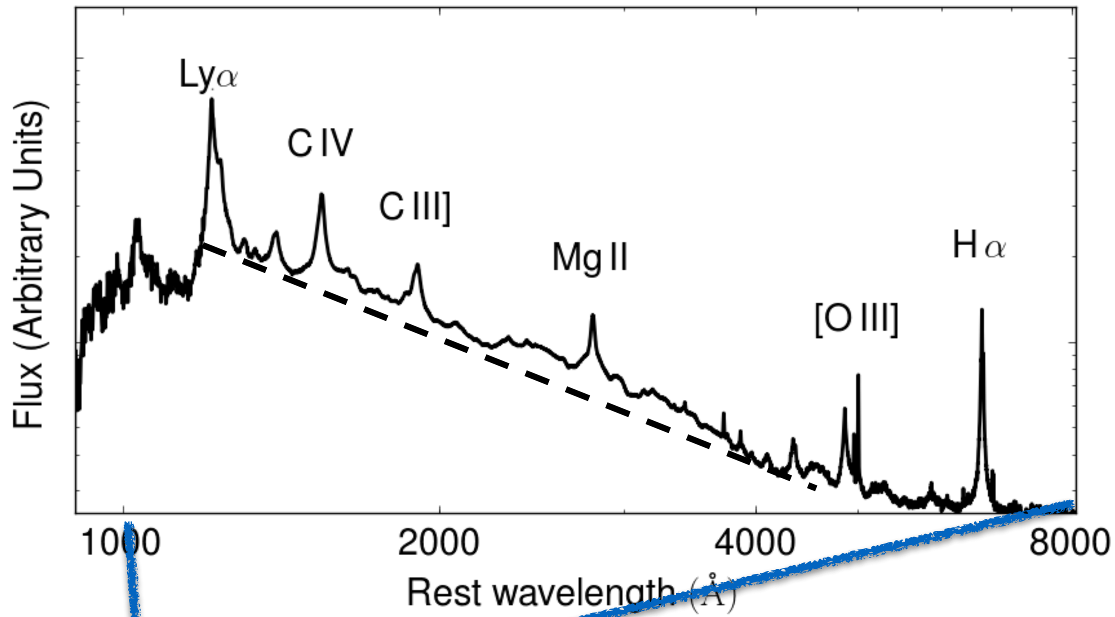


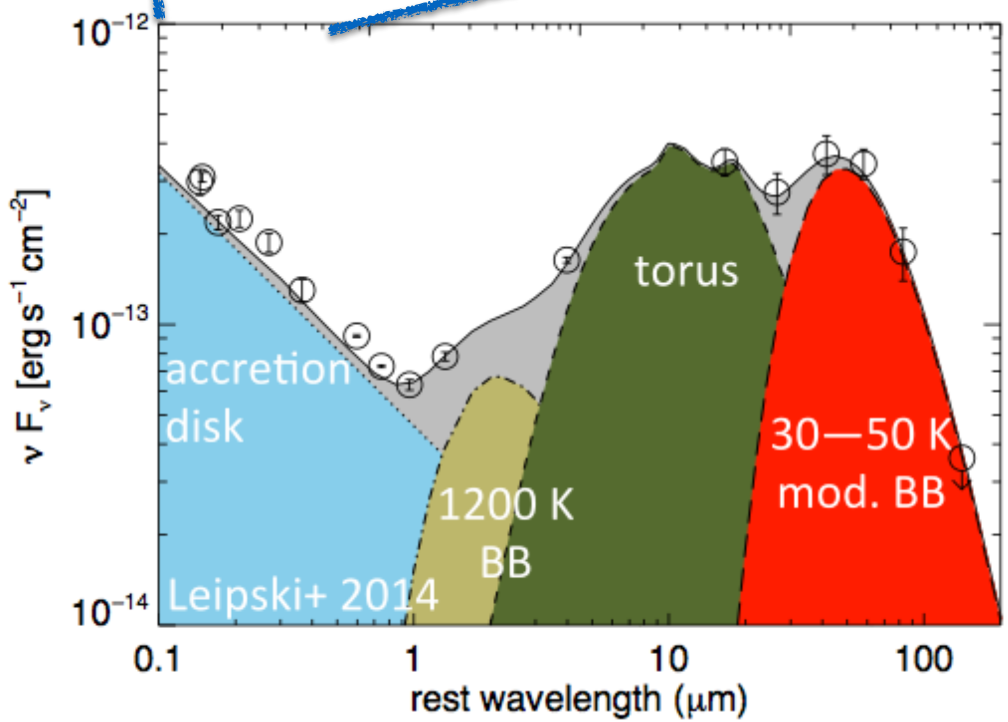
Fan et al. 2006

quasars: spectral energy distribution



quasars: spectral energy distribution

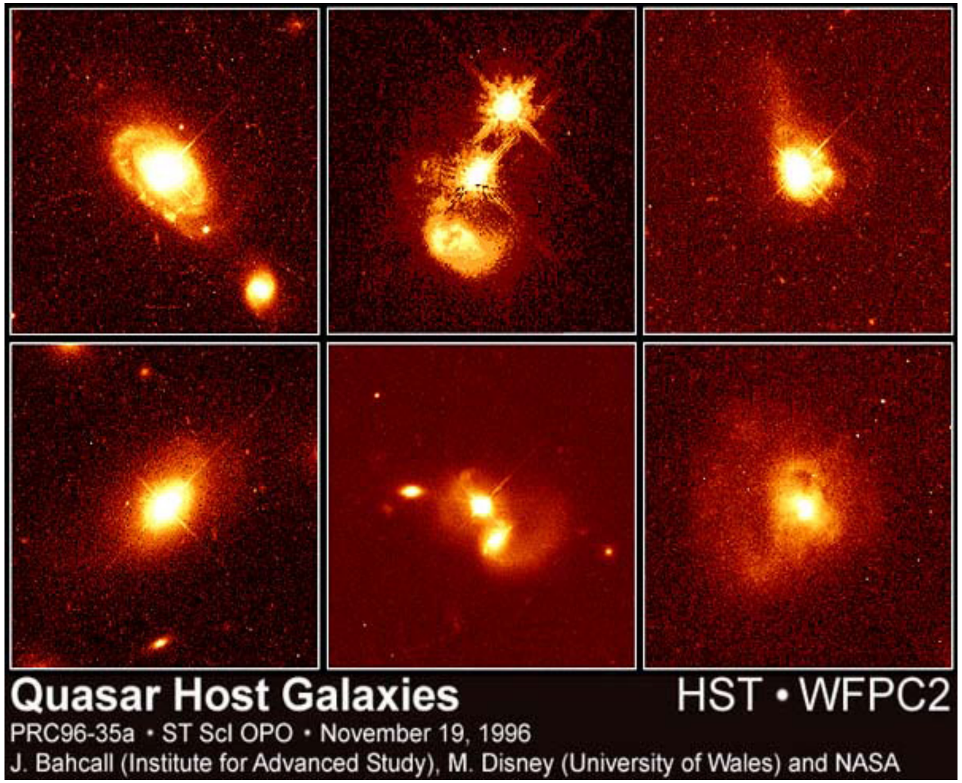




- UV/optical: accretion disk
- Mid-infrared: hot dust and torus
- Far-infrared: cool dust / host galaxy

quasars: a phase of a (host) galaxy

nearby quasars reveal hosts



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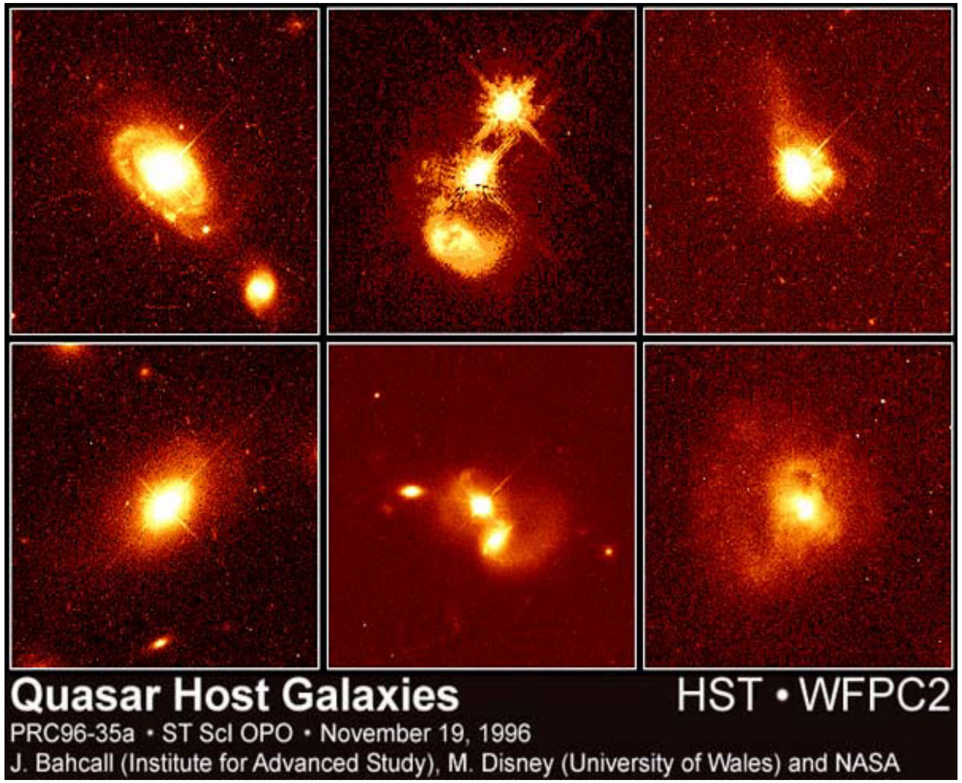
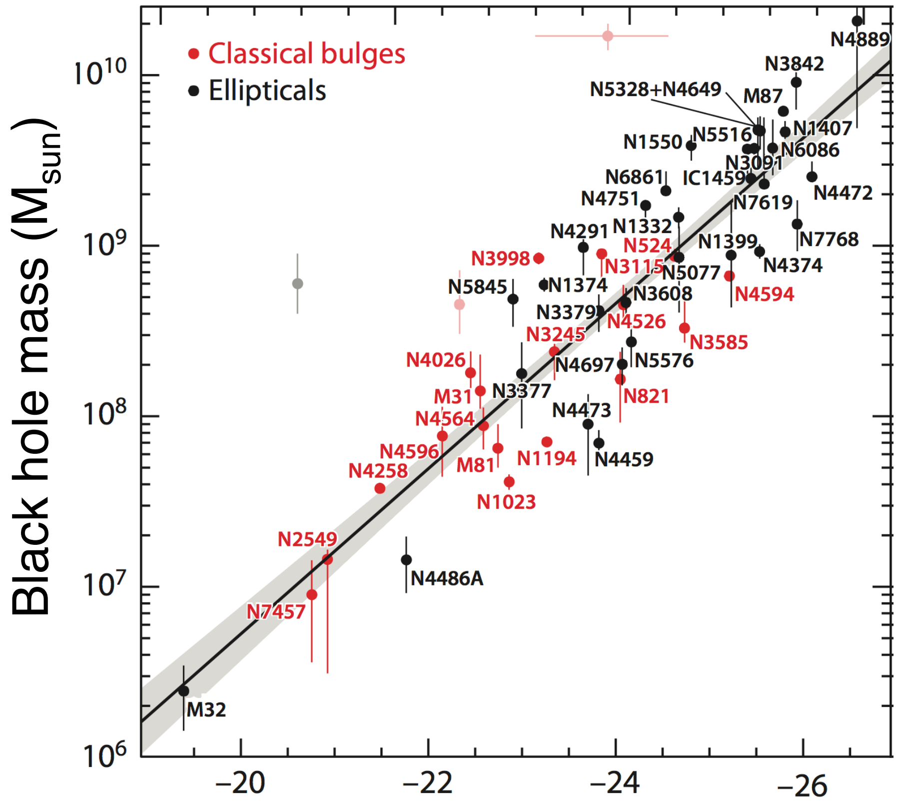


local black hole – bulge mass relation



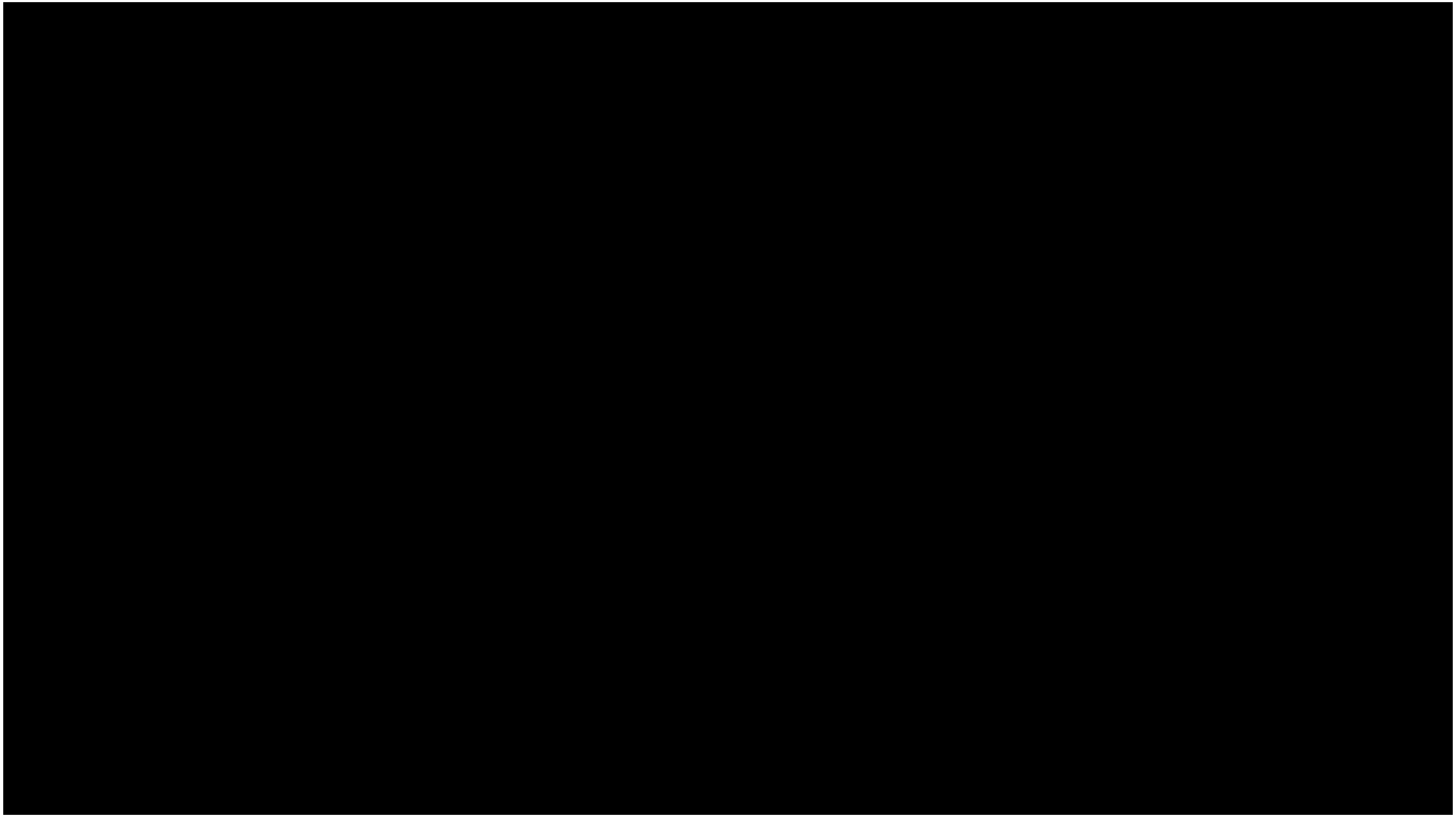
we expect massive black holes to live in the most massive galaxies…

Kormendy & Ho 2013

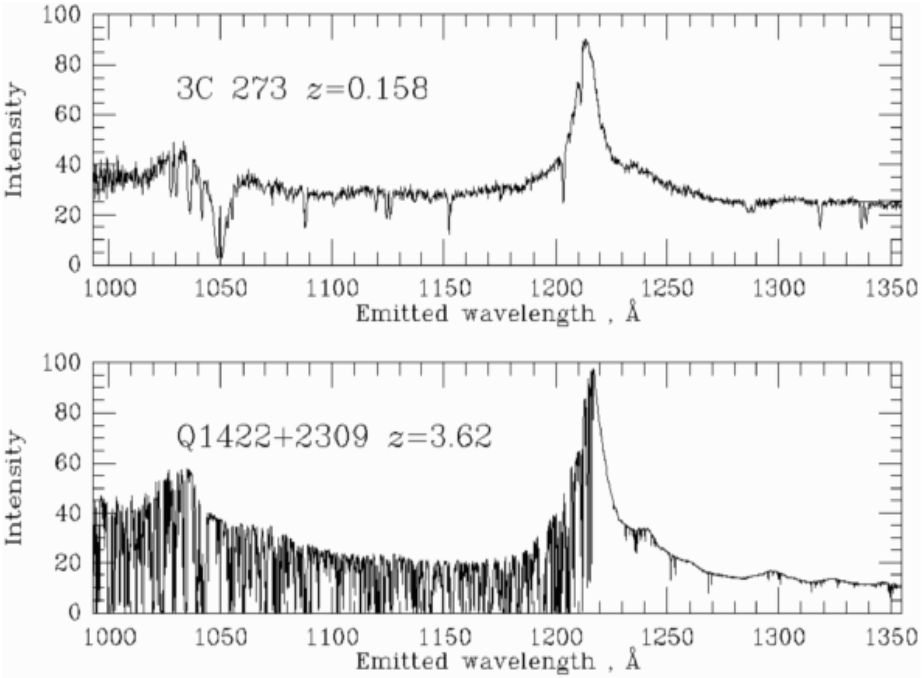
quasars: tracing overdensities

…consequently we expect massive quasar hosts

to live in galaxy overdensities…

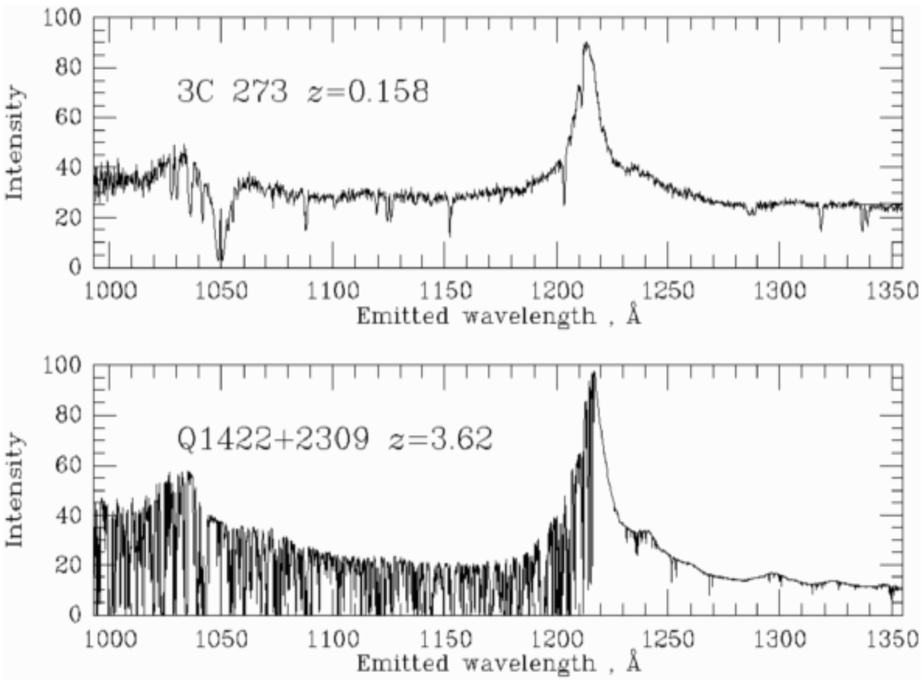


quasars: probes of intergalactic medium



Credits: B. Keel, N. Wright

quasars: probes of intergalactic medium



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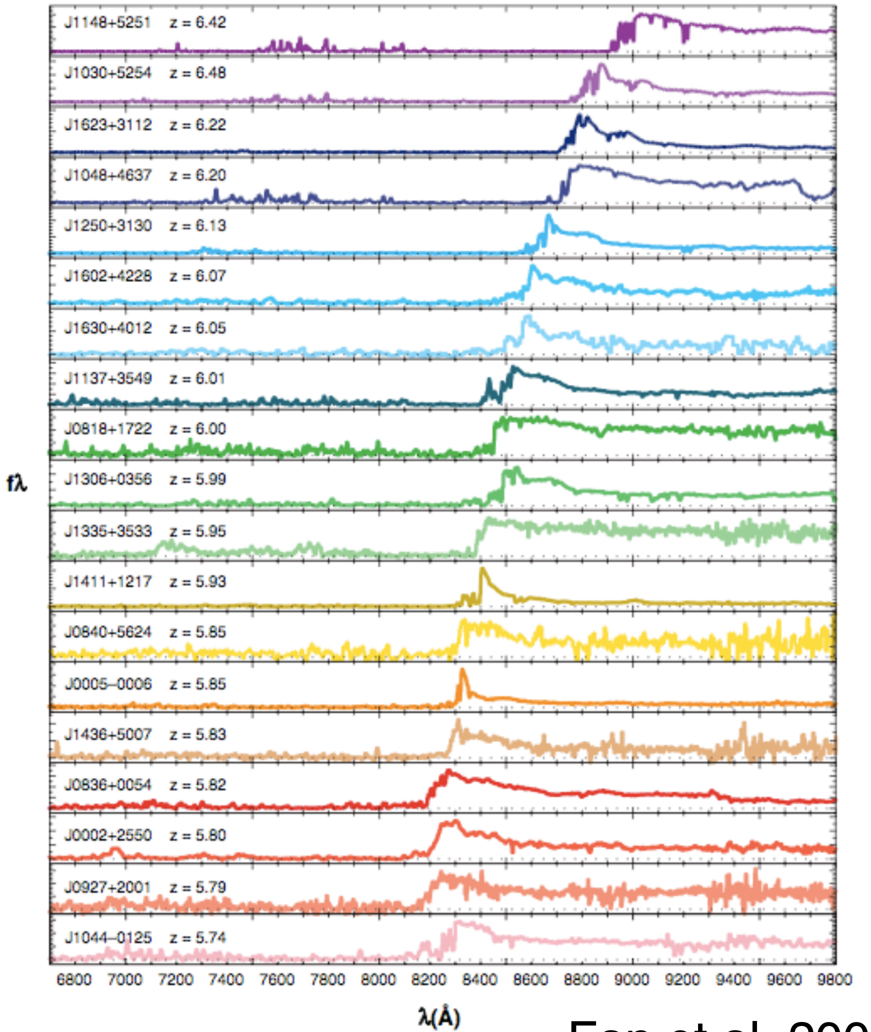
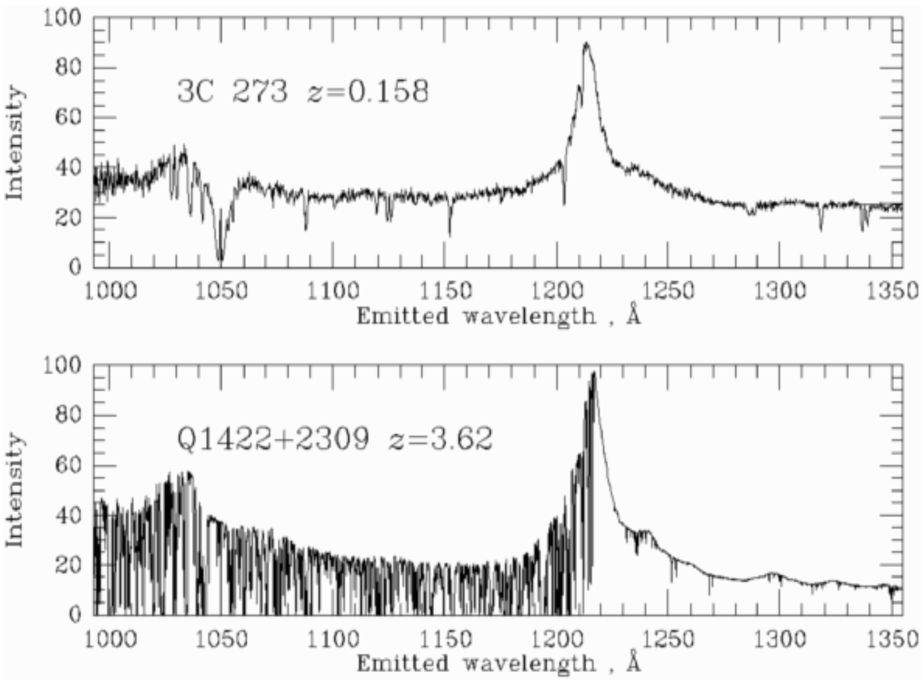


Fan et al. 2006

quasars: probes of intergalactic medium



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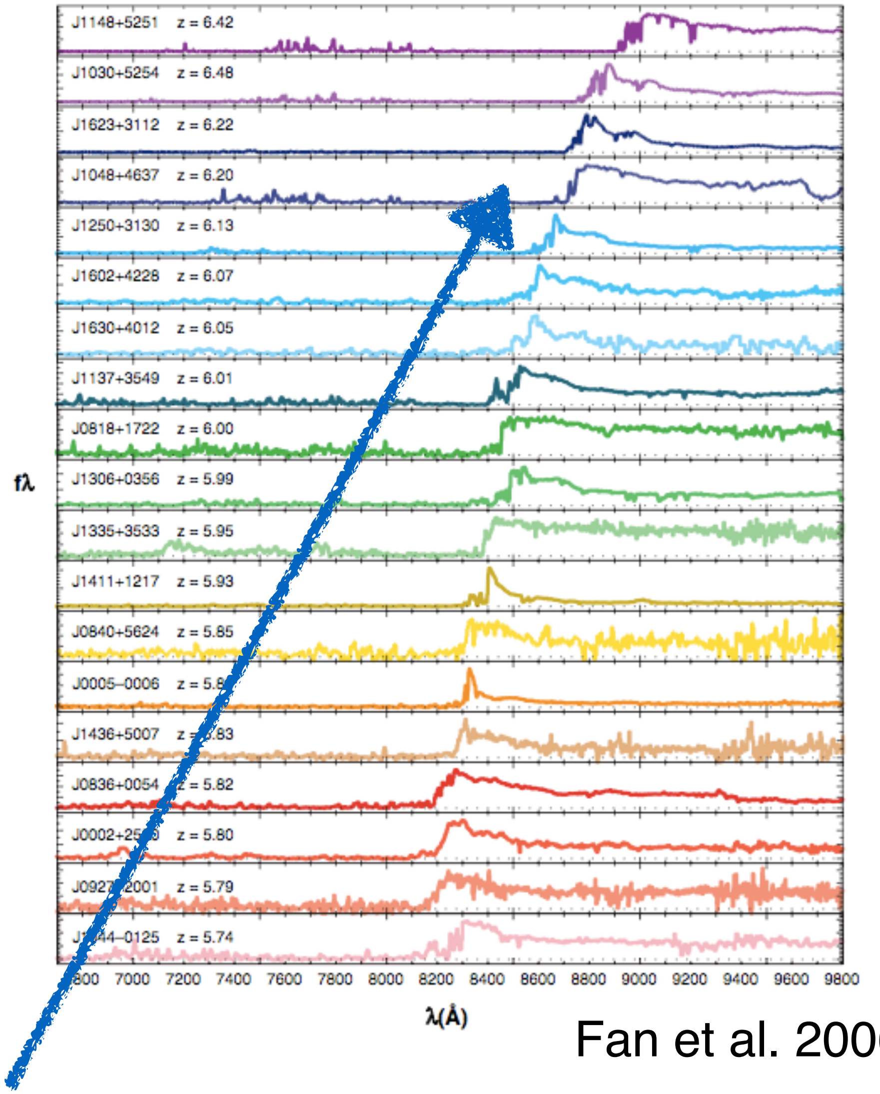


Fan et al. 2006

Gunn Peterson effect

problem: complete absorption if universe is only 10^{-4} neutral

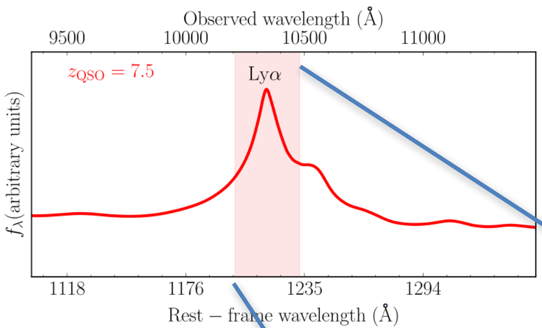
—> not a good measure of neutrality of IGM

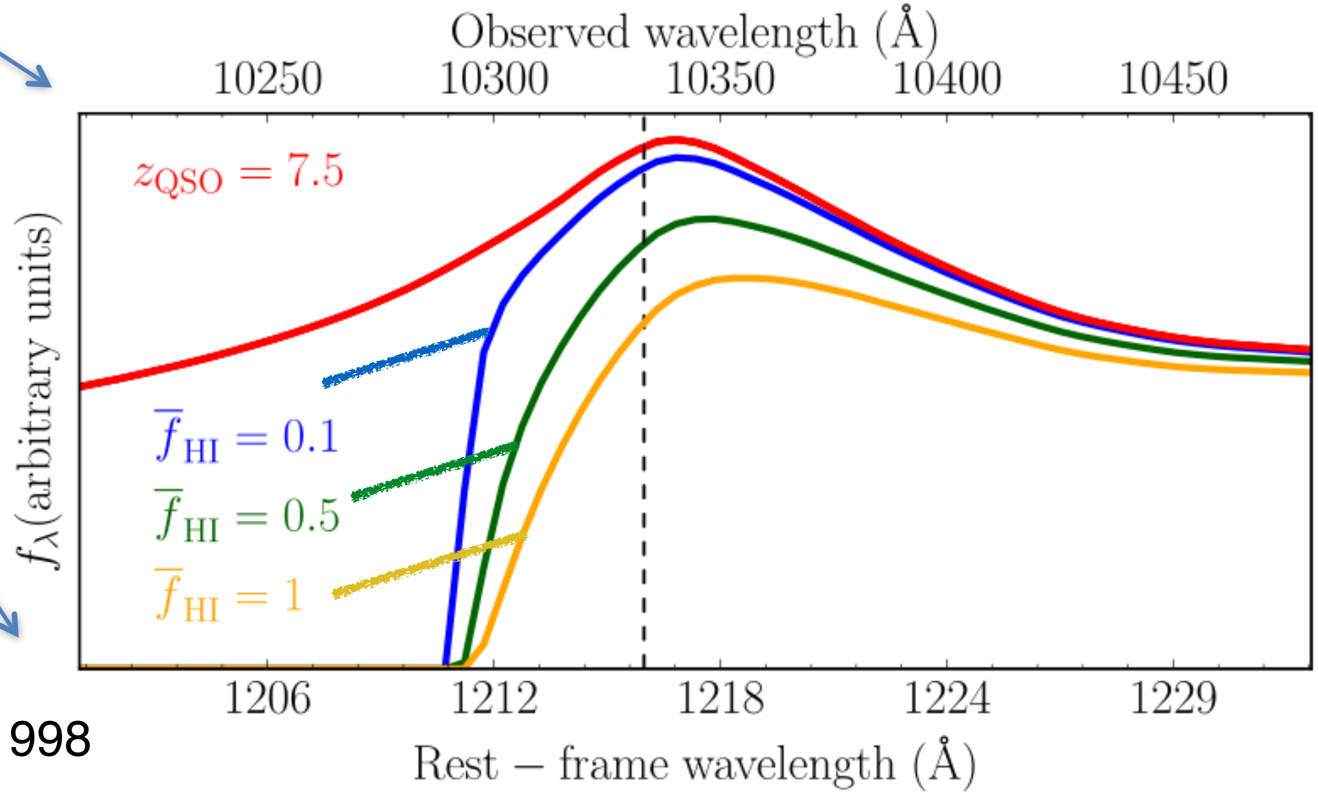
quasars: probes of intergalactic medium

resolution: damping wing of the IGM…

…sensitive to neutral IGM: $f_{HI} > 0.1$

challenge: unknown intrinsic spectrum





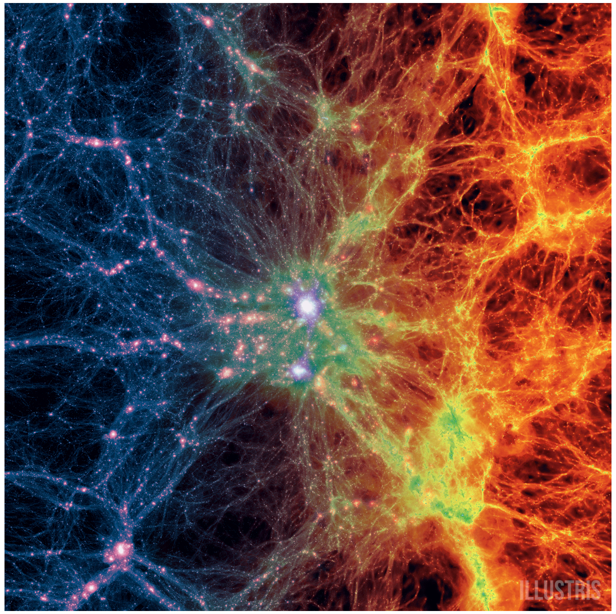
based on Miralda-Escude 1998

outline of this talk

- Characterize massive quasar host galaxies at z>6

- Environment of the first supermassive black holes at z>6

- State of the intergalactic medium at z>6



but first!

but first… we need to find the quasars

finding the needle in the haystack

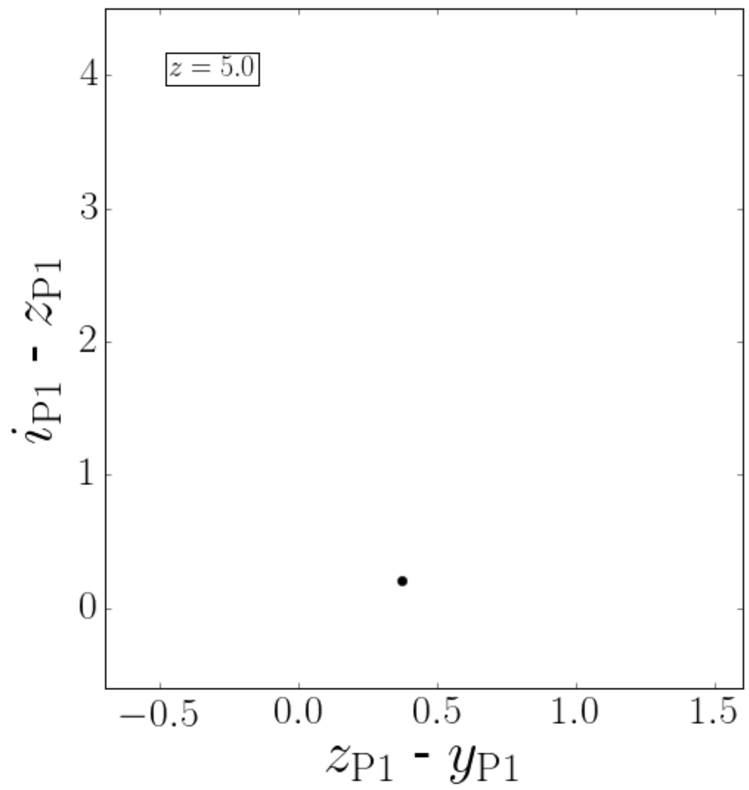
- the challenge:
  - Quasars at z>6 are **very** rare
  - < 1 Gpc^{-3} at z=6, i.e., < 1 per 100 deg^2

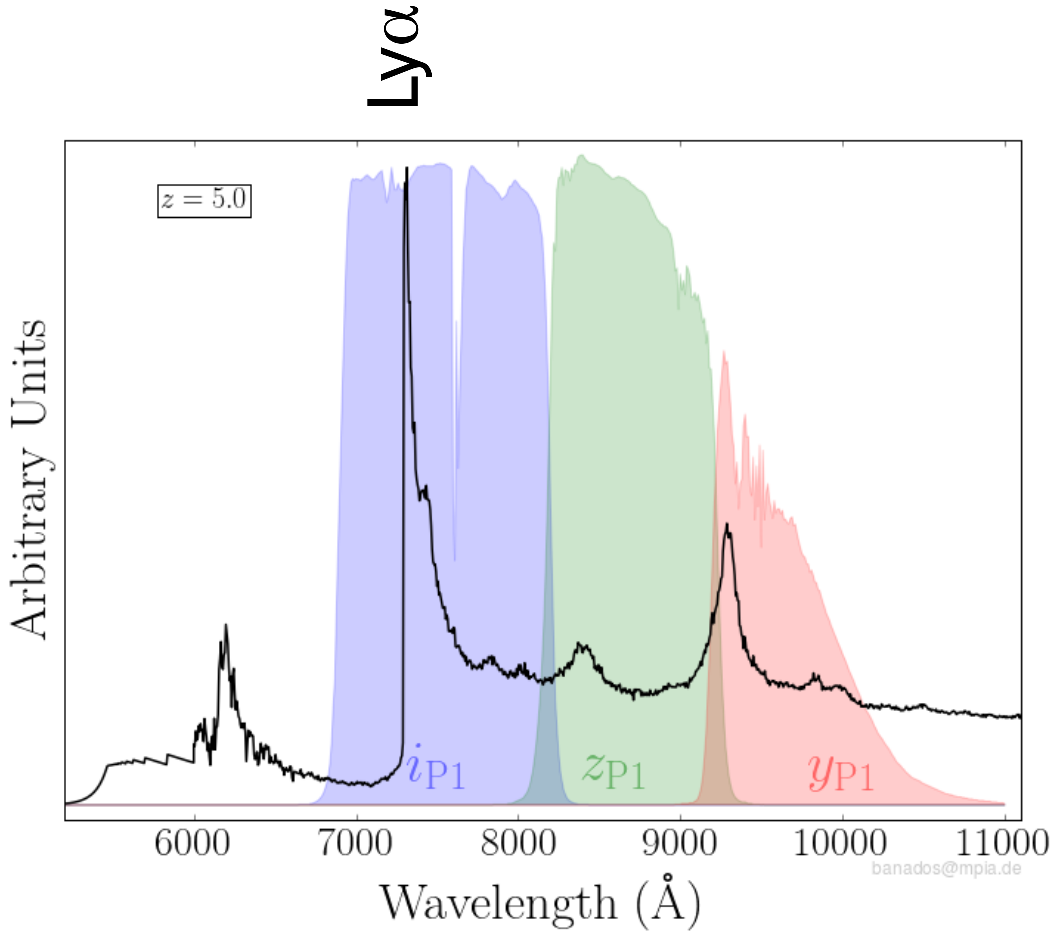
- requirement: large area multi-color surveys

- Pan-STARRS1 database ~4 billion sources

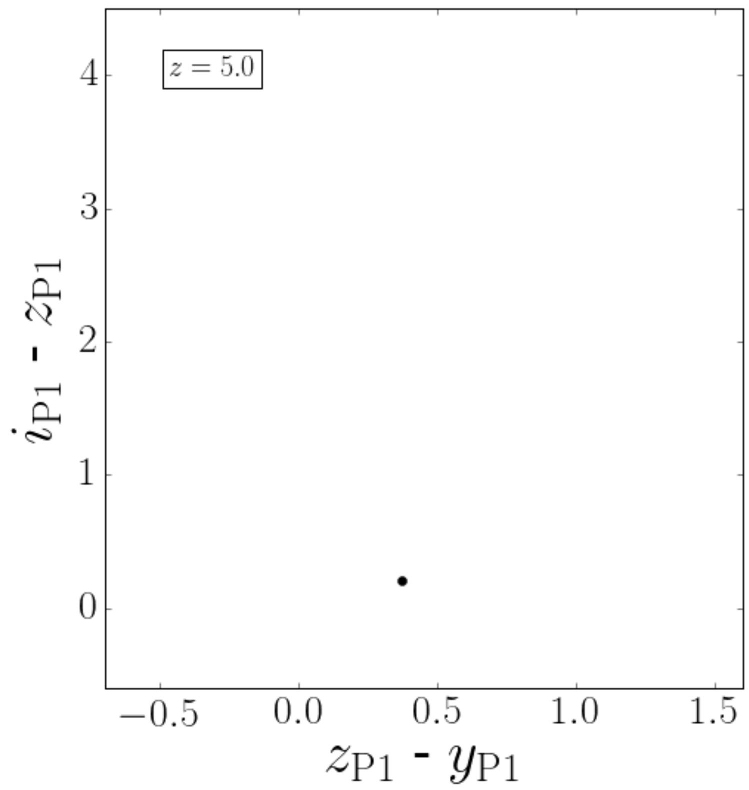
SDSS Pan-STARRS DARK ENERGY SURVEY WISE

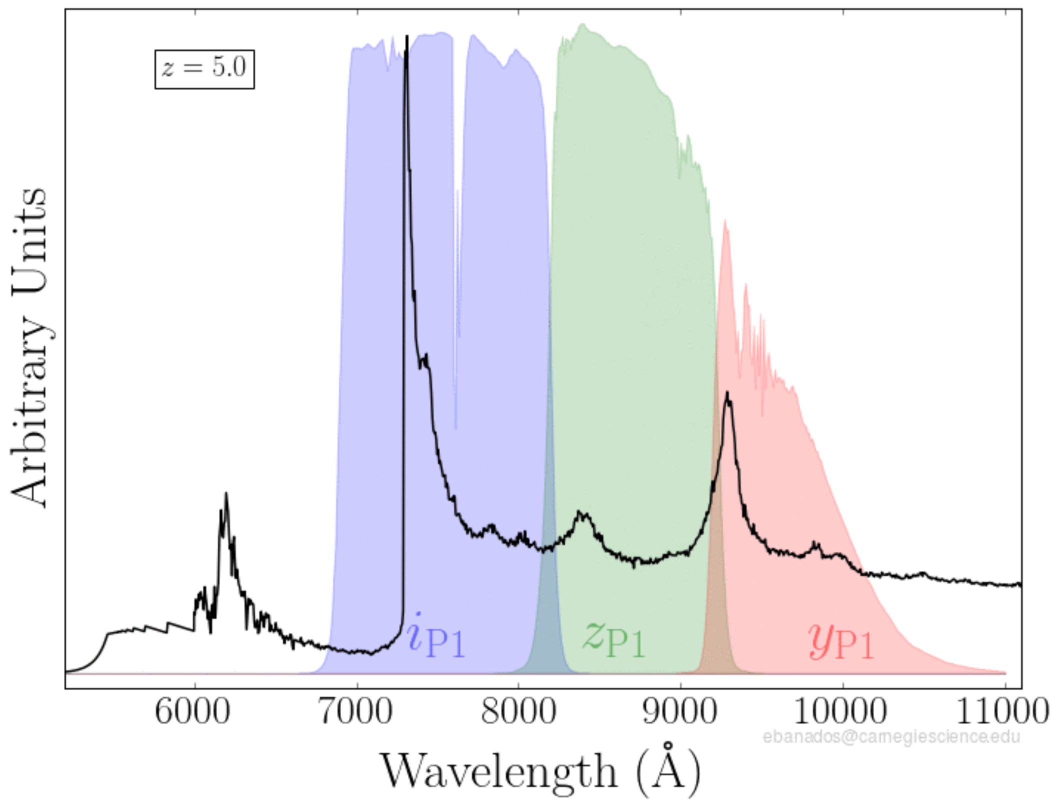
quasar selection



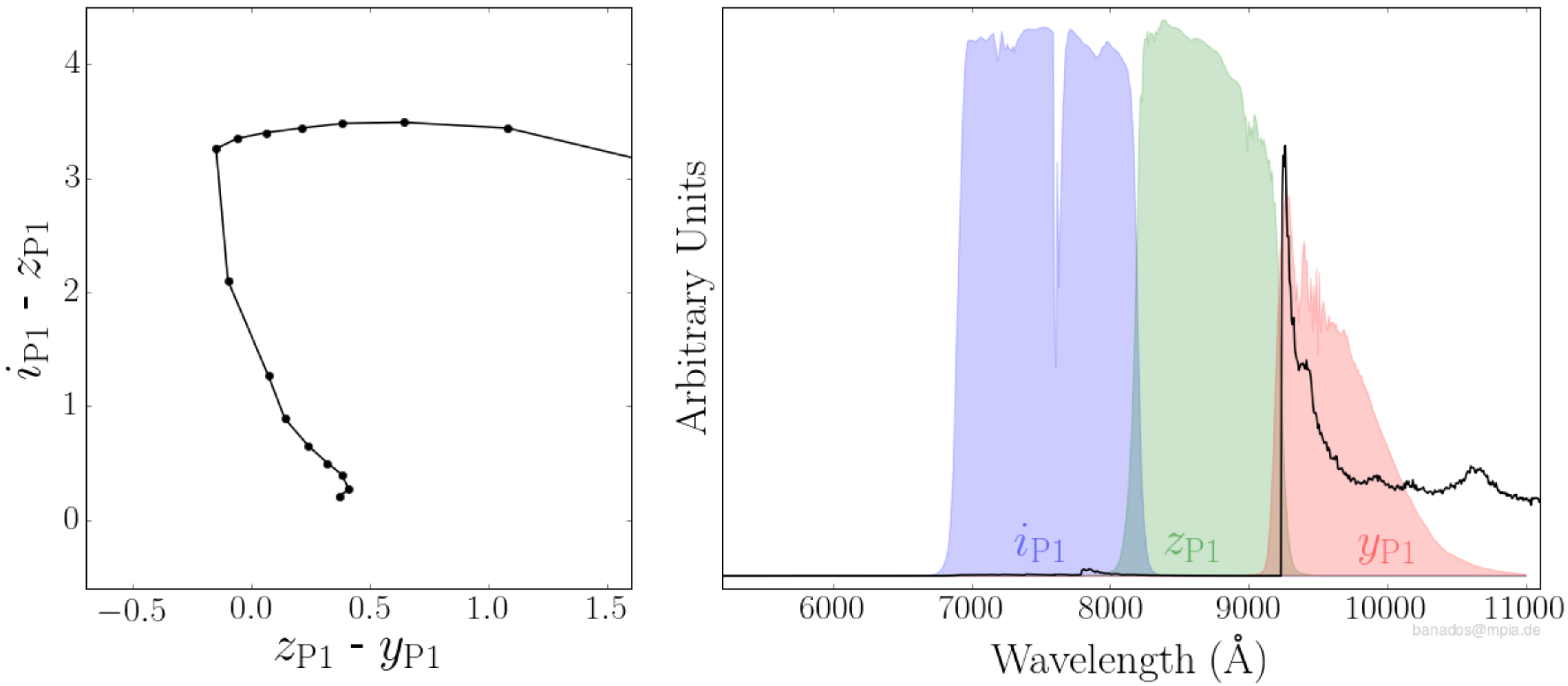


quasar selection

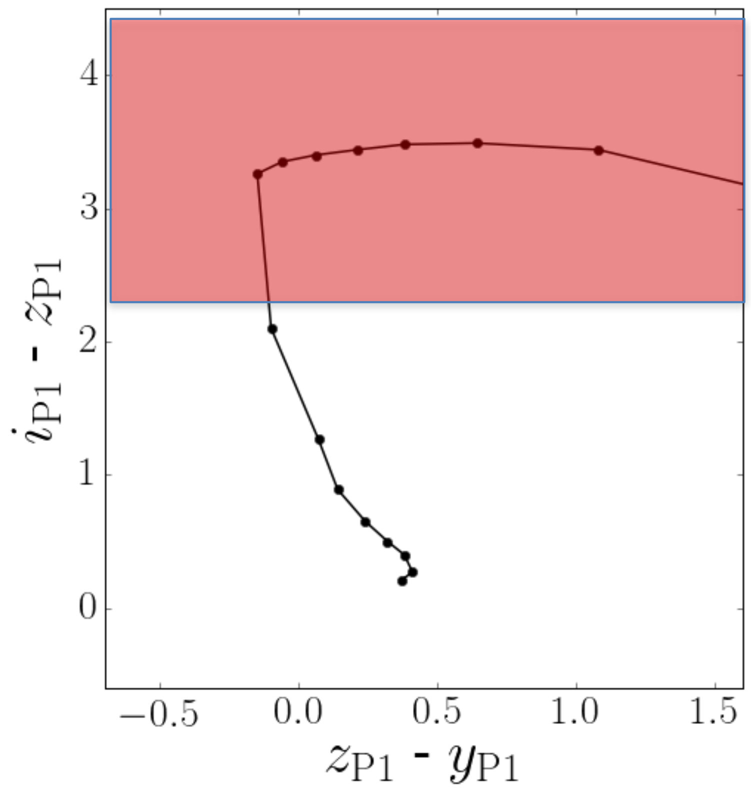


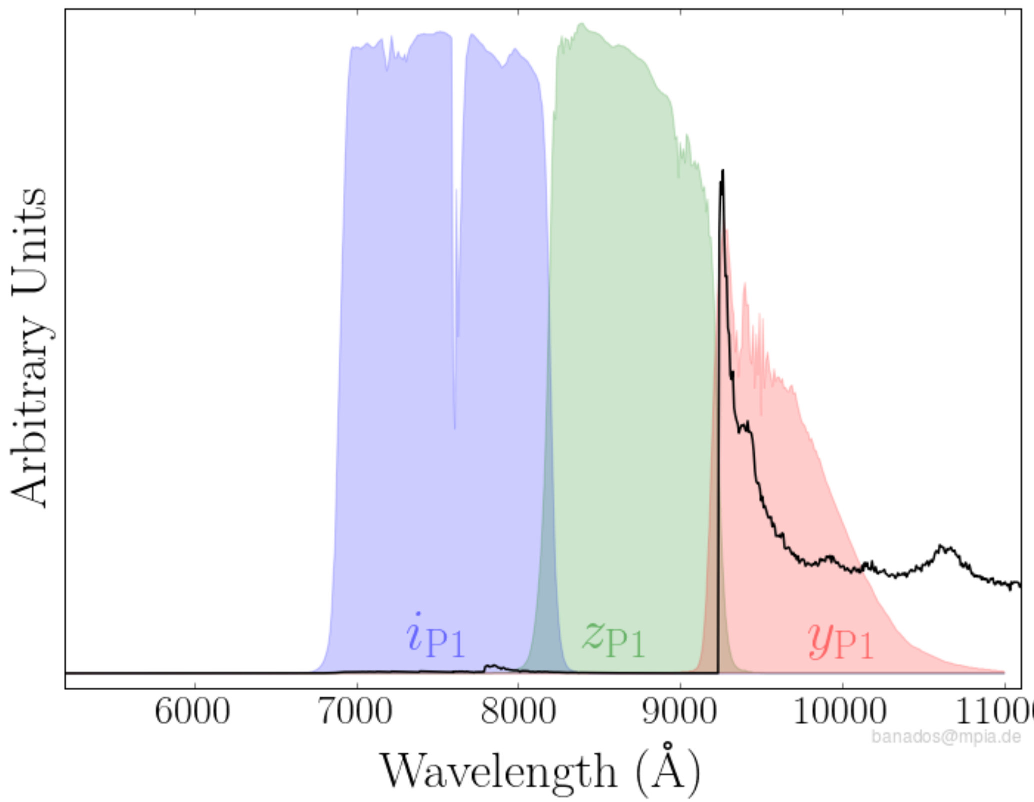


quasar selection

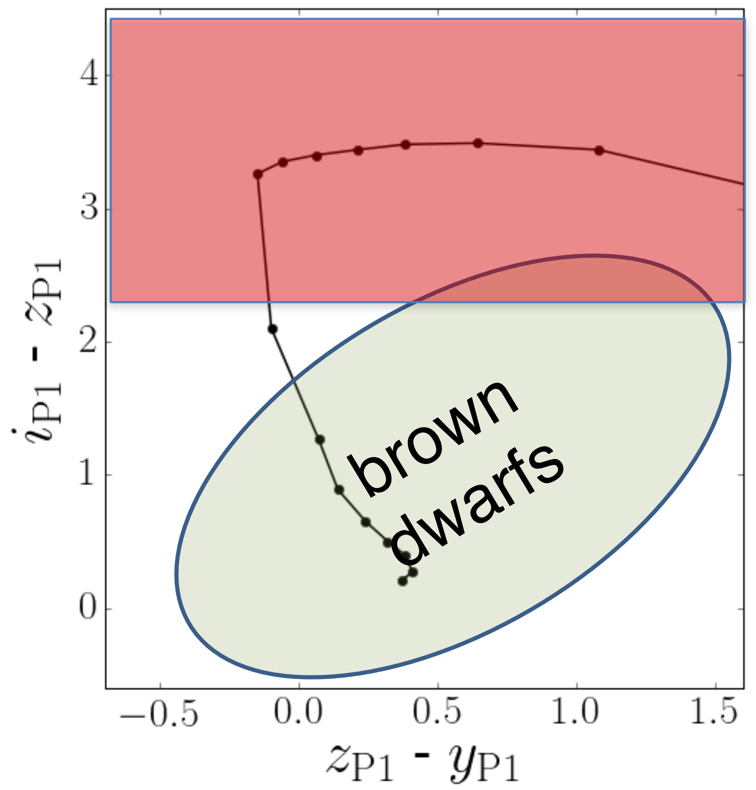


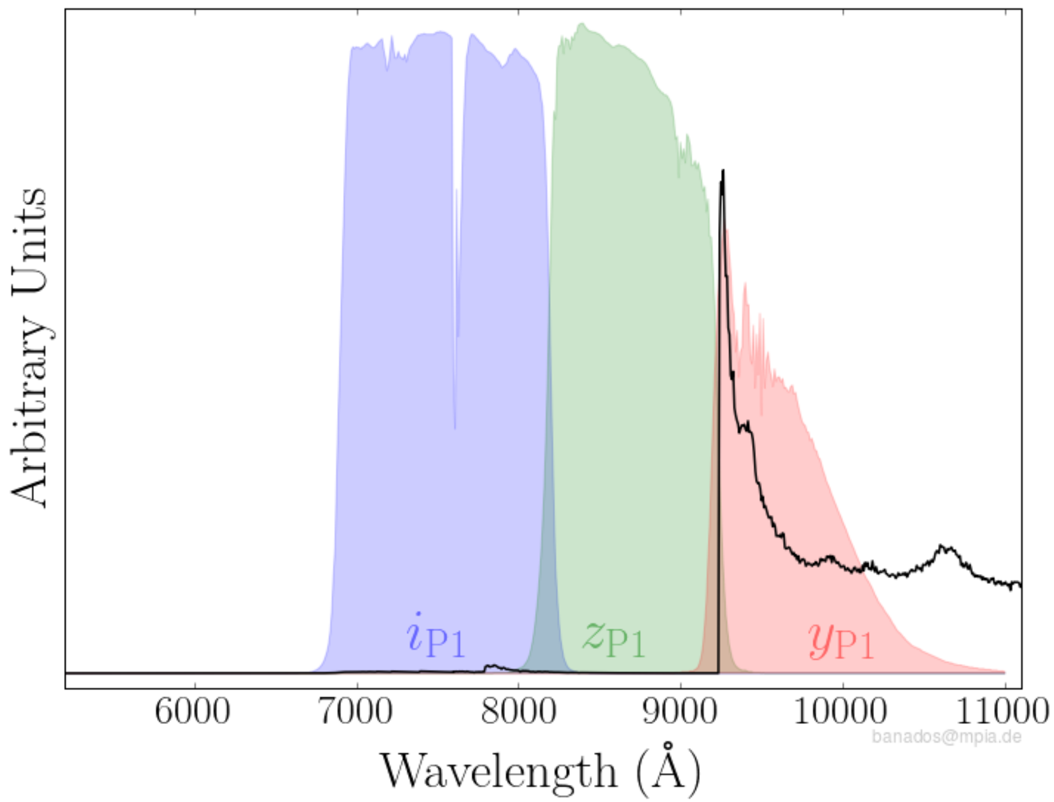
quasar selection



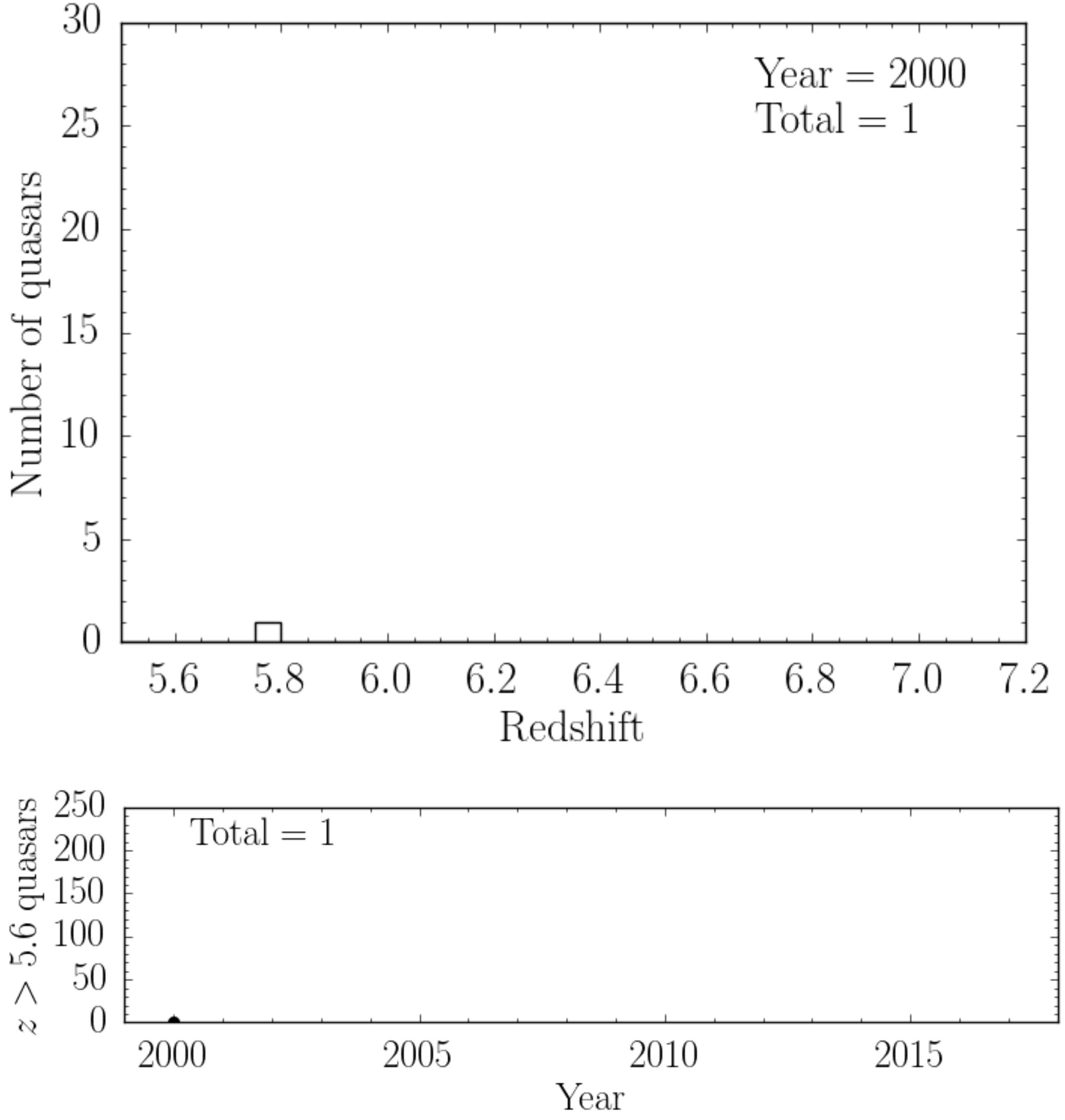


quasar selection





the search for distant quasars



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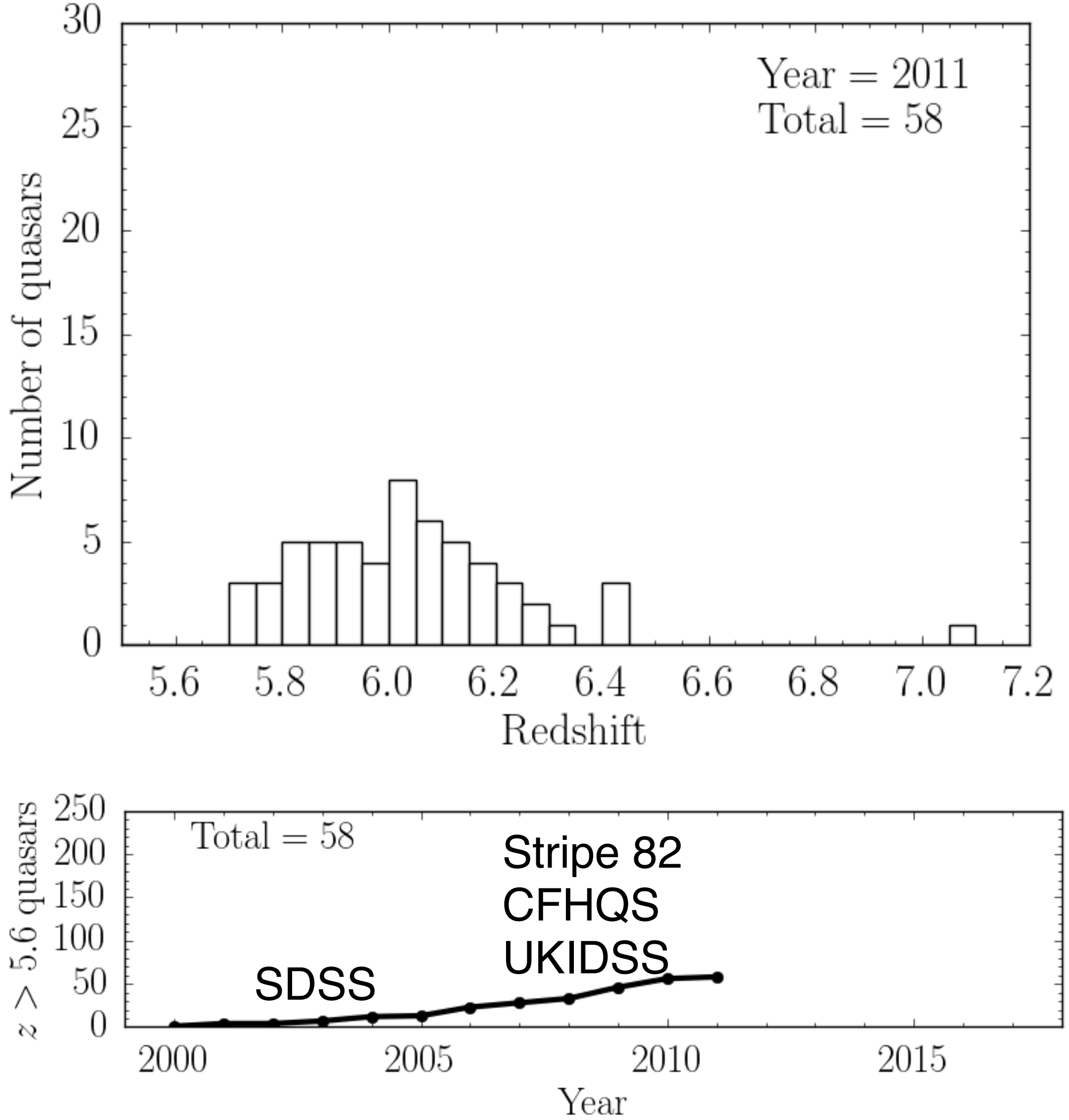
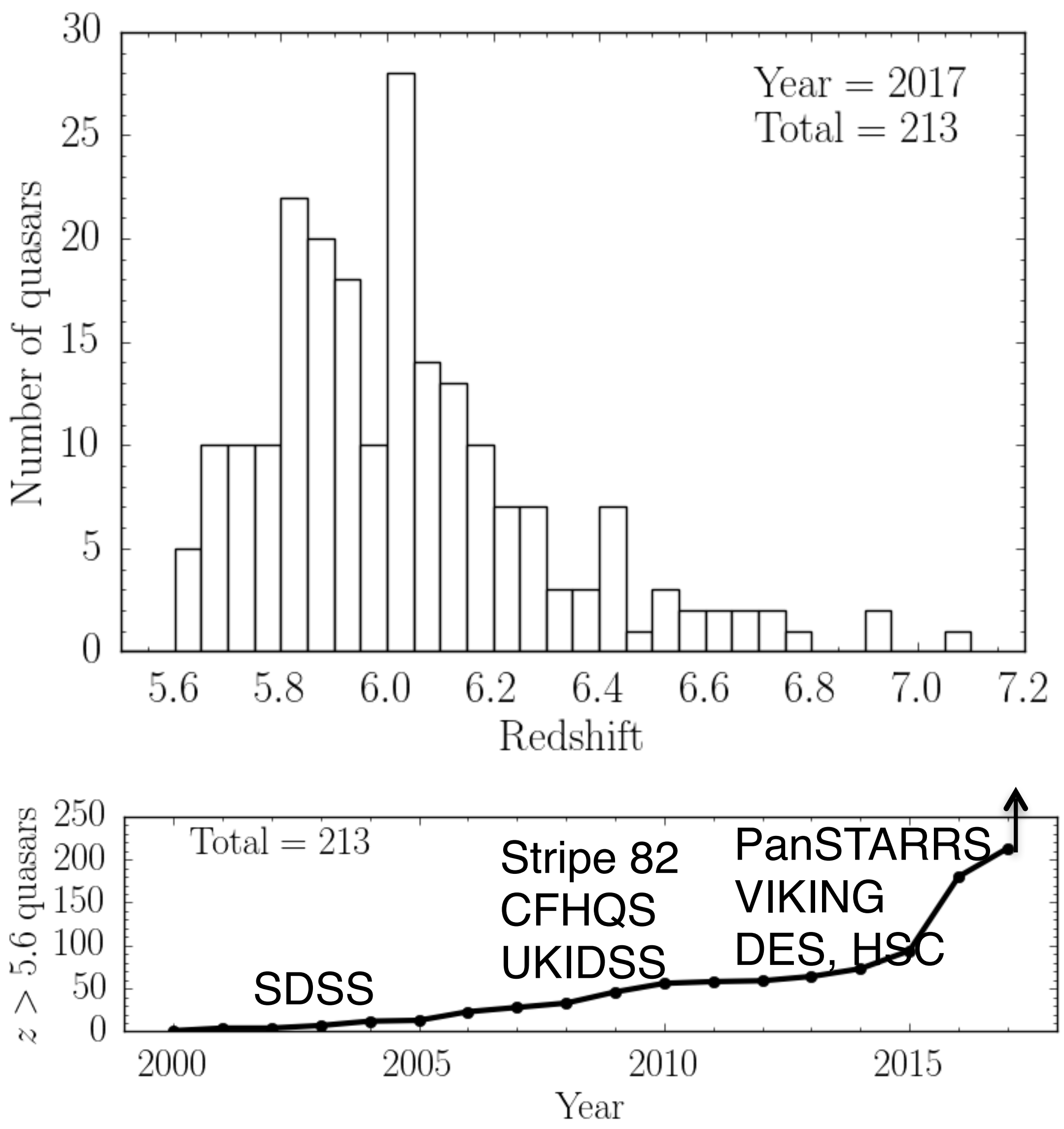
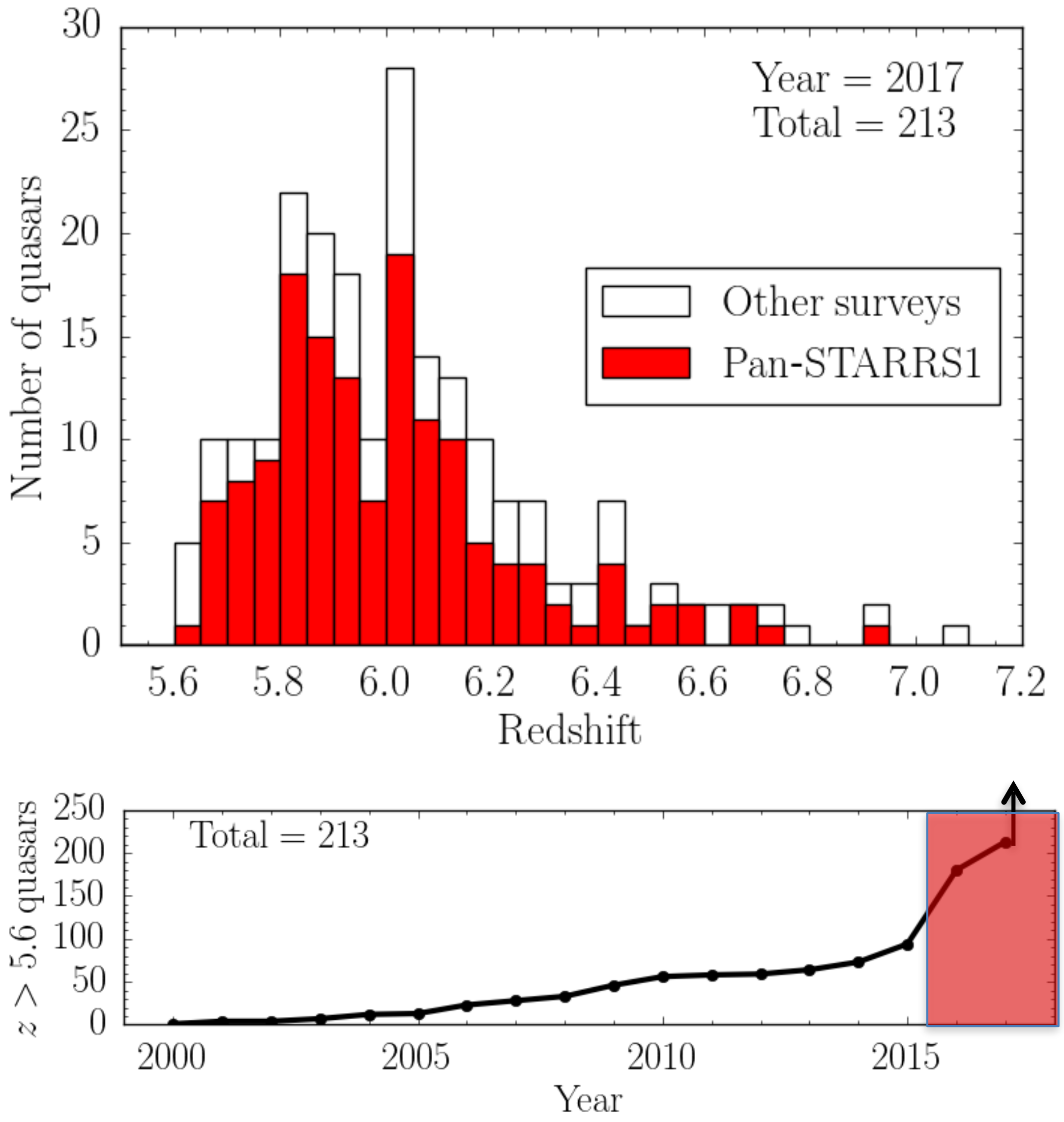


Fan+ 2000-2006
Jiang+ 2008-2009
Willott+ 2007-2010
Mortlock+ 2011

the search for distant quasars



the search for distant quasars

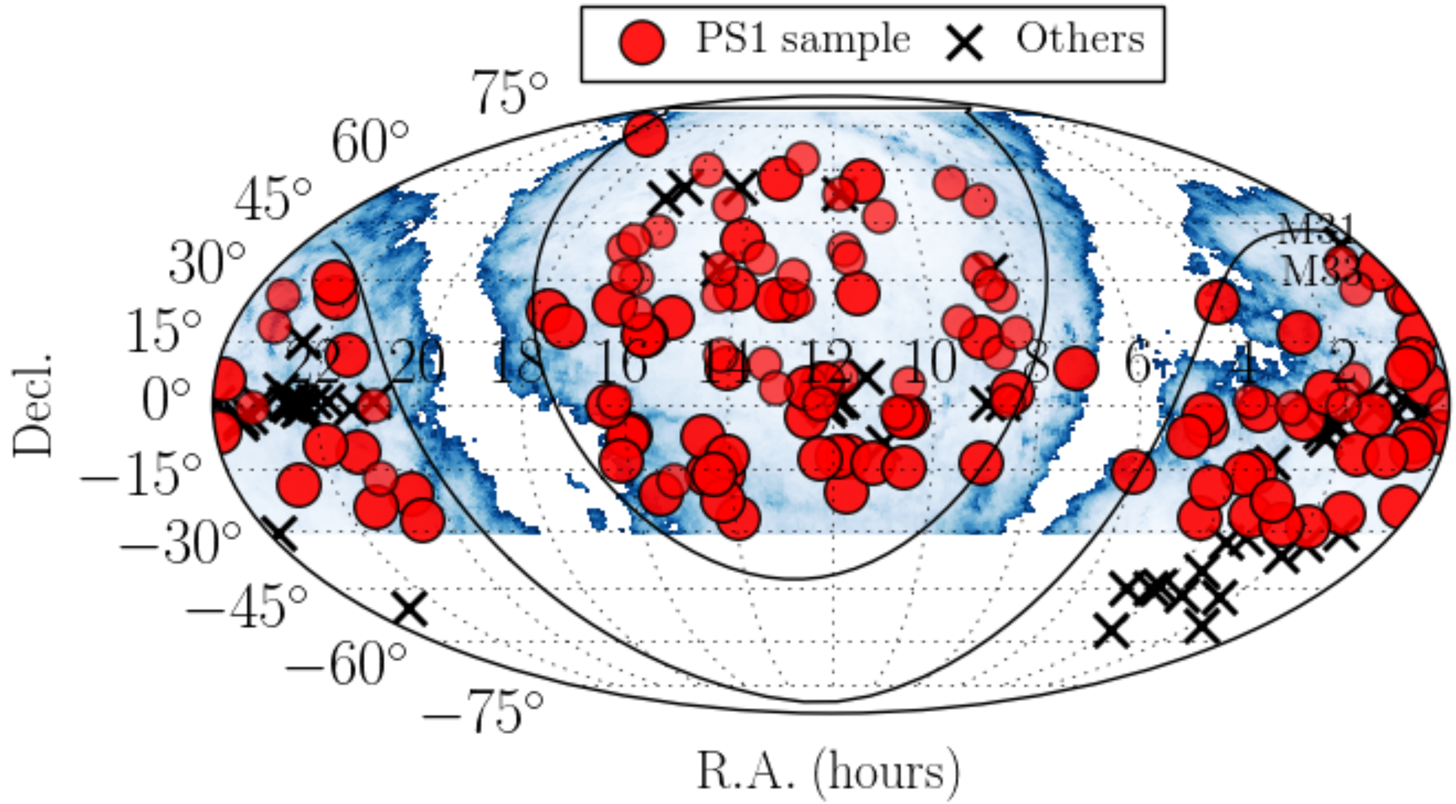


…more than tripled in the last 3 years!

Bañados+ 2014, 2016, 2016, 2017
Venemans+ 2015
Mazzucchelli+ 2017b
Jiang+ 2015, 2016
Reed+ 2015, 2017
Matsuoka+2016, 2017
…

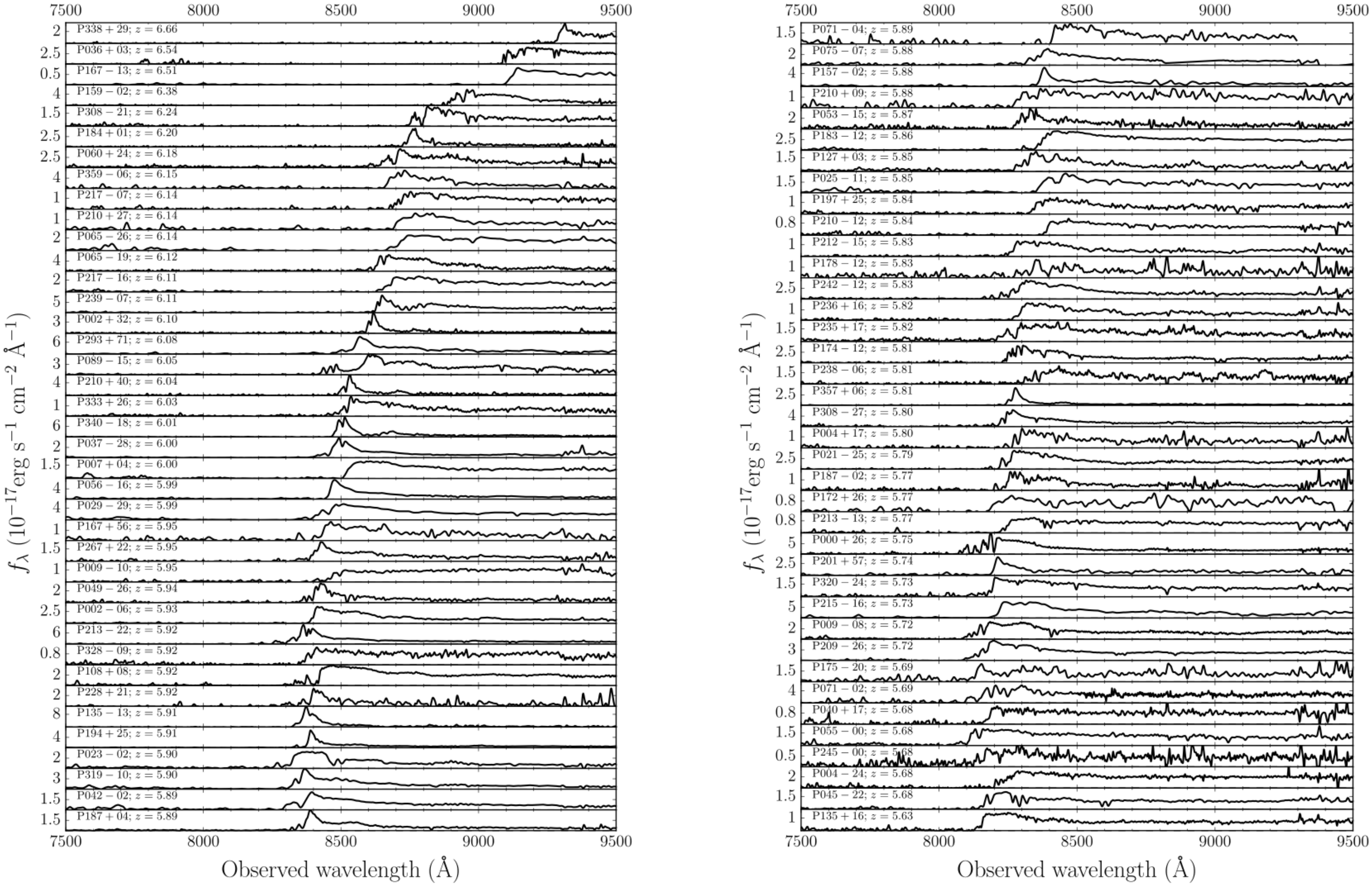
the Pan-STARRS1 z~6 quasar sample

200 z>5.6 quasars black hole masses: few 10^8 to few 10^9 M_{sun}



note: many sources visible from the south

the Pan-STARRS1 z~6 quasar sample



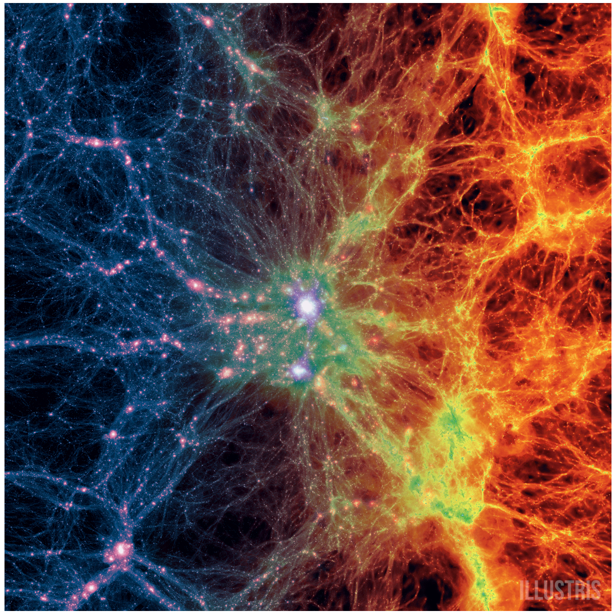
Bañados+ 2016

outline of this talk

- Characterize massive quasar host galaxies at z>6

- Environment of the first supermassive black holes at z>6

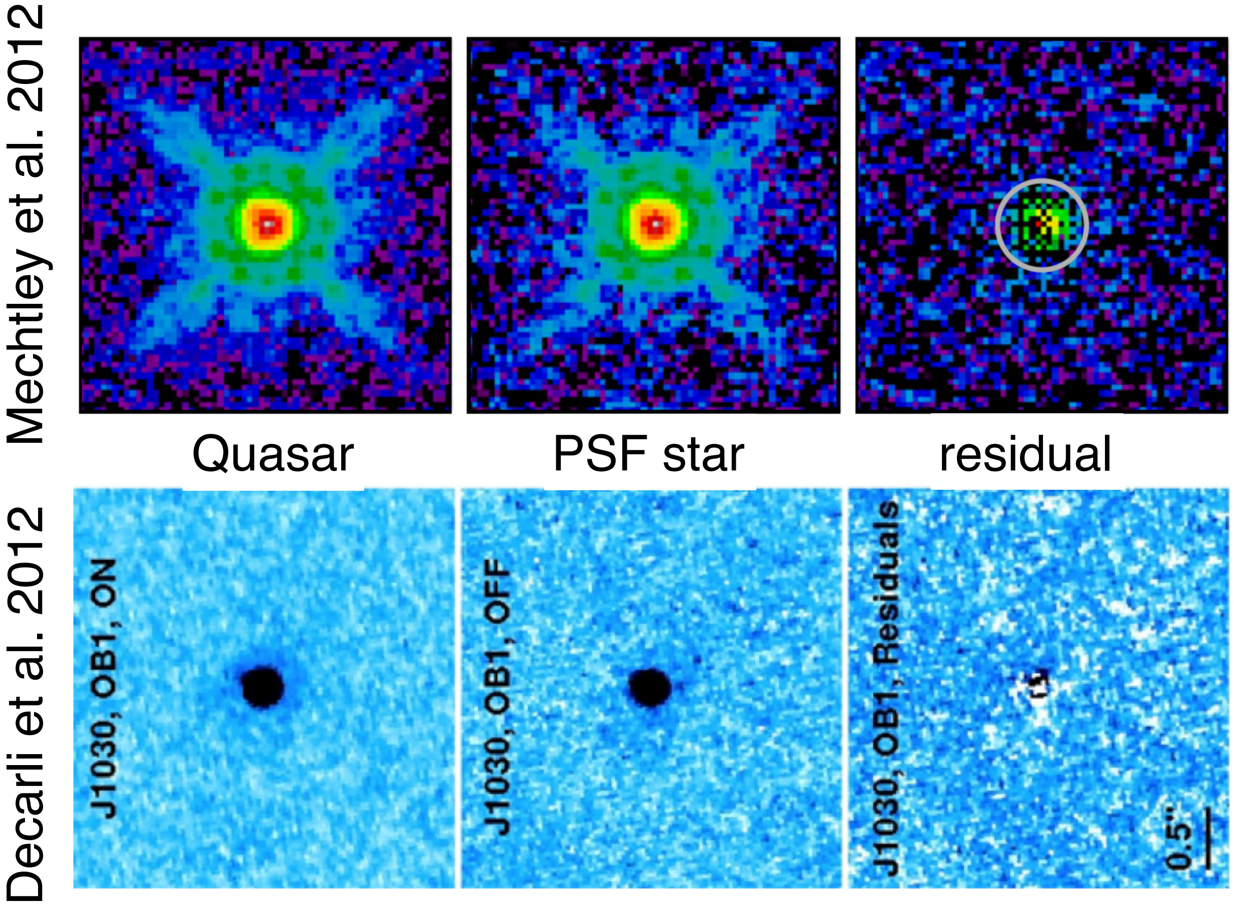
- State of the intergalactic medium at z>6



HST attempts to detect z>6 host galaxies

black hole masses: few 10^9 M_{sun}

—> stellar bulges of ~10^{12} M_{sun} ?

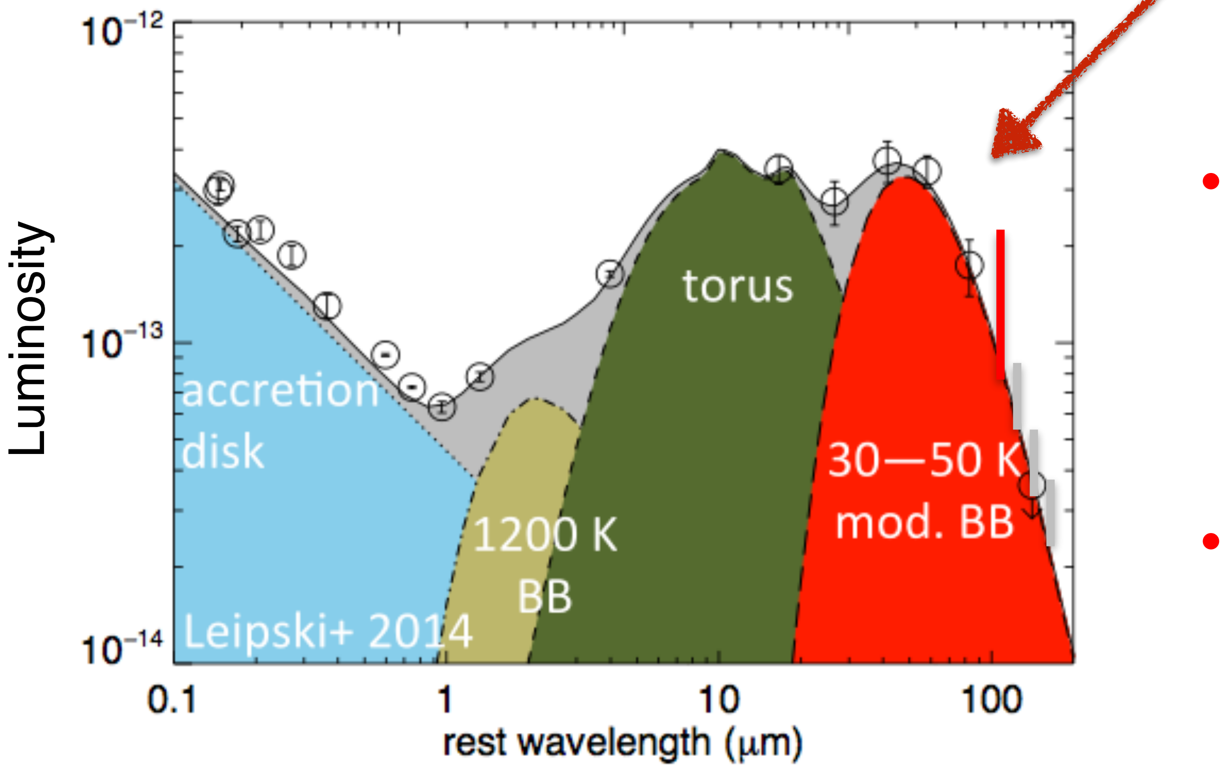


…hosts not detected in continuum or Ly-α

…JWST!

quasar host galaxies

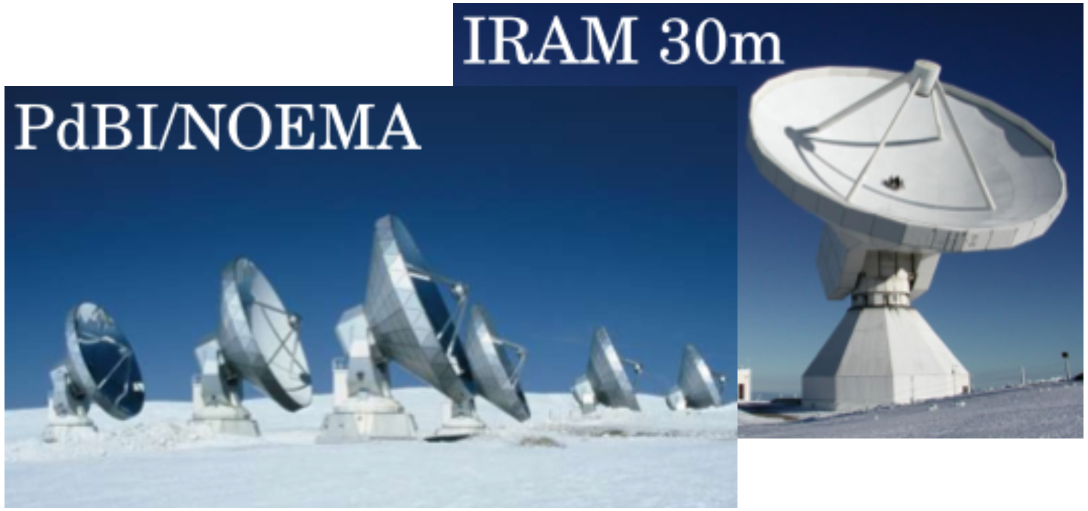
The host galaxies dominate at rest-frame FIR



- Dust continuum
  - Star-formation tracer
  - ISM mass
- [CII] 158 um line
  - Principal ISM coolant
  - Brightest FIR line
  - Star-formation tracer
- CO lines
  - ISM tracer
  - cold gas supply for SF

(sub-)millimeter observations

J1148+5251 (z=6.42) 100s of hours:

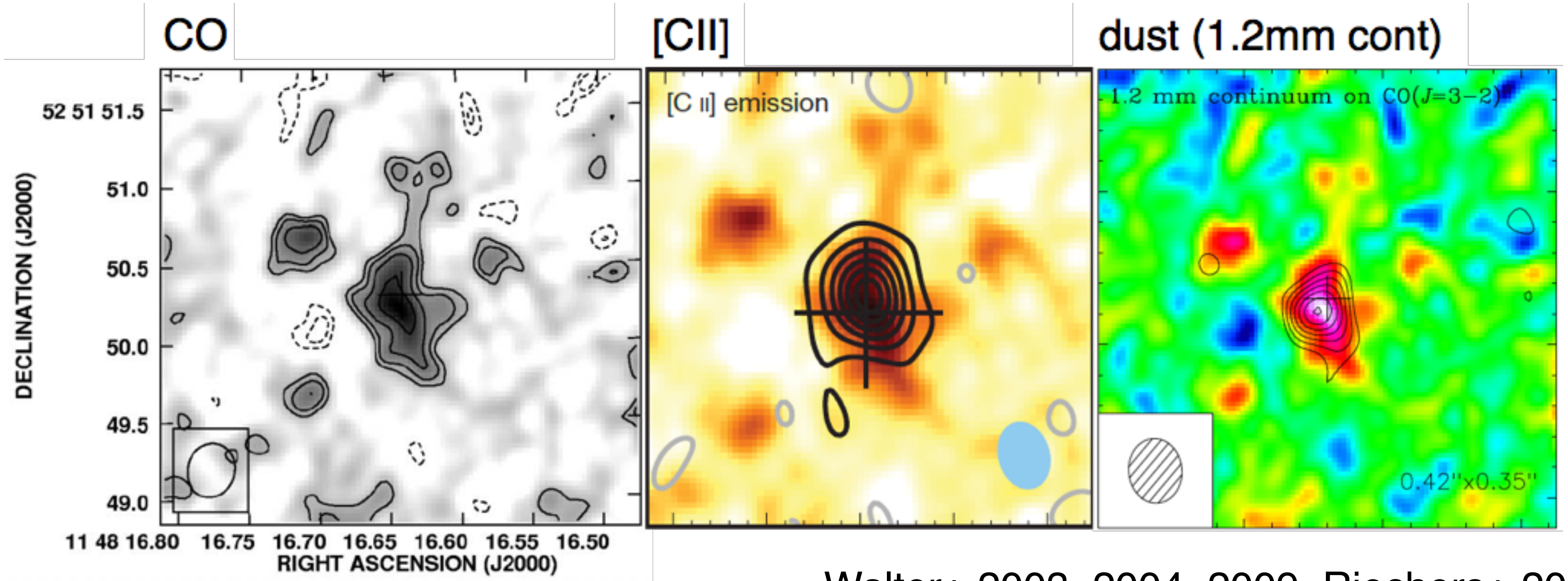


Size: 5 kpc (CO), 2 kpc ([CII]/dust)

$M_{H2} = 2 \times 10^{10}\ M_{SUN}$

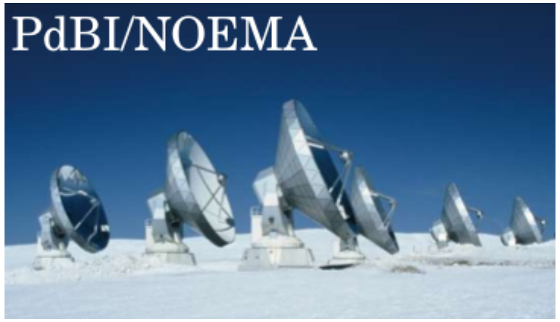
$M_{dyn} < 10^{11}\ M_{SUN}$

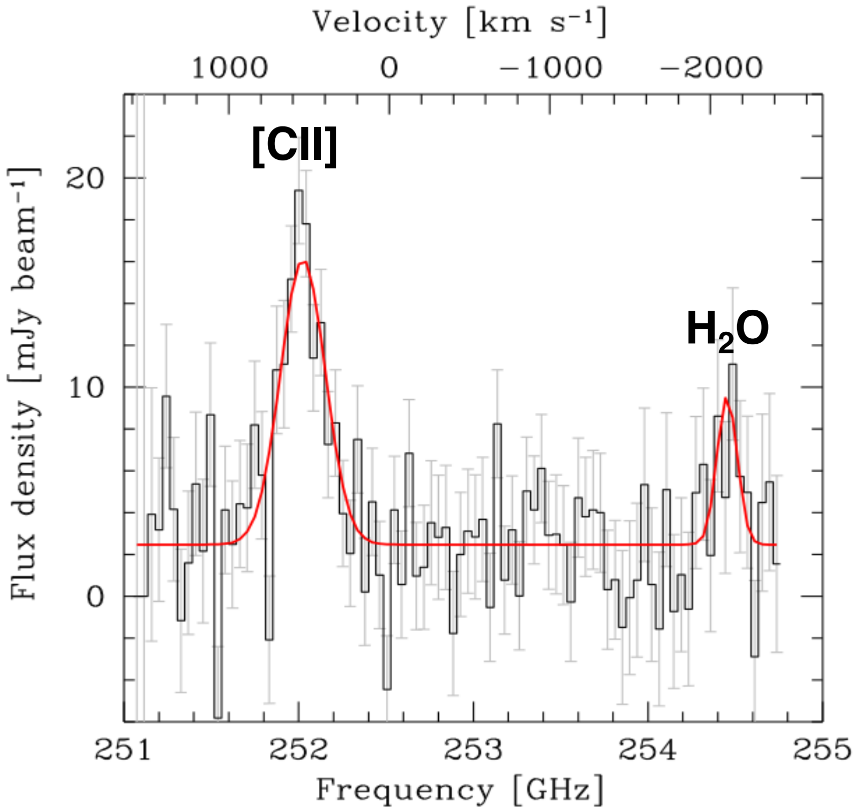
SFRSD=1000 $M_{sun}/yr/kpc^2$



Walter+ 2003, 2004, 2009, Riechers+ 2009

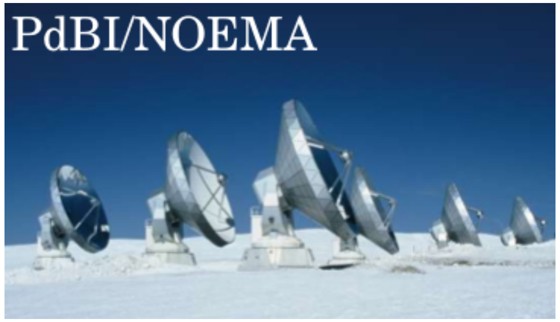
(sub-)millimeter observations

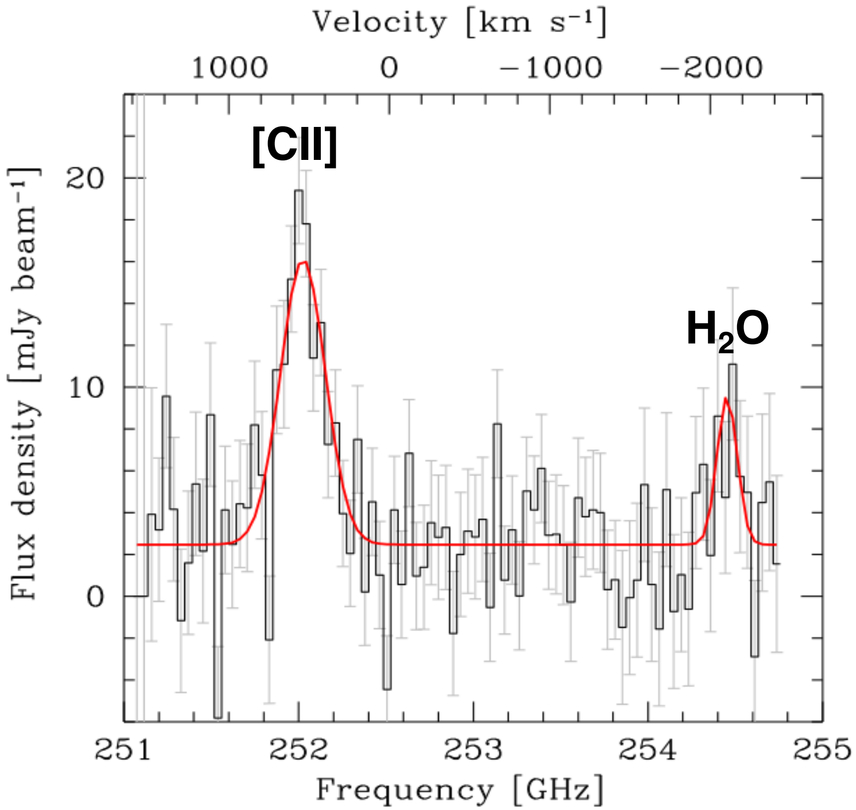




z=6.6 quasar (Banados et al. 2015)
only 3.5 hours with NOEMA!

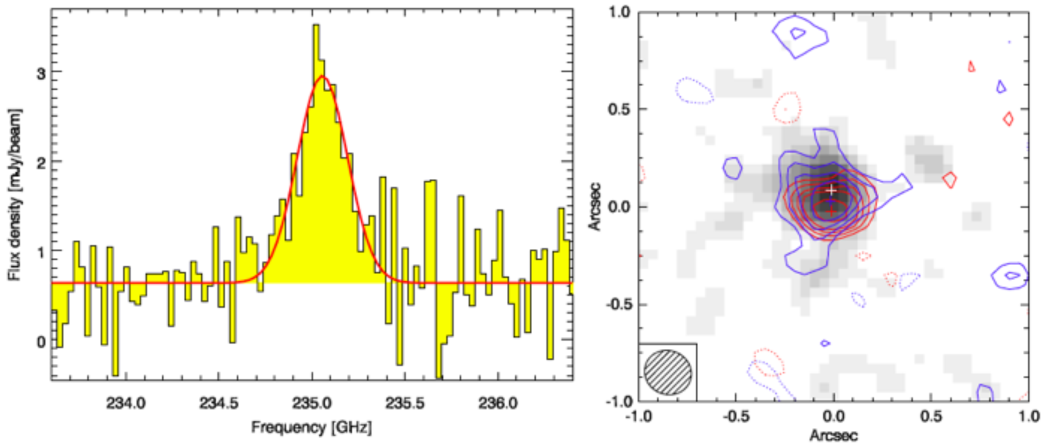
(sub-)millimeter observations





z=6.6 quasar (Banados et al. 2015)
only 3.5 hours with NOEMA!

z=7.08 quasar (Venemans+ 2017)



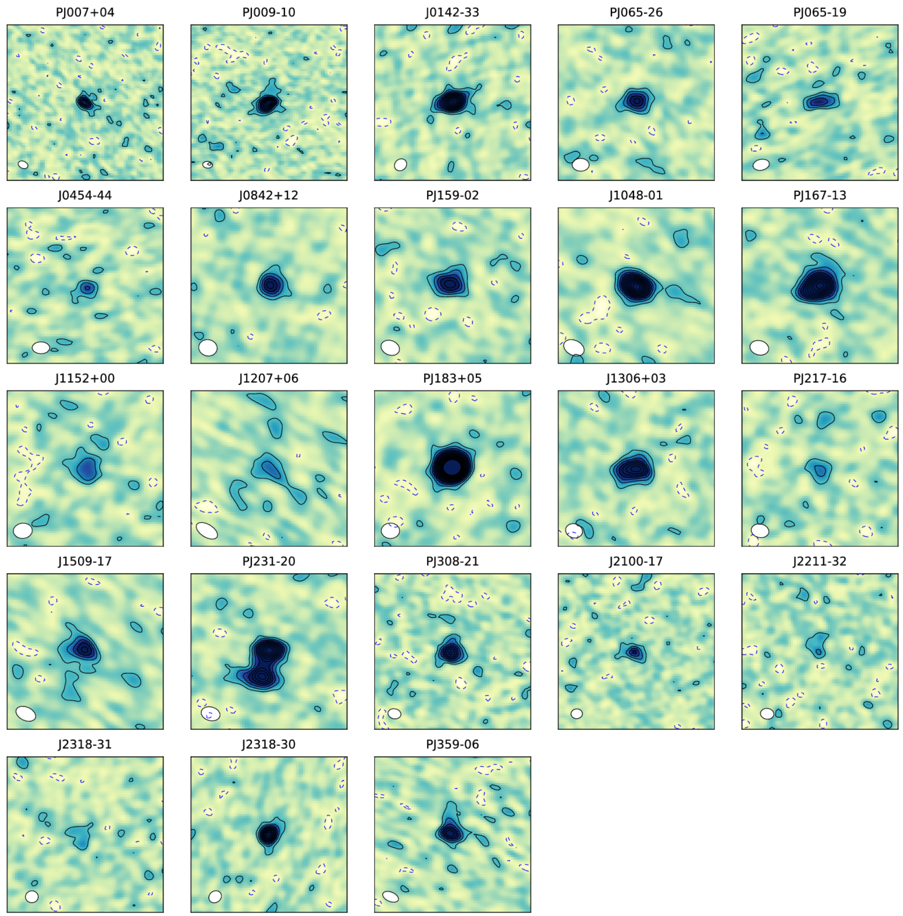
width: 400 km/s

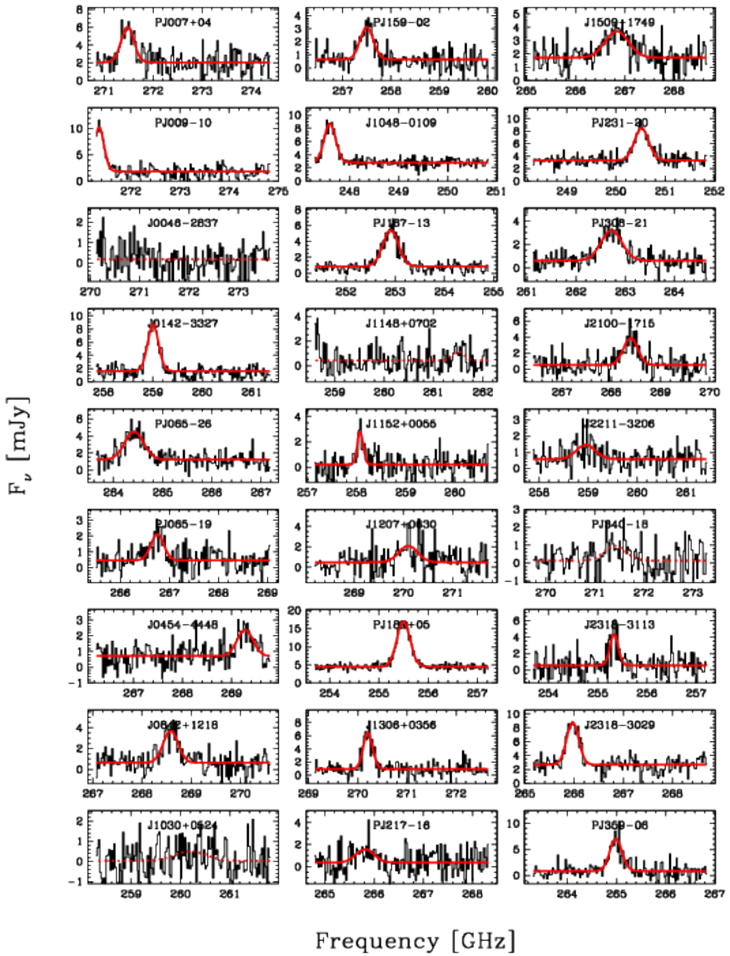
0.24 x 0.22"
(1.3 x 1.2 kpc)

- very compact emission
- no evidence for rotation

ALMA [CII]/FIR survey

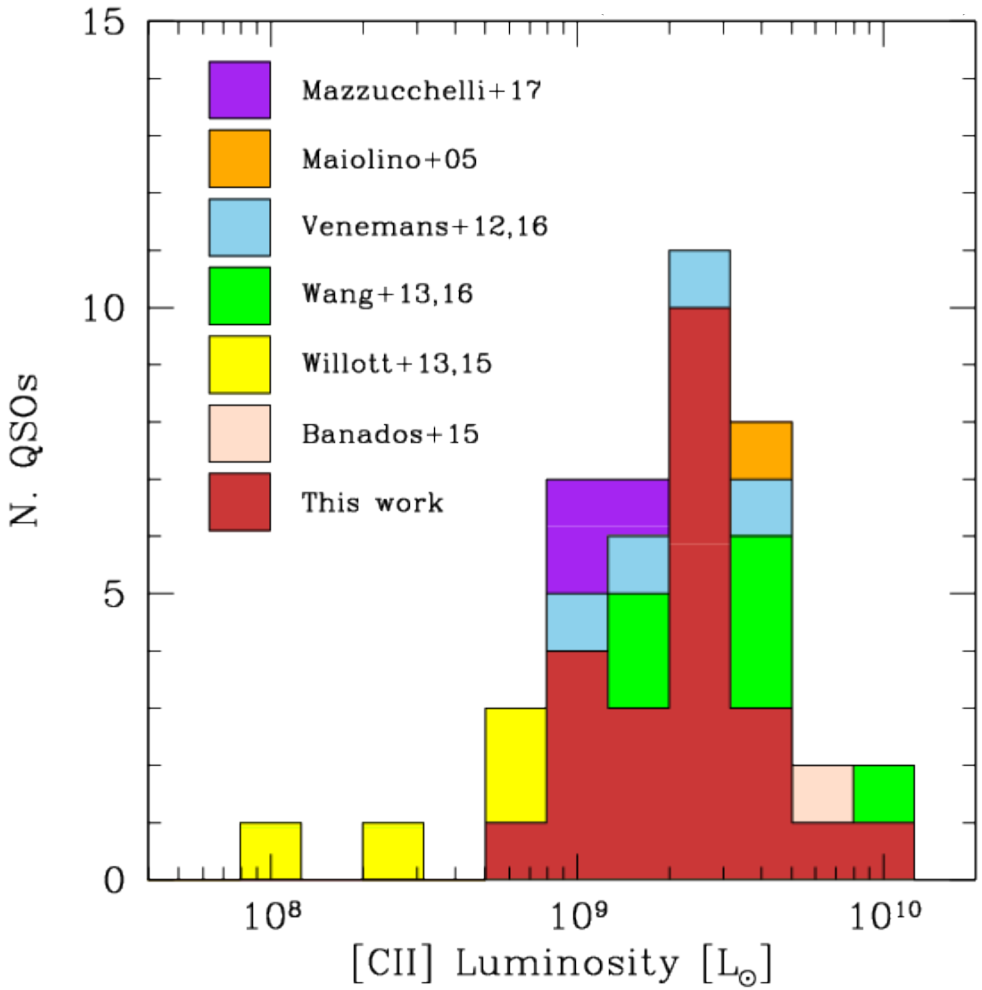
- 27 quasars at $6 < z < 7$
- 8 min on-source
- >100% [CII] + continuum detection!

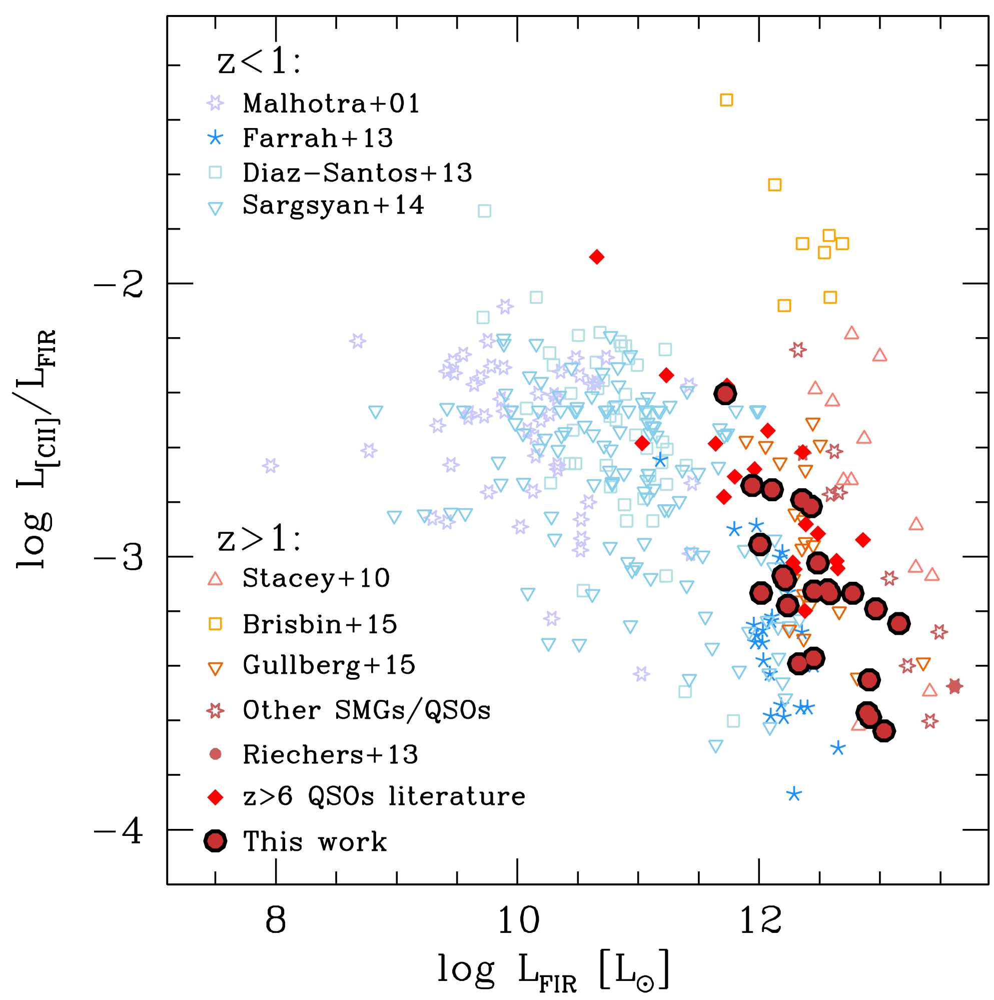




Decarli+ 2017b

ALMA [CII]/FIR survey

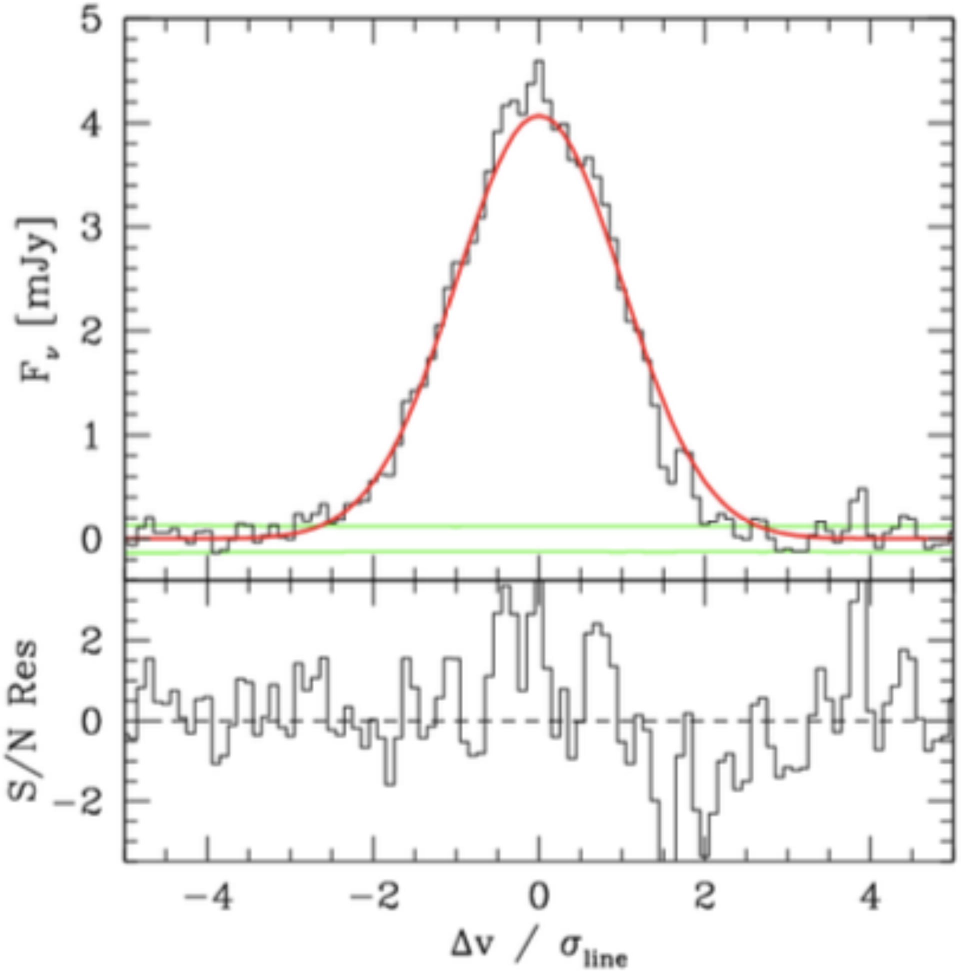




Decarli+ 2017b

ALMA [CII]/FIR survey

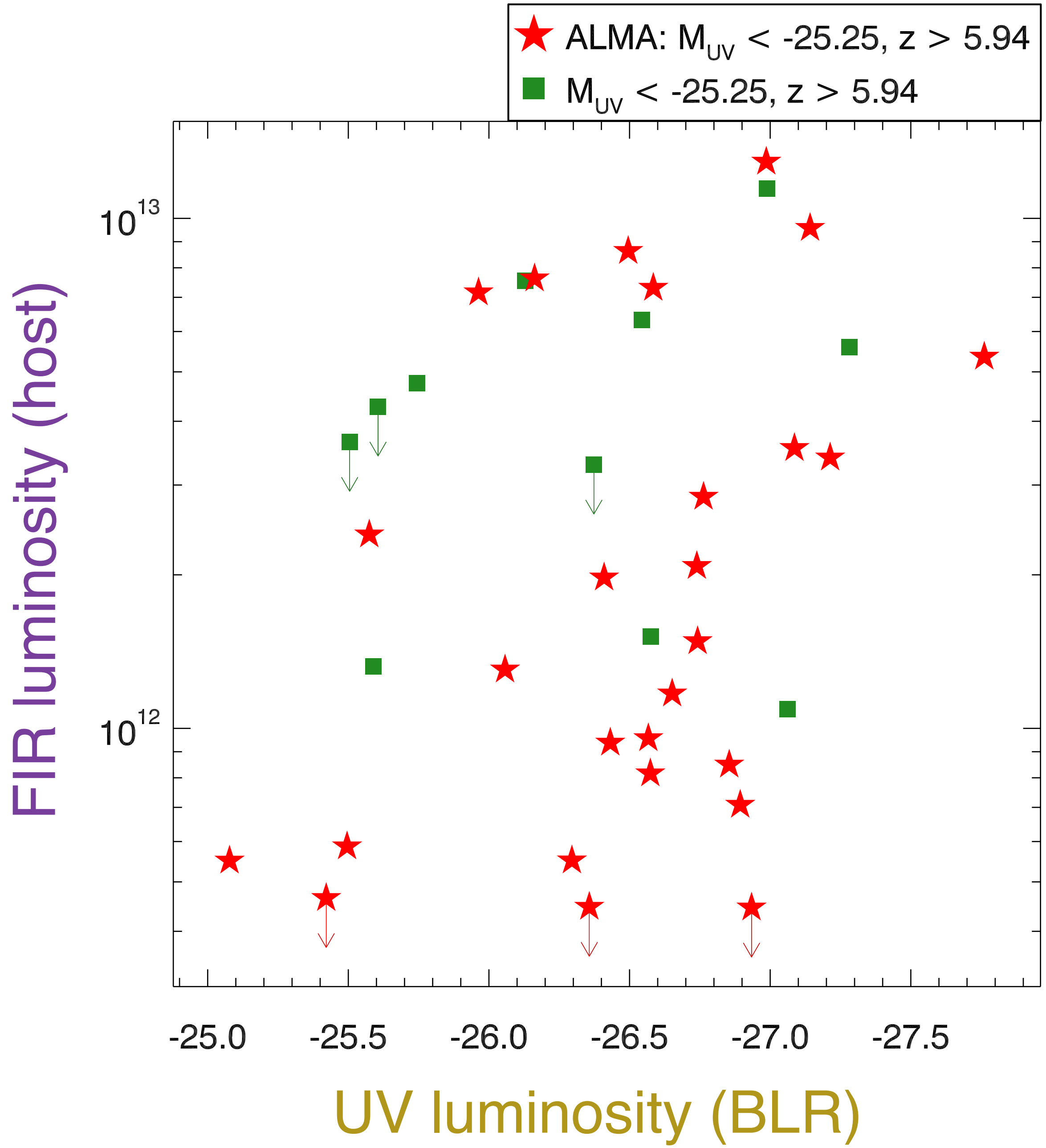
Stack of ~30 [CII] spectra of z>6 quasars



No evidence for outflows in stacked (and individual) [CII] spectra.

Decarli+ 2017b

ALMA [CII]/FIR survey



complete sample of z>6 quasars

FIR luminosity (host)

…do not appear to depend on…

UV luminosity (black hole accretion)

Venemans+ 2018 in prep

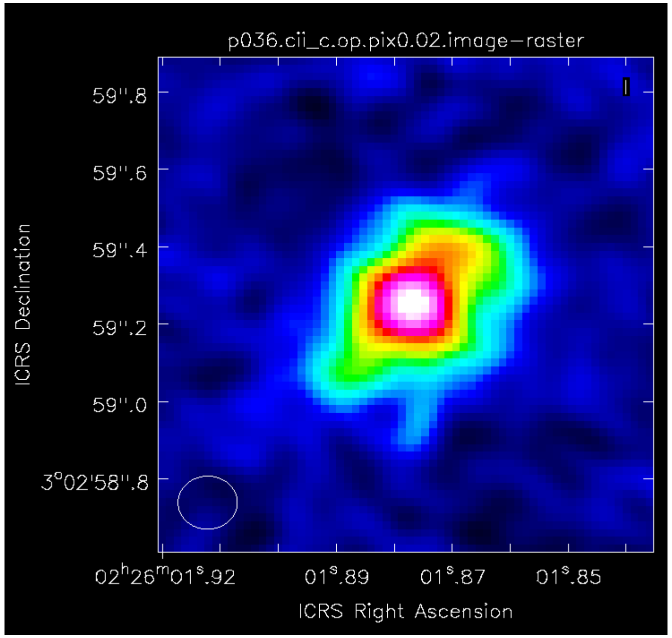
The ALMA revolution: resolution

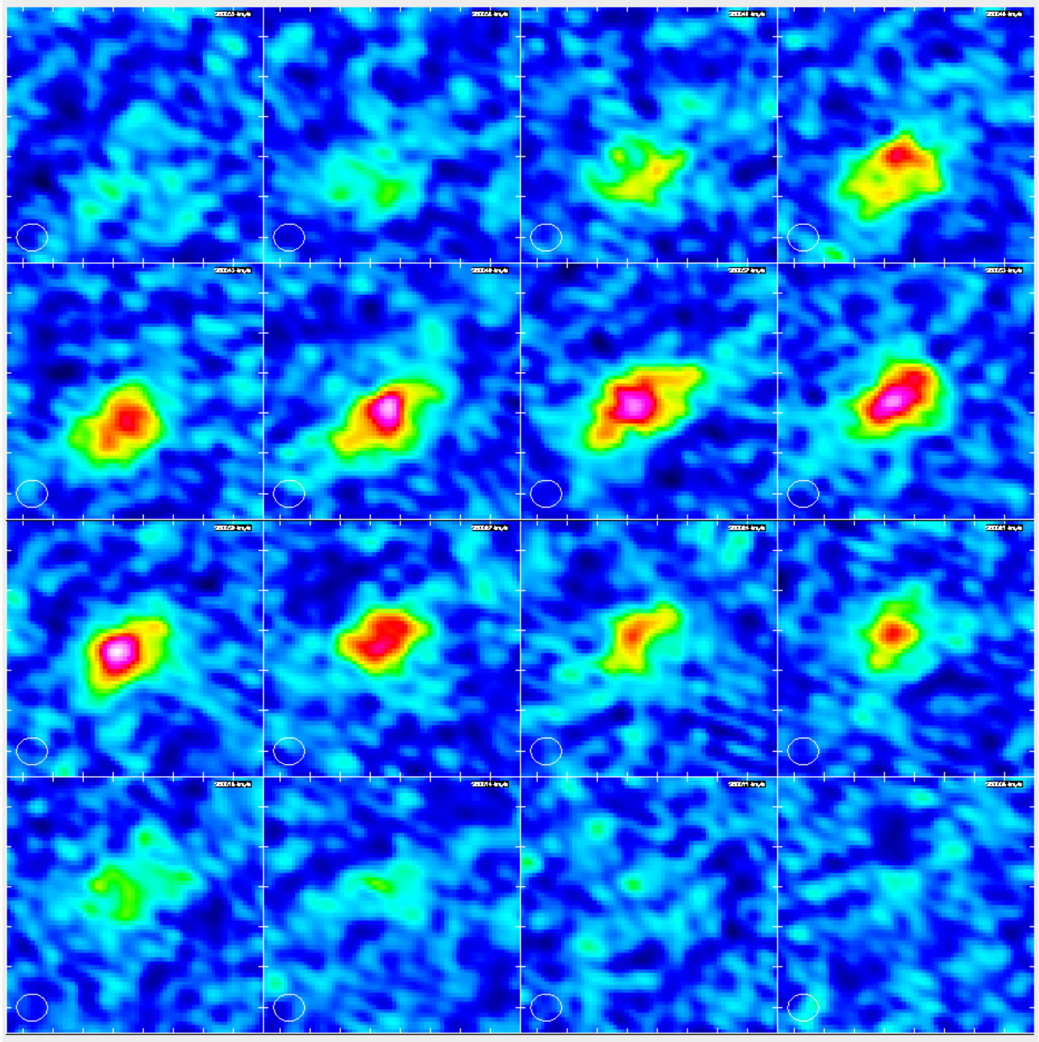
at z=6, 1” = 6kpc
—> sub-kpc resolution can be easily achieved with ALMA!

note: billion solar mass black hole:
ALMA can zoom in to the sphere of influence (few 100 pc)

spatially resolved quasar host kinematics

PJ036+03 at z=6.54 at ~1kpc res.



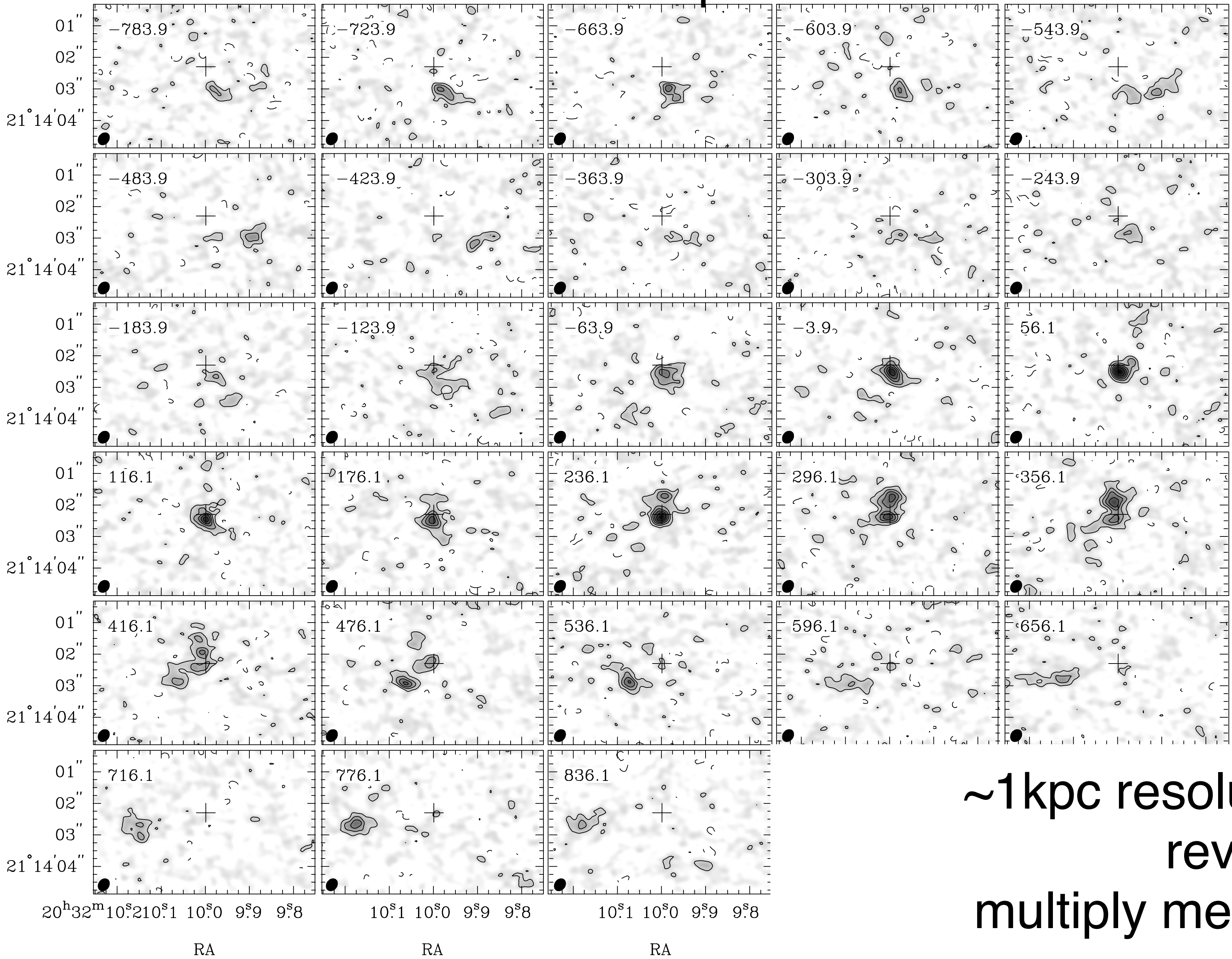


consistent with regular disk rotation

Venemans+ in prep

spatially resolved quasar host kinematics

PJ308-21 at z=6.25 at ~1kpc res.

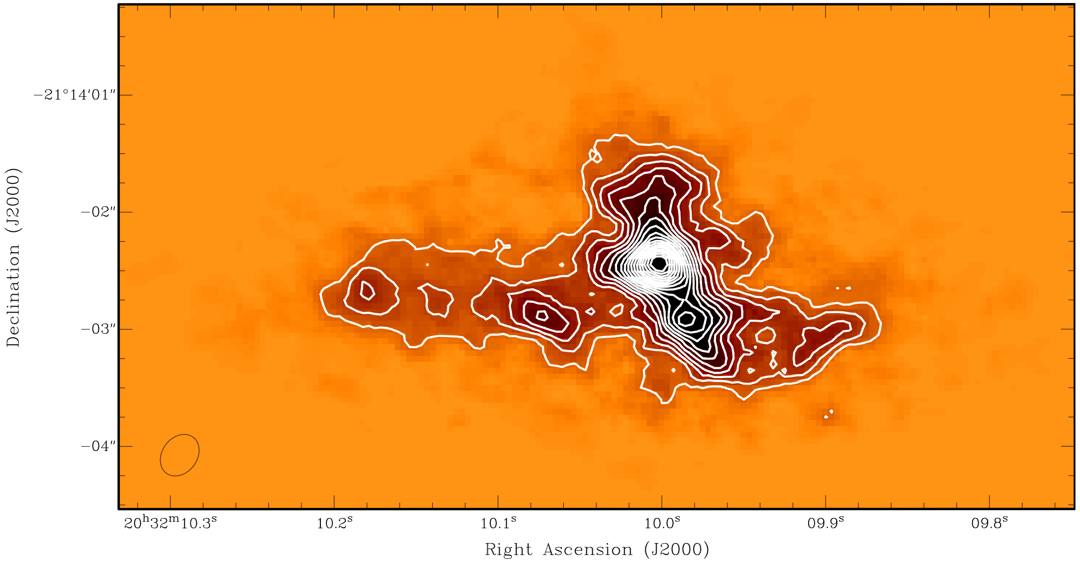


~1kpc resolution imaging
reveals
multiply merging system

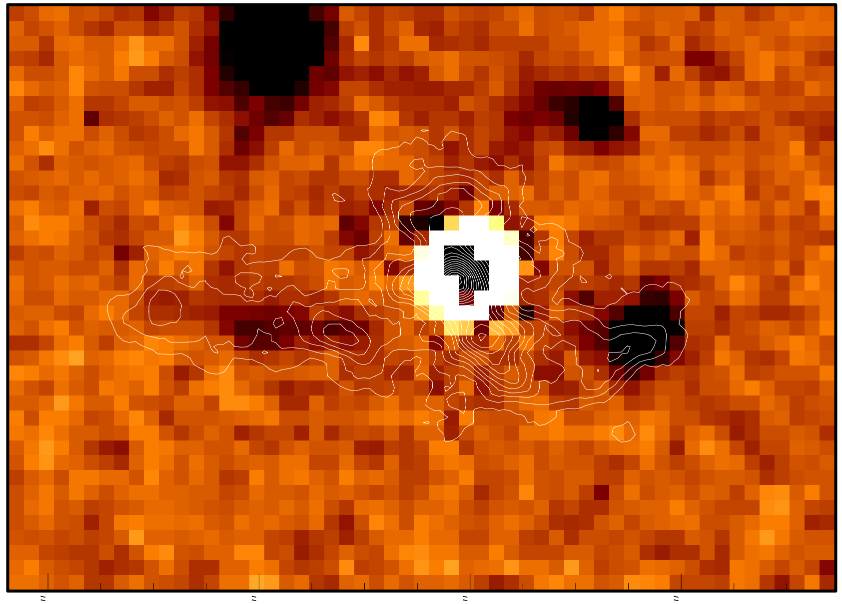
spatially resolved quasar host kinematics

PJ308-21 at z=6.25 at ~1kpc res.

ALMA [CII]



HST NIR (w/o quasar)



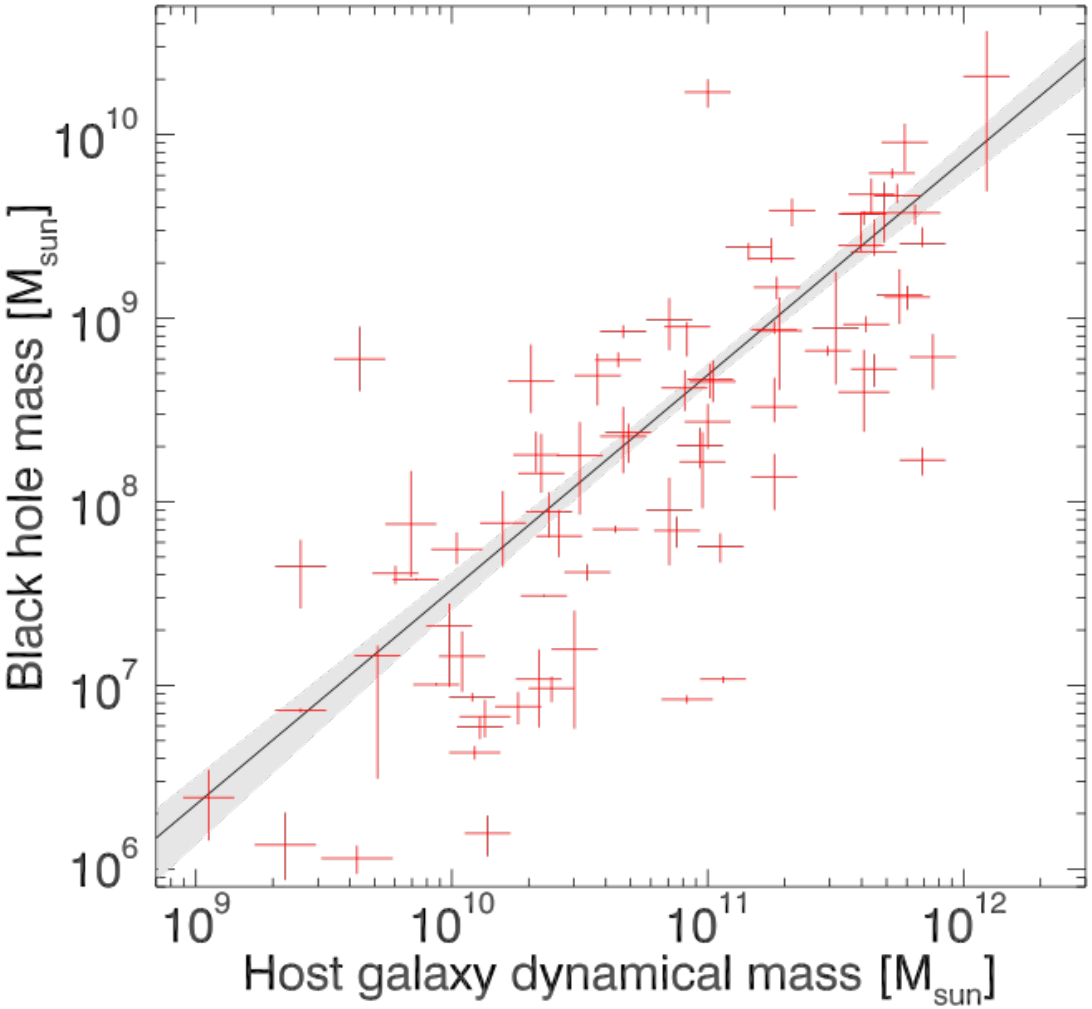
SFR in extended features
(from [CII], FIR, and rest-frame UV): 10 M_{sun} yr^{-1}

SFR in central region: >> 100 M_{sun} yr^{-1}

Decarli+ in prep

black hole - bulge mass relation at z>6

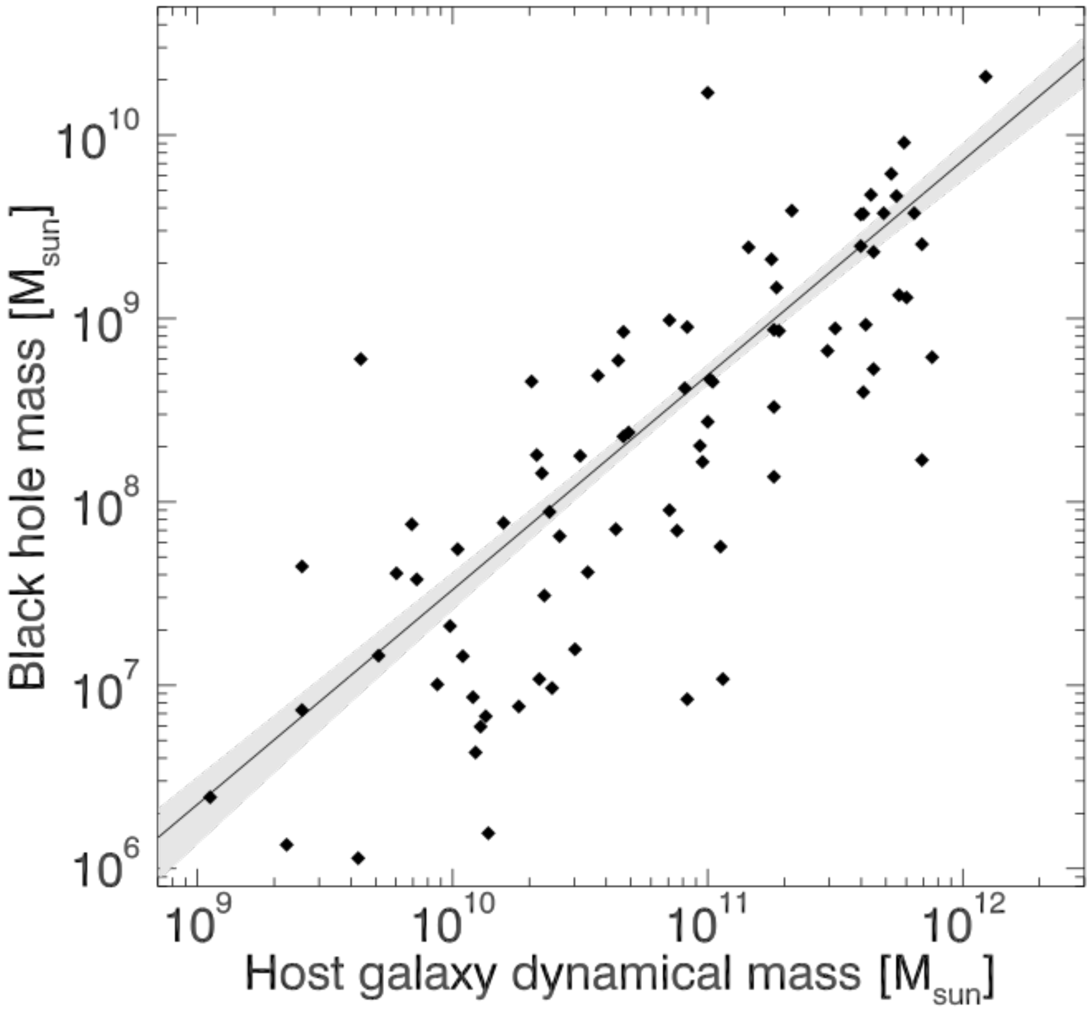
Local black hole–bulge mass relation



Kormendy & Ho 2013

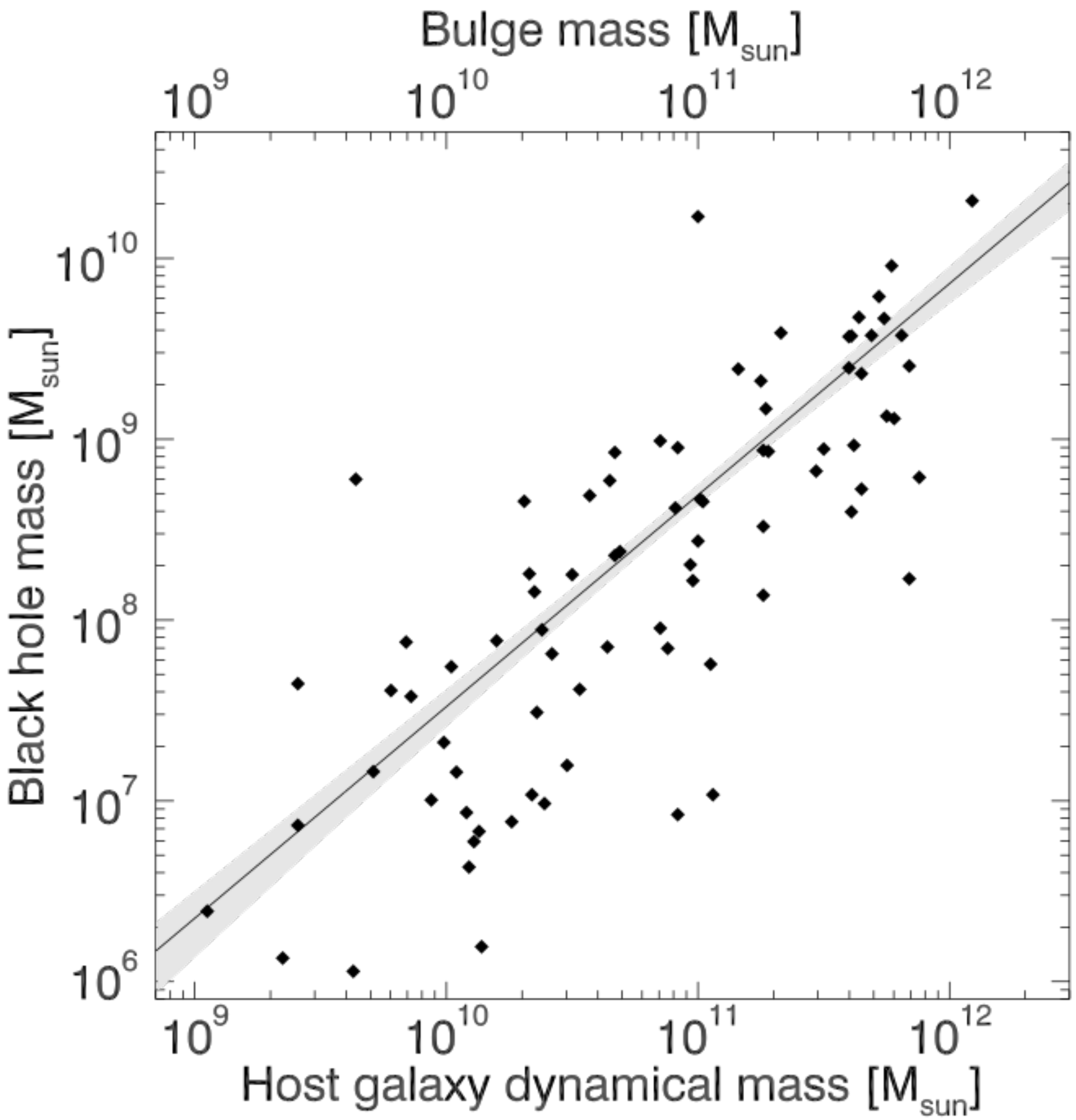
black hole - bulge mass relation at z>6

Local black hole–bulge mass relation



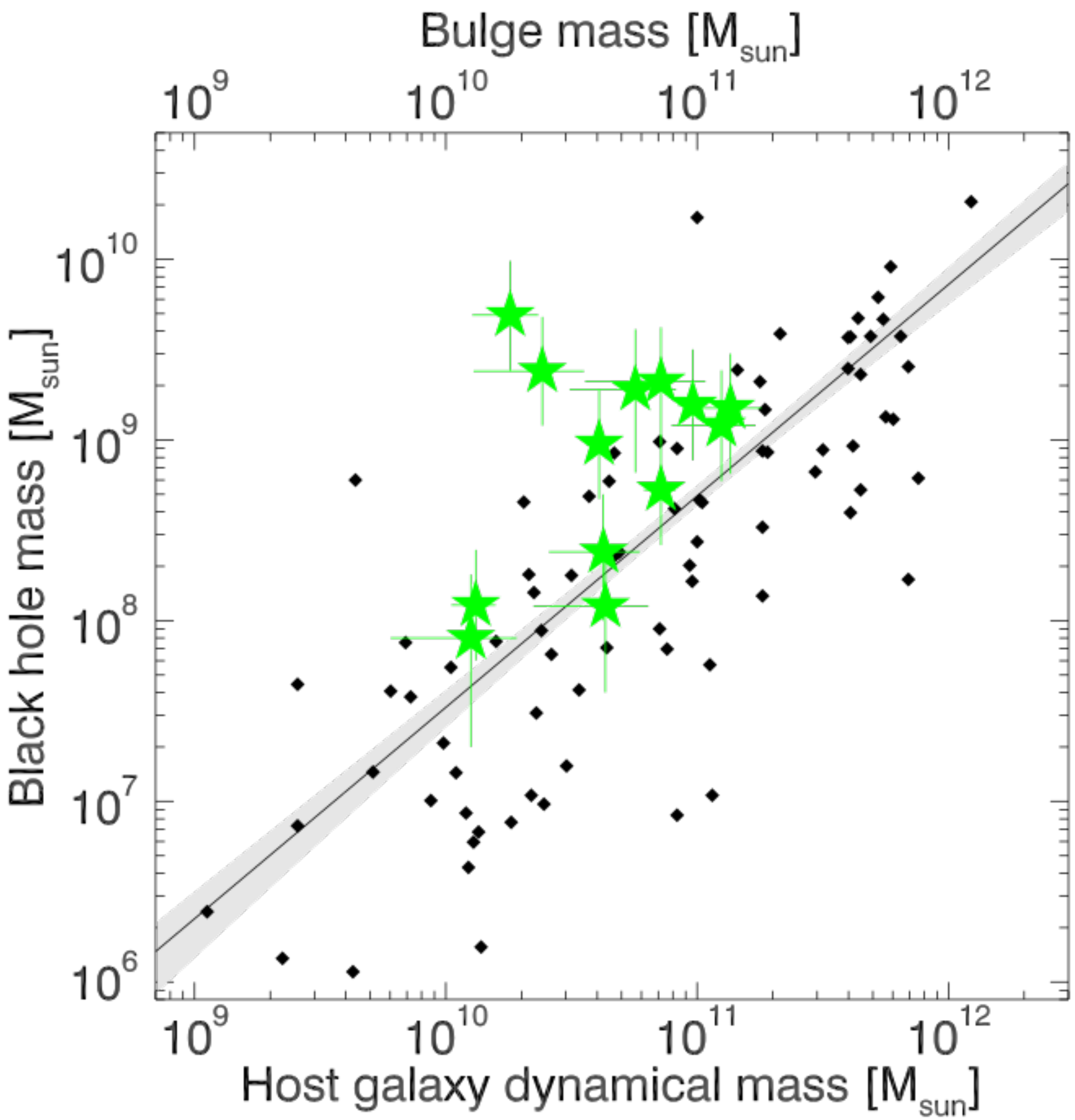
Kormendy & Ho 2013

black hole - bulge mass relation at z>6



Kormendy & Ho 2013

black hole - bulge mass relation at z>6



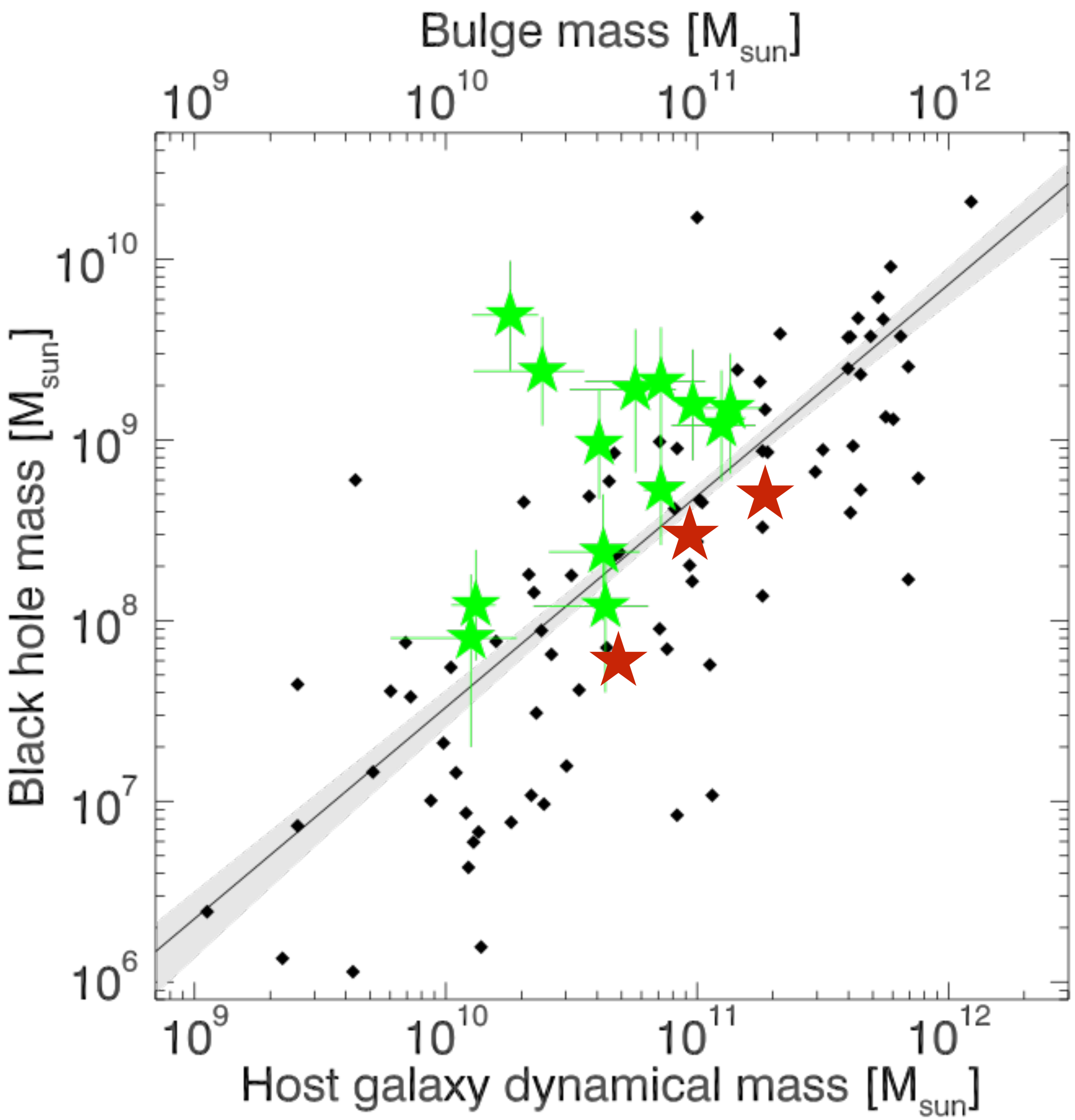
z > 6.5 quasar hosts (Venemans et al. 2016)

+ z~6 quasar host galaxies from literature

Black holes too massive?

Venemans+ 2016

black hole - bulge mass relation at z>6



z > 6.5 quasar hosts (Venemans et al. 2016)

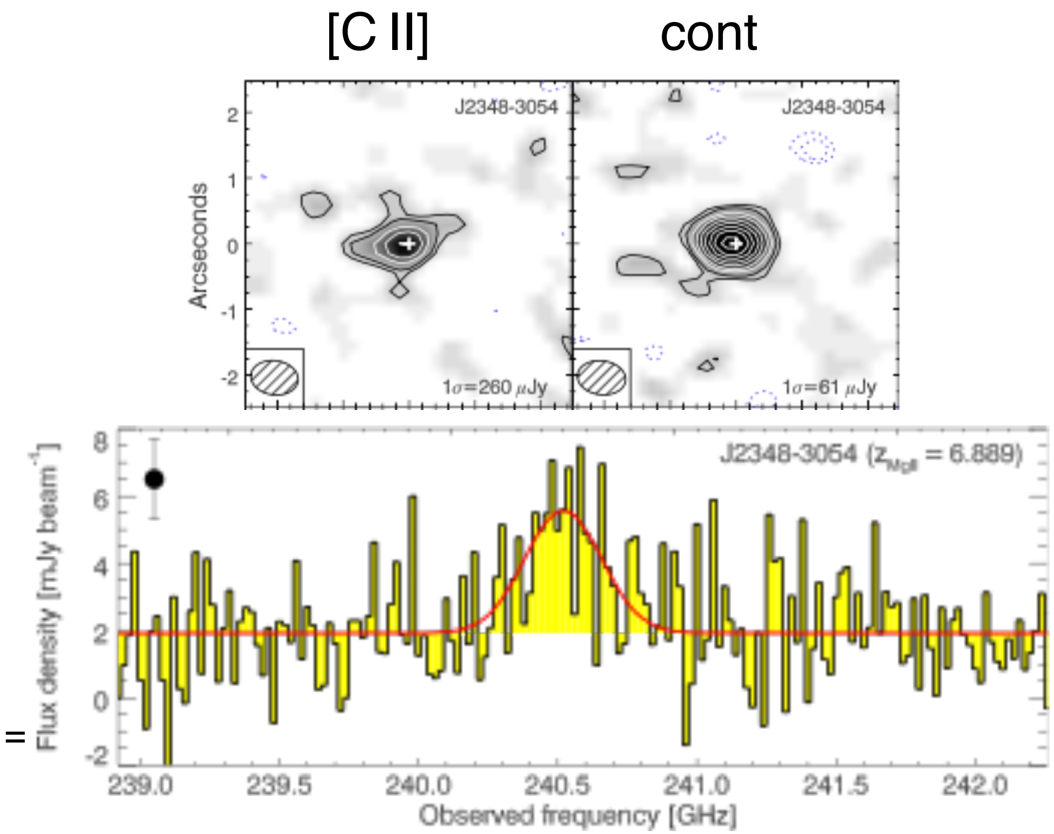
+ z~6 quasar host galaxies from literature

★ Willot et al. 2017

Venemans+ 2016

multi-line ISM diagnostics at z=6.9

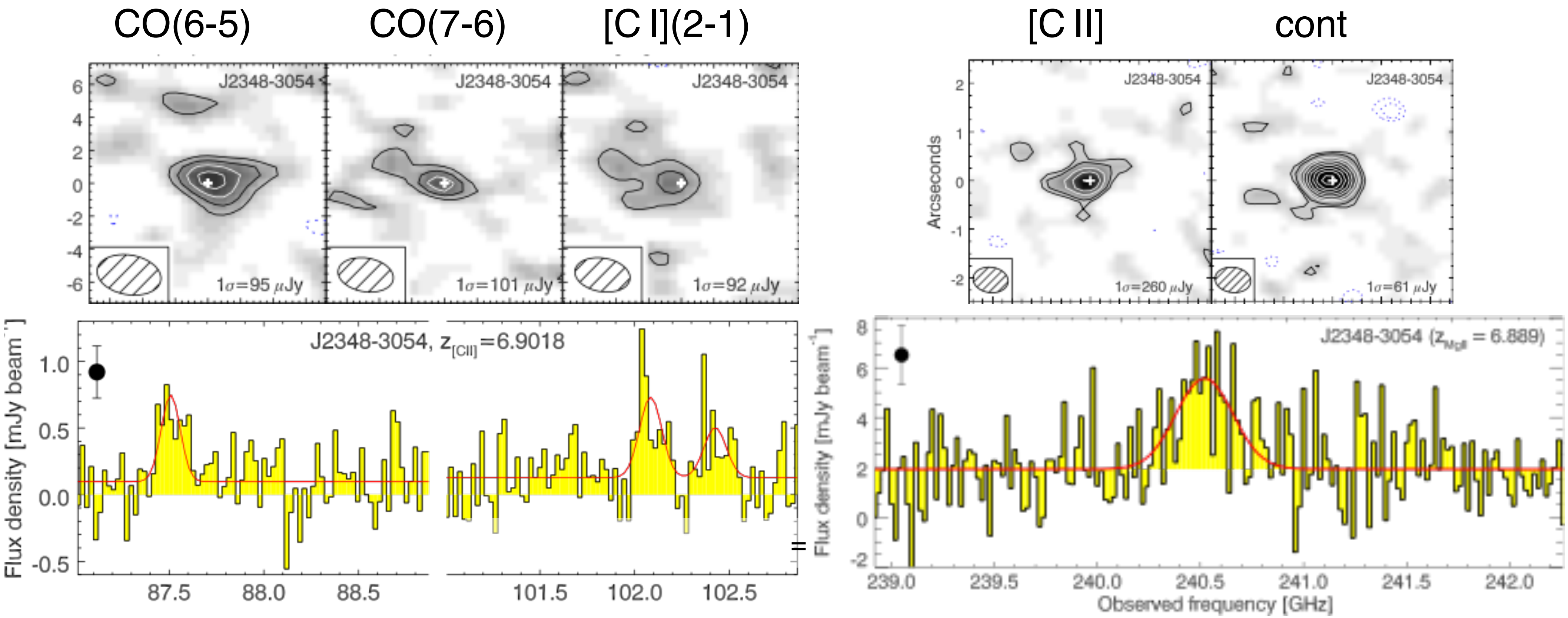
J2348–3054 at z=6.9



Venemans et al. 2017

multi-line ISM diagnostics at z=6.9

J2348–3054 at z=6.9

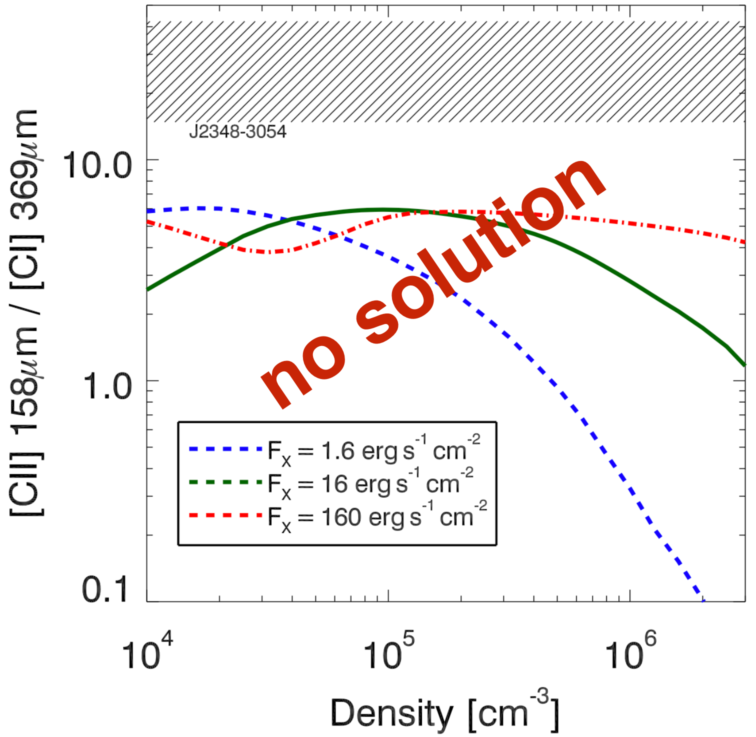


Line ratio [C II]/[C I] ≈ 20

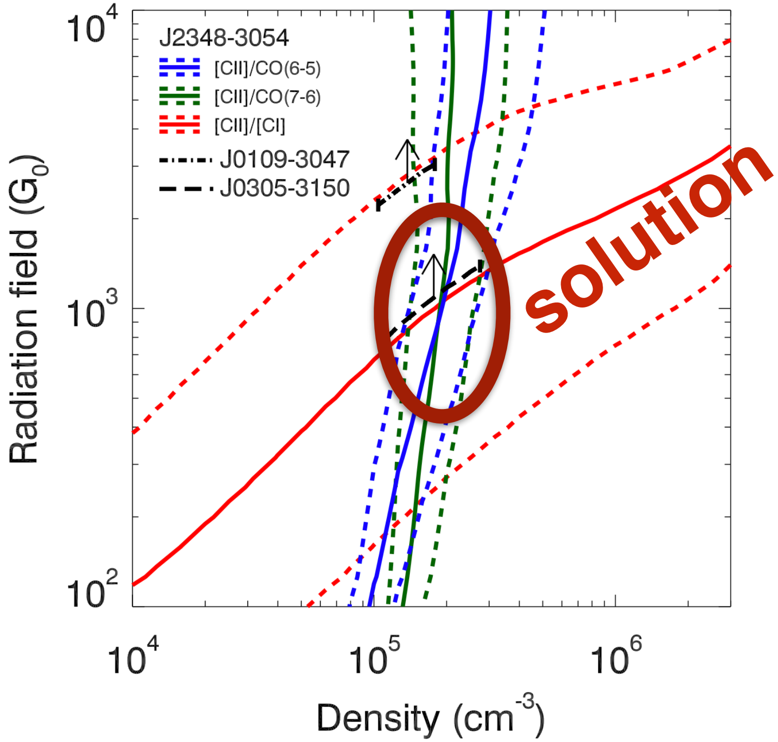
Venemans et al. 2017

multi-line ISM diagnostics at z>6.5

XDR



PDR



global properties not dominated by X-rays

[CII]/[CI] ratio: $G \sim 1000\ G_0$

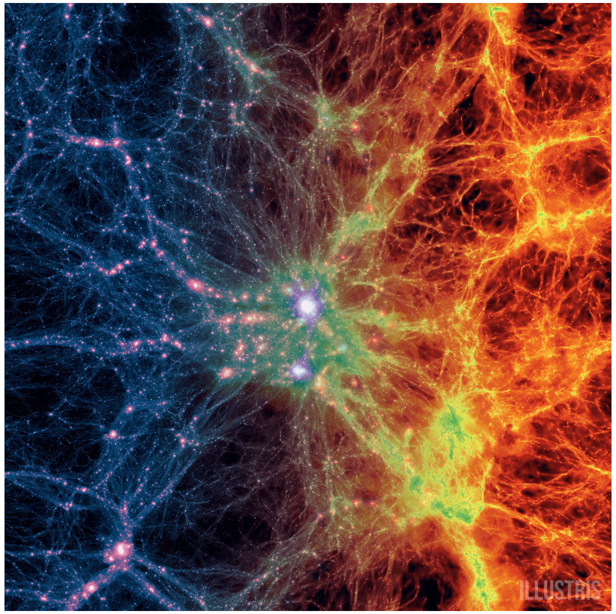
[CII]/CO(7-6) ratio: $n_{gas} \sim 2\ 10^5\ cm^{-3}$

Venemans et al. 2017

outline of this talk

- Characterize massive quasar host galaxies at z>6

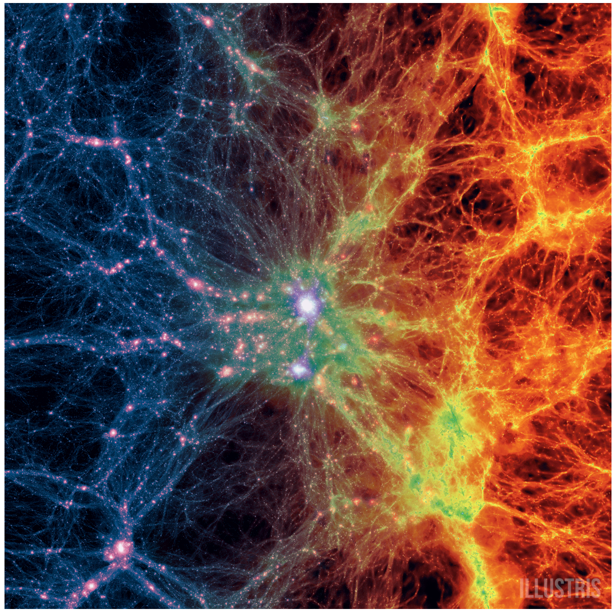
- Environment of the first supermassive black holes at z>6

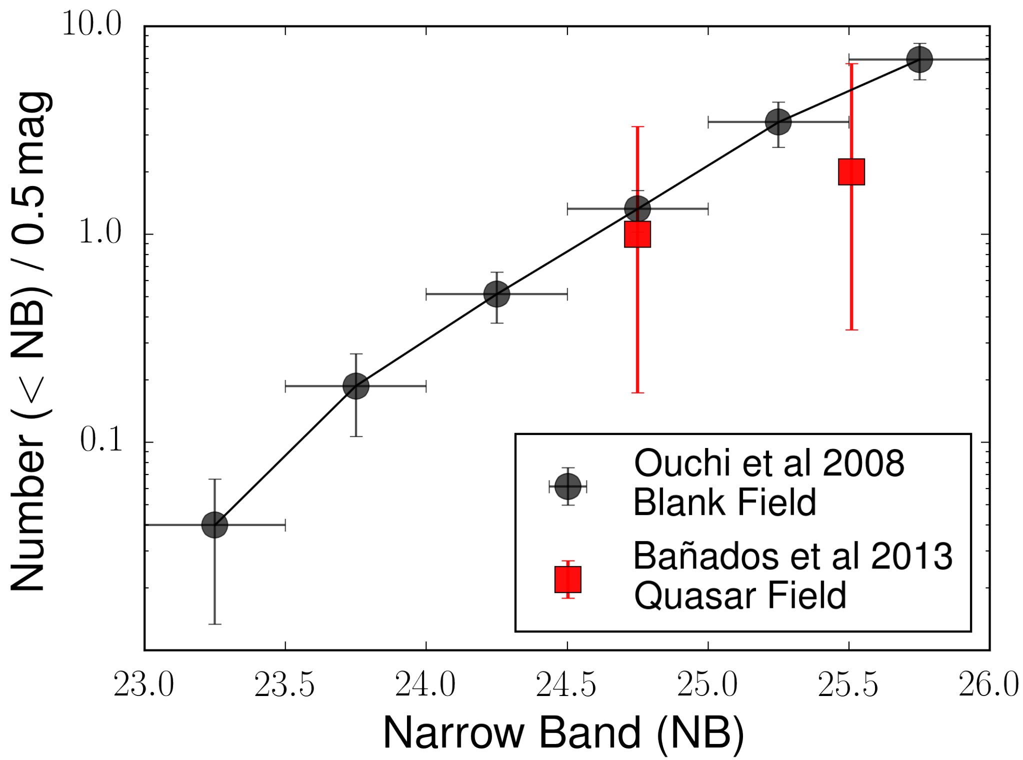


- State of the intergalactic medium at z>6

overdensities around high-z quasars

Searches for Lyman Alpha Emitters around z>6 quasars:





Bañados+ 2013

Mazzucchelli+ 2017a

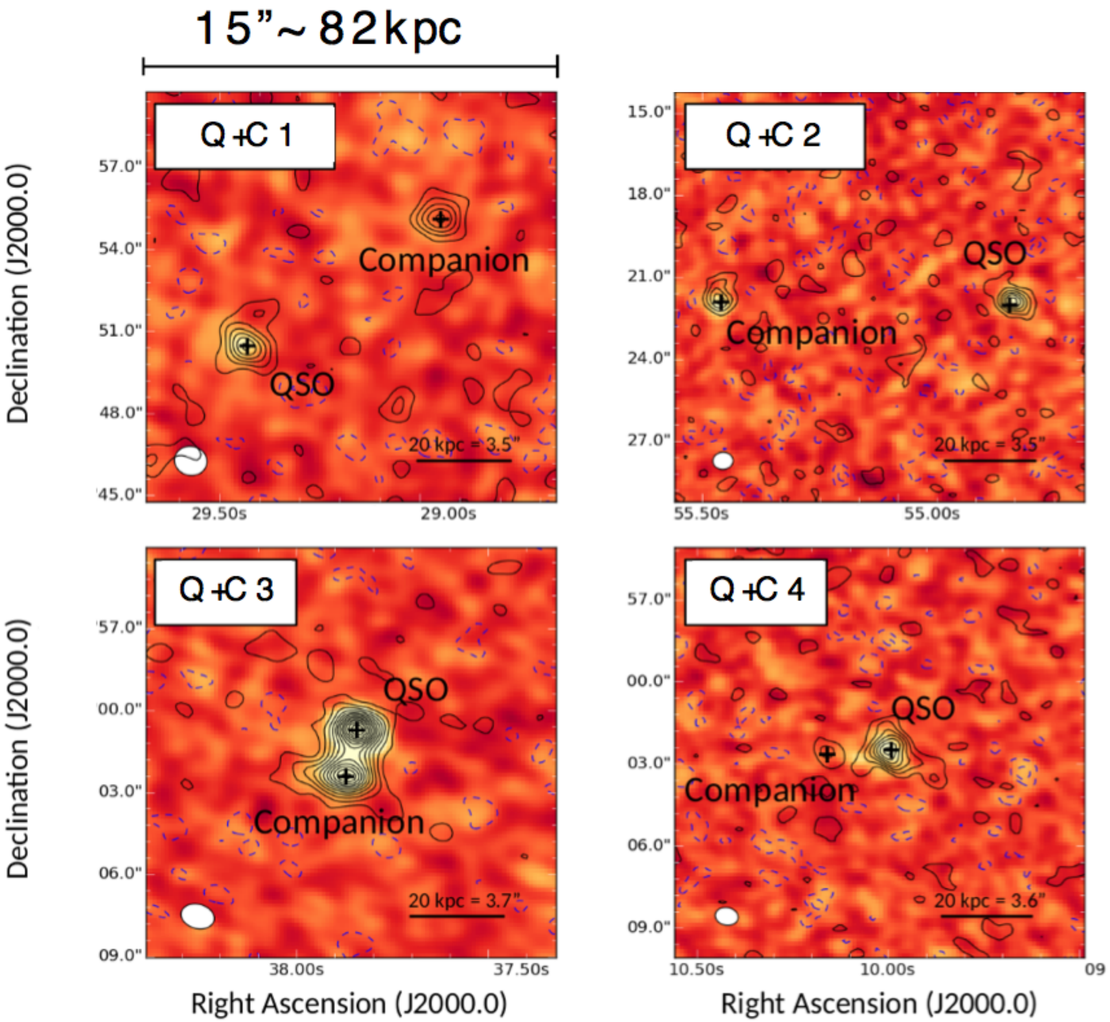
Ota et al. 2017, in prep.

—> no evidence for galaxy overdensities

observations still inconclusive …

overdensities around high-z quasars

FIR-bright companions!

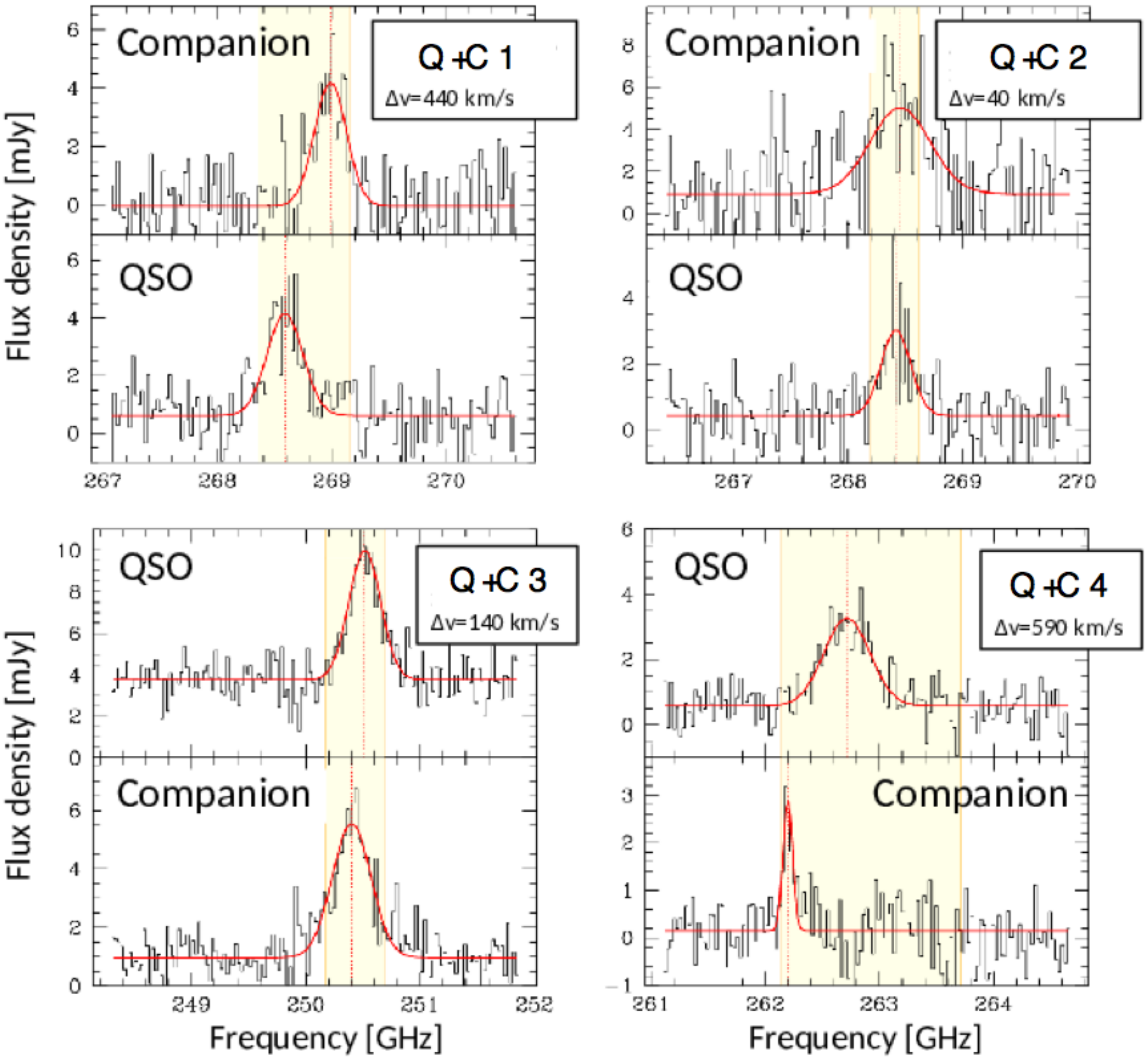


contours: [CII]
color: dust continuum

these companions are not seen in deep Spitzer / HST images

Decarli+ 2017a, Nature

overdensities around high-z quasars

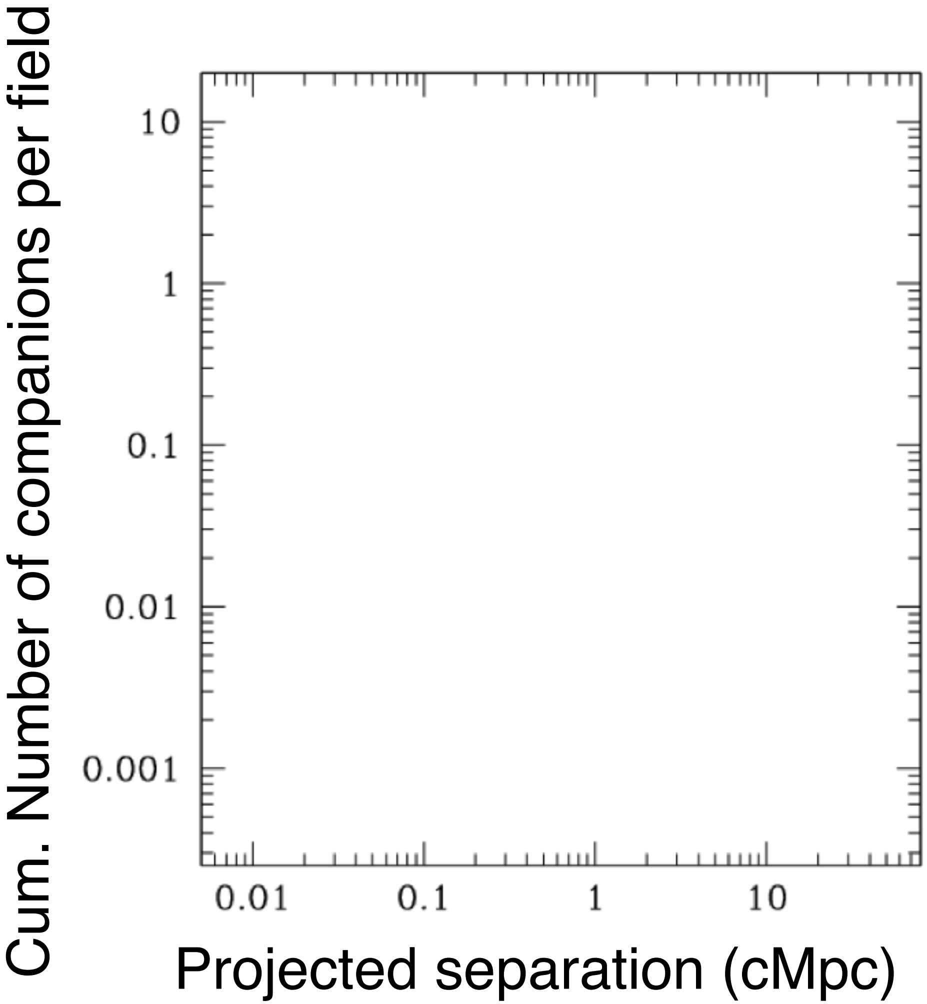


$M_{dyn} = 1 – 30\ 10^{10}\ M_{sun}$

projected separations:
8 – 60 kpc
velocity offsets:
40 – 580 km/s

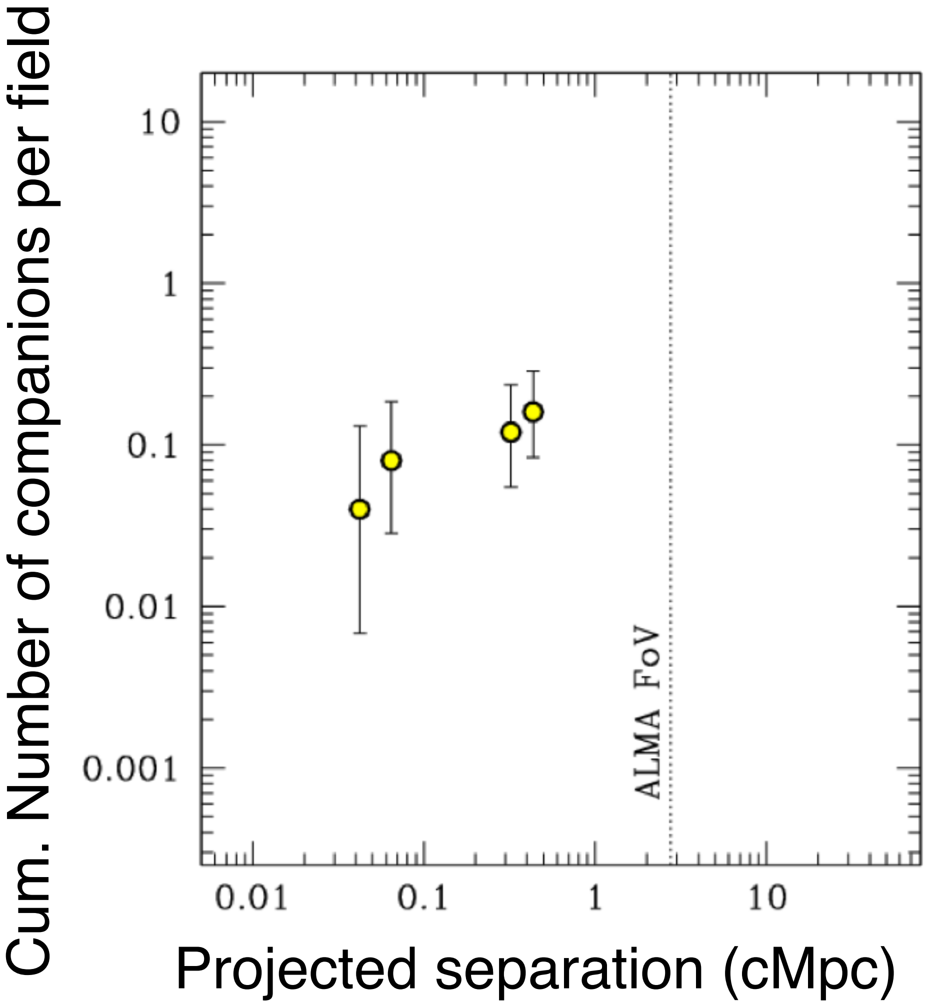
Decarli+ 2017a, Nature

overdensities around high-z quasars



Decarli+ 2017a, Nature

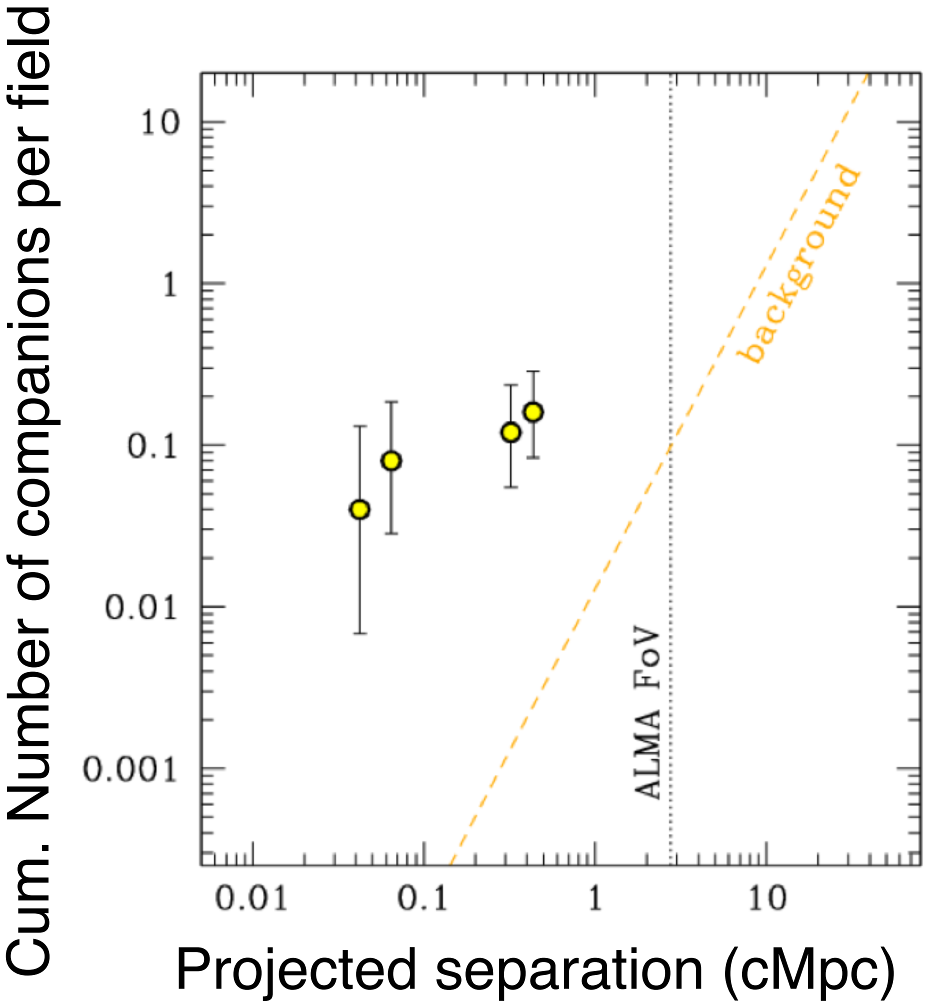
overdensities around high-z quasars



4 companions in 27 fields

Decarli+ 2017a, Nature

overdensities around high-z quasars



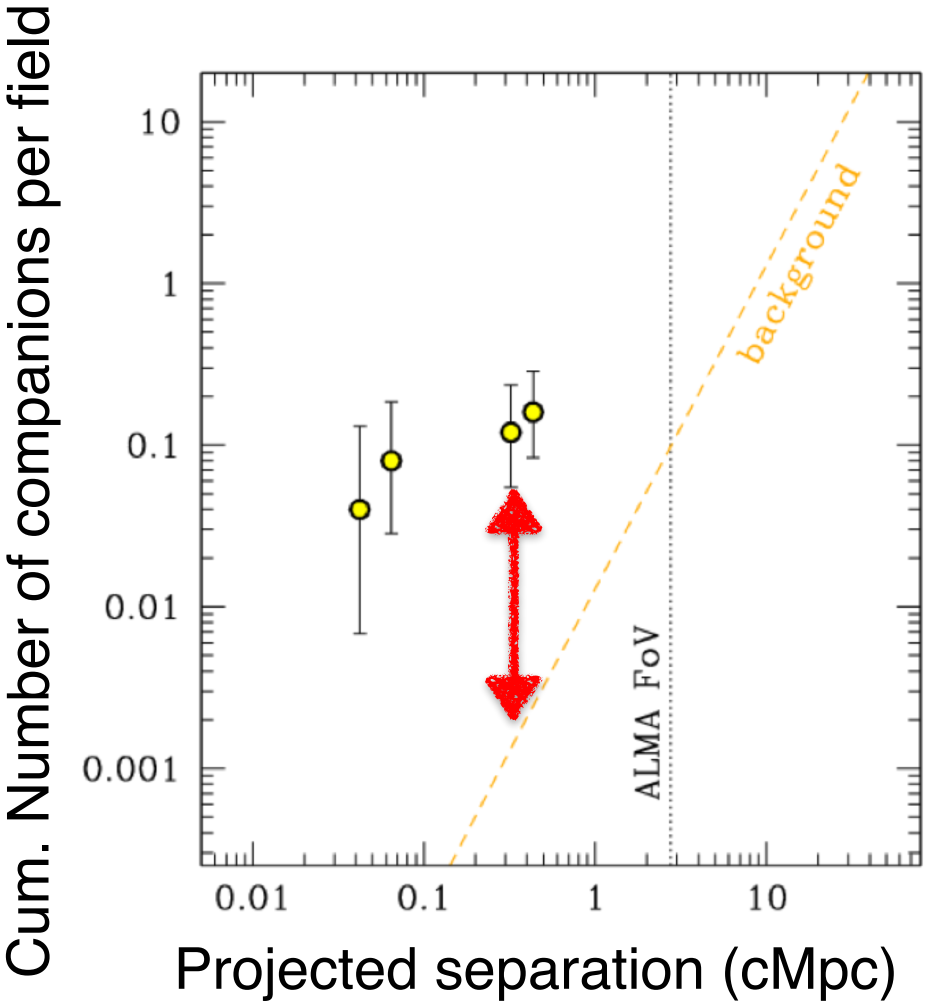
4 companions in 27 fields

Background ~ 2 x 10^{-4} $cMpc^{-3}$

(based on 1 source in HUDF, Aravena+ 2016)

Decarli+ 2017a, Nature

overdensities around high-z quasars



4 companions in 27 fields

Background ~ 2 x 10^{-4} $cMpc^{-3}$

(based on 1 source in HUDF, Aravena+ 2016)

factor > 100 higher than the field!

Decarli+ 2017a, Nature

outline of this talk

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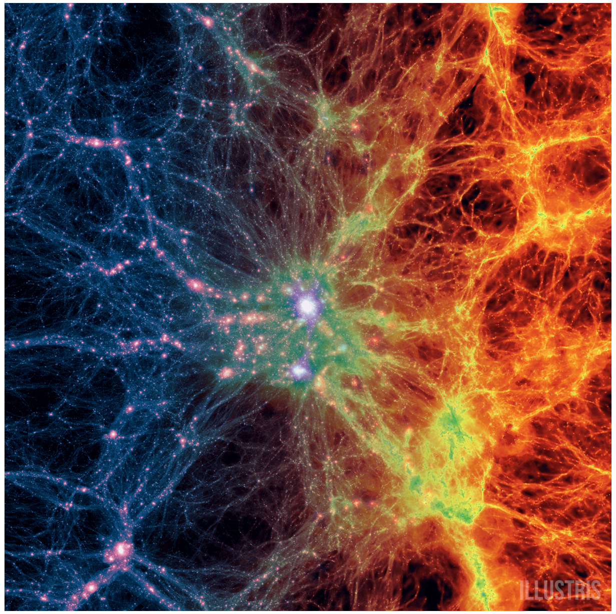
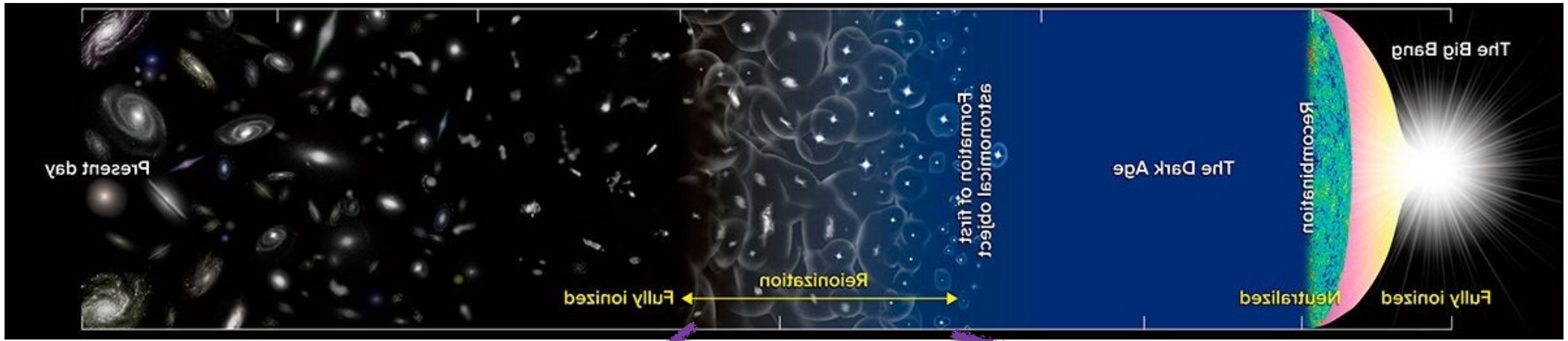
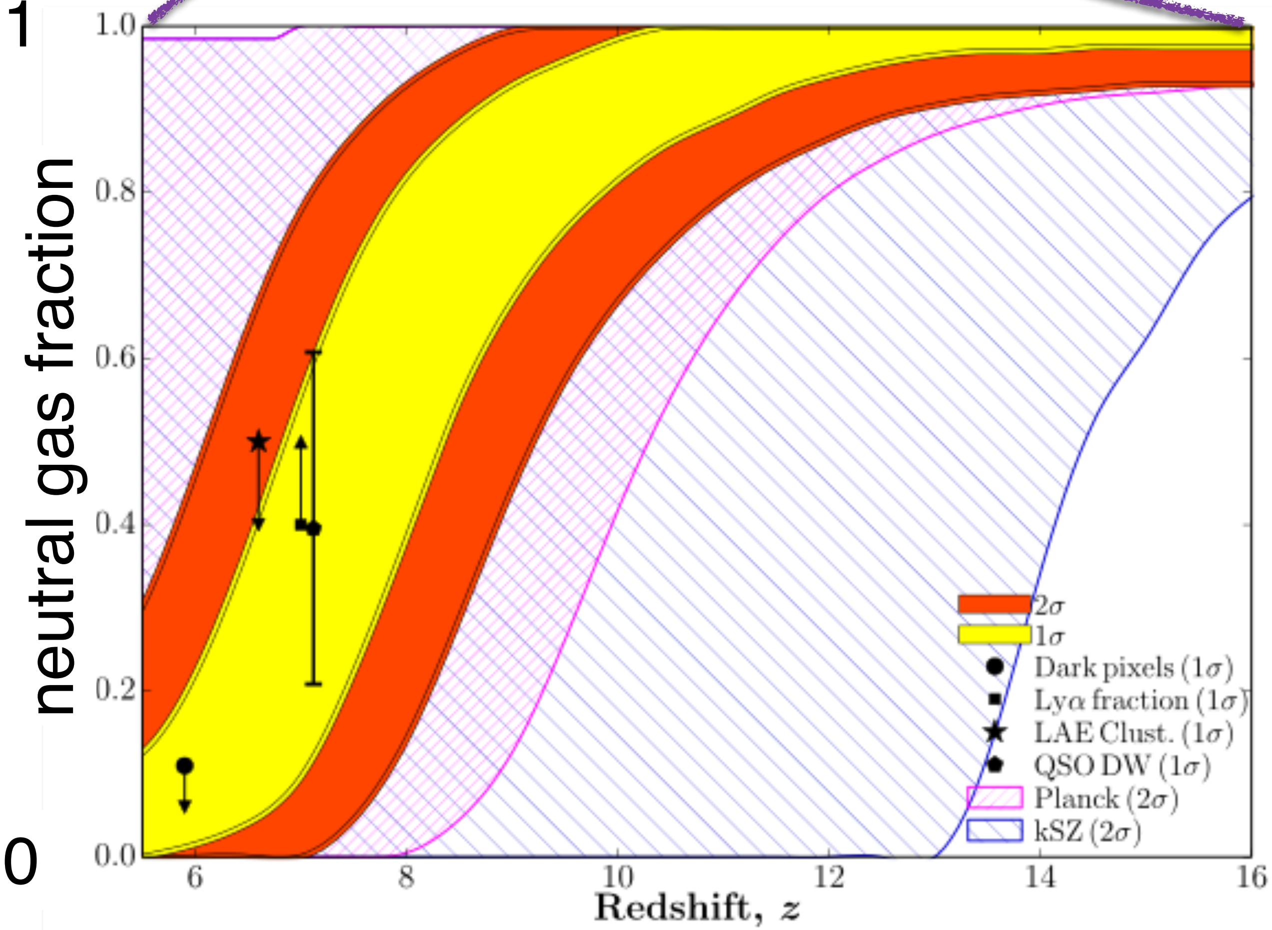
- State of the intergalactic medium at z>6



quasars in the epoch of reionization



neutral 1

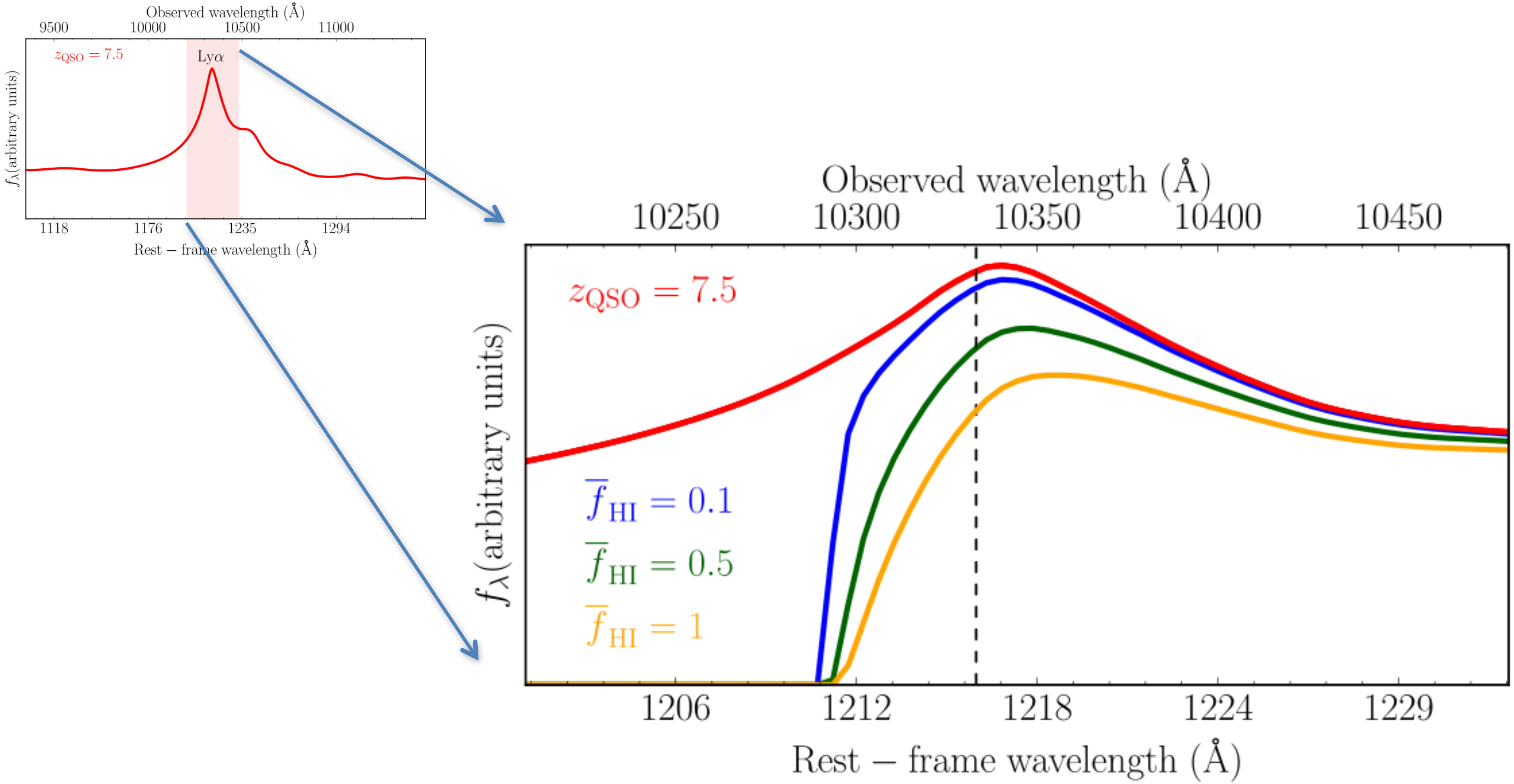


ionized 0

Greig & Mesinger 2017

IGM damping wing

Reminder: Damping wing sensitive to neutral gas fraction

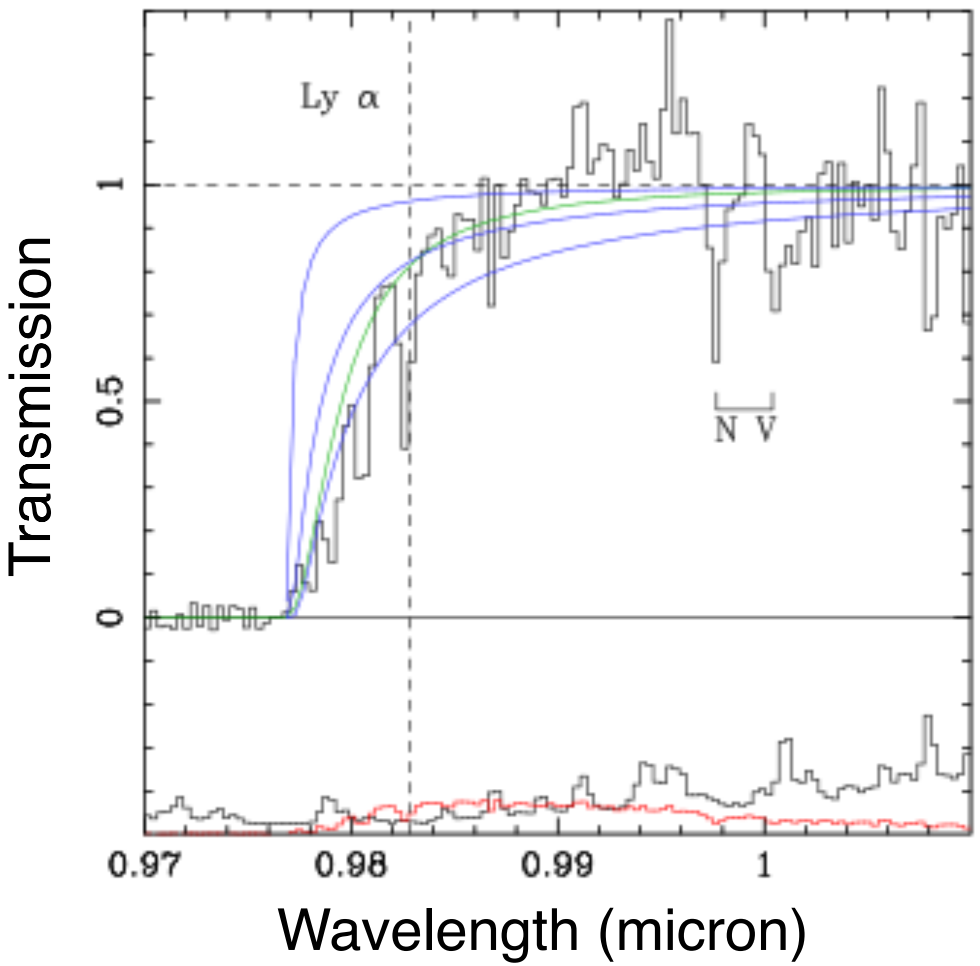


from Miralda-Escude 1998

challenge: unknown intrinsic spectrum

first IGM damping wing signature at z=7.1

z=7.1 quasar J1120 shows damping wing signature :



f_{HI}=0.4+/-0.2 at z=7.1

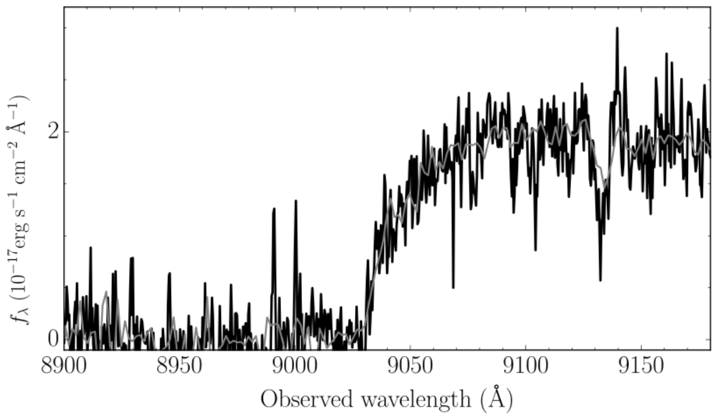
t_{univ}=770 Myr

no clear consensus on IGM absorption nature
e.g., Bosman & Becker 2015

Mortlock+ 2011, Greig et al. 2017

IGM damping wing already at z=6.4?

z=6.4 (t_{univ}=880 Myr) is 110 Myr after z=7.1 (15% of cosmic time)



Bañados+ 2017 subm.

IGM damping wing already at z=6.4?

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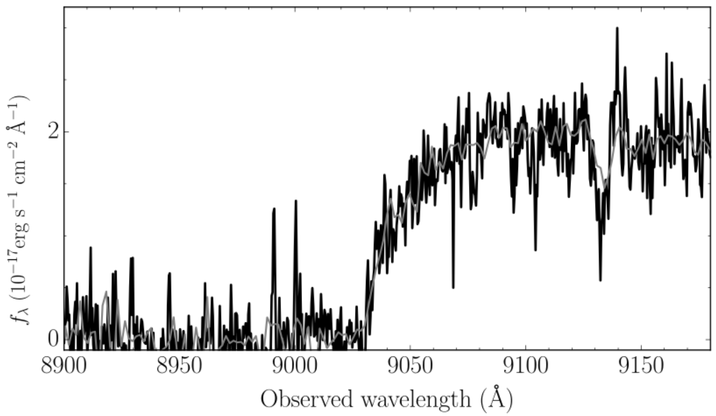
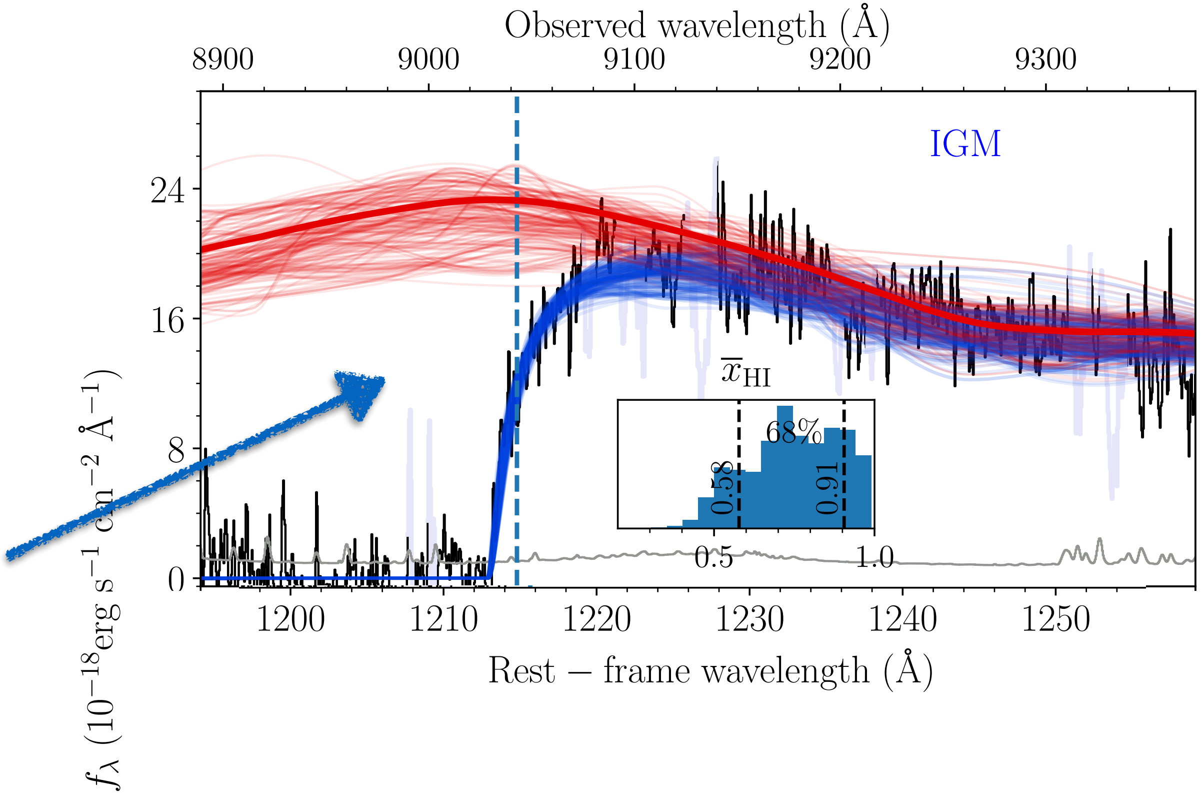


can be modeled with IGM damping wing…



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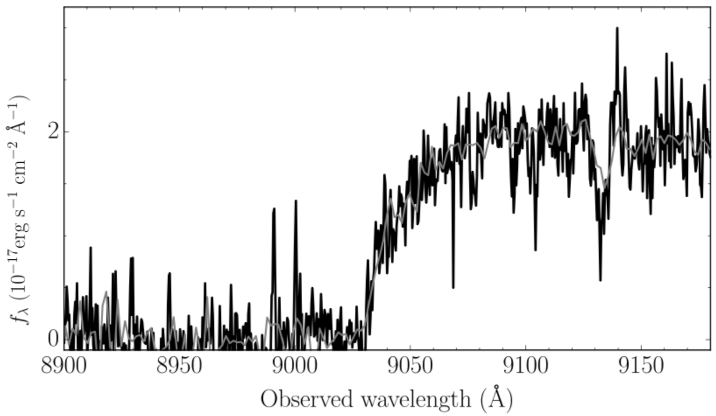
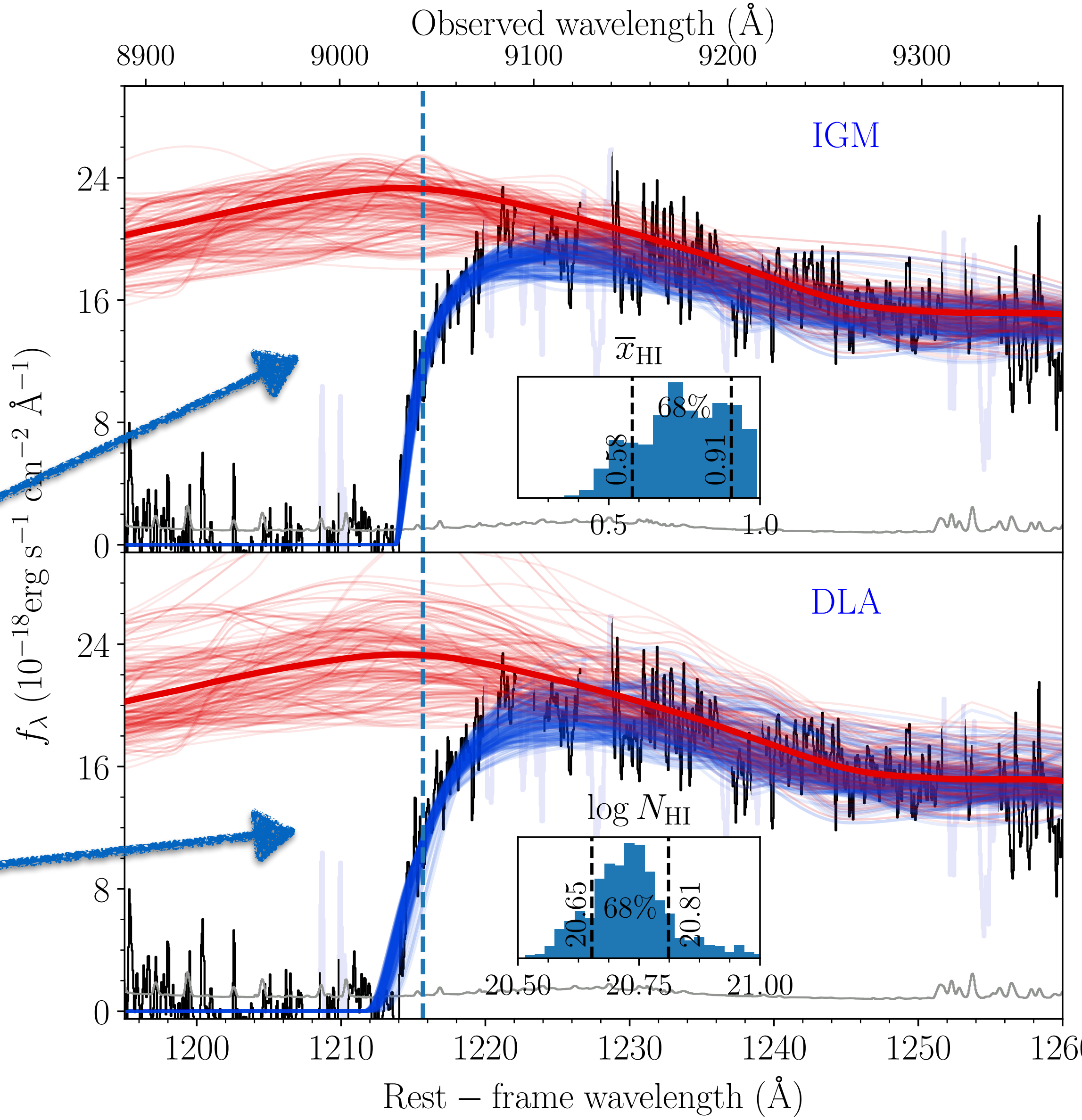


can be modeled with IGM damping wing…

OR

absorber (DLA) at redshift close to quasar



Bañados+ 2017 subm.

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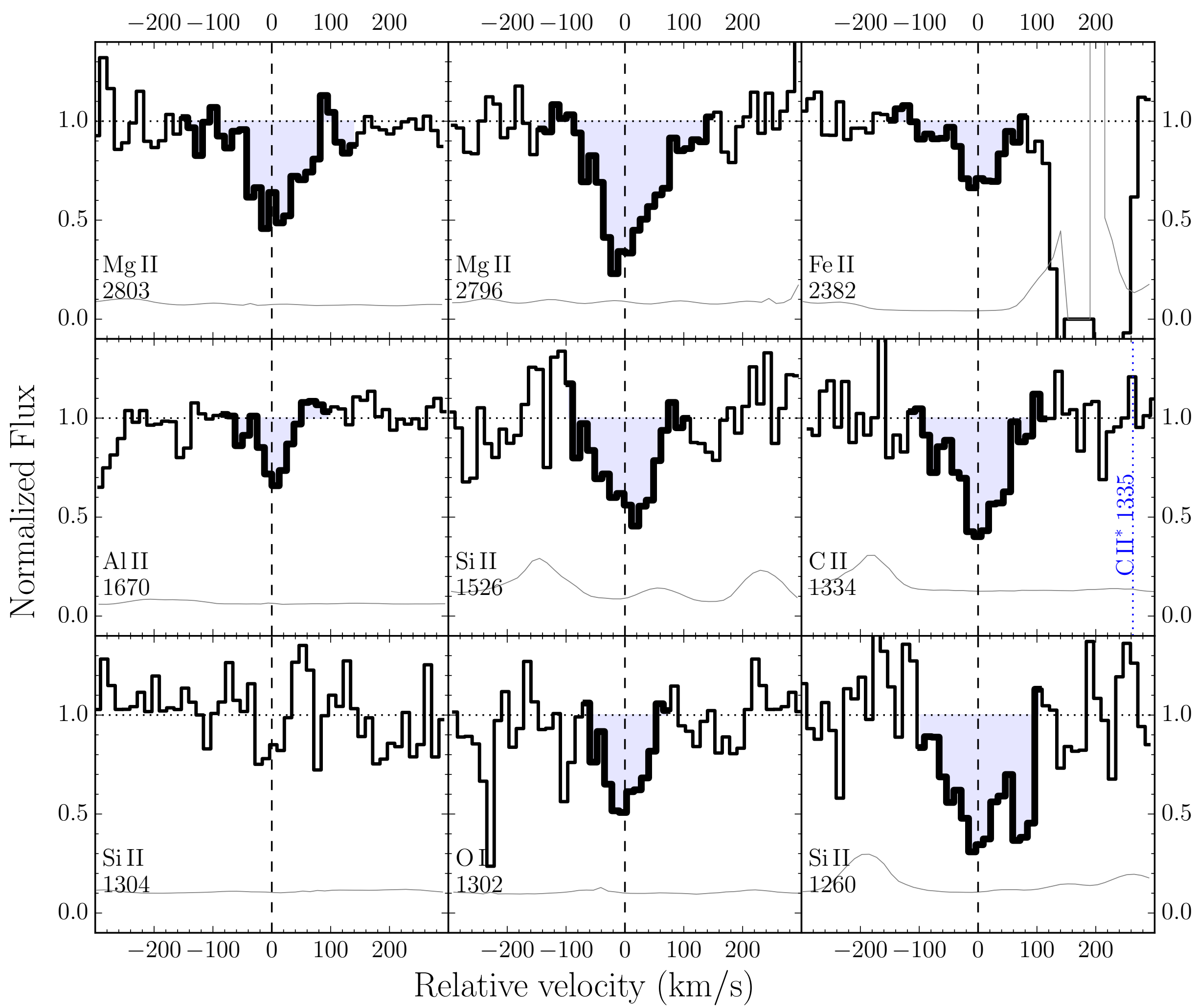


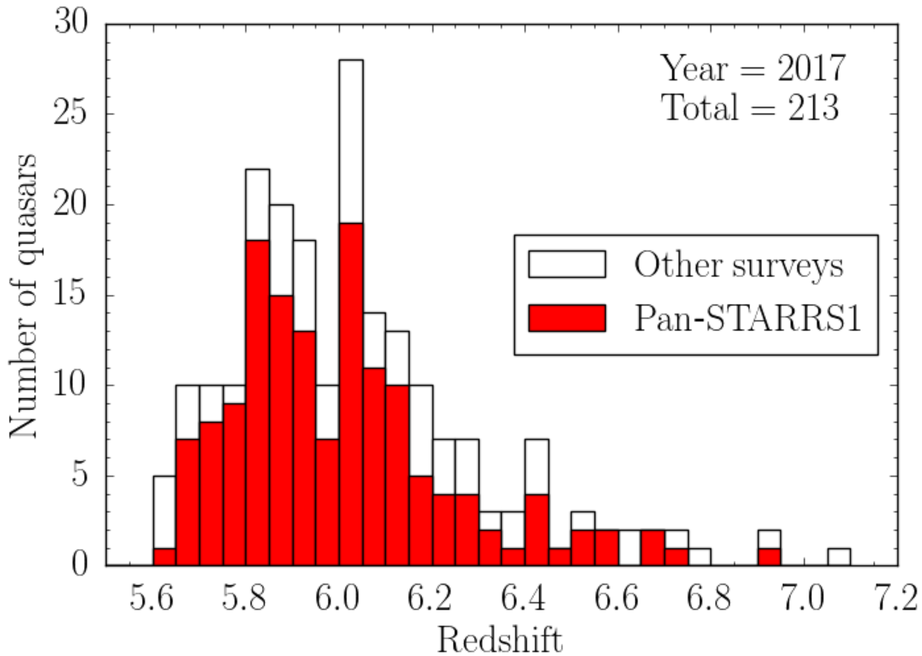
absorber present at z=6.40392, very close to quasar!

very uncommon that we see the the host galaxy in absorption.

caution needed when interpreting IGM Damping Wing features

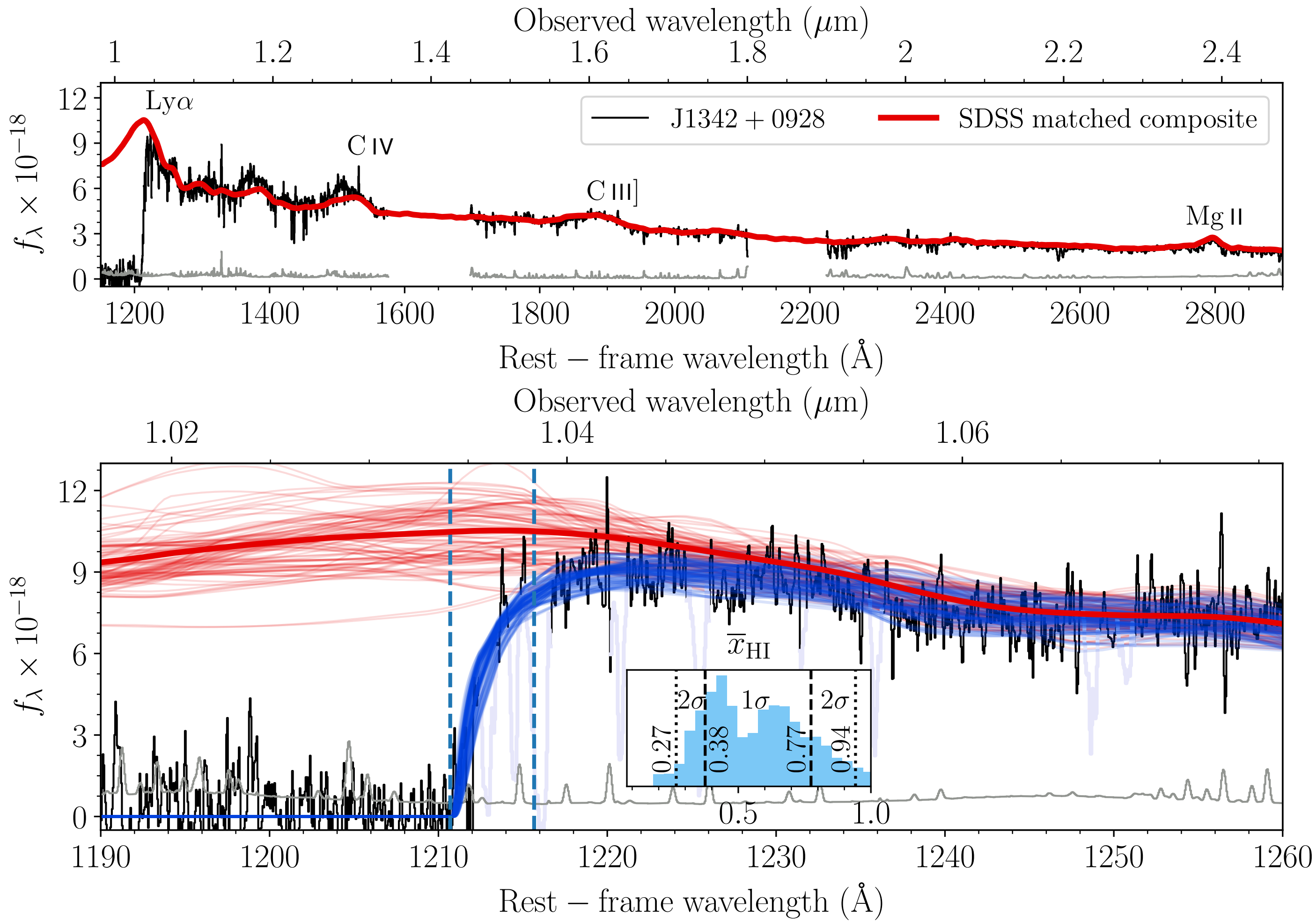
Bañados+ 2017 subm.

We need more quasars at z>7…



new record-redshift quasar at z=7.54

Age of universe: 690 Myr; ~10% younger than at z=7.1



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

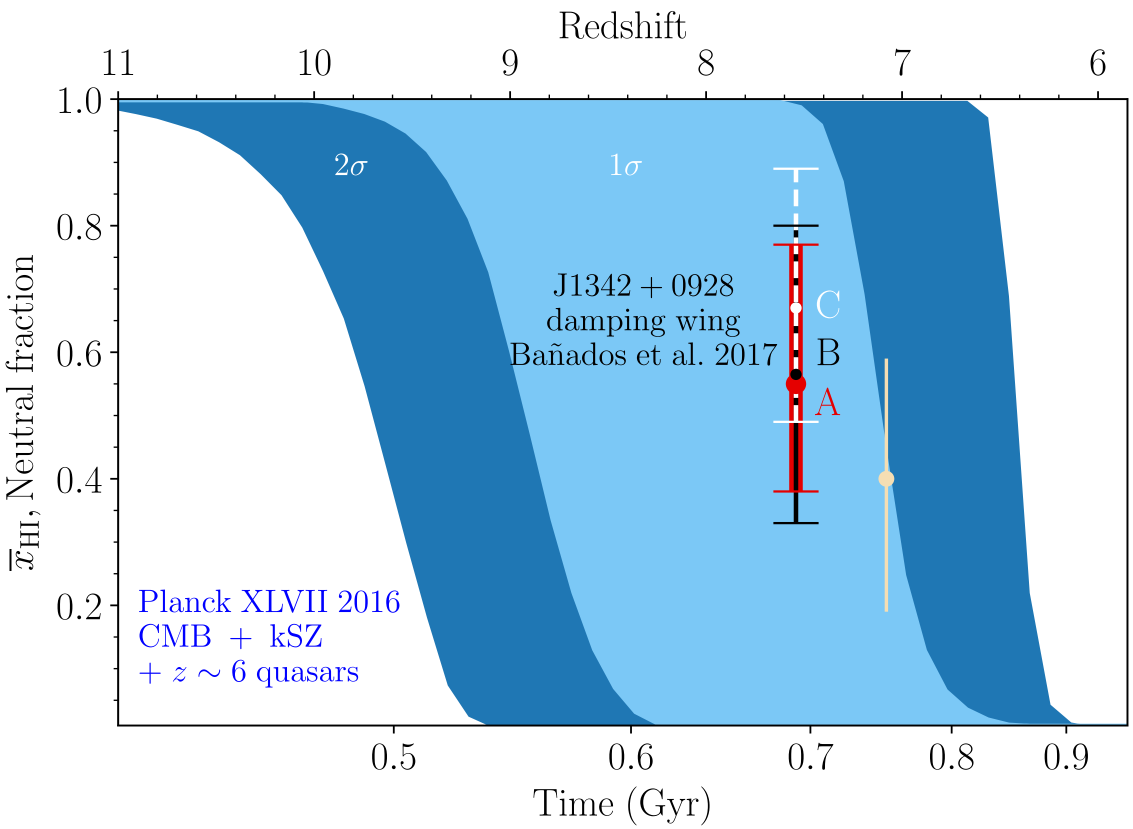
Bañados+ 2017, Nature, subm.

damping wing signature…

…***and*** no evidence for absorber

new record-redshift quasar at z=7.54

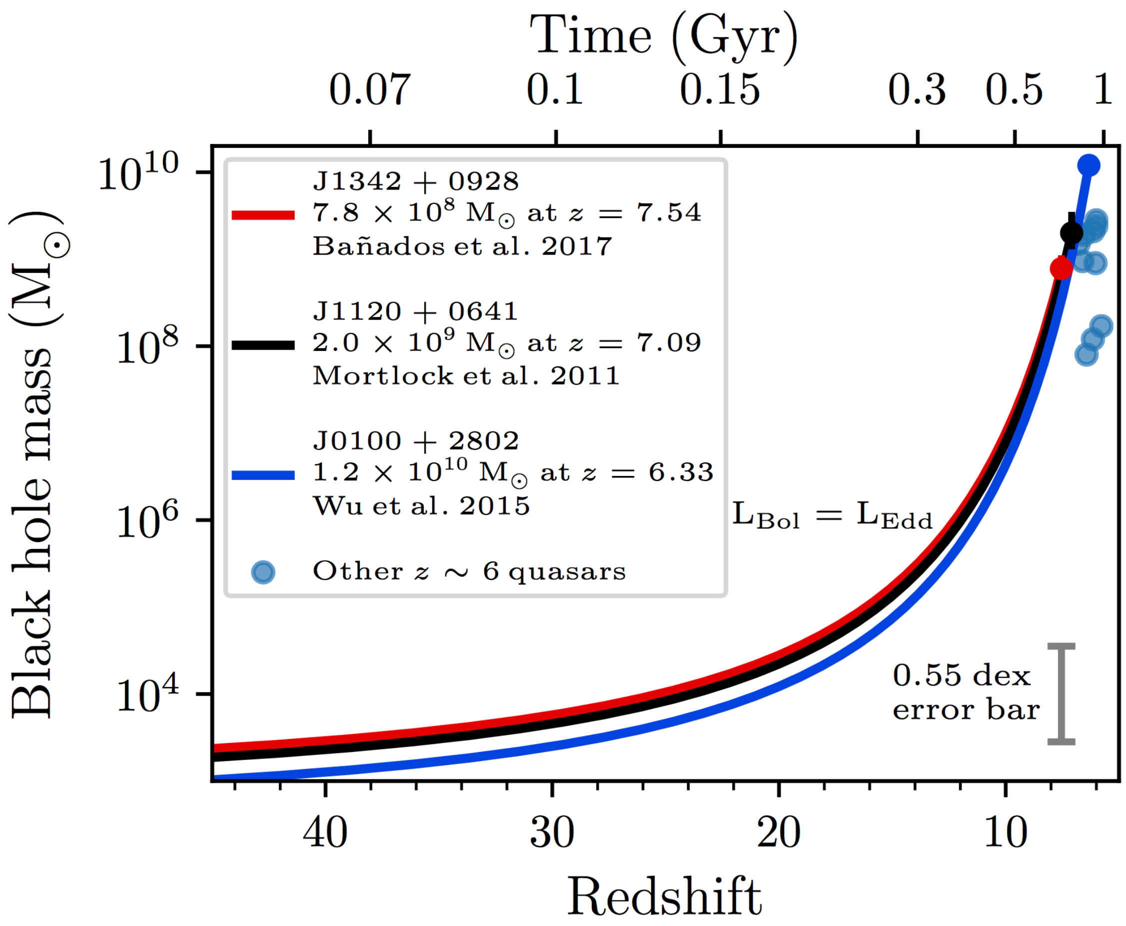
(one sightline) constraint on the IGM at z=7.5



Bañados+ 2017, Nature, subm.

new record-redshift quasar at z=7.54

constraints on early black hole growth

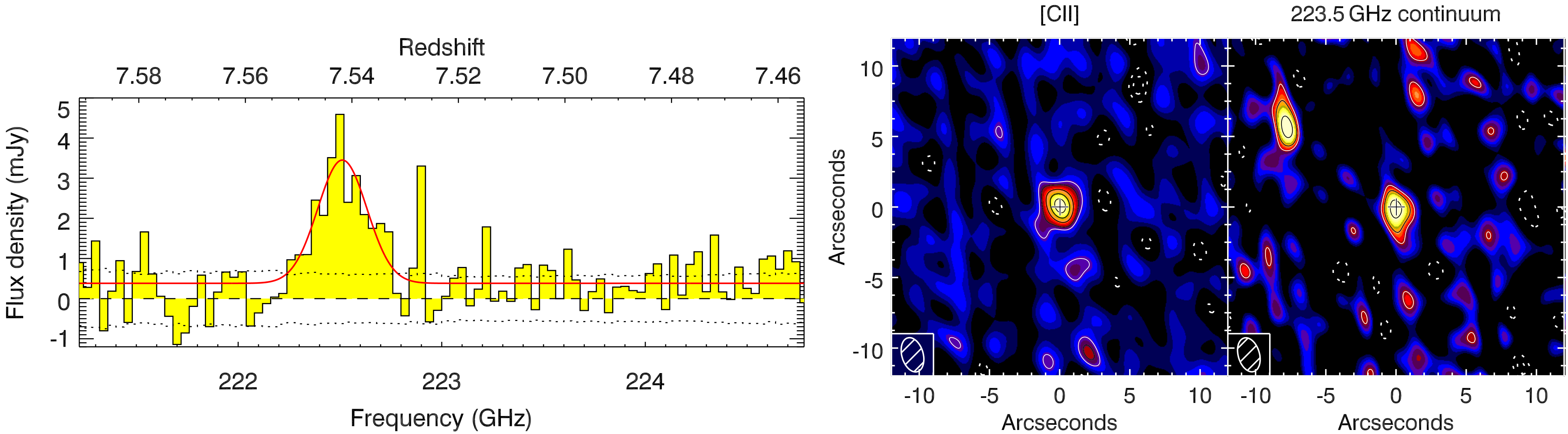


Eddington accretion:
need >1000 M_{sun} BH
at z=40

Bañados+ 2017, Nature, subm.

new record-redshift quasar at z=7.54

this z=7.5 quasar is bright in [CII] and dust emission



currently spatially unresolved, FWHM = 380 km/s

M_{dust} = 1-4 10^8 M_{sun}, $M_{[CII]}$ ~ 5 10^6 M_{sun}

…interesting questions regarding metal production in the very early universe

Venemans et al. 2017

concluding thoughts

quasars in the first Gyr of the universe:

unique probes of physical properties of massive hosts, their environments, and the intergalactic medium.

puzzling findings… out to z=7.5 (t_{univ}=690 Myr)

- rapid early supermassive black hole growth
- significant chemical enrichment already at that time

bright future: EUCLID/WFIRST, LSST, JWST

THE END