The Search for and Physical Nature of the Highest-Redshift Quasars

Michael A. Strauss, Princeton University

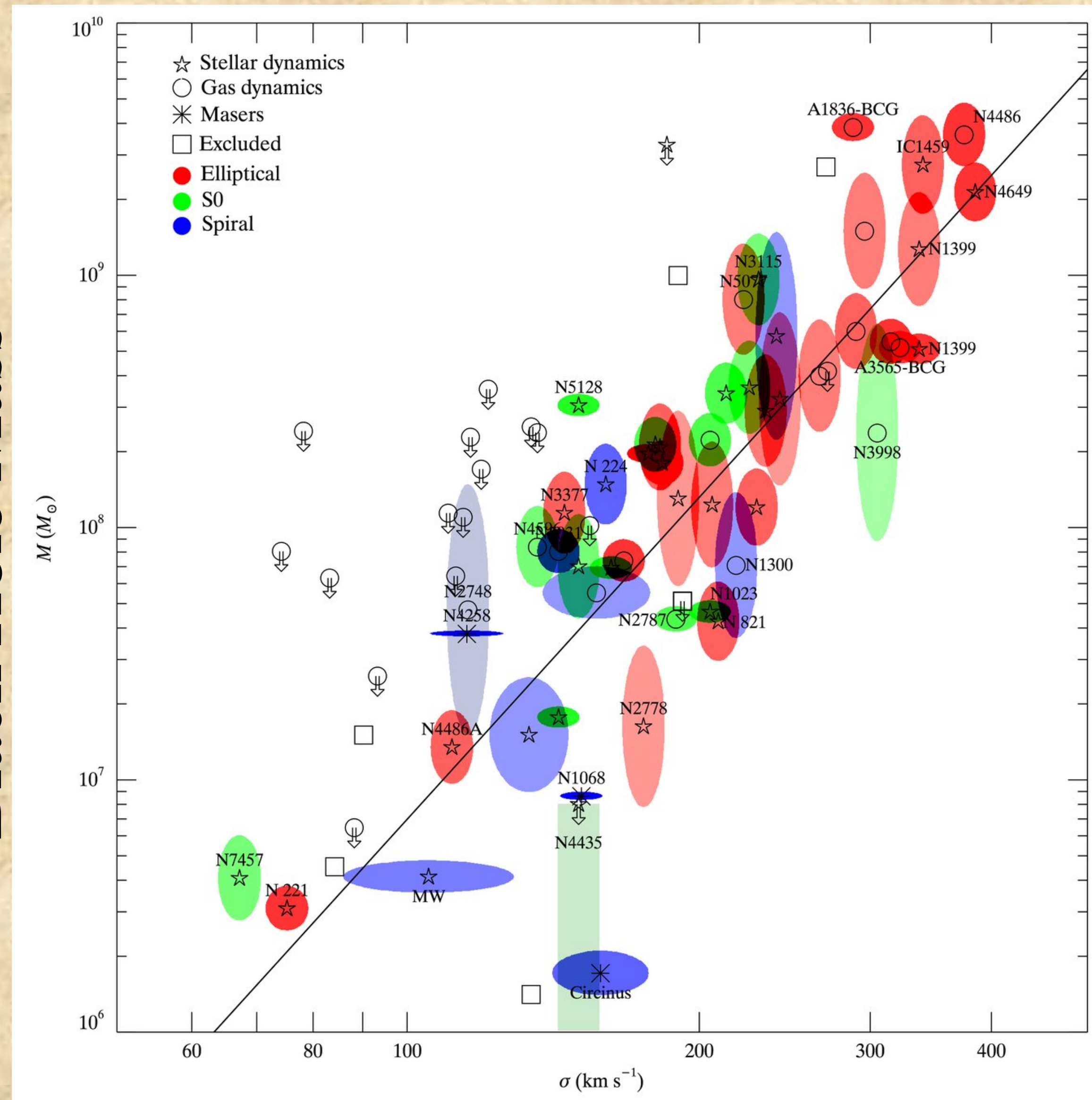
- Quasars 101
- Finding distant quasars
- The physical nature of the highest redshift quasars and their host galaxies
- Host galaxies at lower redshifts
- The nature of obscured quasars (if there’s time!)

Quasars 101

Every galaxy today with an appreciable bulge has a supermassive black hole in the center (10^6-$10^{9.5}$ solar masses).

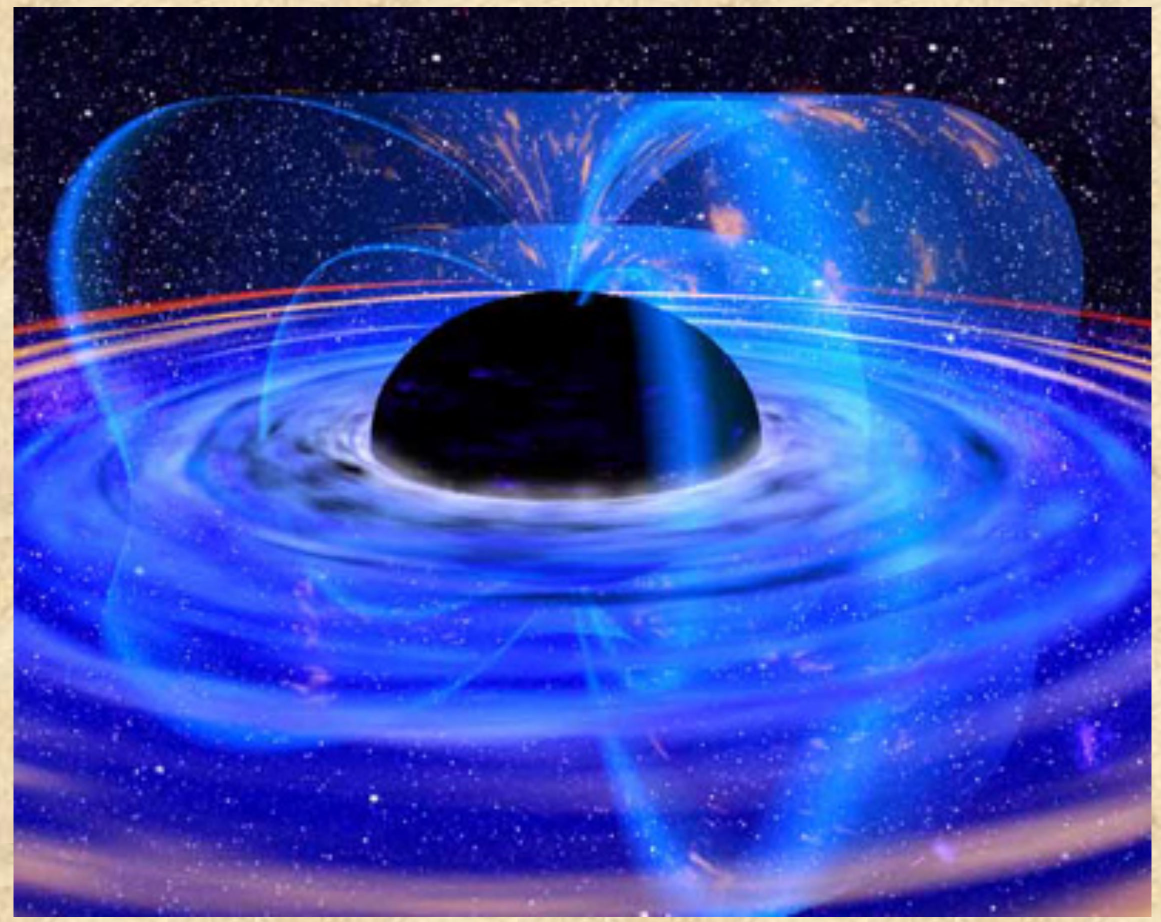
Gultekin et al. 2009

Black Hole Mass

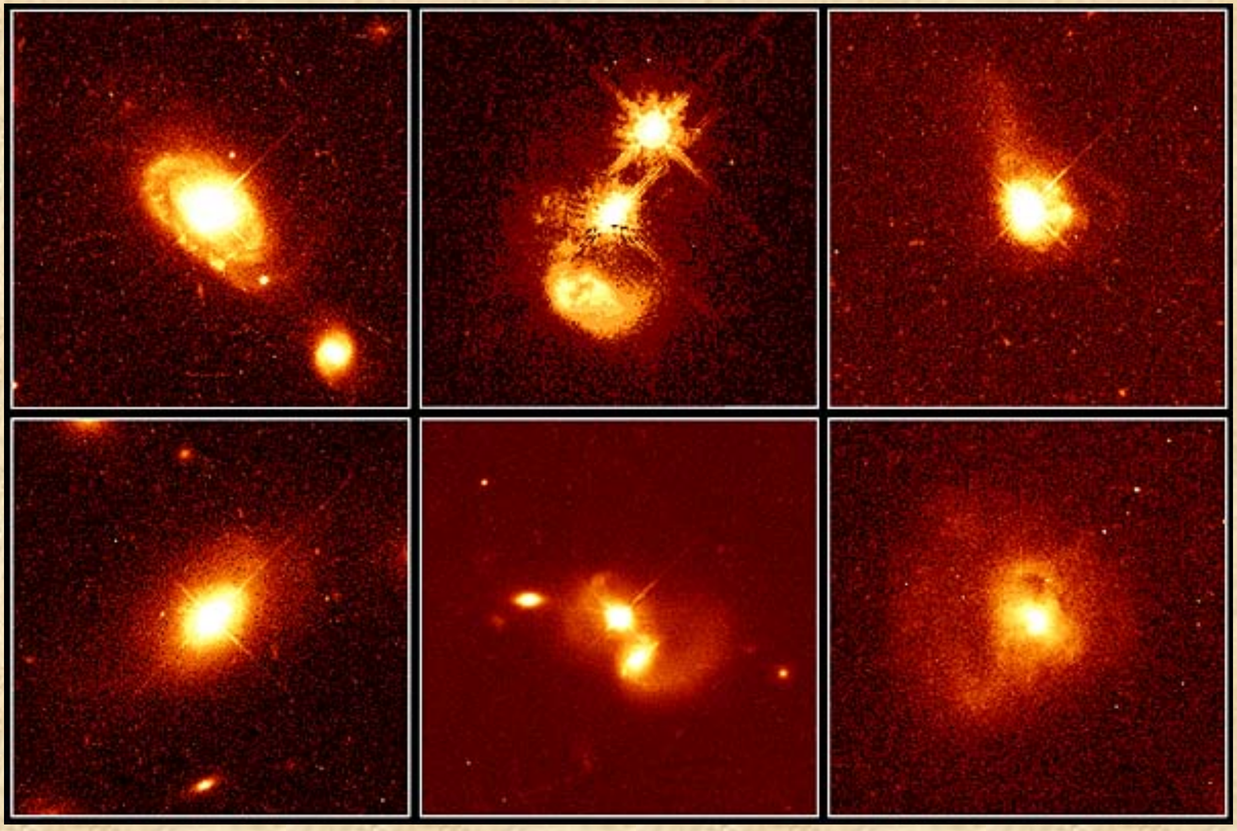


Velocity Dispersion of Bulge

These black holes are mostly quiescent in the present-day Universe, but grew rapidly a few billion years after the Big Bang as material flowed into them via an accretion disk.



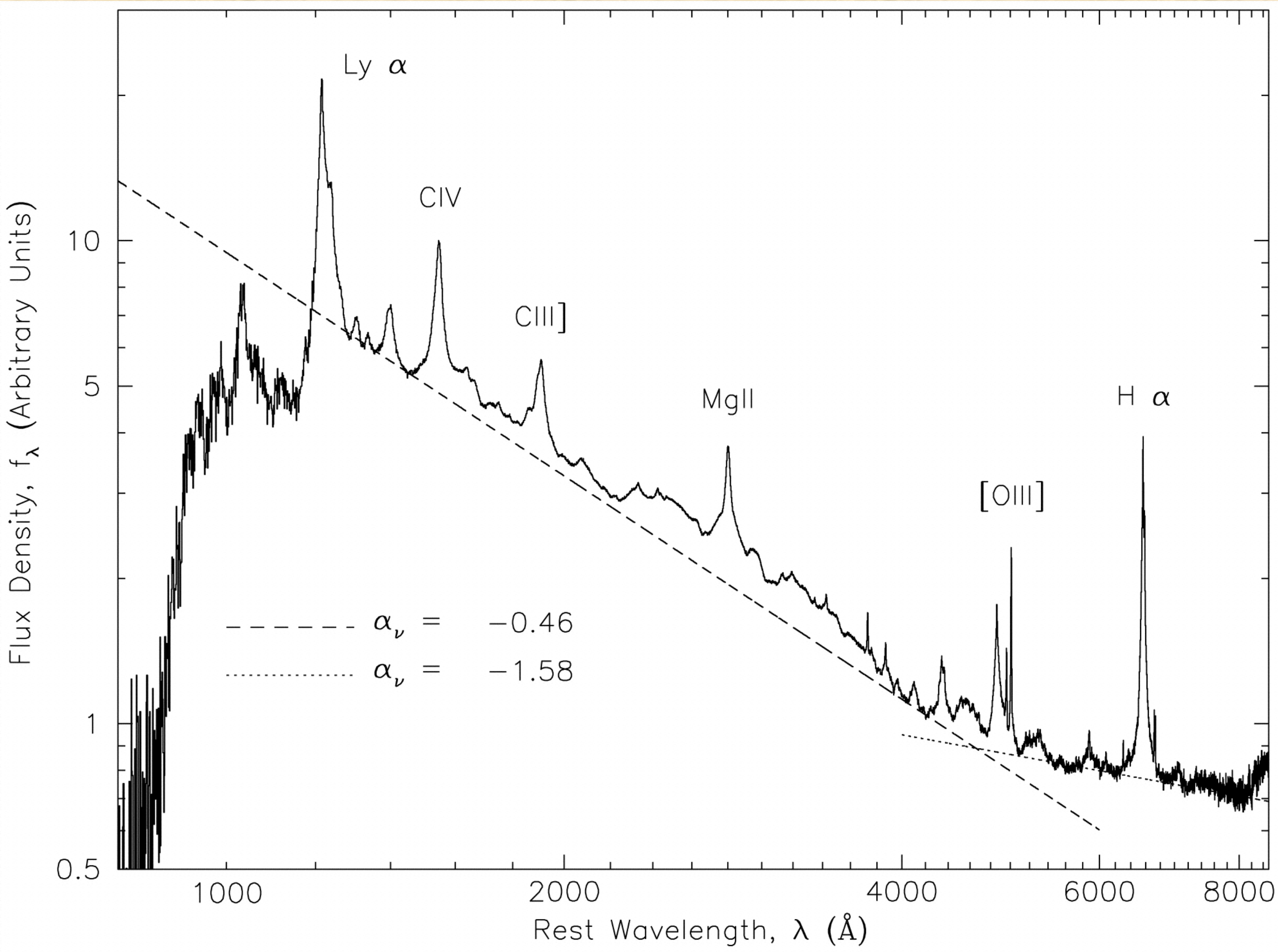
Friction in the accretion disk heats them up enormously. As much as 0.1 mc^2 of the infalling matter can be turned into energy, which we observe as the quasar phenomenon.



Quasars often dramatically outshine their host galaxies, making them appear close to pointlike.

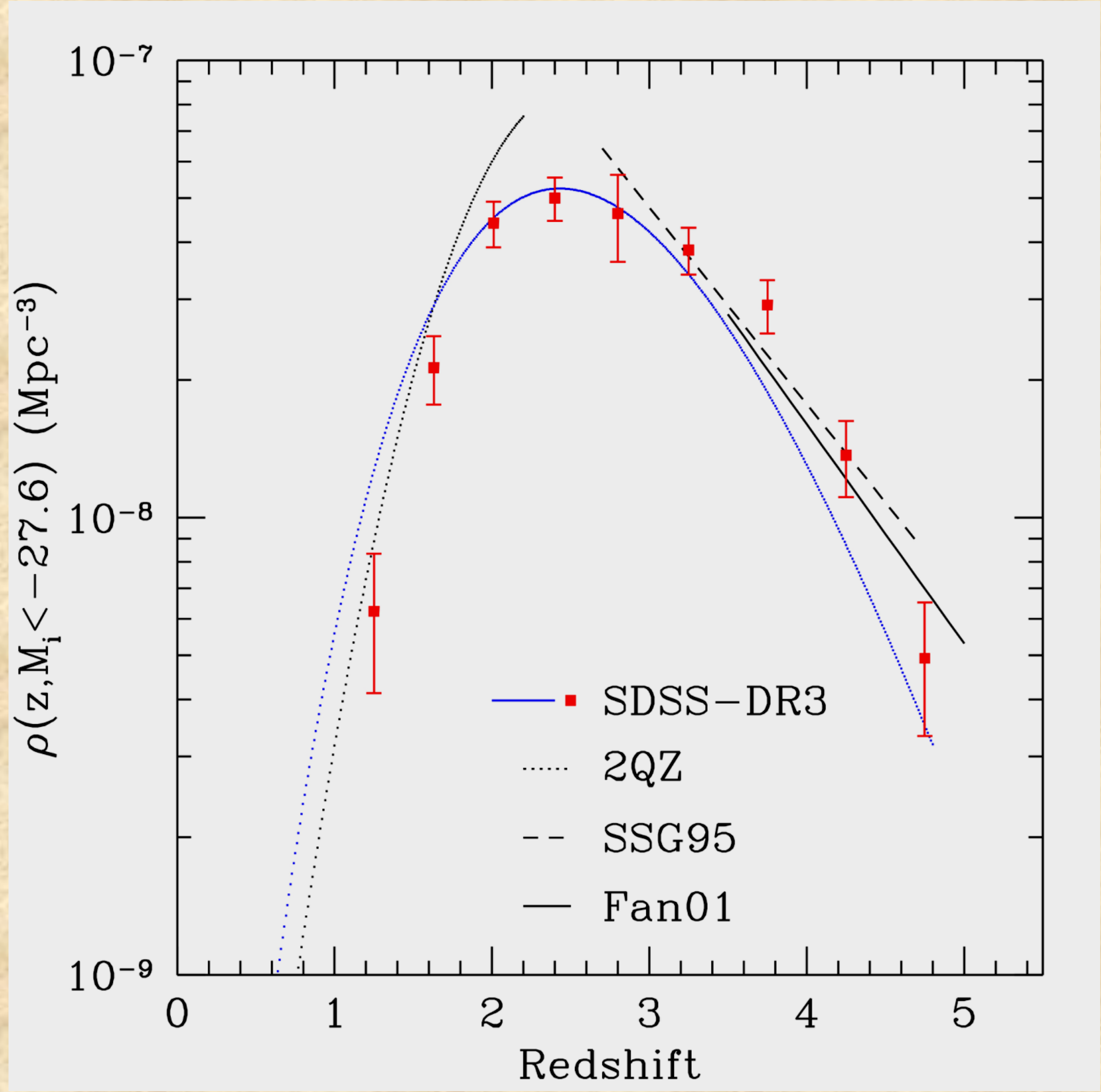
Hubble images of quasars and their hosts, by Bahcall, Kirhakos, and Disney.

(Unobscured) quasars are characterized by a very blue continuum in visible and UV (from the accretion disk), and broad emission lines from fluorescing gas in the deep potential well.



Vanden Berk et al. 2001

We want to study the highest-redshift quasars, probing the end of the dark ages when the first galaxies formed.



The comoving number density of luminous quasars peaks between z=2 and 3. High-redshift quasars are *much* rarer!

Richards et al. 2006

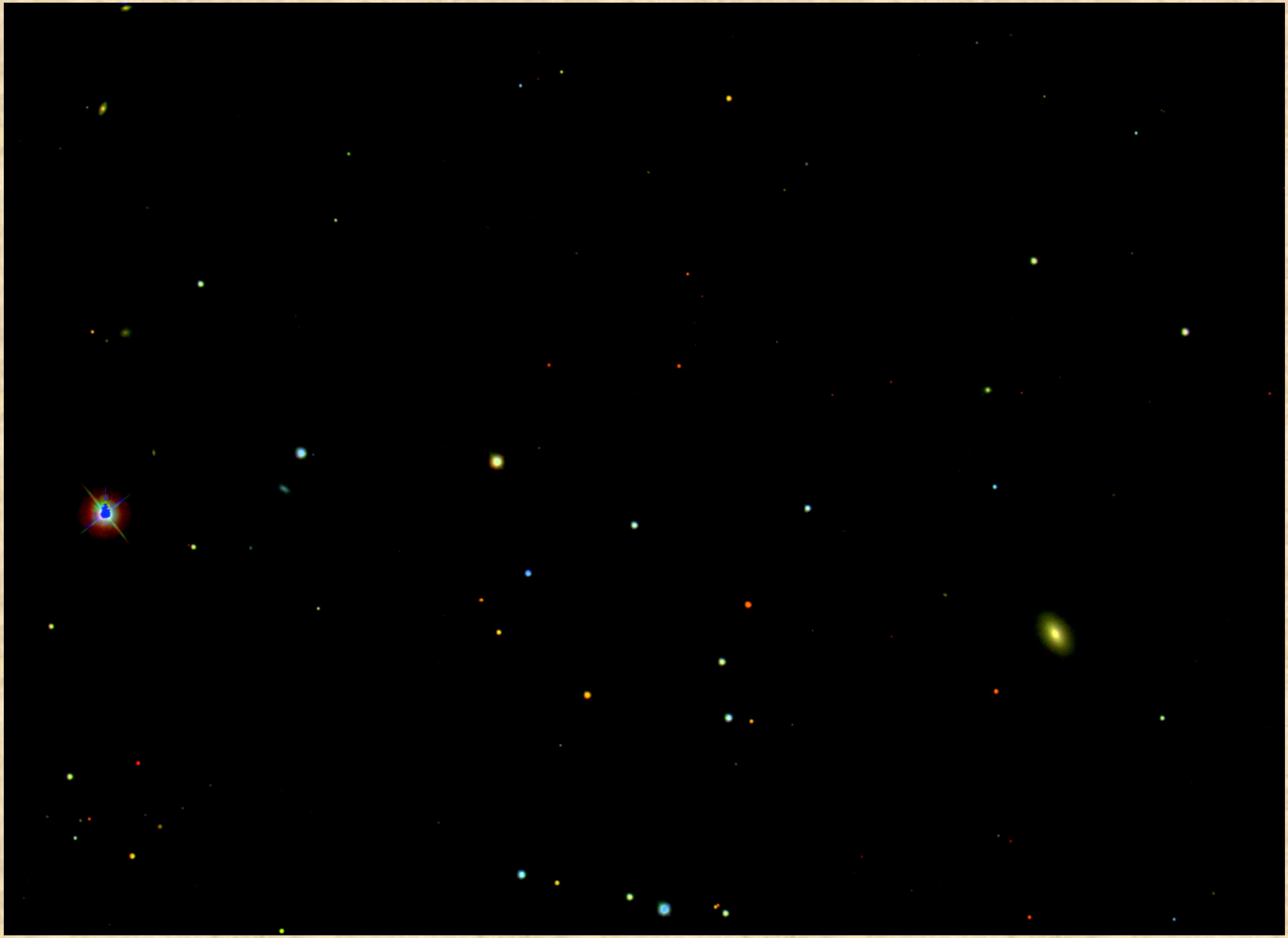
Searching for high-redshift quasars is hard

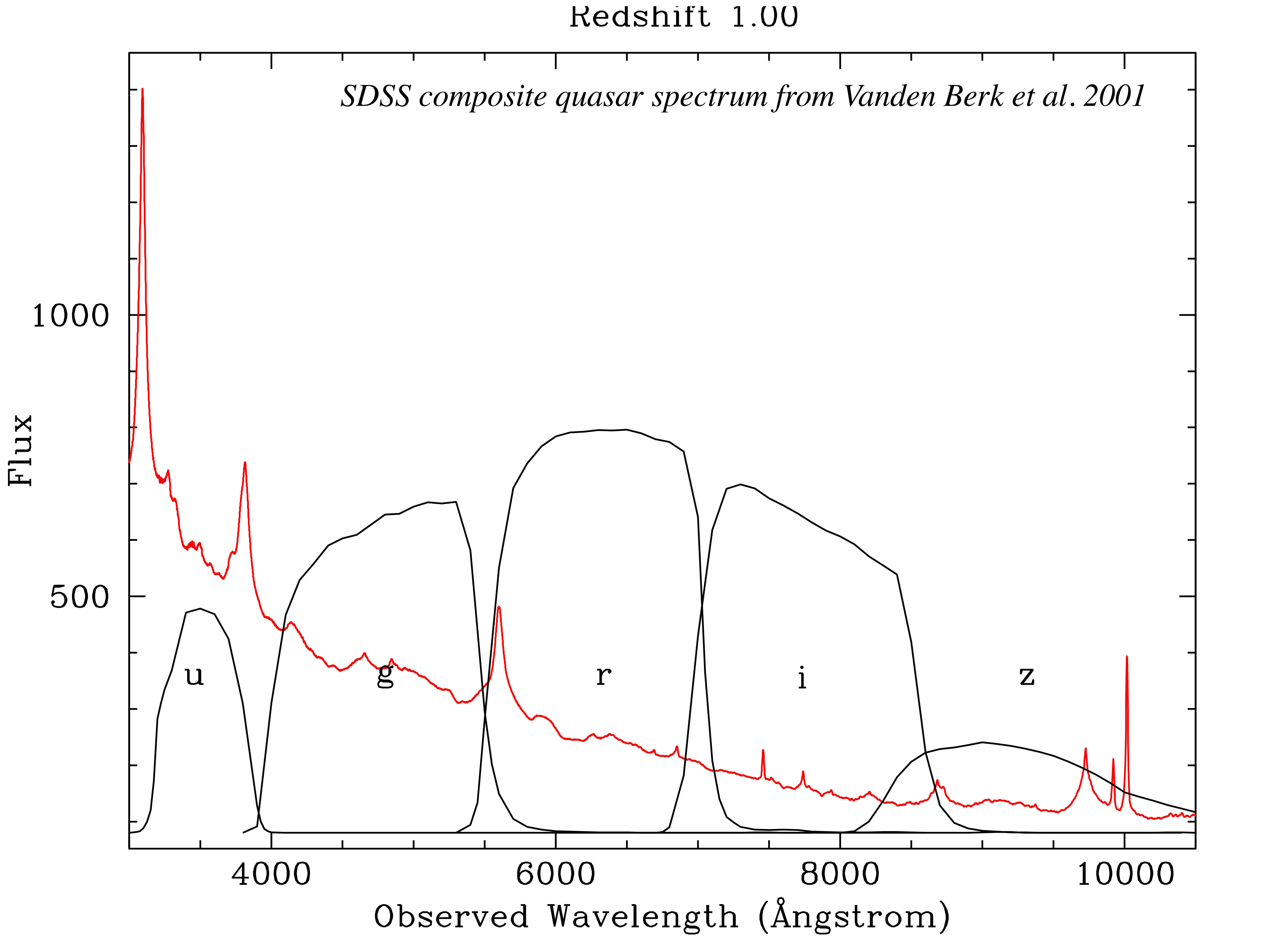
- They are very rare.
- They are faint, and detectable in only the reddest filters.
- They are unresolved, so they look like stars. But they have distinctive colors.

We need wide-field, deep multi-band imaging data to select quasars!

The key surveys are SDSS, Pan-STARRS, and HSC.

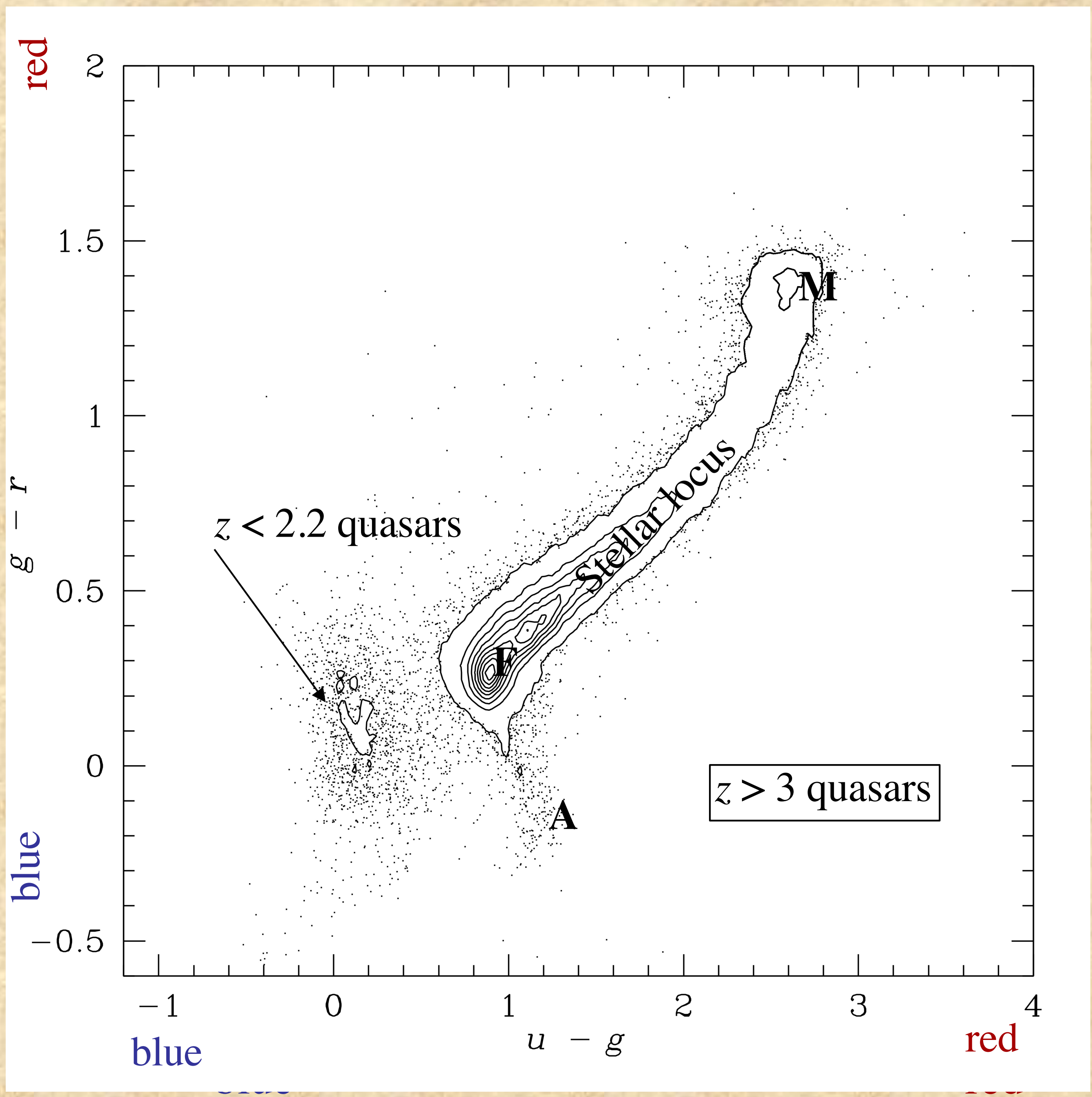
In an image of the sky like this, how do we identify the quasars?

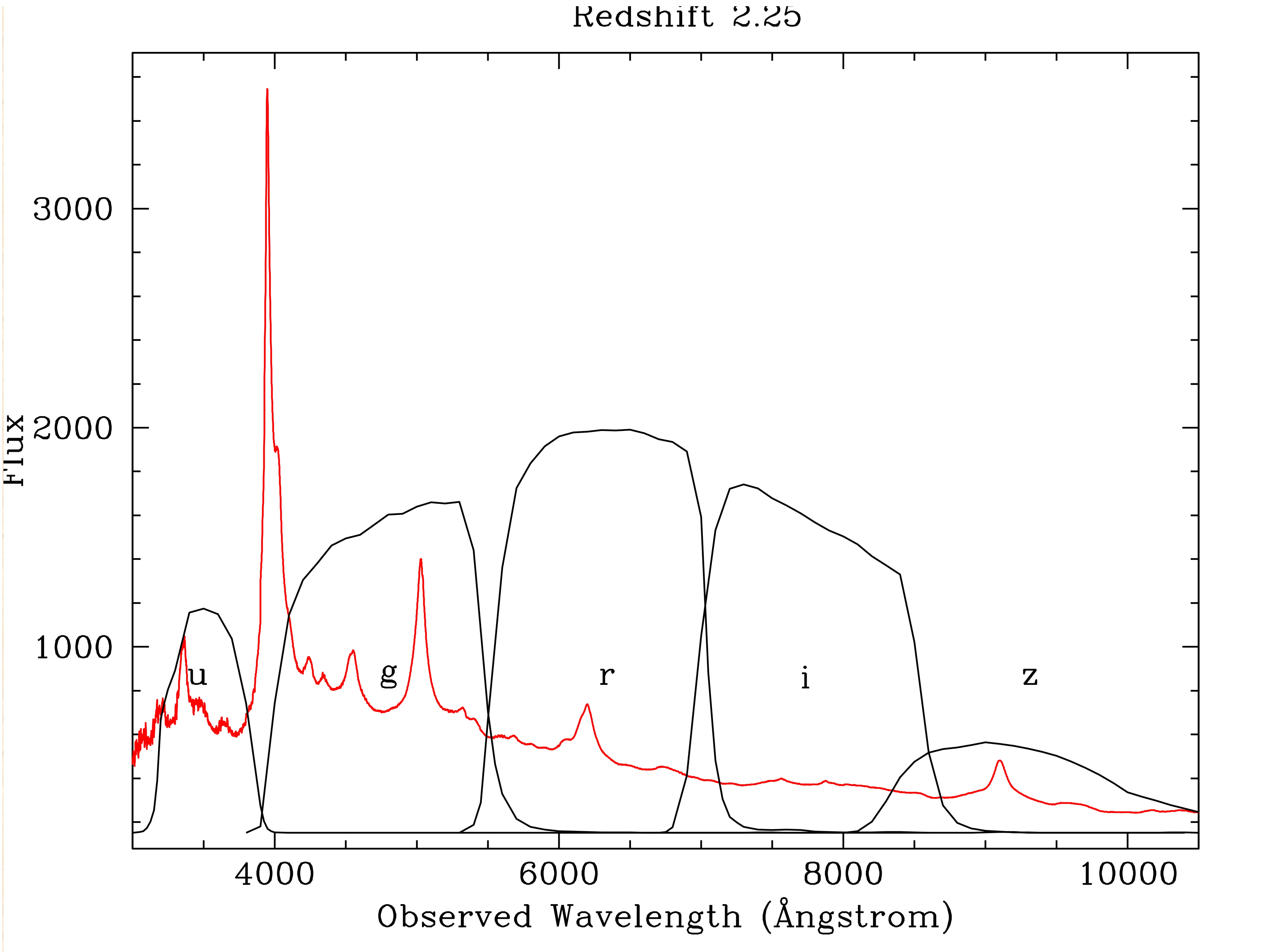


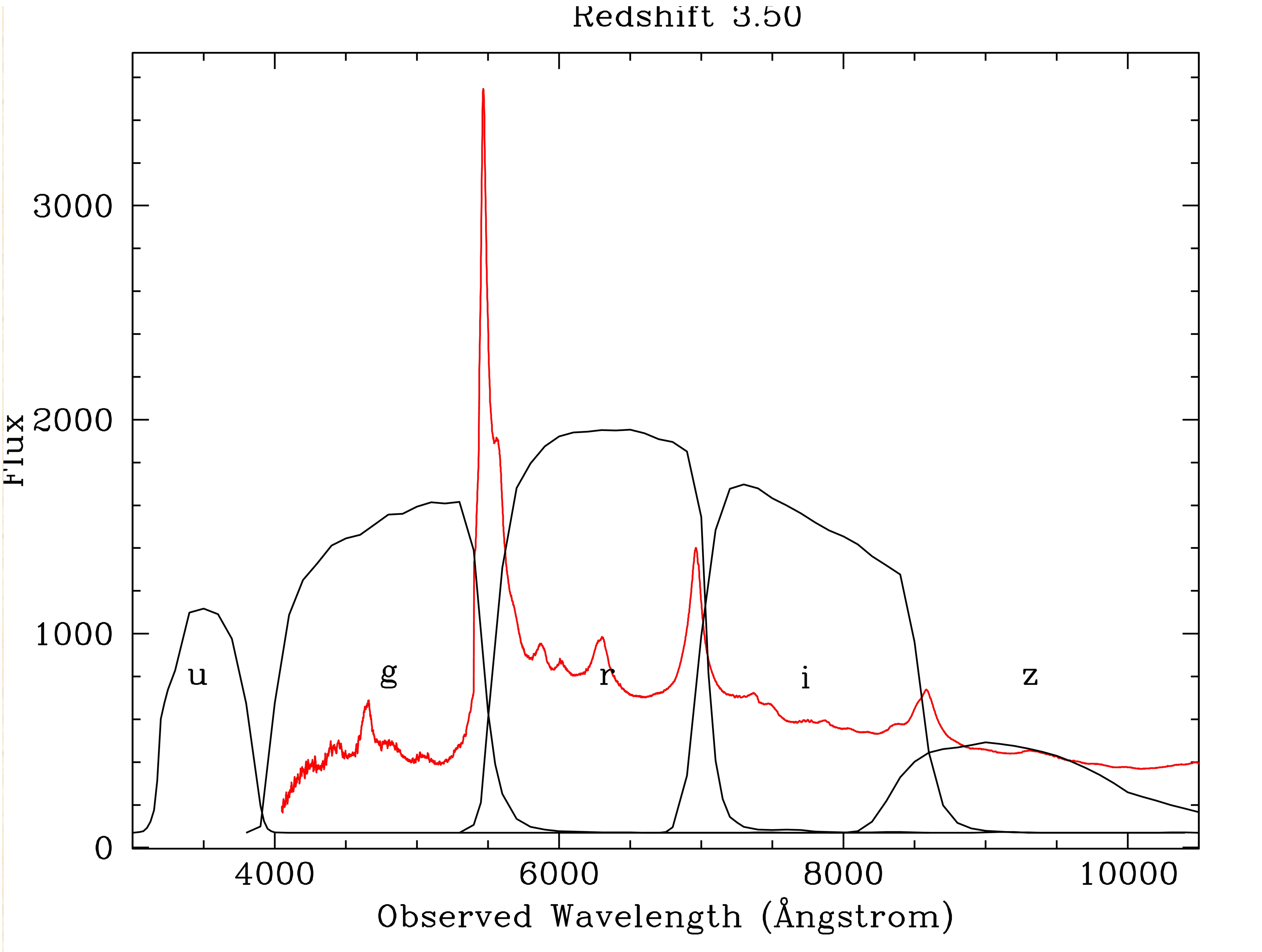

Redshift 1.00
SDSS composite quasar spectrum from Vanden Berk et al. 2001
Flux
1000
500
u
g
r
i
z
4000
6000
8000
10000
Observed Wavelength (Ångstrom)

From the 5 SDSS filters, we can form four independent colors.

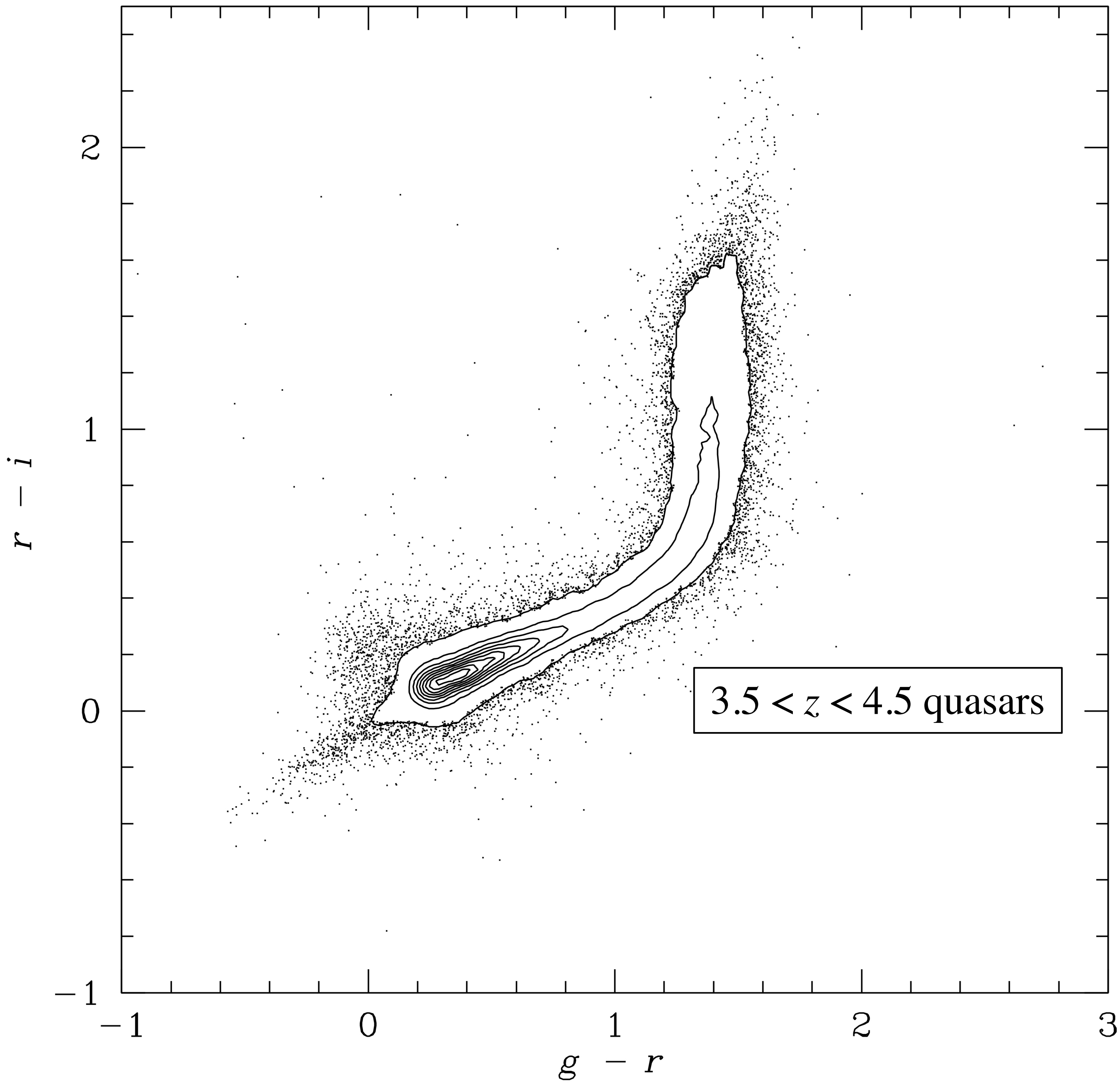
Low-redshift (z<2.2) quasars are blue in *u-g* and *g-r*.

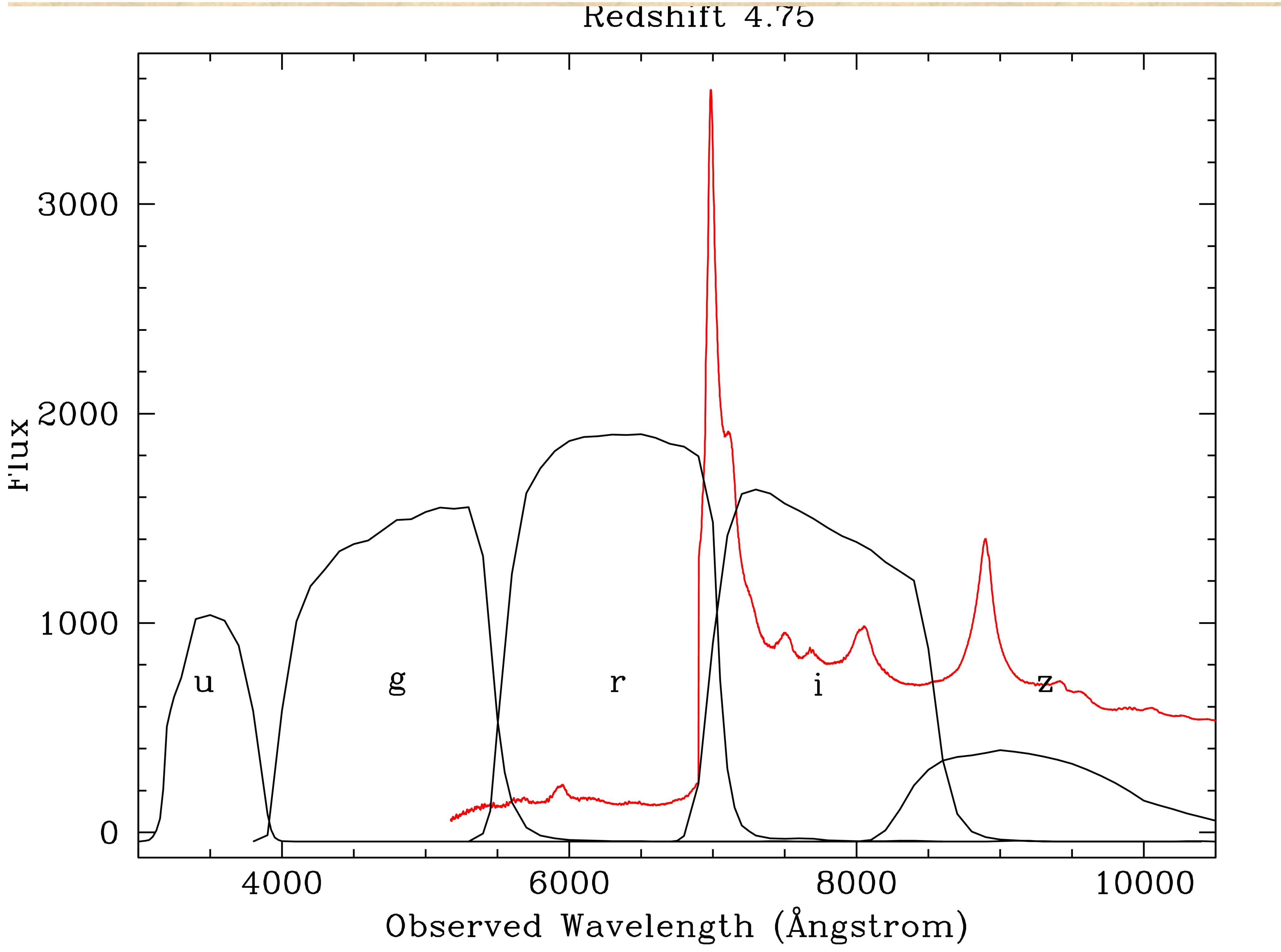


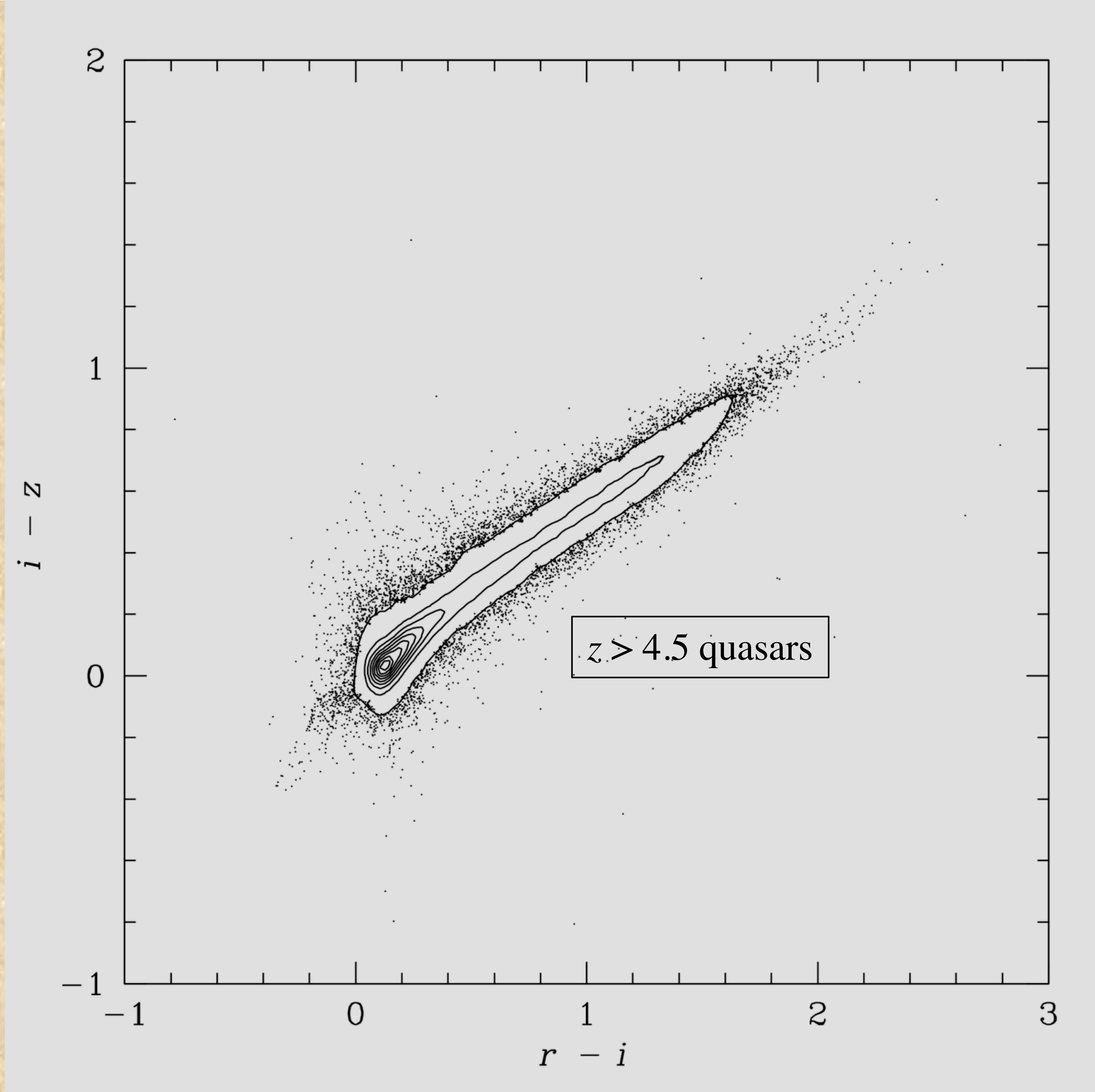

Redshift 2.25
Flux
3000
2000
1000
4000
6000
8000
10000
Observed Wavelength (Ångstrom)
u
g
r
i
z


Redshift 3.50
Flux
Observed Wavelength (Ångstrom)
0
1000
2000
3000
4000
6000
8000
10000
u
g
r
i
z

At $z > 3.5$, quasars drop out of the u-band. The Lyα forest moves into the g band, and quasars become red in g-r.



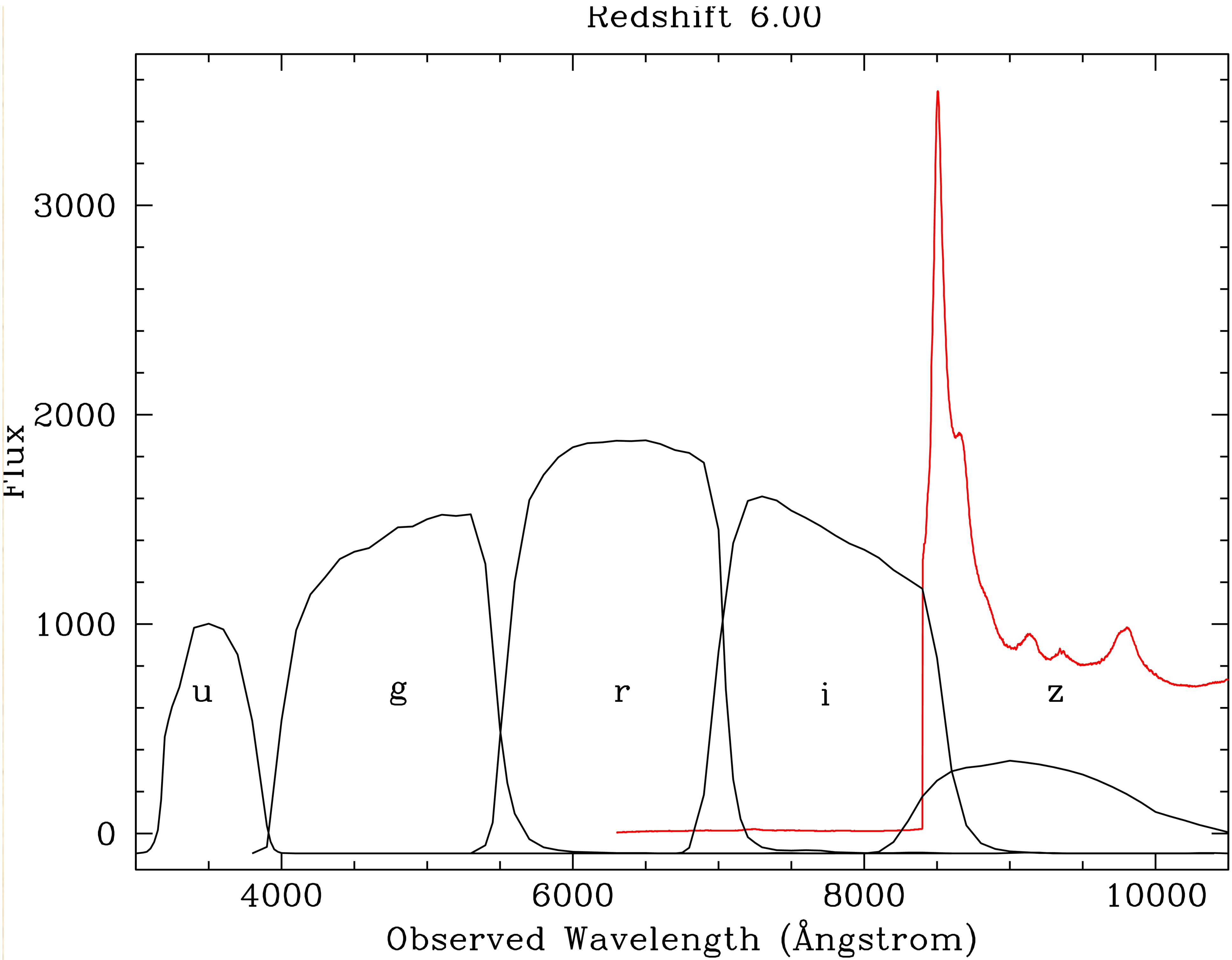

Redshift 4.75
Flux
3000
2000
1000
0
4000
6000
8000
10000
Observed Wavelength (Ångstrom)
u
g
r
i
z



i − z
r − i
z > 4.5 quasars
2
1
0
−1
−1
0
1
2
3

Searching for the highest-redshift quasars

Xiaohui Fan (U. Arizona)
Linhua Jiang (Beijing)
Eduardo Bañados (Carnegie/Princeton)

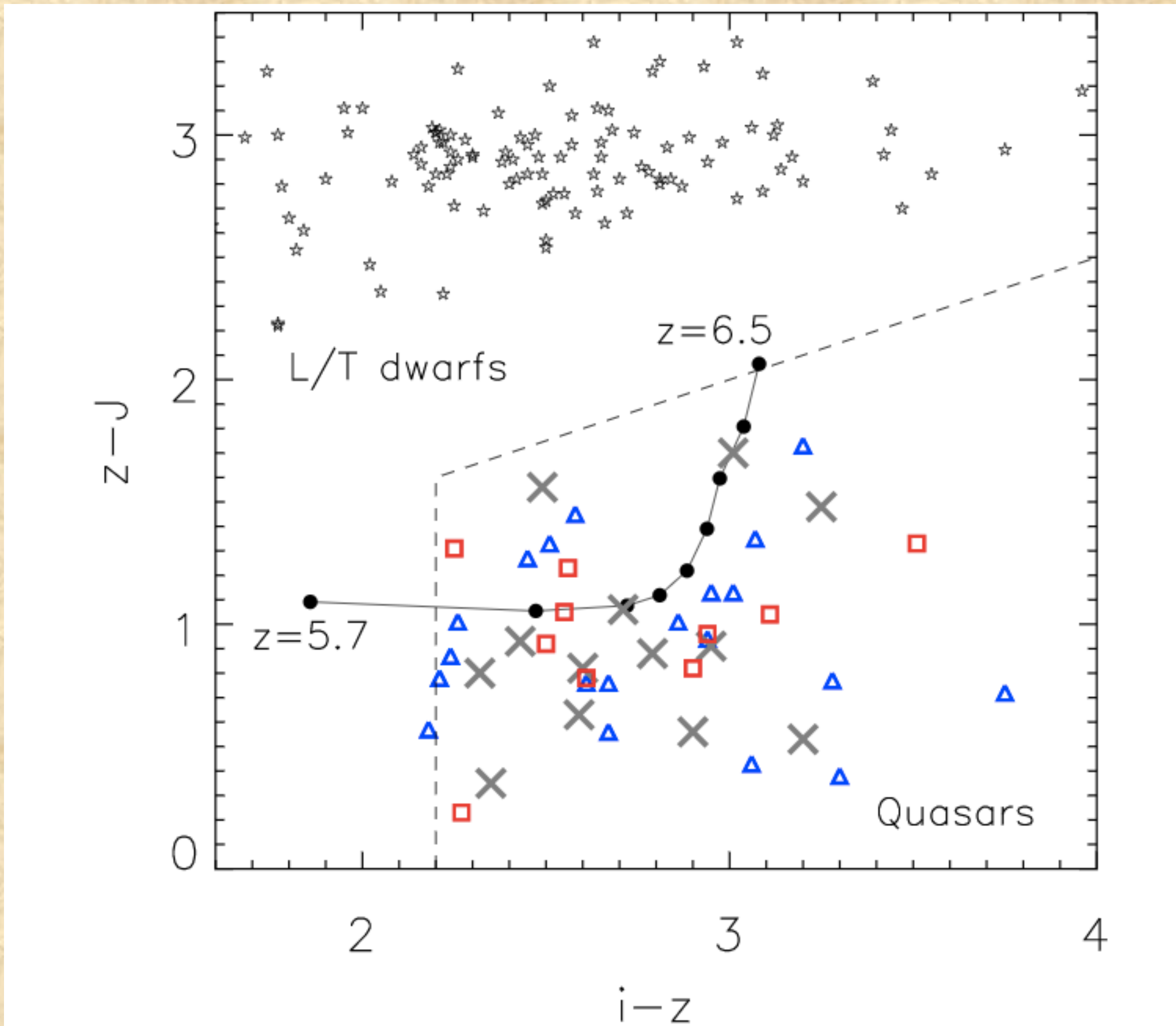


Redshift 6.00
Flux
3000
2000
1000
0
4000
6000
8000
10000
Observed Wavelength (Ångstrom)
u
g
r
i
z

Jiang et al. 2016; J-band data from 2MASS, APO 3.5m, and other telescopes

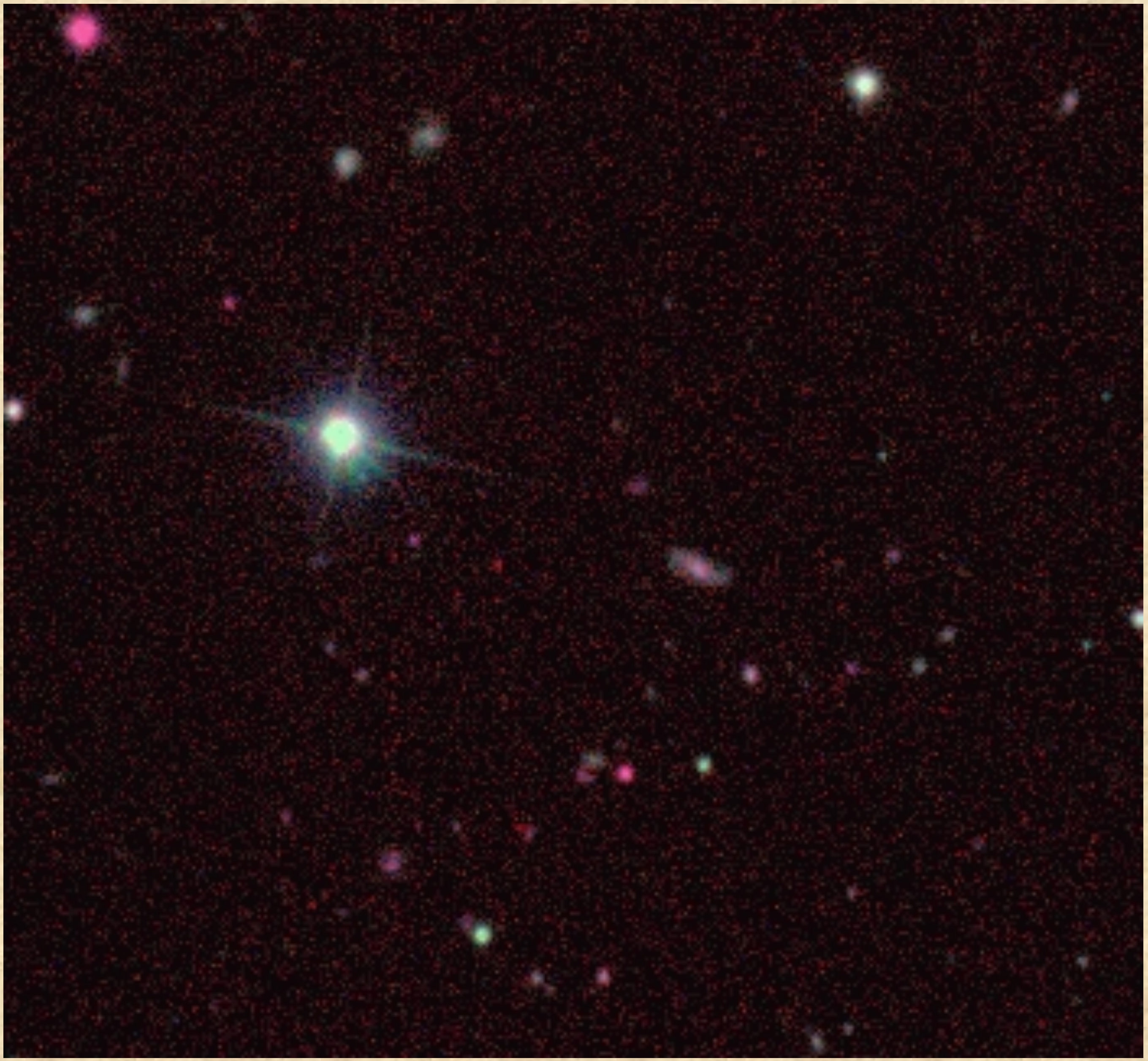
Quasars are red in *i-z*, but blue in *z-J*. Thus they lie far from the stellar/brown dwarf locus.

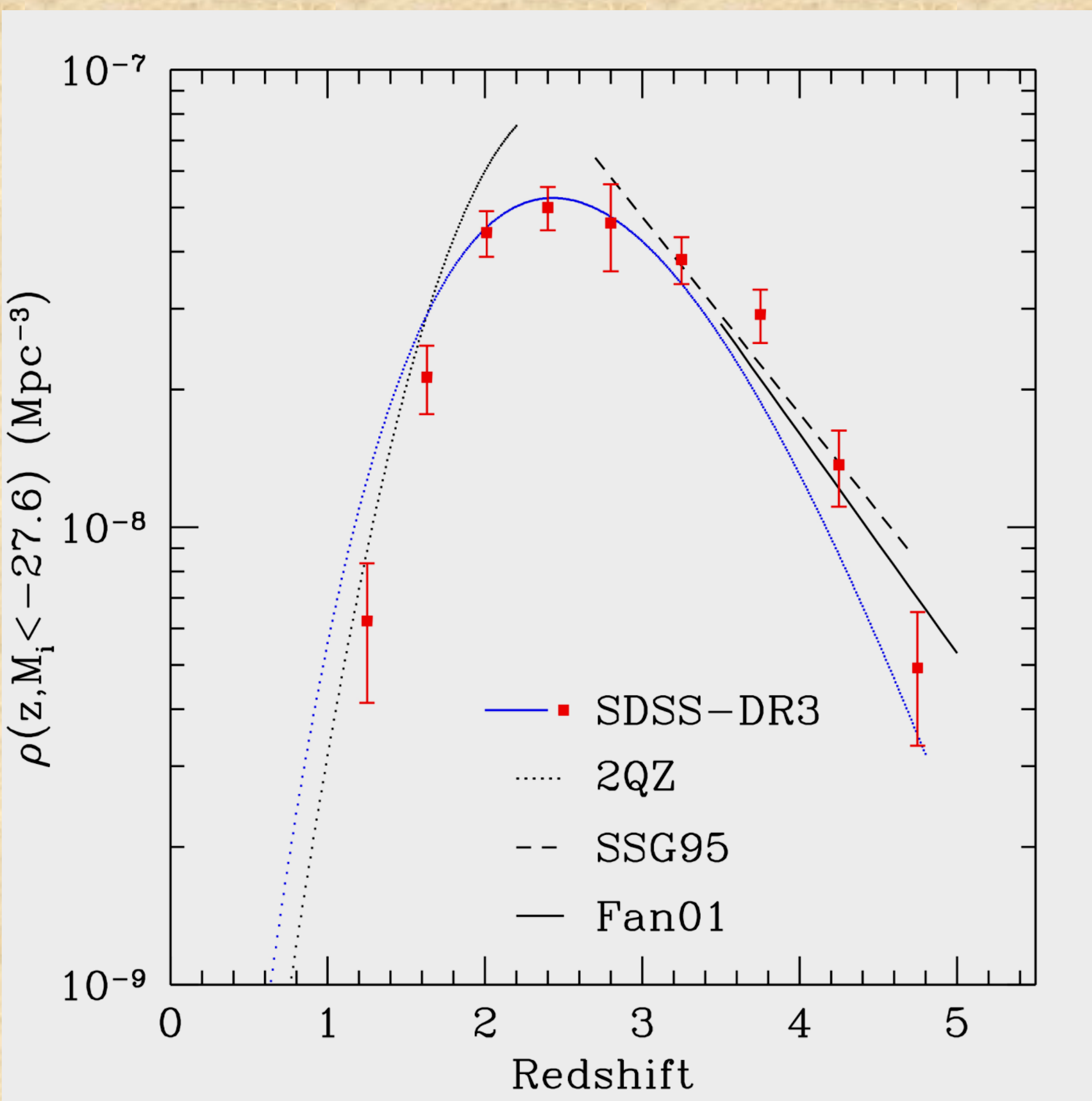
SDSS has used this technique to discover 50+ quasars with *z*>5.5.



Field of *z*~6 quasar, *gri* composite

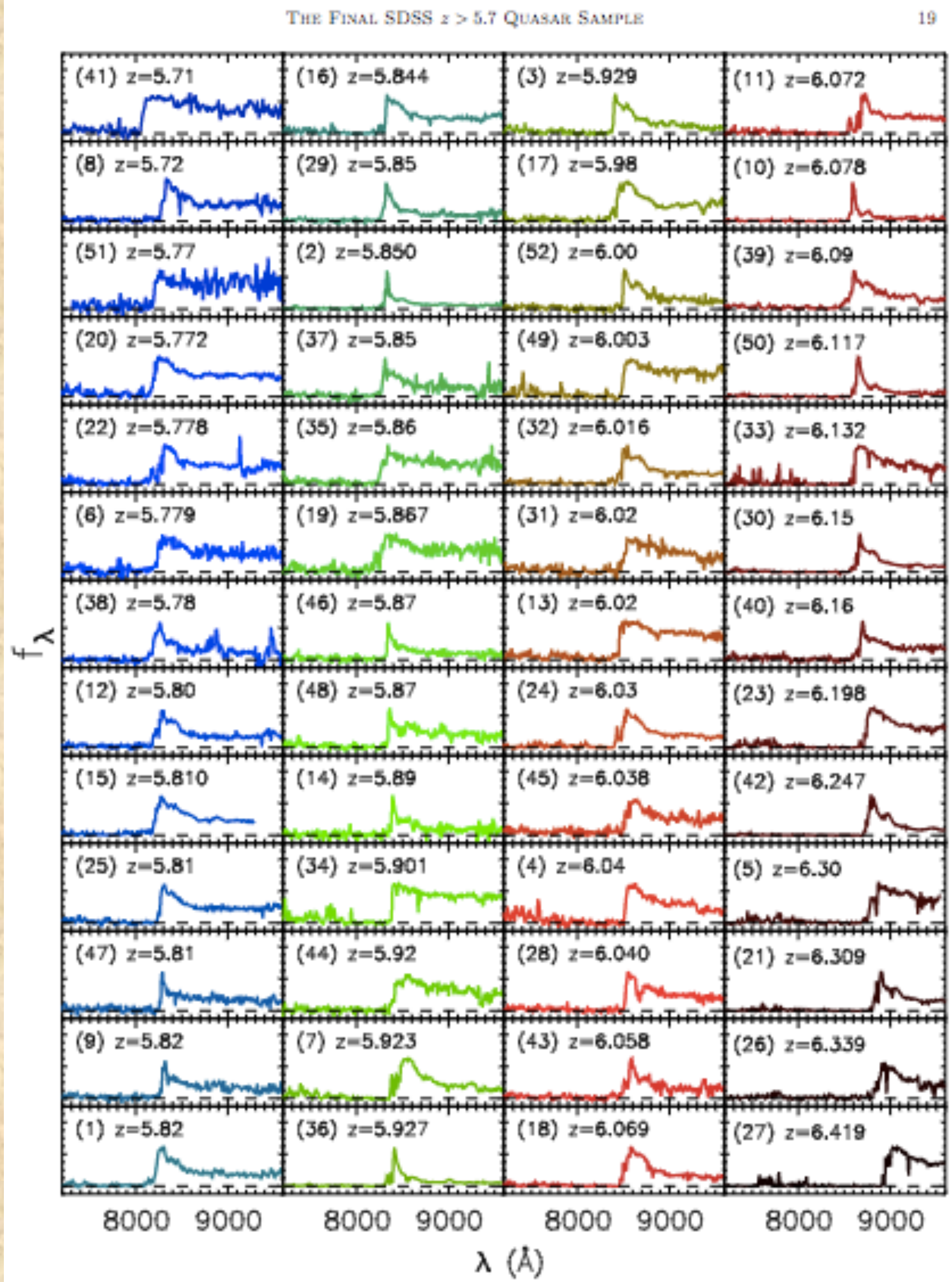
Field of *z*~6 quasar, *riz* composite





High-redshift quasars are rare!

52 SDSS quasars with z>5.7; *Jiang et al. 2016*

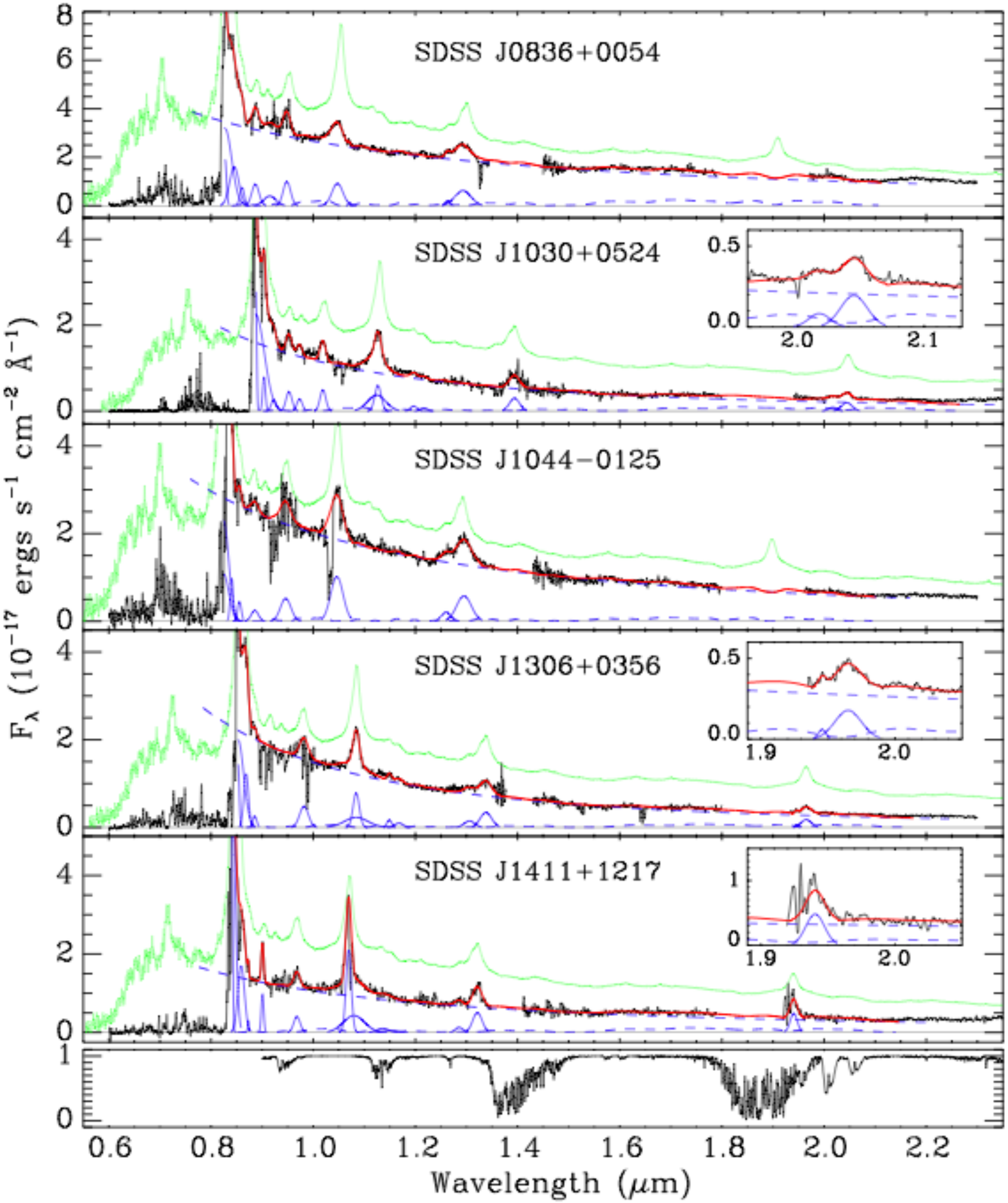


Jiang et al. 2007: Gemini near-infrared spectra of five high-redshift quasars.

Measurements of CIV, MgII line widths give speed of gas in broad-line region. The continuum luminosity is empirically related to the radius of the region, calibrated from AGN with reverberation mapping measurements.

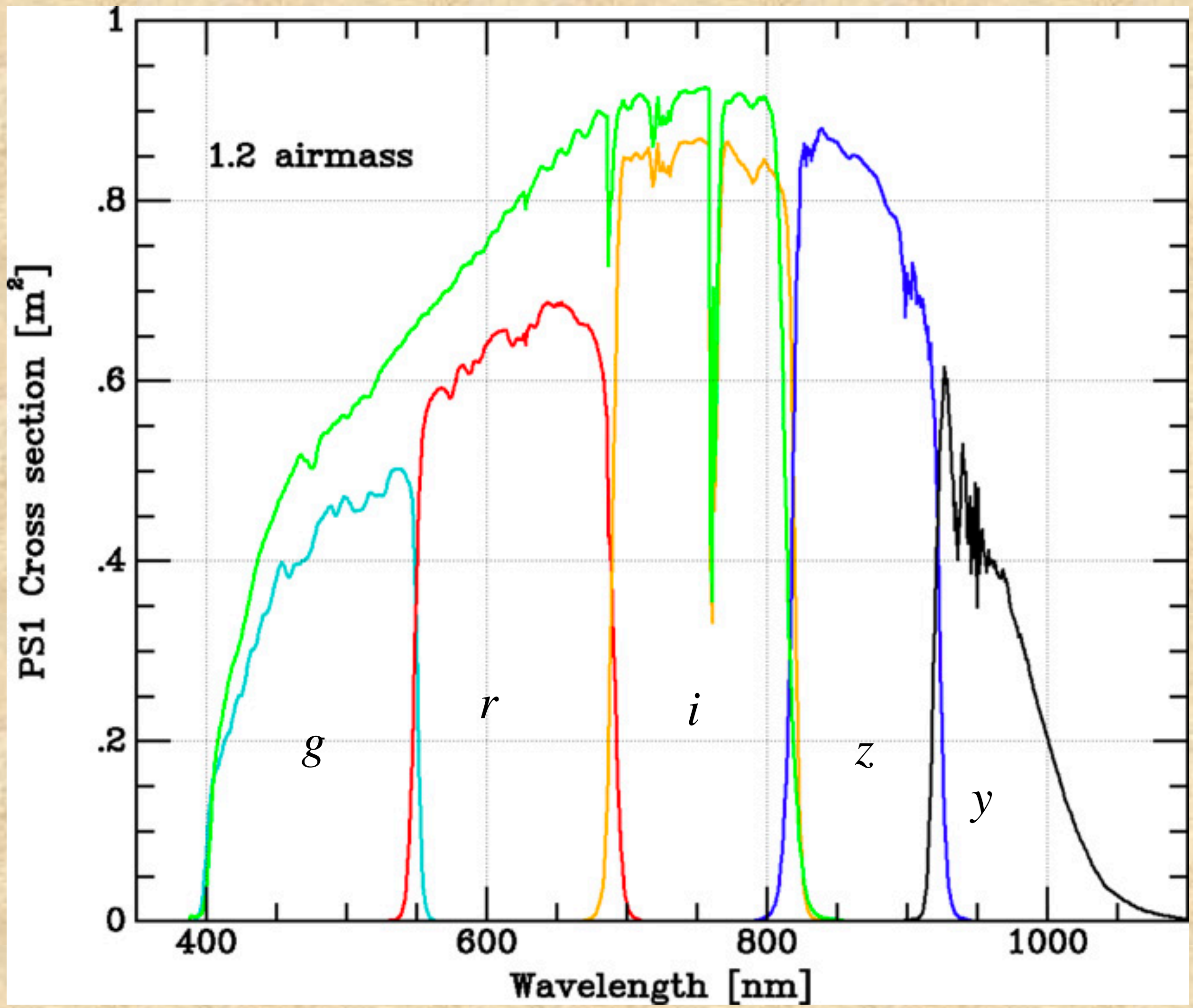
Yields black hole masses 1-3×10^9 solar masses, and Eddington ratios of order 1. Uncertainty of a factor of 3.

Green line: the mean spectra of lower-redshift quasars. ***Indistinguishable from high–z!***

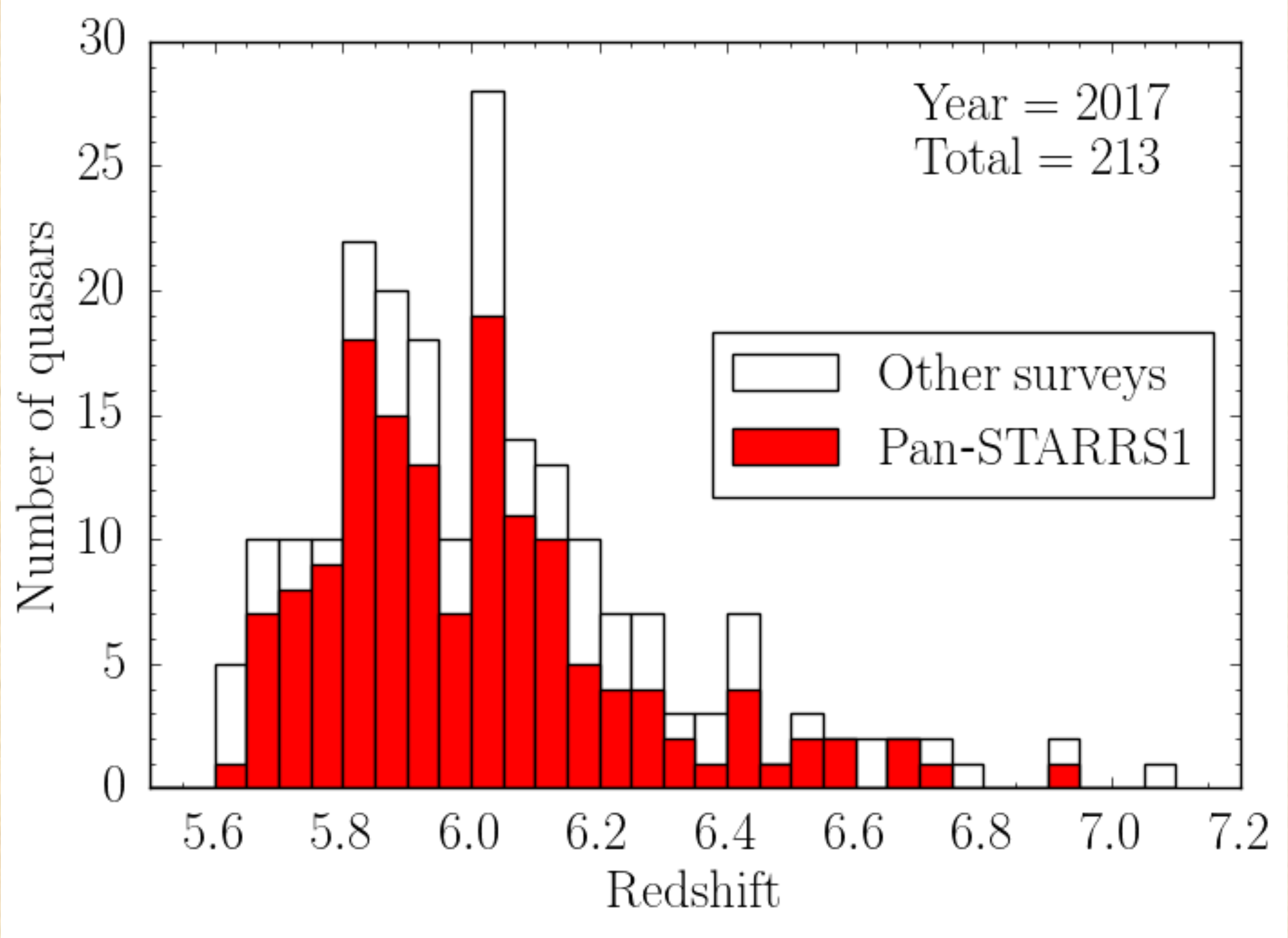


Pushing to higher redshifts requires photometry at longer wavelengths

Tonry et al. 2012: Pan-STARRS filter set.



Redshift distribution of known high-redshift quasars (March 2017)

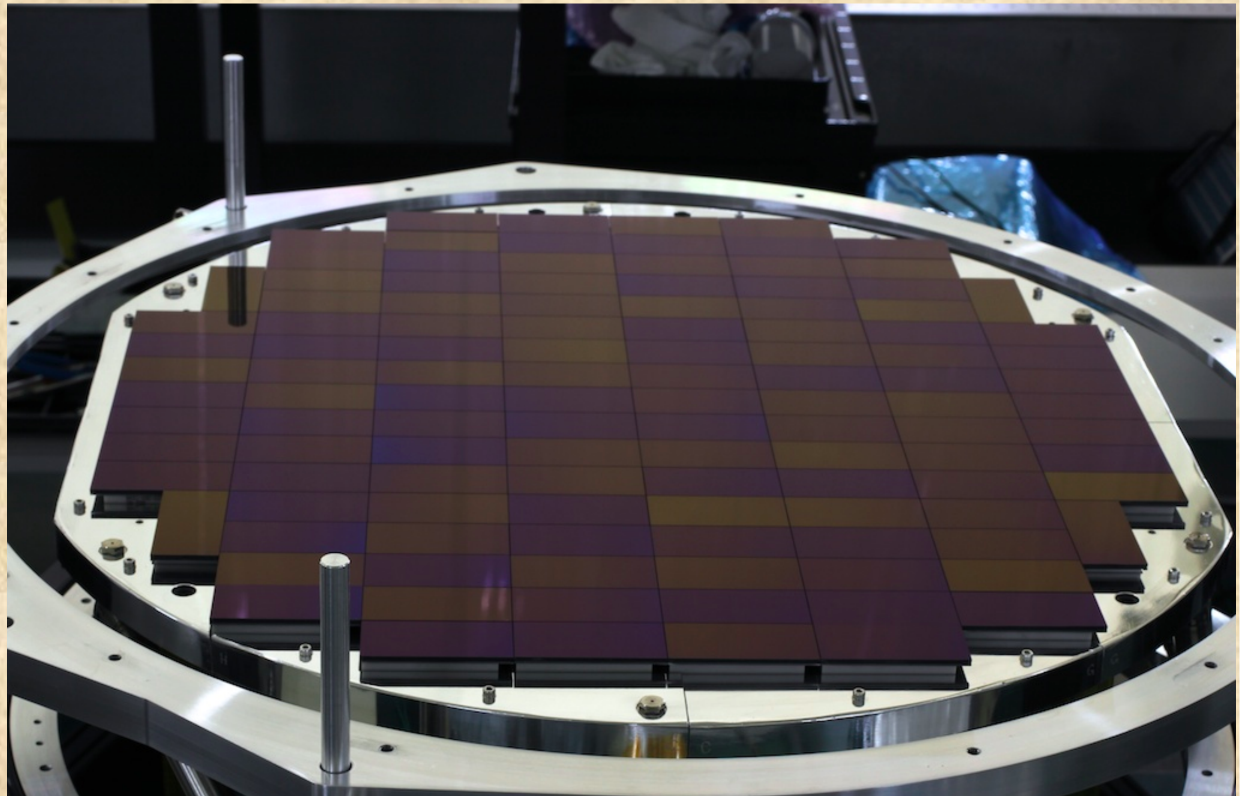


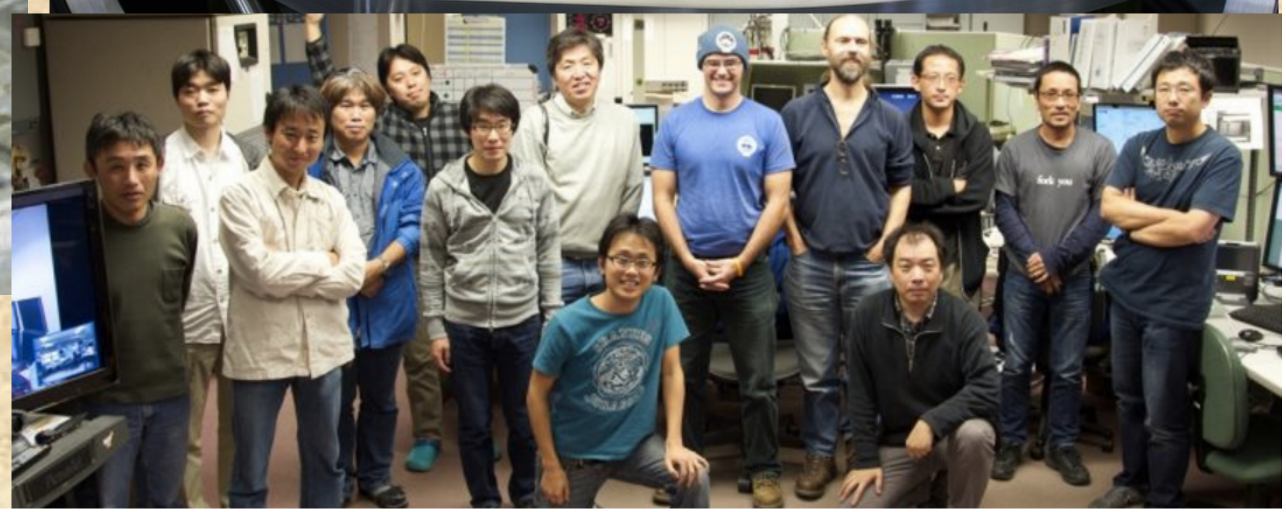
Courtesy Eduardo Bañados

The Subaru Hyper Suprime-Cam High-z Exploration of Low-Luminosity Quasars (SHELLQs)

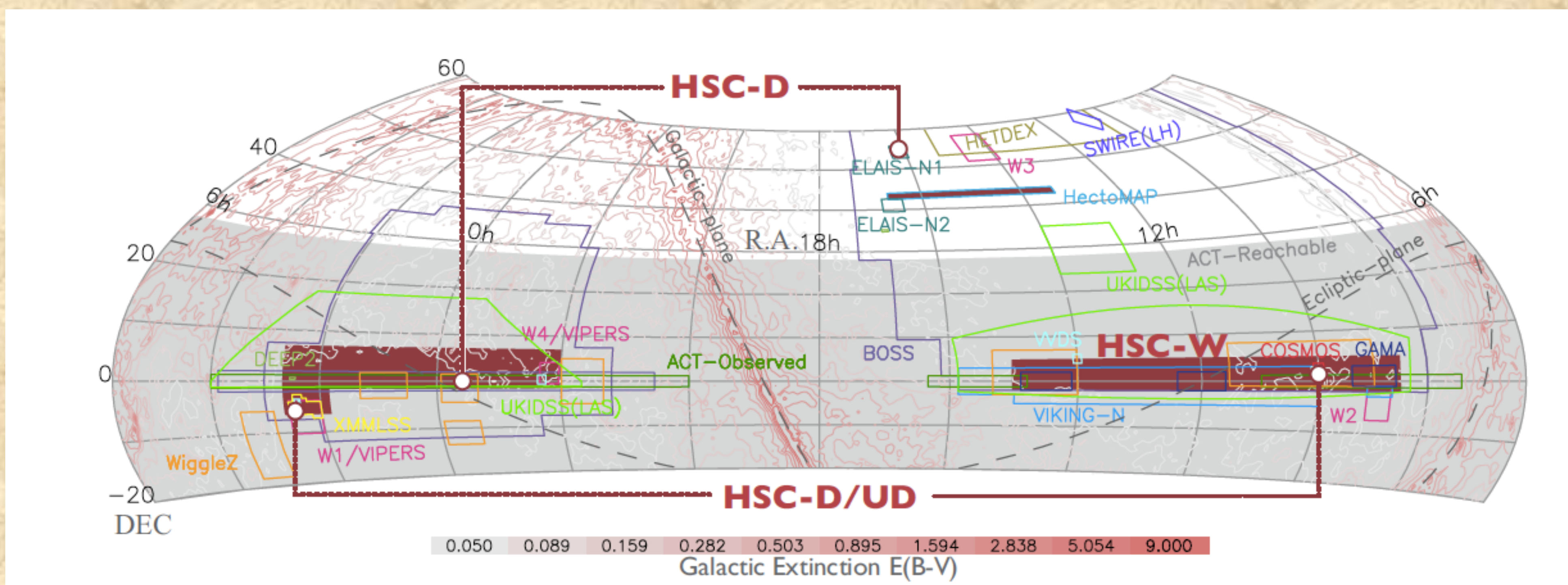
Project led by Yoshiki Matsuoka, NAOJ/Ehime

Hyper-Suprime Cam: 1.77 deg^2 camera on Subaru 8.2m telescope



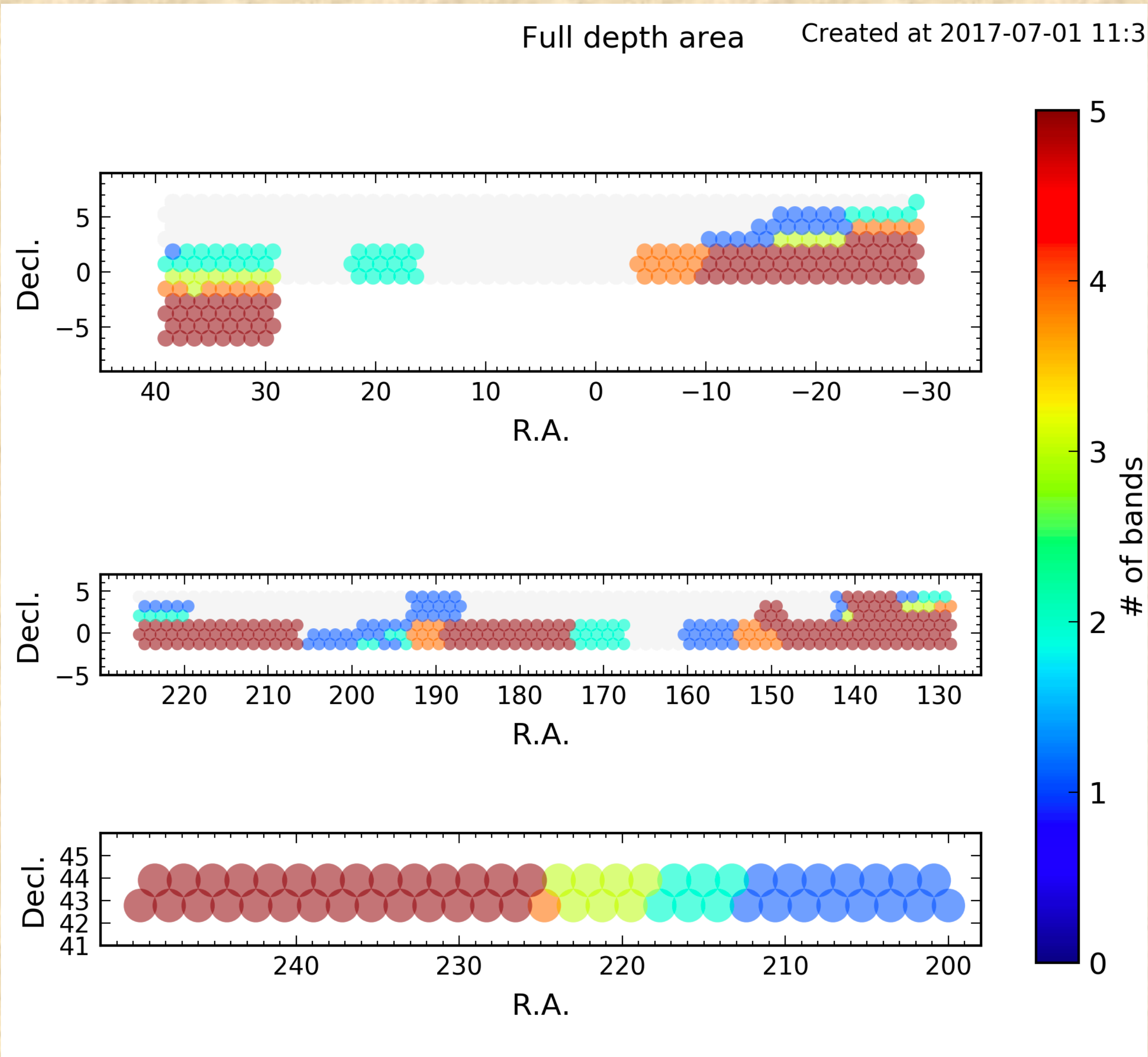


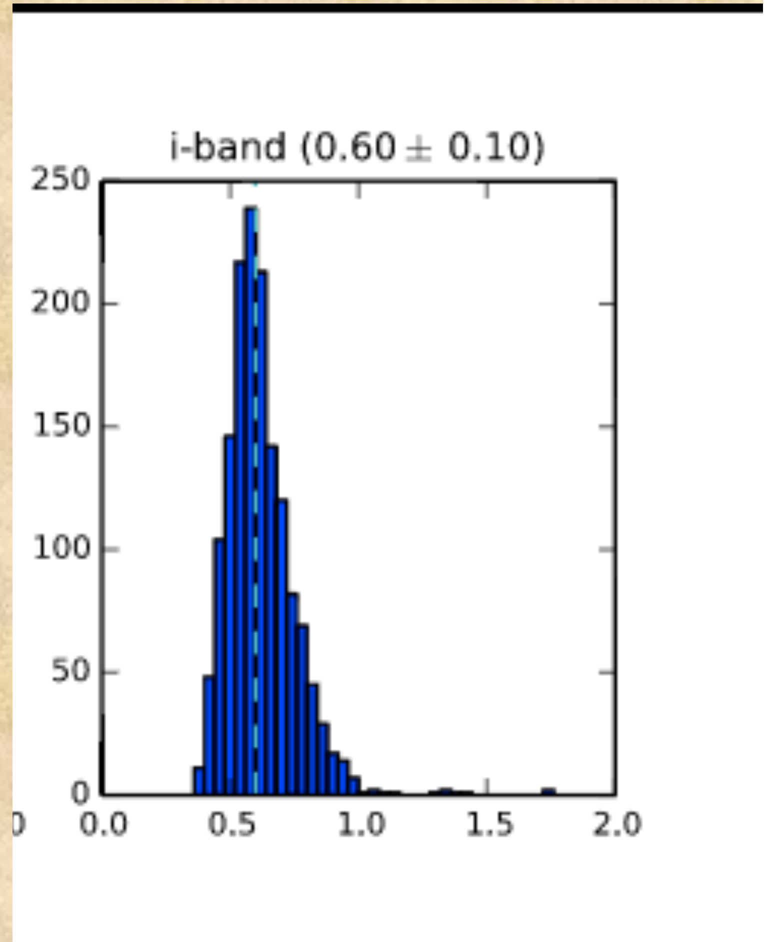
HSC: 300-night survey in grizy + NB filters, over 1400 deg^2 to r=26, plus 28 deg^2 to r=27 and 3.5 deg^2 to r=28. 2014-2019



First public data release (100 deg^2) in February.

Survey progress thus far





Courtesy Naoki Yasuda:
293 deg² in all 5 bands

Median seeing in
i band 0.6 arcsec!

5 arcmin^2 in COSMOS; color composite in *gri*

~1.5 hours in each filter; approaching LSST full depth. ~0.6-0.7" seeing.

This represents <0.01% of the data in hand thus far!

Courtesy Lauren MacArthur

Bayesian probabilistic selection

Quasar probability: $P_Q = W_Q/(W_Q+W_D)$

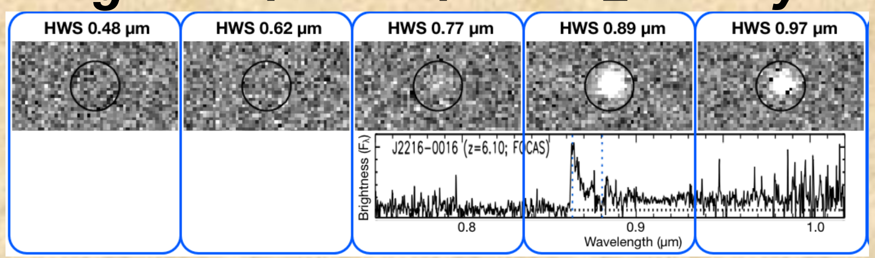
$$W_Q(\mathbf{m}, det) = \int\int \rho_Q(m_{int}, z)\, Pr(det \mid m_{int}, z)\, Pr(\mathbf{m} \mid m_{int}, z)\, dm_{int}\, dz$$

$$W_D(\mathbf{m}, det) = \int\int \rho_D(m_{int}, t_{sp})\, Pr(det \mid m_{int}, t_{sp})\, Pr(\mathbf{m} \mid m_{int}, t_{sp})\, dm_{int}\, dt_{sp}$$

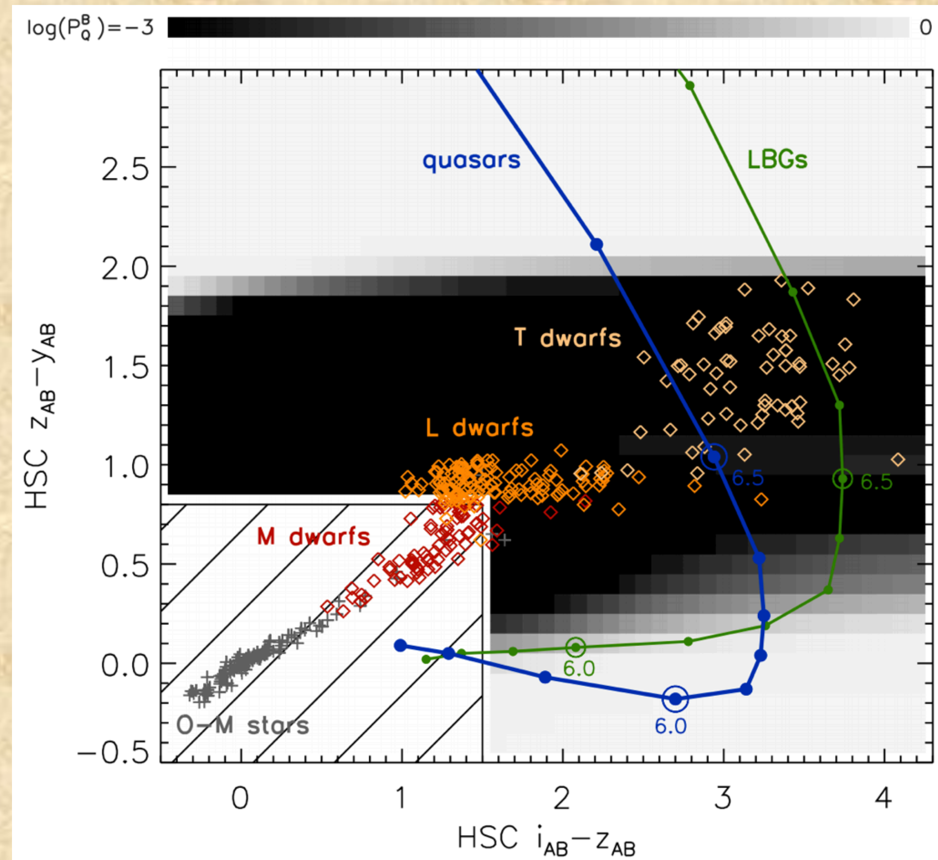
source detection

observed magnitudes in HSC + NIR bands

g r i z y



→ Spectroscopic follow-up of all the photometric candidates with $P_Q > 0.1$ on Subaru/FOCAS, GTC/OSIRIS, Gemini/GMOS-S



P_Q distribution in (i-z vs. z-y)

Progress to date

✶ The HSC survey has imaged ~250 deg^2 (full color, full depth) of the planned Wide

fields, as of Jan 2017. Most of our candidates have come

fro s

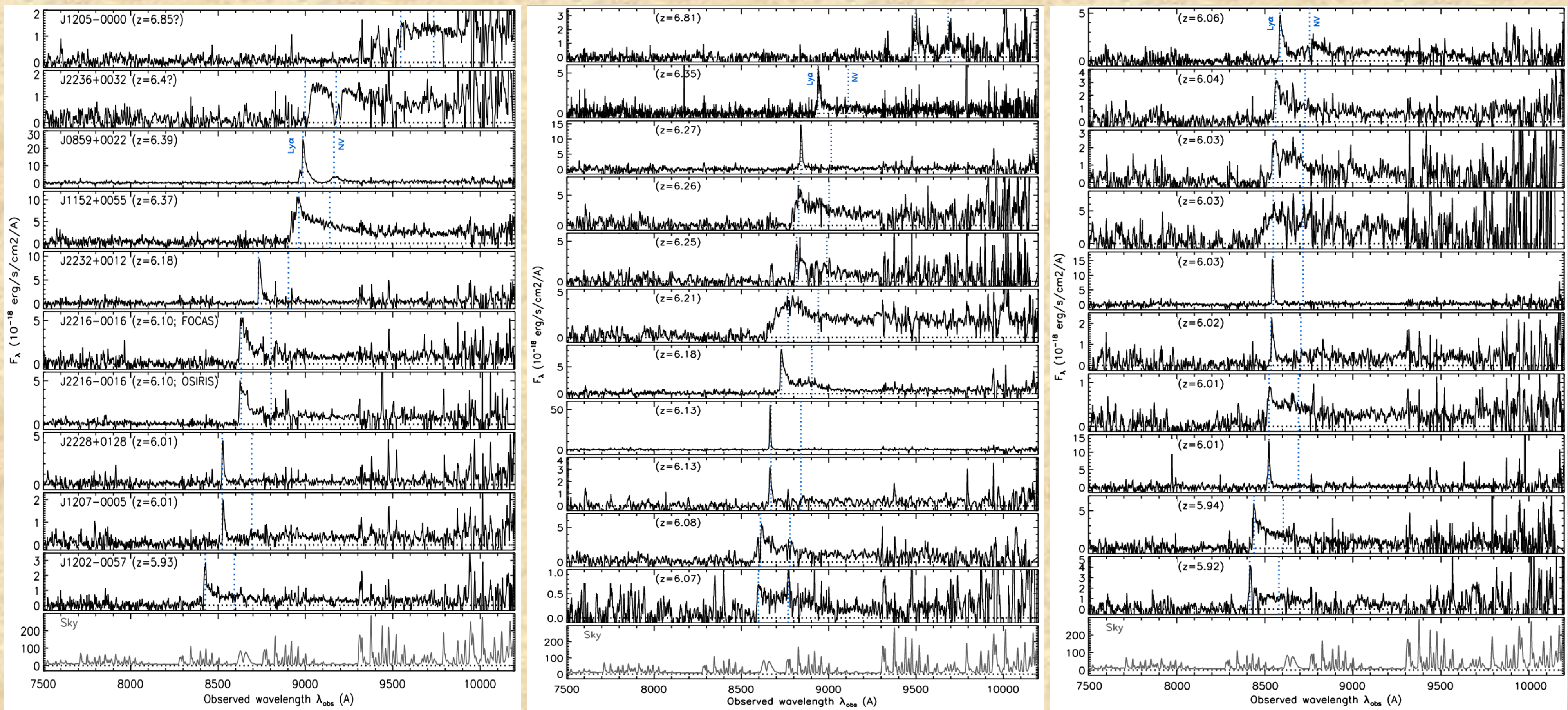
✶ lo :

be :

✔ Subaru/FOCAS: 1 night in S15A... weathered out

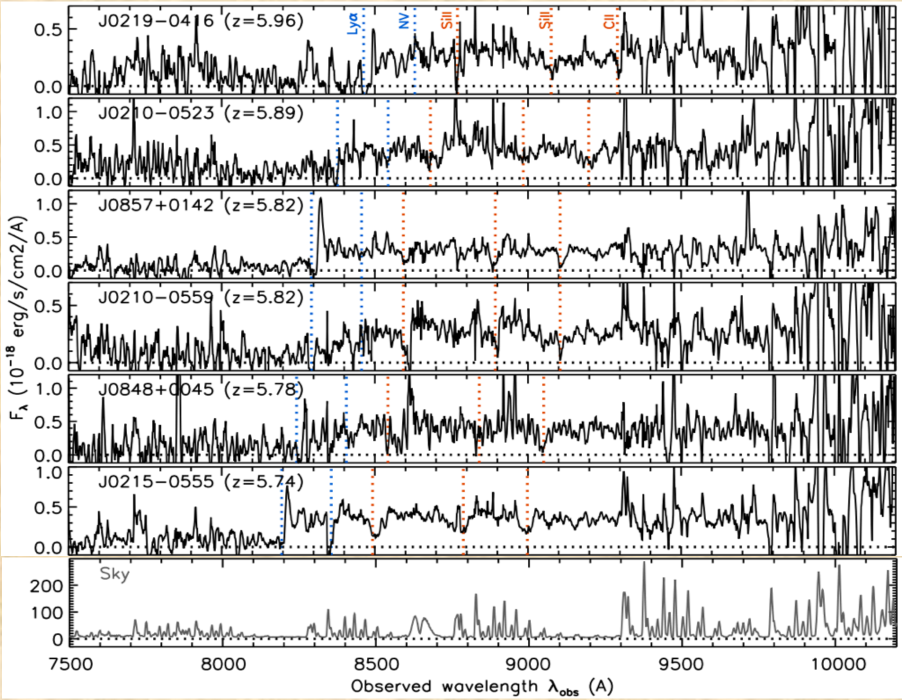
4 nights in S15B... mostly clear

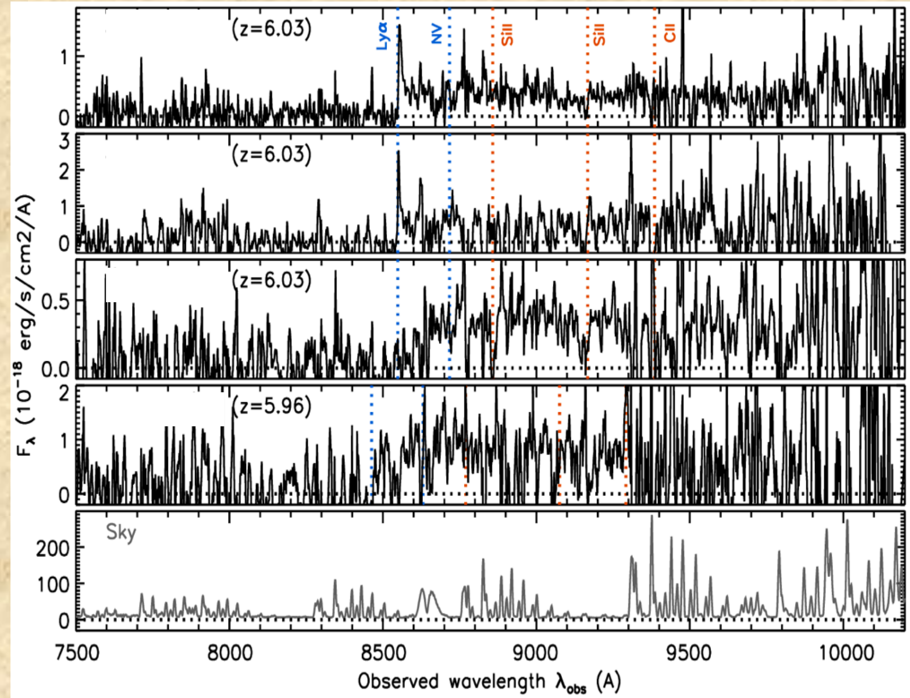
Quasars



- ~30 new quasars at $5.9 < z < 6.9$ (+ 5 quasars recovered) over ~100-150 deg^2.
- *Note the objects with narrow Ly alpha.*
- *We classify all the objects with L(Ly α) > 10^{43} erg/s or FWHM(Ly α) > 500 km/s (uncorrected for IGM absorption) as AGN.*

Galaxies

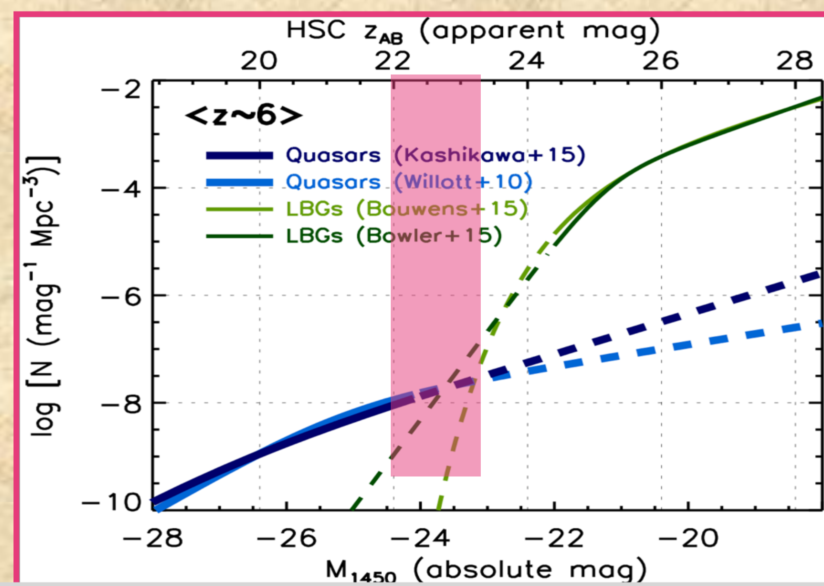




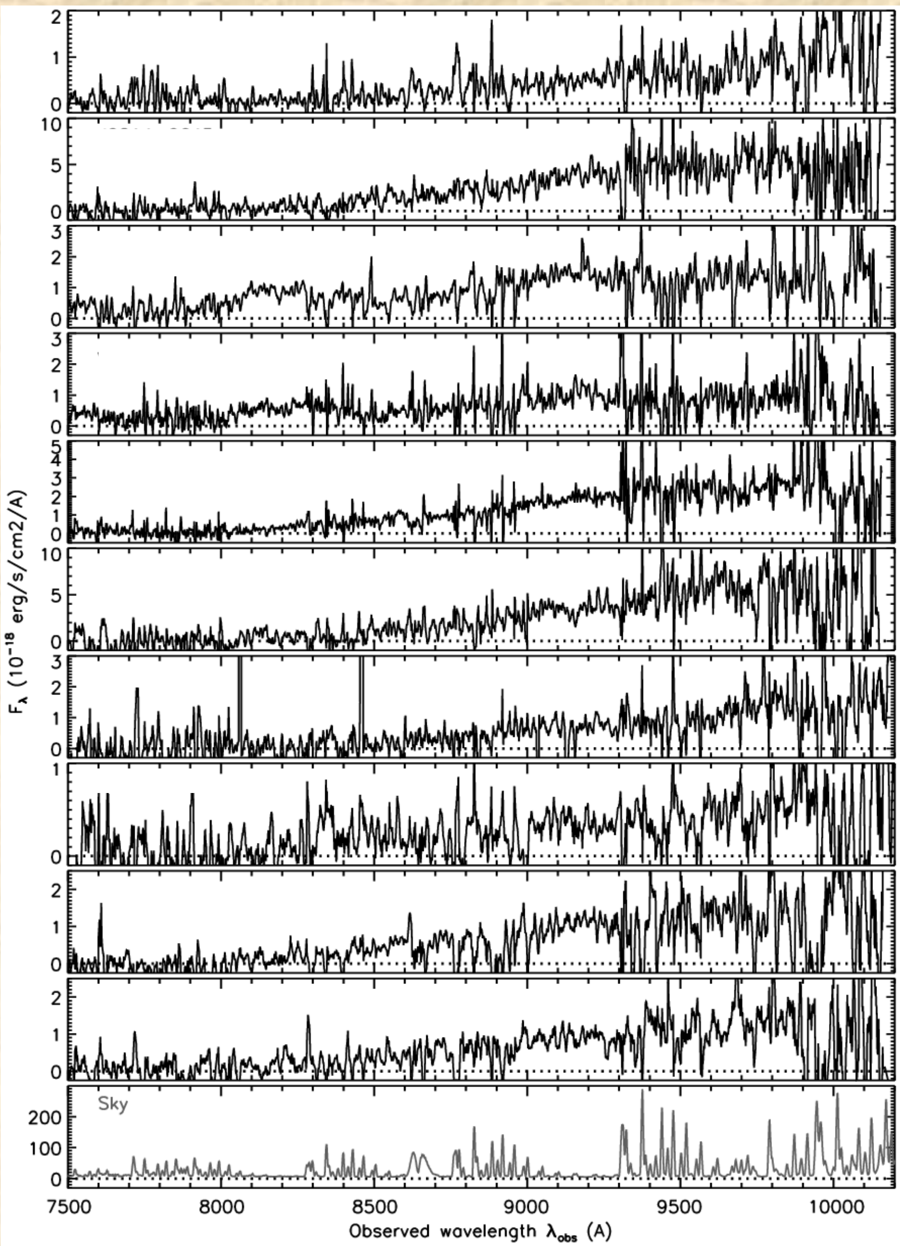
✶ 9 luminous galaxies at $5.7 < z < 6.1$, with $-23.5 < M_{1350} < -22$ mag.

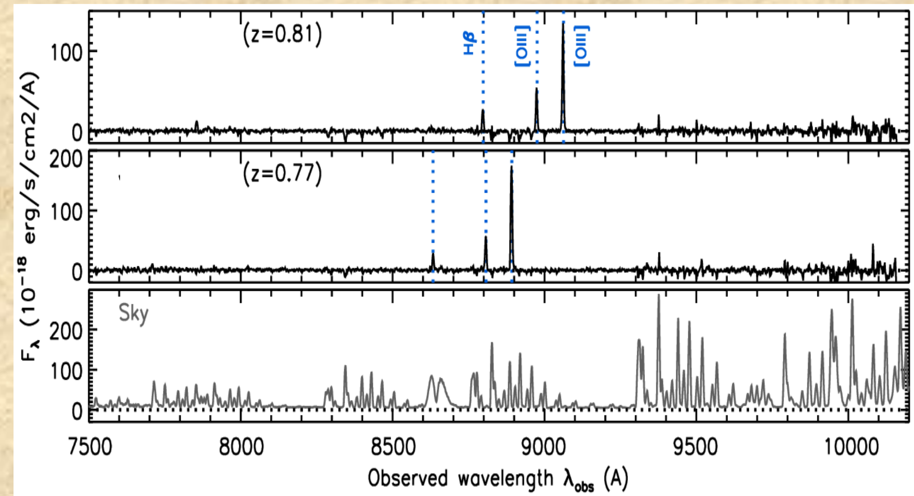
✶ Extended sources are not selected, so this is a lower limit to the number density of high-z luminous galaxies.

Matsuoka+16



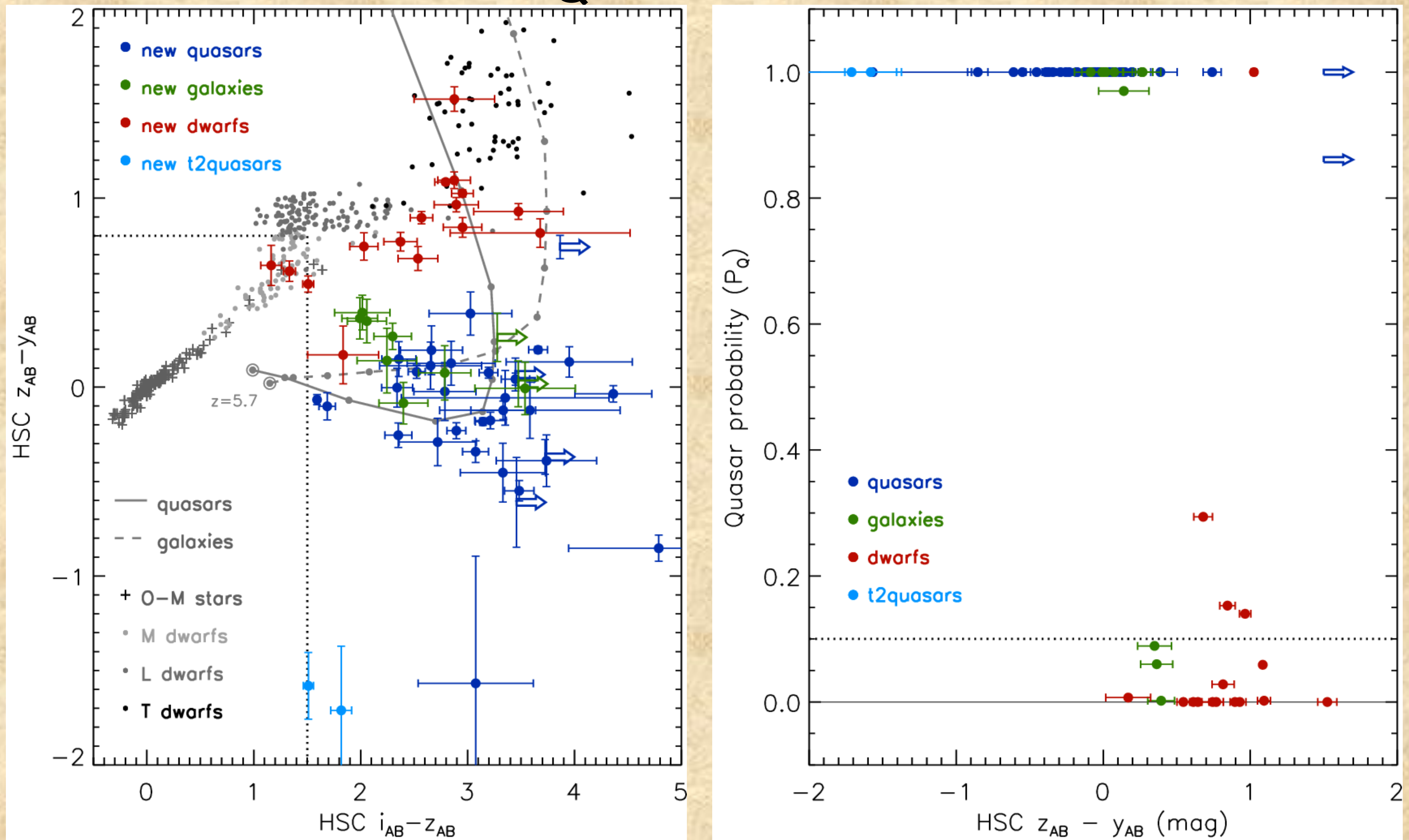
Brown dwarfs and low-z [O III] emitters



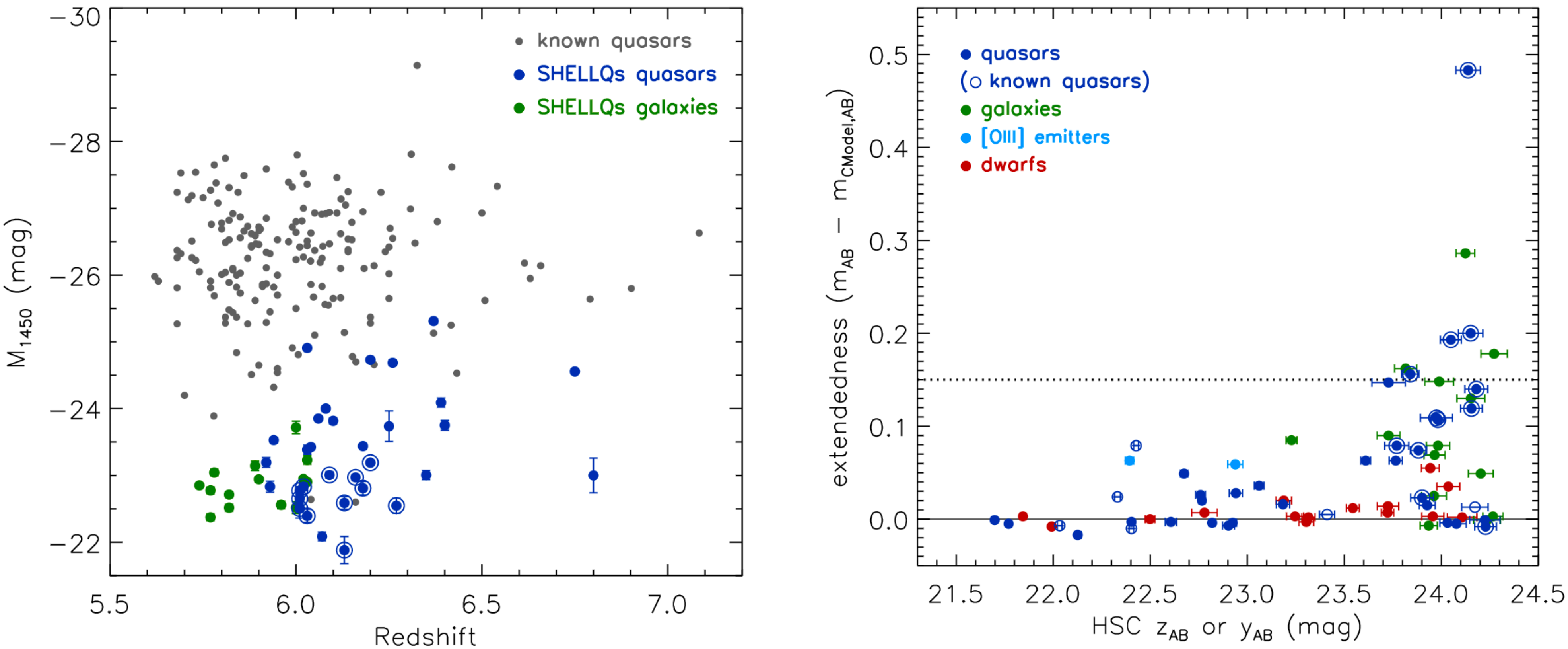


- *Small number of contaminating brown dwarfs. Most of these objects have low quasar probability P_Q.*
- *2 type-II quasars or low-metallicity star-forming galaxies at z ~ 0.8, with $L_{[OIII]} \sim 10^{42.5}$ erg/s. The strong [O III] lines mimic Ly α at z ~ 6.*

Distribution in color and quasar probability P_Q

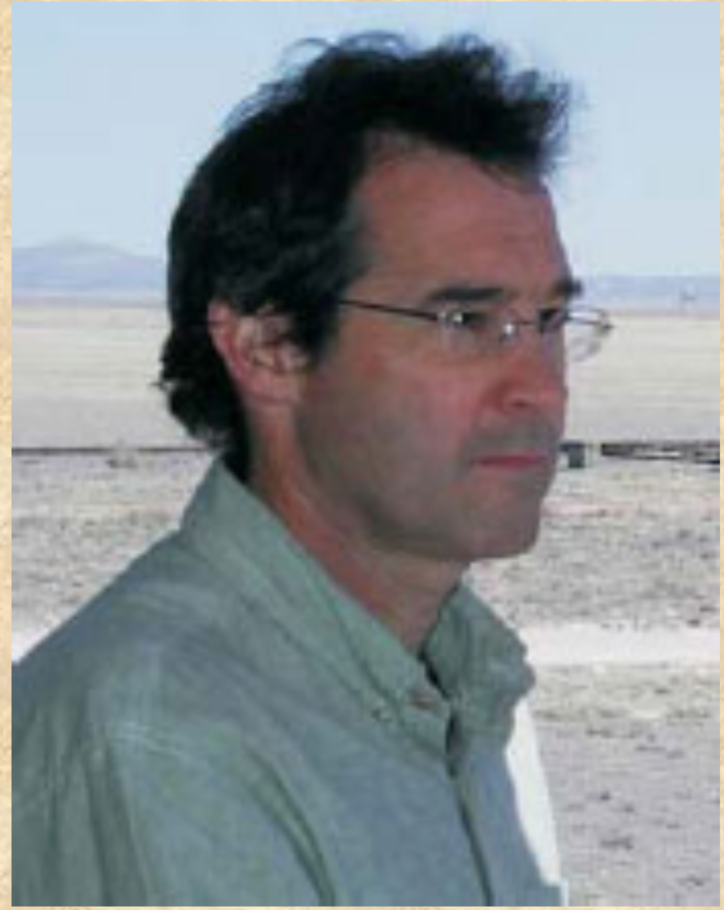


Distribution in Absolute Mag and Extendedness



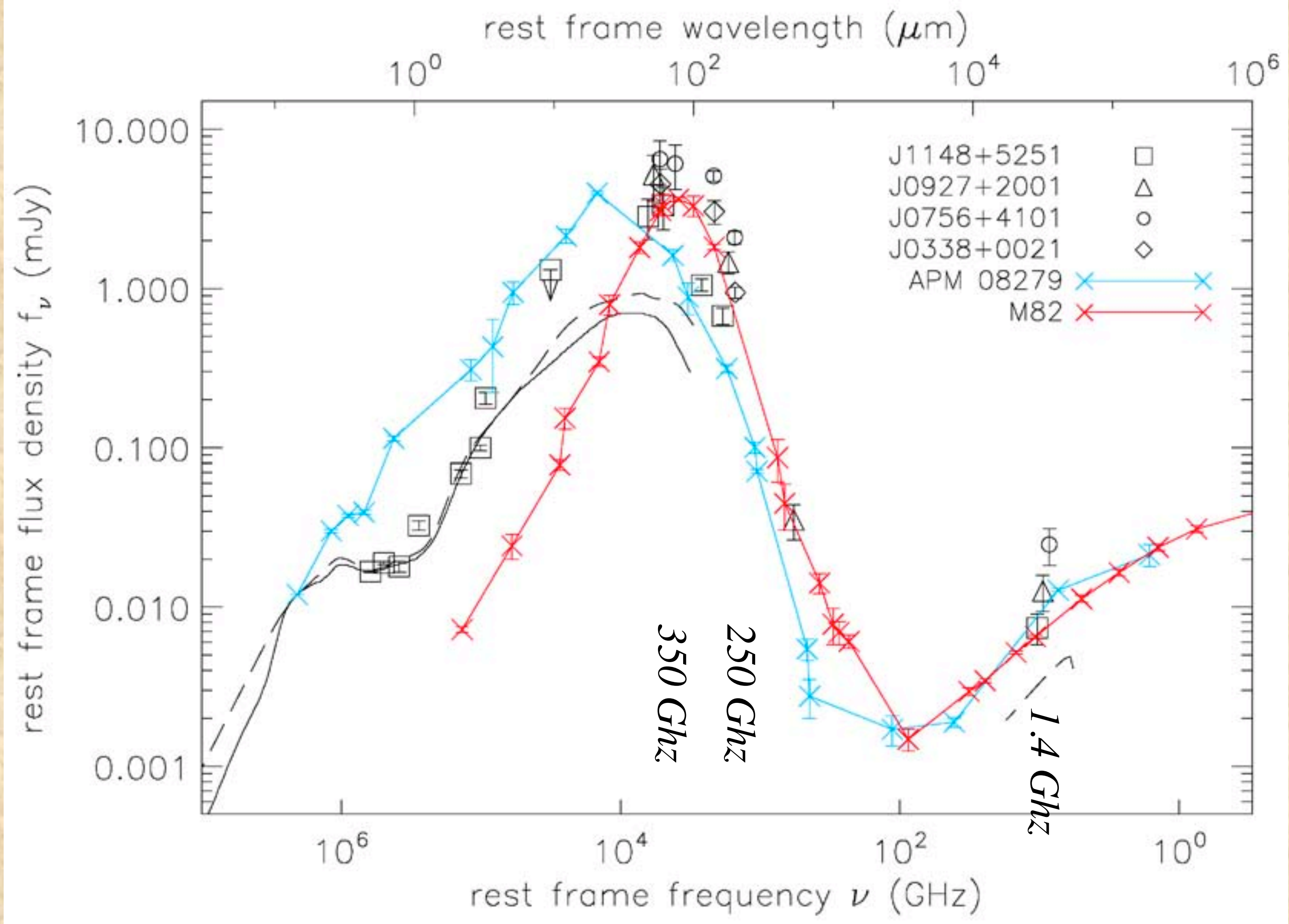
Studying the host galaxies of z~6 quasars at sub-mm wavelengths

Ran Wang, Beijing



Chris Carilli, NRAO

50 K dust heated by star formation or the quasar is detectable at submm wavelengths.



Wang et al. 2008

Pico Veleta, Spain: 30-meter dish with MAMBO 37-channel array bolometer

Very Large Array, New Mexico

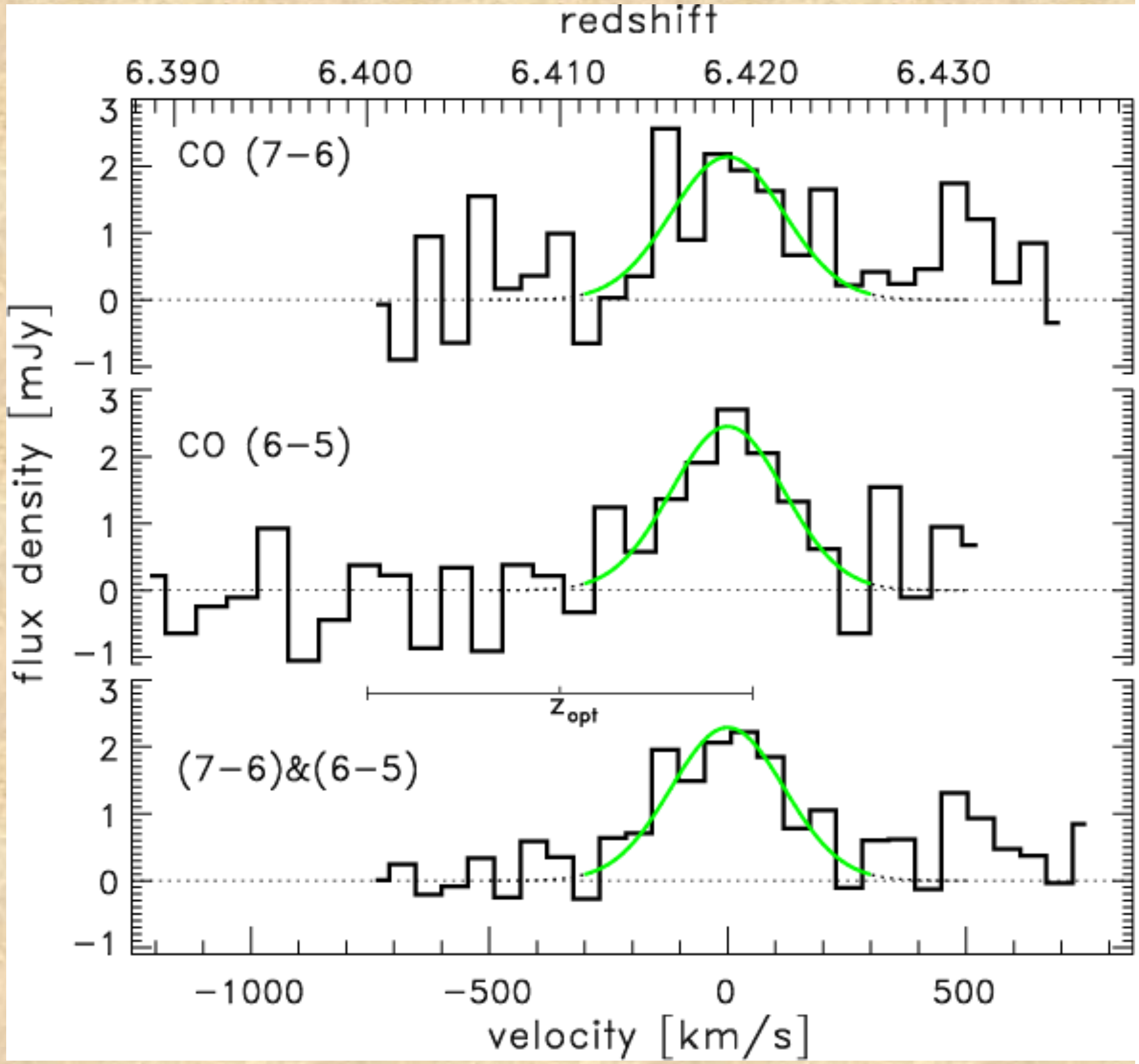
Plateau de Bure, 6-element interferometer in French Alps

- 40 z ~ 6 quasars have been observed at 250 GHz; 1/3 of them are detected (a similar rate to lower-redshift quasars).
- The characteristic inferred dust temperature is ~50 K. From this temperature and the inferred luminosity, one infers spatial extents of 1-2 kpc.
- Dust masses can be estimated; typical numbers are $5\times10^{8}\ M_{sun}$.
- Where there is dust, there is gas: assuming MW ratios, this is $5\times10^{10}\ M_{sun}$ of molecular gas. Can we see it directly?

Rotational Transitions of CO in the highest-redshift SDSS quasar

Rotational ladder (CO 1-0) starts at 115 GHz, or 3 mm. Frequency is proportional to rotational quantum number *J*.

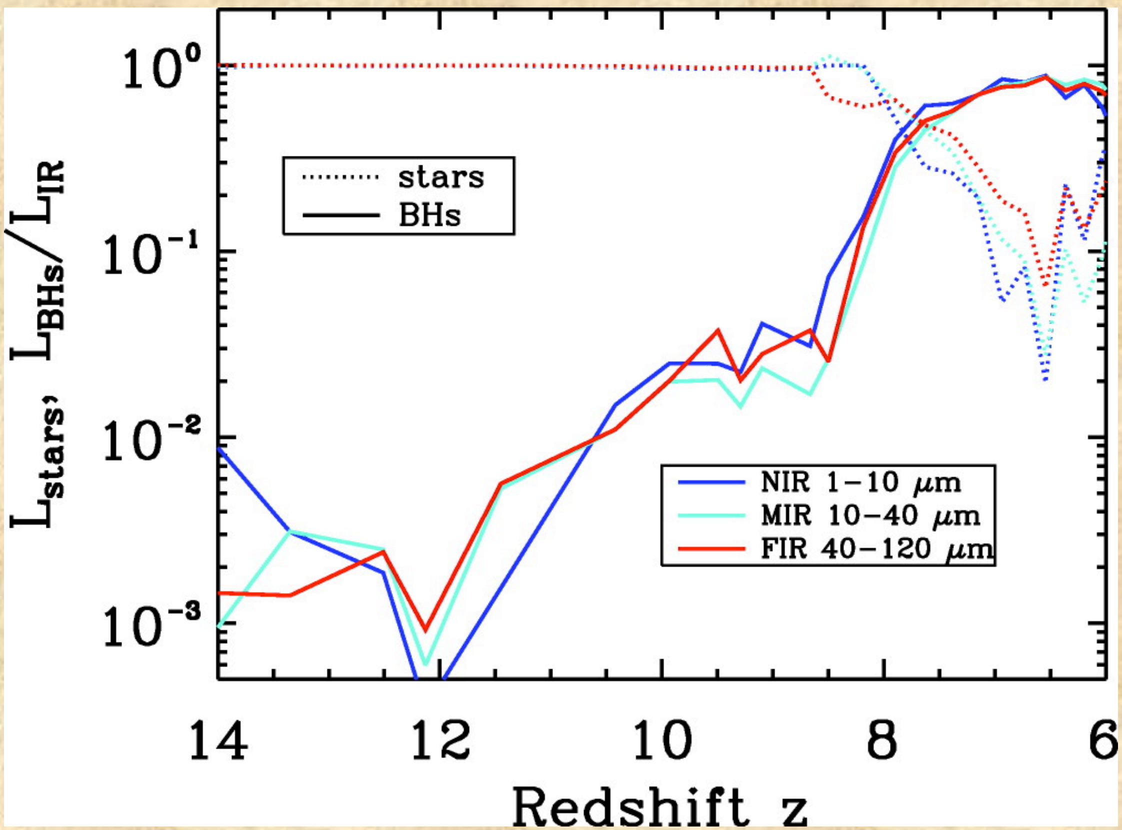
CO 3-2 is redshifted to 46.6 GHz, 7 mm, at z=6.42. CO 6-5 at about 3.5 mm. Observable with MAMBO and VLA.

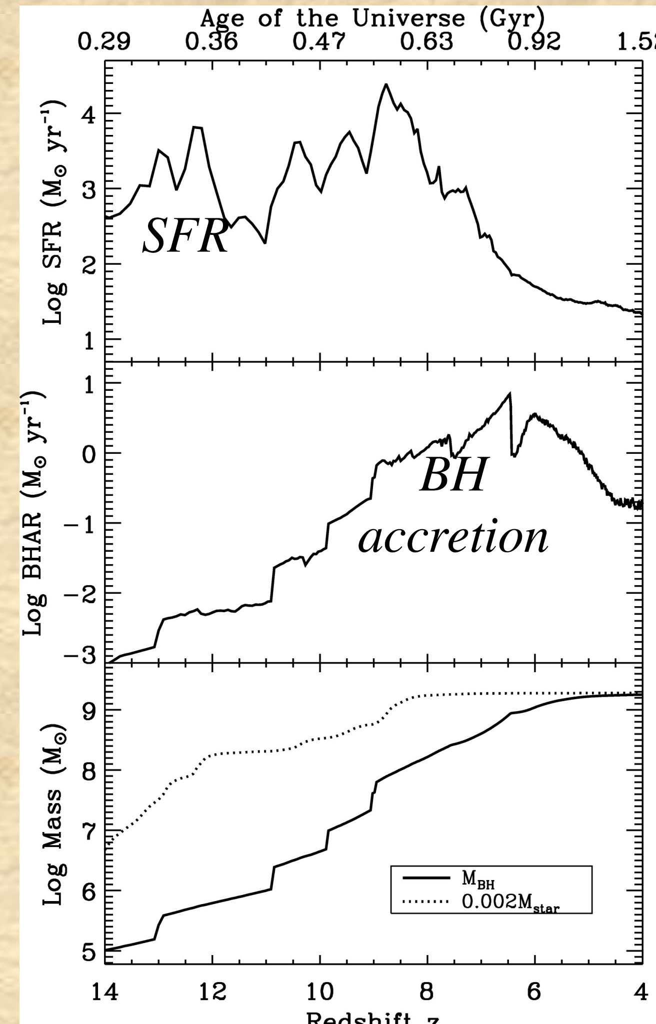


Bertoldi et al. 2003

- CO is a tracer of molecular gas. Gas is too cold (50K) to excite H_2 transitions, so we can't measure it directly.
- Gas masses are based on conversions determined for ultraluminous IRAS galaxies, which in turn assume a global CO/H_2 abundance ratio.
- The resulting *highly uncertain* gas mass is of the order $2 \times 10^{10} M_{sun}$, of the same order as inferred from the dust mass.
- We have discovered the gas reservoir that feeds the central black hole.

Lots of gas, lots of dust, lots of metals: do we also have star formation? ***If*** the star formation is heating the dust, SFR = 1000-3000 M_{sun}/year in these sources!

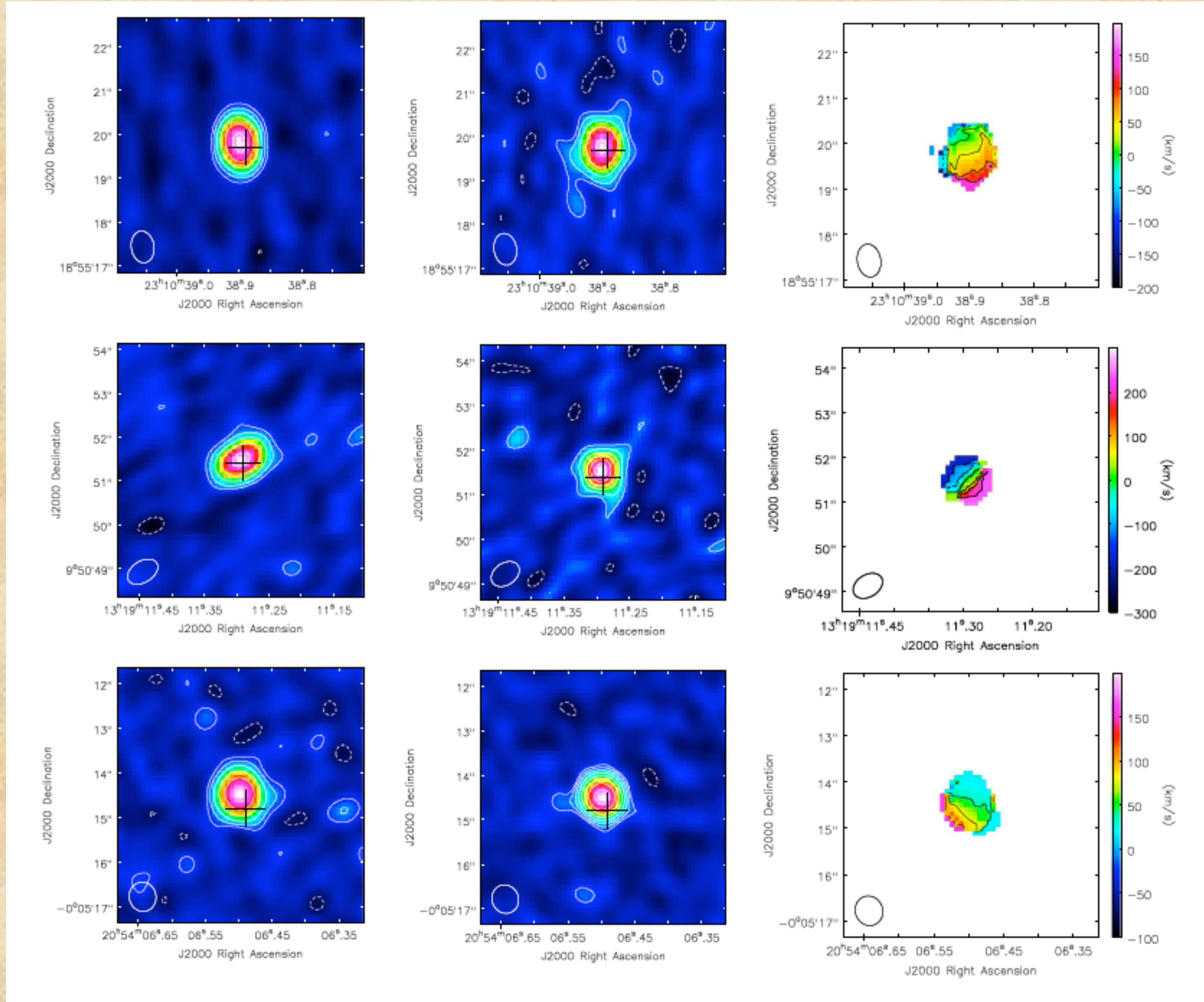




Li et al. 2008, Simulation of a z=6.5 quasar. Most of the far-infrared emission is due to AGN activity at z=6.5; star formation peaks at higher redshift.

The Atacama Large Millimeter Array (ALMA)

Dust Continuum [CII] emission Velocity Field

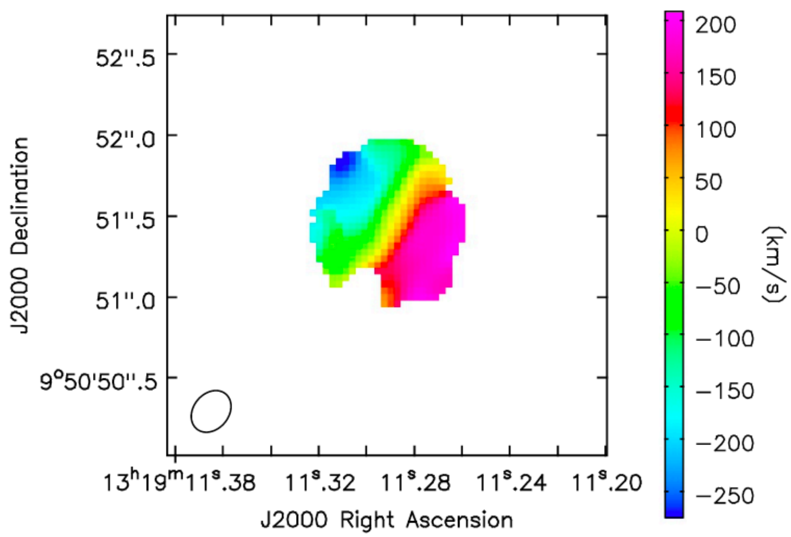


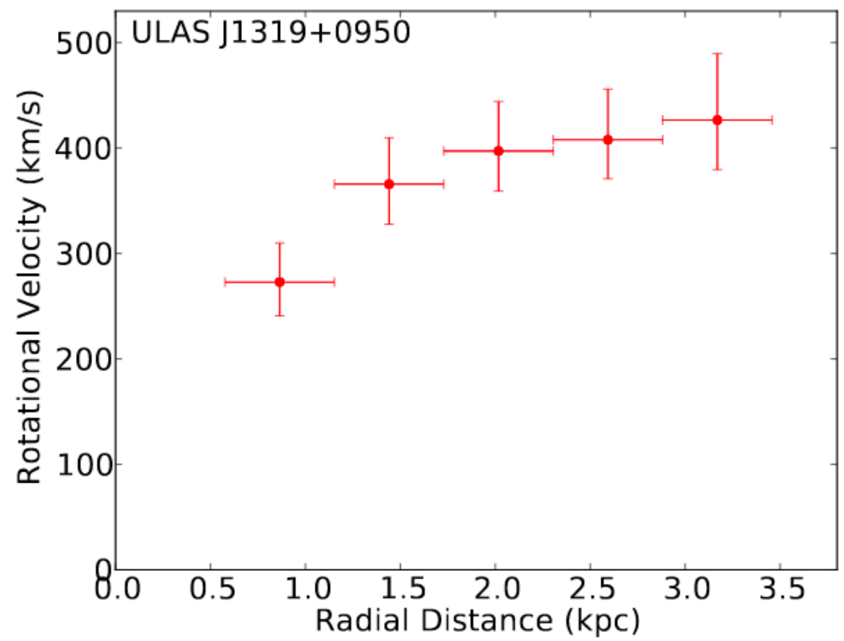
Wang et al. 2013: z~6 quasars in [CII] 158 microns.

Spatially resolved; rotation seen in only 1 hour exposure!

Dynamical masses of a few $\times\ 10^{10}$ solar masses.

We can actually measure an inclination and rotation curve in [CII]!

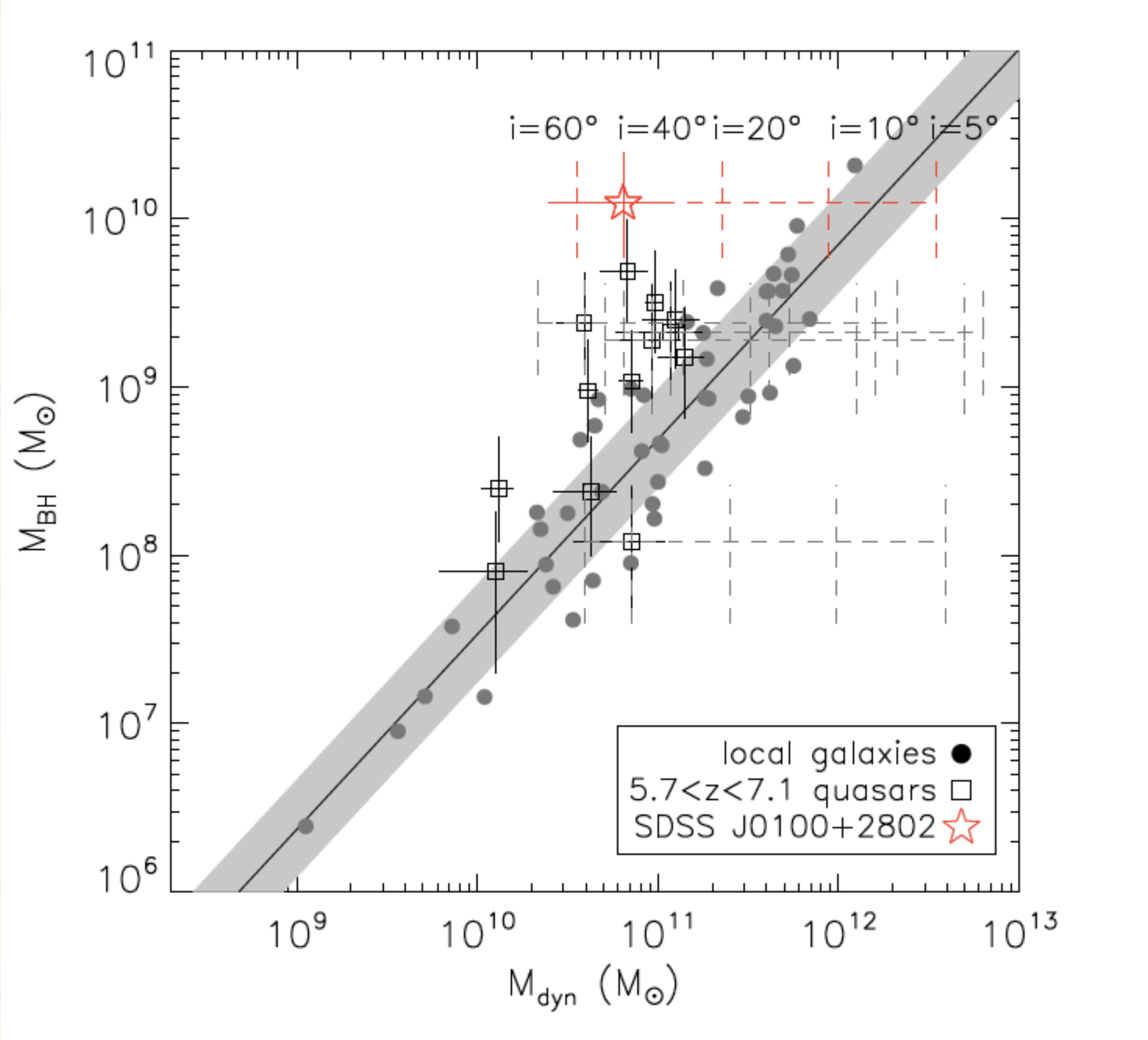




Shao et al. 2017: ULAS 131911.29+095051.4 (UKIRT), z=6.13.
Dynamical mass of 1.3×10^{11} solar masses within 3.2 kpc.

Wang et al. 2016: Black hole mass from CIV line, vs. host galaxy dynamical mass from [CII] ISM emission. *The black hole/host ratio is significantly higher at z~6 than at present!*

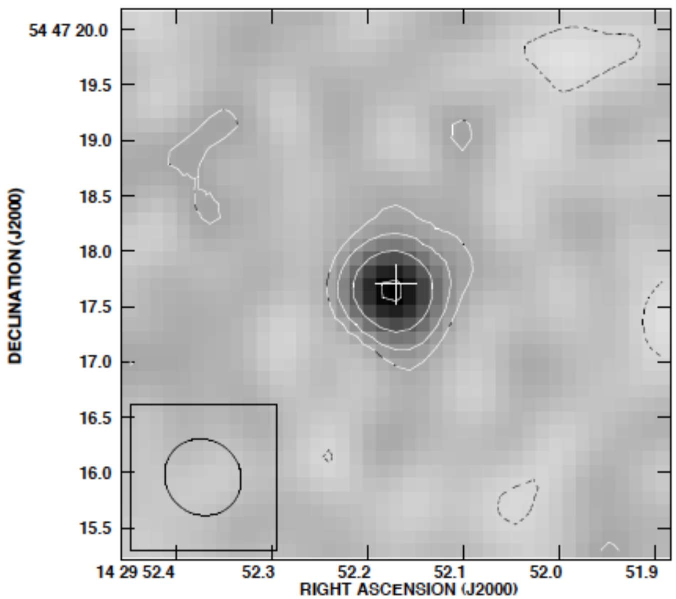
Black hole mass, from emission-line widths



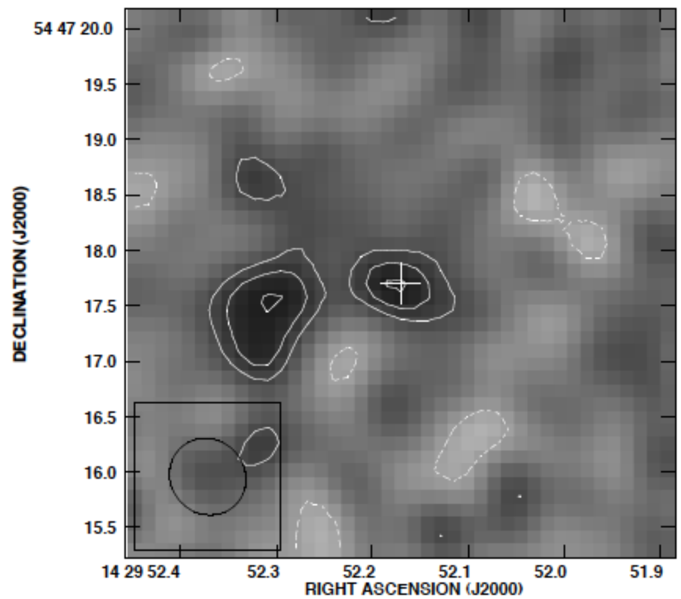
Host galaxy mass, from [CII] dynamical measurements (ALMA)

A quasar at z=6.18, seen in CO(2-1) with the EVLA

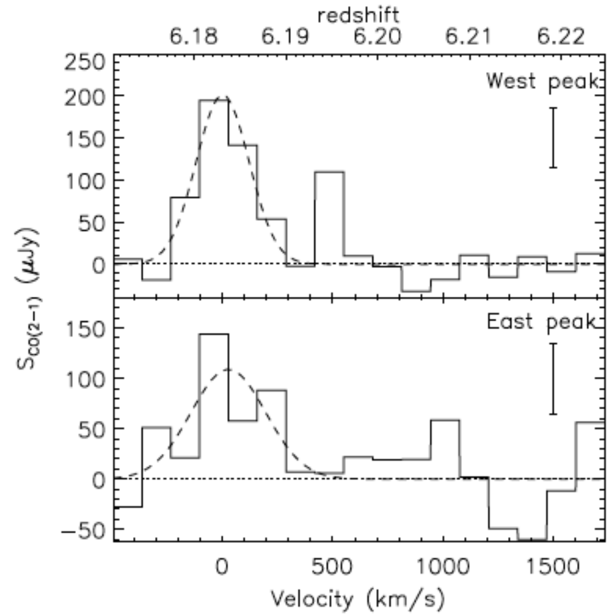
Continuum at 32 GHz

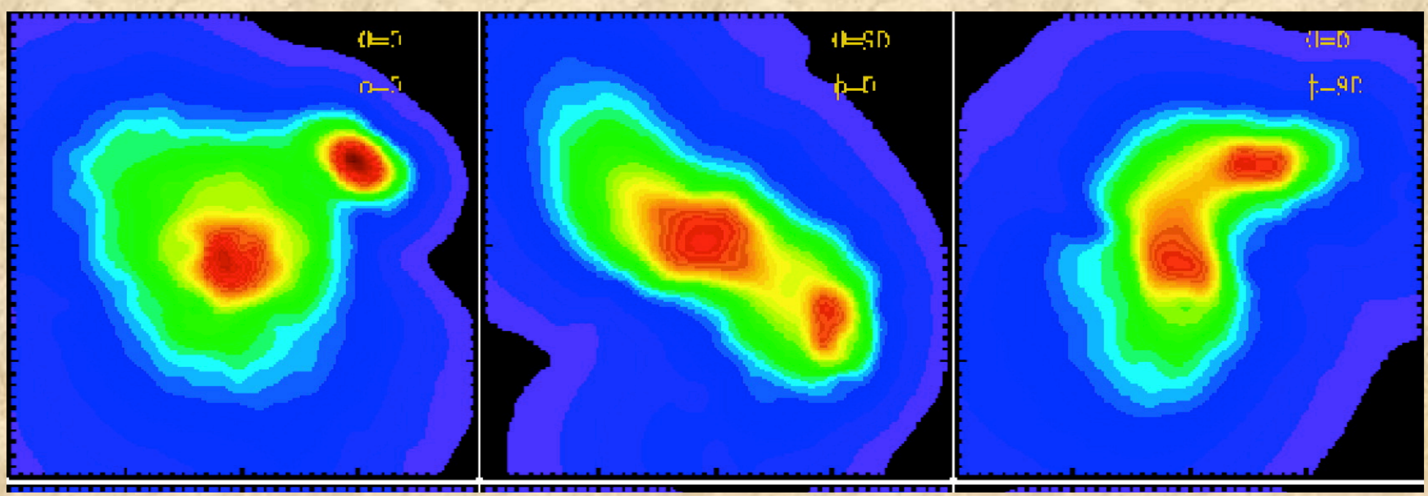


CO emission



CO spectra

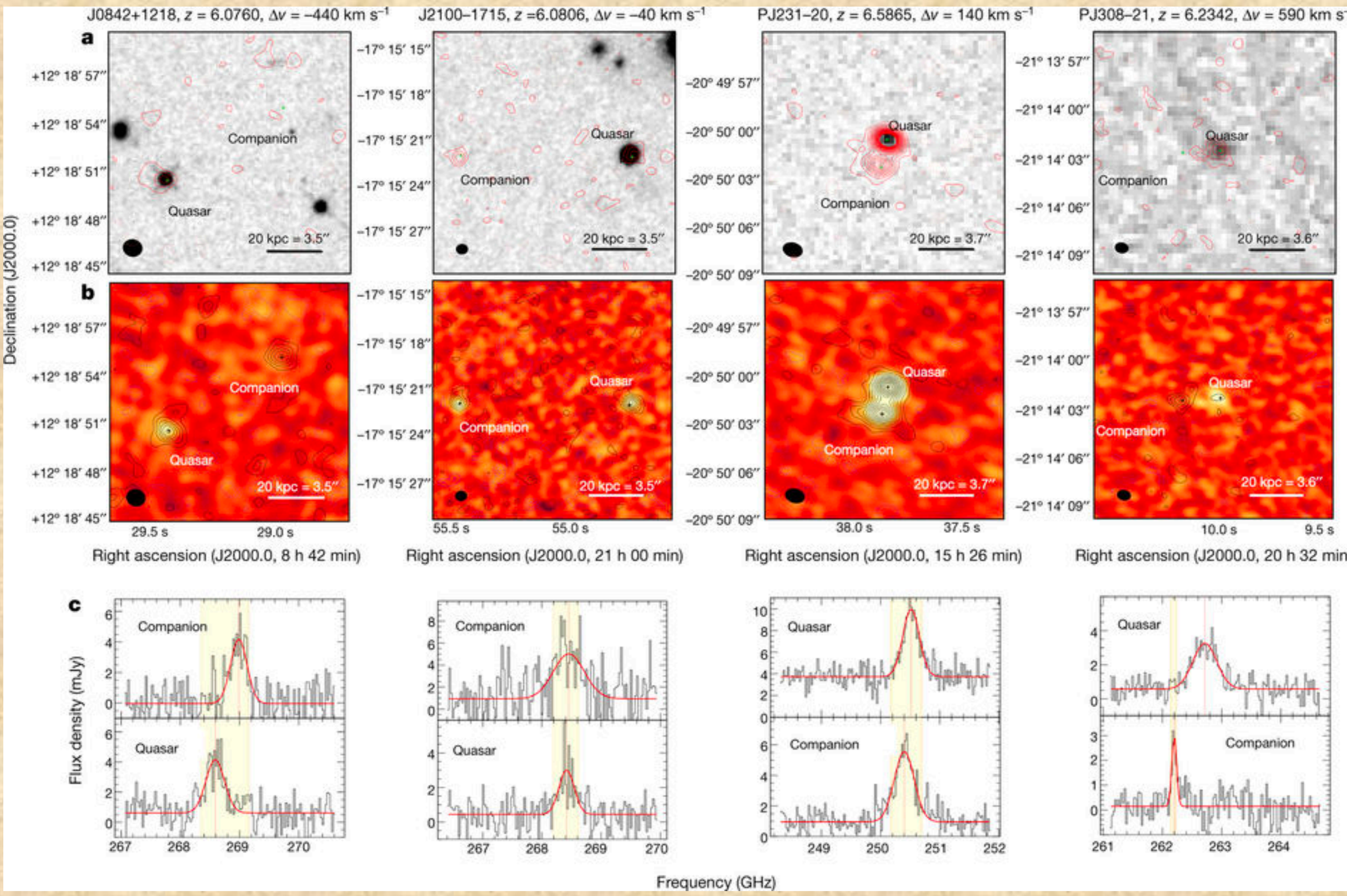




Wang et al. 2011

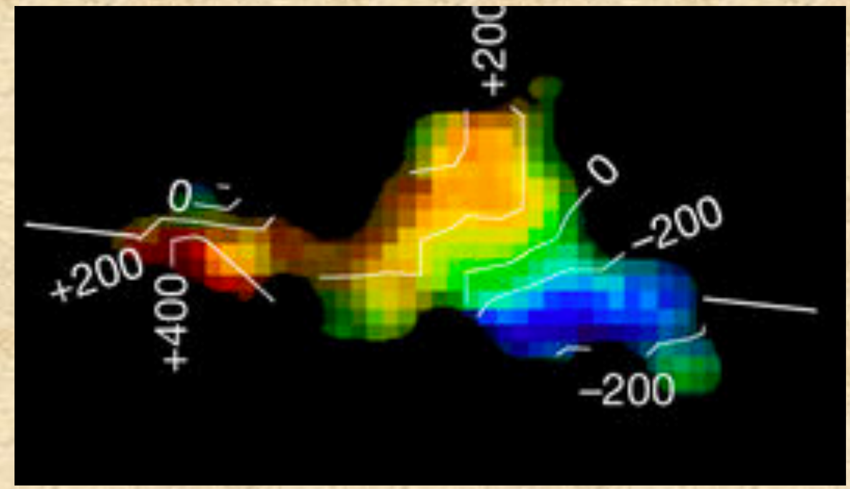
This is reminiscent of substructure predicted in simulations of CO emission by Narayanan et al. 2008

Companion galaxies to quasars appear to be common at high redshift



Decarli et al. 2017: Dust, rest-frame UV, and [CII] emission in four high-redshift quasars with companions. Note that the companions are undetected in starlight.

Roberto Decarli, Heidelberg



Strong velocity gradient seen in one source.

- Companions seen in 4 of 24 quasars observed, in both dust continuum and [CII]
- Star formation rates of hundreds of solar masses per year.
- Dynamical masses of 10^{11} solar masses; are these progenitors to massive galaxies seen at redshift ~4?