Clustering of high-redshift (z>2.9) quasars from SDSS

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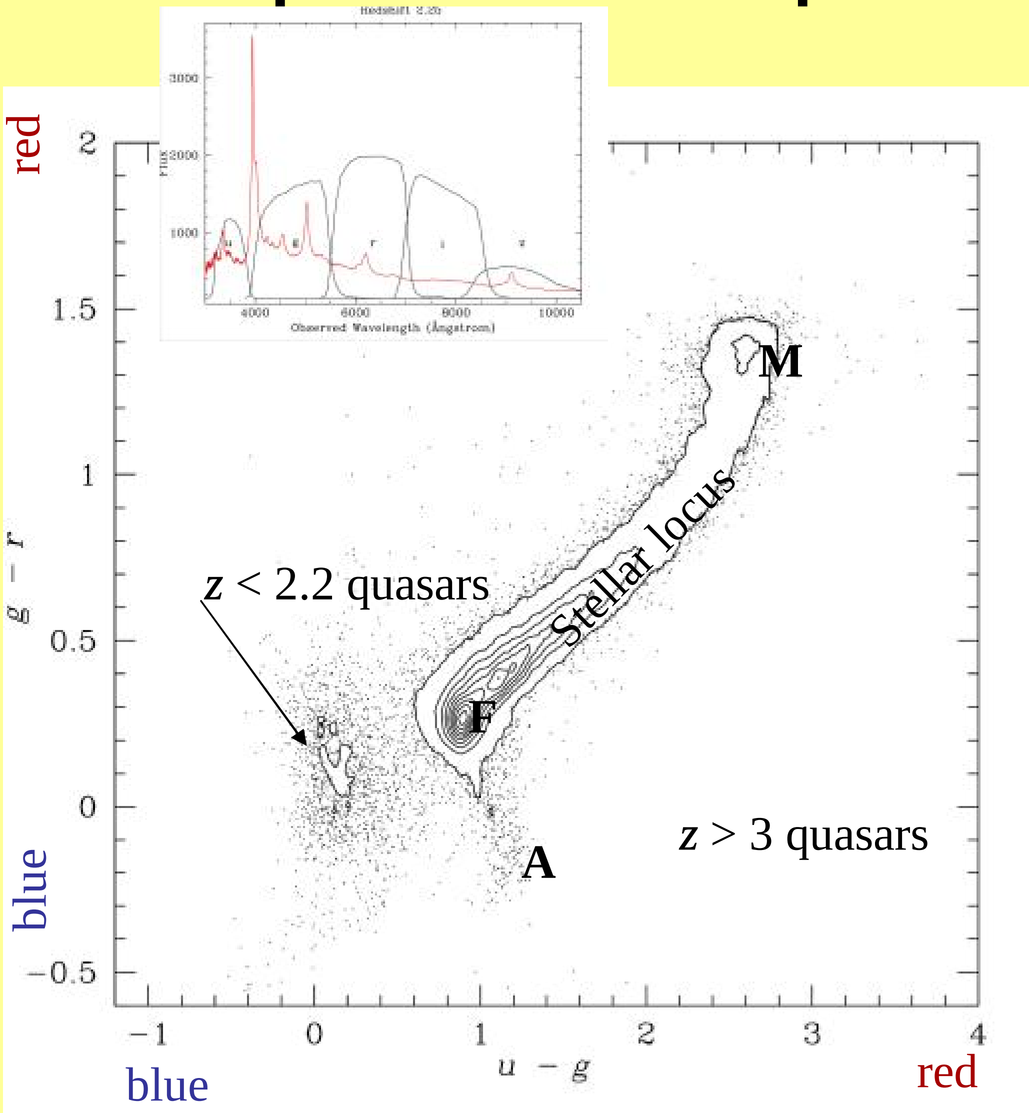
Outline

- The spectroscopic quasar sample
- Quasar clustering at low redshift ($z<2.8$)
- Quasar clustering at high redshift ($z>2.9$) and its implications for quasar environments and lifetimes
- Future work

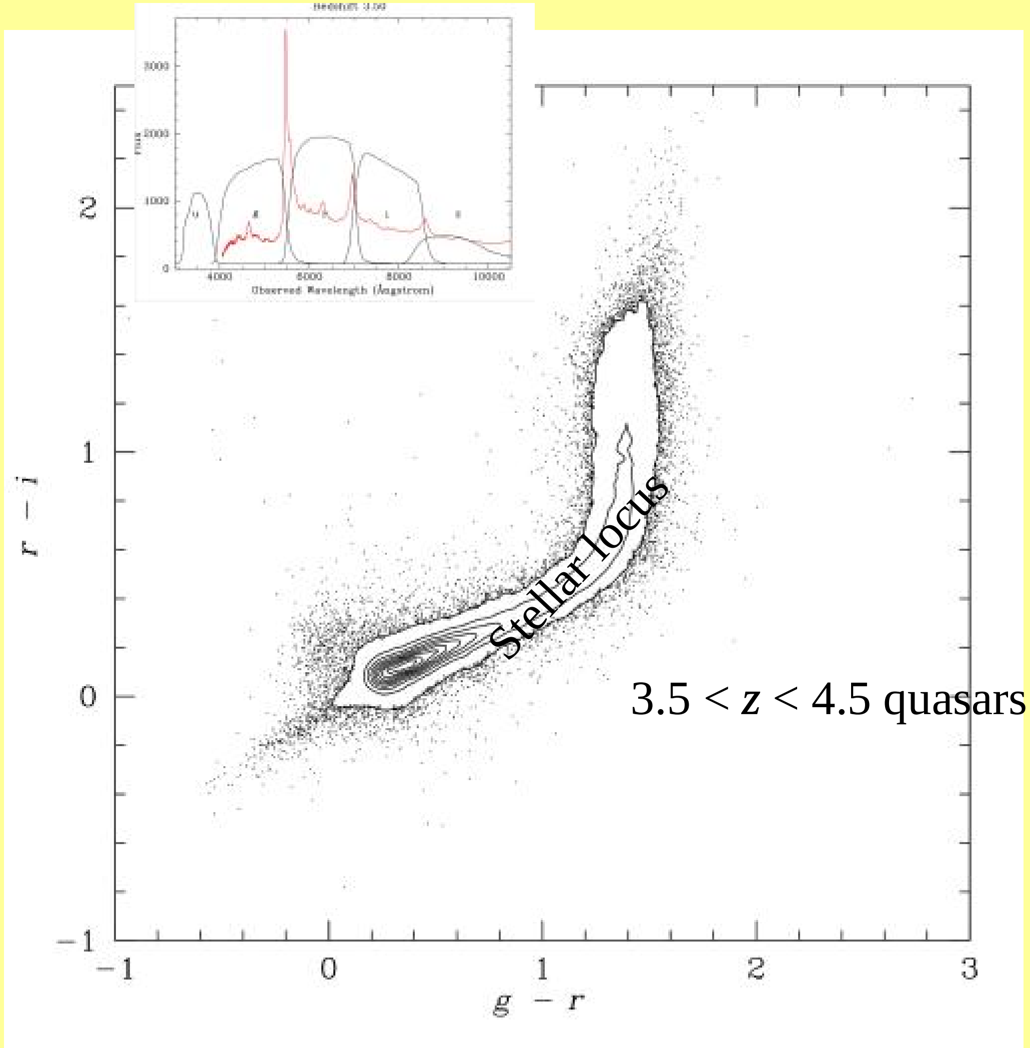
spectroscopic main quasar sample

- Color selection of quasar targets (ugri color cube for z<3.5; griz for z>3.5)
- Spectroscopic follow-ups



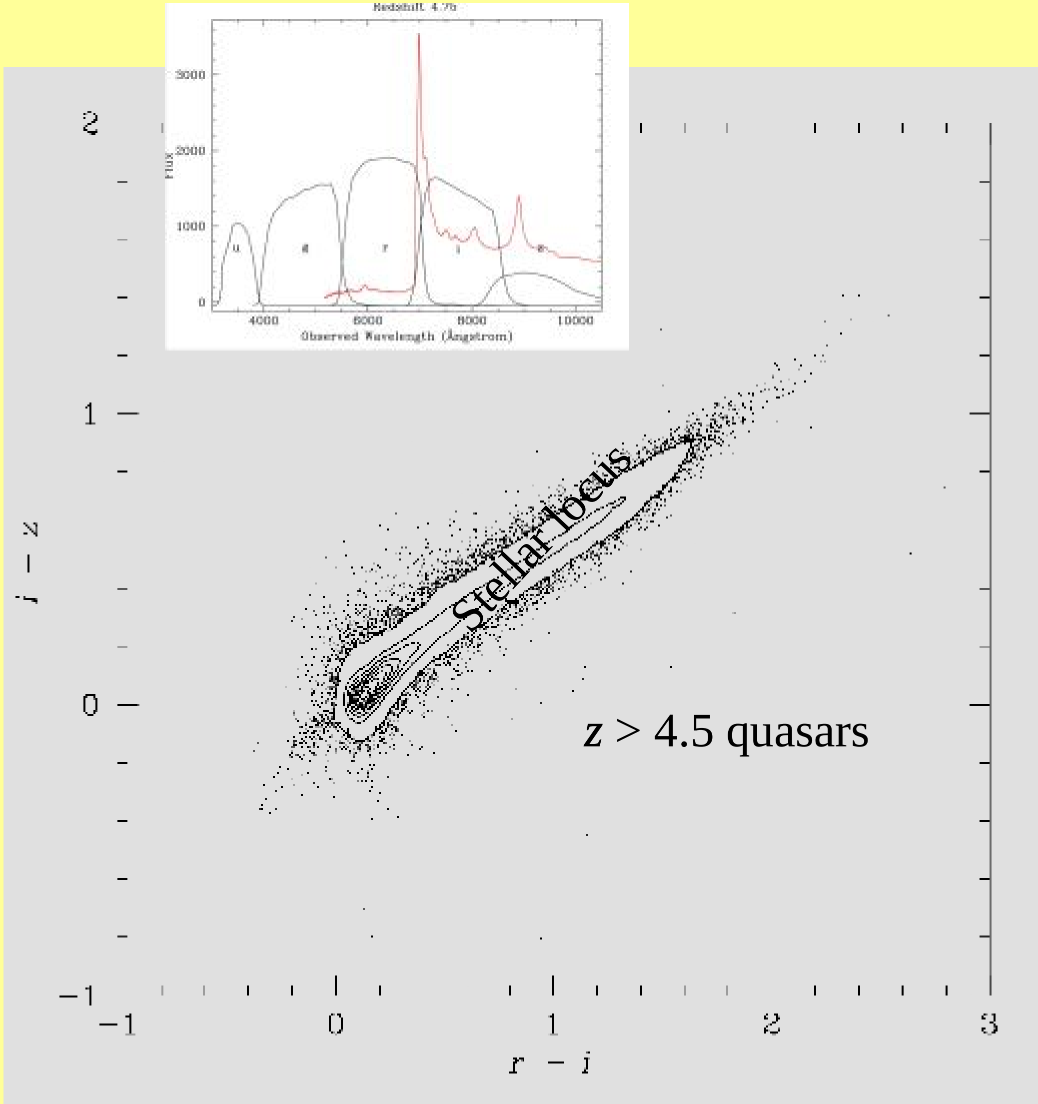
spectroscopic main quasar sample

- Color selection of quasar targets (ugri color cube for z<3.5; griz for z>3.5)
- Spectroscopic follow-ups



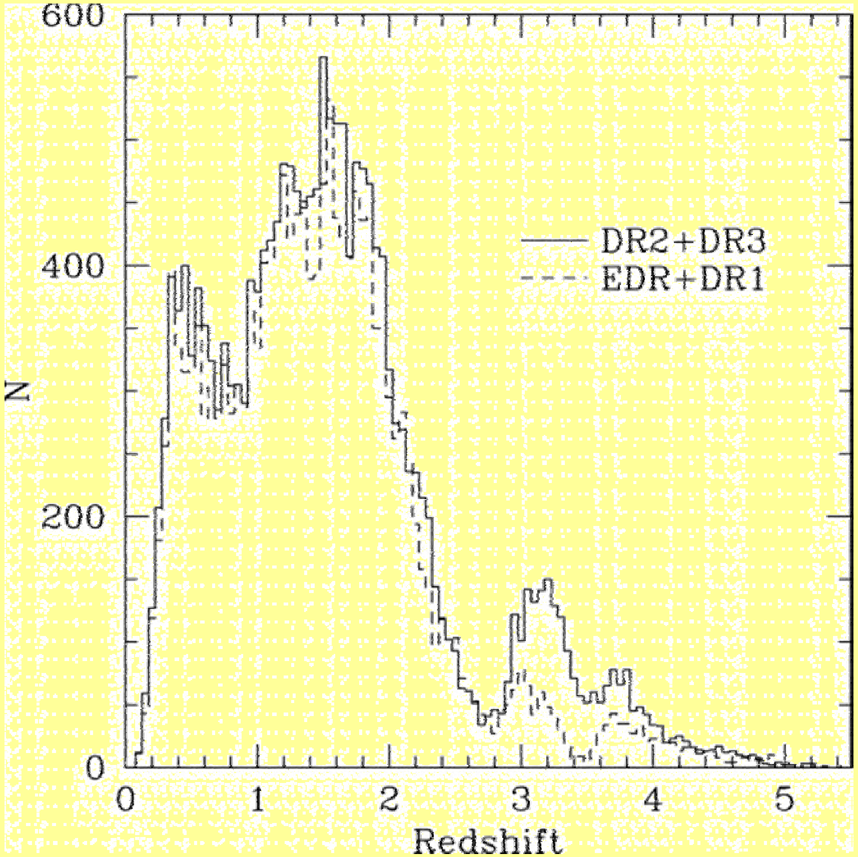
spectroscopic main quasar sample

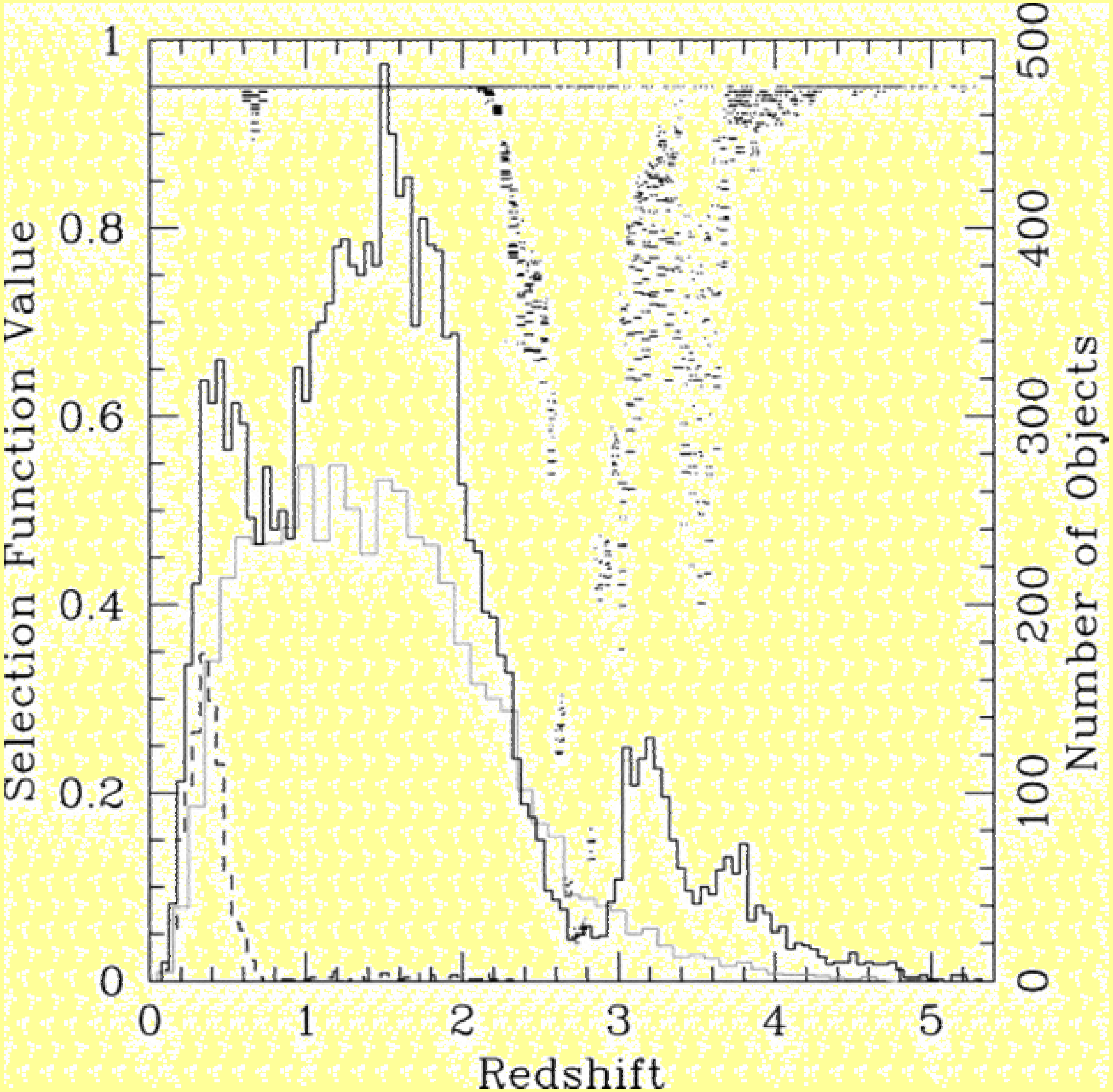
- Color selection of quasar targets (ugri color cube for z<3.5; griz for z>3.5)
- Spectroscopic follow-ups (selection efficiency: ~ 50%)



spectroscopic main quasar sample

- Color selection of quasar targets (ugri color cube for z<3.5; griz for z>3.5)
- Spectroscopic follow-ups
- Flux-limited to i=19.1 for z<3;i=20.2 for z>3
- Very complete at most redshifts; Incomplete at z~2.7 and z~3.5 (especially for EDR+DR1)

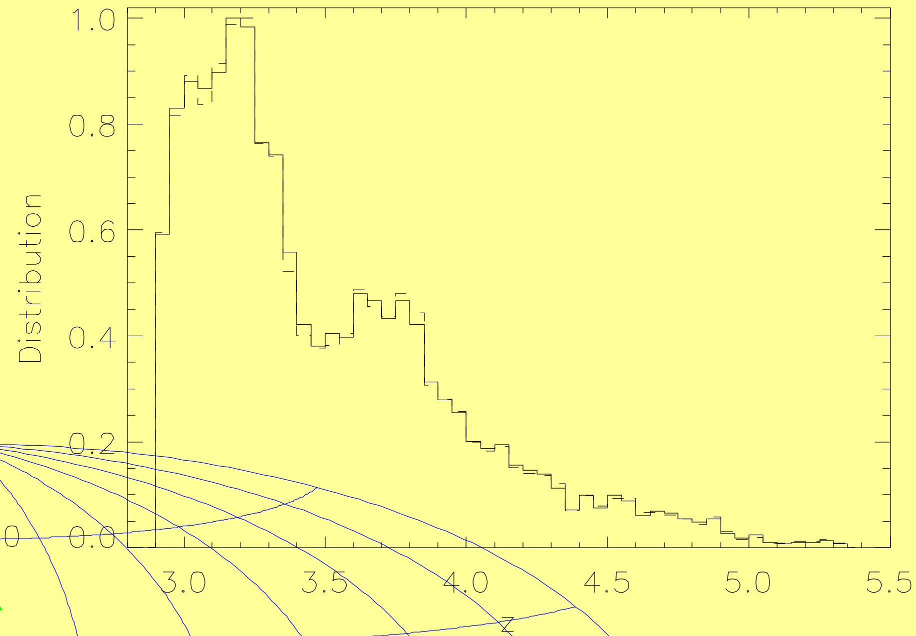


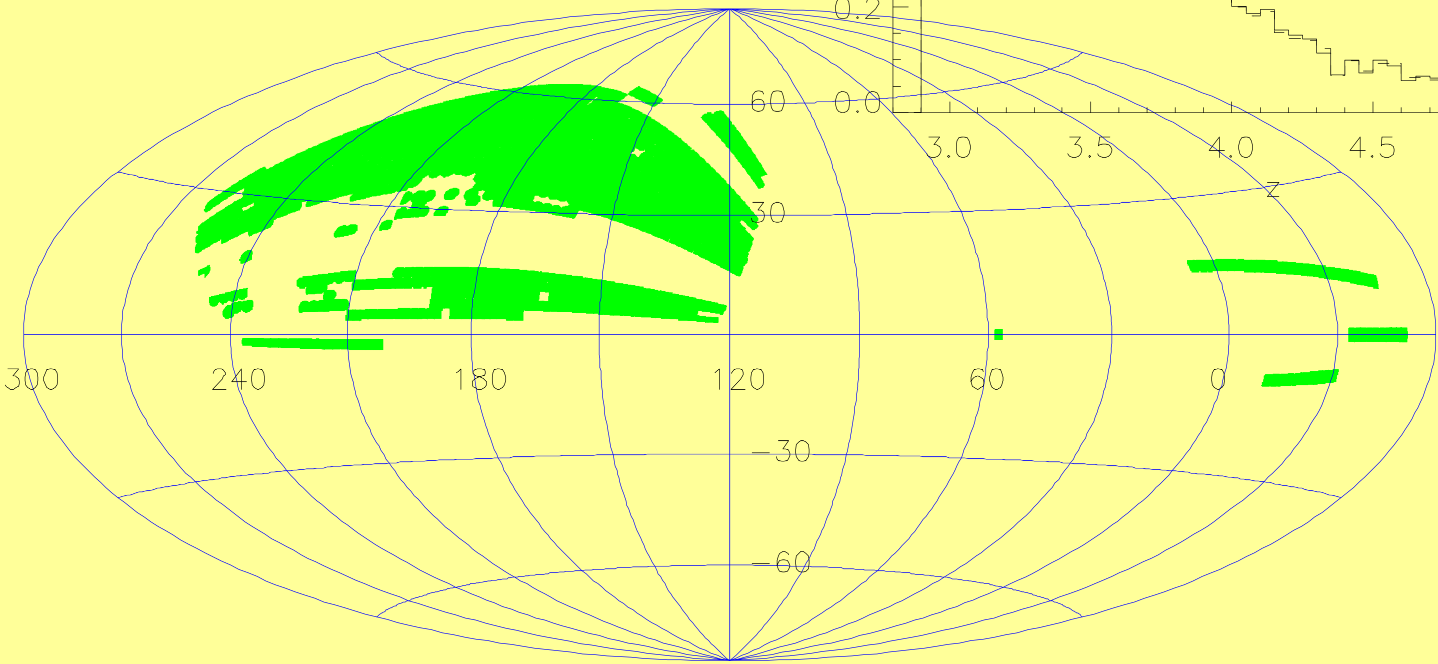


Selection Function Value
Number of Objects
Redshift
0
0.2
0.4
0.6
0.8
1
0
1
2
3
4
5
0
100
200
300
400
500

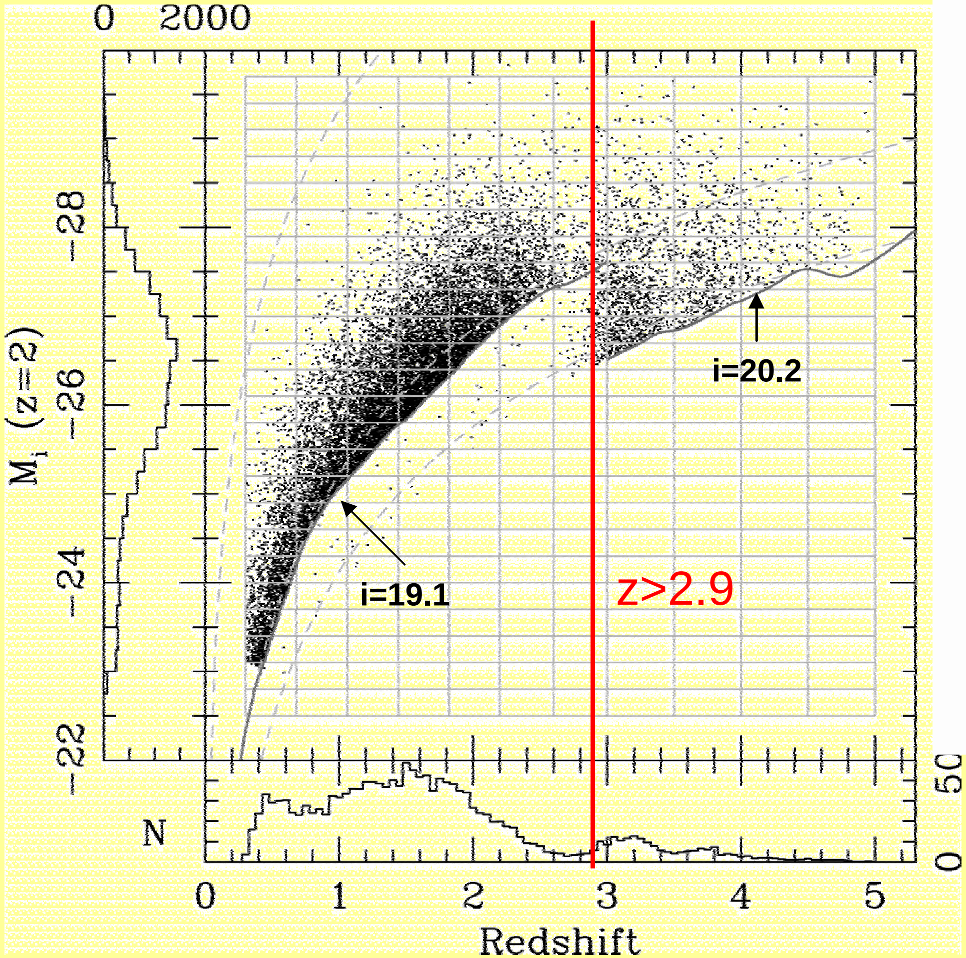
Quasar clustering subsample

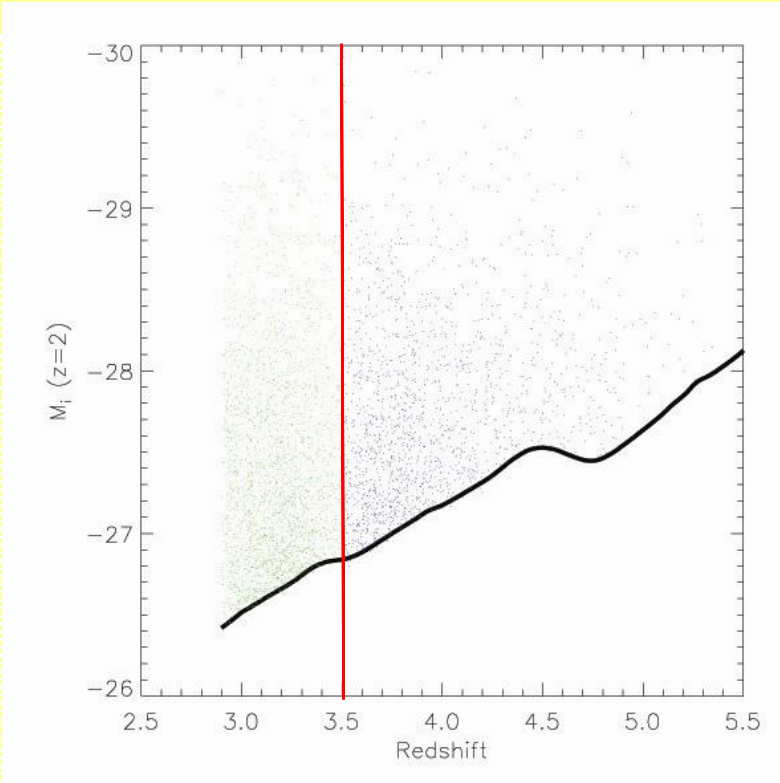
- ~ 4500 (z>2.9) in our clustering sample
- ~ 4000 deg^2 sky coverage





High redshift quasars are very bright!





Richards et al. (2006)

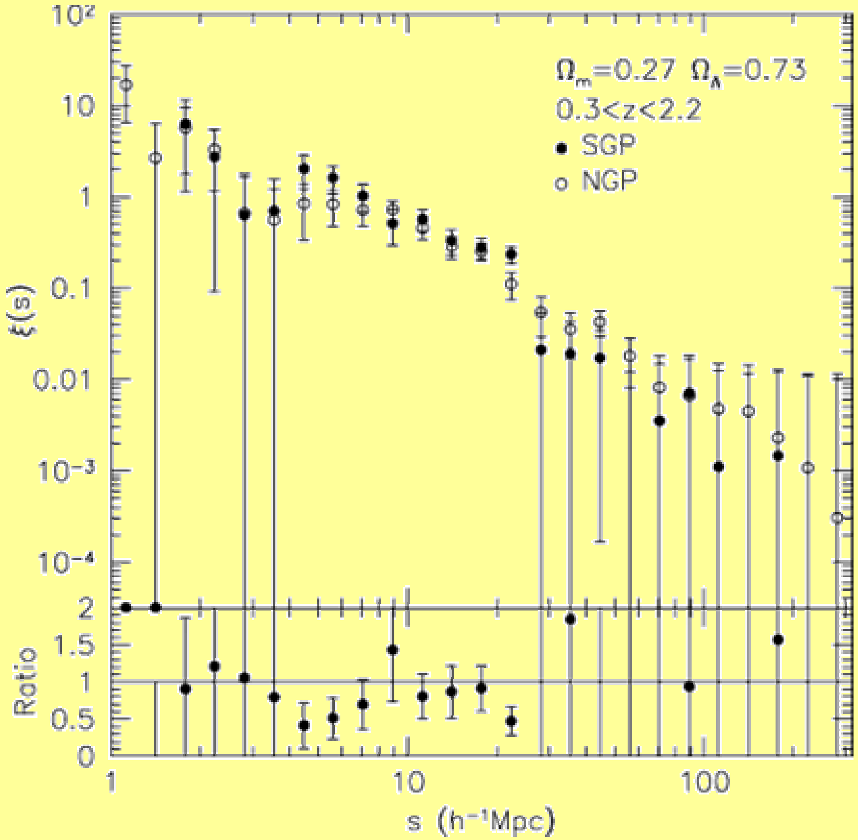
Clustering of quasars (previous results)

- *Osmer (1981), Shaver (1984), Iovino & Shaver (1988), Croom & Shanks (1996), Kundic (1997), La Franca et al. (1998) ...*
- *2QZ: Porciani, Magliocchetti & Norberg (2004), Croom et al. (2005), Porciani & Norberg (2006)*
- *SDSS: Myers et al. (2006; 2007a), Connolly et al. (2007)*
- *All at $z < 2.8$*

Quasars have similar clustering properties as galaxies

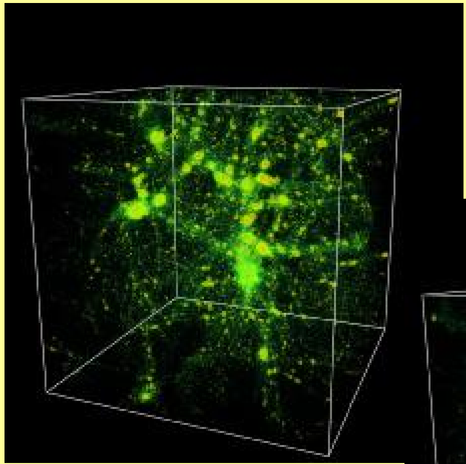
- At z<2.8, the correlation function of quasars can be fitted by a power law, $x = \left(\frac{r}{r_0}\right)^{g}$ with

$$g \approx 1.8,\ r_0 \approx 5\,h^{-1}\mathrm{Mpc}$$

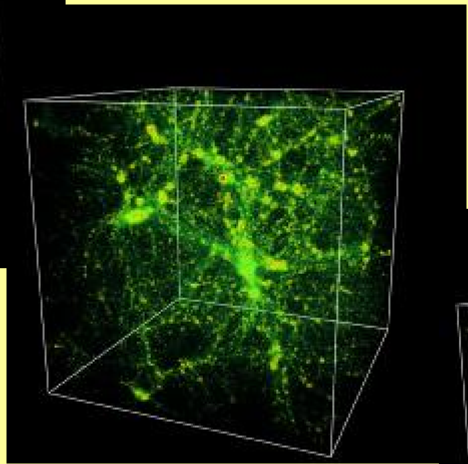


Croom et al. (2005)

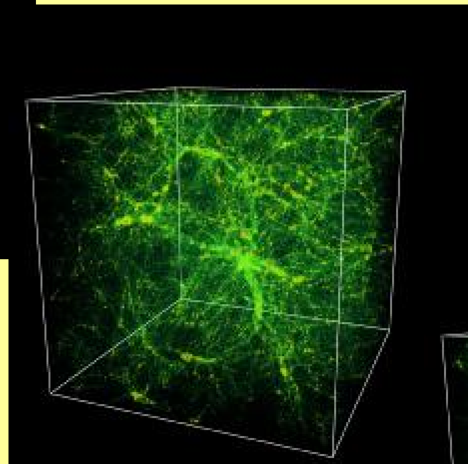
Just as galaxies, quasars are biased tracers of the underlying dark matter



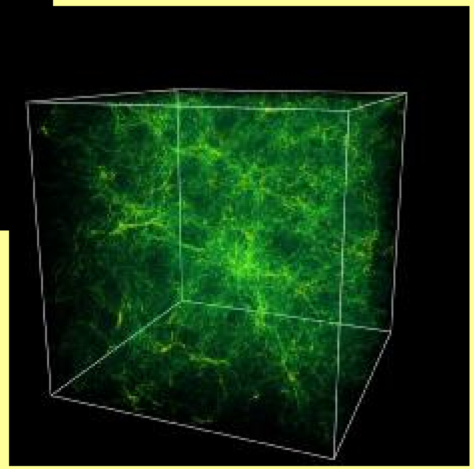
Z=0



Z=1



Z=3



Z=6

Dark matter simulations
by *Renyue Cen*

What can we learn from quasar clustering?

- Dark matter clustering + linear bias model = clustering of (massive) dark matter halos
- Comparison with quasar clustering infers quasar environments.
- Constraint on quasar lifetimes (Martini & Weinberg 2001; Haiman & Hui 2001)

$$\Phi(z) = \int_{M_{\min}}^{\infty} dM \frac{t_Q}{t_H(M,z)} n(M,z)$$

Martini & Weinberg (2001); Haiman & Hui (2001)

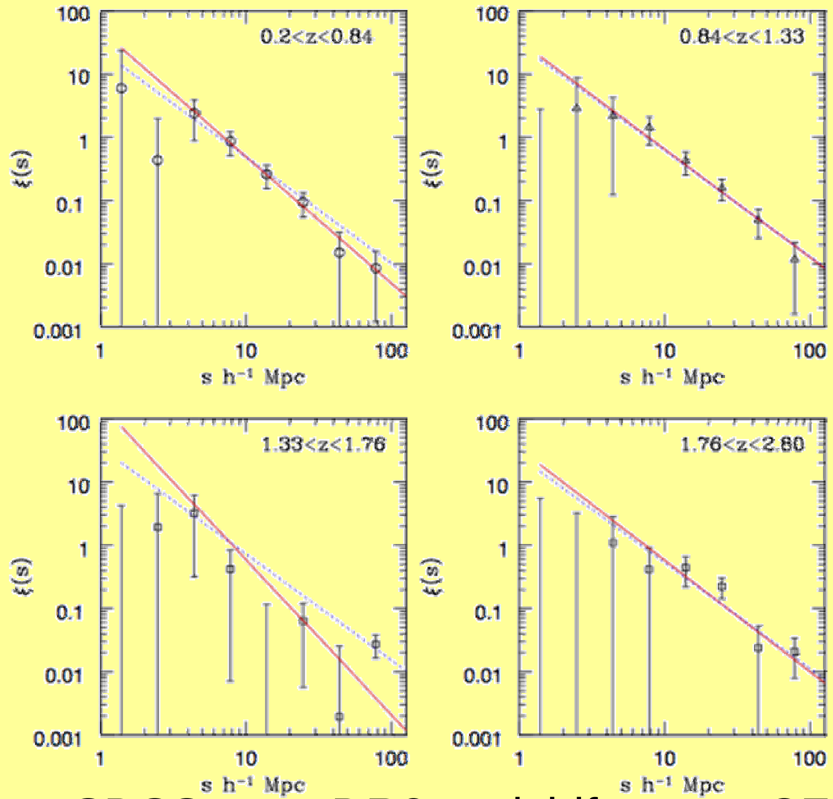
Integrated luminosity function

Determined from quasar clustering

Duty cycle

Halo mass function

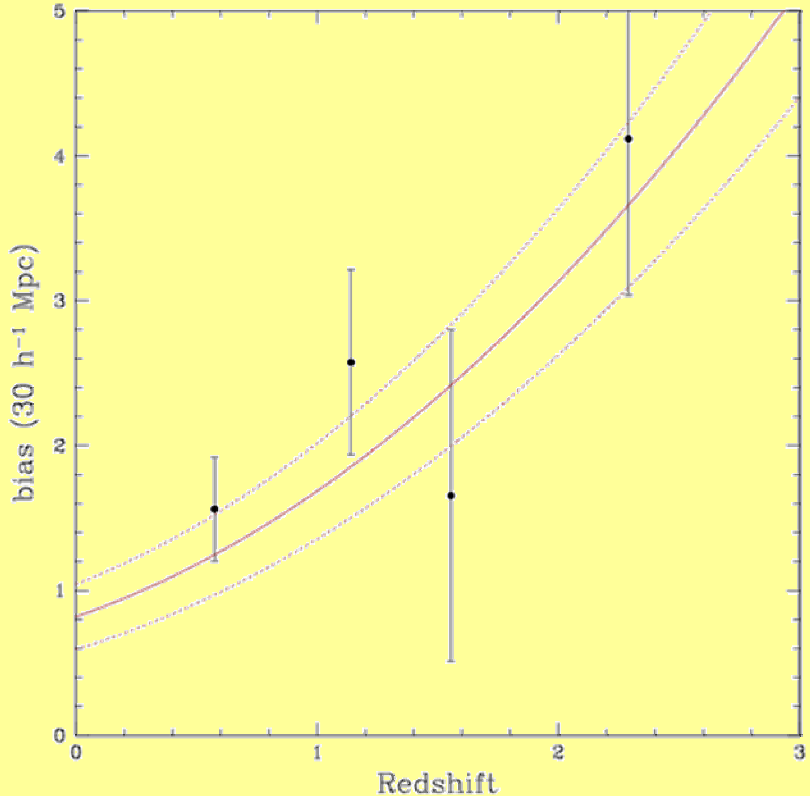
Evolution of quasar clustering at z<2.8



SDSS spec DR3, redshift space CF

Connolly et al. (2007)

They found no significant
evolution of clustering strength.



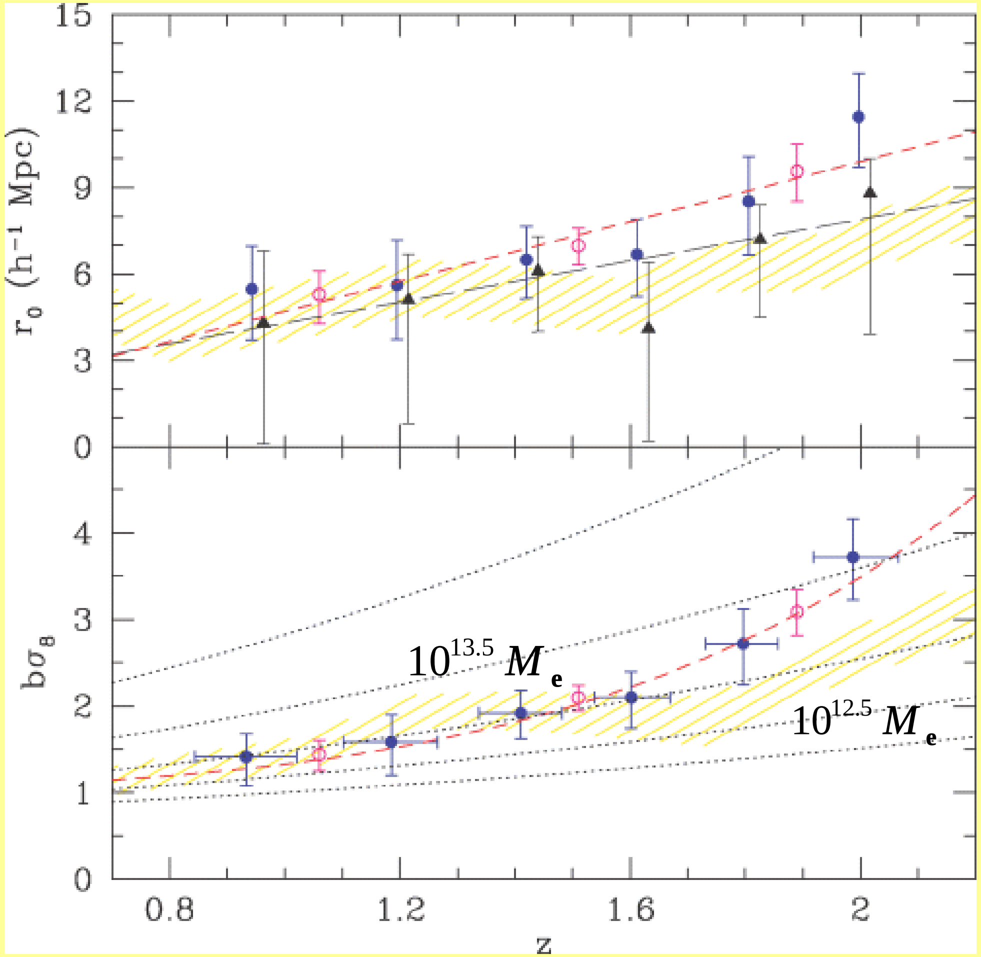
The effective bias as a function of redshift

Host halo mass and quasar lifetime at z<2.8

Porciani et al. (2004), Croom et al. (2005)

- Quasar host DM halo mass ~ $\text{a few } \times 10^{12}\, h^{-1} M_{\mathbf{e}}$
- Quasar lifetime $t_Q : 10^6 - 10^8 \text{ yr}$

Evolution of quasar clustering at z<2.8

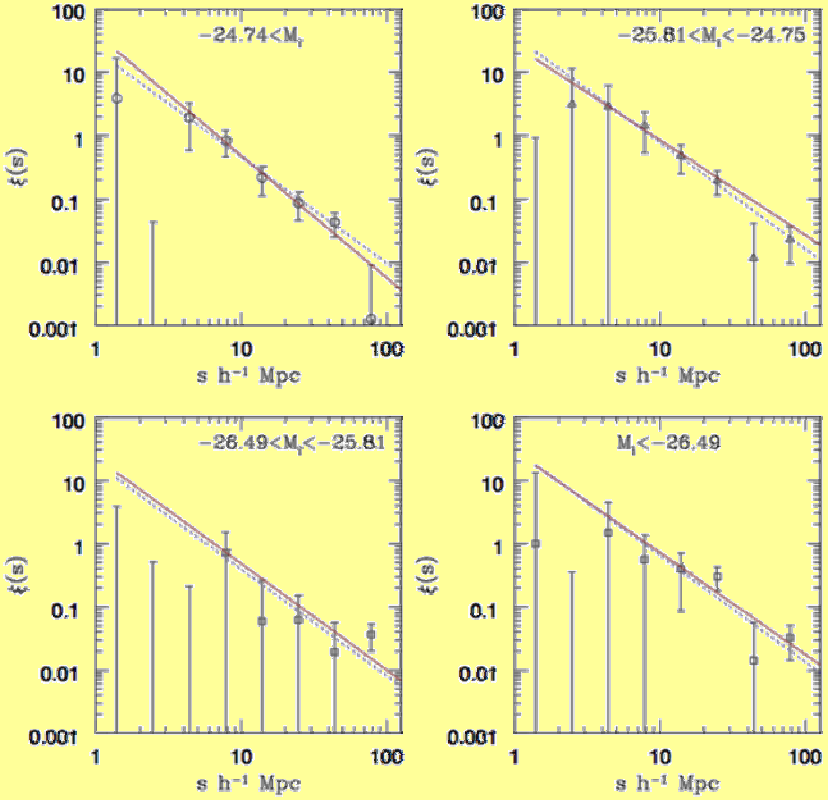


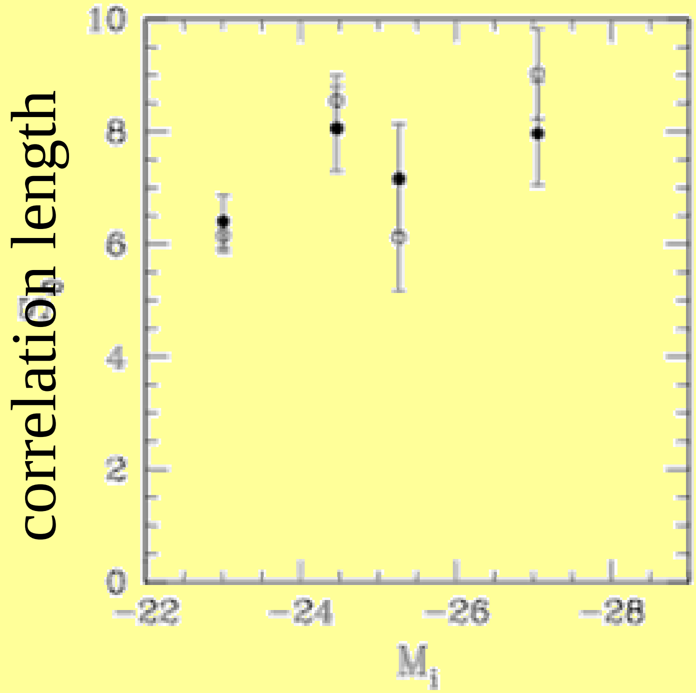
0.8<z<2.1

Porciani & Norberg (2006)

Luminosity dependence at z<2.8

- No luminosity dependence at low redshift? (Croom et al. 2005; Porciani & Norberg 2006; Connolly et al. 2007; da Angela et al. 2007)





Connolly et al. (2007)

Luminosity dependence at $z<2.8$

At moderate redshift, luminosity also depends on Eddington ratio, so $\xi(r)$ doesn't depend on luminosity (Lidz et al. 2006)

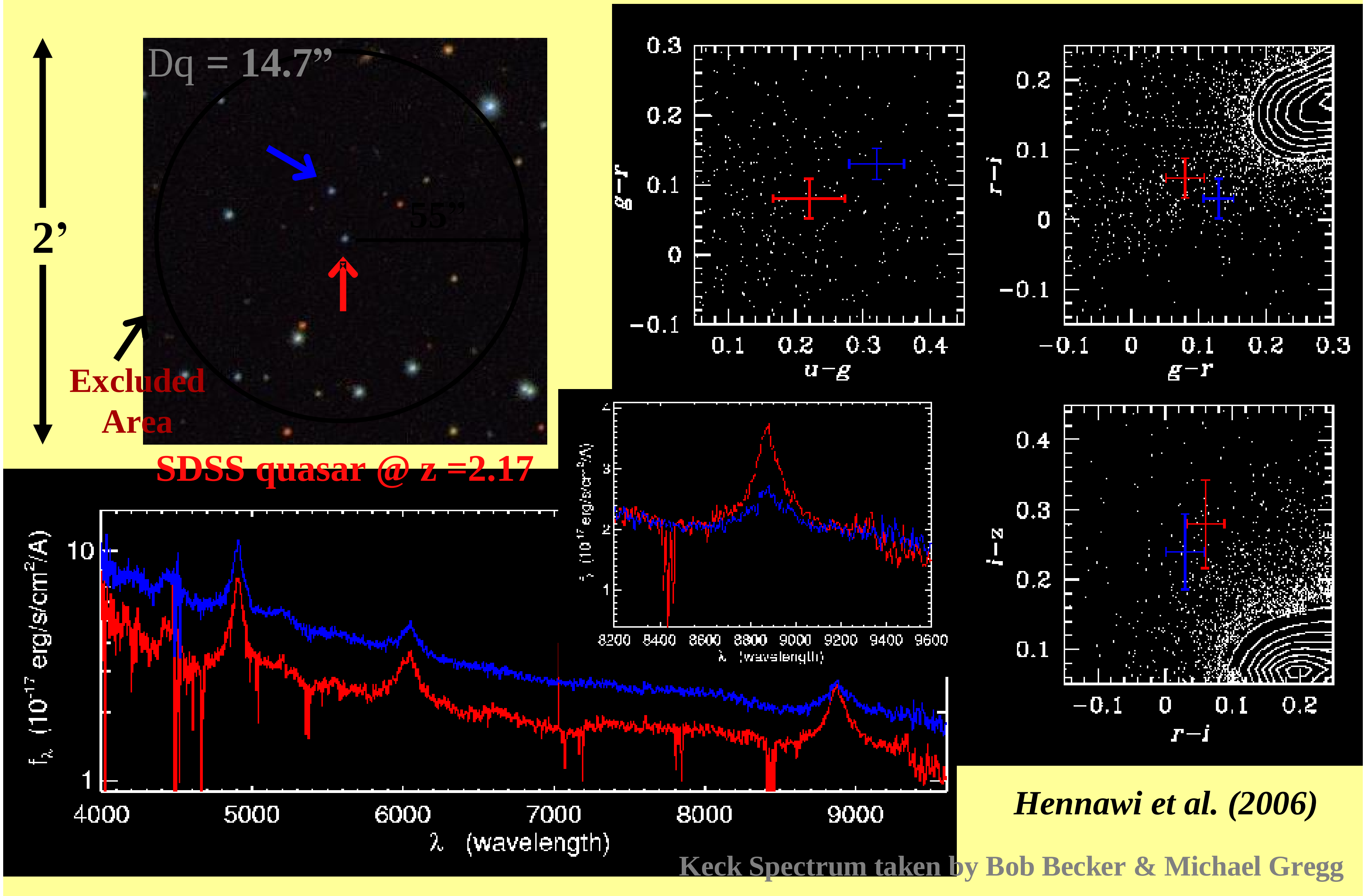
However, at high redshift ($z>3$), quasar luminosities are close to Eddington luminosity (Kollmeier et al. 2006).

Would luminosity-dependent clustering be observable at $z>3$?

Small-scale quasar clustering

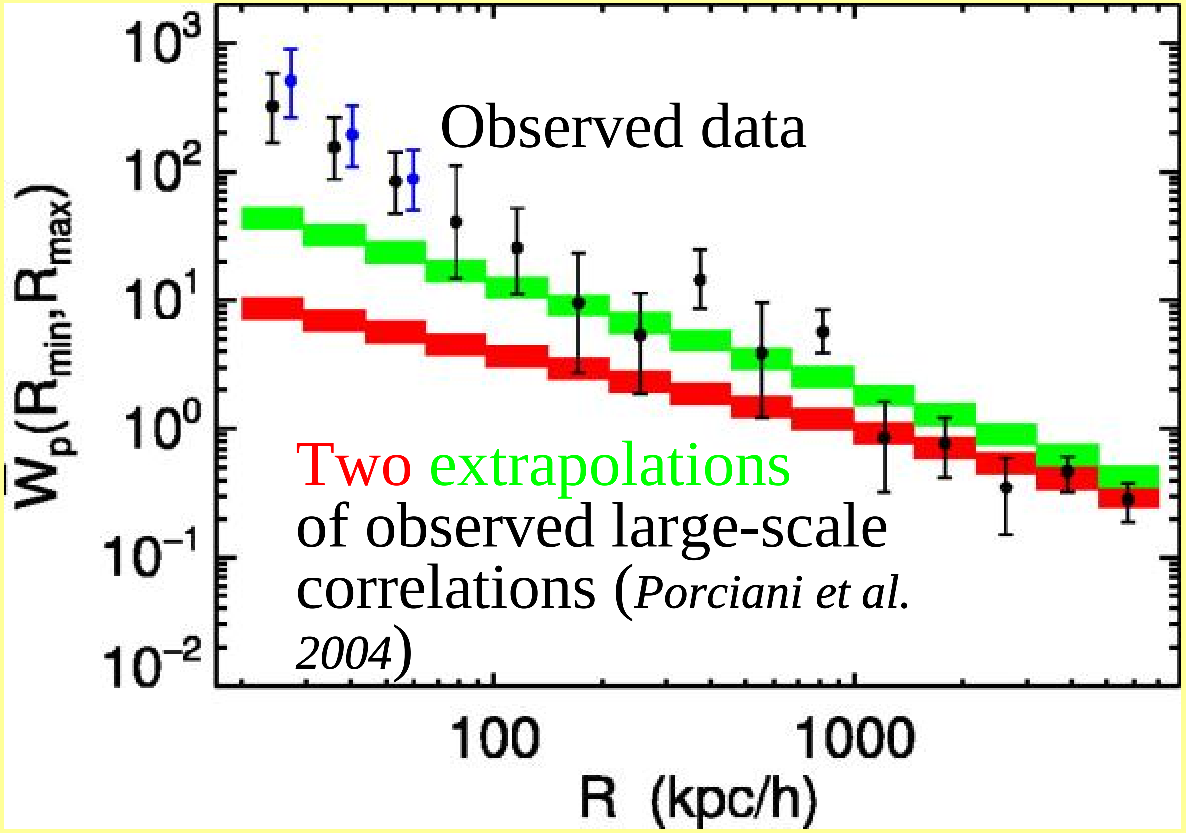
Most clustering analyses are restricted to scales above 1 Mpc because: close quasar pairs are rare; fiber collisions (for SDSS spectrographs, ~1’).

Small-scale quasar clustering



Small scale clustering

220 quasar pairs with proper separation <1 *h*-1Mpc



Substantial excess below 100 kpc!

Summary of quasar clustering at z<2.8

- Clustering strength and bias increases with redshift, with b ~ 4 at z ~ 2.5
- Quasar host DM halo mass ~ $\text{a few} \times 10^{12}\, h^{-1} M_{\odot}$
- Quasar lifetime $t_Q \sim 10^6 - 10^8$ yr
- No significant evidence of luminosity-dependent clustering
- Excess of small-scale clustering

High redshift (z>2.9) quasar clustering

Powered by SMBHs with mass (Mclure & Dunlop 2004; Kollmeier et al. 2006)

$$M_{\rm BH} > 10^8\ M_\odot$$

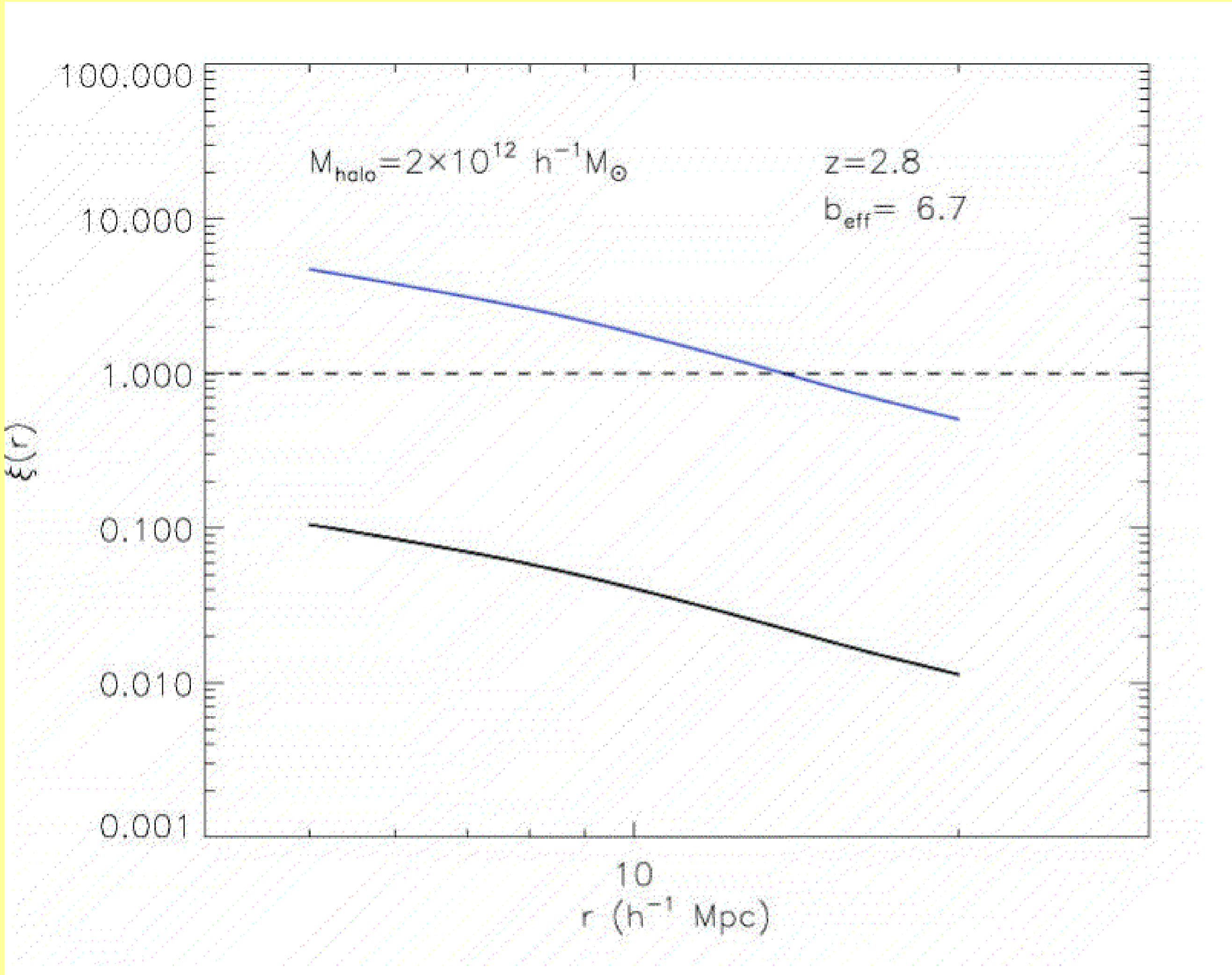
If the scaling relation between SMBH mass and DM halo mass holds to high redshift (Ferrarese 2002), then it implies quasar host DM halos have mass

$$M_{\rm halo} \sim 10^{12} - 10^{13}\ M_\odot$$

And these massive DM halos are highly biased (Bardeen et al. 1986; Mo & White 1996; Jing 1998; Sheth & Tormen 1999)

$$\xi_{\rm QSO} = \xi_{\rm halo} = b^2 \xi_{DM}$$

High redshift (z>2.9) quasar clustering



High redshift (z>2.9) quasar clustering

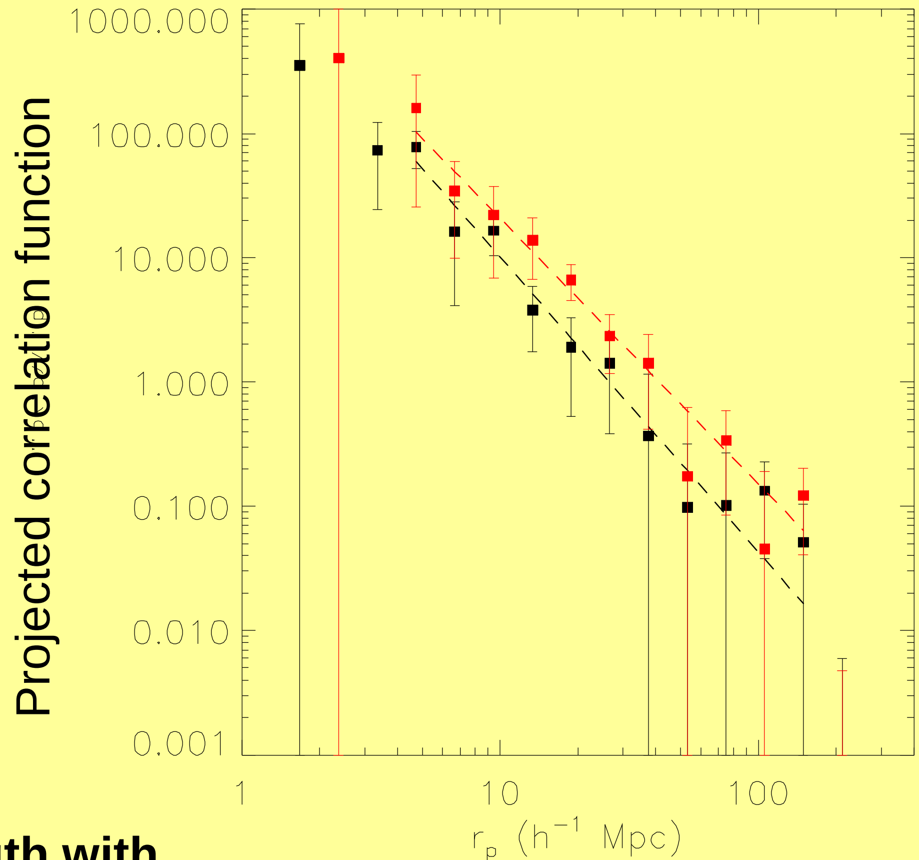
Assuming fixed
power law index $g = 2$

- For $2.9 < z < 3.5$:

  $r_0 = 16.9 \pm 1.7\, h^{-1}\mathrm{Mpc}$

- For $z > 3.5$:

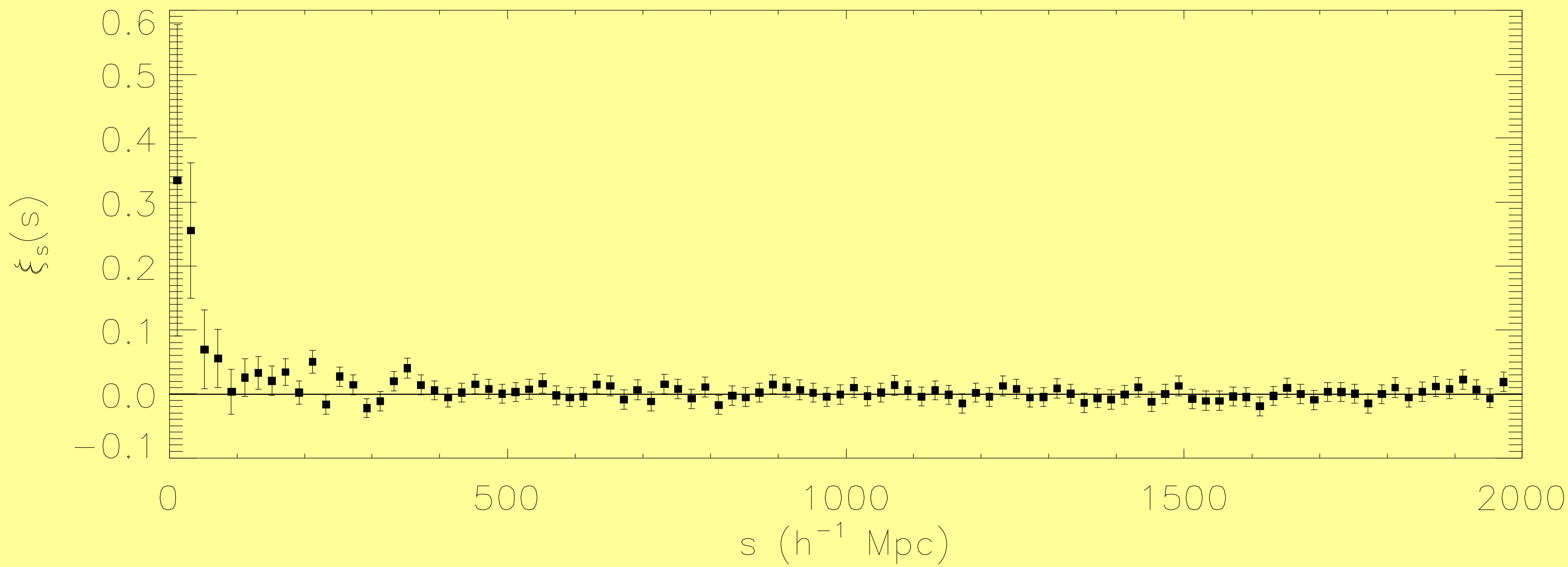
  $r_0 = 24.3 \pm 2.4\, h^{-1}\mathrm{Mpc}$



Projected distance on the sky

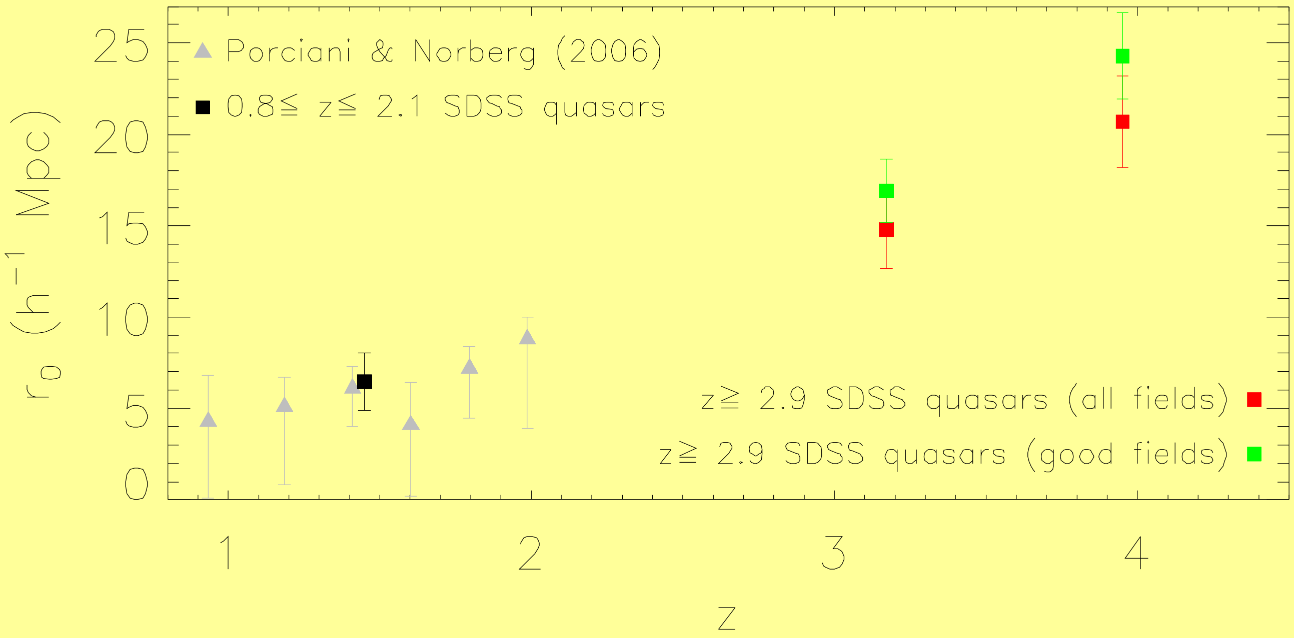
The increase in clustering strength with redshift may be due to two effects: luminosity-dependent clustering, and an ever-increasing bias

High redshift (z>2.9) quasar clustering



Clustering at very large scales >>100 Mpc

High redshift (z>2.9) quasar clustering



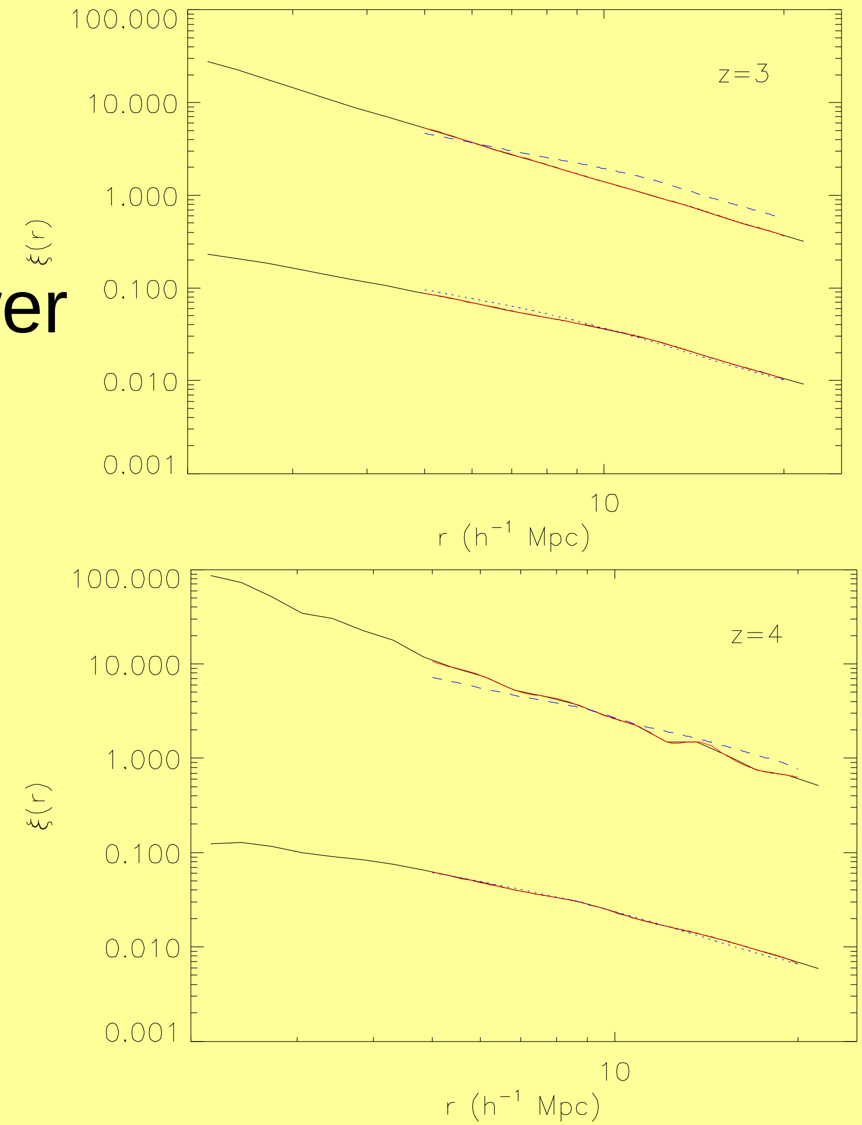
Evolution of correlation length r0

High redshift (z>2.9) quasar clustering

- 3rd year WMAP cosmological parameters; CDM power spectrum
- Linear bias fitting formula (Jing 1998)
- Integrated correlation function

$$x_{20} = \frac{3}{r_{\max}^3}\int_{r_{\min}}^{r_{\max}} x(r)\, r^2\, dr$$

$$r_{\min} = 5\,h^{-1}\mathrm{Mpc},\ r_{\max} = 20\,h^{-1}\mathrm{Mpc}$$

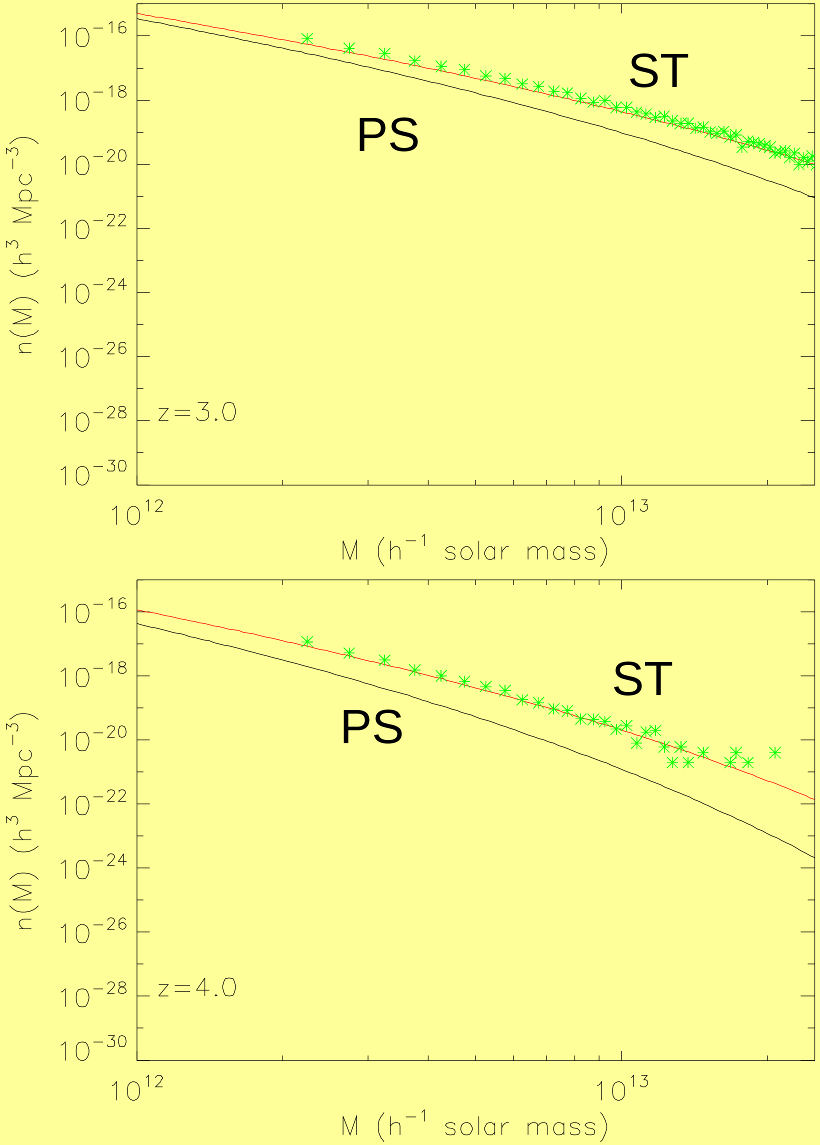


Simulation results by *Paul Bode*

High redshift (z>2.9) quasar clustering

- halo mass function: Sheth-Tormen (ST) vs Press-Schechter (PS)

  ST halo mass function is better!



Simulation results by Paul Bode

High redshift (z>2.9) quasar clustering

- Host halo mass

for $2.9 < z < 3.5$:

$$M_{\text{halo}} = (2-3)\times 10^{12} M_{\odot}, b \approx 10$$

for $z > 3.5$:

$$M_{\text{halo}} = (4-6)\times 10^{12} M_{\odot}, b \approx 15$$

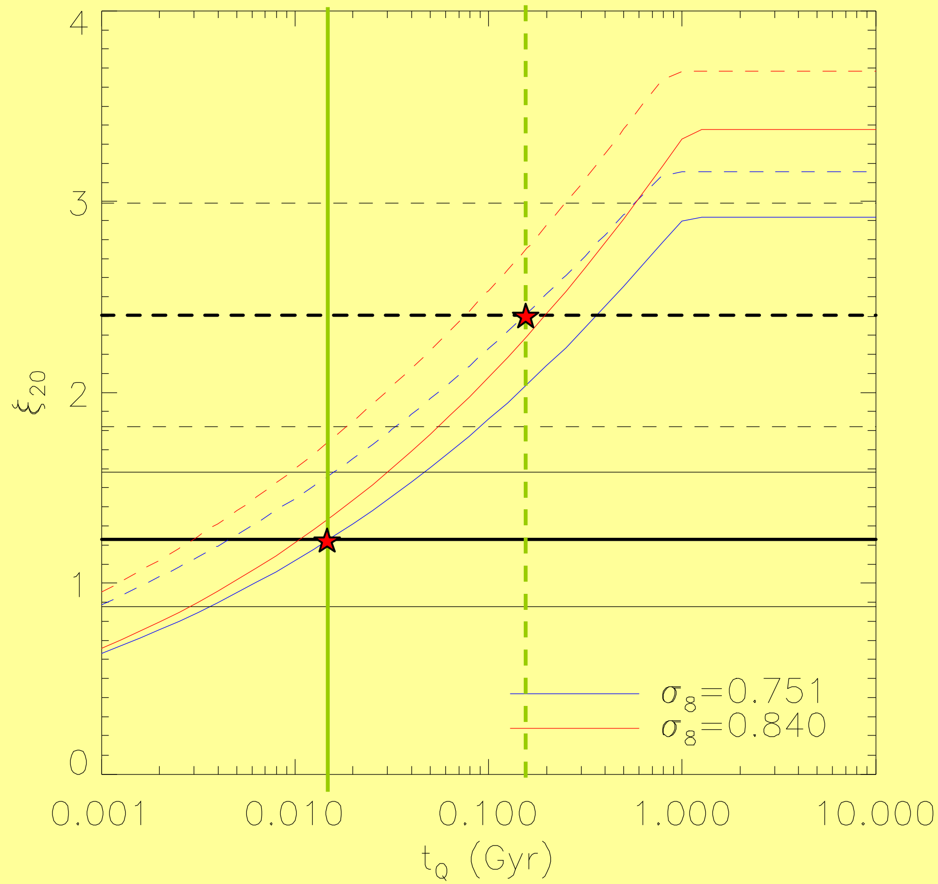
Higher redshift quasars are more luminous and powered by more massive SMBHs

- Quasar lifetimes

for $2.9 < z < 3.5$: $t_Q = 4-50\,\text{Myr}$

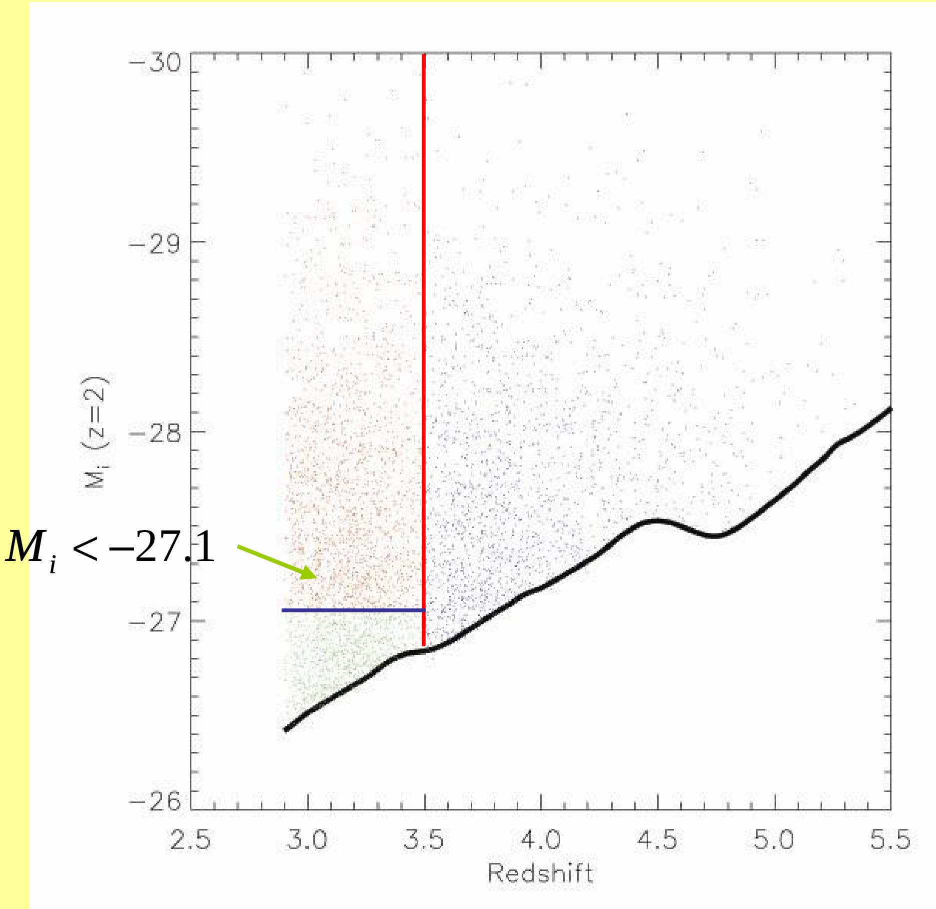
for $z > 3.5$: $t_Q = 30-600\,\text{Myr}$

The estimated quasar lifetimes are very sensitive on the clustering strength!



High redshift (z>2.9) quasar clustering

- Luminosity dependence of high redshift quasar clustering?



High redshift (z>2.9) quasar clustering

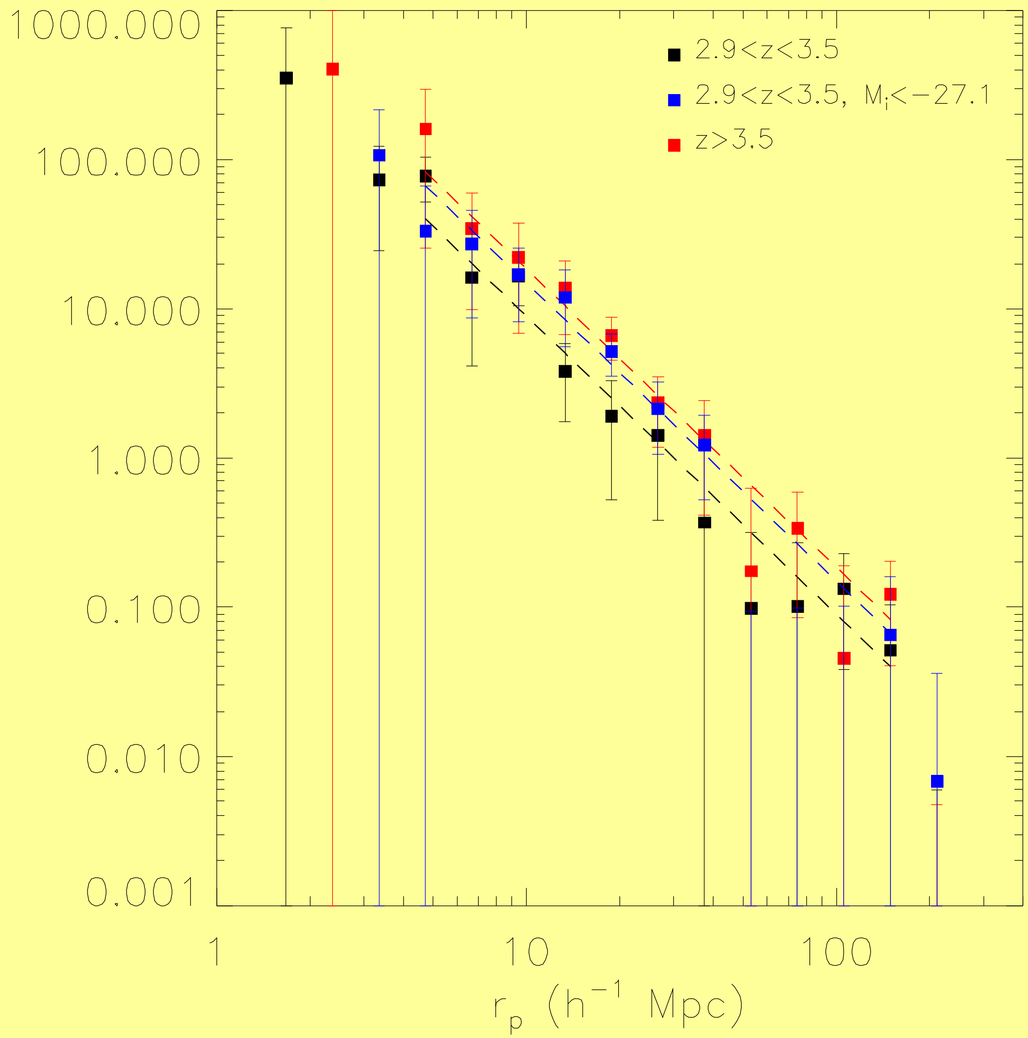
- Luminosity dependence of high redshift quasar clustering?
- Fitted results:

$$g = 2$$

$$r_0 = 16.9 \pm 1.7\, h^{-1}\text{Mpc}$$

$$r_0 = 21.8 \pm 2.1\, h^{-1}\text{Mpc}$$

$$r_0 = 24.3 \pm 2.4\, h^{-1}\text{Mpc}$$



Summary of quasar clustering at z>2.9

- Much more strongly clustered than low-redshift counterparts (three times stronger); with b>~10 (higher redshift and higher luminosities)
- Host DM halo mass ~ $\text{a few } \times 10^{12}\, h^{-1} M_{\mathbf{e}}$, increases with redshift due to flux limited sample
- $t_Q \,\mathbf{:}\, 10^{6} - 10^{8}\ \text{yr}$, or in terms of duty cycle, ~ 0.004-0.05 for 2.9<z<3.5; ~ 0.03-0.6 for z>3.5
- Luminosity-dependent clustering?

Future work

- Luminosity dependence of quasar clustering, or, dependence on SMBH mass
- Clustering of various quasar populations, such as BALs, radio-loud quasars
- Small-scale quasar clustering at high redshift (Hennawi et al., in preparation)
- High-redshift galaxy counts