Title: The Evolution of Quasars with Cosmic Time

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URL: http://www.pirsa.org/13020120

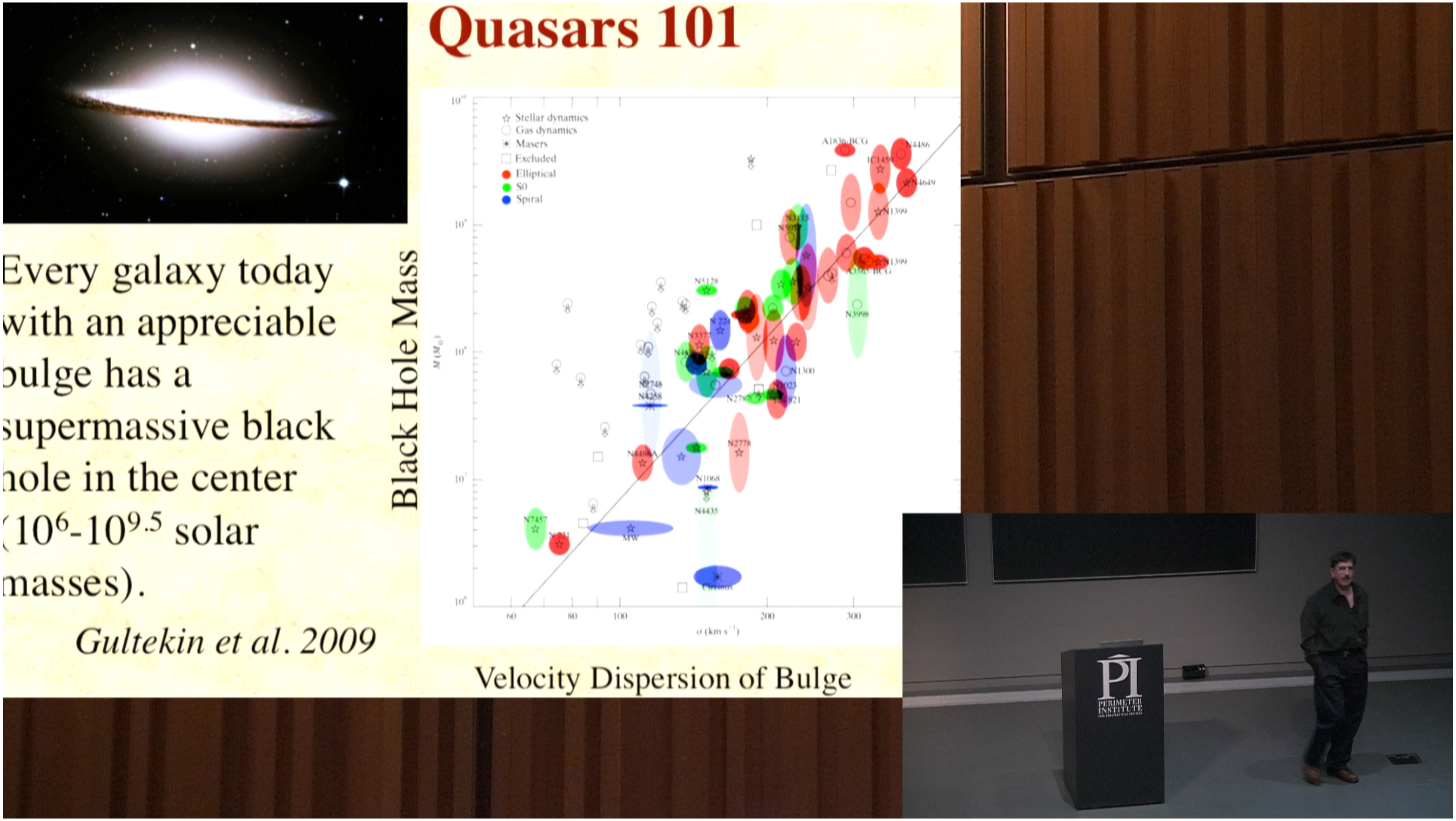
Abstract: While the luminosity and mass distributions of quasars has evolved dramatically with cosmic time, the physical properties of quasars of a given luminosity are remarkably independent of redshift. I will describe recent results on the spectra of luminous quasars, the dark matter halos in which they sit, and the intergalactic medium of their host galaxies, that are essentially indistinguishable from moderate redshifts to z>6.

The one property apparently unique to the highest-redshift quasars is that some small fraction show evidence for having very little infrared excess from hot dust.
Dust obscuration is another theme in quasar studies; an appreciable fraction of the growth of black holes may be hidden at optical wavelengths by dust. I will describe searches for obscured quasars at high redshift and low, and studies of their demographics and physical properties.

The Evolution of Quasars with Cosmic Time

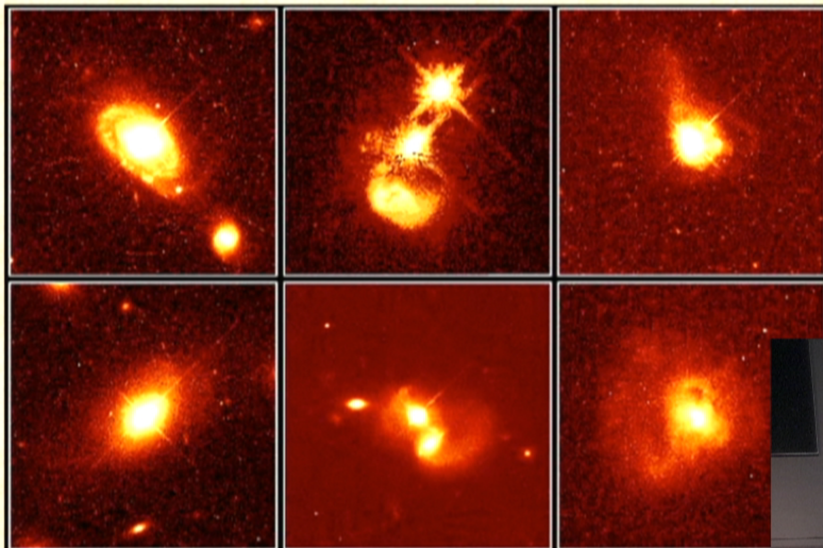
Michael A. Strauss, Princeton University

- Quasars 101
- The evolution of quasar number density
- The evolution of quasar clustering
- The physical nature of the highest redshift quasars and their host galaxies


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
Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
σ (km s⁻¹)
PERIMETER INSTITUTE

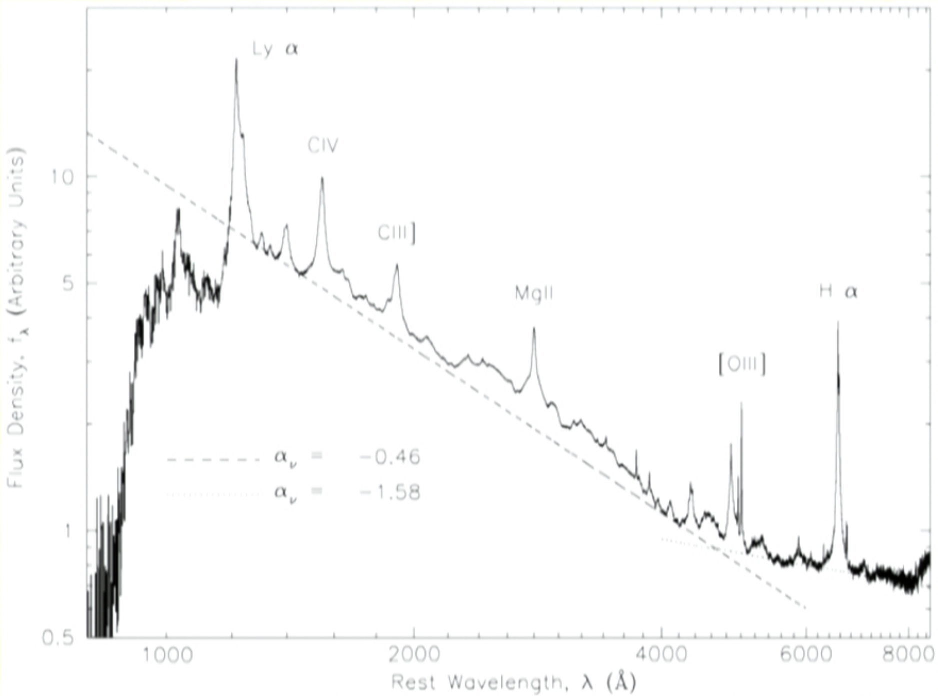
These black holes are mostly quiescent in the present-day Universe, but grew rapidly a few billion years after the Big Bang as material flowed into them via an accretion disk.

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.



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

(Ordinary) 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

The Sloan Digital Sky Survey

An international consortium carrying out surveys of the sky since 1998.

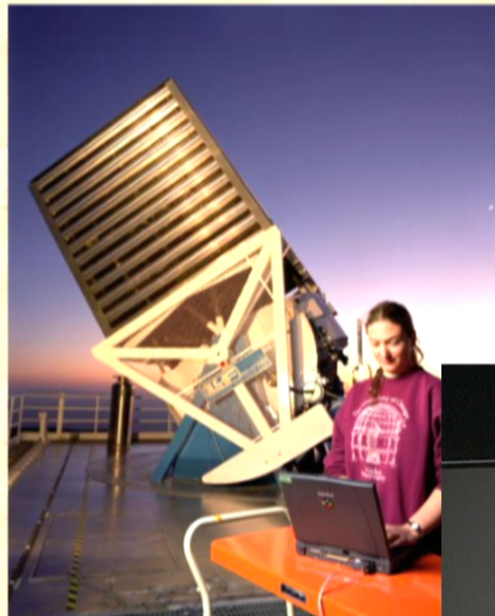
Jim Gunn

Connie Rockosi

A dedicated 2.5m telescope surveying the Northern Sky in visible light in five photometric bands using modern CCD technology over 14,500 deg^2 (1/3 of the Celestial Sphere).

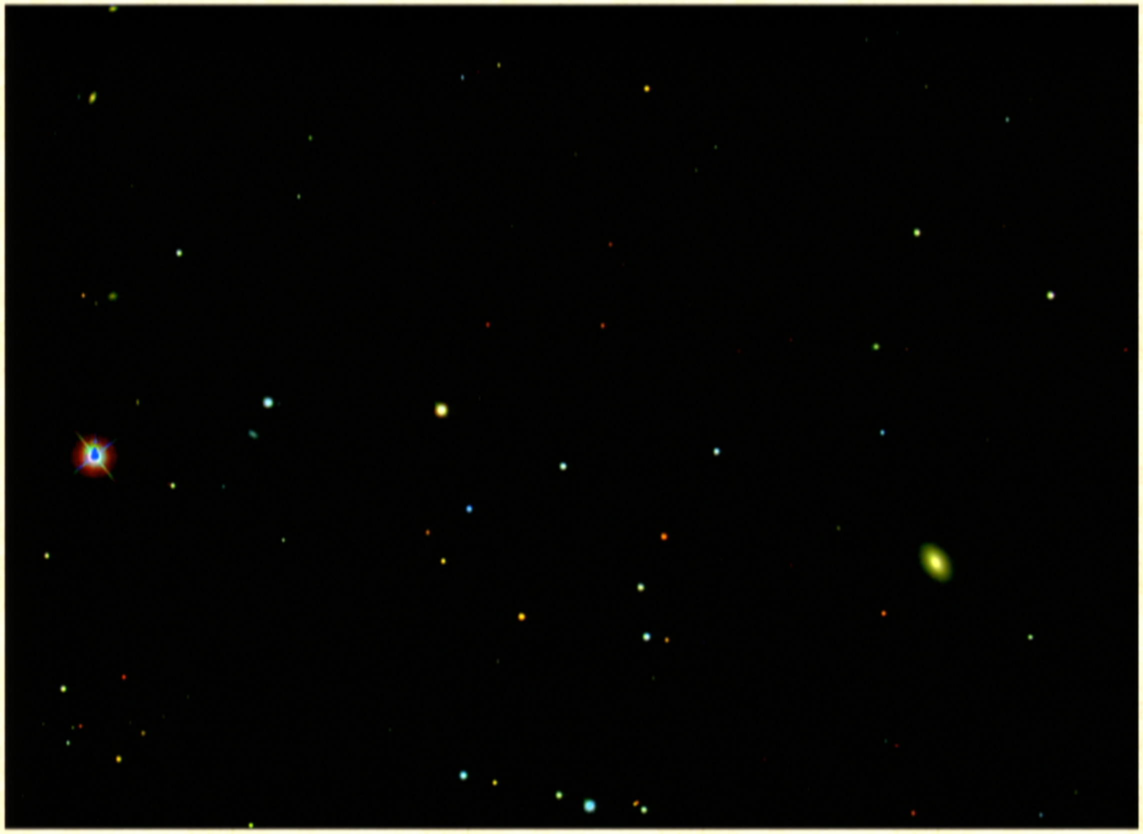
A spectroscopic redshift survey of two million galaxies and three hundred thousand quasars (and a lot of stars!) to study their properties and distribution in space.

An emphasis on highest quality photometric and astrometric calibration.



A dedicated 2.5-meter telescope, 3° field of view

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



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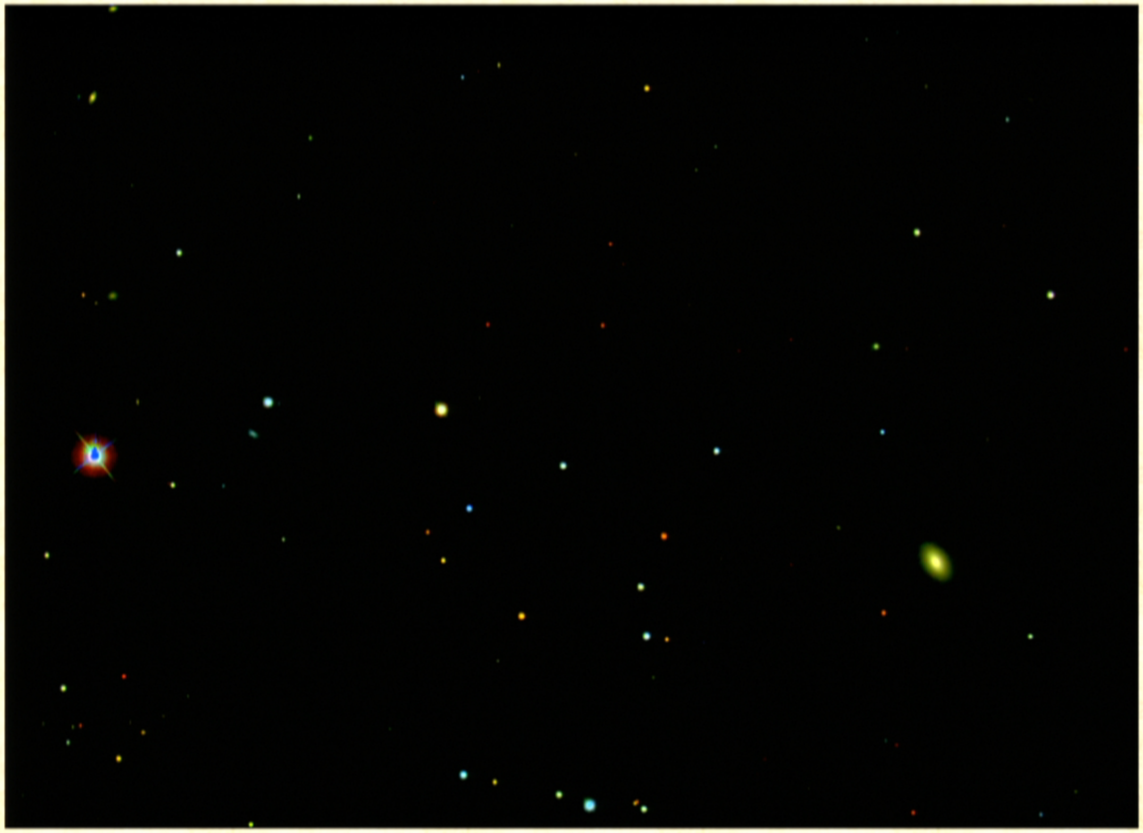
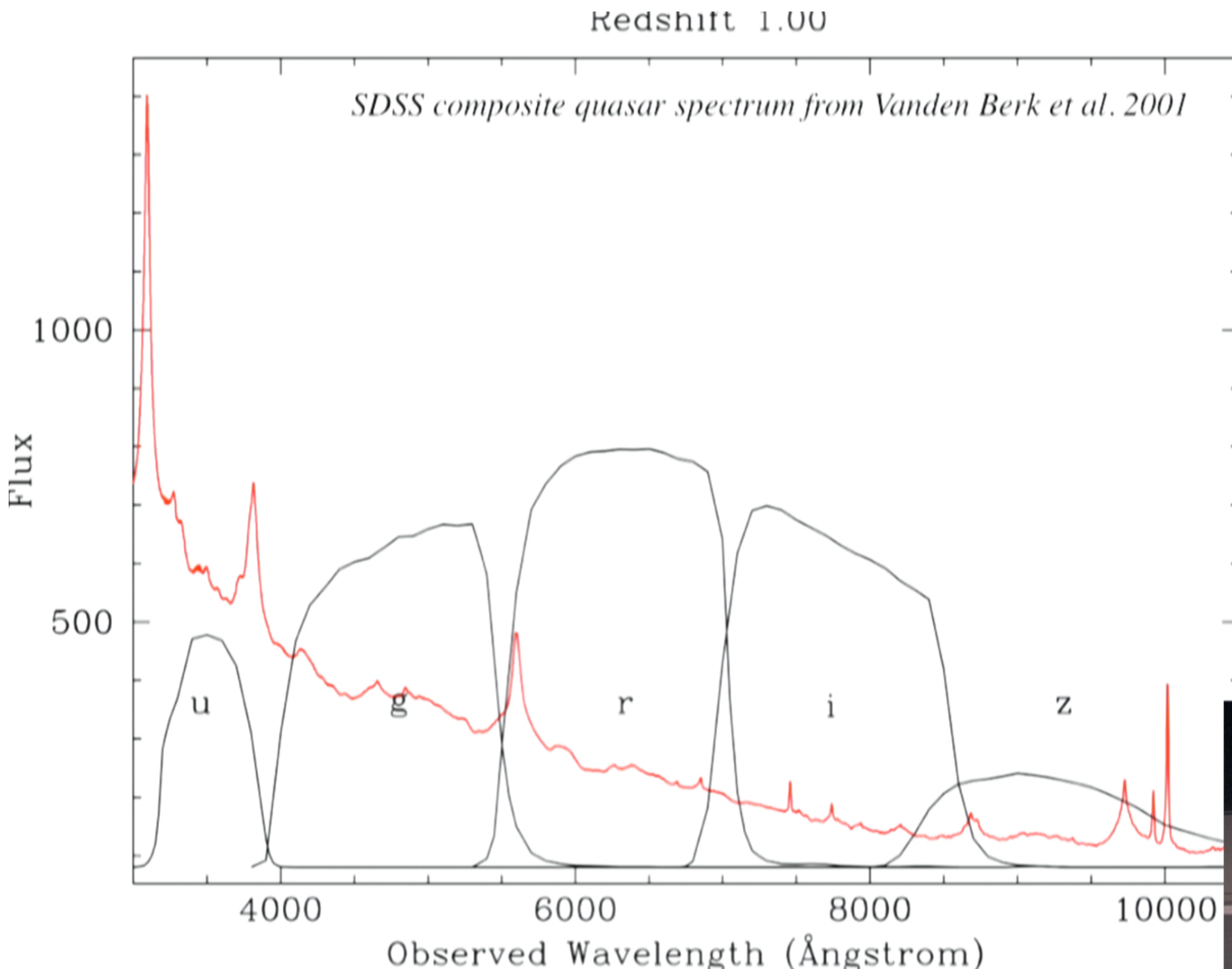
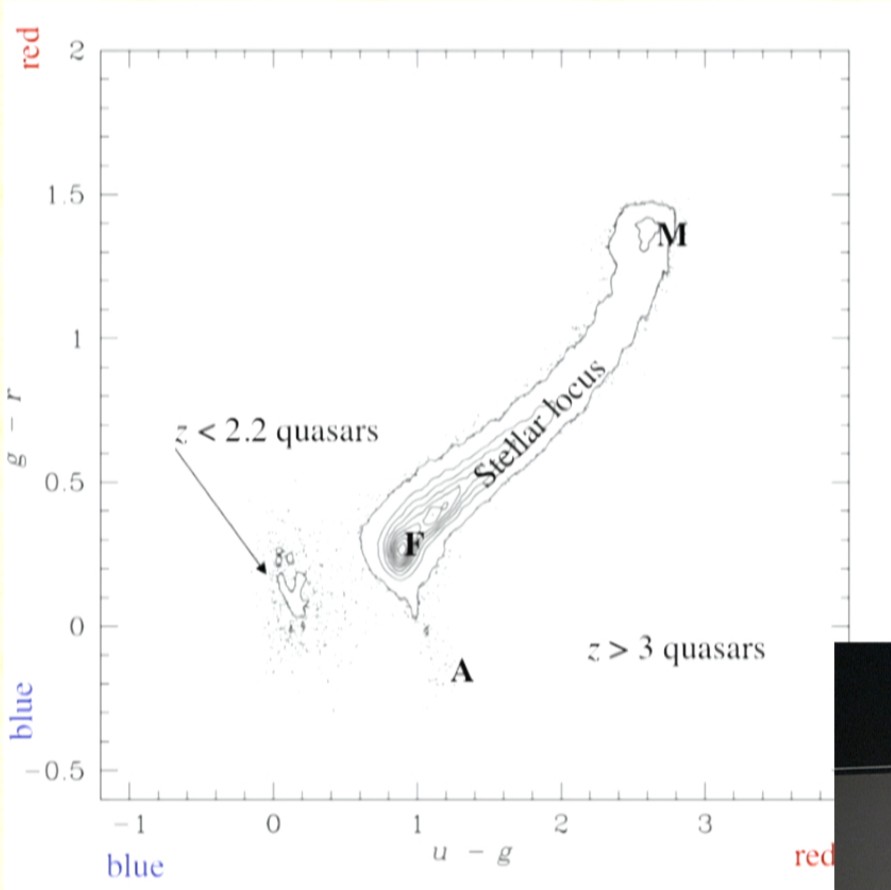
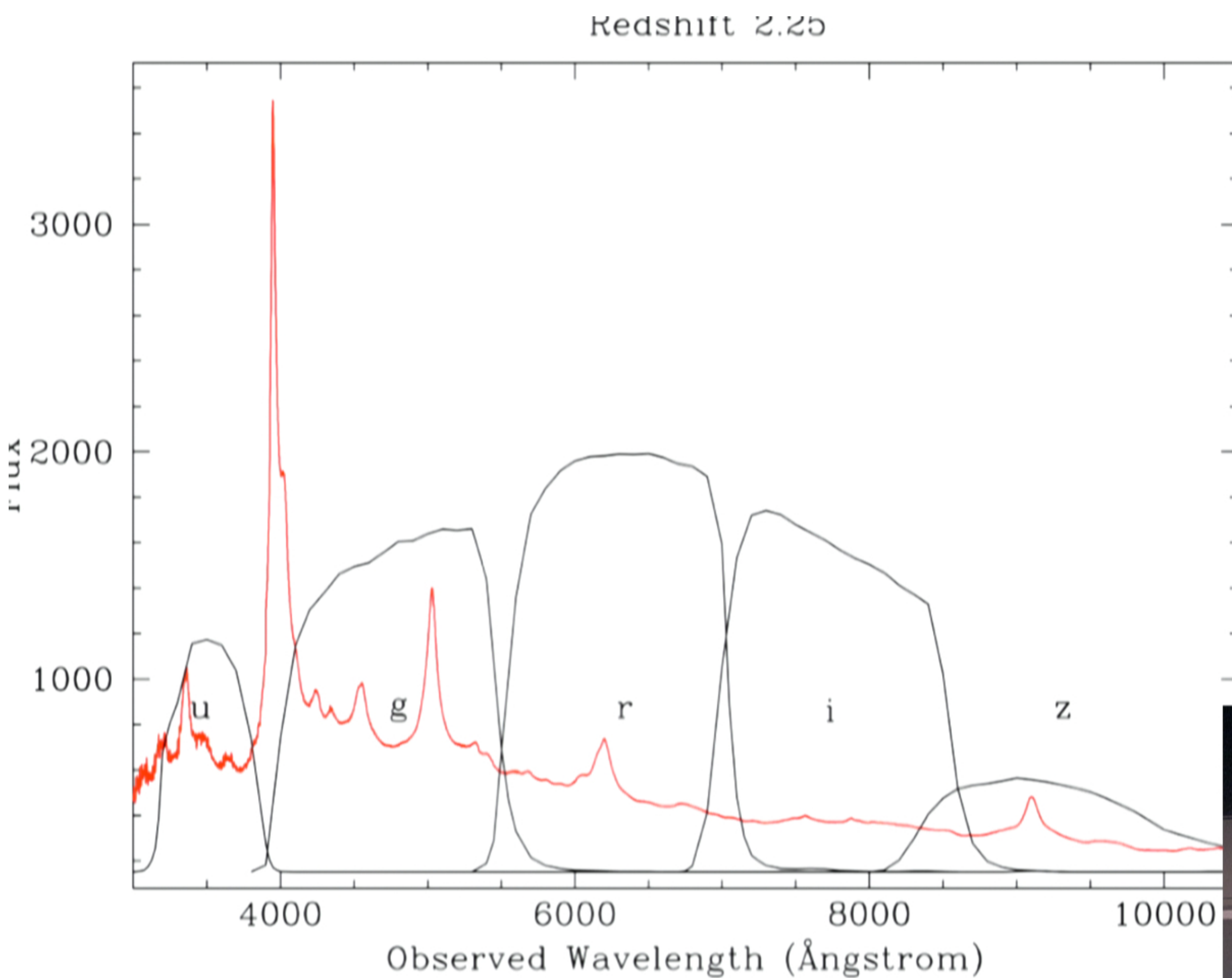


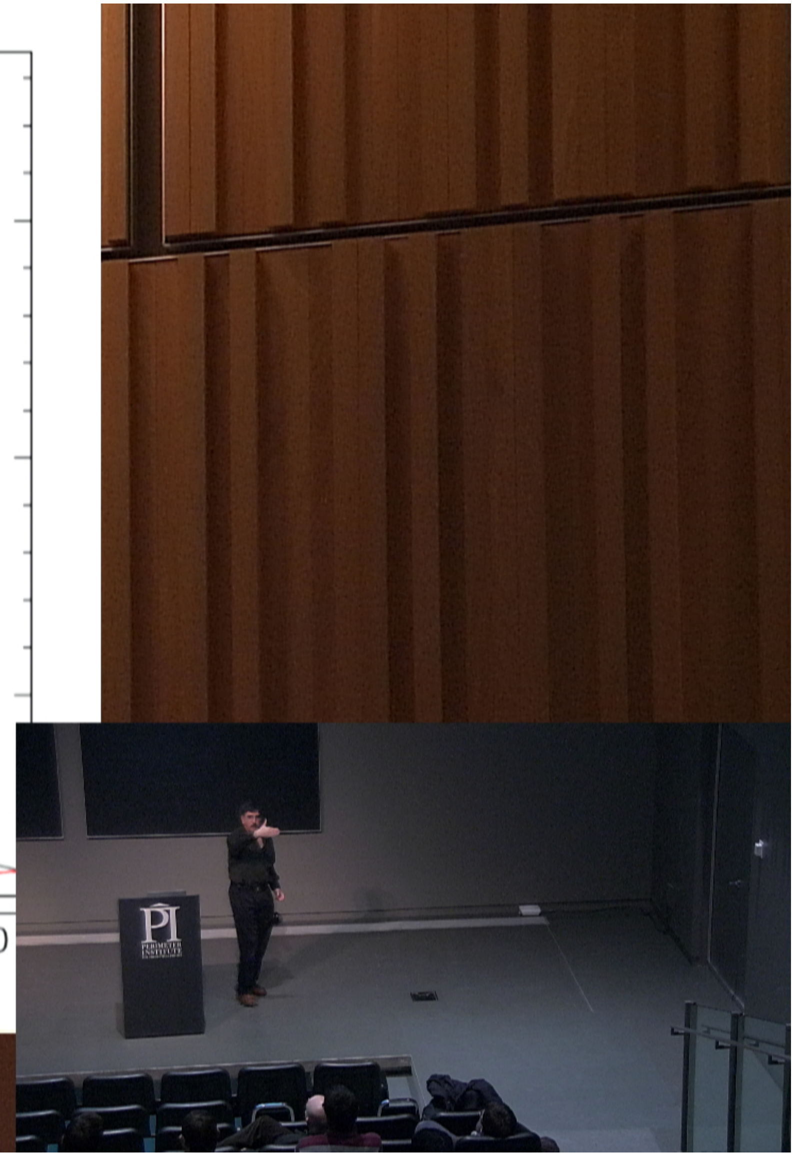

Redshift 1.00
SDSS composite quasar spectrum from Vanden Berk et al. 2001
Flux
1000
500
u
g
r
i
z
4000
6000
8000
10000
Observed Wavelength (Ångstrom)

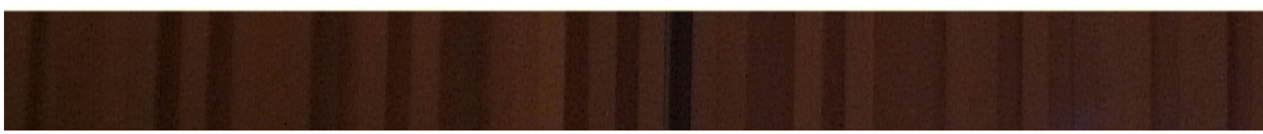
From the 5 SDSS filters, we can form four independent colors.

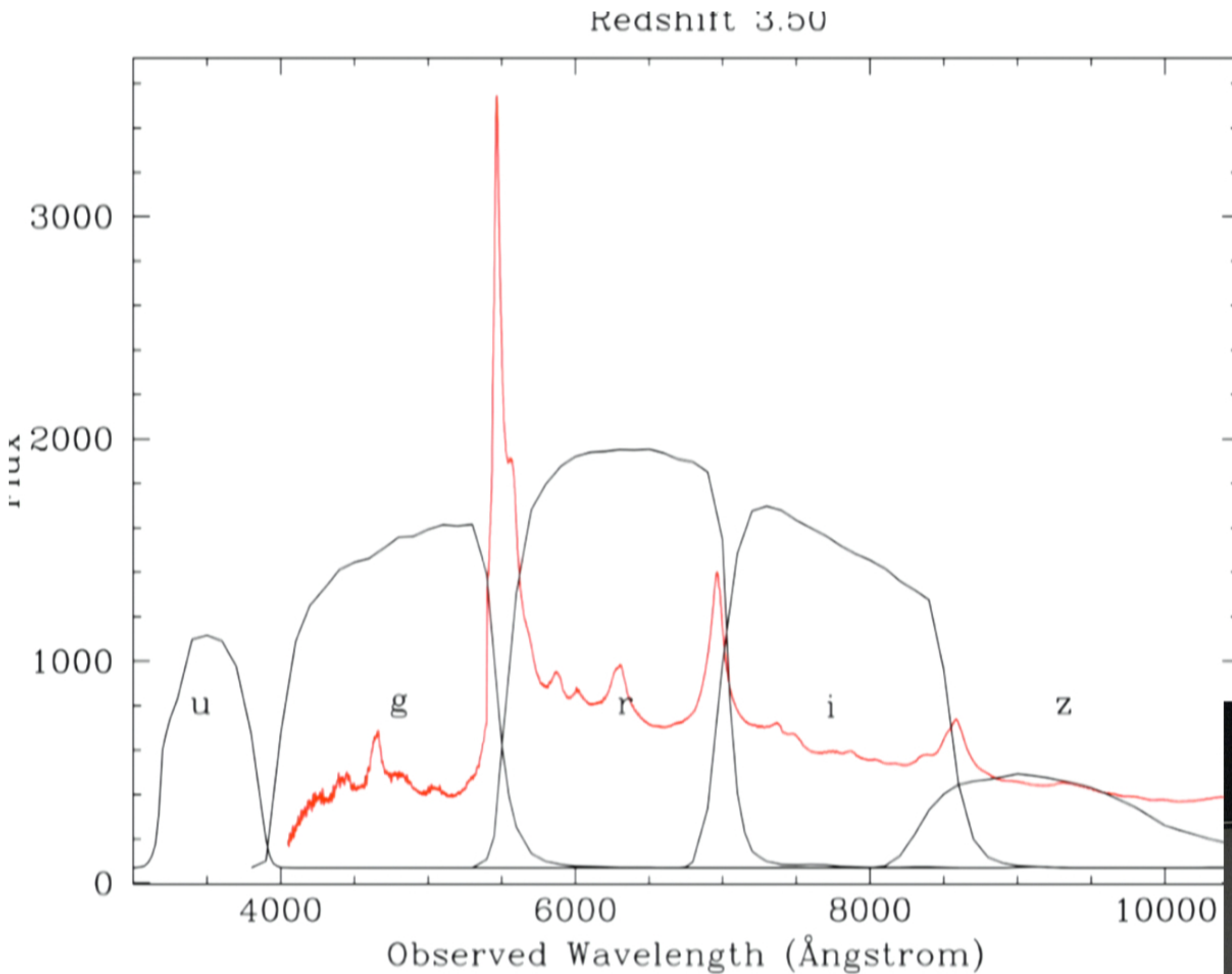
Low-redshift (z<2.2) quasars are blue in u-g.




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






Redshift 3.50
Flux
3000
2000
1000
0
4000
6000
8000
10000
Observed Wavelength (Ångstrom)
u
g
r
i
z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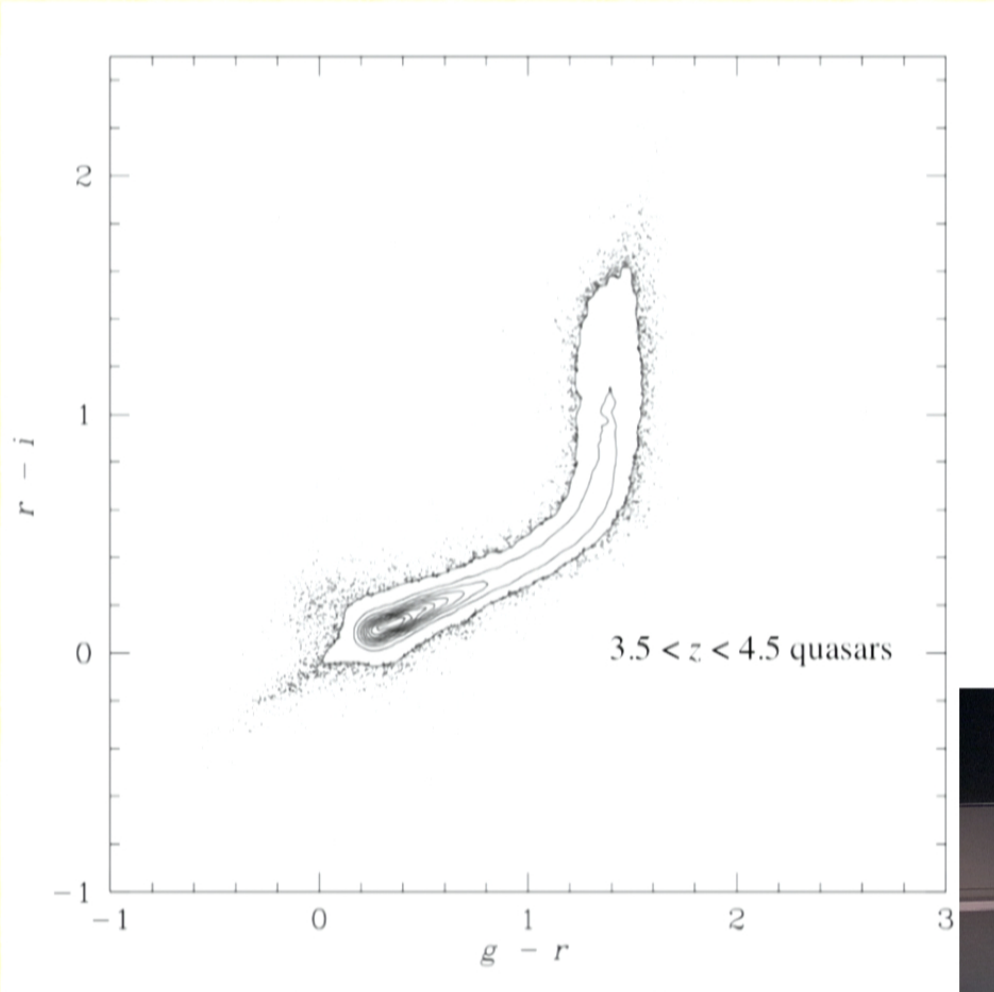
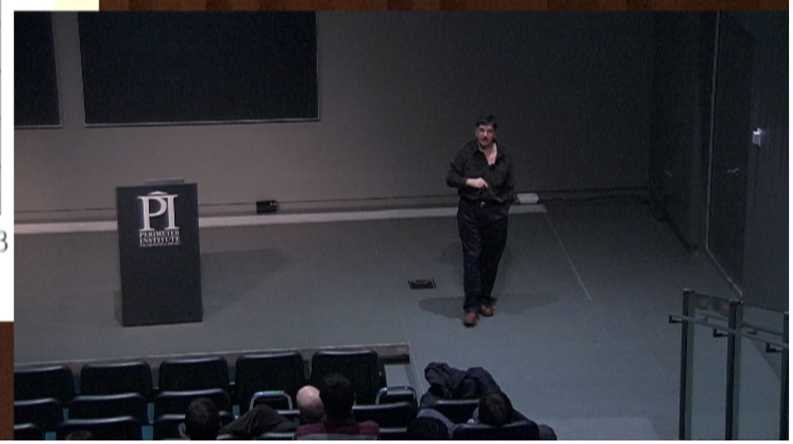
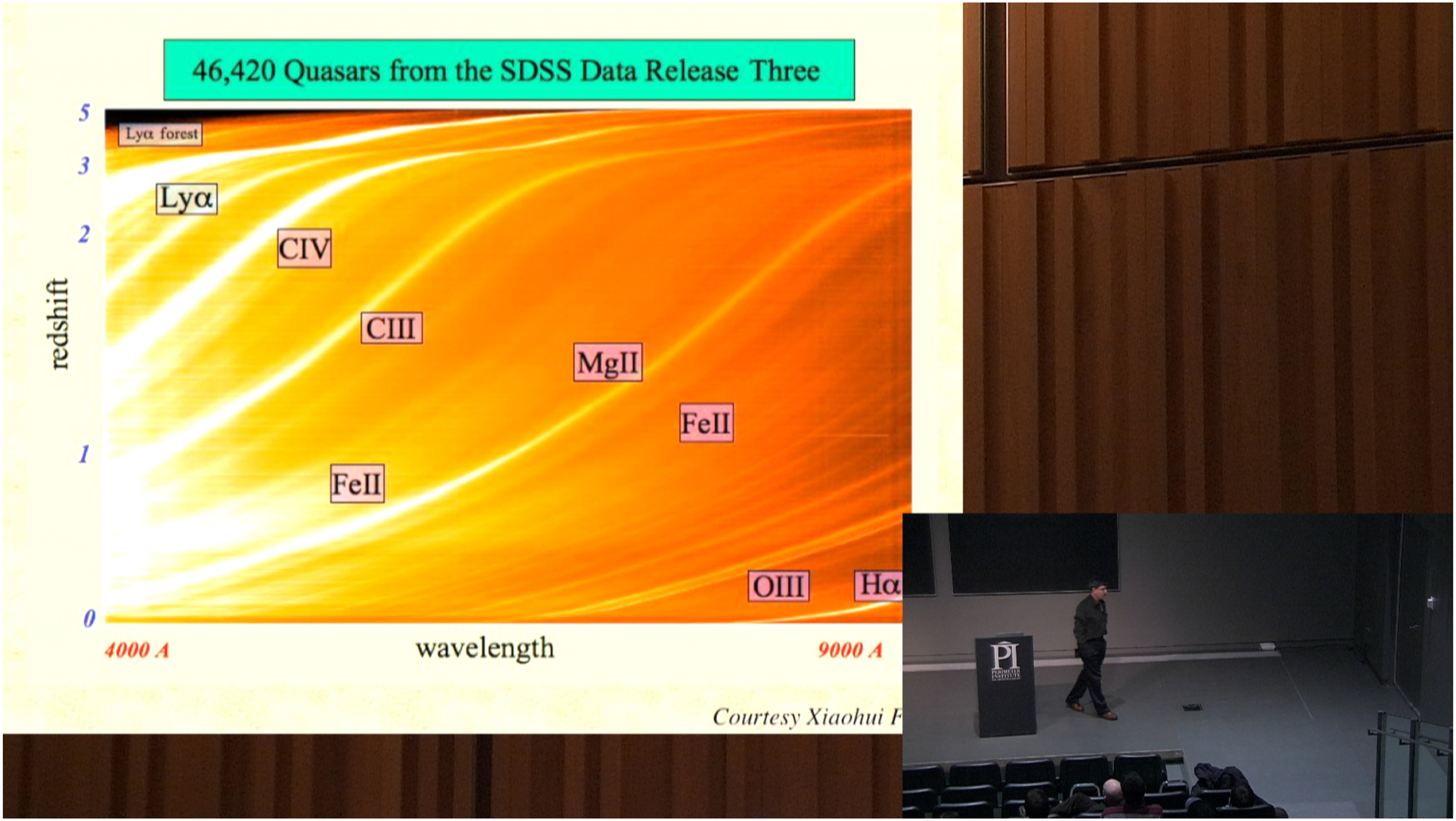
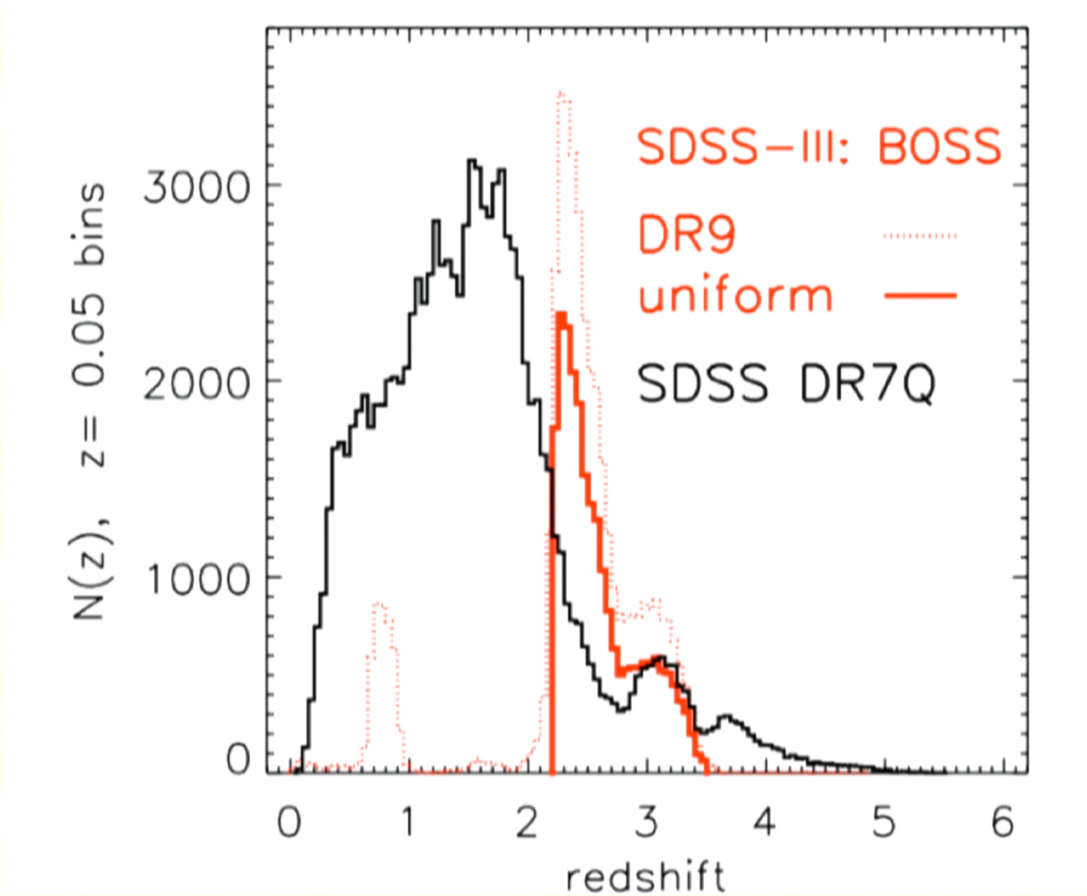
At $z > 3.5$, quasars drop out of the u-band. The Lyα forest moves into the g band, and quasars become red in g-r.






46,420 Quasars from the SDSS Data Release Three
Lyα forest
Lyα
CIV
CIII
MgII
FeII
FeII
OIII
Hα
5
3
2
1
0
redshift
4000 A
wavelength
9000 A
Courtesy Xiaohui F

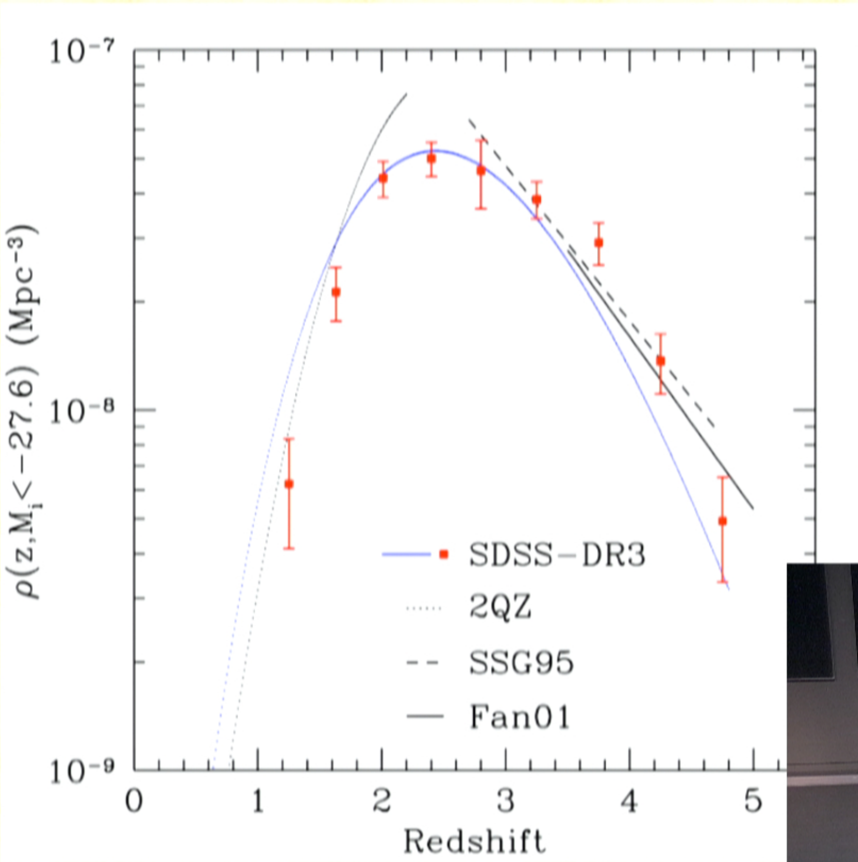


Ross et al. 2012: SDSS has sampled quasars to redshifts of 5 and beyond

Evolution of the Quasar Number Density

Gordon Richards, Drexel U.   Scott Croom, Sydney   Nic Ross, LBL

Comoving number density of luminous quasars peaks between z=2 and 3

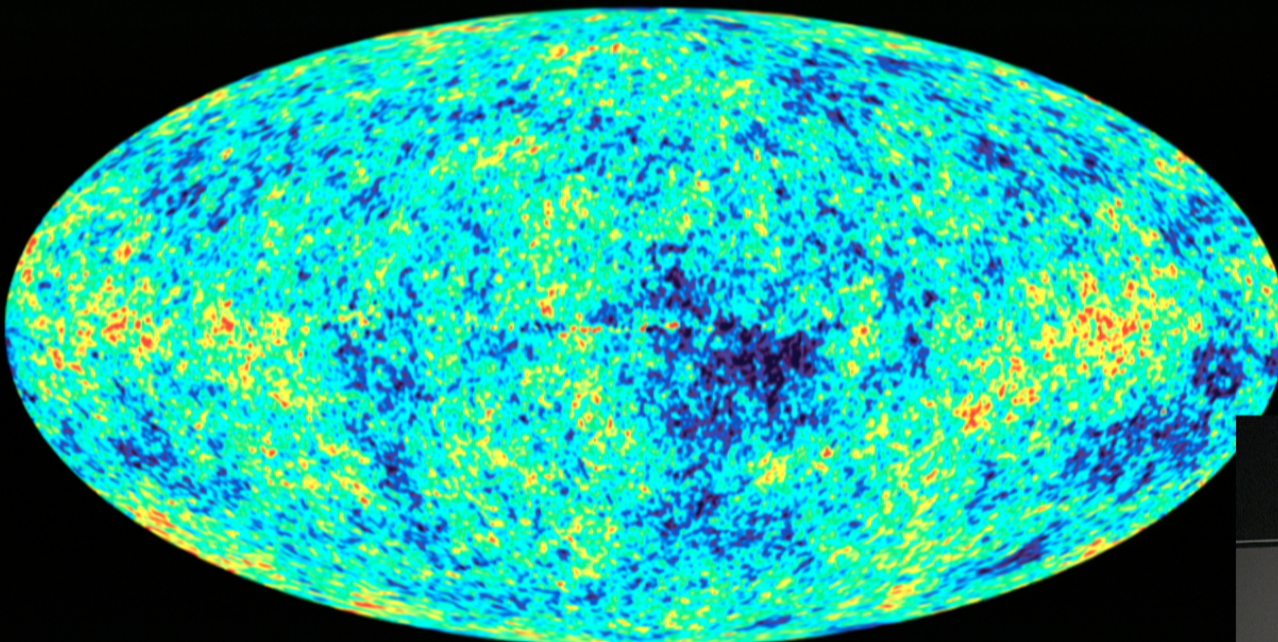


Richards et al. 2006

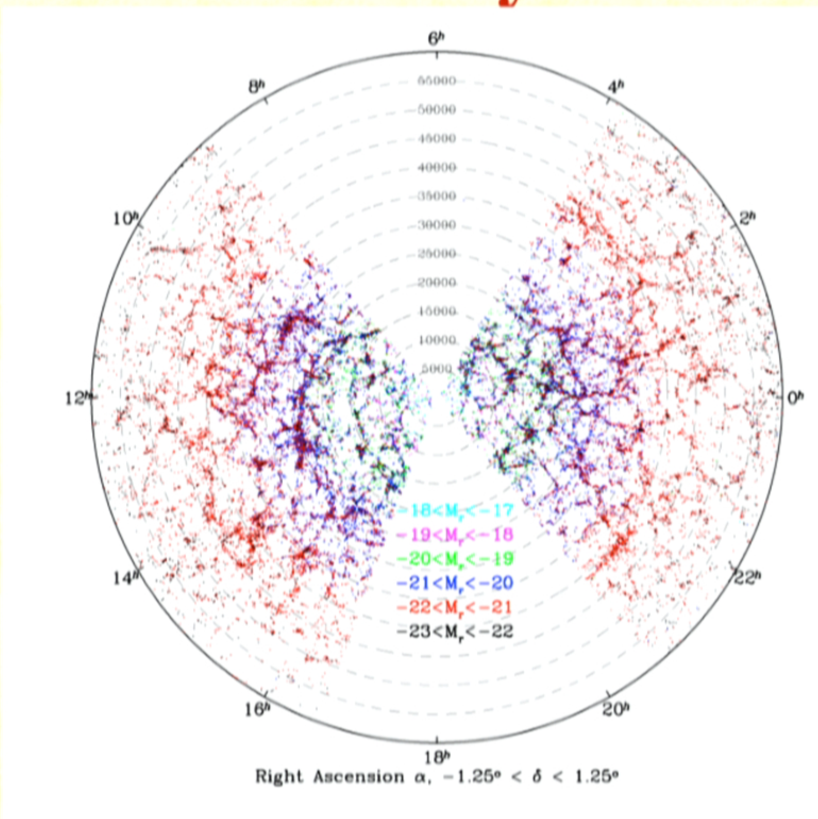
The clustering of quasars and its cosmological evolution

Yue Shen, Carnegie

Cosmic Microwave Background Fluctuations: 10^{-5} at z=1000



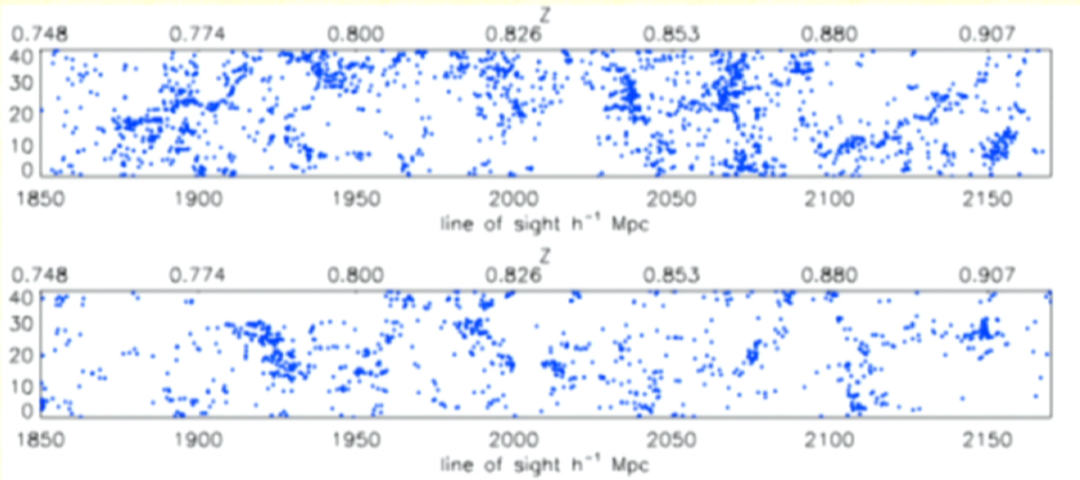
The Present-Day Galaxy Distribution is Very Clustered



Dark Matter Clustering Grows with Time

- Our cosmological model allows us to predict the strength of dark matter clustering at any epoch in the past, and therefore at any redshift.
- At high redshift (back in time), the dark matter clustering should be weaker.

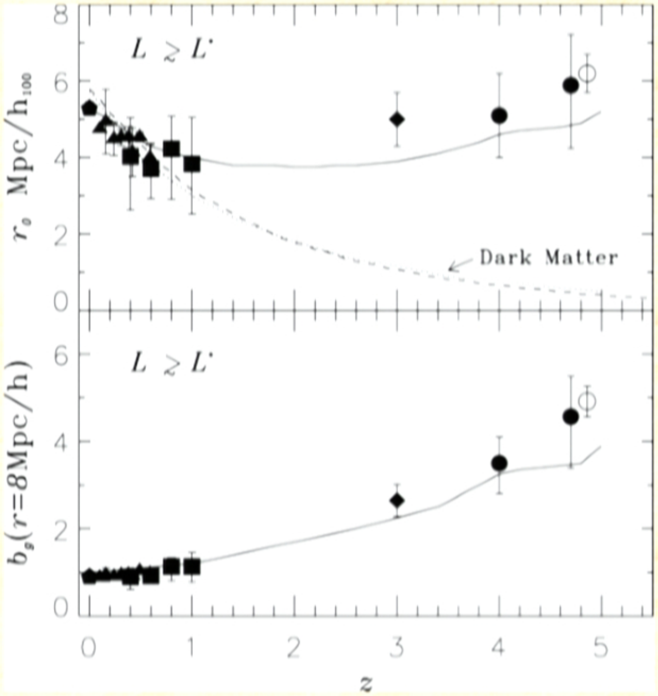
But galaxies at high redshift are known to be strongly clustered as well.



Pie diagrams from Deep2 survey; Coil et al. Courtesy Ena Choi

The filamentary structure familiar at low redshift is apparent at high redshift as well.

The comoving clustering length of luminous galaxies is roughly independent of z at least to $z \sim 5$.



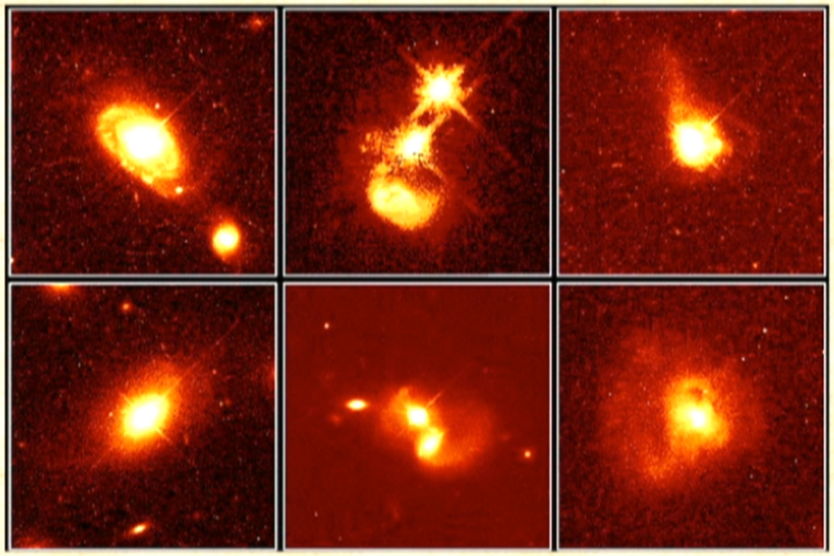
Ouchi et al. 2004

Therefore, the distribution of galaxies must be increasingly biased relative to the dark matter at high redshift,

$\delta_{galaxies} = b\ \delta_{dark\ matter}$

How about quasars?

Quasars are powered by the ubiquitous supermassive black holes in the cores of ordinary massive galaxies

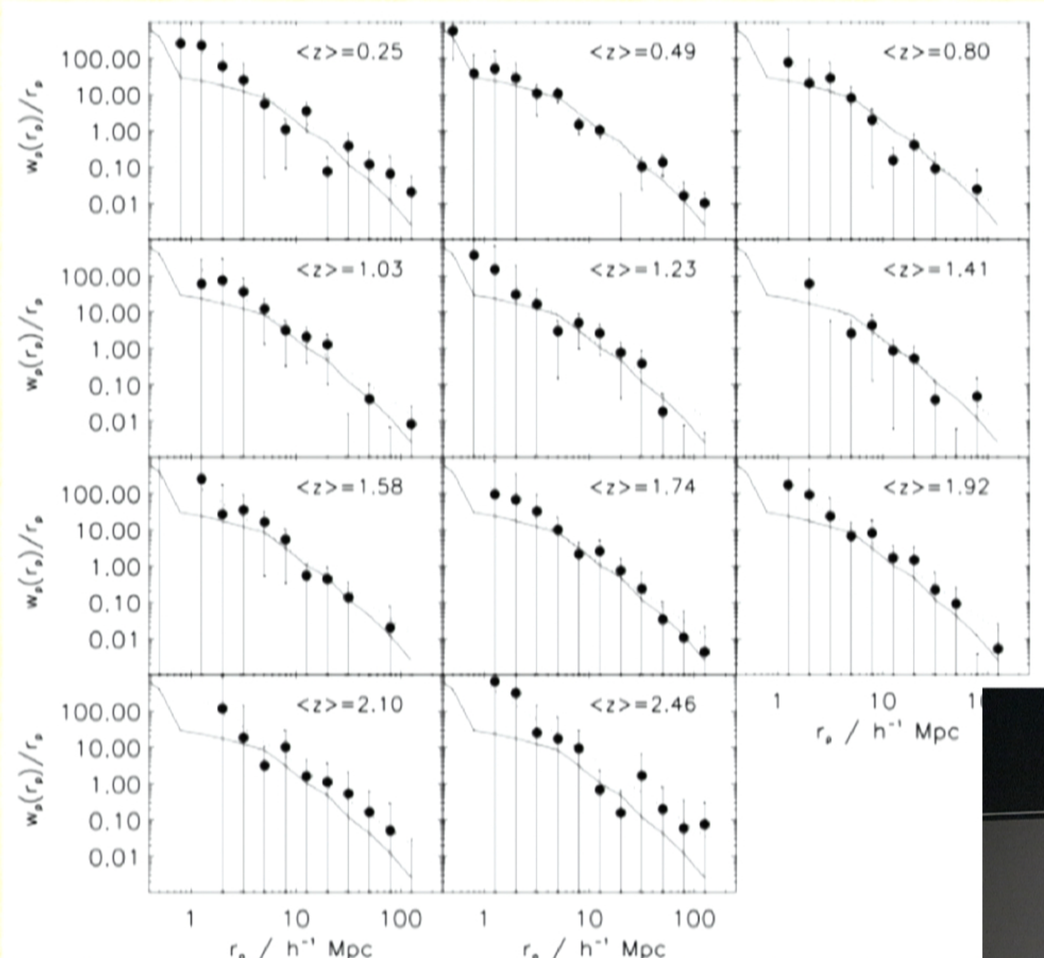


Therefore, we'd expect that the clustering of quasars should be similar to that of luminous galaxies, at the same redshift.

Bahcall, Kirhakos et al.

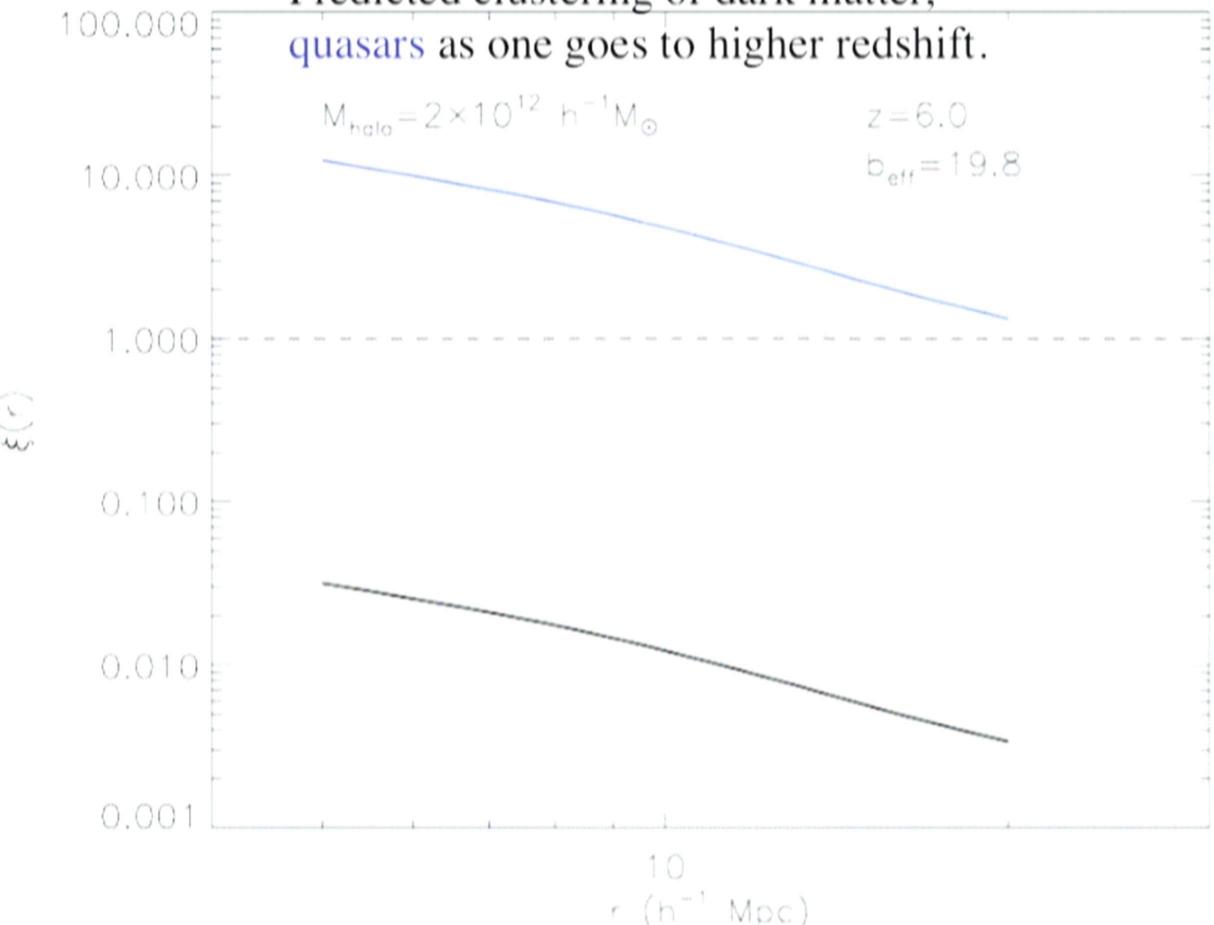
SDSS DR5 quasar sample, a complete sample of ~30,000 objects. Projected correlation function in redshift slices.

The clustering length changes very little with redshift.



Ross et al. 2009

Predicted clustering of dark matter, quasars as one goes to higher redshift.



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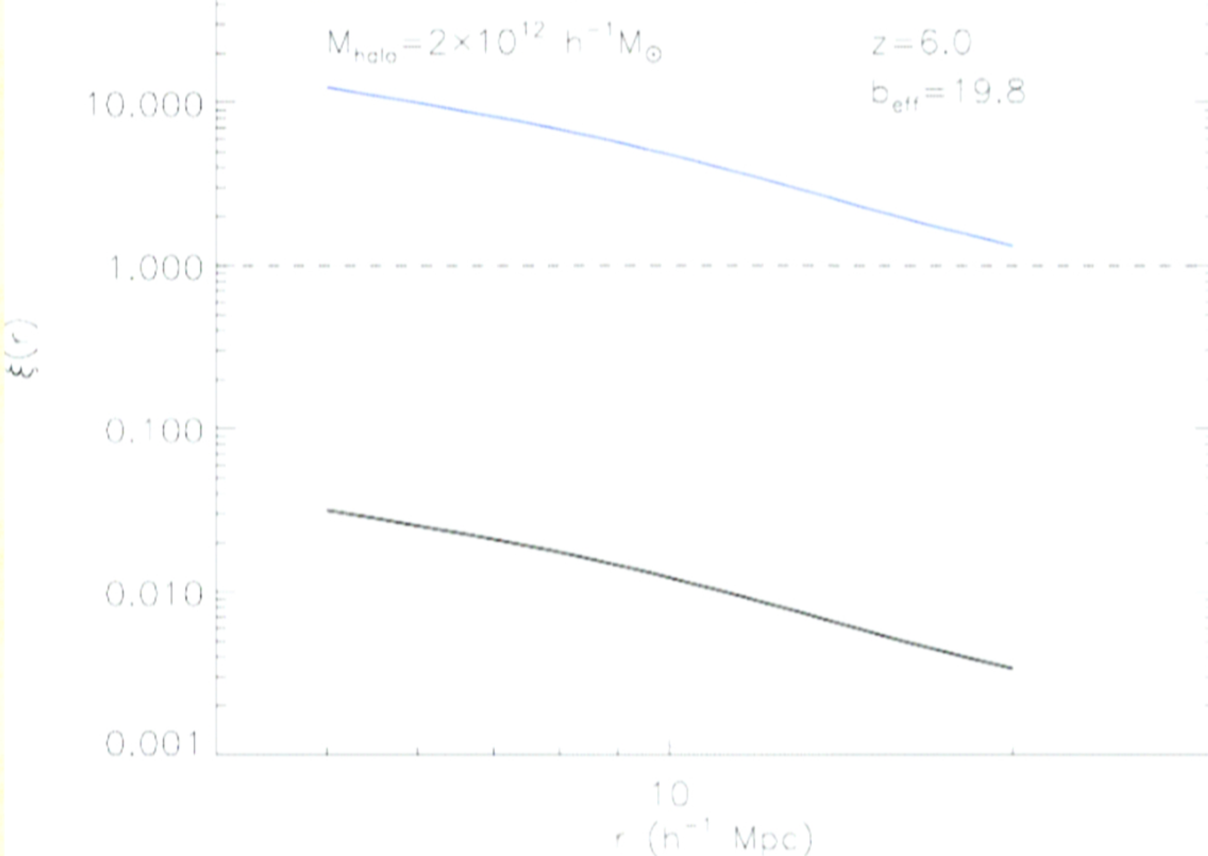
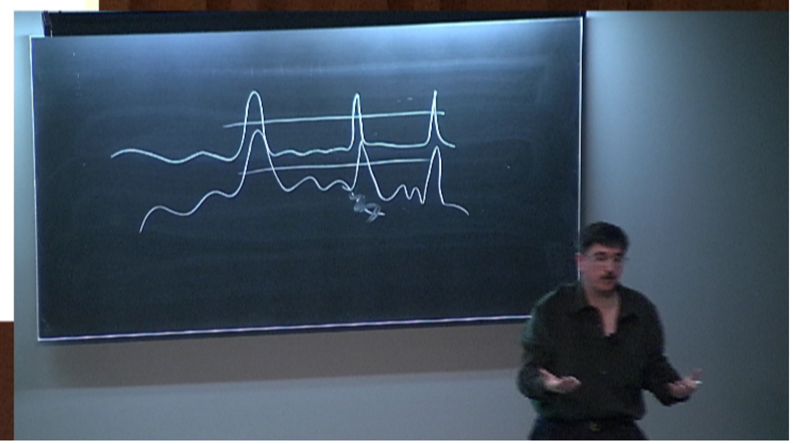
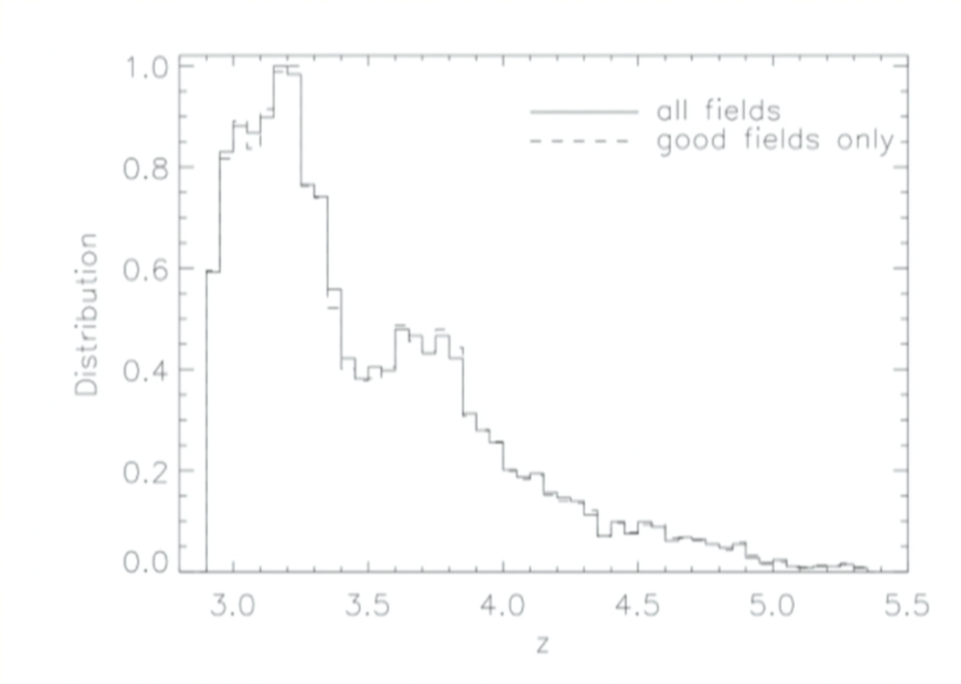




Let's measure this with the SDSS high-z quasar sample.

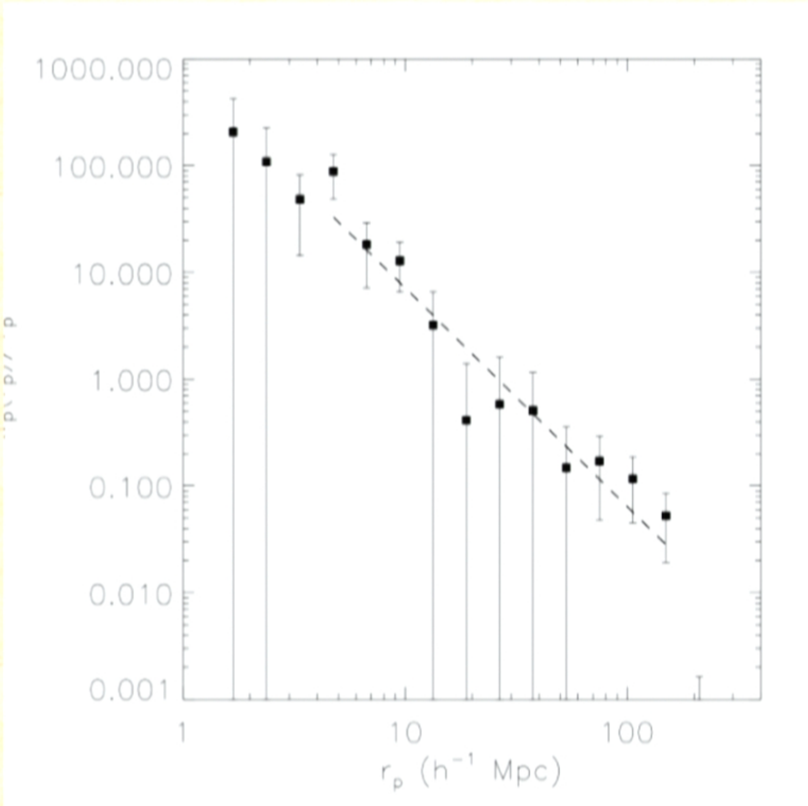


4400 z>2.9 quasars in a uniformly selected sample over 4000 deg^2 from DR5. Mean spacing between quasars is 150 h^{-1}Mpc. This is a sparse sample!

Shen et al. 2007

Measured correlation function for 2.9 < z < 5 quasar sample

Projected correlation function



Projected distance on the sky

Equivalent to

$\xi(r) = (r/r_0)^{-\gamma}$

r_0**=15.2±2.7 Mpc/h**

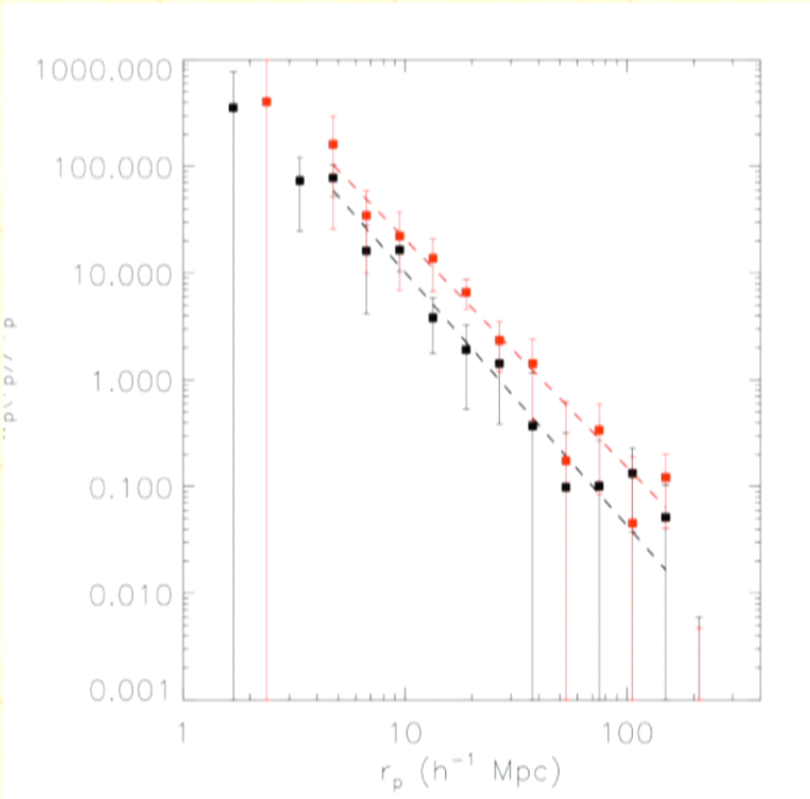
γ**= 2.0±0.3**

A bias of 10!

At these redshifts, ordinary galaxies have r_0~5 Mpc/h

Shen et al. 2007

So the clustering was larger in the past



For 2.9 < *z* < 3.5:

r_0=16.9±1.7 Mpc/h

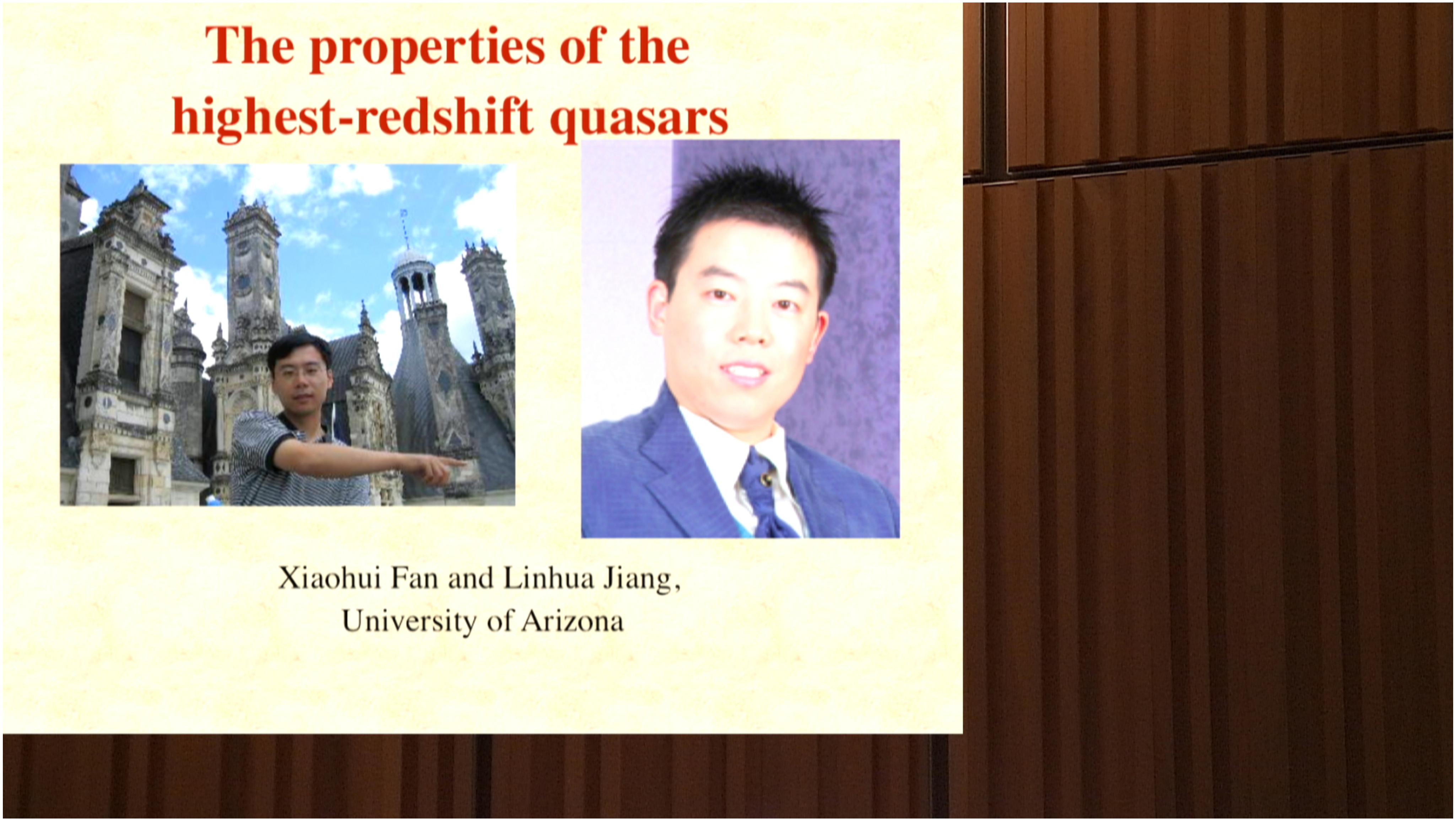
***b*~10**

For *z* > 3.5:

r_0=24.3±2.4 Mpc/h

***b*~15**

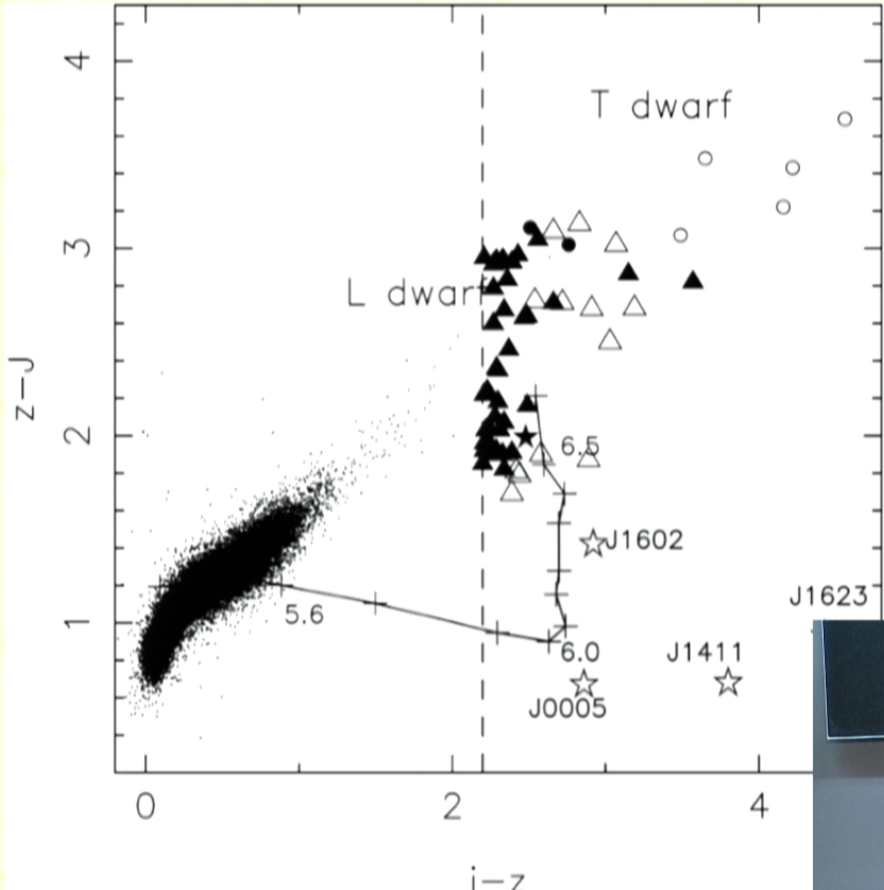
We infer that luminous quasars live in dark matter halos of mass ~2 ×10^{12} solar masses, independent of redshift.

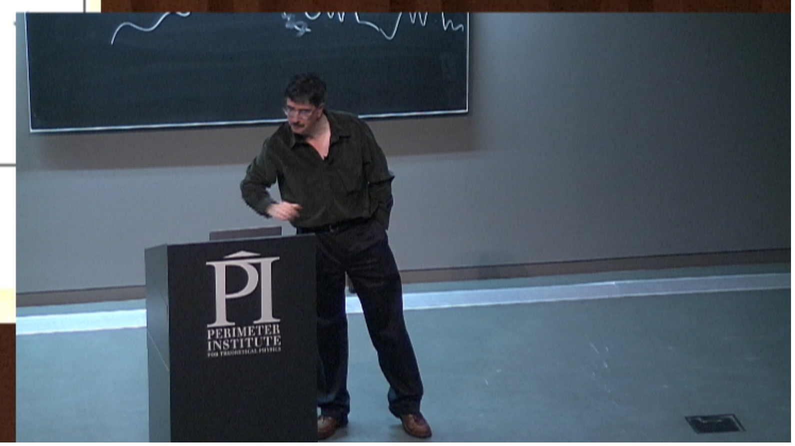

The properties of the
highest-redshift quasars
Xiaohui Fan and Linhua Jiang,
University of Arizona

Fan et al 2004; J-band data from 2MASS, APO 3.5m, and other telescopes

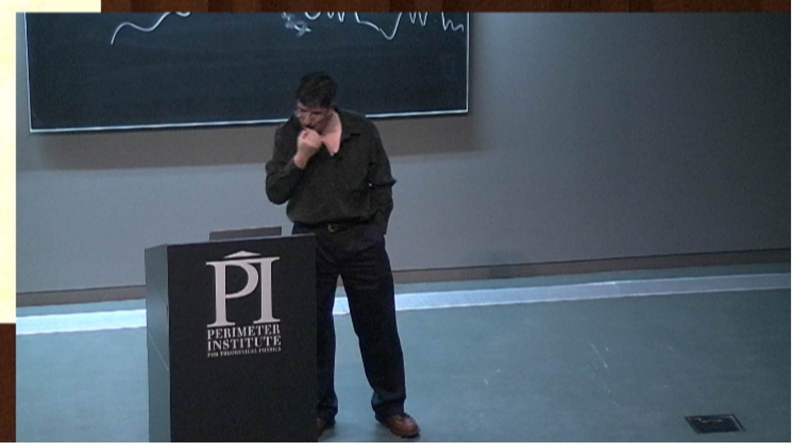
Quasars are red in i-z, but blue in z-J.

We have used this technique to discover most of the 70 known quasars with z>5.5 (others are from CFHTLS, UKIDSS, Pan-STARRS)

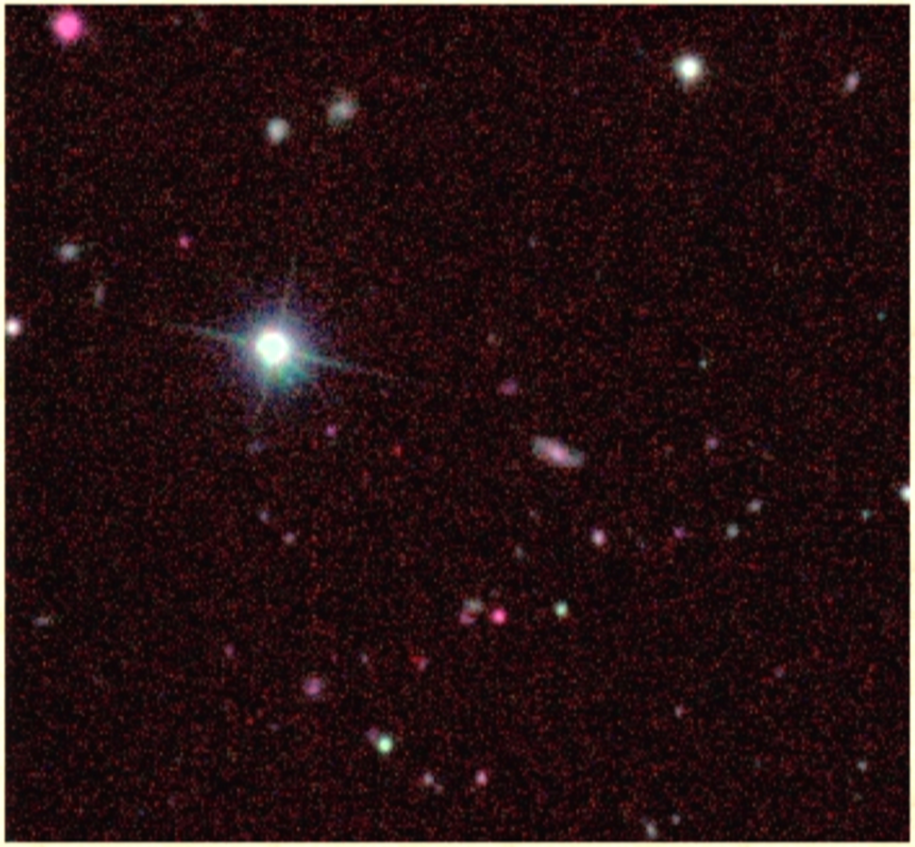


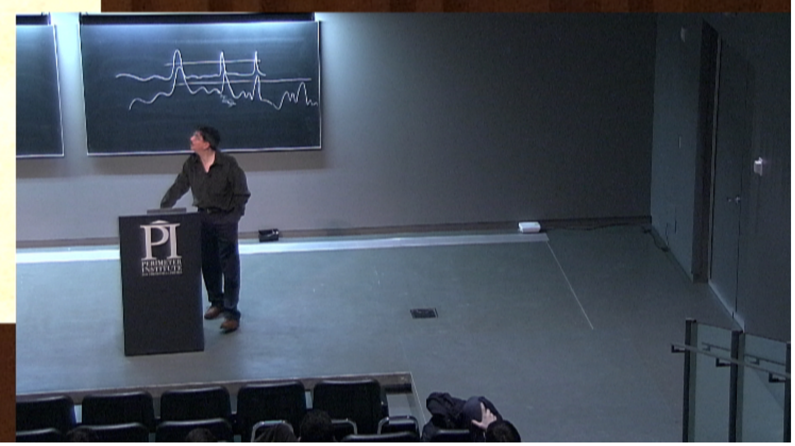


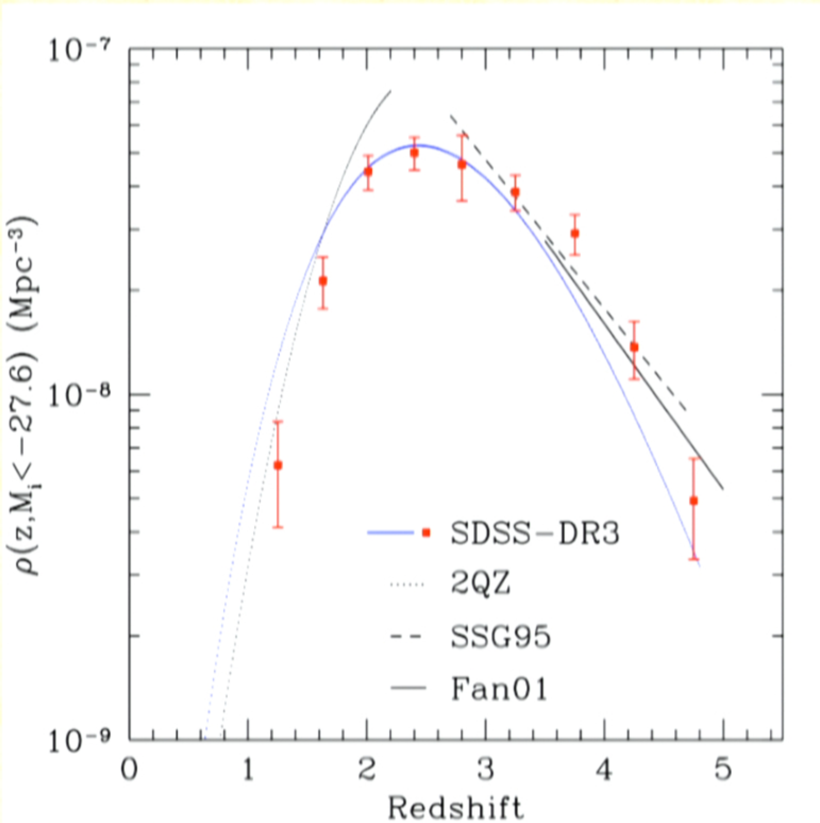
Field of z~6 quasar, *gri* composite



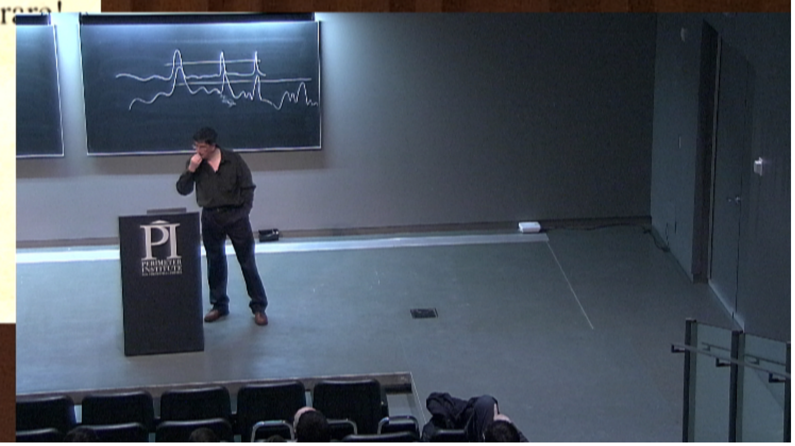
Field of z~6 quasar, *riz* composite



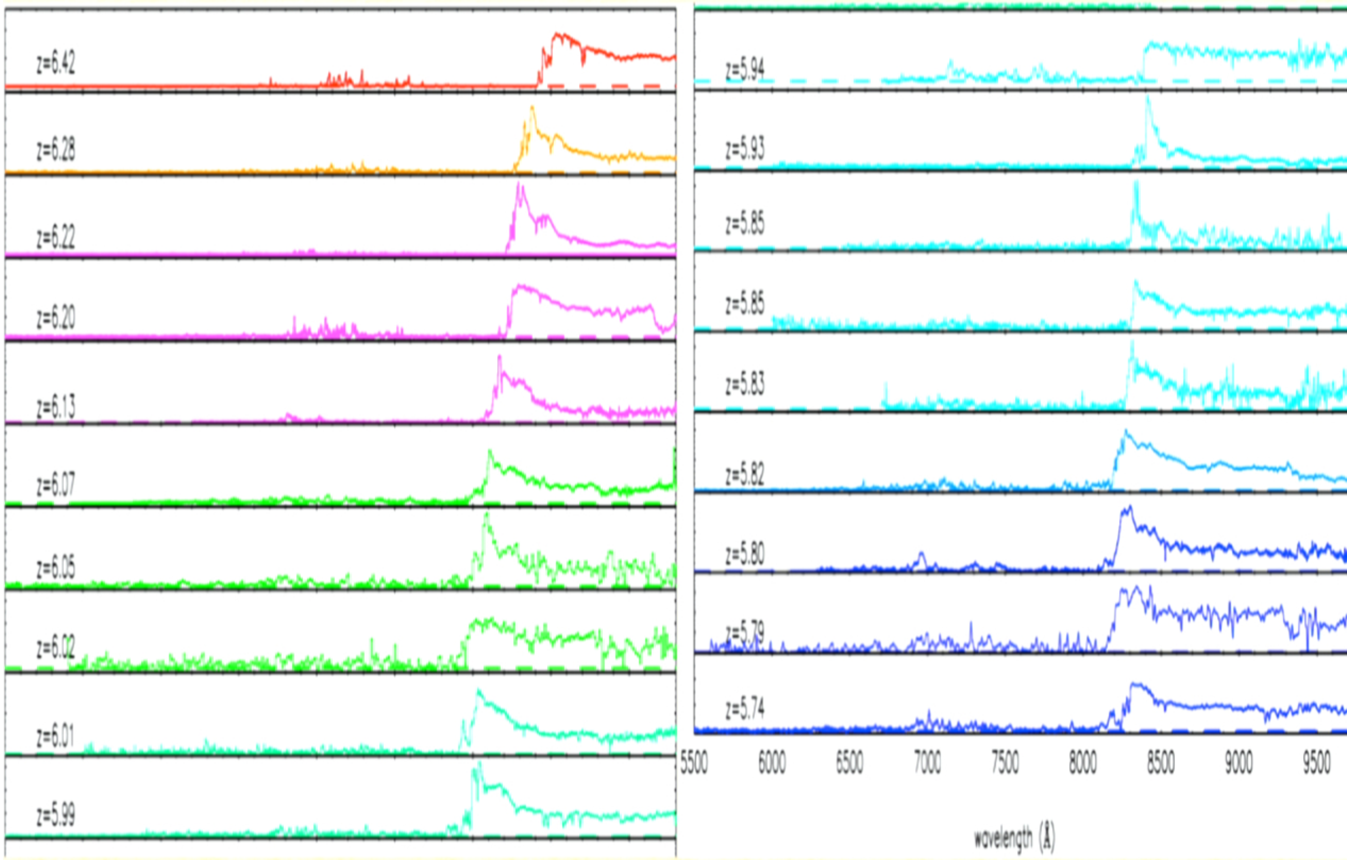




High-redshift
quasars are r



70 quasars now known with z>5.7, 10^9 yrs after the Big Bang



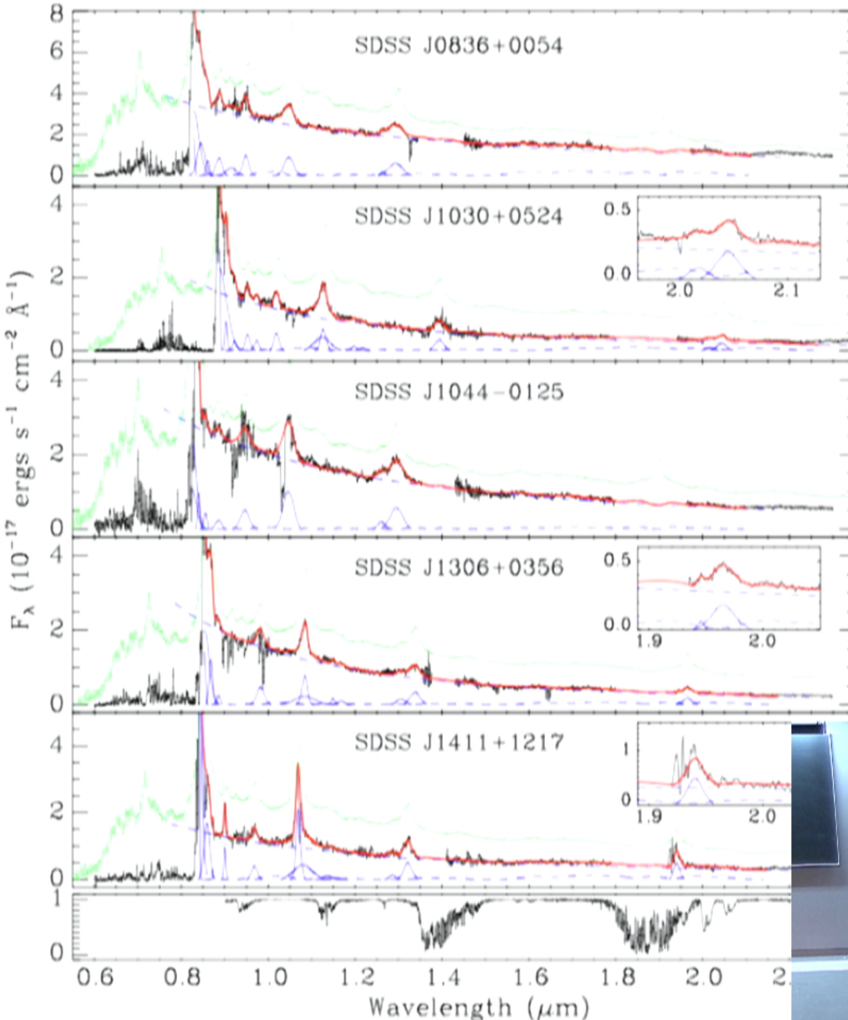
Fan et al. 2006

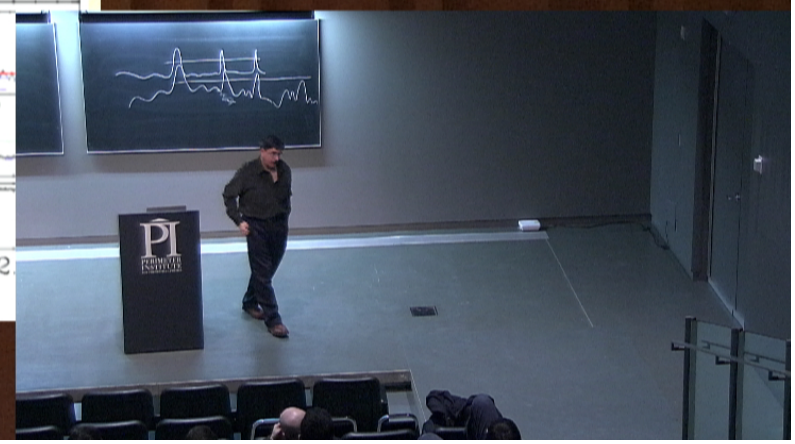
Jiang et al. 2007: Gemini near-infrared spectra of five high-redshift quasars.

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.

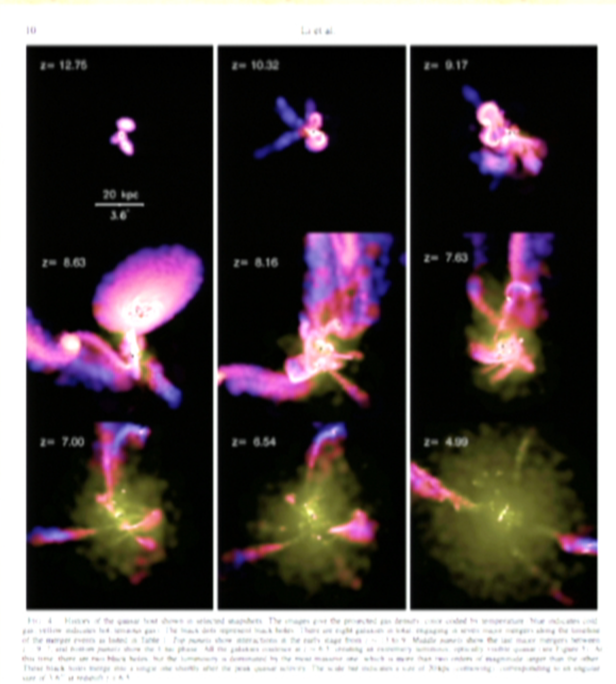
Green line: the mean spectra of lower-redshift quasars.



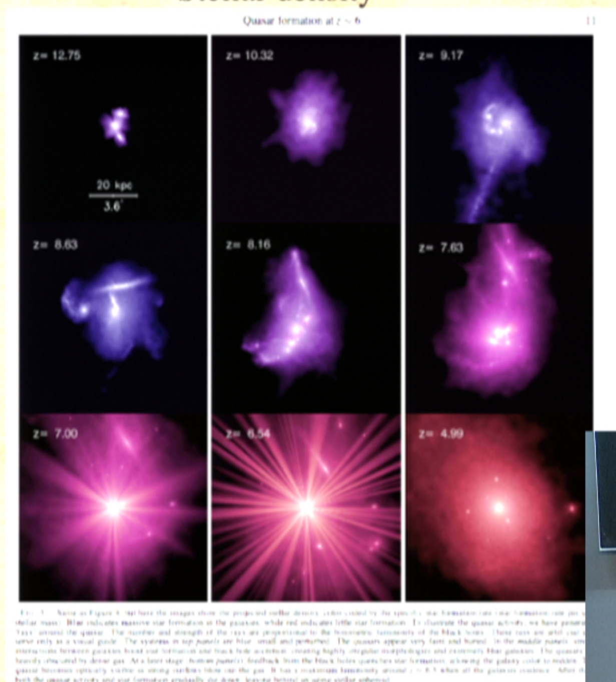


Simulations of an 8×10^{12} solar mass dark matter halo at high redshift

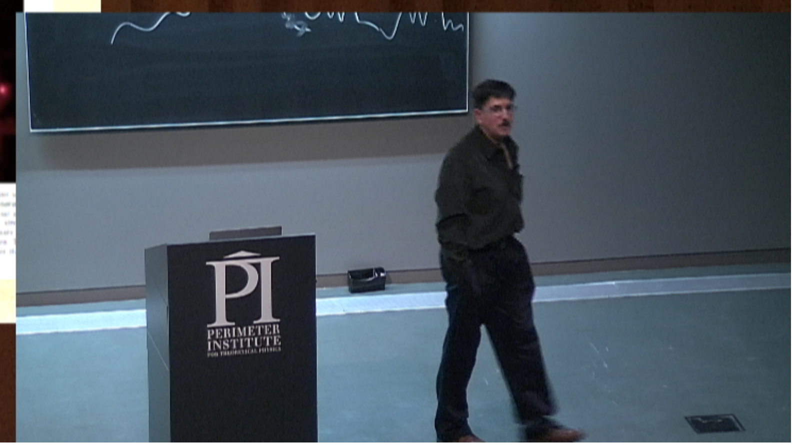
Gas density coded by temperature



Stellar density



Y. Li et al. 2006 (the Harvard Group)



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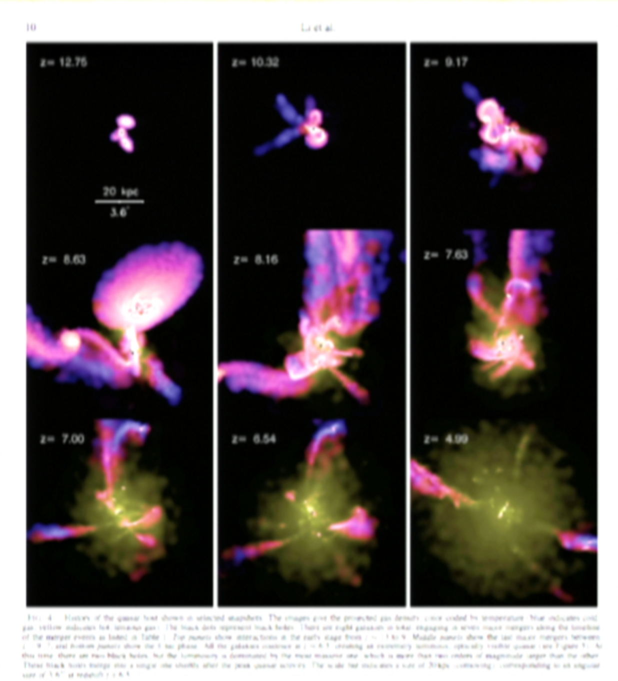

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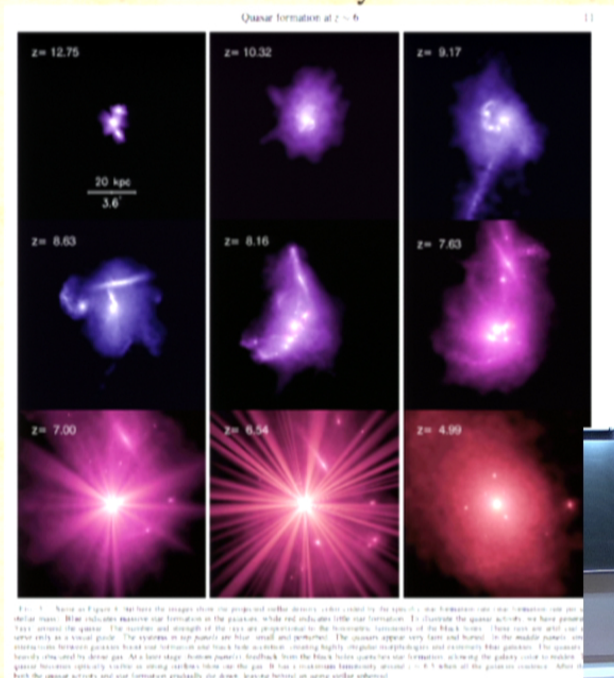

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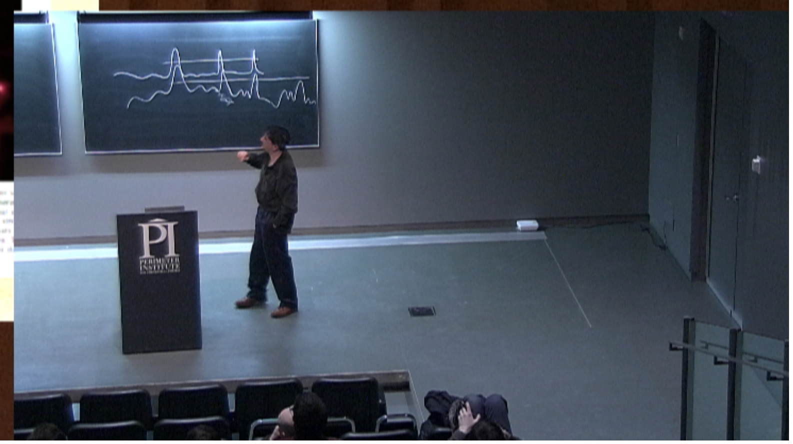
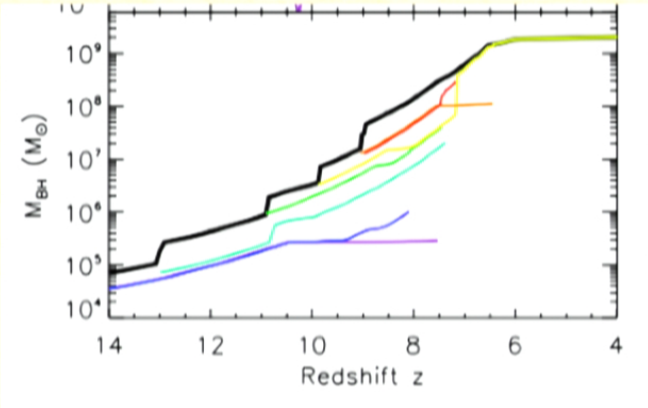
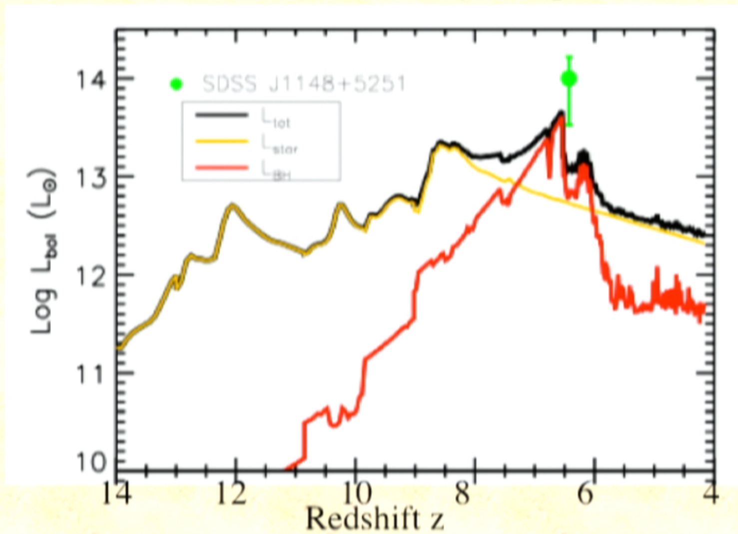
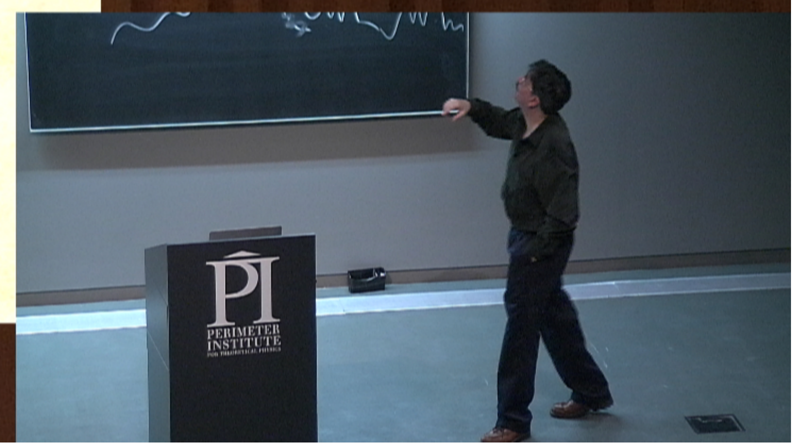




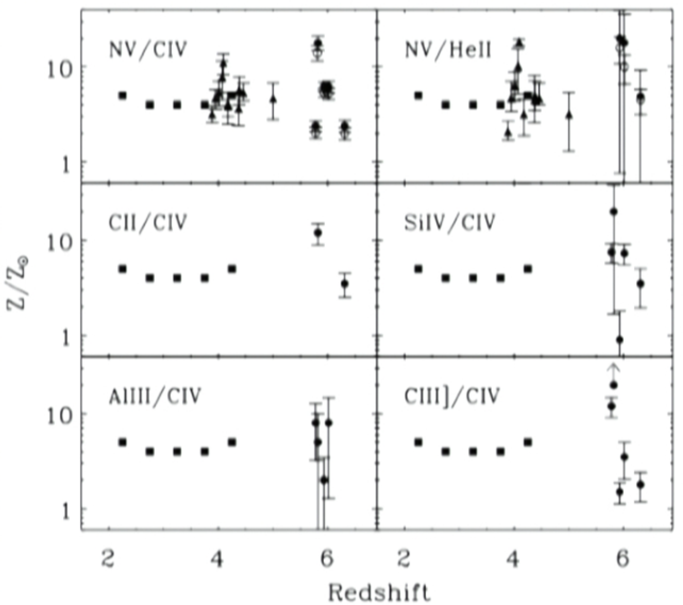
The growth of the black hole mass

The luminosity of quasar and host





Supersolar metallicity at *z*~6



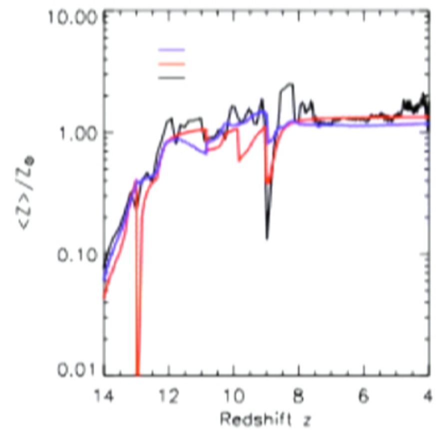
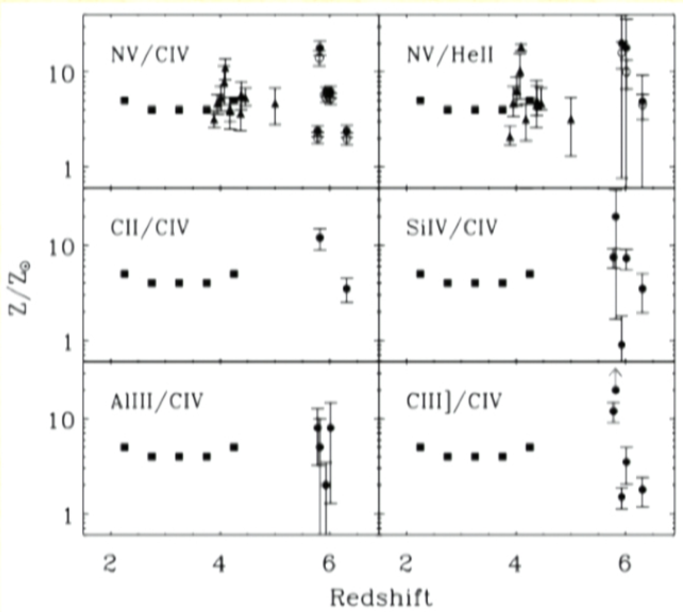


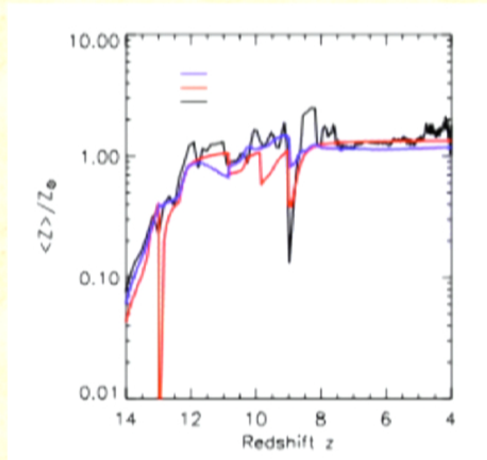
FIG. 7.— Time evolution of mass-weighted metallicity in the quasar host, from gas (blue curve), stars (red curve), and the mean value in the central region ($R < 1$ kpc) of each galaxy (black curve). The blue hatched region indicates the range of 25%–75% of the gas metallicity.

Metallicity (as measured using various line ratios as proxies) shows no obvious trend with redshift, all the way to z~6

Li et al's model explains this as well.

Supersolar metallicity at z~6





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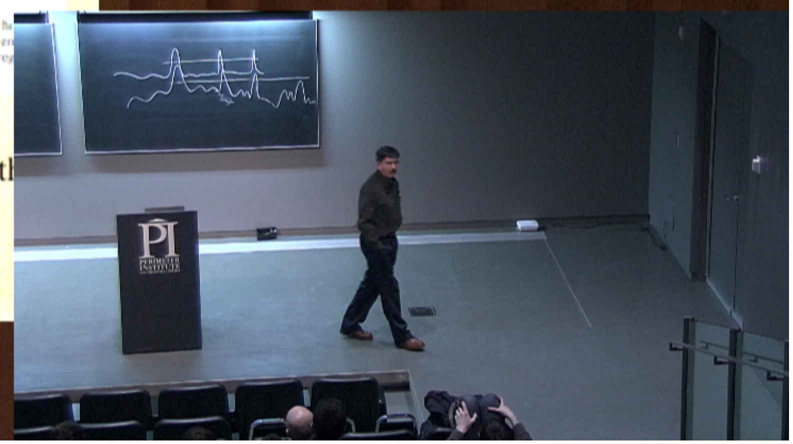
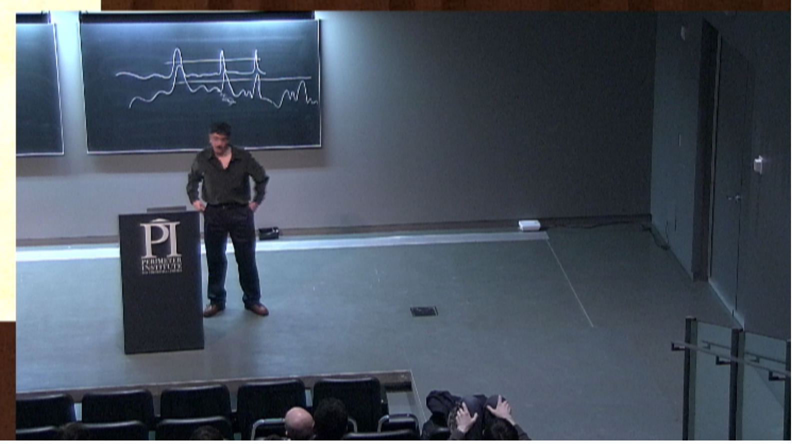


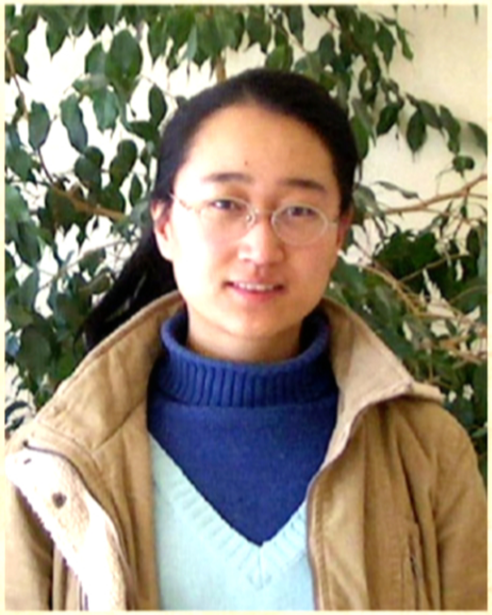
The properties of the highest-redshift quasars are very similar to those of similar luminosity at lower redshift:

- Similar SEDs, from radio to X-rays
- Similar metallicities
- Similar line ratios
- Similar dark matter halo masses

What about their host galaxies?



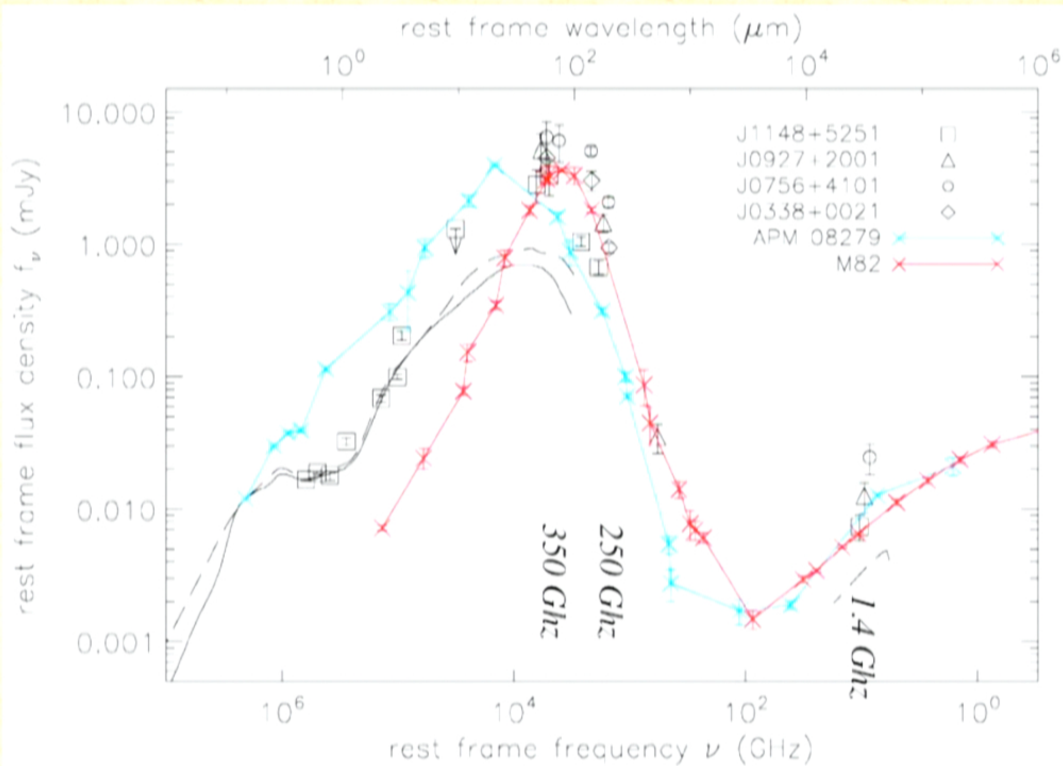
Studying the host galaxies of z~6 quasars at sub-mm wavelengths



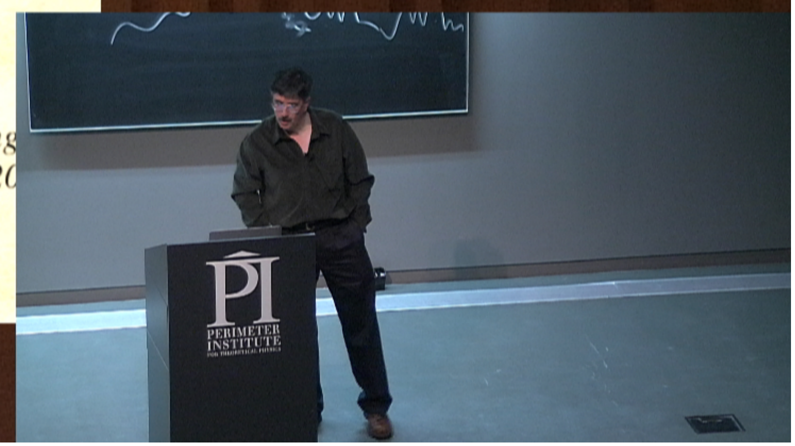
Ran Wang, Steward Observatory

Chris Carilli, NRAO

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



Wang al. 20



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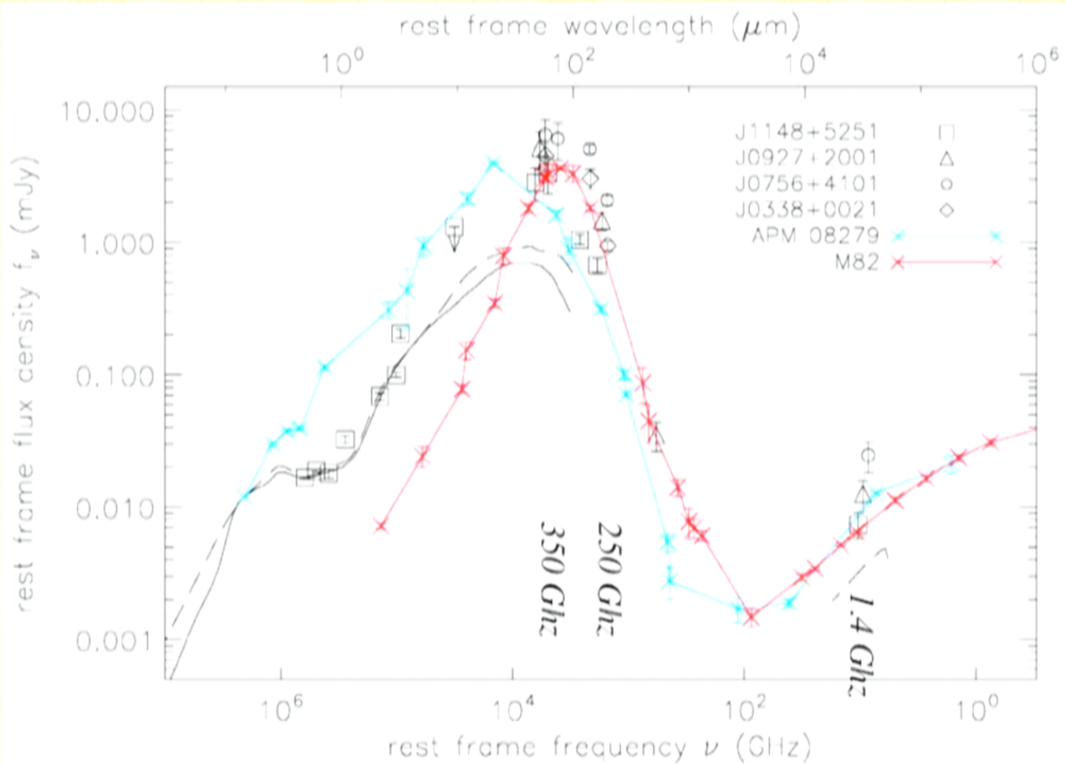
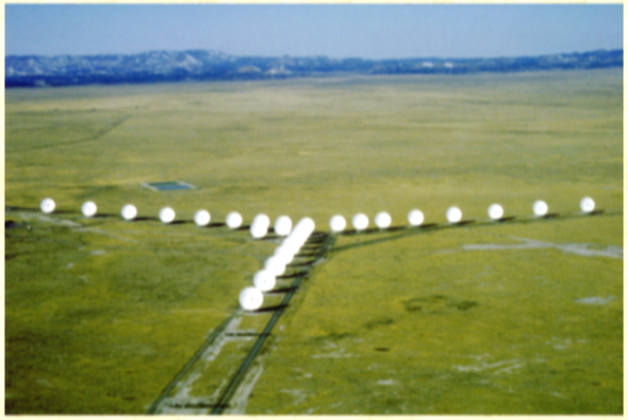


Wang et al. 2008

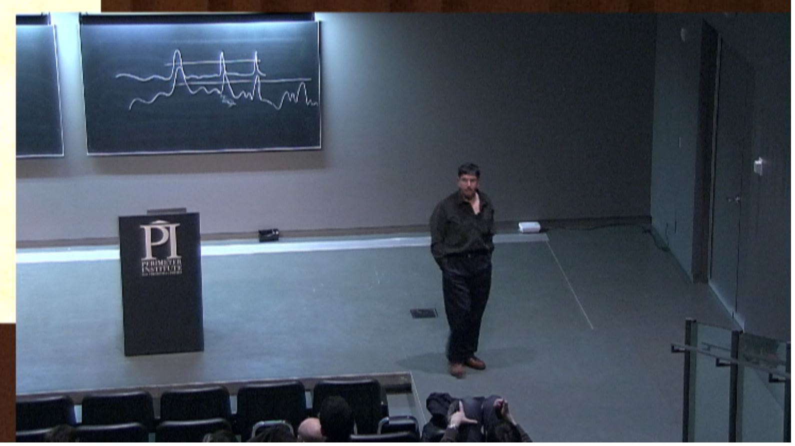
Pico Veleta, Spain: 30-meter dish with MAMBO 37-channel array bolometer



Very Large Array, New Mexico

Plateau de Bure, 6-element interferometer in French Alps

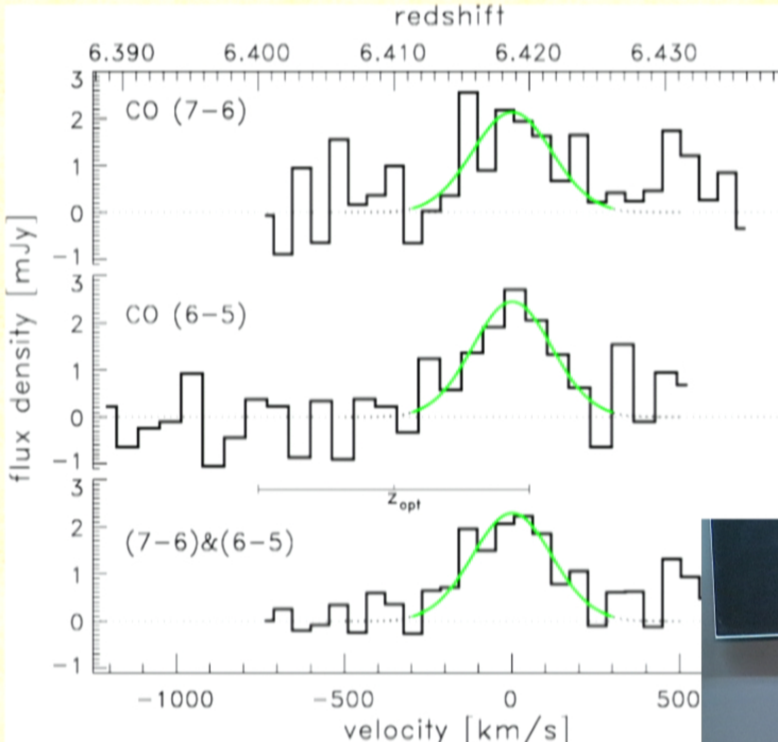
- 40 z ~ 6 quasars have been observed at 250 GHz; 1/3 of them are detected (a similar rate to lower-redshift quasars).
- The characteristic inferred dust temperature is ~50 K. From this temperature and the inferred luminosity, one infers spatial extents of 1-2 kpc.
- Dust masses can be estimated; typical 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?



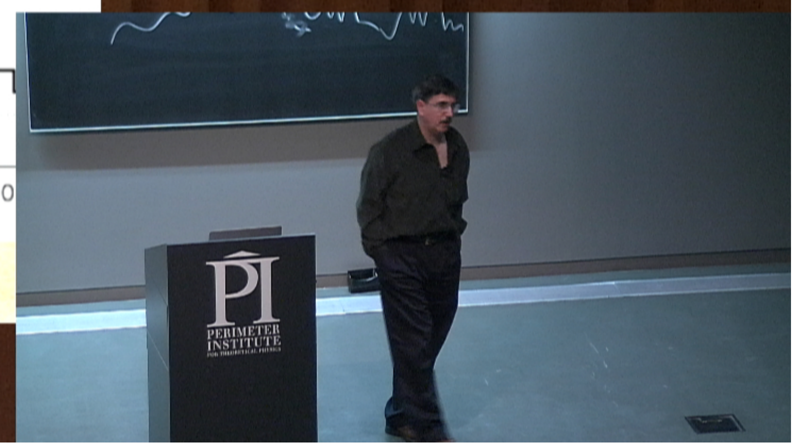
Rotational Transitions of CO in the highest-redshift SDSS quasar

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

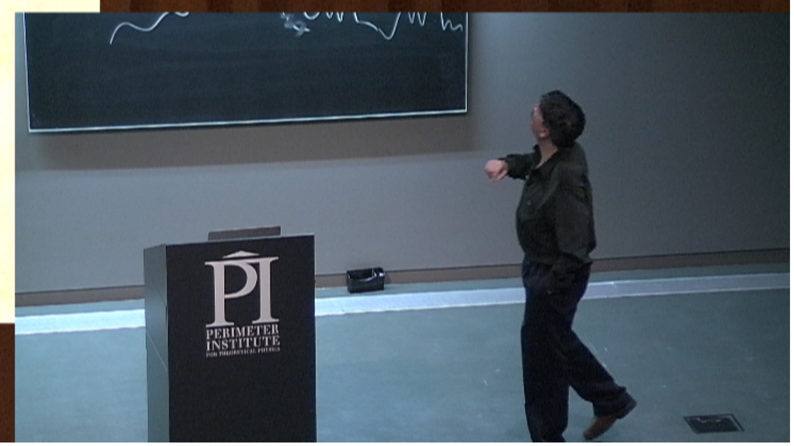
CO 3-2 is redshifted to 46.6 GHz, 7 mm, at z=6.42. CO 6-5 at about 3.5 mm. Observable with MAMBO and VLA.



Bertoldi et al. 2003

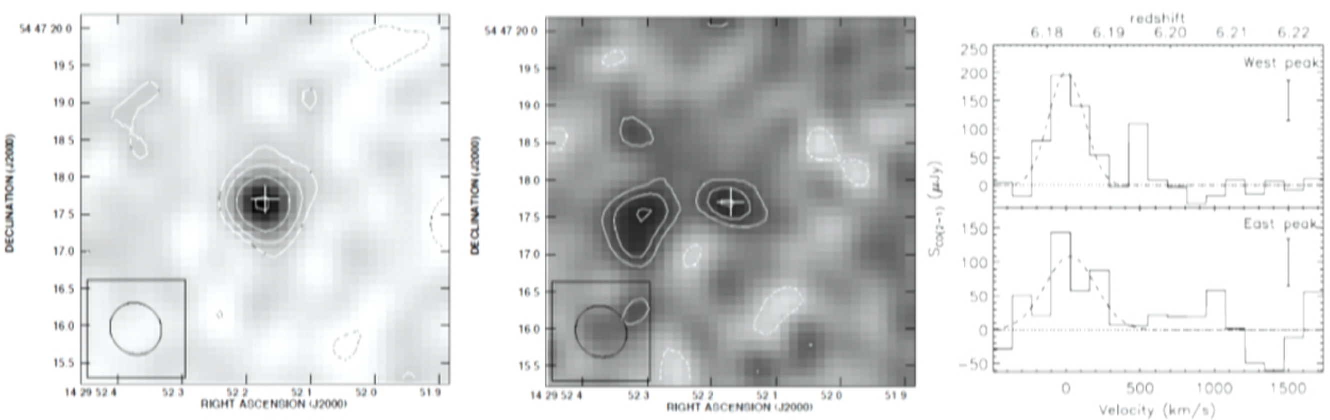


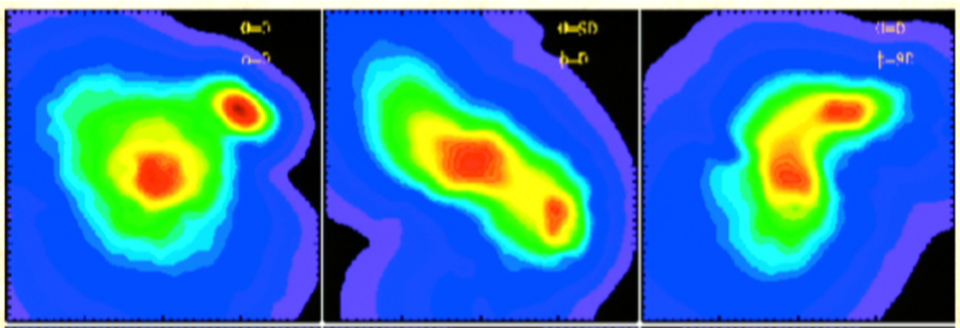
- CO is a tracer of molecular gas. Gas is too cold (50K) to excite H_2 transitions, so we can't measure it directly.
- Gas masses are based on conversions determined for ultraluminous IRAS galaxies, which in turn assume a global CO/H_2 abundance ratio.
- The resulting *highly uncertain* gas mass is of 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.



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

Continuum at 32 GHz   CO emission   CO spectra



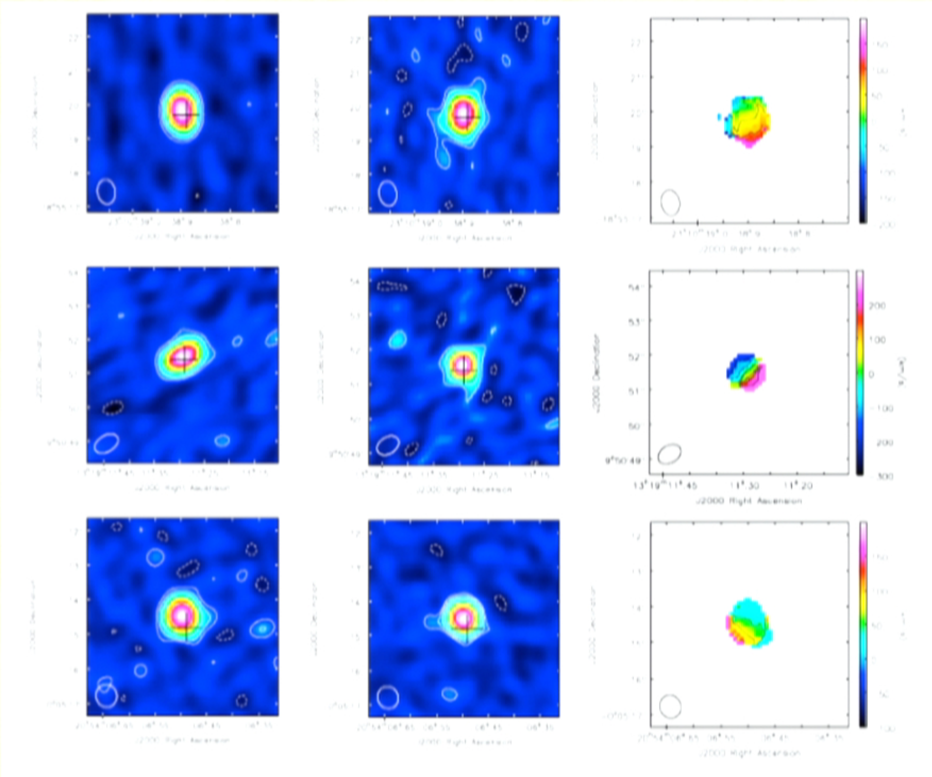


Wang et al. 2011

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

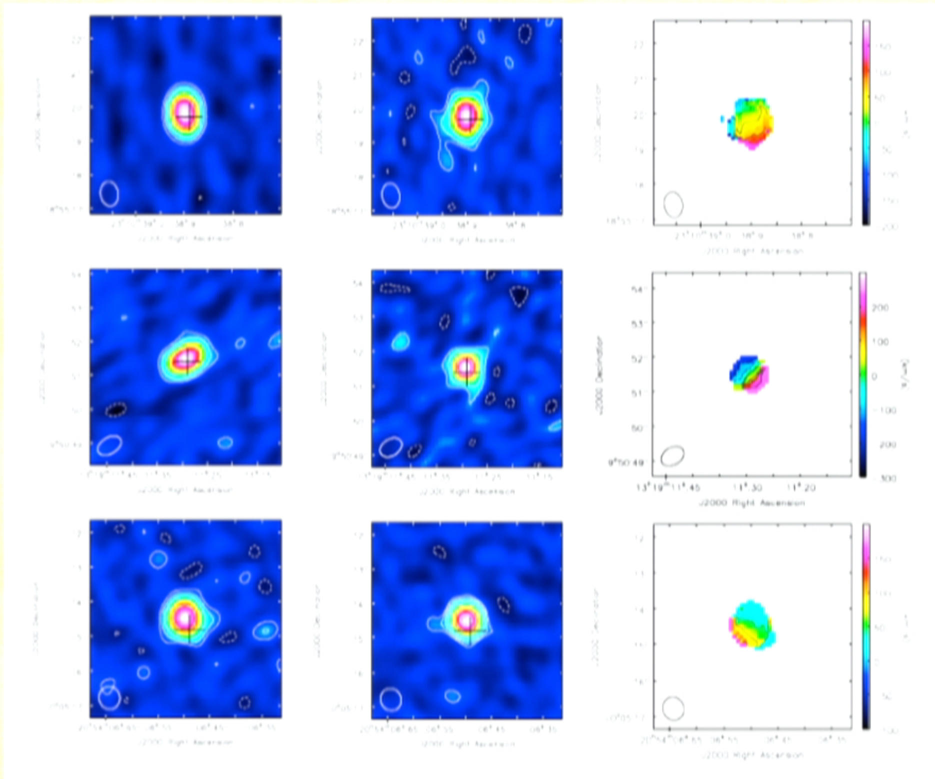
The Atacama Large Millimeter Array (ALMA)

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

Dust Continuum [CII] emission Velocity Field



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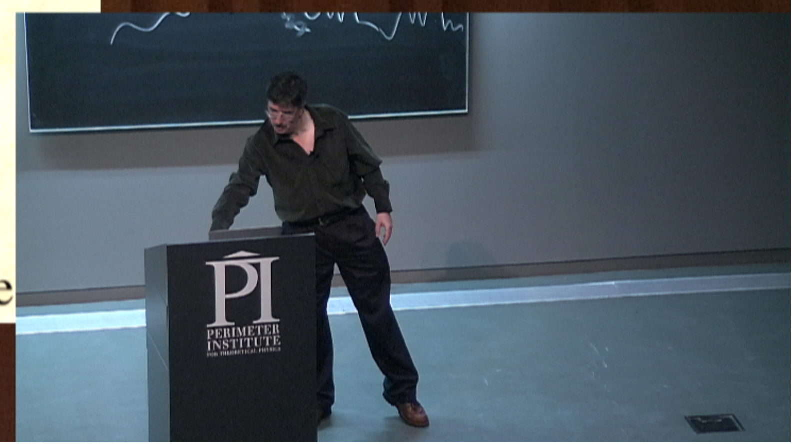

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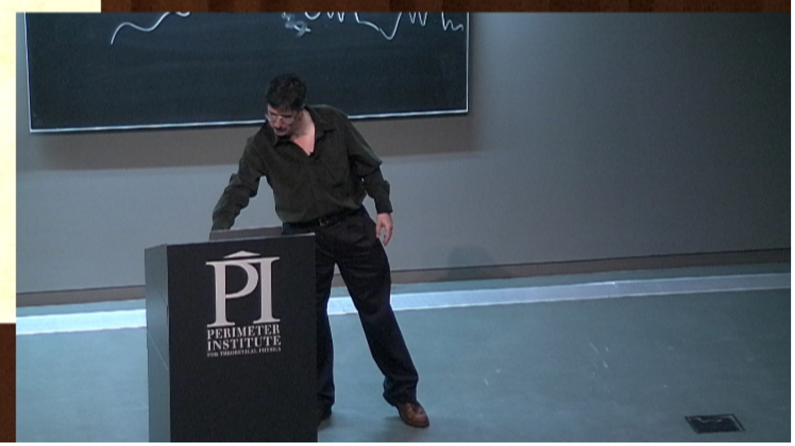
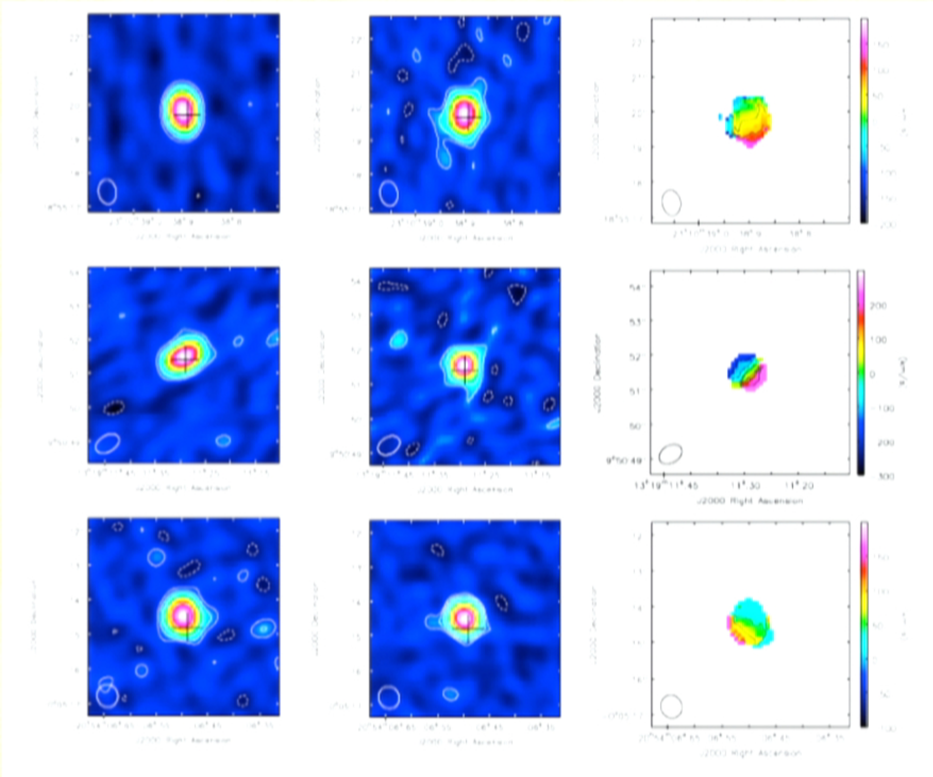


Dust Continuum [CII] emission Velocity Field



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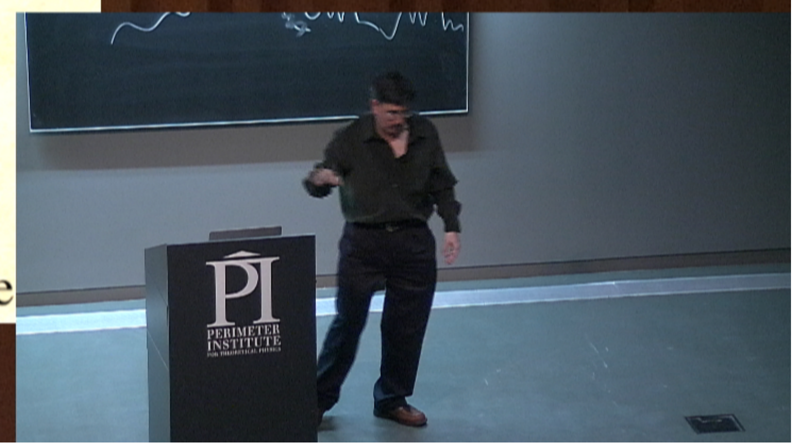
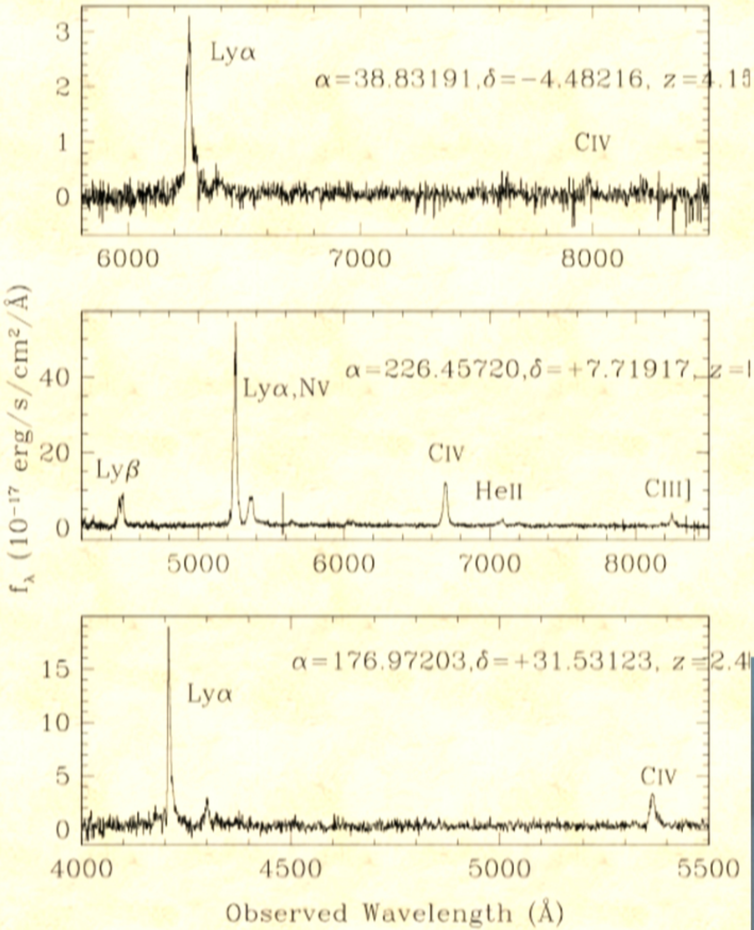
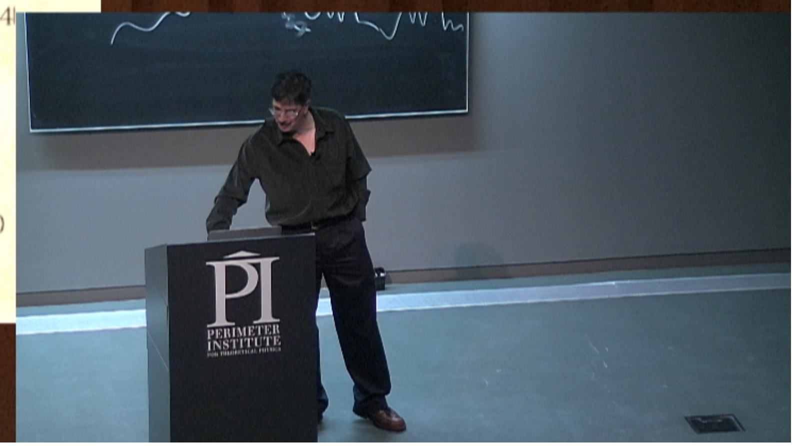


Rachael Alexandroff,
Princeton ➔ JHU

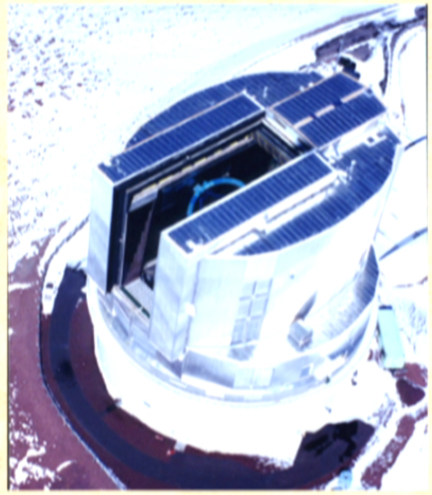
We are finding a population of obscured quasar candidates at z~2-3 in SDSS. Weak continuum, no broad emission lines suggest central region is hidden.





We Need to Push Quasar Studies to Lower Luminosities

The Prime Focus Spectrograph on the Subaru 8.2m Telescope, to carry out SDSS-like surveys on a much bigger telescope.

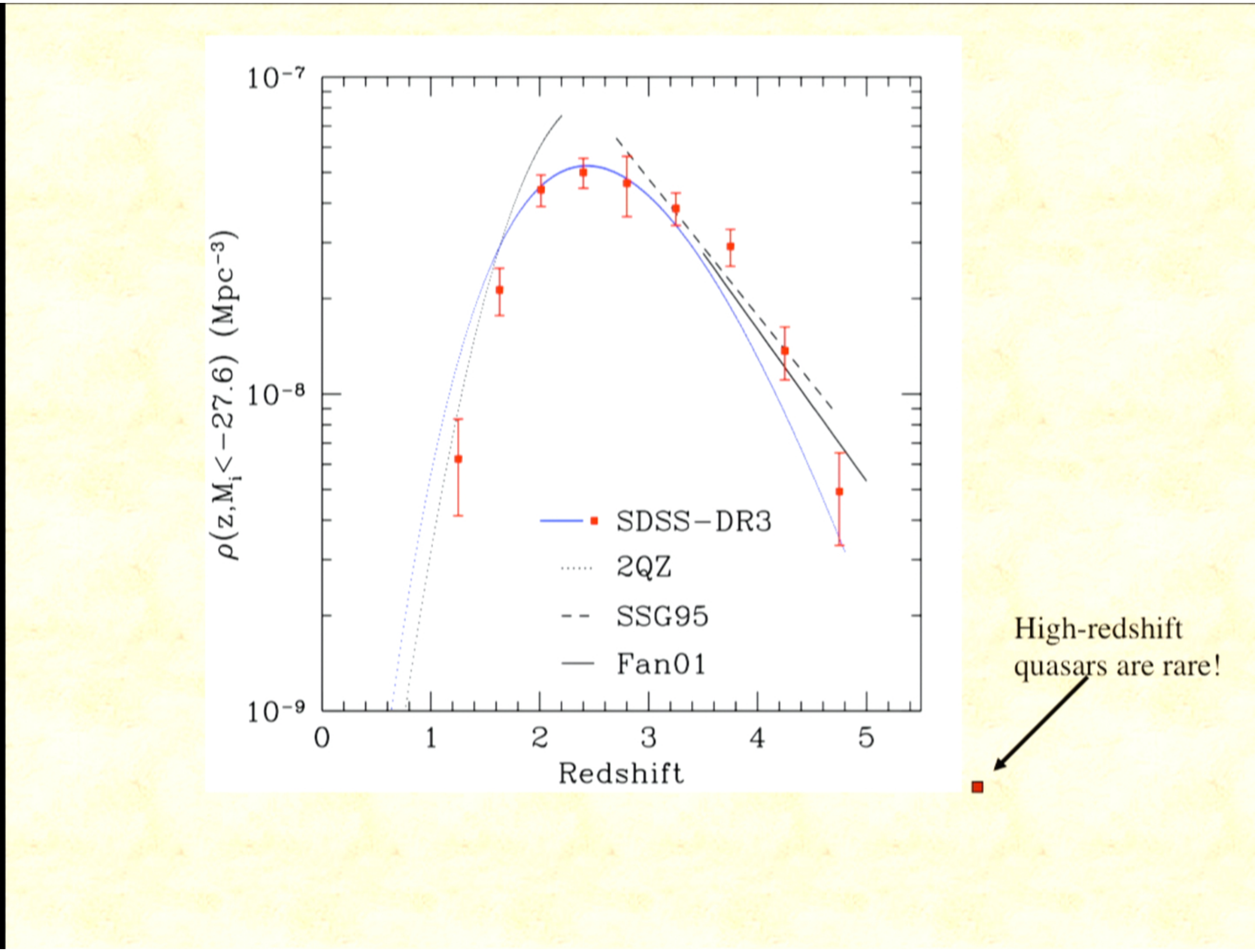


すみれ SuMIRe

Subaru Measurements of Images and Redshifts

Looking Forward

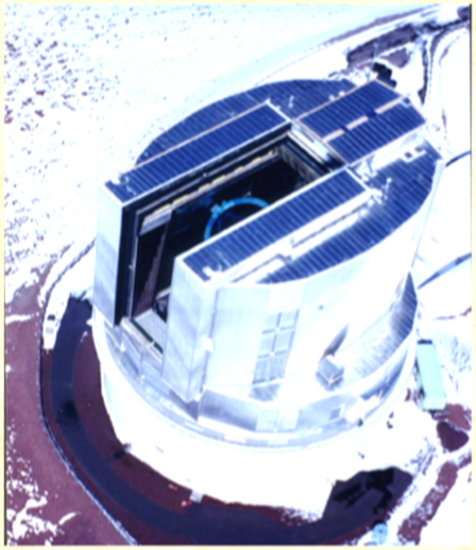
- Quasar properties at a given luminosity are amazingly insensitive to redshift.
- ALMA, EVLA will allow more sensitivity, higher spatial resolution for studies of molecular lines in quasar hosts at all redshift.
- We need more dynamic range in luminosity. Next-generation surveys (including Pan-STARRS, HSC, PFS, LSST) will find substantially fainter high-redshift quasars.
- Understanding the nature and demographics of obscured quasars, and the relationship to the dust apparent in high-z quasars, is key. Multi-wavelength data will be an important part of the story.
- Have we really found examples of dust-free quasars at high redshift? Exploring their full SED will be particularly important.



10^{-7}
10^{-8}
10^{-9}
$\rho(z, M_i < -27.6)$ (Mpc^{-3})
0
1
2
3
4
5
Redshift
SDSS−DR3
2QZ
SSG95
Fan01
High-redshift
quasars are rare!

We Need to Push Quasar Studies to Lower Luminosities

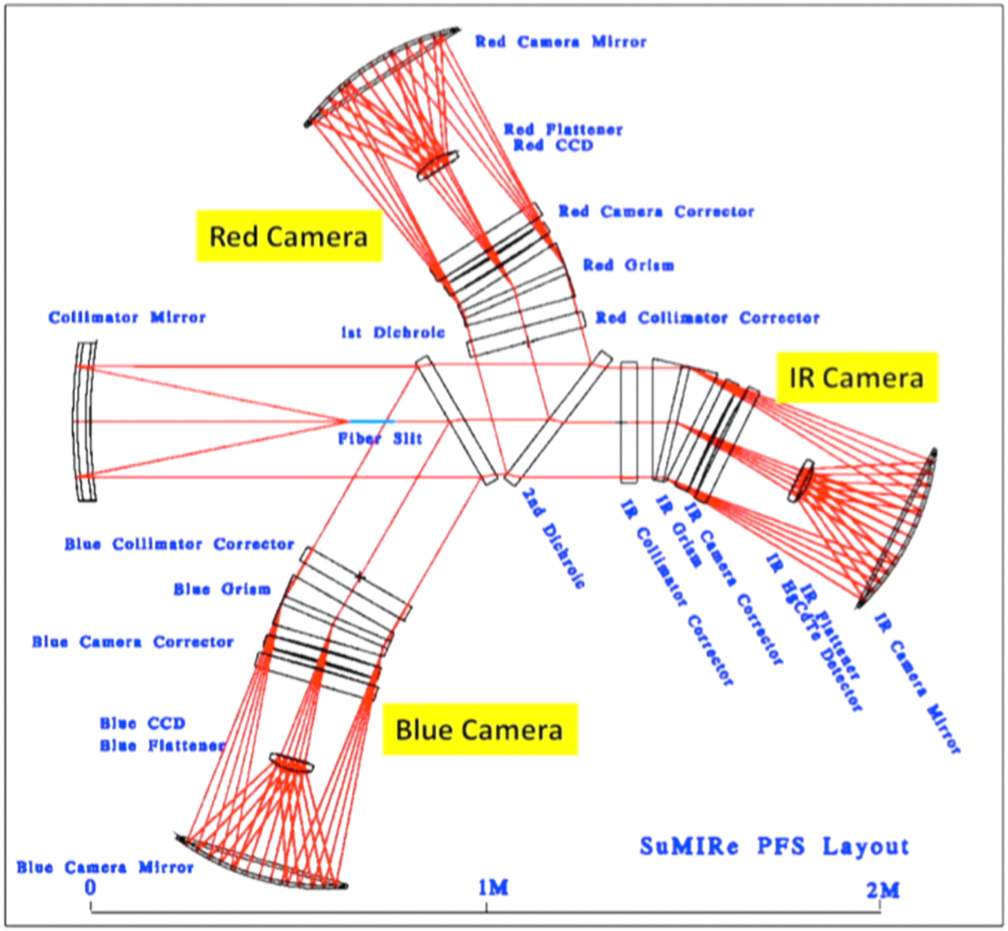
The Prime Focus Spectrograph on the Subaru 8.2m Telescope, to carry out SDSS-like surveys on a much bigger telescope.



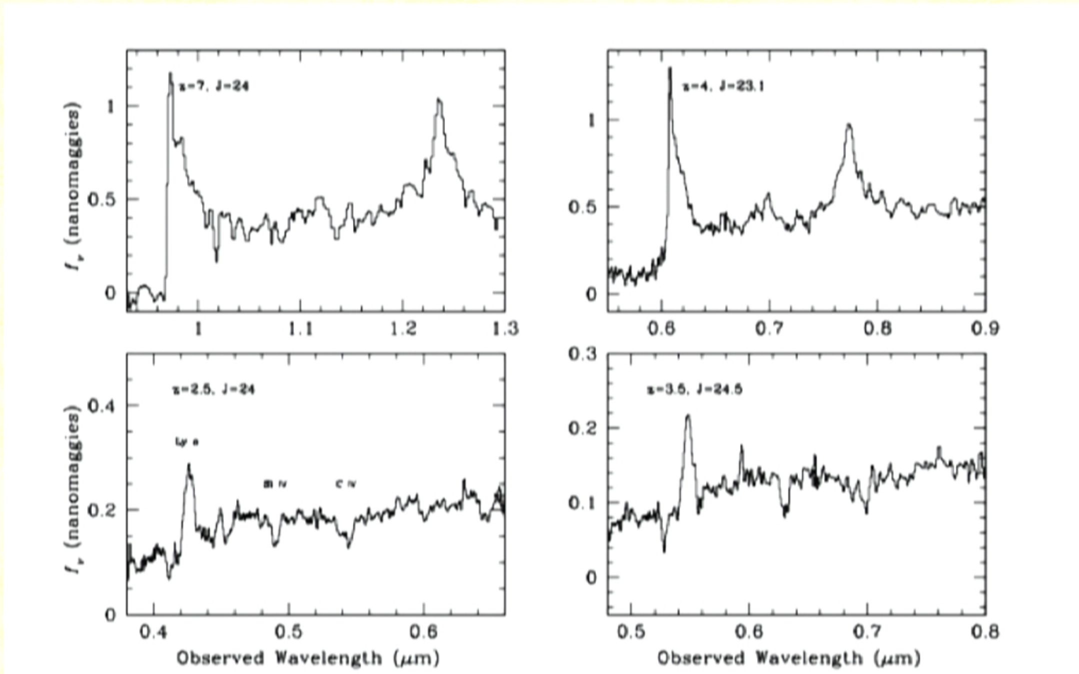
すみれ SuMIRe

Subaru Measurements of Images and Redshifts

Four identical spectrographs, each taking 600 fibers on one of the largest telescopes in the world.



Simulations of Spectral Quality



Simulations of smoothed 30-minute exposures of quasars and high-z star-forming galaxies.