The Evolving Luminosity and Color Dependent Clustering of Galaxies

Ramin Skibba (U. of California, San Diego)

Collaborators: Alison Coil, Daniel Eisenstein, Mike Blanton, and the PRIMUS team

Fermilab, 28 October 2013

the general outline:

- hierarchical structure formation
- relating theory (DM haloes) & observations (galaxies)
- results: luminosity and color-dependent clustering
- results: evolution of galaxy clustering

1. we show how luminosity and color-dependent clustering evolves between z~0 and z~1

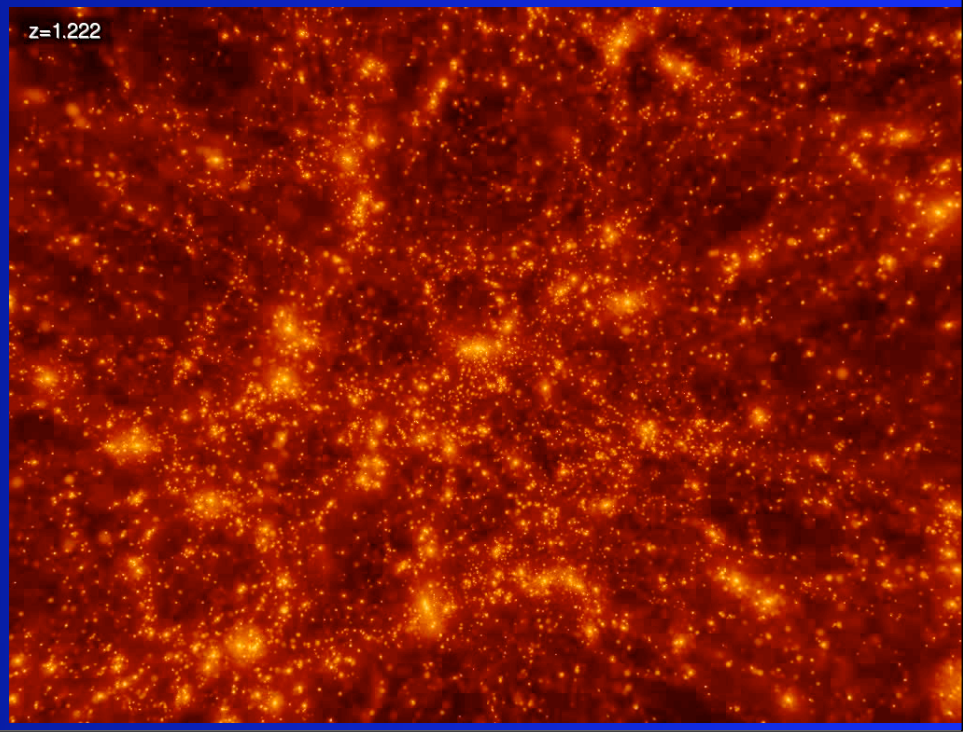
2. we show how 'cosmic variance' (sample fluctuations) can be an important effect

Skibba, Smith, Coil, et al., 2013, *ApJ*, submitted
Skibba, Sheth, Croton, et al. 2013, *MNRAS*, 429, 458

Some questions to explore:

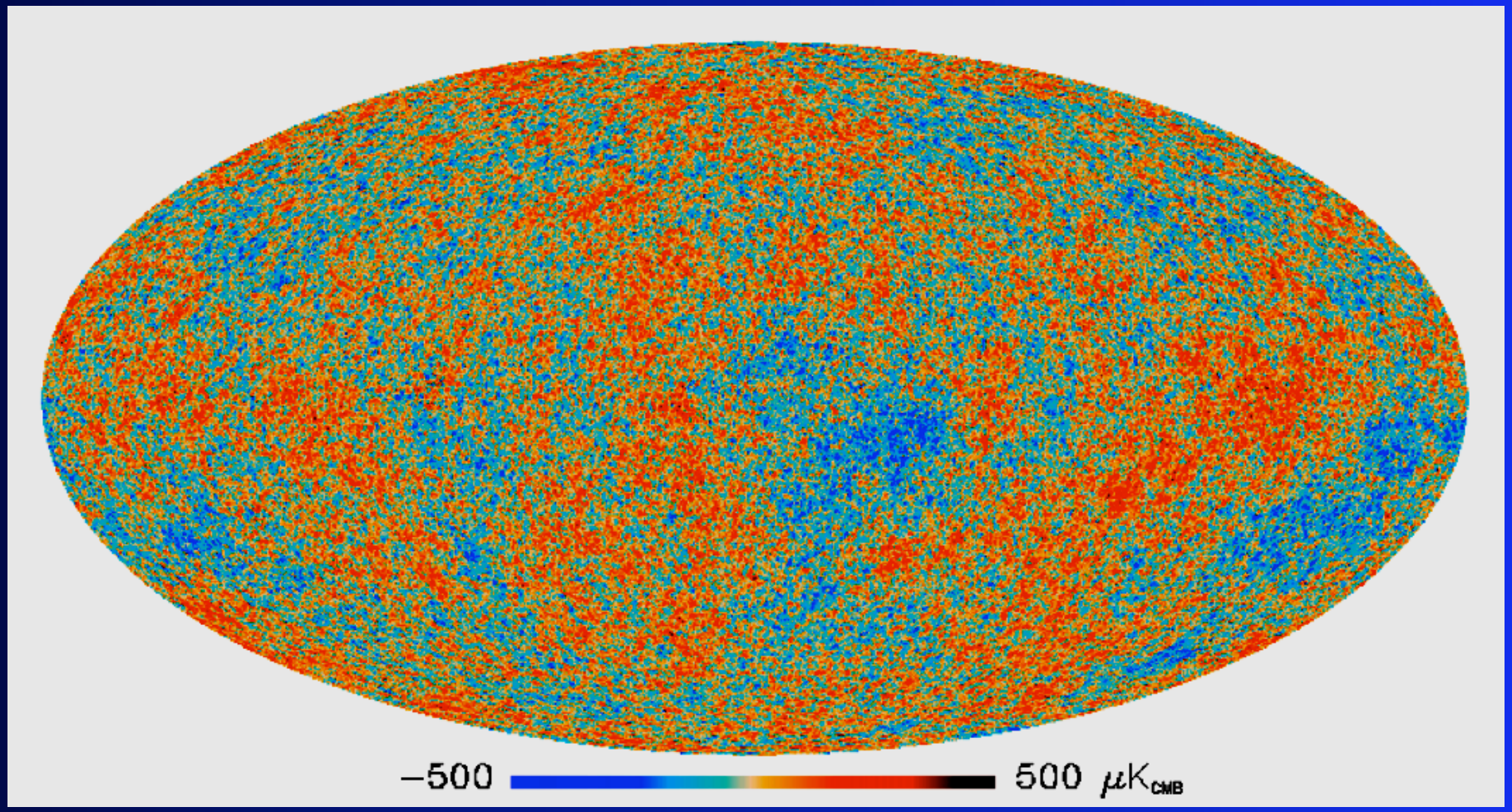
How do galaxy formation and evolution depend on a galaxy's small or large-scale environment?

How are galaxies affected by the dark matter haloes that host them?



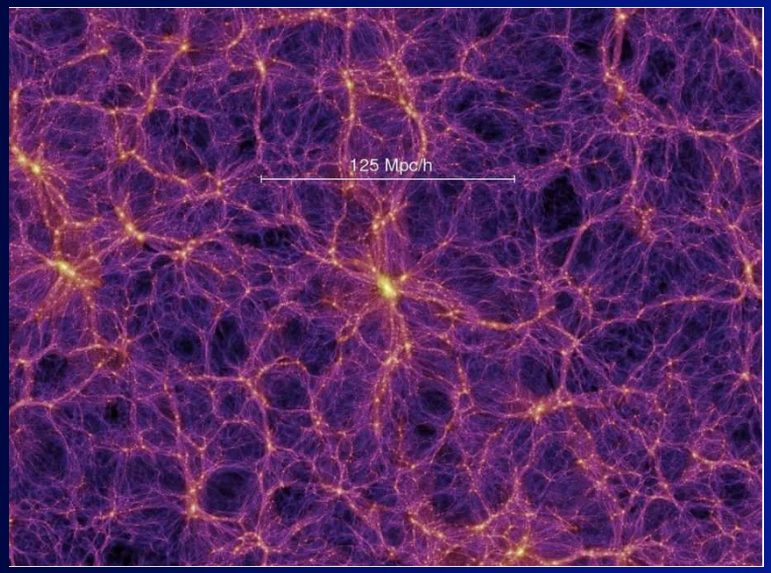
Large-scale structure, in the CMB

Constraints from *Planck* on the primordial density fluctuations:

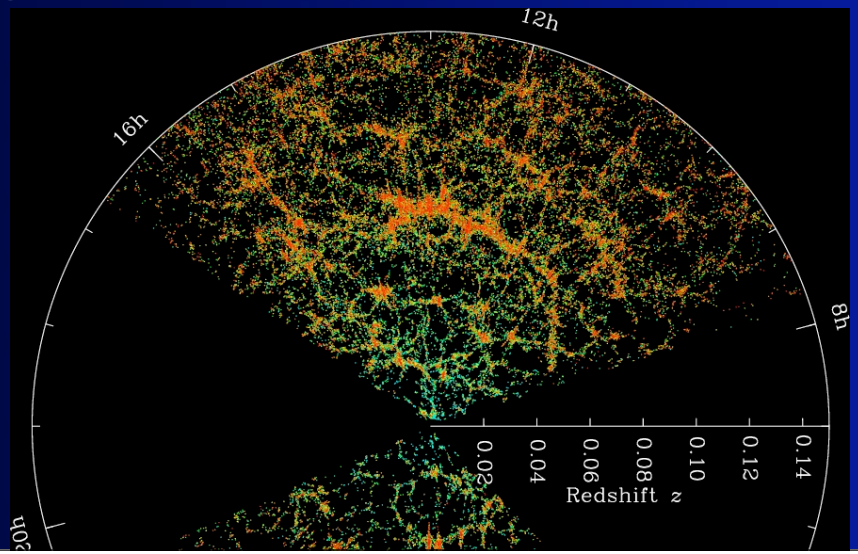


Growth of large-scale structure: haloes vs galaxies

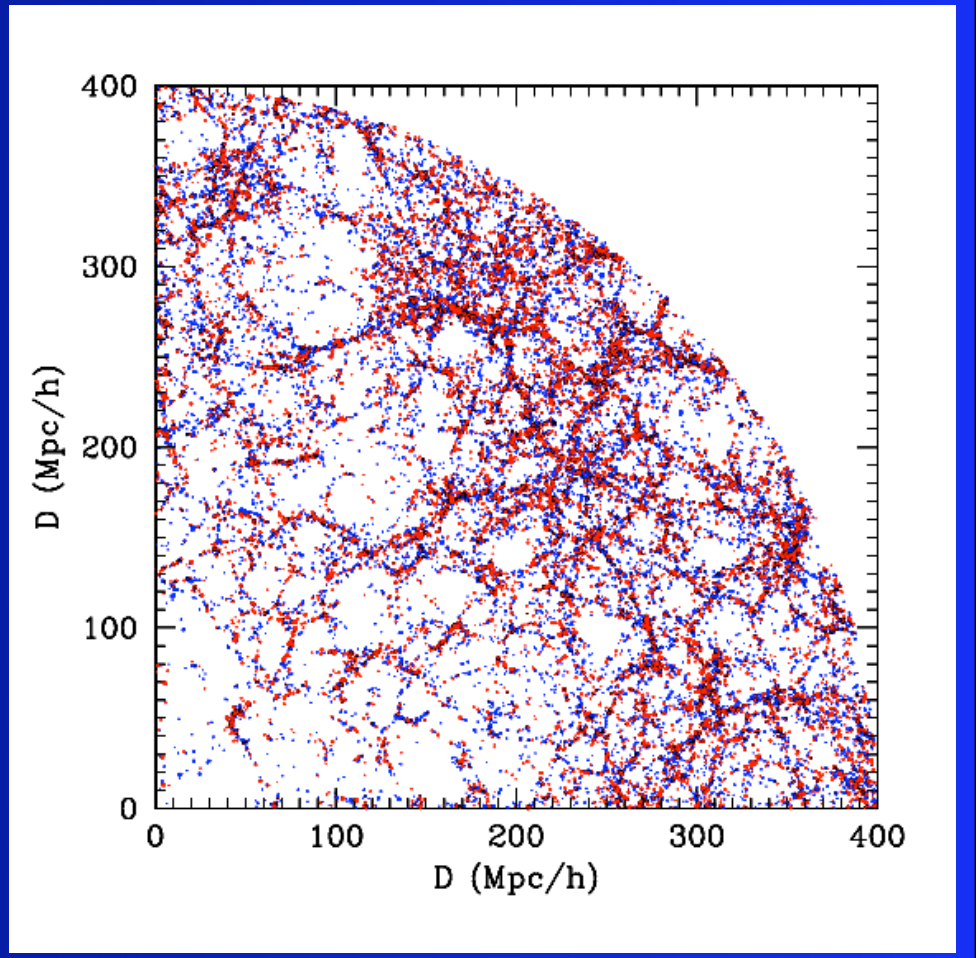
haloes in Millennium (Springel+ 2005)



galaxies in SDSS (courtesy: M. Blanton)



galaxies in SDSS-like mock catalog

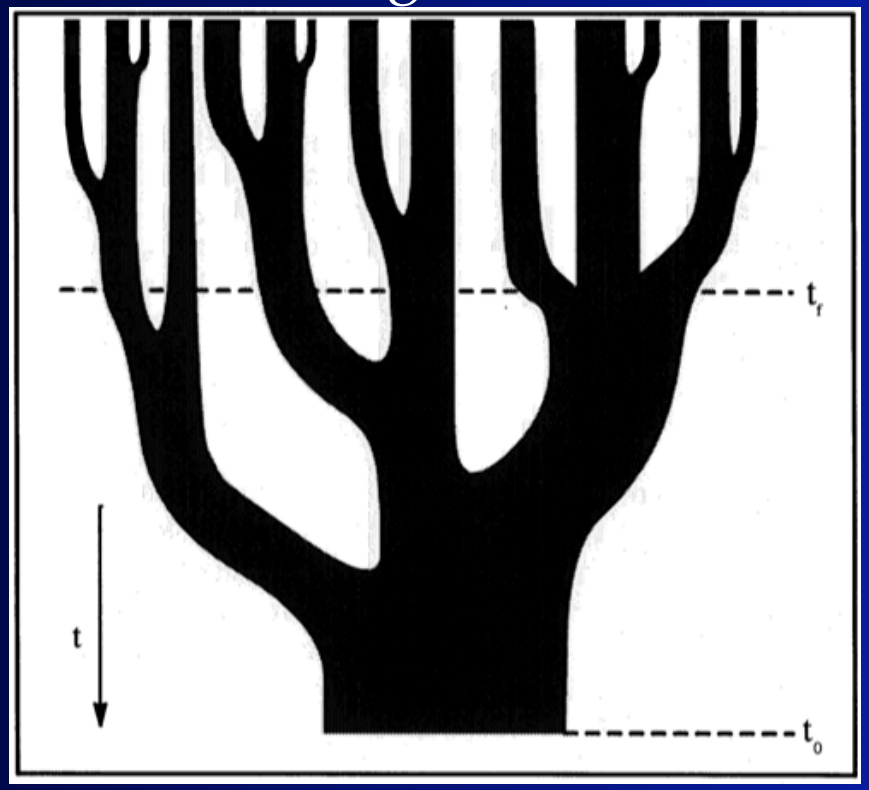


Skibba et al. (2013a)

Hierarchical structure formation

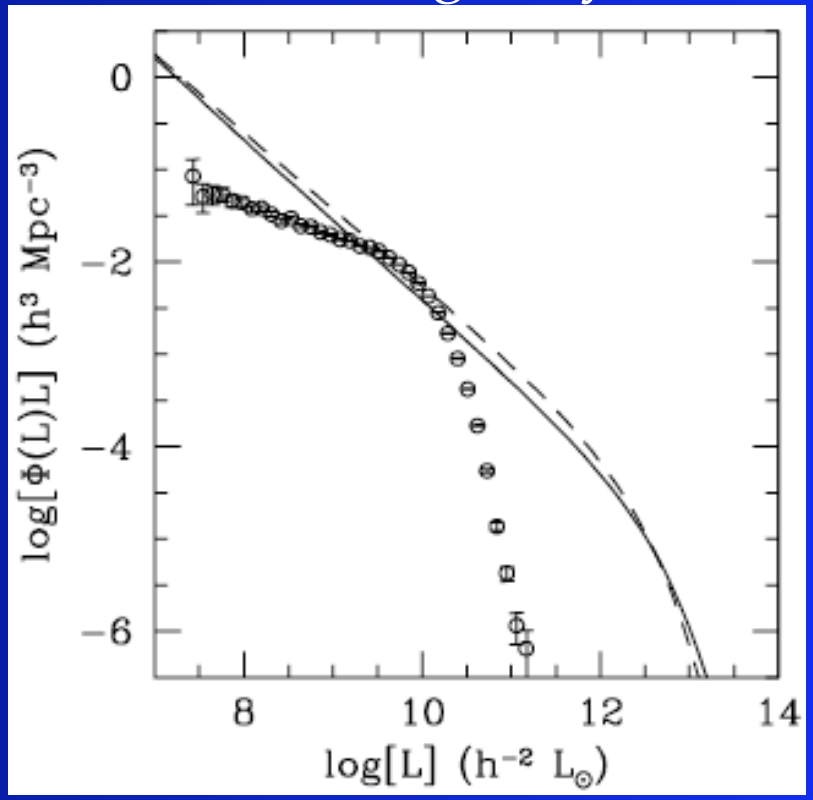
Hierarchical structure formation results in assembly of group and cluster haloes

merger tree



Lacey & Cole (1993)

halo MF vs galaxy LF

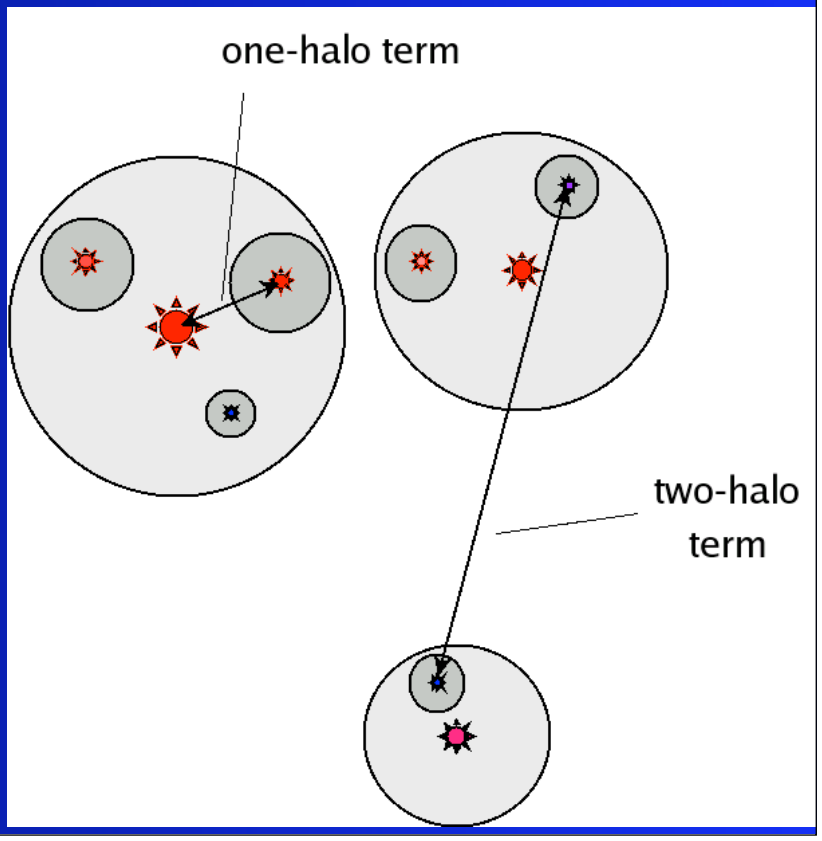


Yang et al. (2003); Benson et al. (2003)

Halo model of galaxy clustering

3 main types of *halo models*:
halo occupation distributions, conditional luminosity functions, subhalo abundance matching
(see Cooray & Sheth 2002; Mo, van den Bosch & White 2010)

central and satellite galaxies:
$\langle N_{\rm gal} \,|\, M \rangle = \langle N_{\rm cen} \,|\, M \rangle + \langle N_{\rm sat} \,|\, M \rangle$

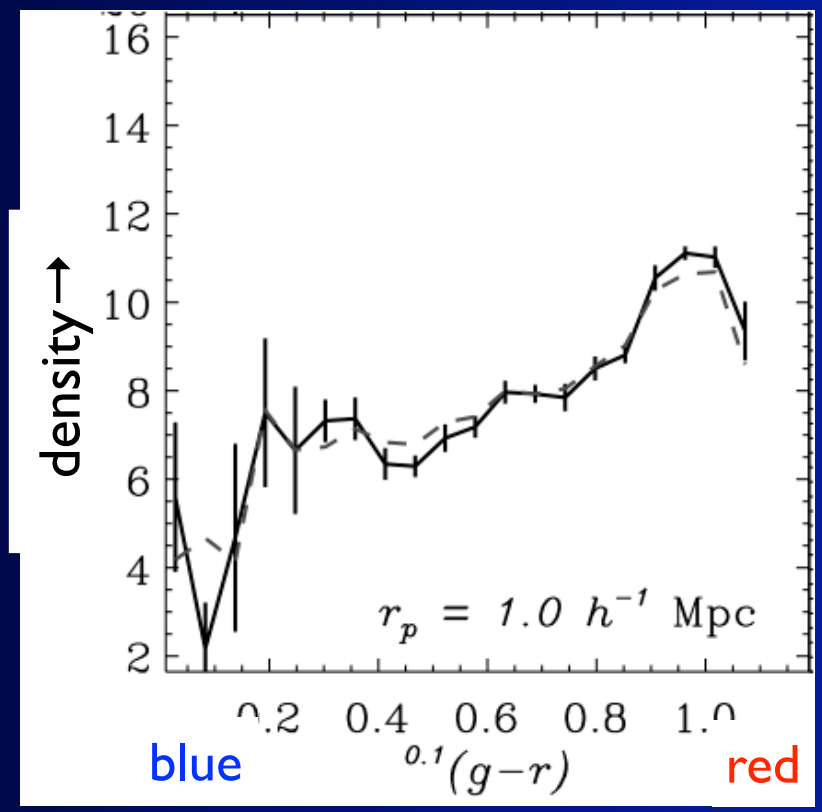


open question: galaxy distributions determined only by halo mass?

environmental correlations: color

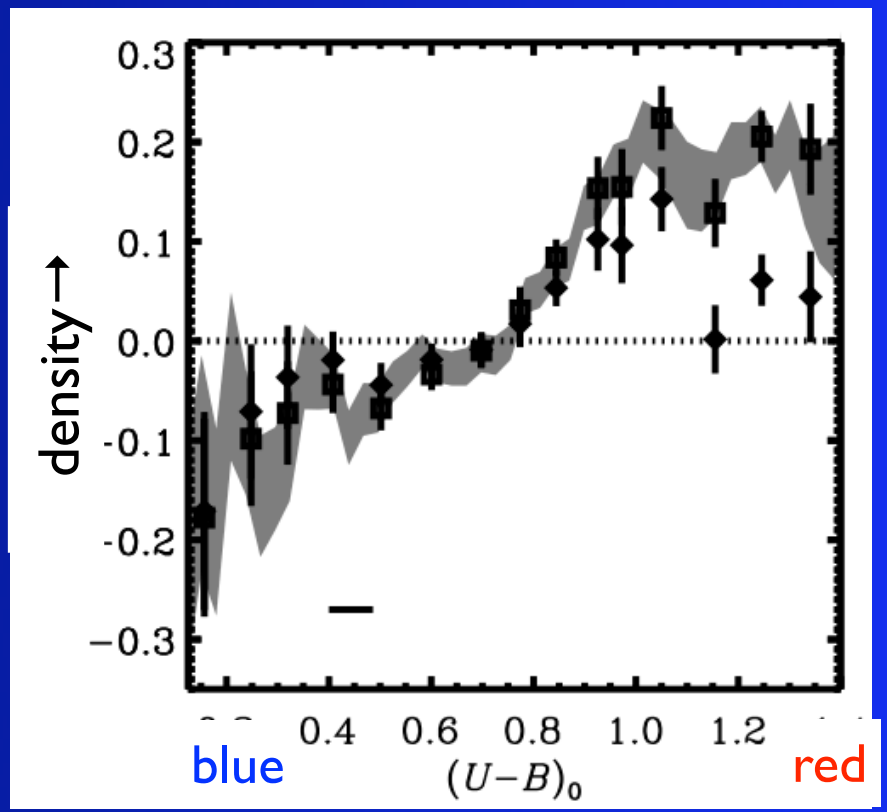
different methods: **density estimators**, **clustering measures**, group catalogs, void stats, lensing, satellite kinematics, etc.

low-redshift galaxies



Blanton & Berlind (2007)

z~1 galaxies



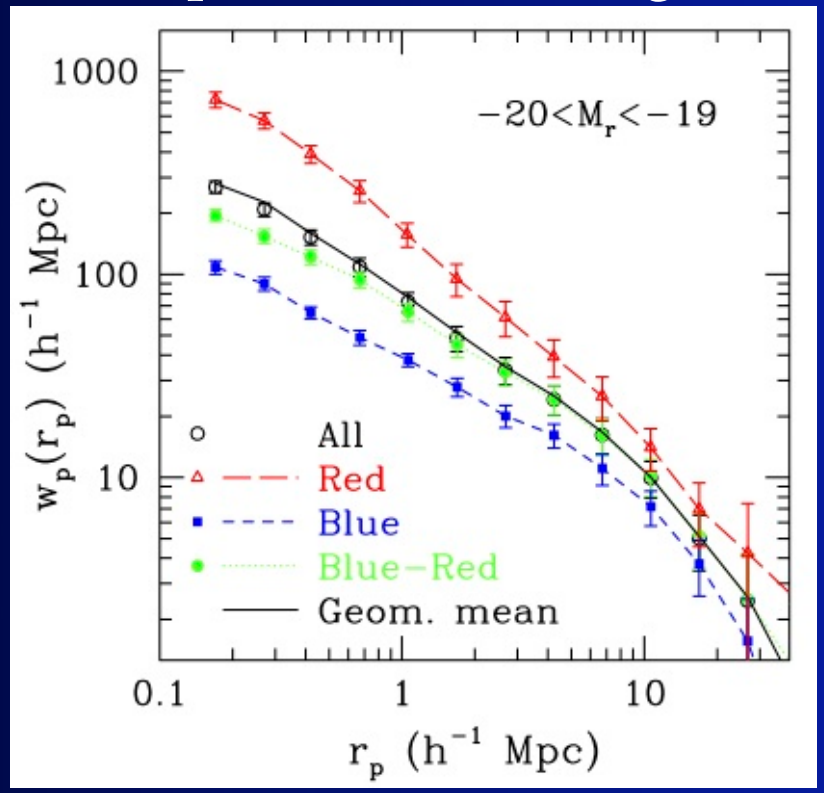
Cooper et al. (2006)

environmental correlations: color

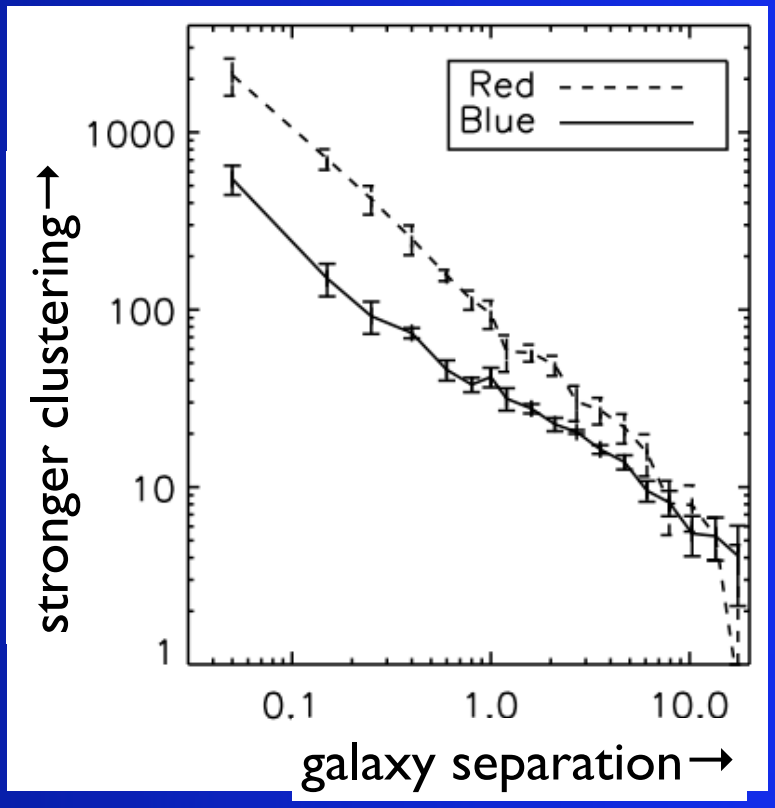
galaxy clustering can quantify environmental correlations

redder galaxies tend to be more strongly clustered than bluer ones

color-dependent clustering at z~0.1 and z~1



Zehavi et al. (2011)



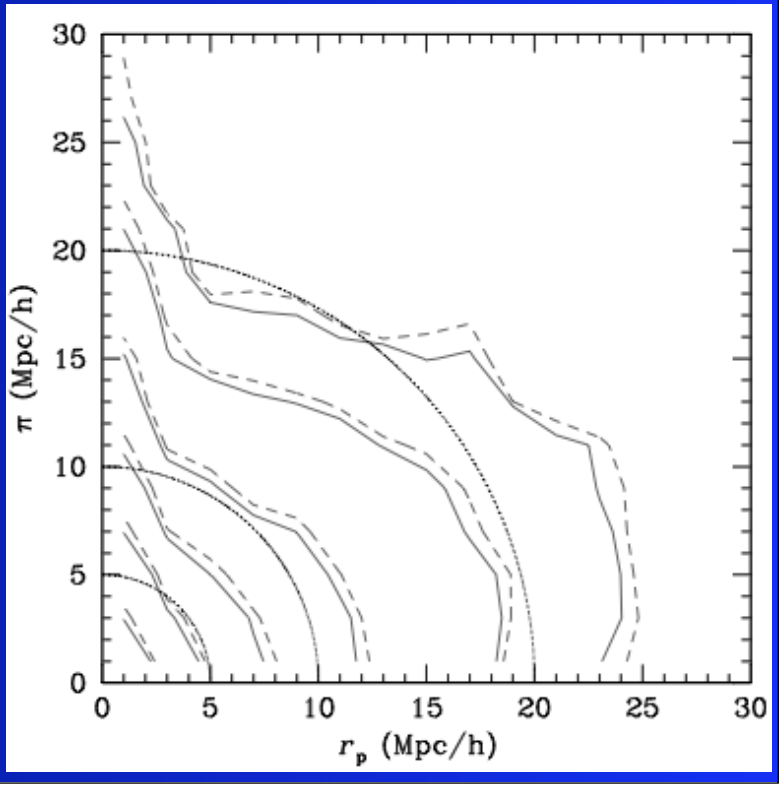
Coil et al. (2008)

measuring galaxy clustering

$\xi(r)$ quantifies excess probability dP over random of finding pairs of objects at separation r (Peebles 1980):

$$dP = n[1 + \xi(r)]dV$$

projected CFs integrate over nonlinear & linear redshift-space distortions:



Skibba et al. (2006)

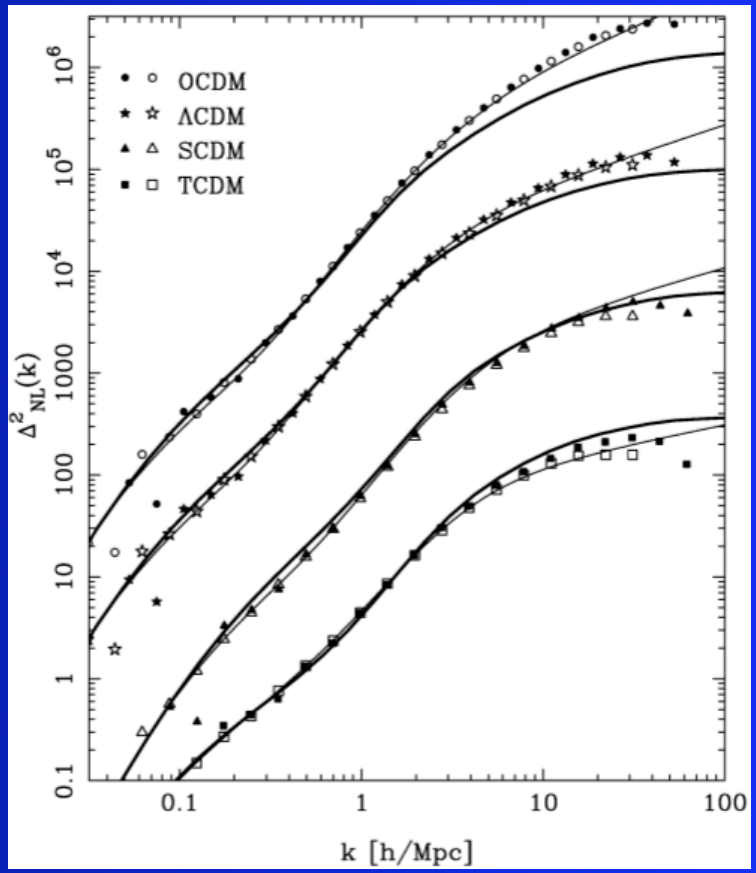
quantifying clustering strength and bias

projected CF:

$$w_p(r_p) = 2\int_0^\infty \xi(r_p,\pi)d\pi = 2\int_{r_p}^\infty \frac{r\xi(r)}{\sqrt{r^2 - r_p^2}}$$

solve for clustering length
& slope from power-law,
$\xi=(r/r_0)^{-\gamma}$

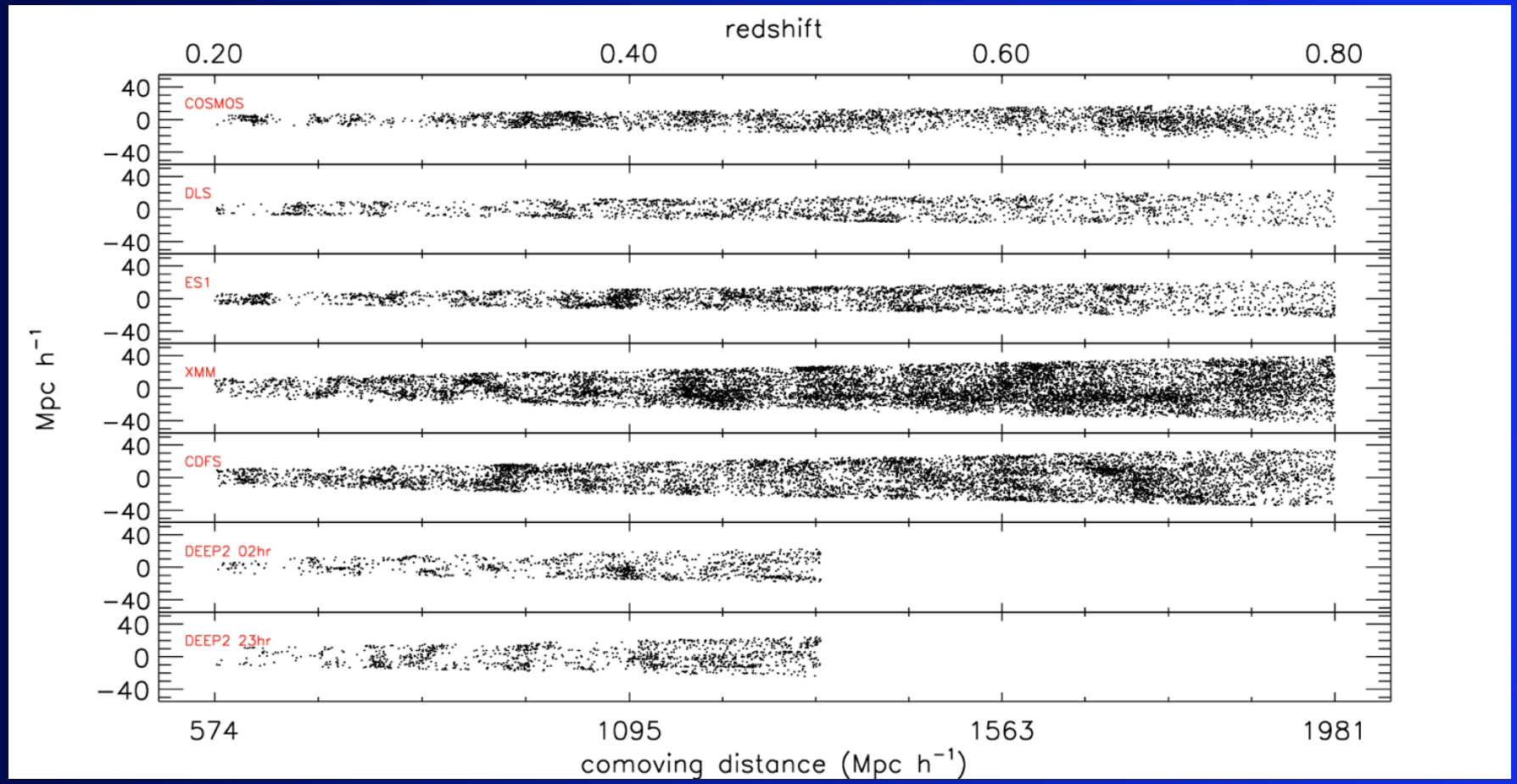
galaxy bias is relative to
(non)linear DM clustering:



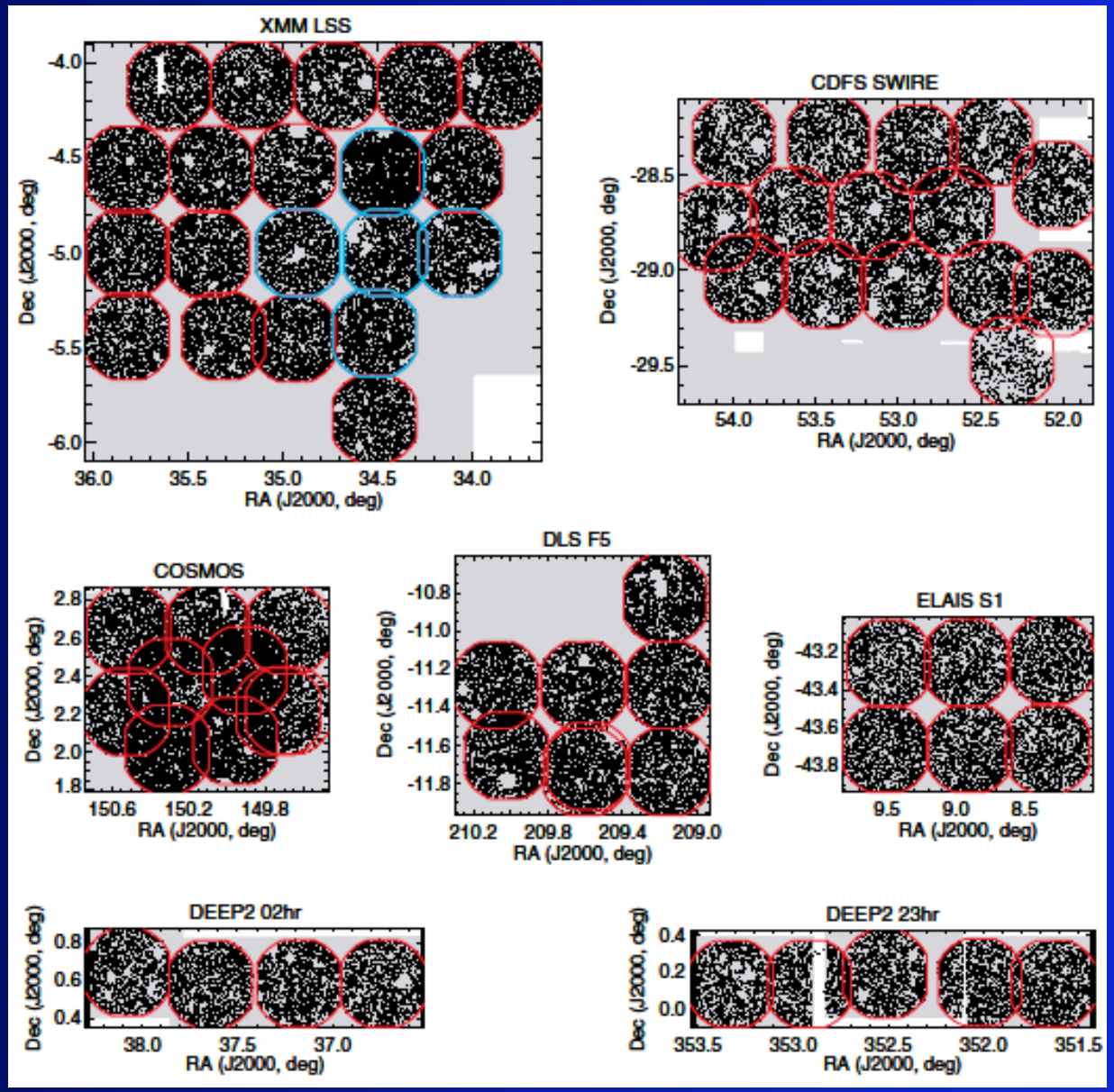
Smith et al. (2003)

Galaxy clustering in the PRIMUS survey

PRIMUS (Coil et al. 2011) survey of seven independent fields, from which we construct volume-limited catalogs at $0.2<z<1.0$ (complementary to VIPERS)



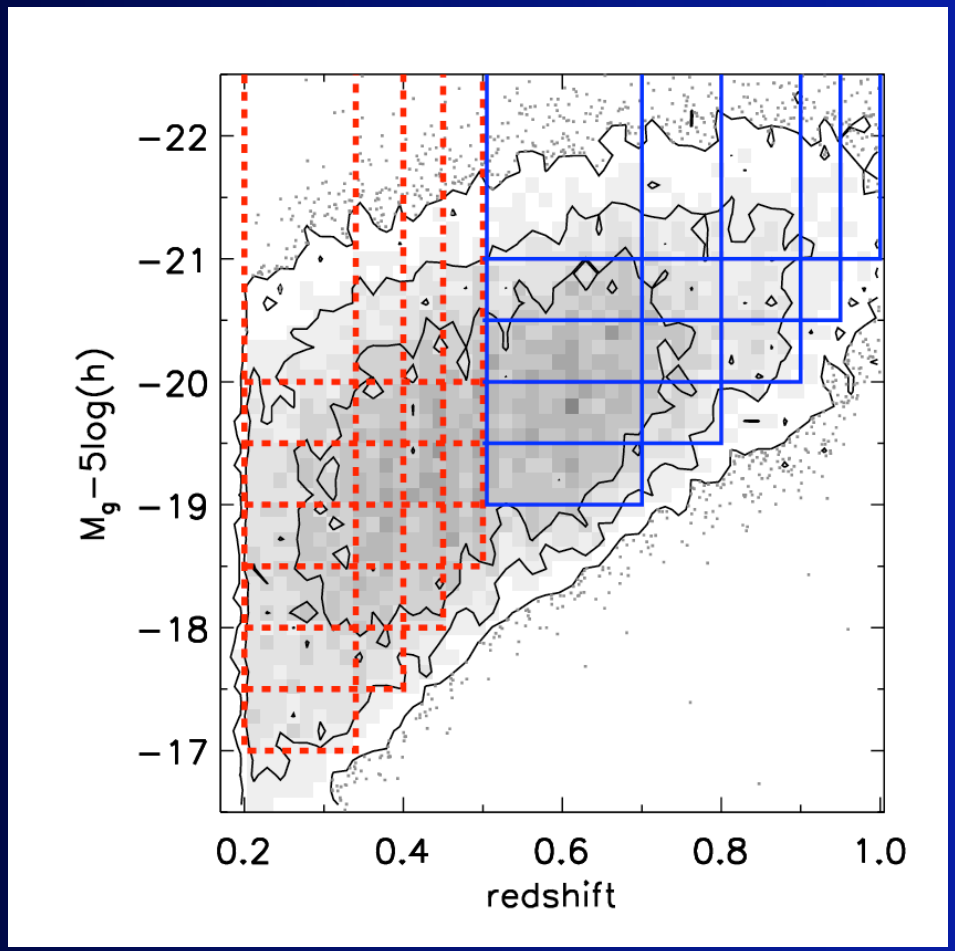
The PRIMUS Fields



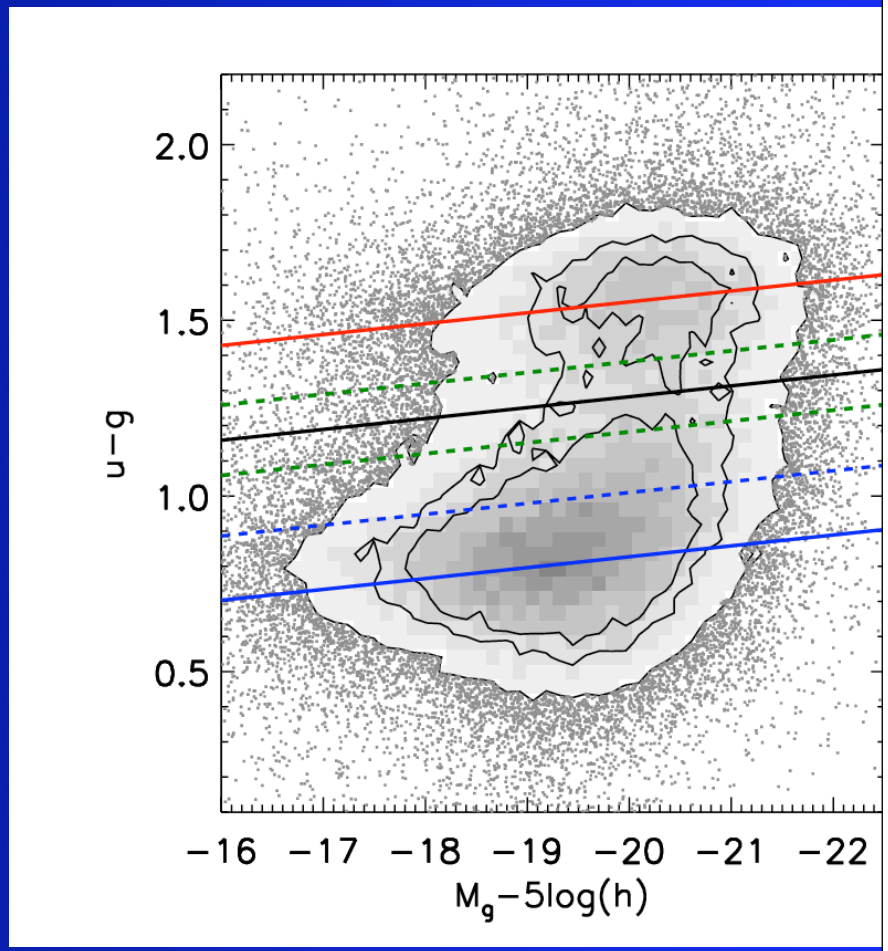
Coil et al. (2011)

Selecting Galaxy Catalogs

luminosity-selected samples

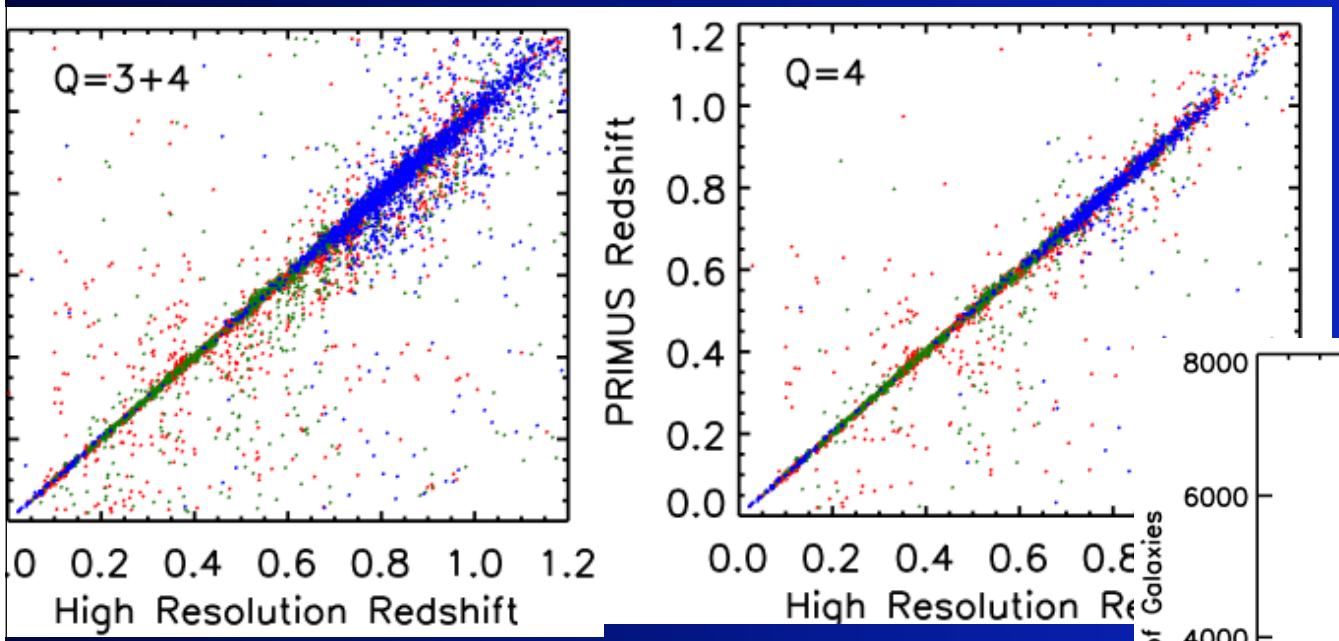


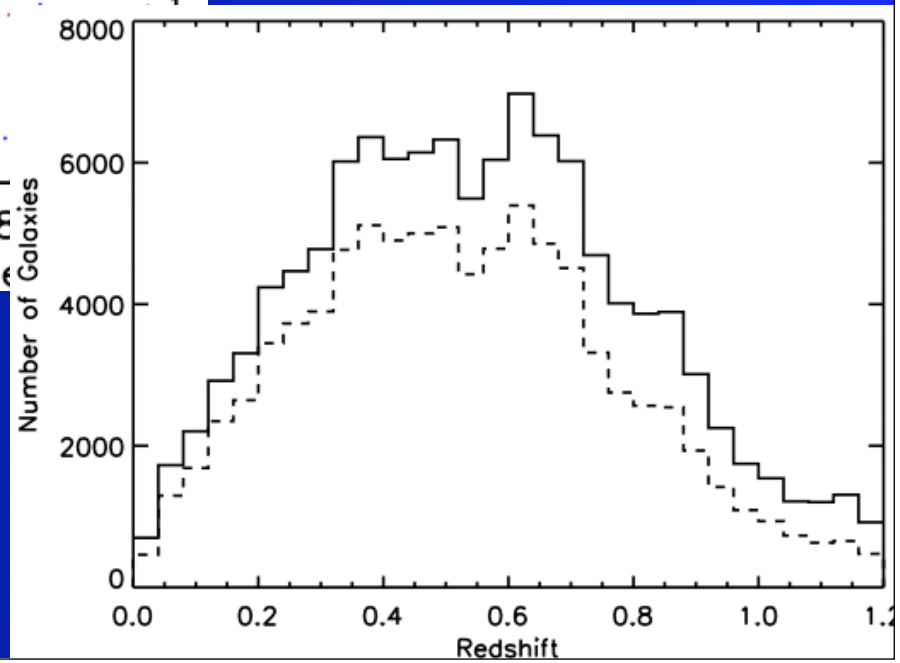
color bins in CMDs



redshift distributions, completeness weights, random catalogs, other complications

magnitude & density-dependent weights (incl. spectro slit collisions) -- see Coil et al. (2011)

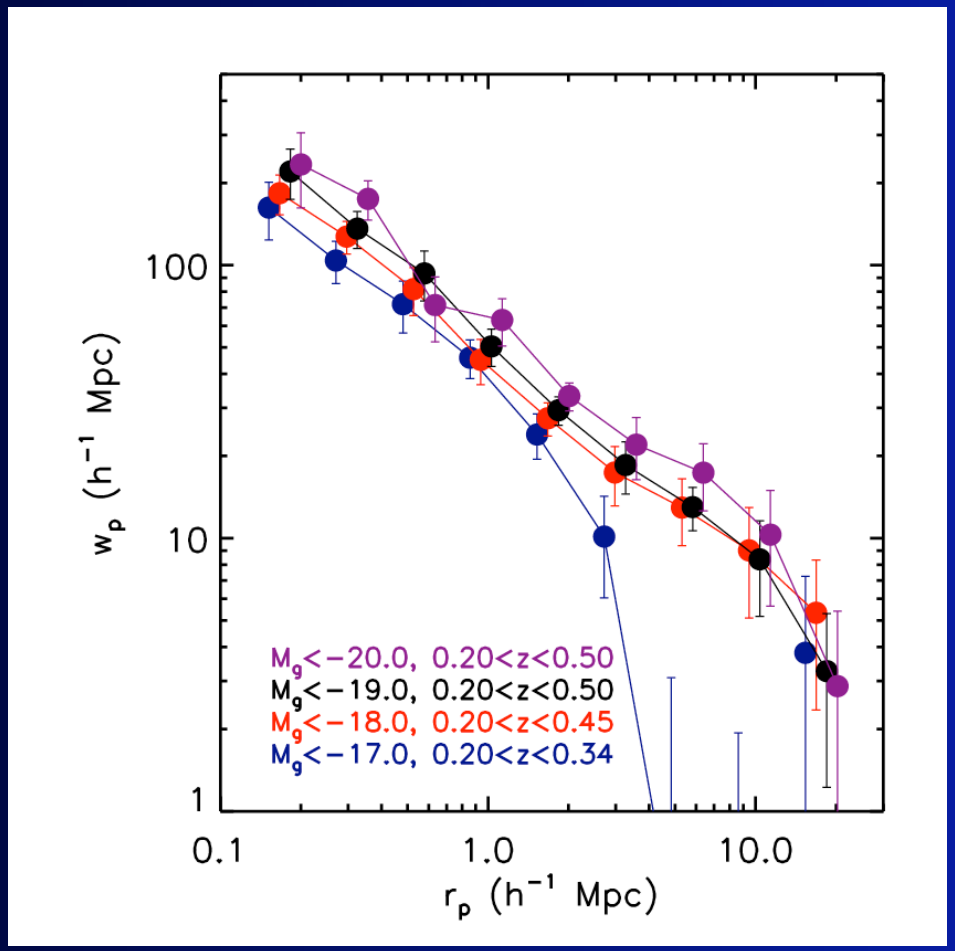




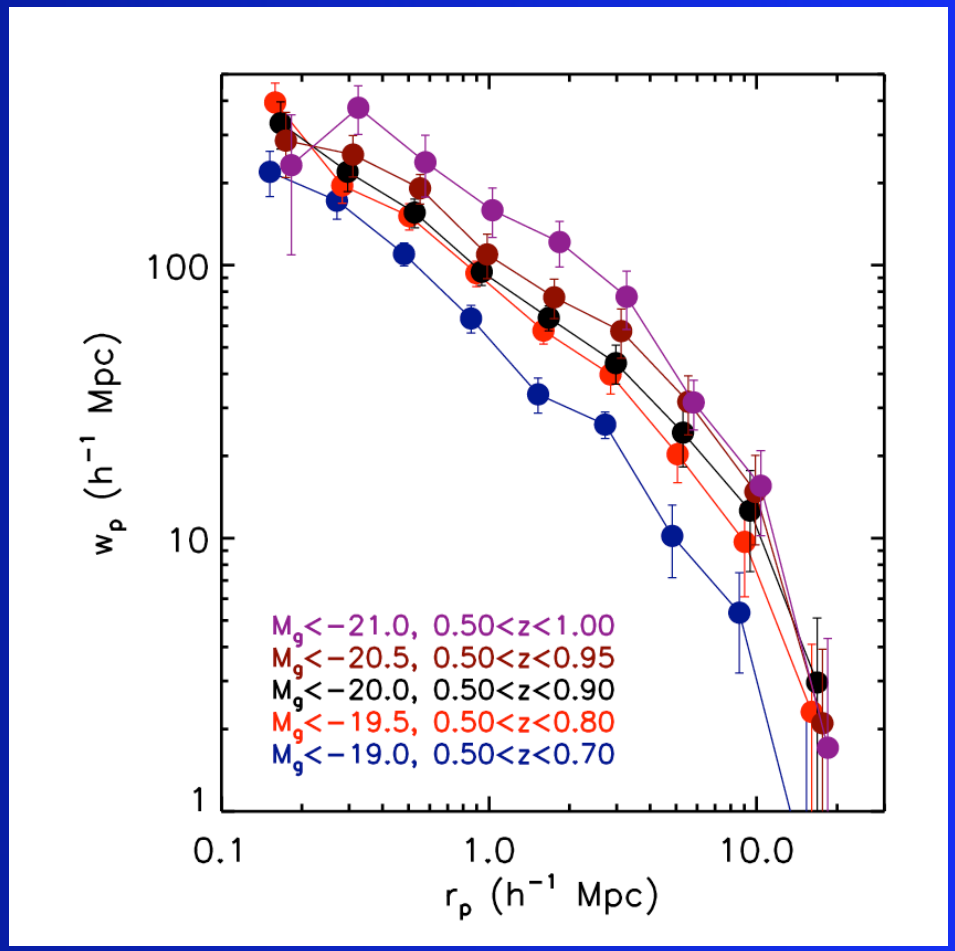
redshift determination & accuracy (Cool et al. 2013)

Luminosity dependent clustering

(mean) luminosity-dependent clustering

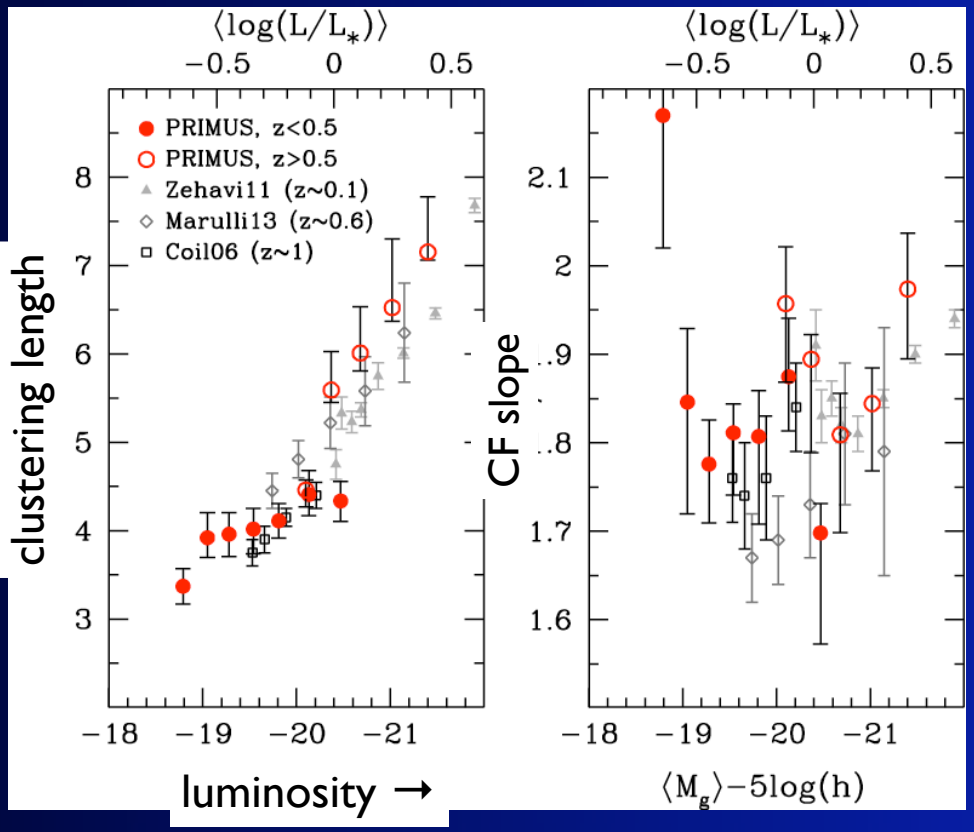


L-dependent high-z clustering

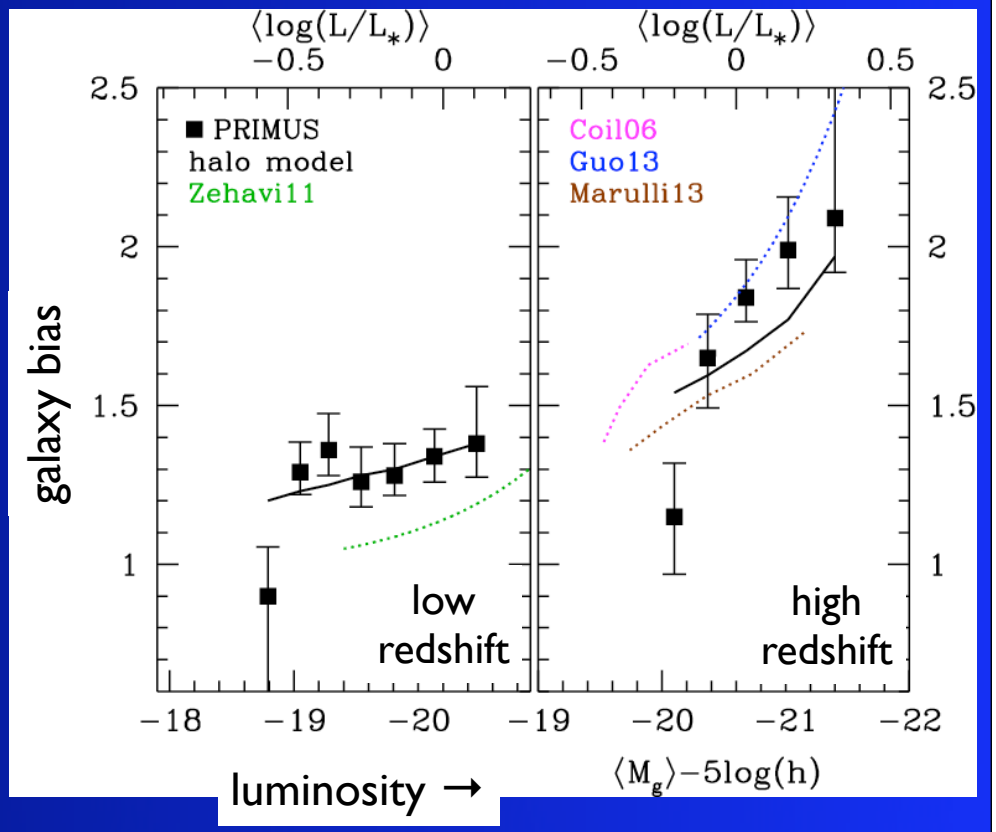


Clustering strength and bias

clustering length and slope



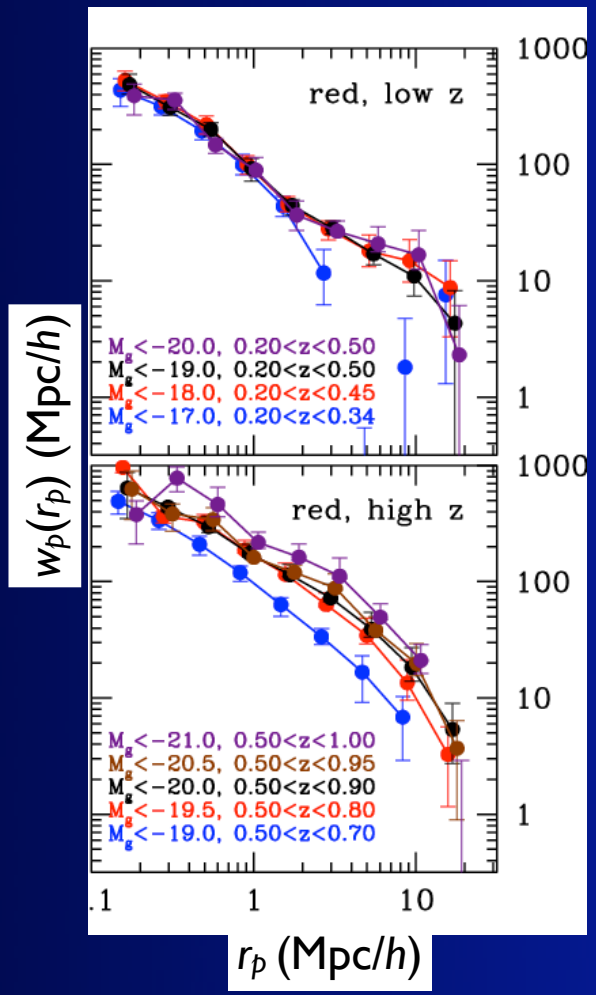
galaxy bias



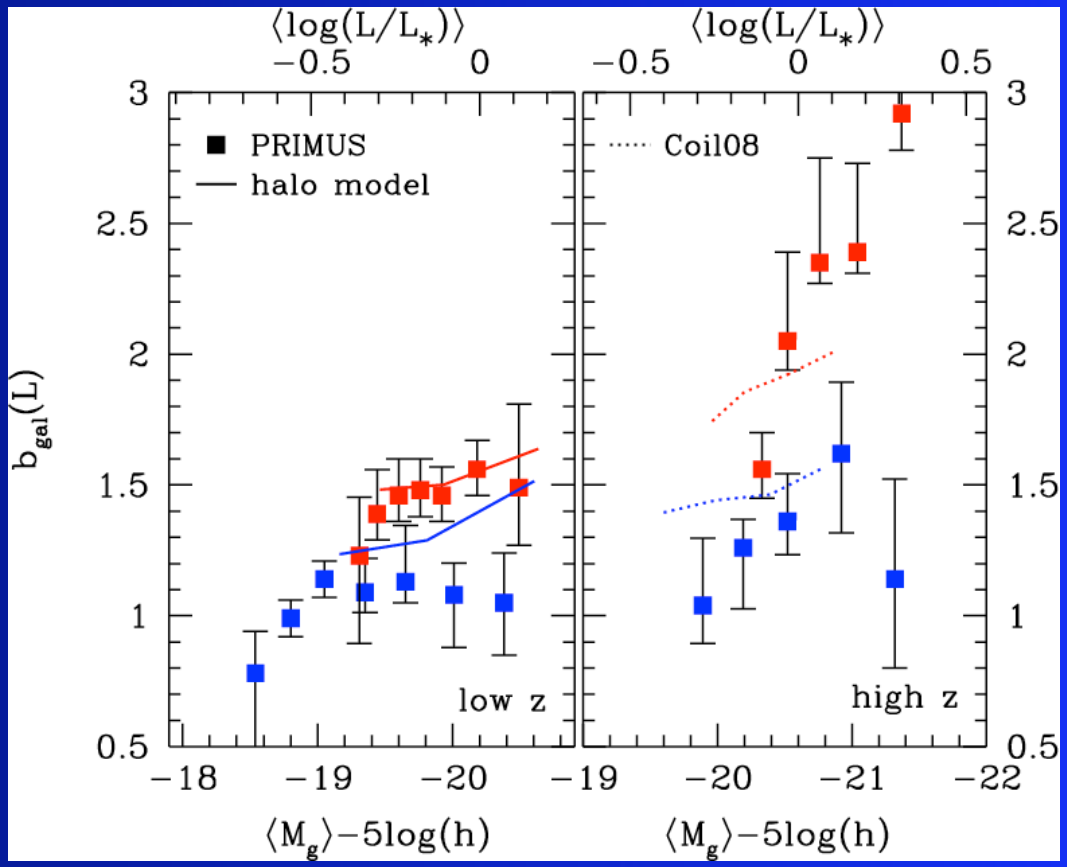
Skibba et al. (2013b)

Color dependent clustering: red vs blue

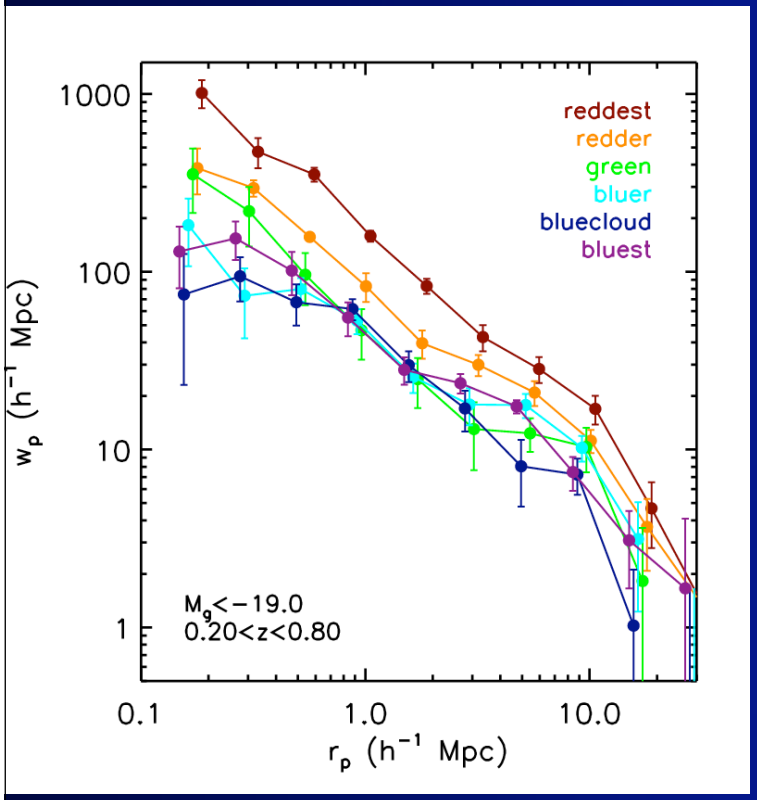
L-dependent CFs of red galaxies



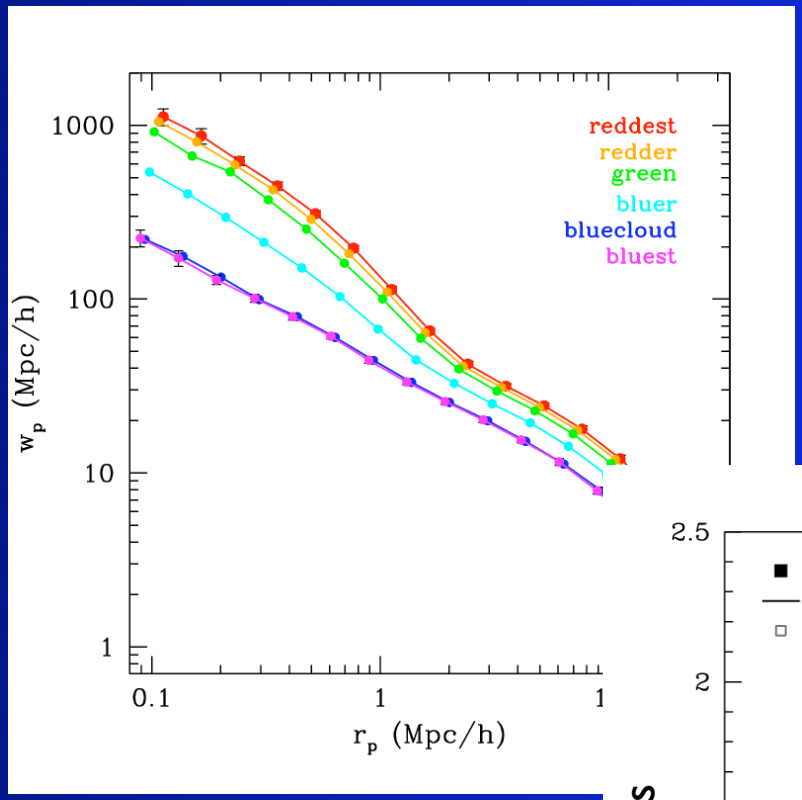
clustering length and slope



Color dependent clustering

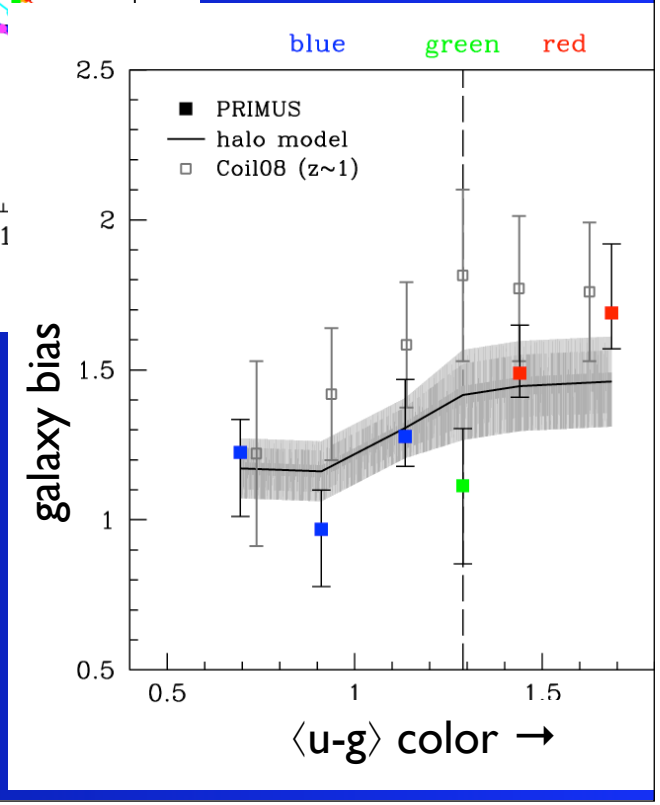


PRIMUS



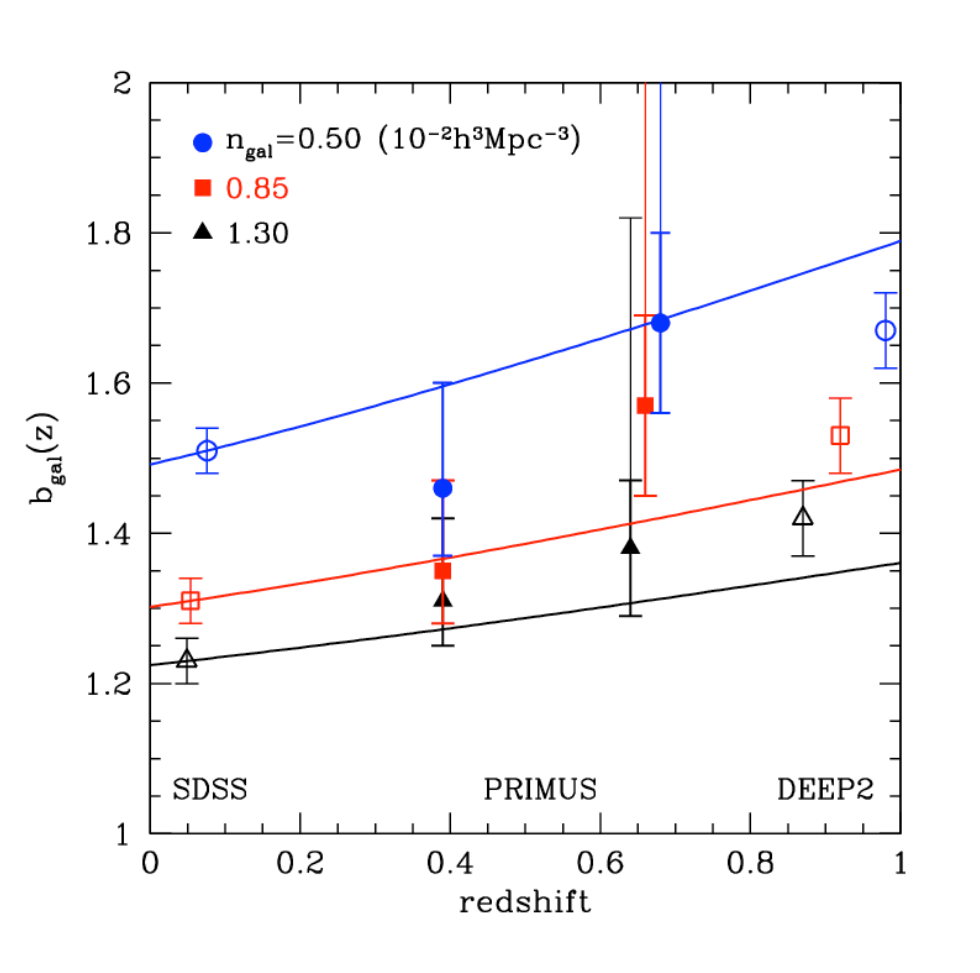
model (mock)

color dependent bias



Large-scale clustering evolution

evolving bias vs passive evolution

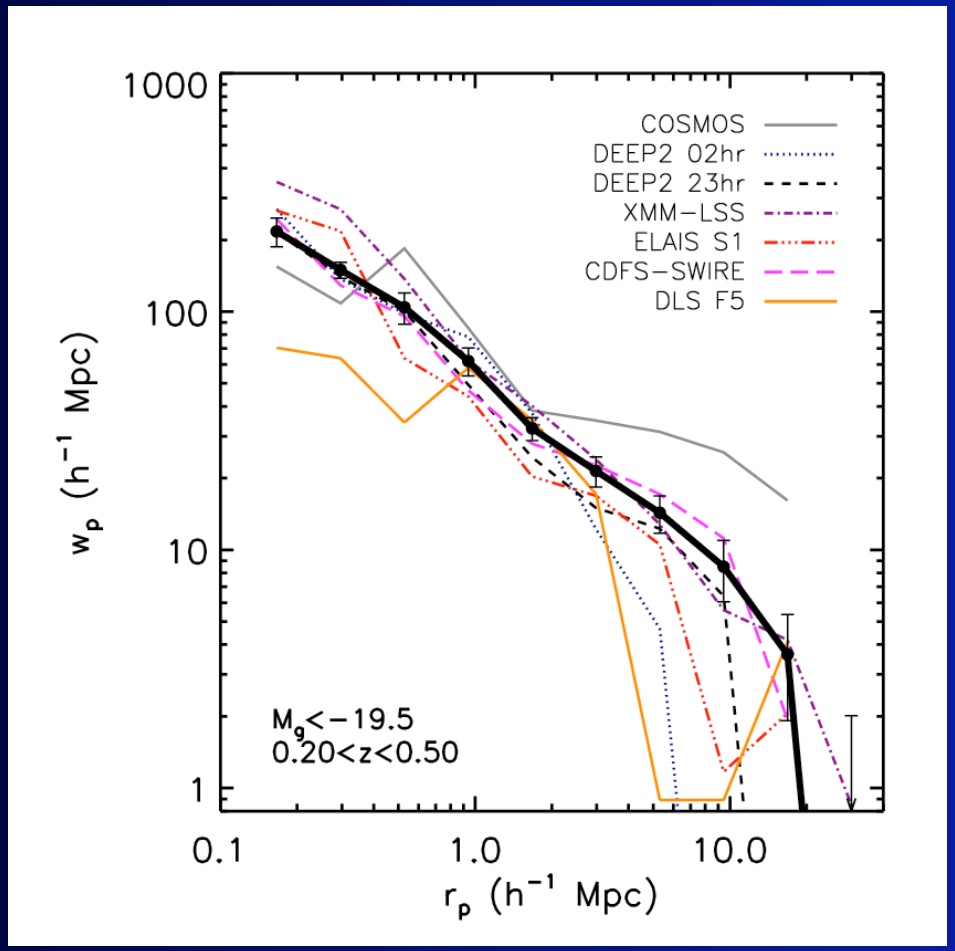


passive evol: large-scale clustering follows linear growth factor *D(z)*:

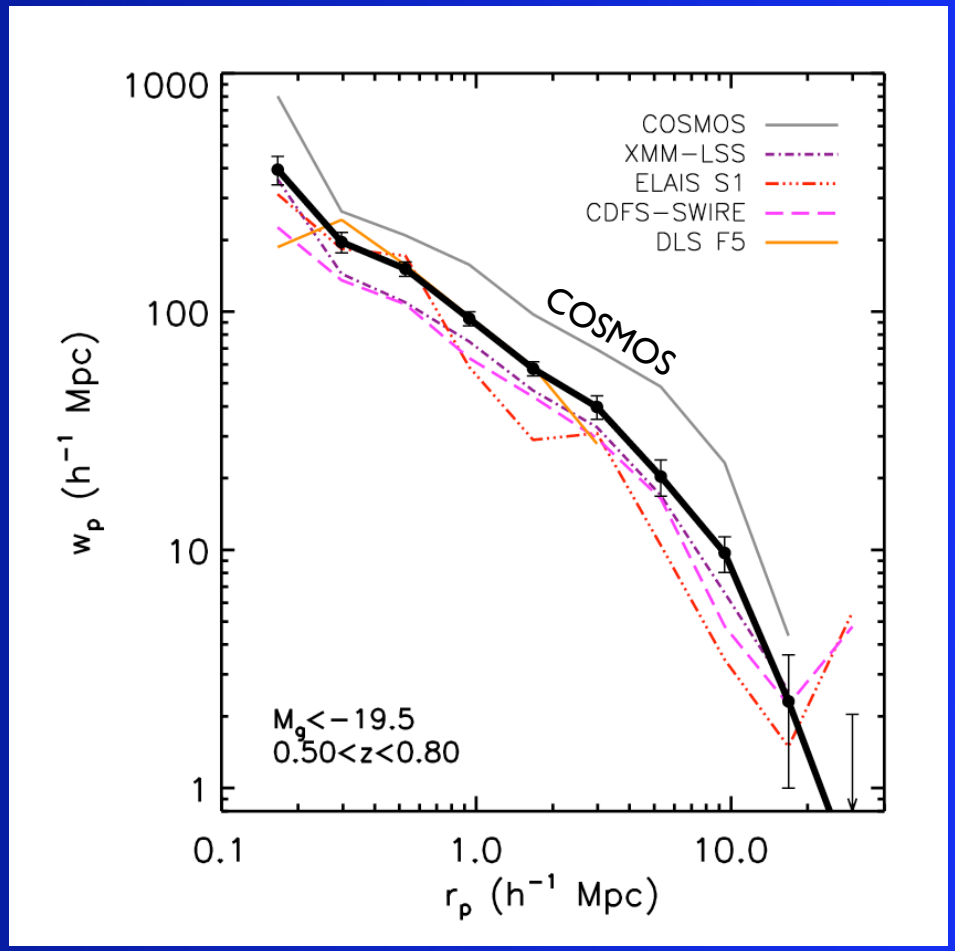
$$b_{gal}(z) = (b(z_0) - 1)\frac{D(z_0)}{D(z)} + 1$$

Cosmic variance

field-to-field variation: low-z

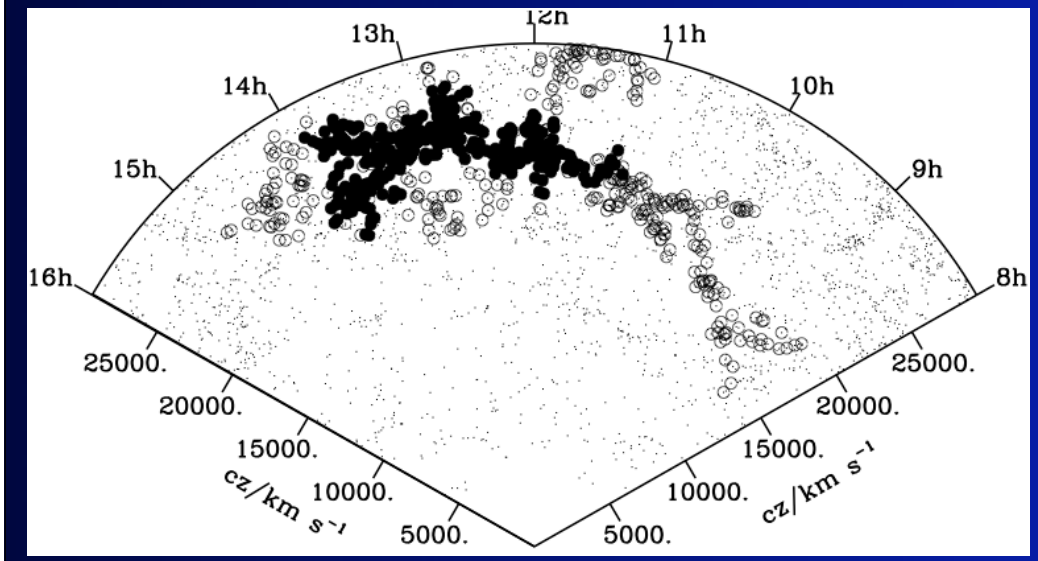


field-to-field variation: high-z



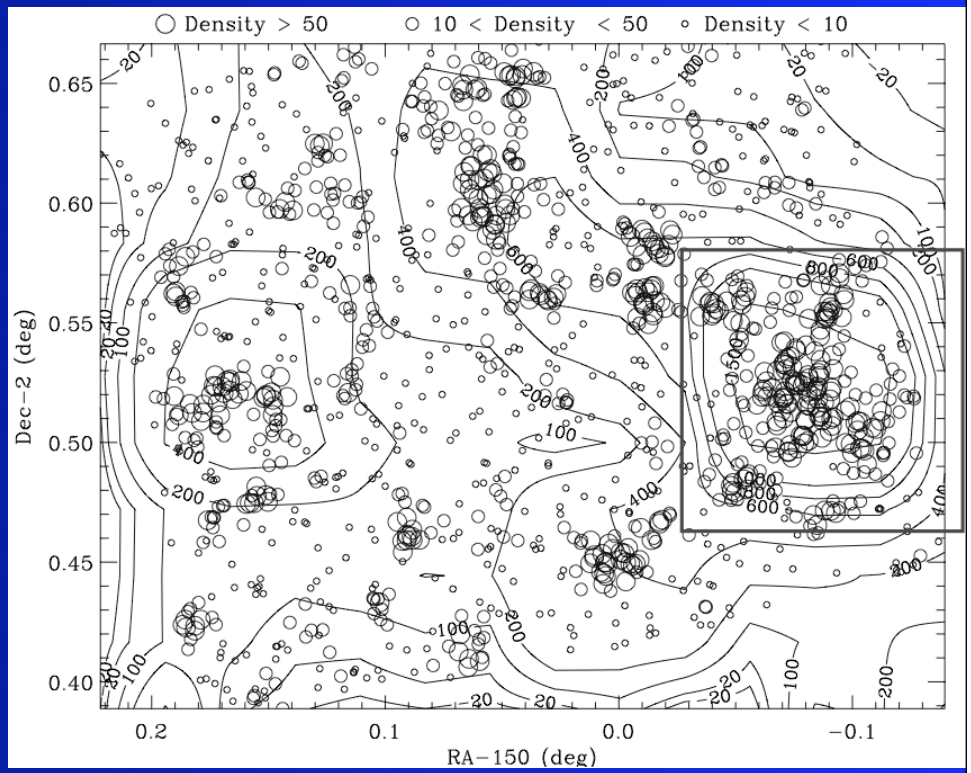
Cosmic variance: effect of LSS

Sloan Great Wall structure (see Zehavi et al.; Norberg et al.)



most massive structure in the Hubble volume? (Sheth & Diaferio 2011)

and LSS in COSMOS (see Guzzo; Scoville; Knobel; Kovac et al.)



Mark correlation functions: introduction

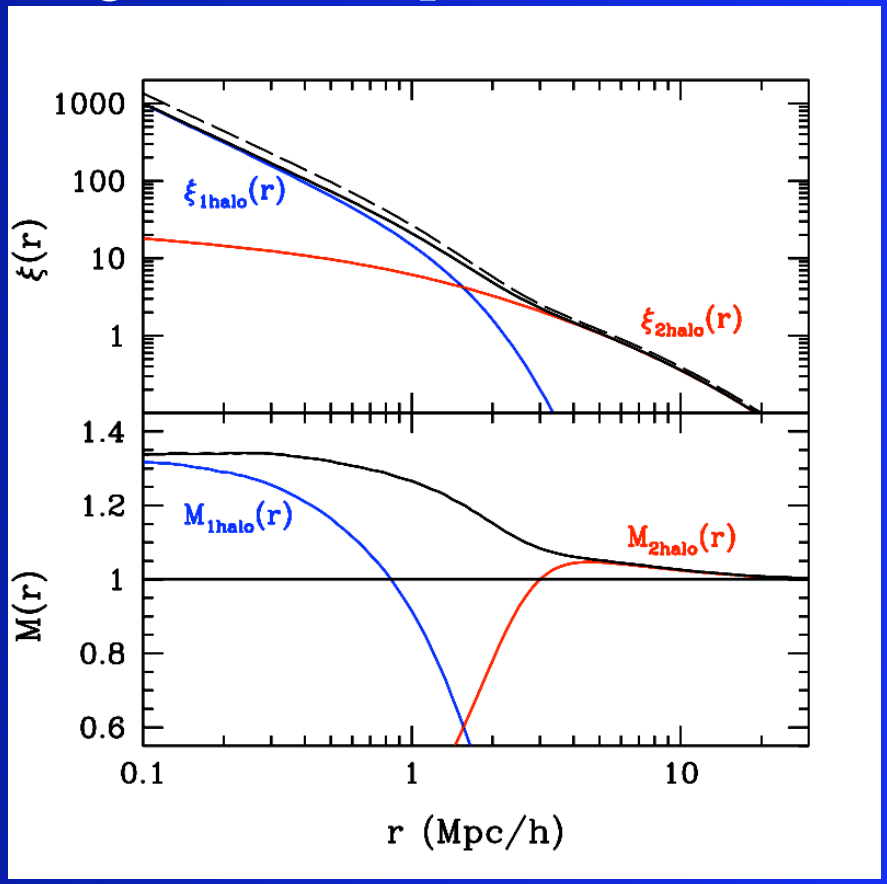
Galaxy clustering described by:

$$\xi(r) \equiv \xi_{1\mathrm{halo}}(r) + \xi_{2\mathrm{halo}}(r)$$

Environmental dependence of galaxy properties described by *marked* clustering stats:

$$M(r) \equiv \frac{1 + W(r)}{1 + \xi(r)}$$

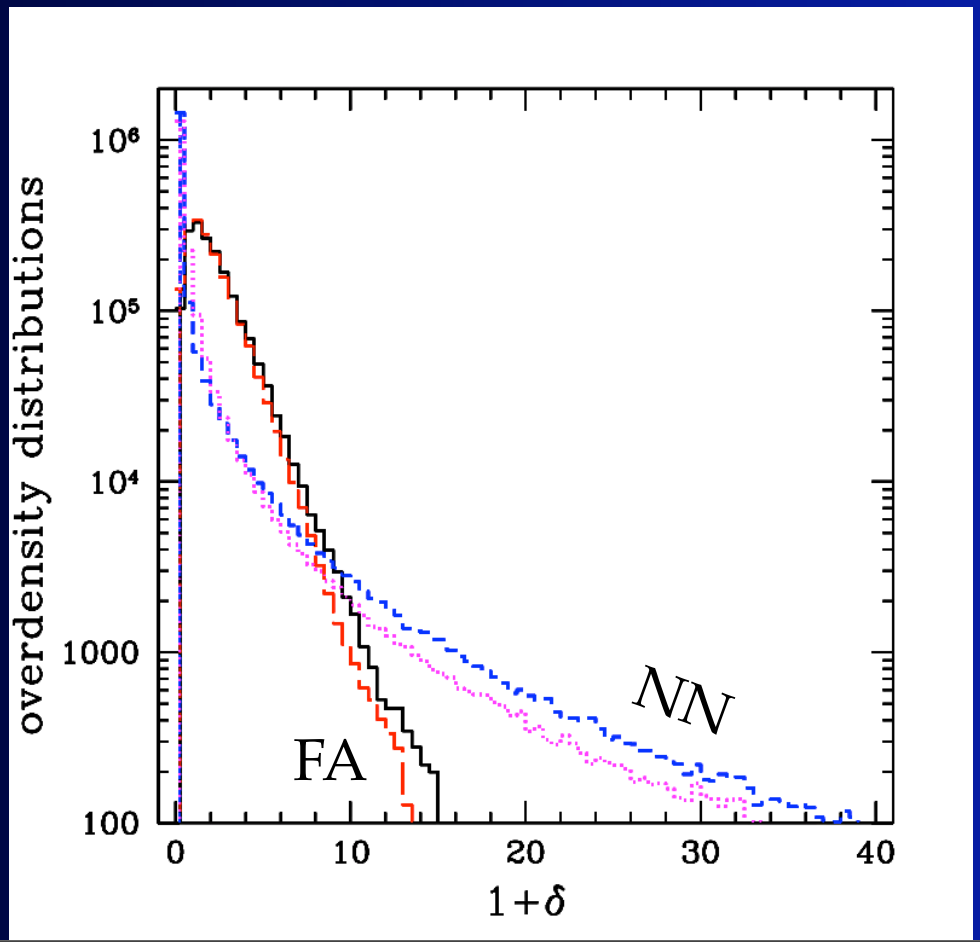
single halo + separate halo terms

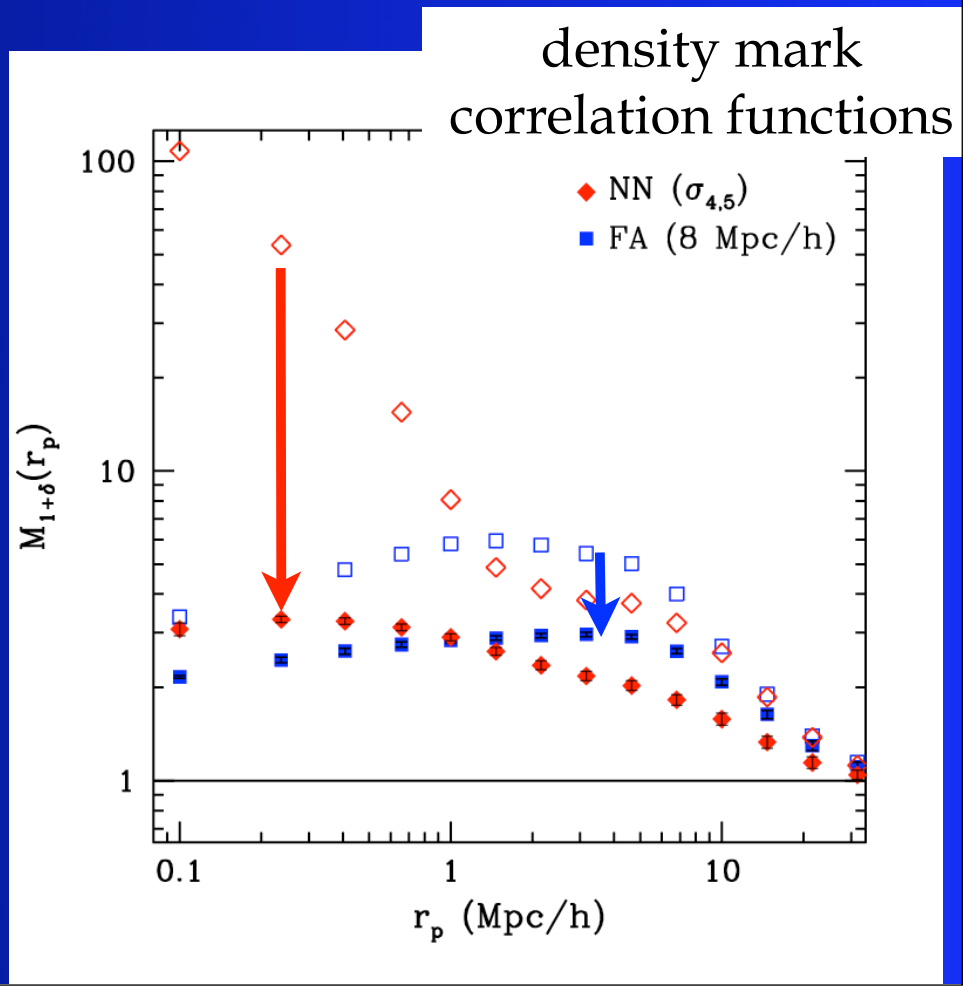


Applications of rank-ordered mark CFs

shows an ***important application of rank ordering***, *which removes the dependence on mark distributions*

allows for simple interpretation: **FA densities sensitive to large scales (r_p >1 Mpc/*h*), and NN to small scales**

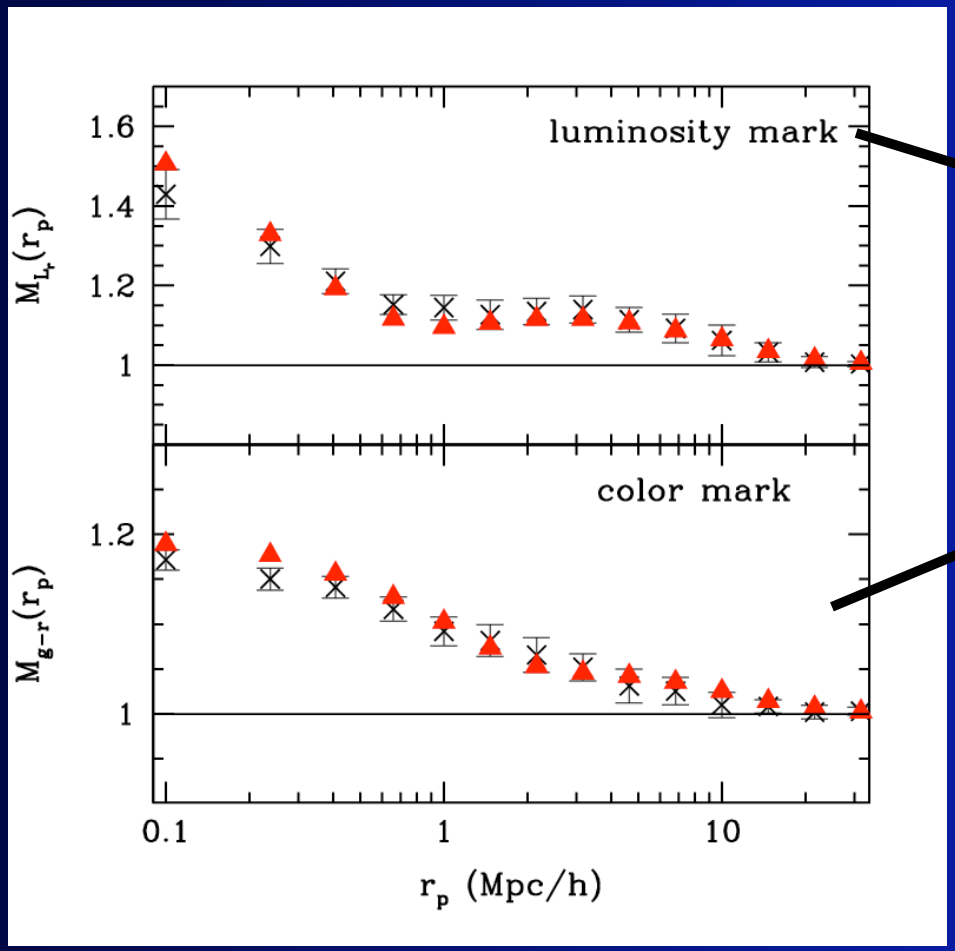




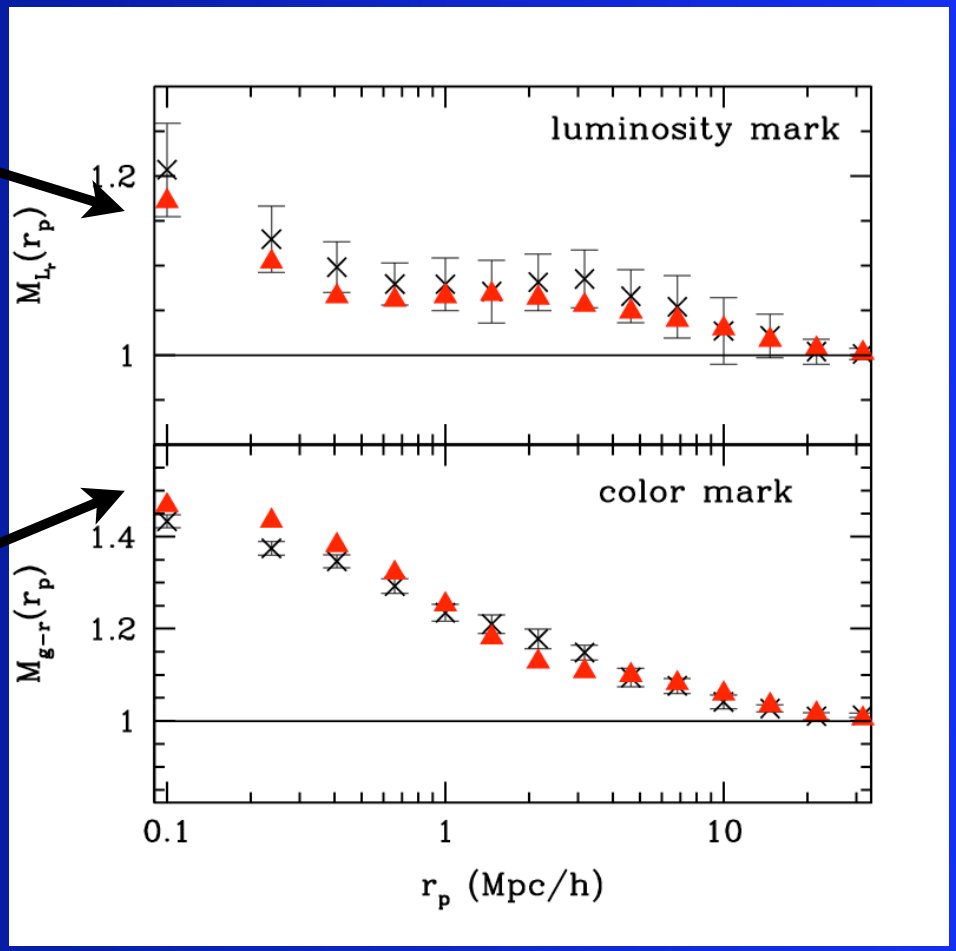
Results: rank-ordered luminosity and color MCFs

another app.: rank-ordered mark CFs (right) demonstrate that *color is better tracer of environment than is luminosity*

luminosity & color MCFs



rank-ordered luminosity & color MCFs

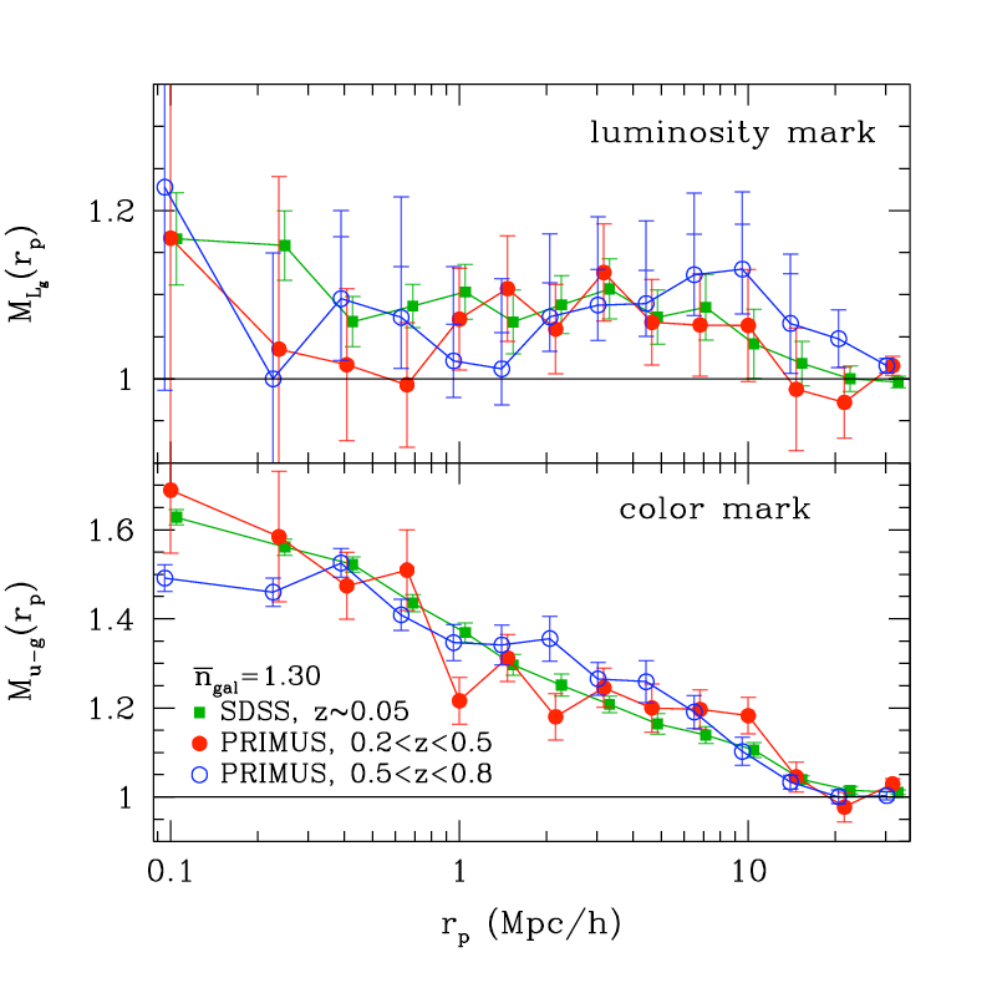


Skibba et al. (2013a)

mark clustering evolution in PRIMUS

SDSS (low-z) vs PRIMUS ($0.2<z<0.8$) rank-ordered mark CFs:

non-evolution of these mark CFs imply **not much evolution of L-M_{halo} and C-M_{halo} relations since (z~1)**



Skibba et al. (2013b)

Work-in-progress and Future Plans

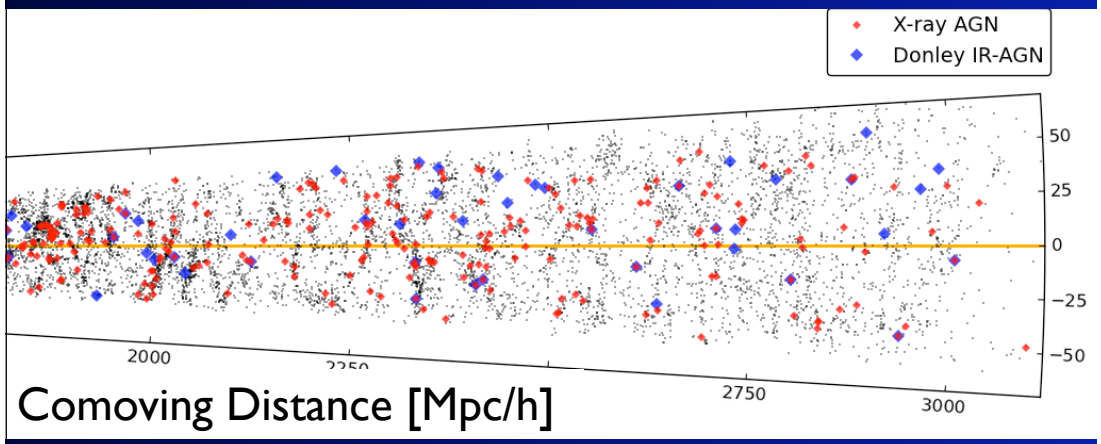
1. halo occupation modeling of evolving and *L* & *C*-dependent clustering

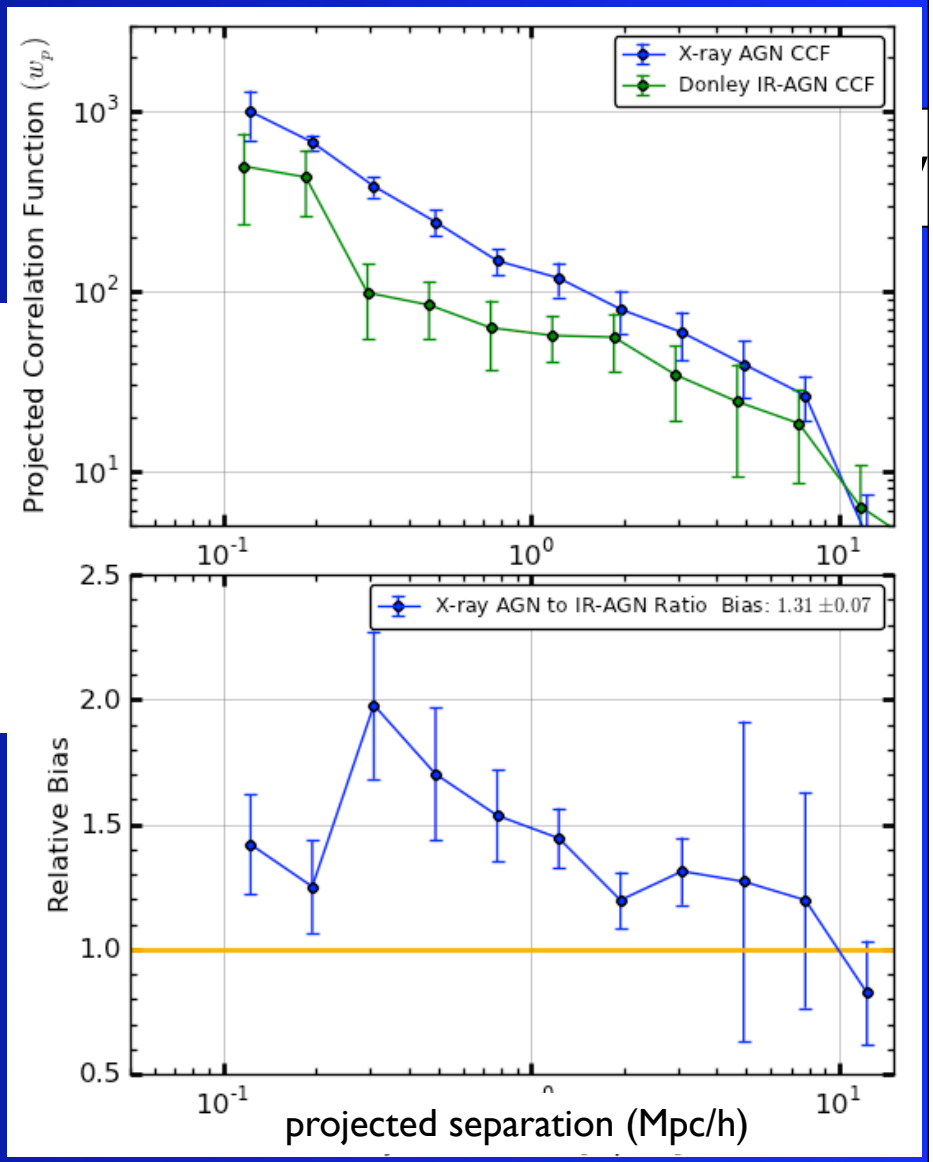
2. age/abundance matching modeling of clustering (with Doug Watson and Andrew Hearin)

3. clustering of (U)LIRGs, and dependence on IR luminosity & star formation activity

Other PRIMUS Clustering Work

X-ray vs IR AGN clustering by Alex Mendez (preliminary)

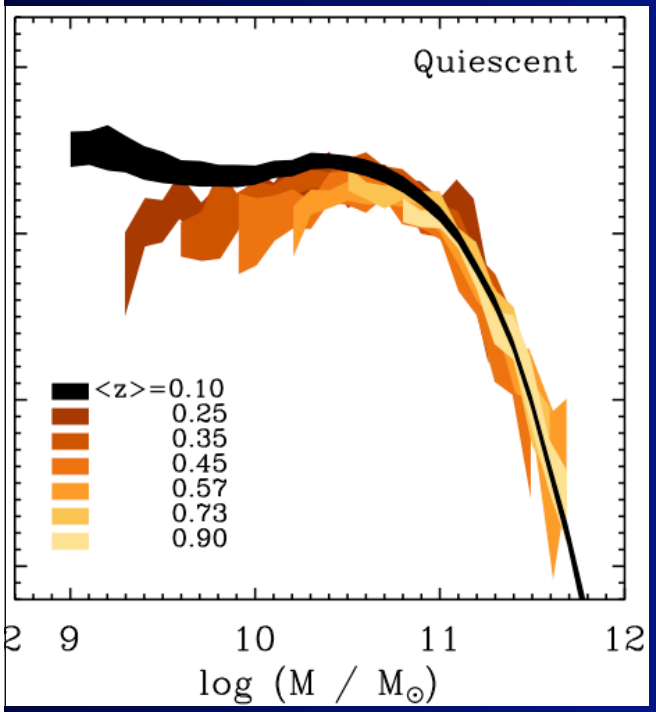




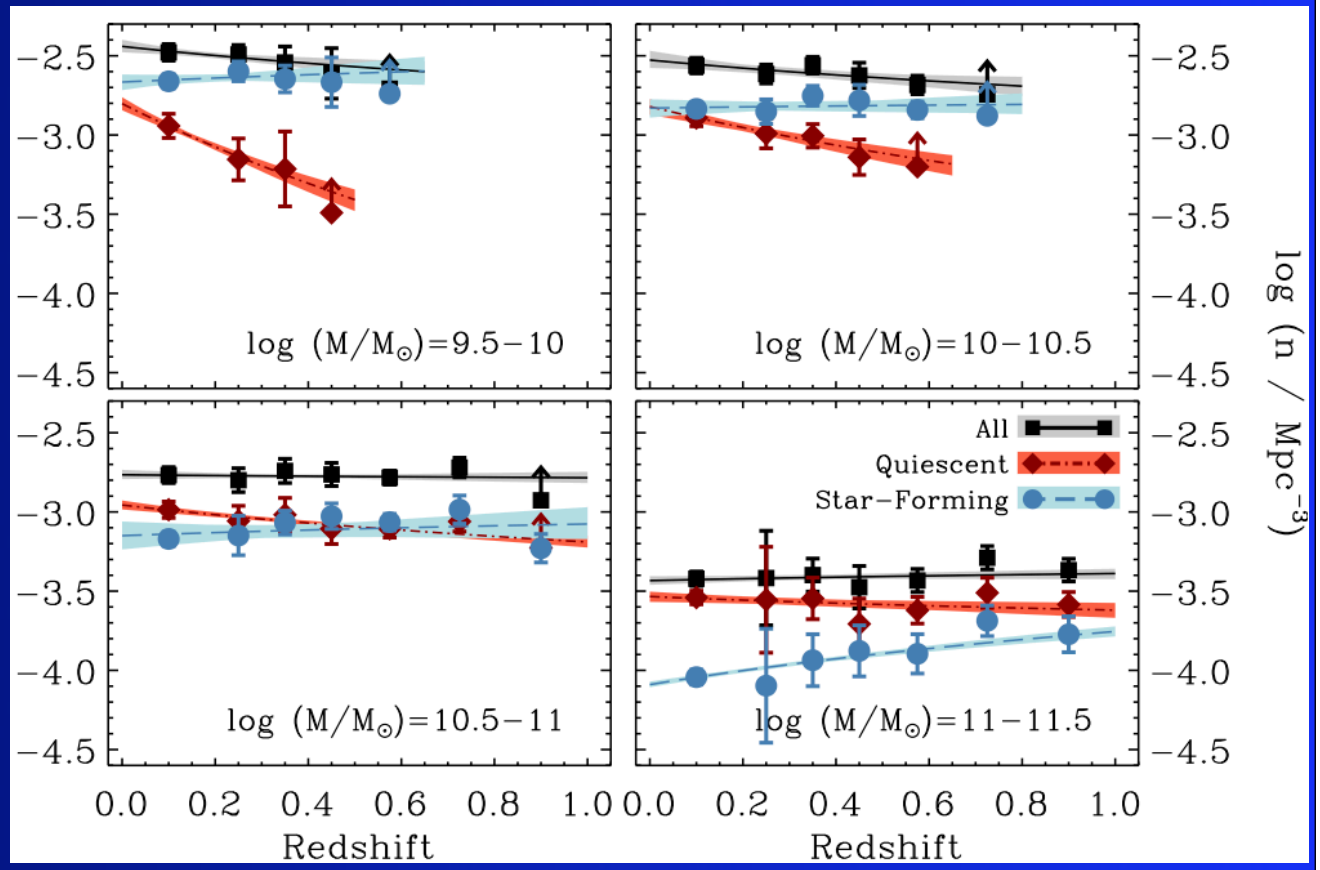
also: spectro-photo cross-CFs of galaxies by Aaron Bray (not shown)

see also: Coil et al. (2009)

Other PRIMUS Work



Moustakas et al. (2013)



also: work on star formation in close pairs (**Wong** et al.); AGN accretion rates (**Aird** et al.); evolution of star-forming "main sequence" (**Coil** et al.); obscured SF on red sequence (**Zhu** et al.); environment-dependent stellar MFs (**Hahn** et al.); evolving AGN properties (**Azadi** et al.)...

Conclusions

- **measurements of luminosity and color dependent clustering, and constraints on halo models**
- **galaxy bias evolution** consistent with 'passive evolution'
- **'cosmic variance' can be significant source of uncertainty** in high-z clustering measurements, even for large-area catalogs
- **mark clustering statistics are powerful tools**, very sensitive to environmental correlations; rank-ordered mark stats allow for direct comparisons, with many applications