What Can We Learn from Galaxy Clustering I:

Why Galaxy Clustering is Useful for AGN Clustering

Alison Coil
UCSD

Talk Outline

1. Brief review of what we know about galaxy clustering from observations

2. Very briefly: what cosmological constraints galaxy clustering can provide

   (Shaun Cole will talk next about what we learn about galaxy evolution from clustering measurements)

3. AGN-galaxy cross-correlation measurements

4. Using galaxy clustering to interpret AGN clustering

Galaxy Clustering Measurements

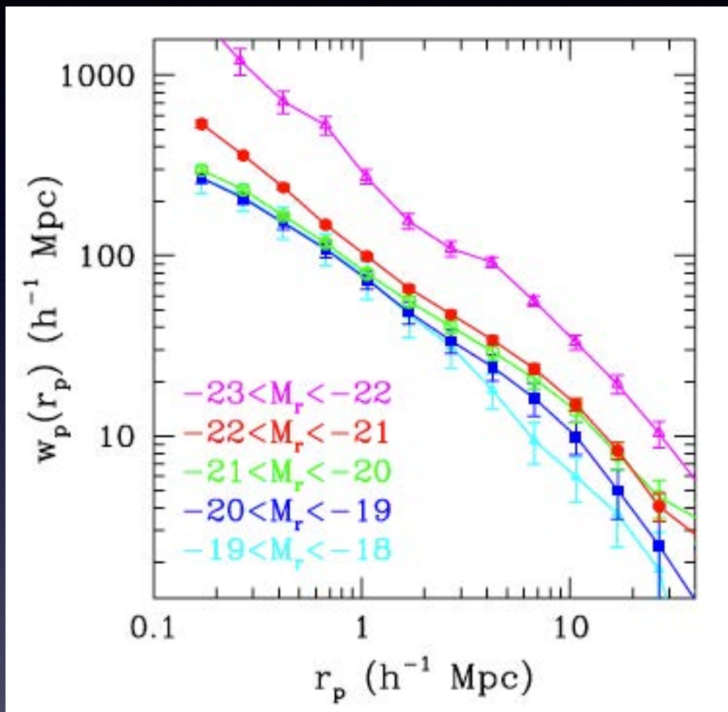
There are fairly strong clustering dependencies with galaxy properties such as luminosity, color, stellar mass, and SFR.

Generally speaking: brighter, redder, more massive and/or quiescent galaxies are more clustered than fainter, bluer, less massive and/or star forming galaxies
- at $z\sim0$ at least to $z\sim3$.

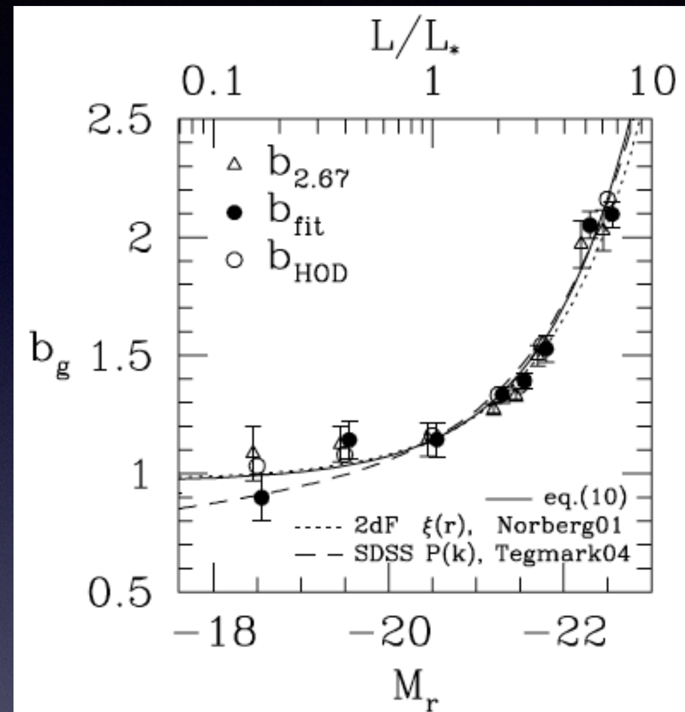
Cosmic variance can hamper measurements from small volumes (with single and/or small fields), so always best to use multiple fields - the more, the better!

Luminosity Dependence

clustering amplitude



bias



L/L*

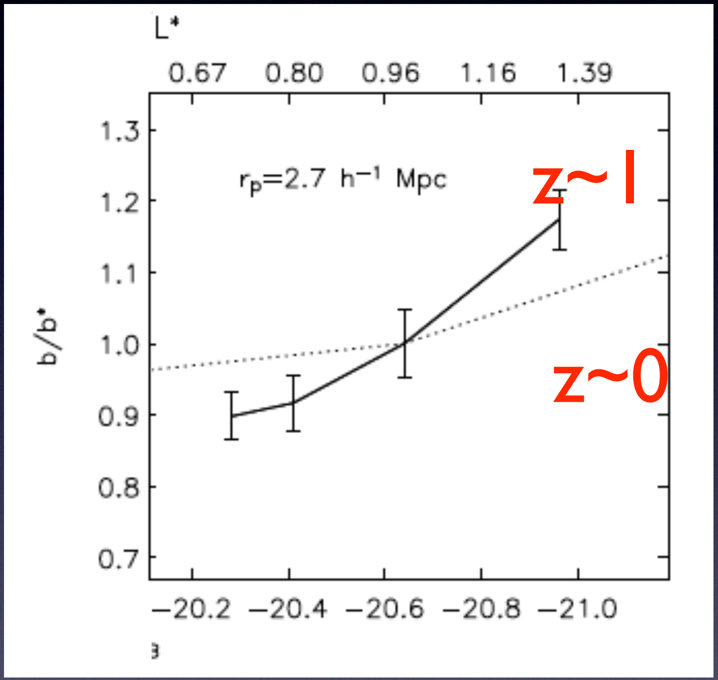
SDSS, Zehavi et al. 2011

Luminosity dependence at z~0 is now really well quantified.
Strong luminosity dependence above L*, not below L*!

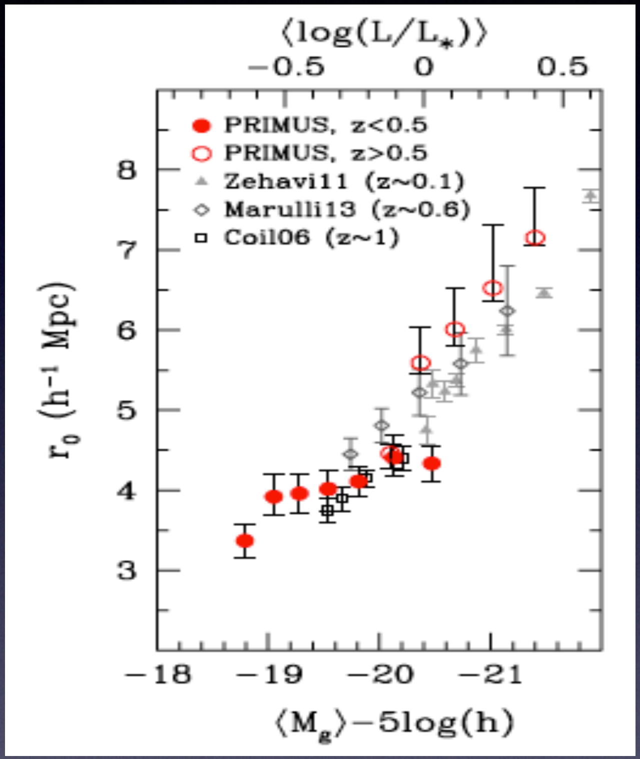
Luminosity Dependence

L/L*

bias



clustering scale length

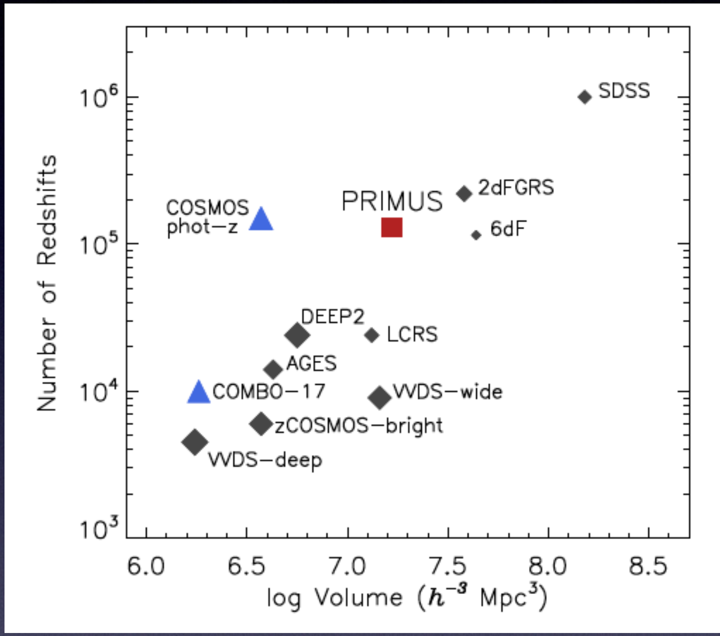


DEEP2, Coil et al. 2009

PRIMUS, Skibba et al. 2014

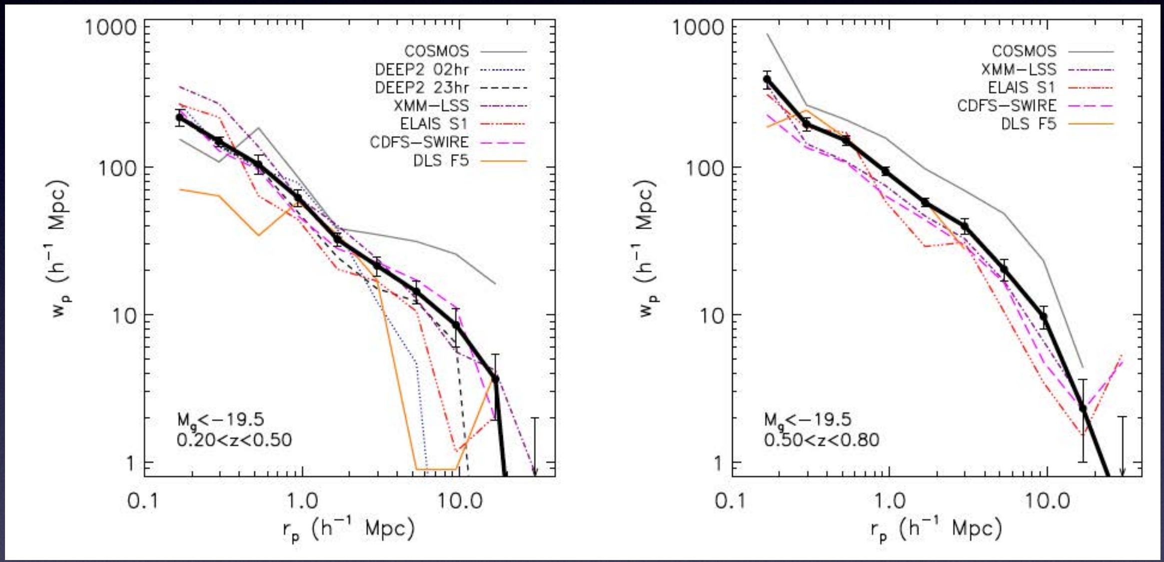
Slightly stronger dependence with L/L* at higher z than at z~0.

Cosmic Variance



0.2< z <0.5

0.5< z <0.8



Coil et al. 2011

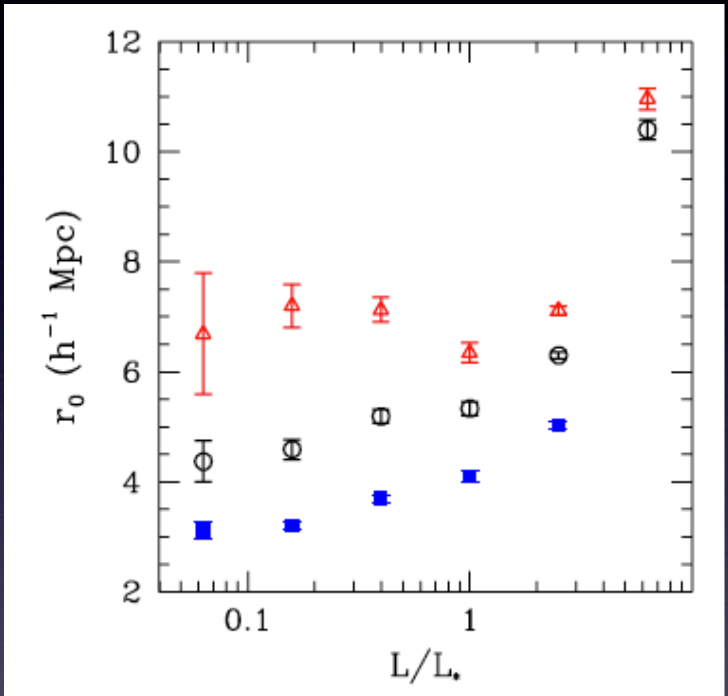
PRIMUS, Skibba et al. 2014

Volume of PRIMUS is 1/2 that of 2dF!
Yet cosmic variance is still the dominant error.
COSMOS is an outlier in terms of clustering amplitude at intermediate redshift.

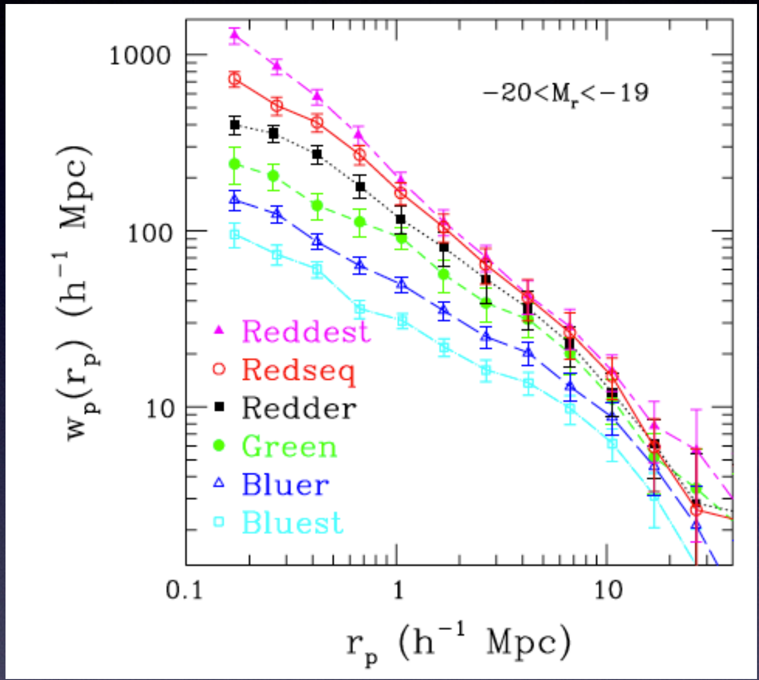
Color Dependence

L/L*

clustering scale length



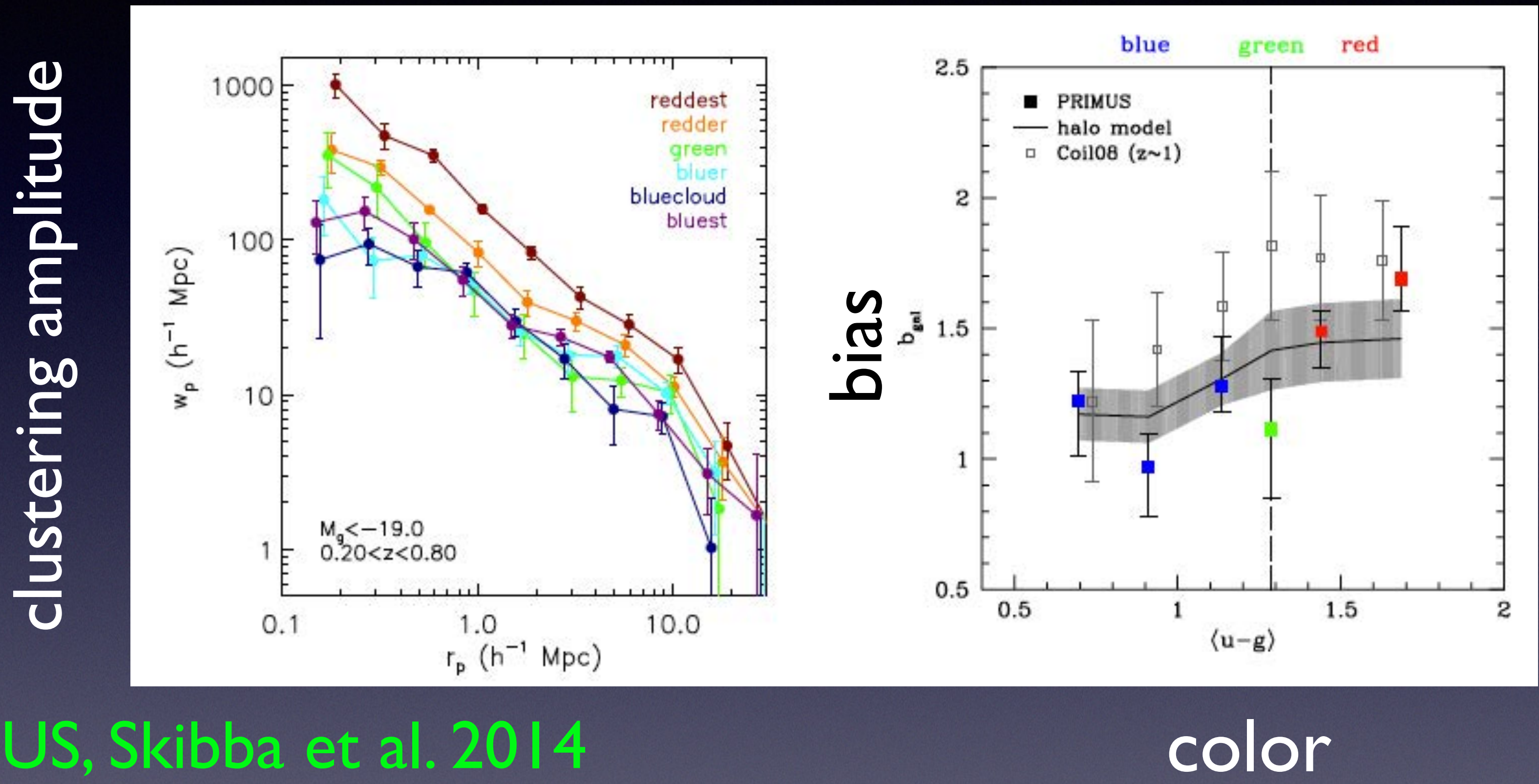
clustering amplitude



SDSS, Zehavi et al. 2011

At a given luminosity, red galaxies are much more clustered than blue galaxies. At z~0, below L* red galaxies are even more clustered! (satellites in massive groups and clusters) Dependence on color within the blue cloud alone.

Color Dependence

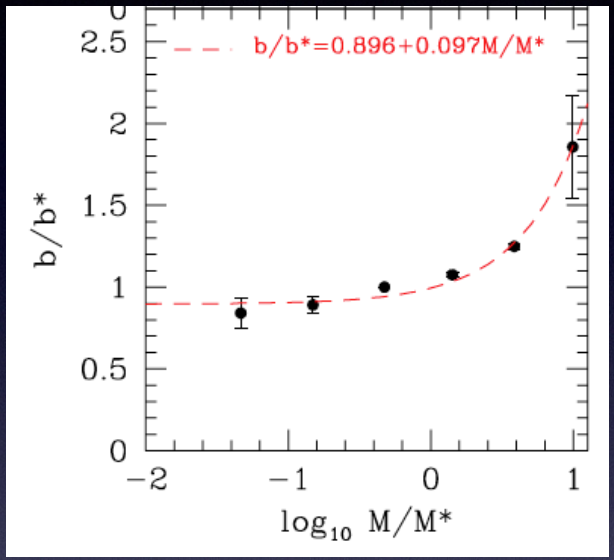


PRIMUS, Skibba et al. 2014

Even at z~1 the samples are large enough to split into finer color bins - see similar trends as at z~0, w/ larger errors.
Find just as strong of a dependence with color as with luminosity.

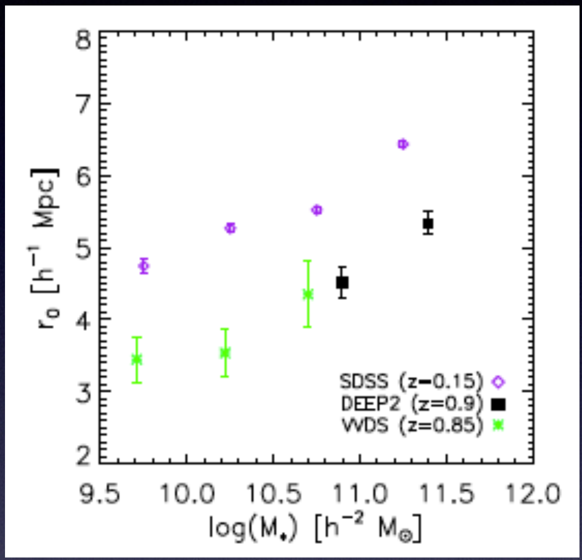
Stellar Mass Dependence

bias



stellar mass

clustering scale length



stellar mass

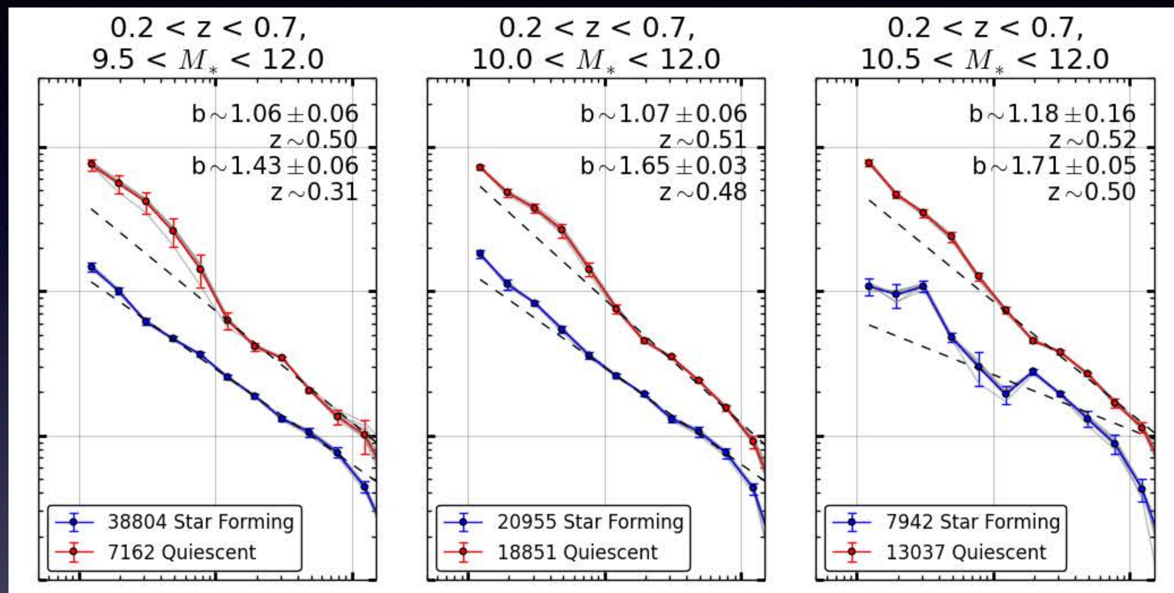
SDSS, Li et al. 2006

DEEP2, Mostek et al. 2013

See similar trend with stellar mass at both z~0 and z~1. At a given stellar mass the clustering amplitude is lower at higher z.

SFR Dependence

clustering amplitude



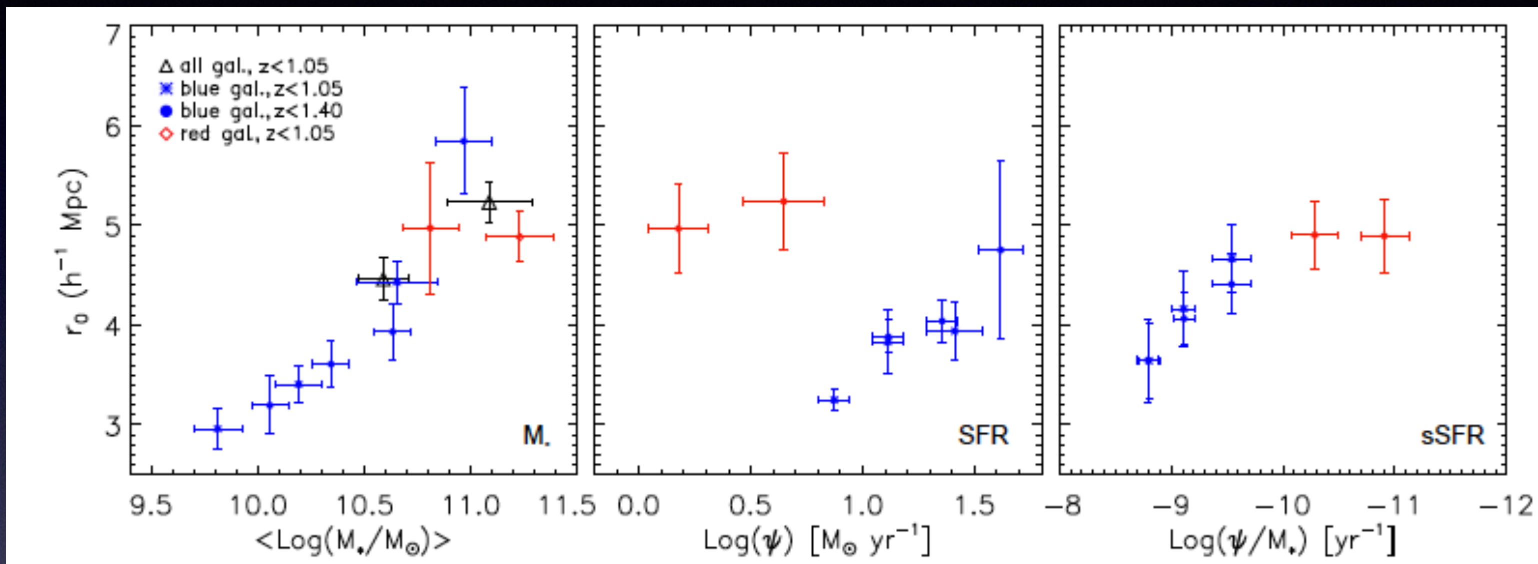
r_p

PRIMUS, Mendez et al. in prep

At a given stellar mass, quiescent galaxies are more clustered than star forming galaxies.

SFR and sSFR Dependence

scale length



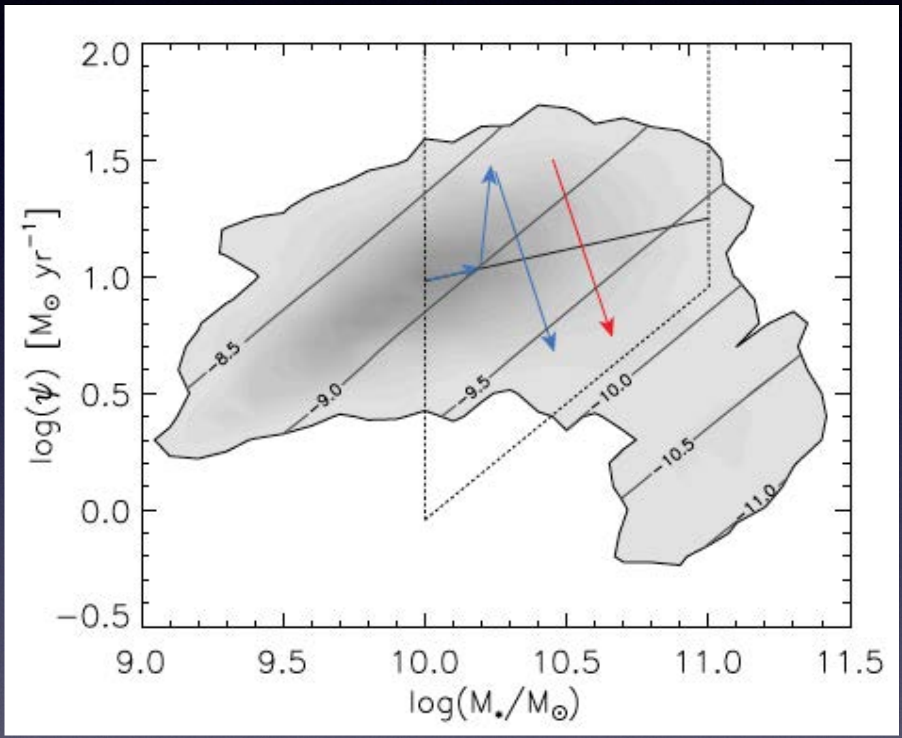
stellar mass SFR sSFR

DEEP2, Mostek et al. 2013

Not many papers measure SFR and sSFR dependence of clustering, but very worthwhile! Strong trends with both SFR and sSFR, within the SF population. With sSFR can infer an evolutionary trend, as galaxies grow and their star formation shuts down.

SFR and sSFR Dependence

SFR



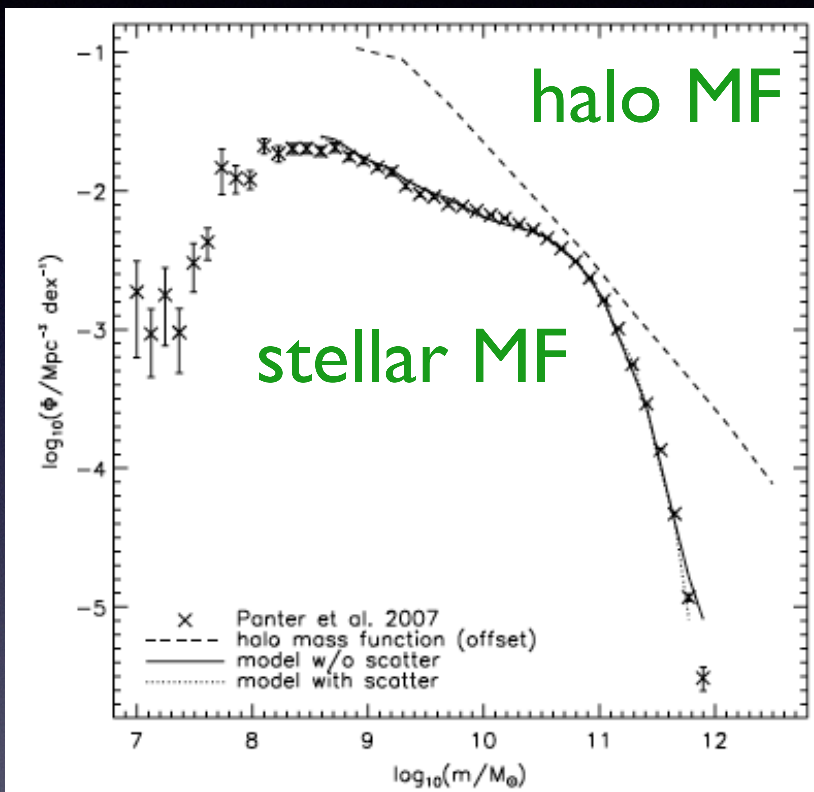
stellar mass

DEEP2, Mostek et al. 2013

Can measure clustering 'across' the main sequence of star formation - less clustered above than below.

Implies that galaxies evolve from above to below - not consistent with most evolution being along the sequence and then experiencing a brief merger stage with a high SFR before quenching.

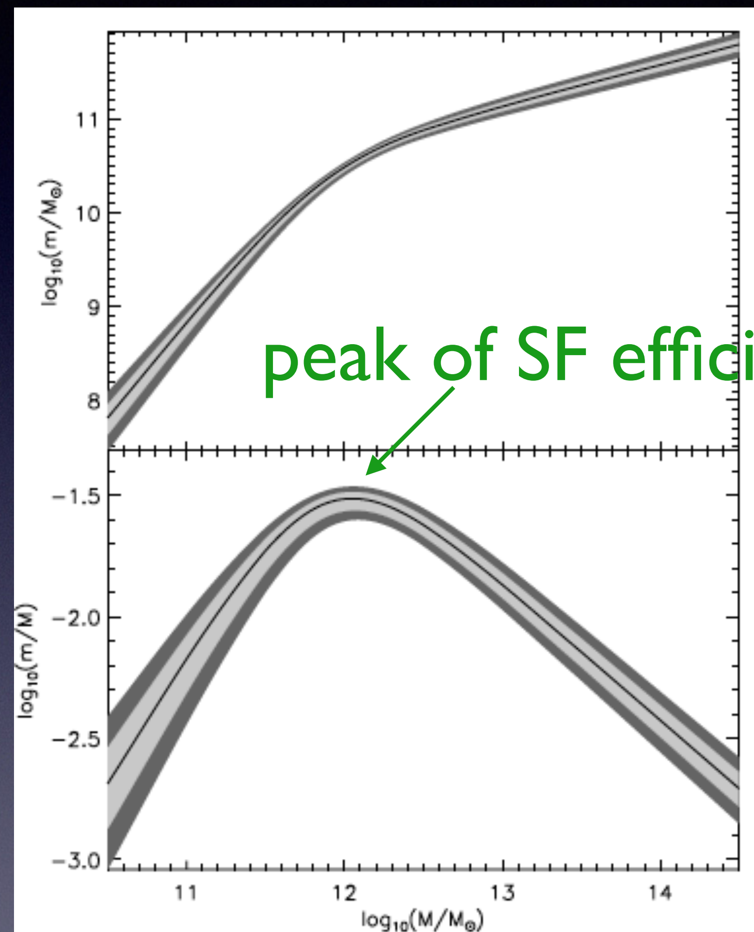
Stellar Mass - Halo Mass Relation



stellar mass

stellar mass

stellar/halo mass



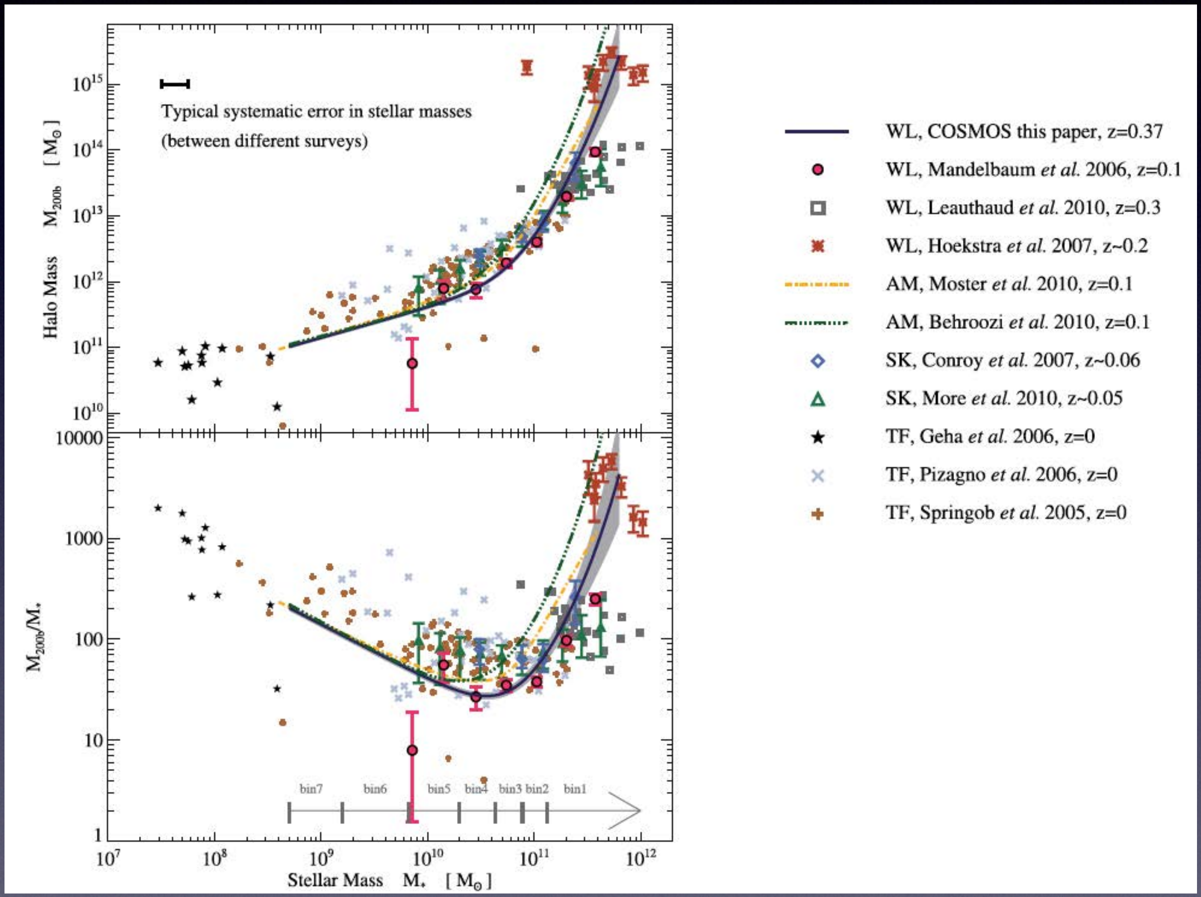
halo mass

Moster et al. 2010

Abundance matching predictions

Stellar Mass - Halo Mass Relation

halo/stellar mass   halo mass



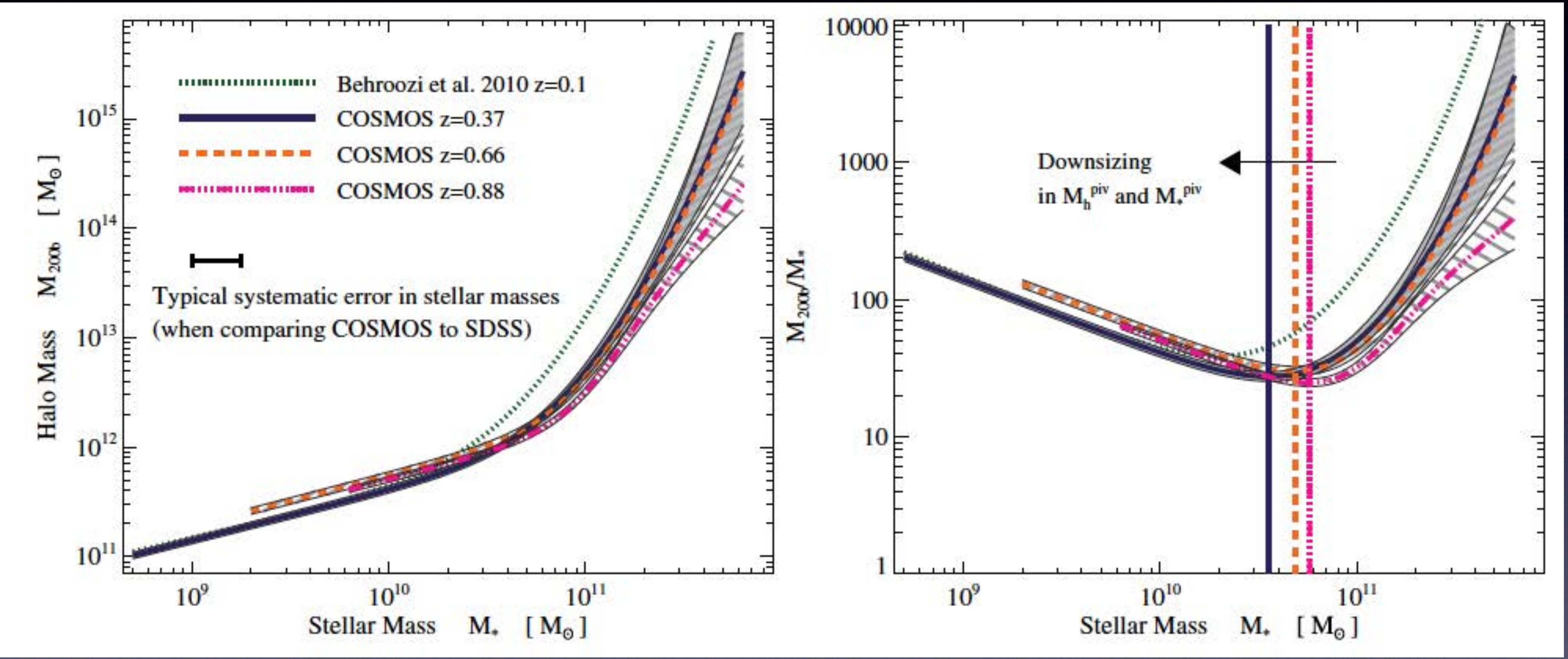
stellar mass

Using a combination of galaxy clustering, weak lensing, and number densities, can measure the stellar to halo mass relation (SHMR) to z=1.

A power law at low masses, rises sharply around log M ~10.8 - agrees fairly well with predictions.

Leauthaud et al. 2010

Stellar Mass - Halo Mass Relation



Leauthaud et al. 2010

See little evolution to z=1. Some differences with abundance matching predictions.

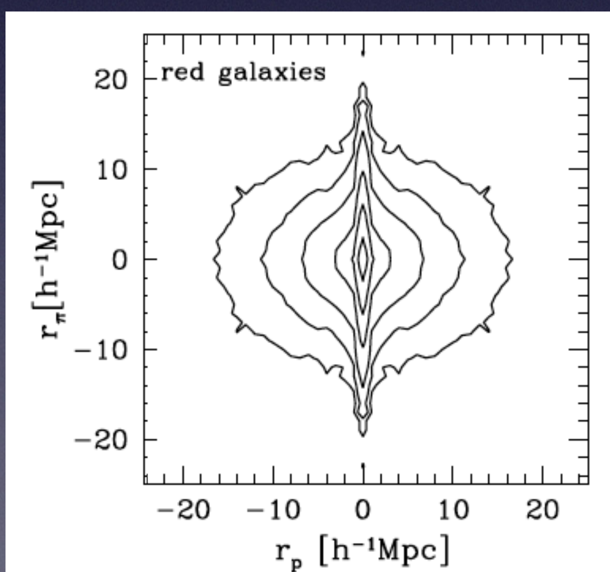
Constraining Cosmological Parameters

Redshift Space Distortions

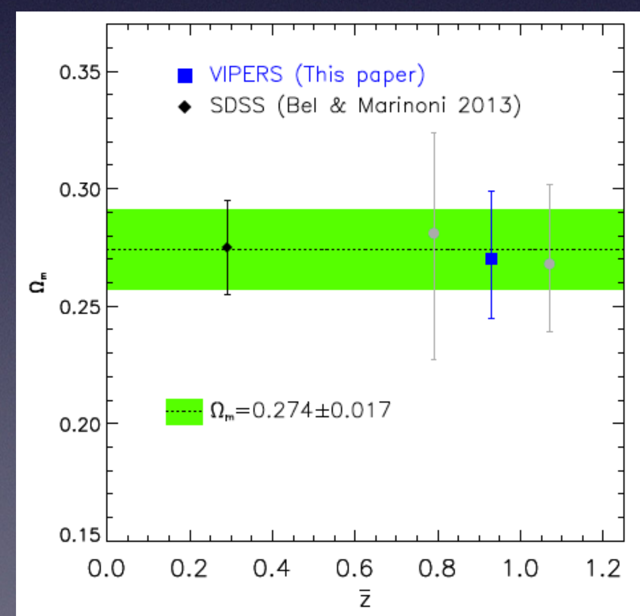
$$\xi_2/\xi_0 = f(n)\frac{\frac{4}{3}\beta + \frac{4}{7}\beta^2}{1 + \frac{2}{3}\beta + \frac{1}{5}\beta^2}$$

$$\beta = \Omega_{\mathrm{matter}}^{0.6}/b$$

From the redshift space to real space clustering ratio (independent of bias):



omega matter



Guo et al. 2014

Bel et al. 2014

Constraining Cosmological Parameters

Baryon Acoustic Oscillations

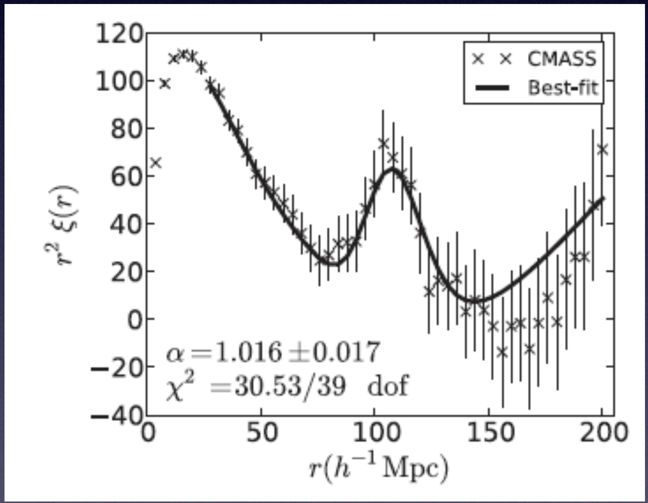
- sound waves frozen into plasma at decoupling (z~1100)
- scale is the sound horizon at last scattering
- detected as enhancement in clustering on scales ~100 Mpc/h at z=0

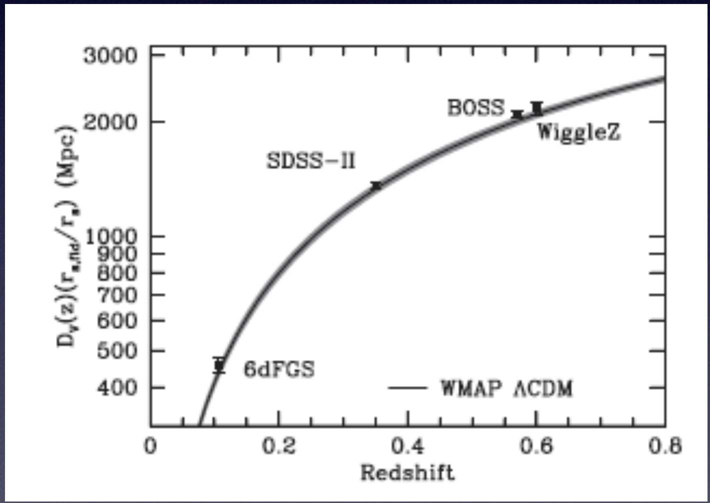
- low systematic uncertainties! mostly simple, linear physics
- small non-linear effects (<0.5%) - calibrated well

- can use any 'tracers' of large-scale structure
- want to probe large volumes, can use fairly low density tracers
- can use bright, rare sources (very bright galaxies, quasars, AGN)
- challenge is to do very large surveys to get high statistical precision
- best to use spectroscopic redshifts

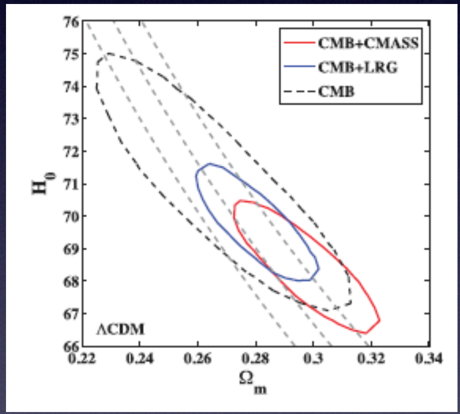
Constraining Cosmological Parameters

Baryon Acoustic Oscillations





H0

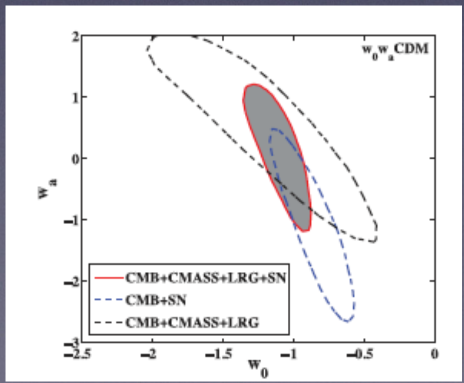


omega matter

Anderson et al. 2012

- distance-redshift plot for BAO measurements using spec-z's only

wa

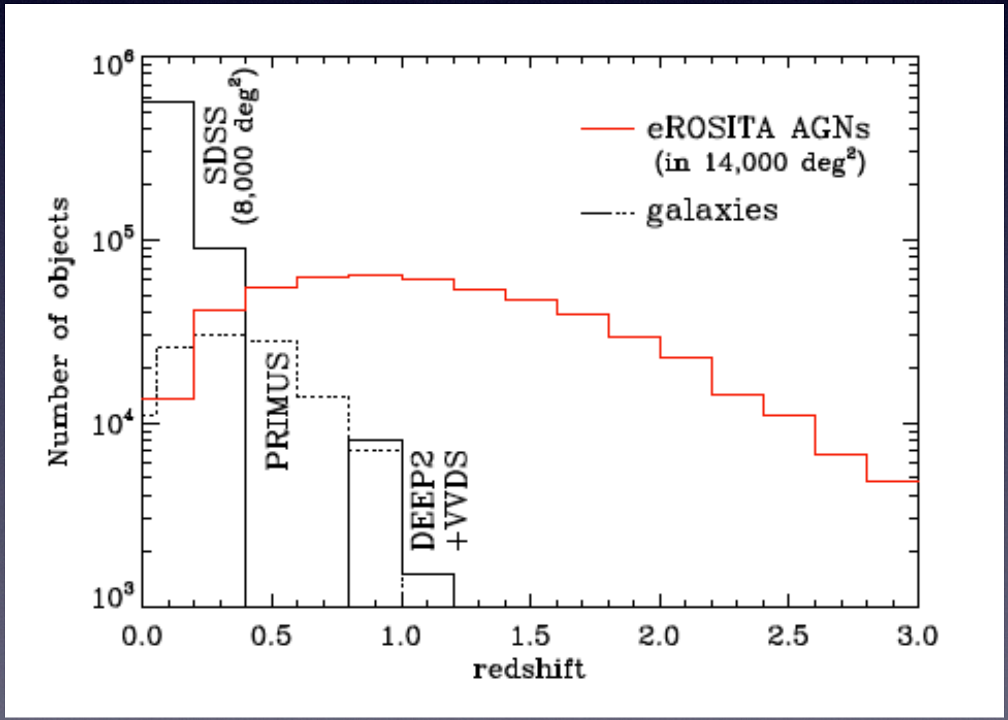


dark energy evolution: $w(a) = w_0 + (1{-}a)w_a$

w0

Constraining Cosmological Parameters

Baryon Acoustic Oscillations



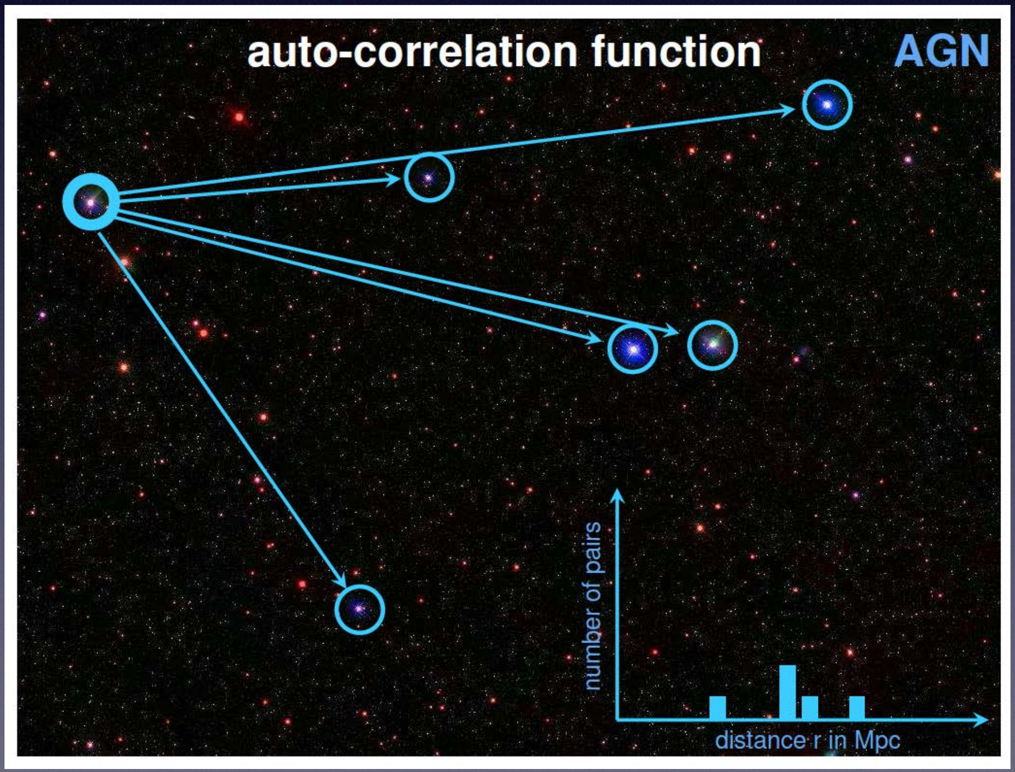
Future surveys: eROSITA

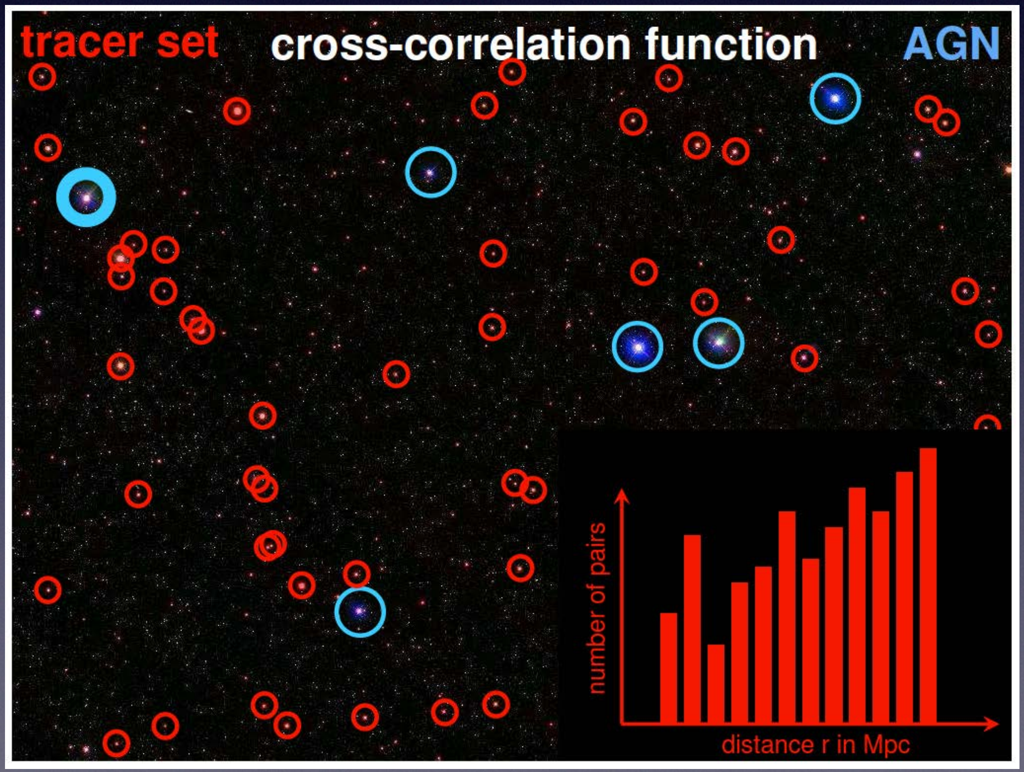
- expected AGN with spec-z's from 4MOST over 14,000 sq. deg.
- expect ~3σ BAO detection with AGN alone!

Krumpe et al. 2013

Galaxy-AGN Cross-Correlations

What is it?





Galaxy-AGN Cross-Correlations

Why is this useful?

The main benefit is smaller errors than with AGN auto-correlation function, as the galaxy sample is much larger, so you're not dominated by Poisson statistics.

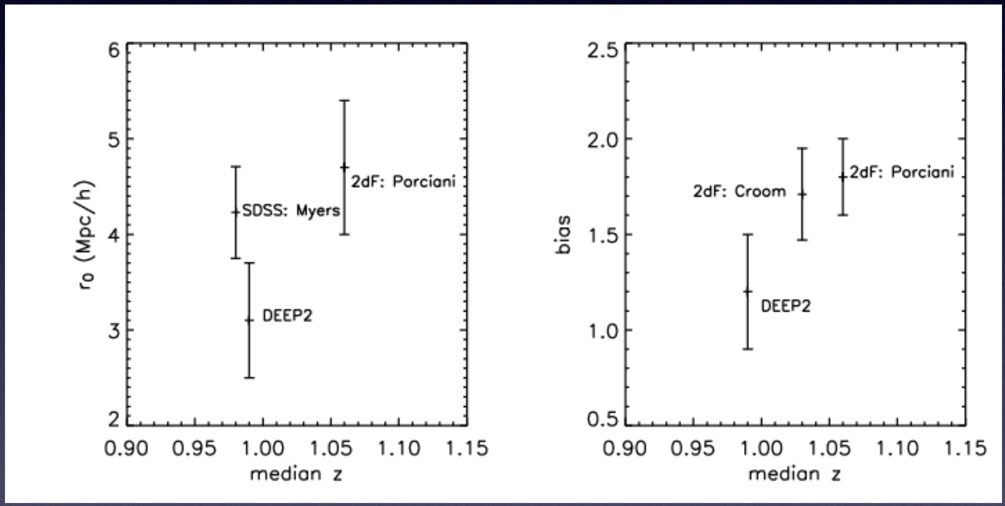
These smaller errors in turn allow you to split your AGN sample into bins (redshift, luminosity, hardness ratio, etc.).

A nice benefit is that you don't need to know the spatial selection function for the AGN, just the galaxies!

Galaxy-AGN Cross-Correlations

Why is this useful?

scale length



redshift

Coil et al. 2007

Example: Quasar clustering in DEEP2 using ~50 quasars compared to SDSS and 2dF using ~1000's quasars. The DEEP2 measurement was done using the cross-correlation function with 10,000s galaxy redshifts. Very similar error bars!

Galaxy-AGN Cross-Correlations

How do you measure it?

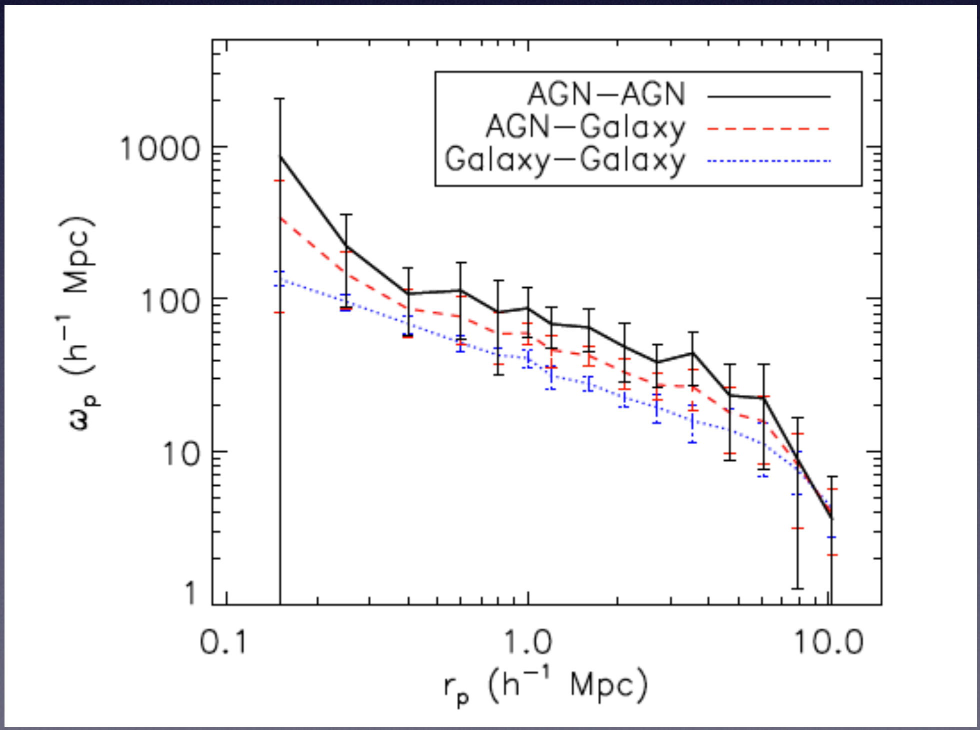
$$\xi(r) = \frac{AG(r)}{AR(r)} - 1$$

- Counts of AGN-galaxy pairs, as a function of separation, relative to counts of AGN-random points.
- The random matches the galaxy sample, not the AGN sample.
- Galaxy sample does not have to be volume-limited! Can use all the galaxies you have, doesn't matter how biased they are.

Galaxy-AGN Cross-Correlations

How do you measure it?

Then back out the AGN auto-correlation function:



$$w_{\mathrm{AA}}(r_p) = \frac{w^2_{\mathrm{AG}}(r_p)}{w_{\mathrm{GG}}(r_p)}$$

Coil et al. 2009

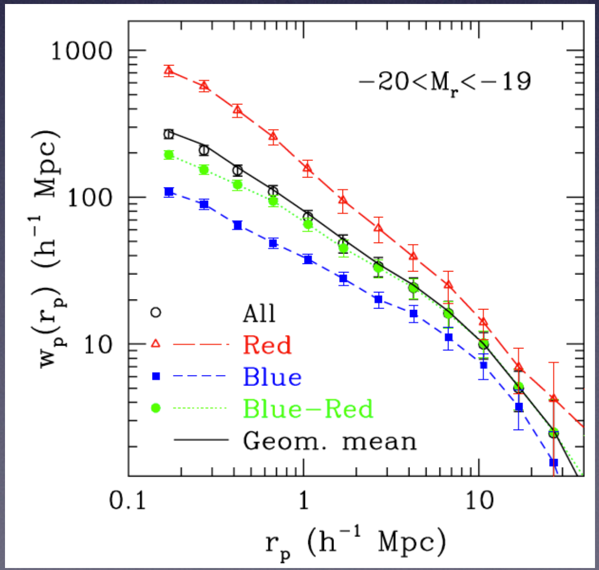
Galaxy-AGN Cross-Correlations

What are the limitations?

You need a lot of galaxy redshifts! Works well out to z~1.5 for now, need larger galaxy samples at higher z.

The technique relies on galaxy and AGN samples being well mixed spatially. This should be fine, as AGN and galaxies occupy the same halos.

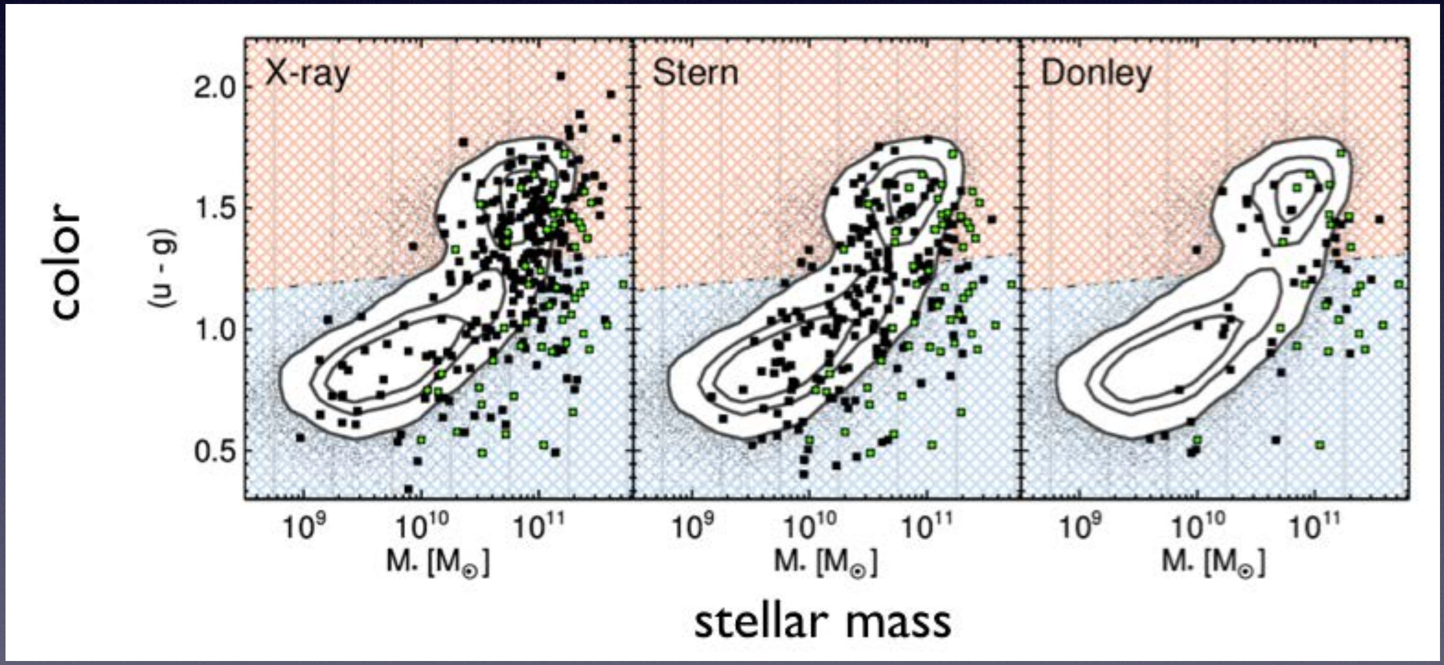
Works well for red and blue galaxies at r > 1 Mpc/h, which are not as well mixed within halos as galaxies and AGN:



Zehavi et al. 2011

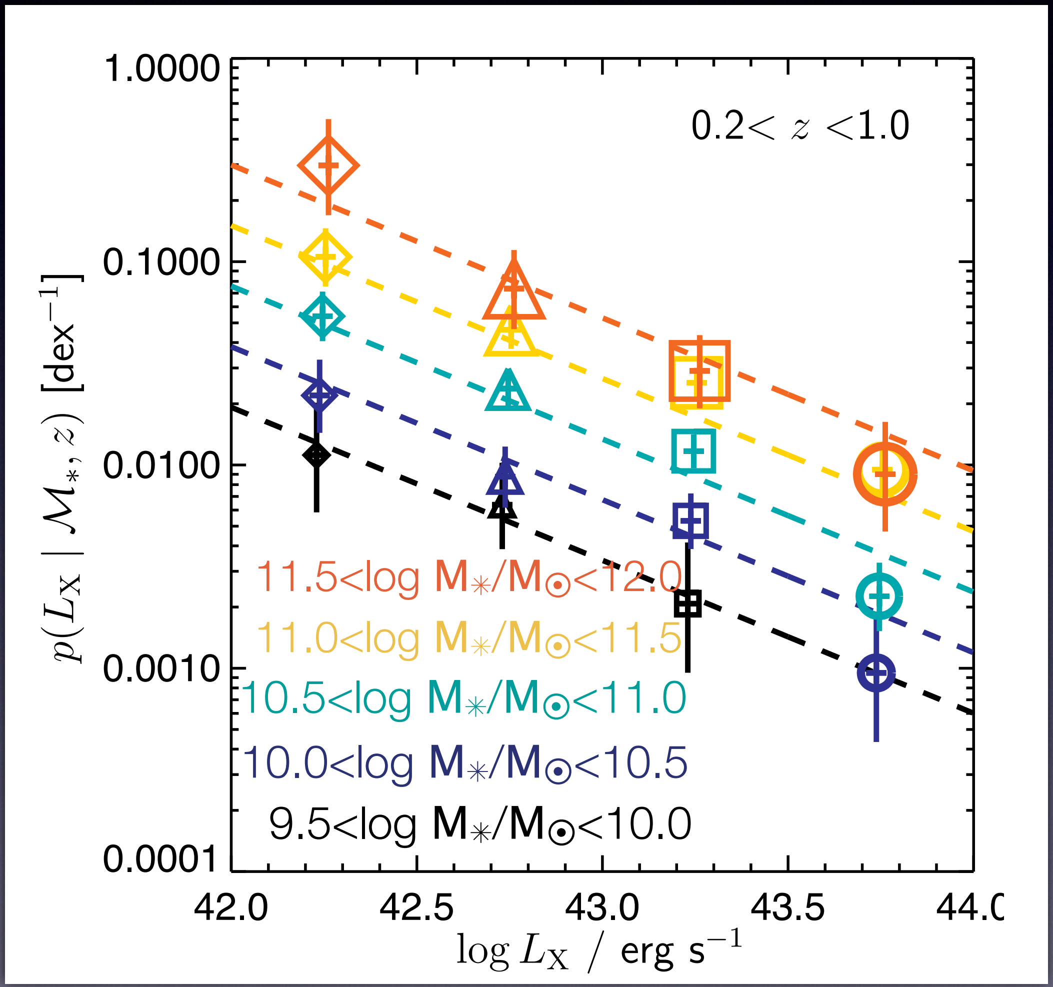
Interpreting AGN Clustering

We don't detect all AGN!



PRIMUS, Mendez et al. 2013

Interpreting AGN Clustering



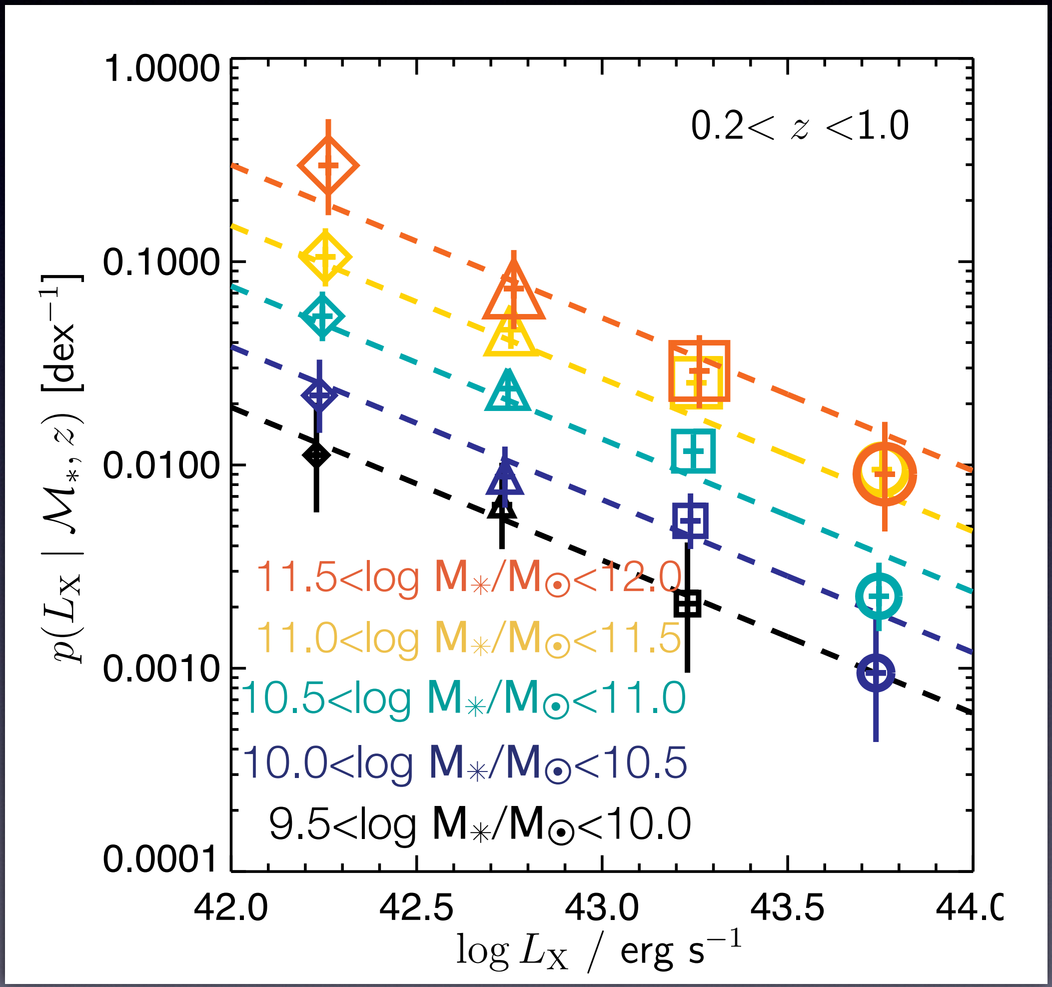
L_X

At a given L_X, the probability of a galaxy hosting an AGN is higher for more massive host galaxies.

The shape of the L_X distribution is independent of host galaxy stellar mass.

Aird et al. 2011

Interpreting AGN Clustering



L_X - accretion rate

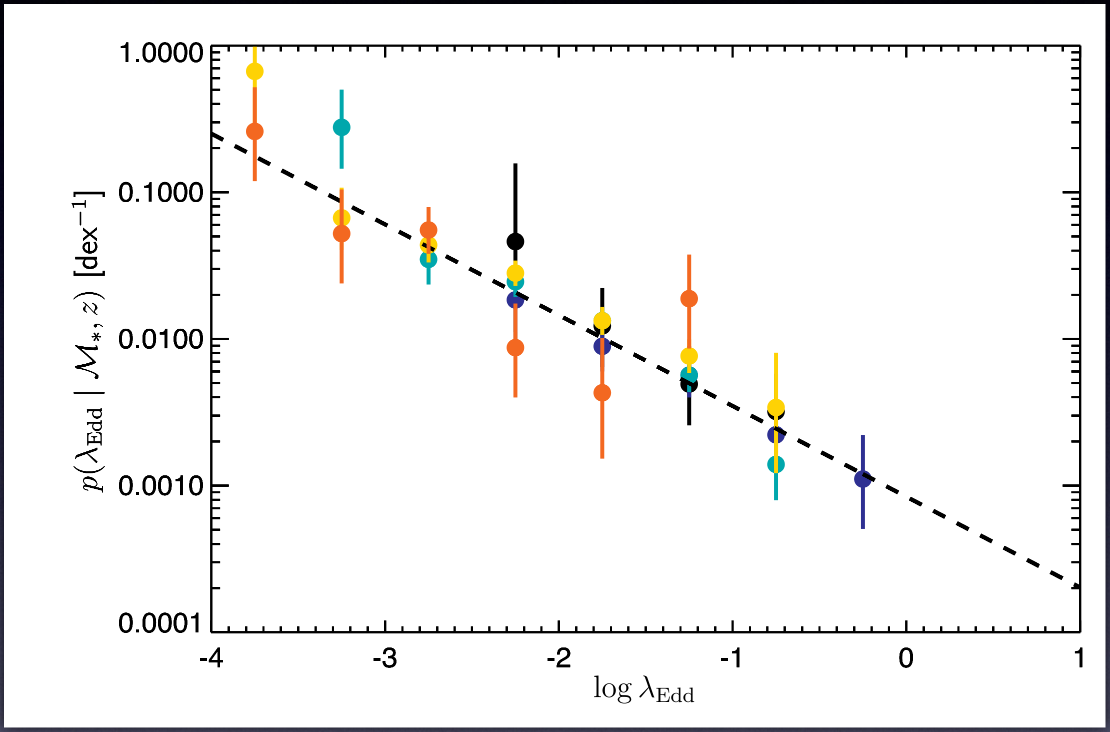
Massive galaxies are more likely to host an AGN of a given L_X.

But more massive galaxies host more massive AGN!

The rise with stellar mass simply reflects that more massive AGN *are easier to detect.*

Aird et al. 2011

Interpreting AGN Clustering



specific accretion rate (~Eddington ratio)

When plot probability as a function of L_X/stellar mass (~L_{bol}/L_{Edd},) the stellar mass dependence disappears!

There is a *single* Eddington ratio distribution that does not depend on stellar mass (normalization depends on redshift and SFR).

AGN are *not* predominantly in massive galaxies - selection effect driven by the Eddington ratio distribution.
The incidence of AGN is independent of stellar mass!

Interpreting AGN Clustering

What this means is that you can't interpret the observed clustering of AGN as the clustering of 'all' AGN. It is the clustering of the detected AGN, down to the flux limit of your sample.

There is always a strong stellar mass bias!

Hard to compare with theoretical models, unless they also put a 'flux limit' in their simulations (X-ray or optical for spectroscopic follow-up). Or match the stellar mass distribution of hosts.

Have to be very careful with how you interpret measurements of AGN clustering!

Interpreting AGN Clustering

How to address this? Whenever possible, compare the clustering of your AGN sample to a "matched" galaxy sample, with the same distribution of:

redshift

stellar mass

SFR

(or luminosity and color)

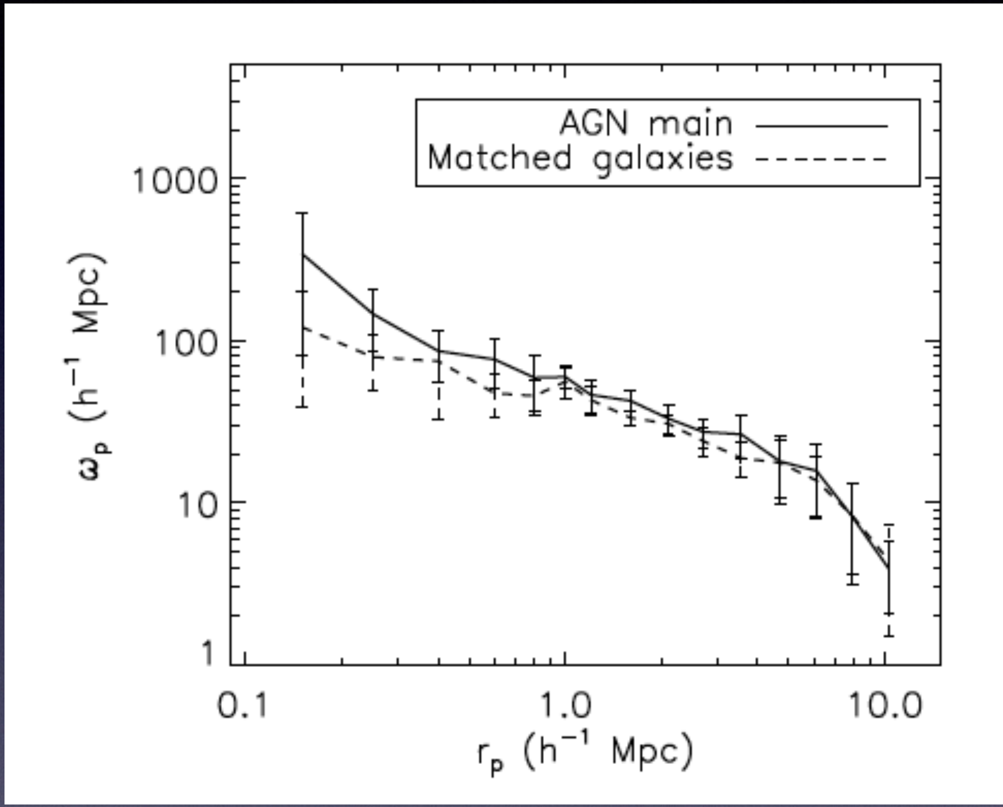
Then you can answer the question: for the distribution of galaxy types that host the kind of AGN observed, are those galaxies with observed AGN more or less clustered than those galaxies without observed AGN?

Interpreting AGN Clustering

The relevant questions become:

- Which galaxies host AGN?
- Is there anything special about the large-scale environment of a galaxy that impacts whether it has an AGN?
  - Are mergers required to trigger AGN?
  - Can secular processes trigger AGN? If so, at what level?
- How do we understand the AGN zoo of clustering measurements in terms of galaxy clustering?

Using Matched Galaxy Samples

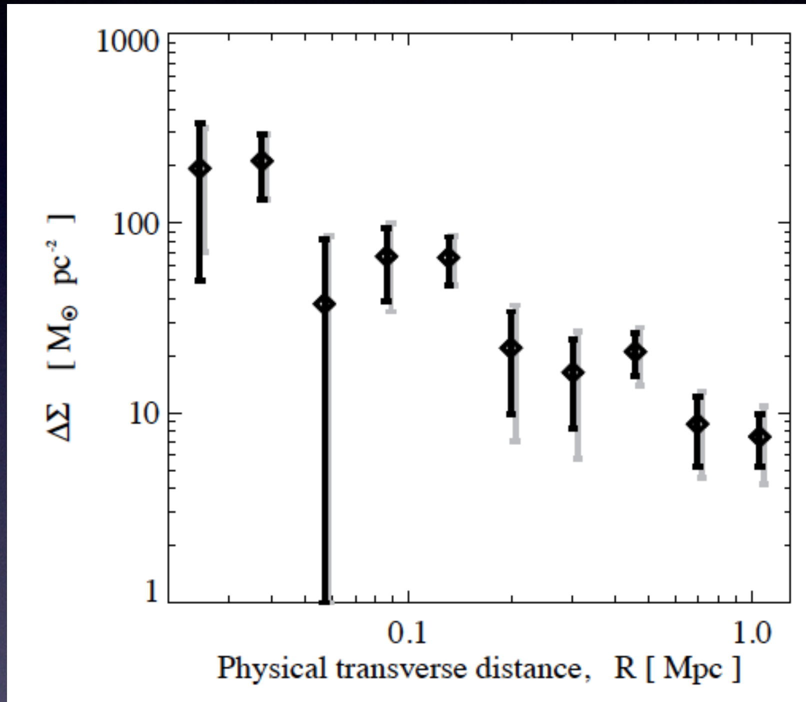


Coil et al. 2009

DEEP2: compared X-ray AGN clustering to matched luminosity, color, and redshift galaxy sample. Found that AGN were a more clustered than matched galaxies.

Using Matched Galaxy Samples

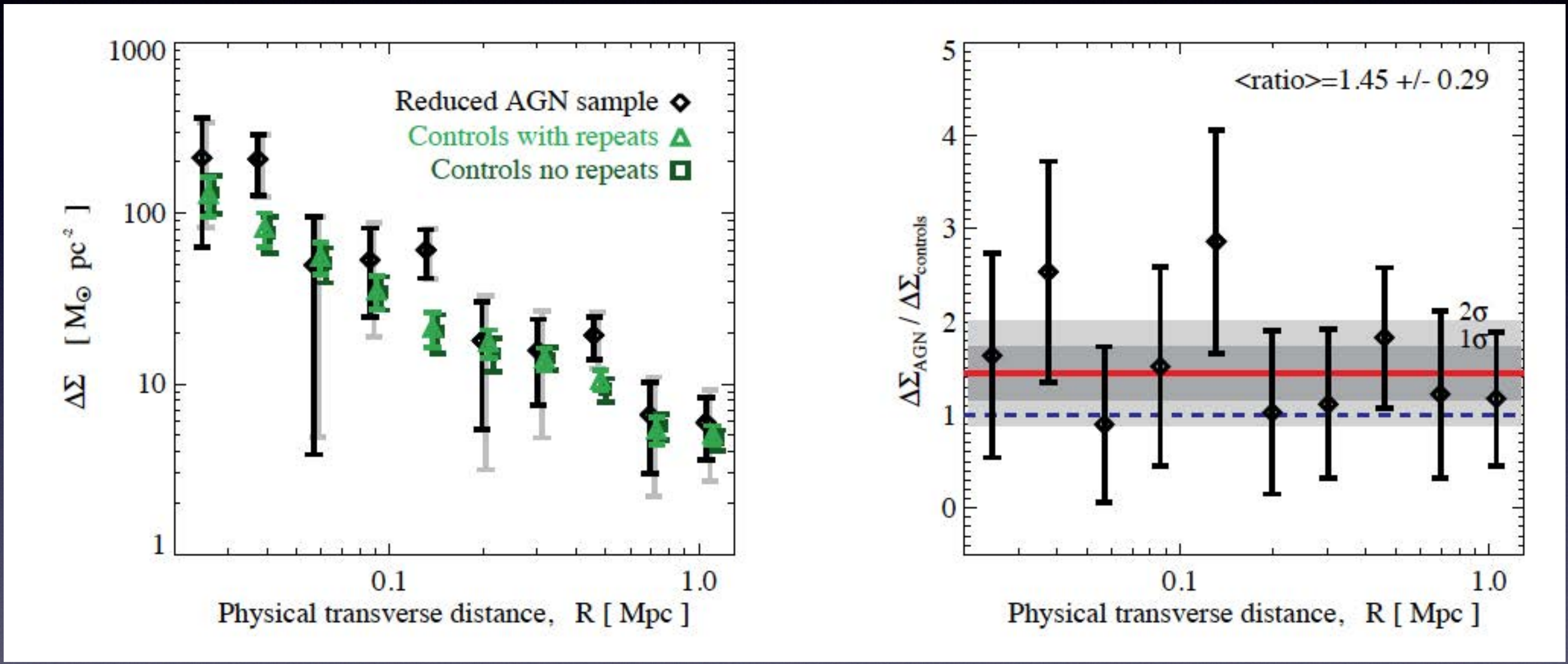
lensing signal



Leauthaud in prep.

Weak lensing measurement of X-ray AGN (with log stellar mass >10.5) in COSMOS — similar to clustering, but smaller scales. How to interpret this signal?

Using Matched Galaxy Samples

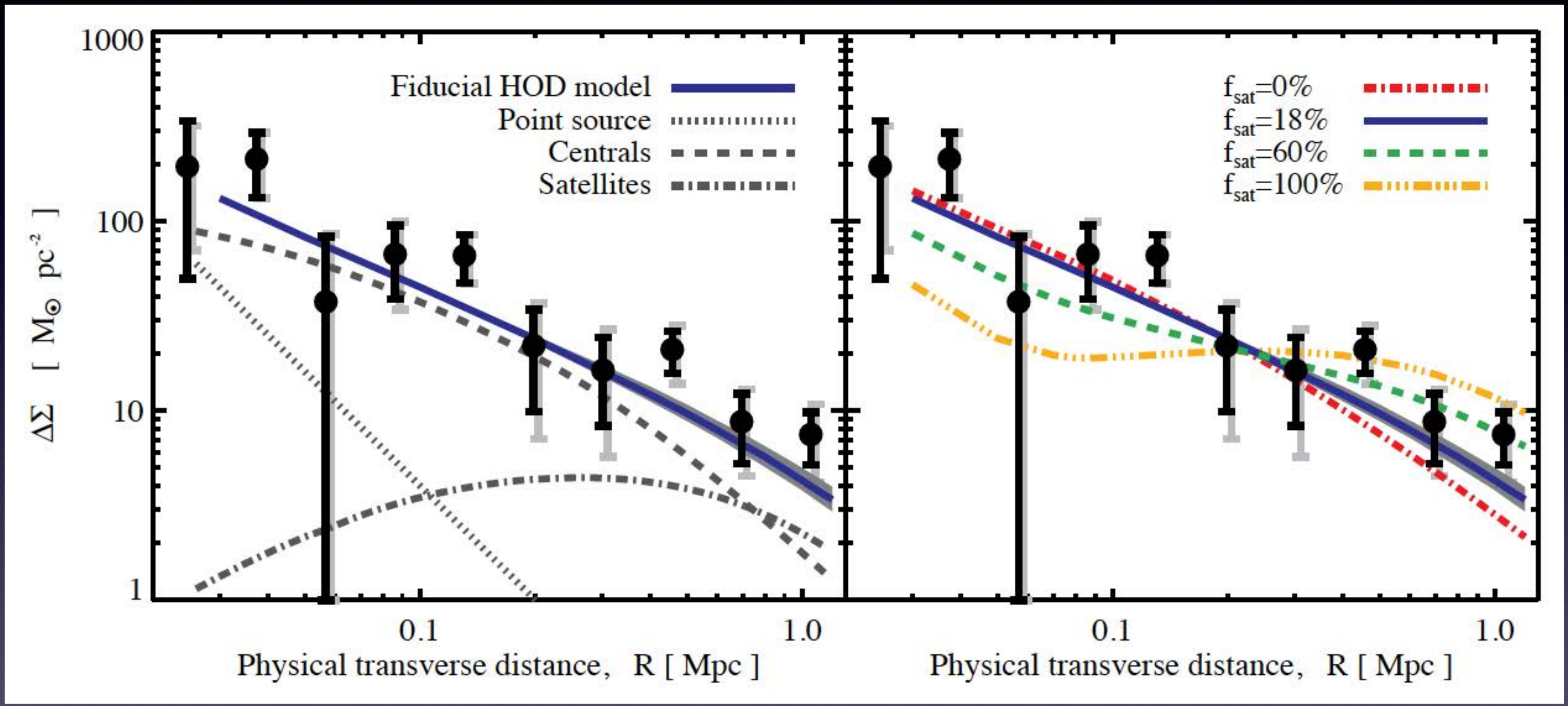


Leauthaud in prep.

Compare to a stellar mass and redshift matched galaxy 'control' sample - see consistent lensing signal.

Using Matched Galaxy Samples

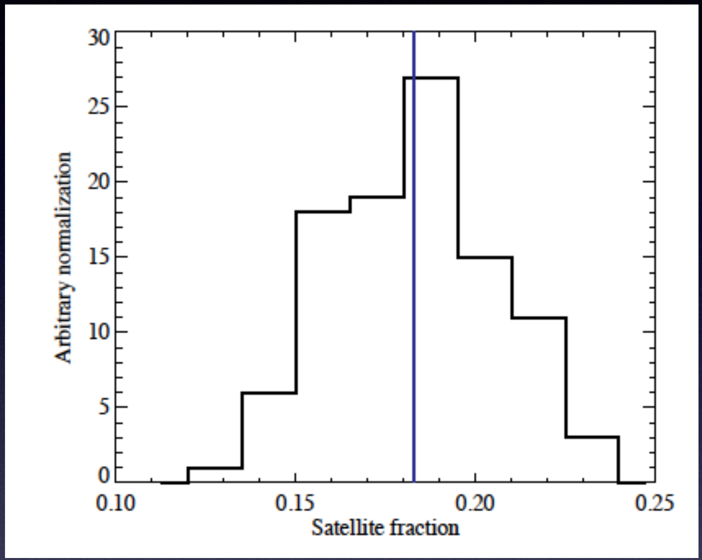
lensing signal



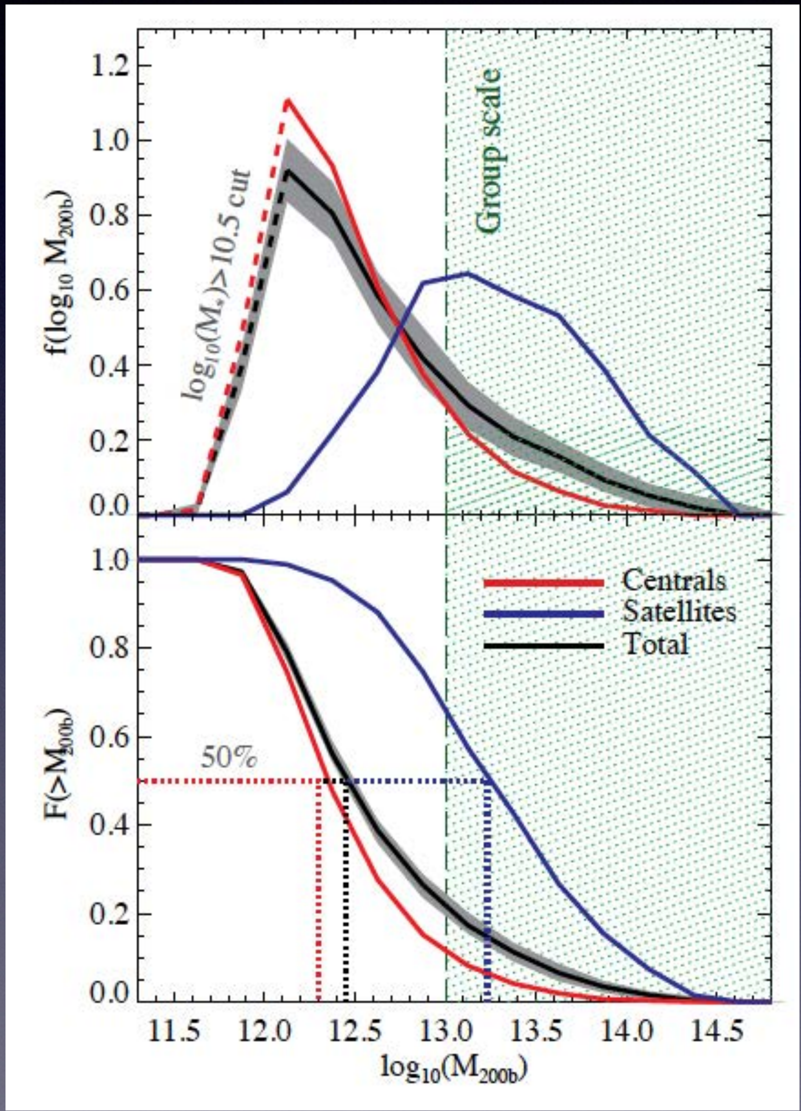
Leauthaud in prep.

Can compare with prediction from previously-derived SHMR, for the stellar mass distribution of the X-ray AGN hosts. Can also constrain the satellite fraction.

Using Matched Galaxy Samples



halo mass prob. function



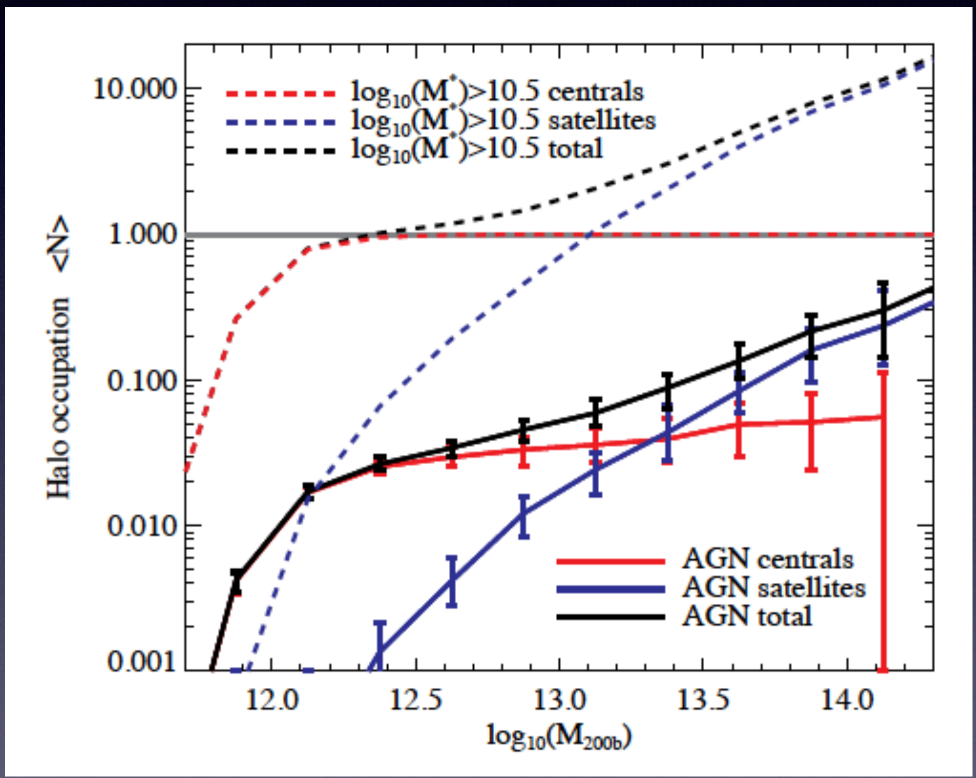
cumulative halo mass function

Leauthaud in prep.

Can constrain the satellite fraction (18%) and determine the halo mass distribution (for centrals and satellites separately).

Using Matched Galaxy Samples

halo occupation



halo mass

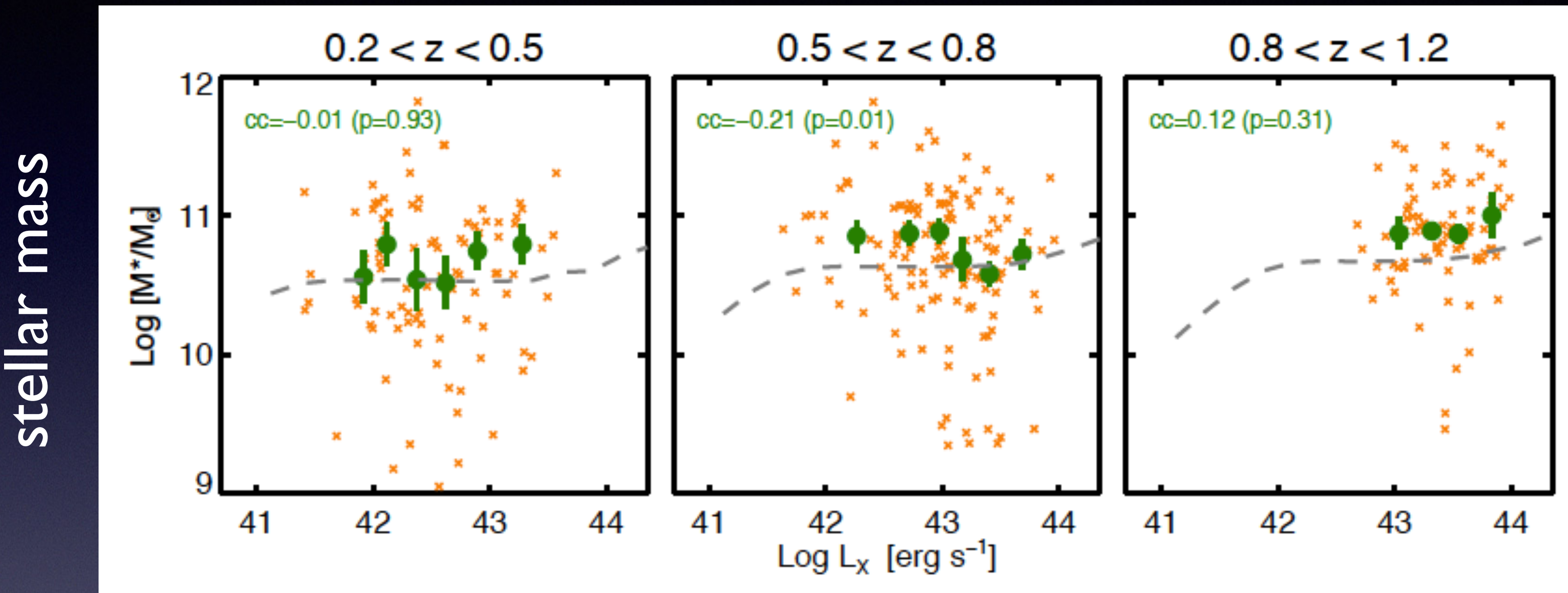
Leauthaud in prep.

Can also measure the HOD *of this AGN sample* (with the associated stellar mass and flux limits).

Very powerful technique, but need host galaxy stellar masses and to determine the SHMR first.

Ideally also want to use a SHMR for star forming and quiescent galaxies, separately.

Lack of Correlation b/w Stellar Mass and L_X



PRIMUS, Azadi in al. (2014)

Narrow line hard band X-ray AGN show no correlation between host stellar mass and L_X at intermediate redshift, for 41< log L_X <44. Dashed line from Aird et al. (2012) uses observed stellar mass function + Eddington ratio distribution.

Take Home Points

- Understanding galaxy clustering is not only useful but necessary for understanding AGN clustering.

- AGN-galaxy cross-correlation functions are a fantastic tool for measuring AGN clustering with relatively small error bars.

- Have to be very careful with how you interpret measurements of AGN clustering! There is always a bias towards high stellar mass in observed AGN samples (at least for low to moderate luminosity AGN).

- Best to compare AGN clustering with matched galaxy samples when possible, to aid interpretation - ideally match in redshift, stellar mass, and SFR.