AGN Clustering and Environment Results

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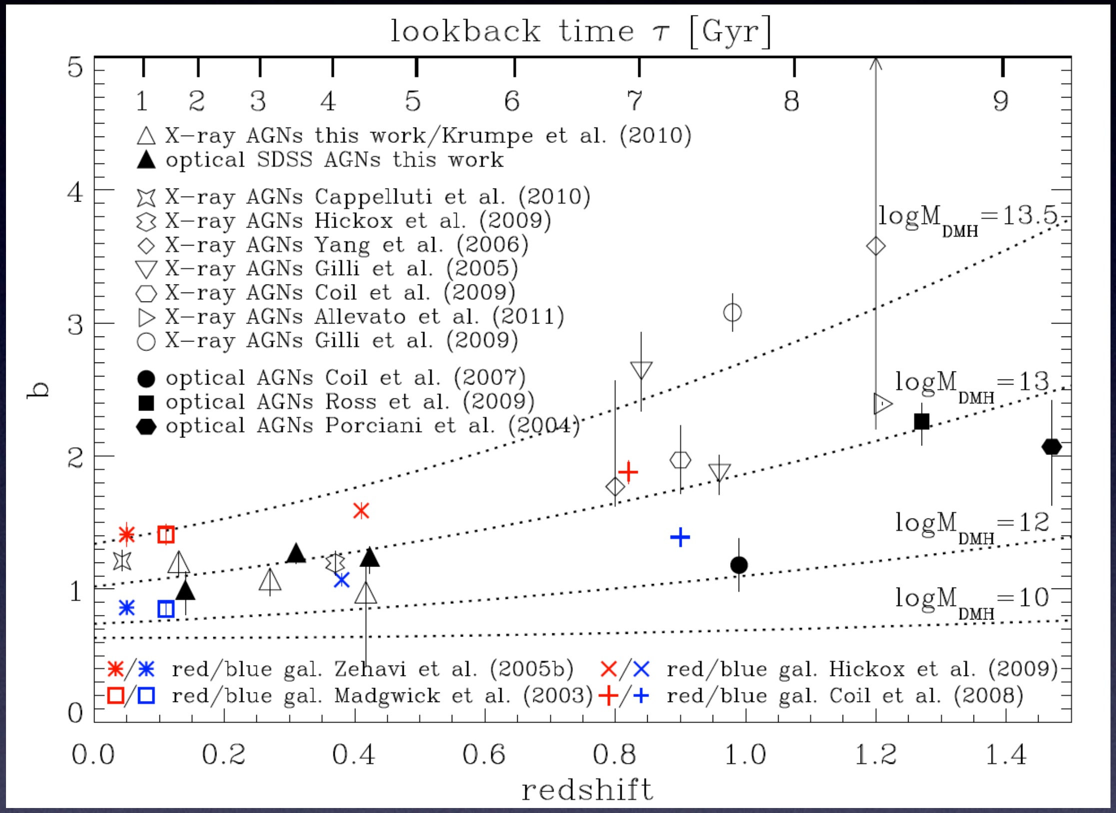
AGN Clustering Results

AGN clustering papers generally find that AGN are in dark matter halos of log M~12.5-13.5 and conclude that AGN are in group environments.

bias



redshift

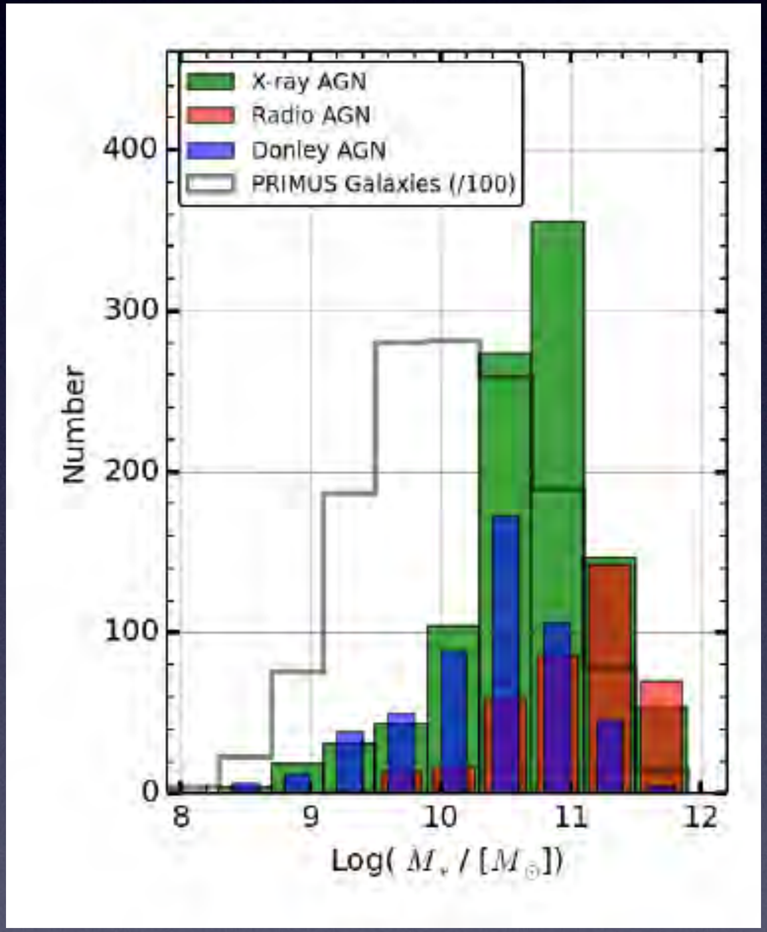
Do this by measuring the two-point correlation function and comparing with a dark matter simulation, identifying dark matter halos of a given mass with the same clustering amplitude.

Interpretations of this often ignore AGN selection effects.

AGN Selection Biases

All AGN selection techniques have biases:

number



stellar mass

PRIMUS survey

galaxies

X-ray AGN

IR AGN

radio AGN

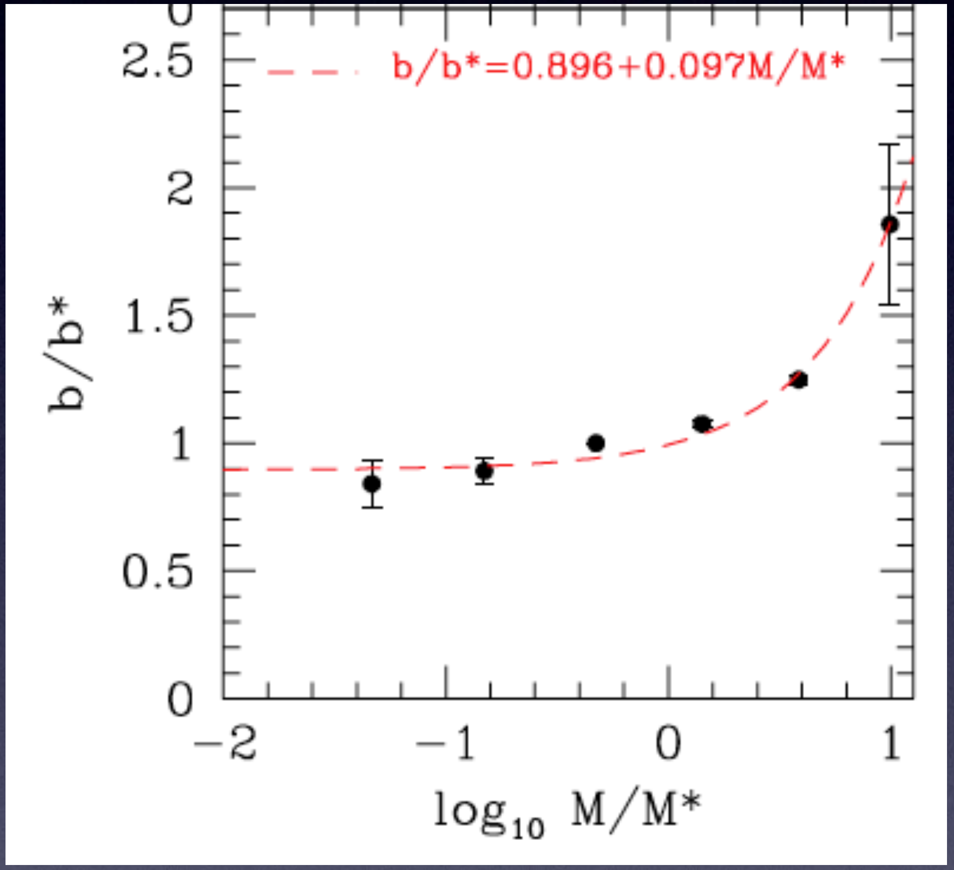
Mendez, Coil et al. 2016

AGN are easier to identify in higher mass galaxies.

Galaxy Clustering

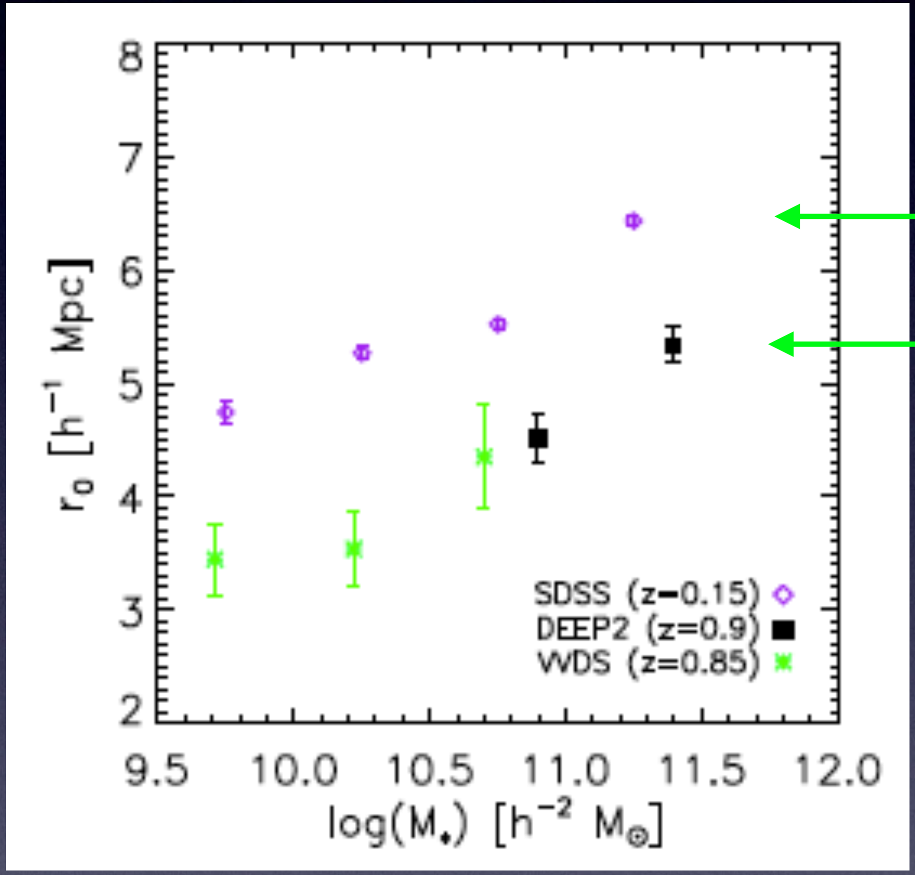
Clustering depends on galaxy stellar mass

bias



stellar mass

clustering scale length



SDSS

DEEP2/ VVDS

stellar mass

SDSS, Li et al. 2006

DEEP2, Mostek et al. 2013

Similar trend with stellar mass at both z~0 and z~1.

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 that sample.

There are AGN in lower mass / less clustered galaxies as well, just harder to see them (ie, Aird et al. 2012, 2018).

Difficult to compare with theoretical models, unless models also put a 'flux limit' in their simulations. Or match the stellar mass and ideally SFR distribution of AGN hosts.

Have to be very careful with how you interpret measurements of AGN clustering! Don't over-interpret to mean that those environments trigger AGN activity.

AGN Selection Biases

All AGN selection techniques have biases:

PRIMUS survey

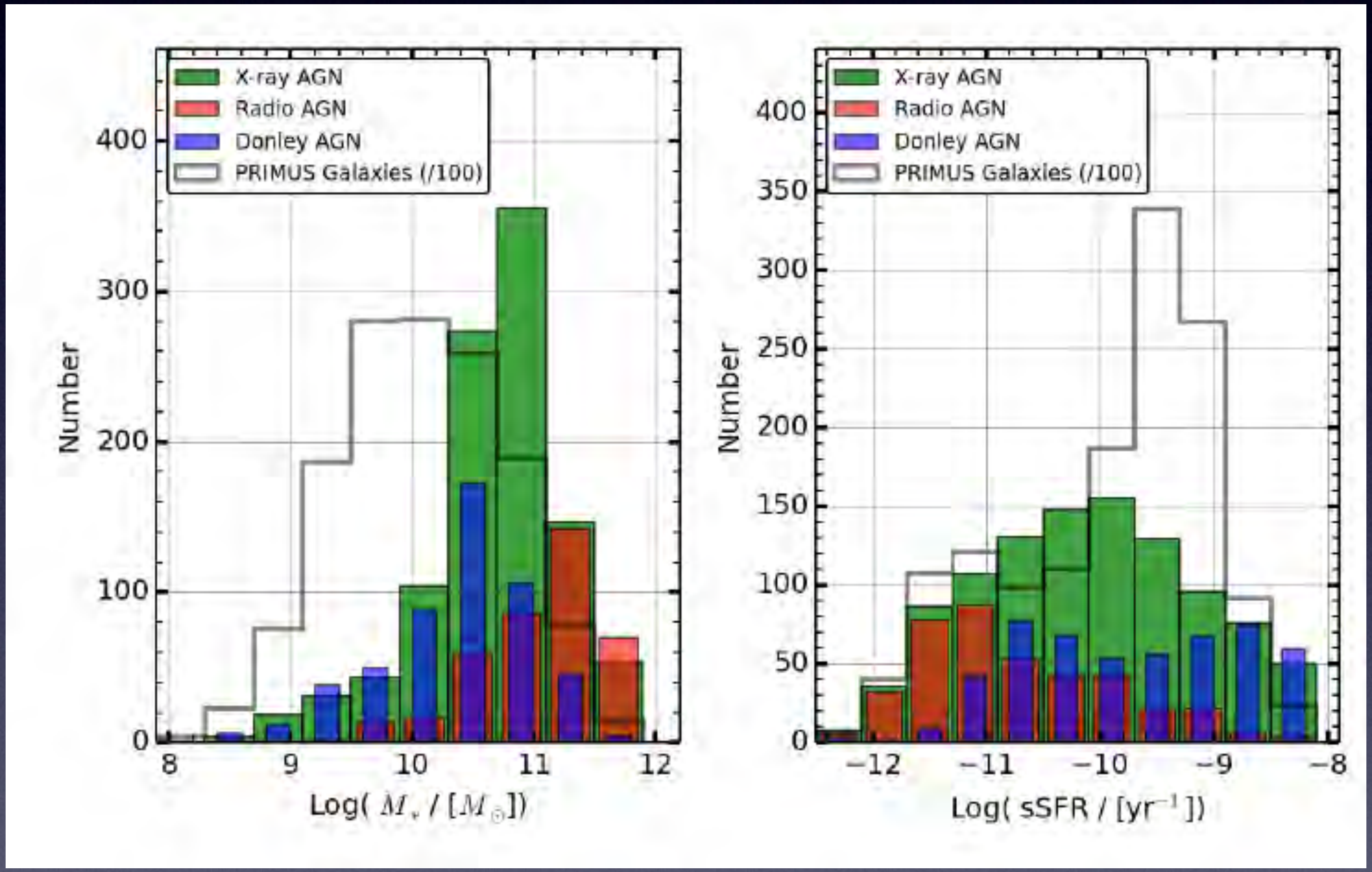
galaxies

X-ray AGN

IR AGN

radio AGN

number



stellar mass

sSFR

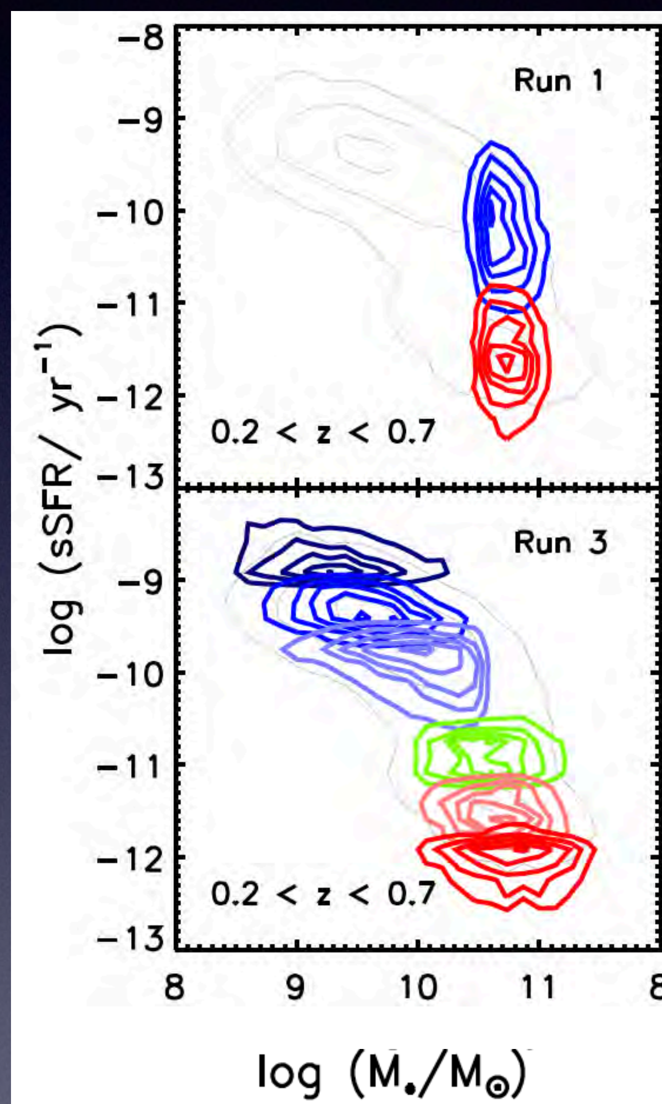
Mendez, Coil et al. 2016

There are additional selection biases with SFR for AGN identification at different wavelengths! X-ray is the least biased.

Galaxy Clustering

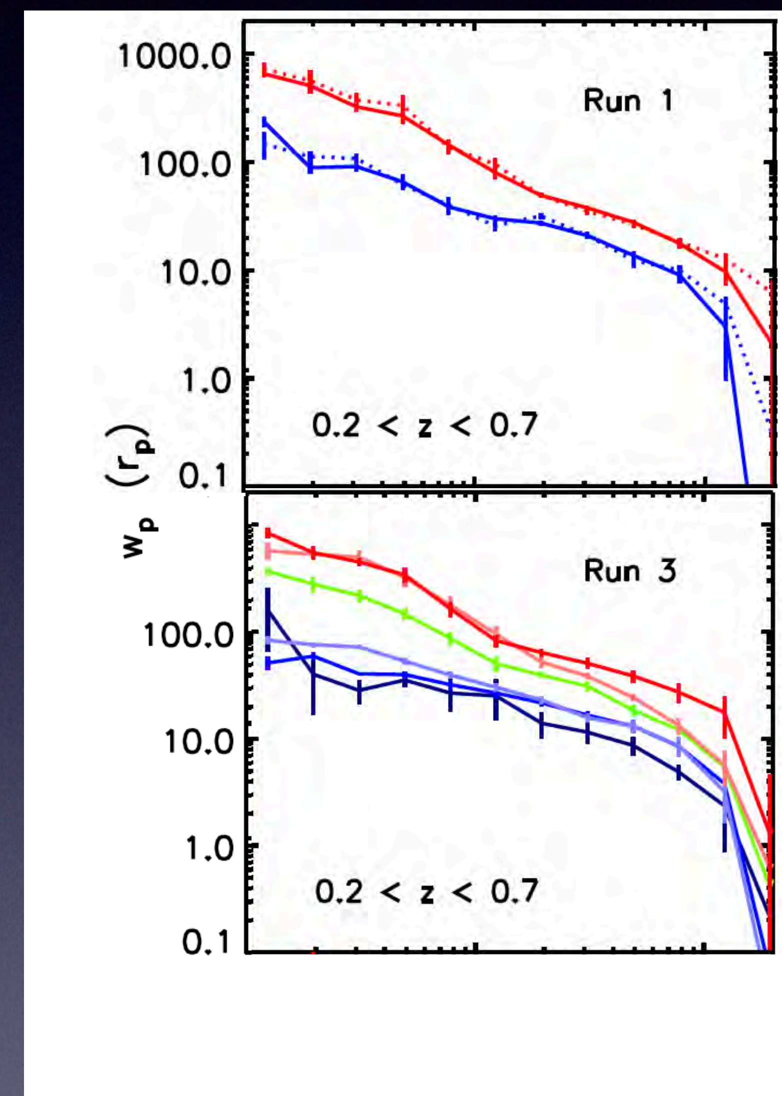
Clustering also depends on galaxy SFR

galaxy specific SFR



galaxy stellar mass

clustering strength



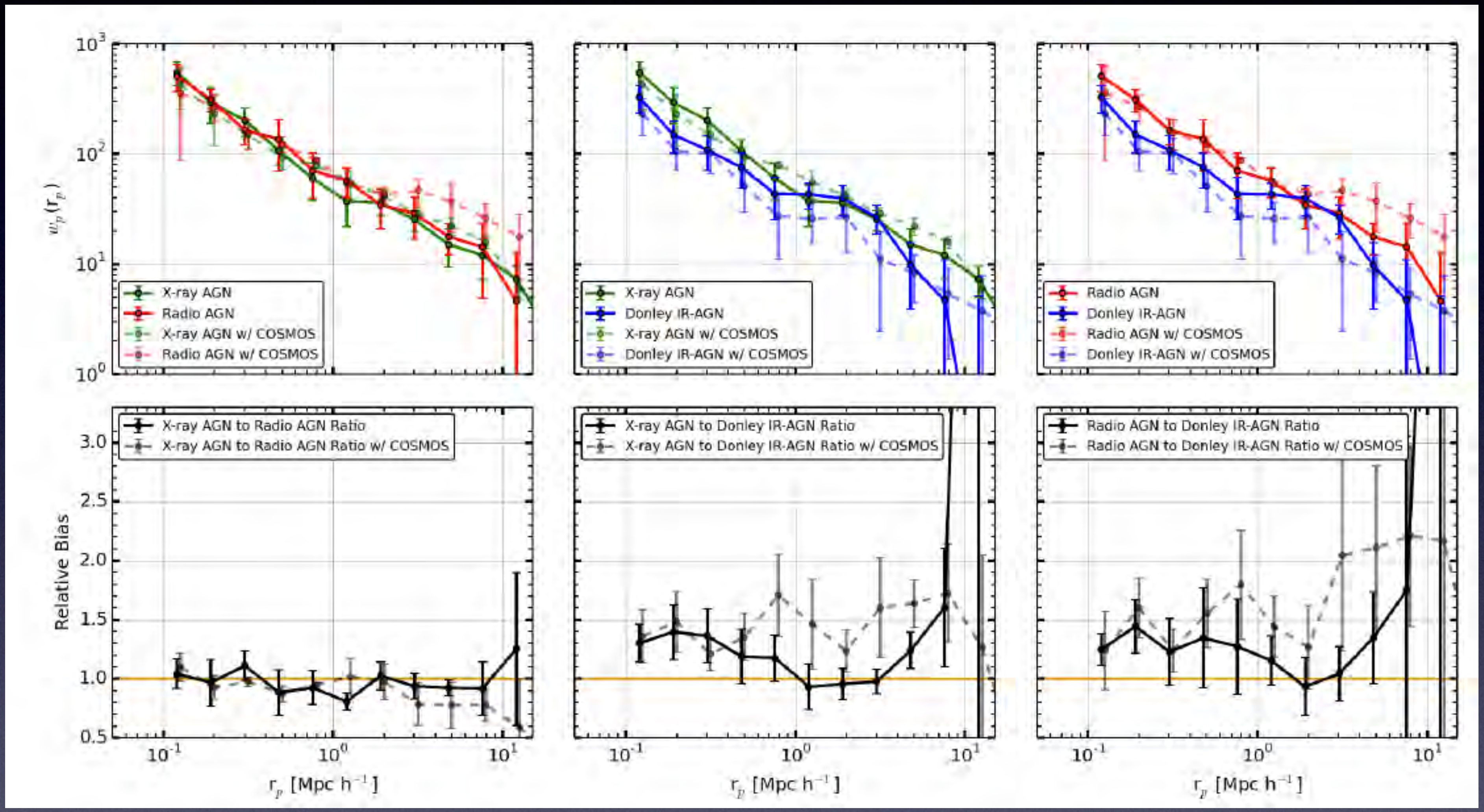
galaxy separation

PRIMUS, Coil et al. 2017

Clustering Dependence on AGN Wavelength

2-pt corr. fnct.

relative bias



radio
IR
X-ray

Mendez, Coil et al. 2016

galaxy separation

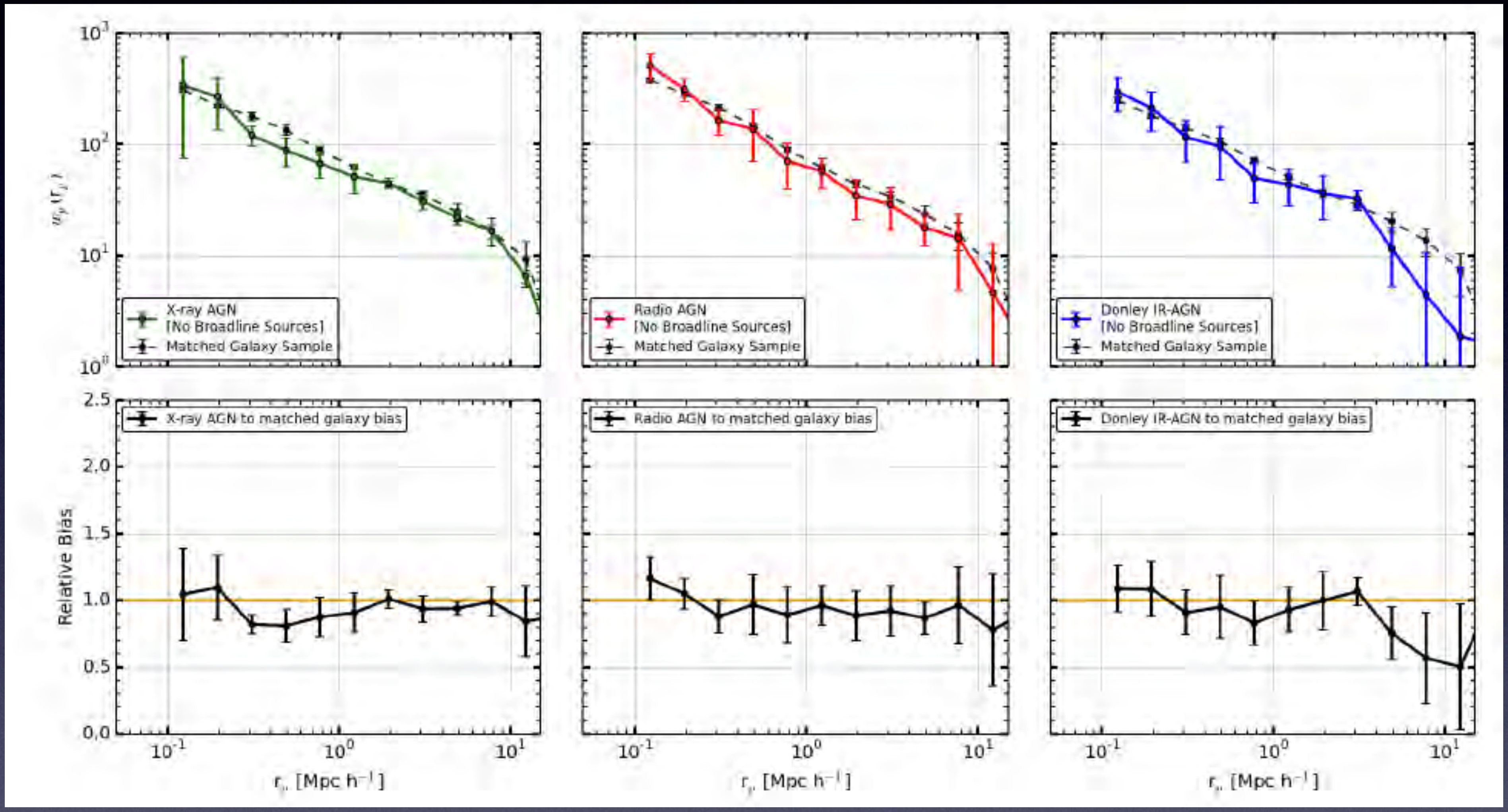
PRIMUS survey

AGN selected at different wavelengths have different clustering properties: radio and X-ray AGN are more clustered than IR AGN

Clustering Dependence on Wavelength

2-pt corr. fnct.

relative bias



radio
IR
X-ray

Mendez, Coil et al. 2016

galaxy separation

This is due to differences in their host galaxy populations - matching stellar mass and SFR of hosts makes differences disappear.

Galaxies of a given stellar mass and SFR have the same clustering properties whether they host an AGN or not.

Interpreting AGN Clustering

How to address this observationally? 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)

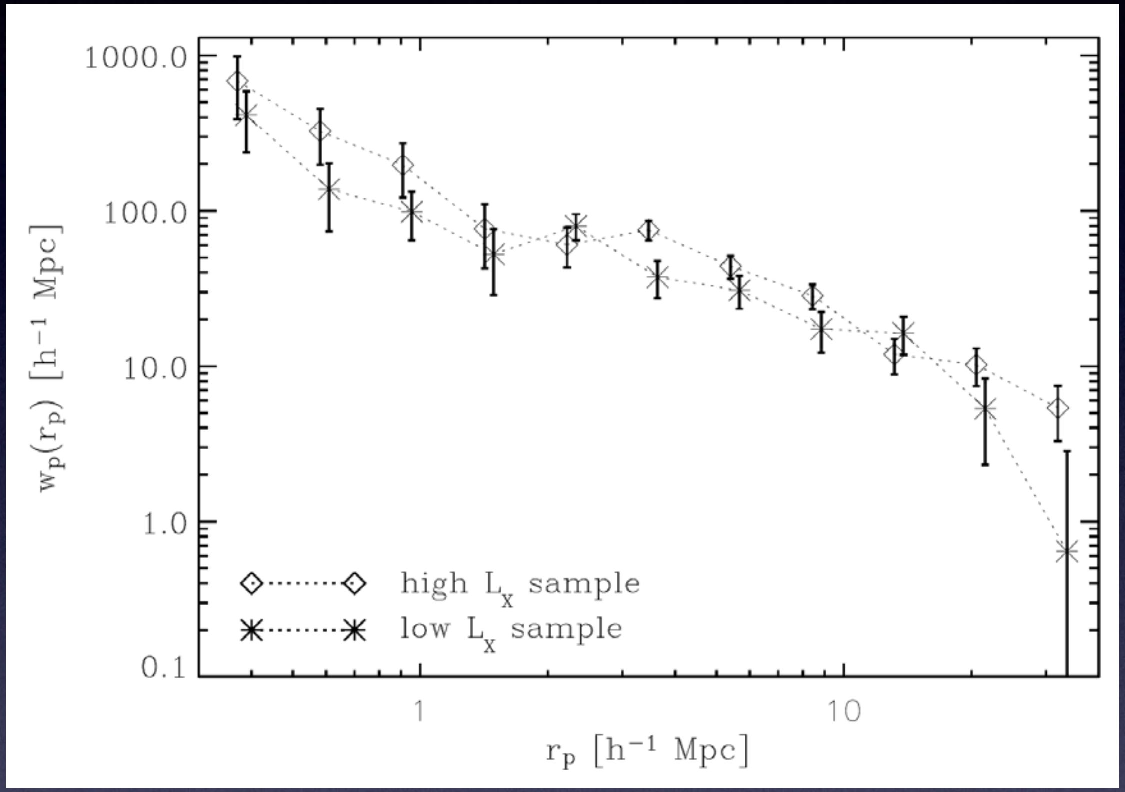
Then you can answer the question: for the distribution of galaxy types that host the kind of AGN observed, are those galaxies with observed AGN more or less clustered than those galaxies without observed AGN?

Clustering Dependence on AGN Properties

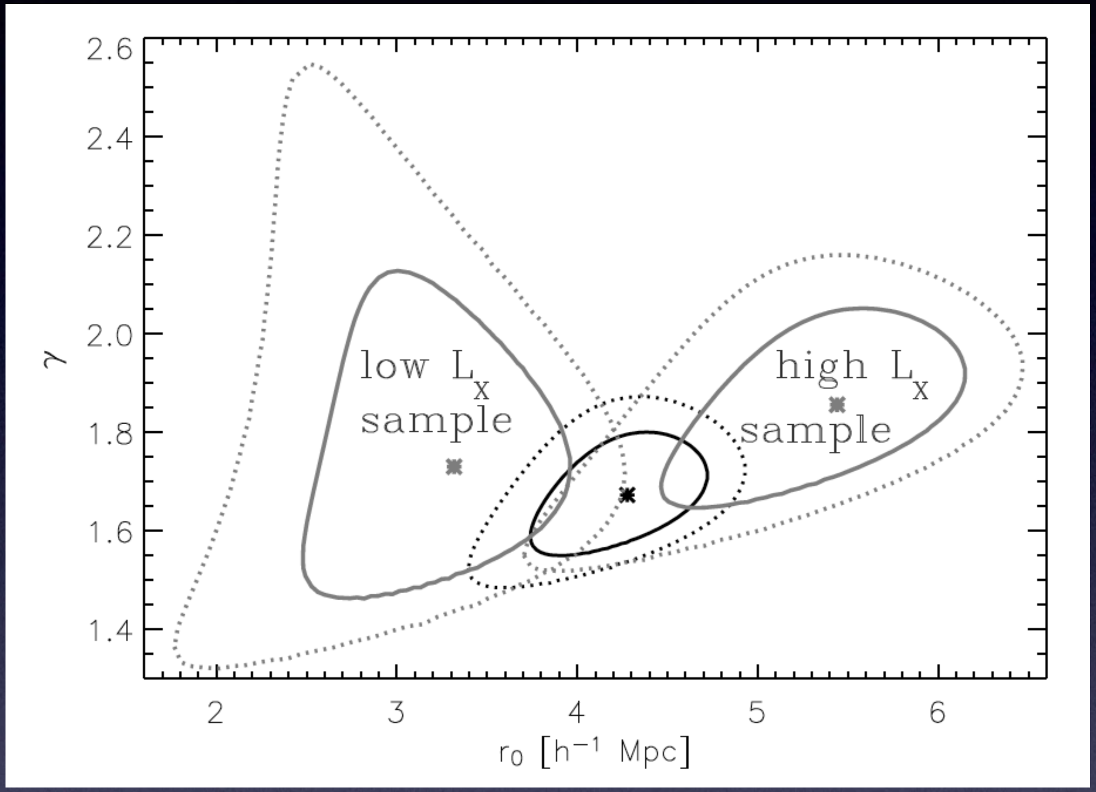
Useful to measure the dependence of AGN clustering on AGN properties:

- AGN luminosity
- BH mass
- Eddington ratio
- obscuration

Dependence on AGN Luminosity



Krumpe et al. 2010



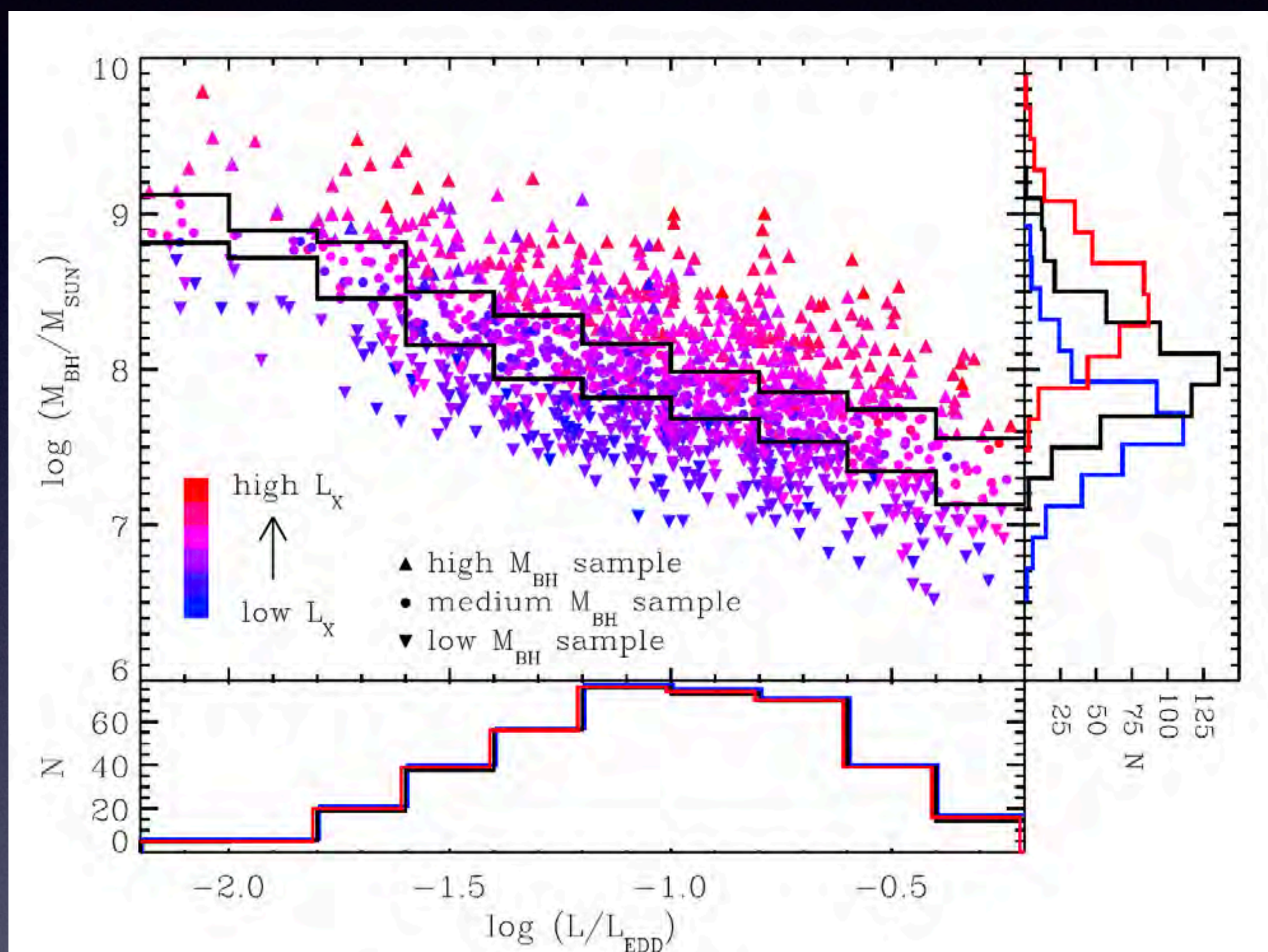
clustering scale length

X-ray AGN from ROSAT All Sky Survey cross-correlated with SDSS LRGs at z~0.2

There is a weak dependence of clustering amplitude on L_X, often detected at only ~2-3σ given the limited luminosity range of many AGN surveys. Some instances of detection are >3σ.

Dependence on BH Mass + L/L_{Edd}

$\log(M_{BH})$



$\log(L/L_{Edd})$

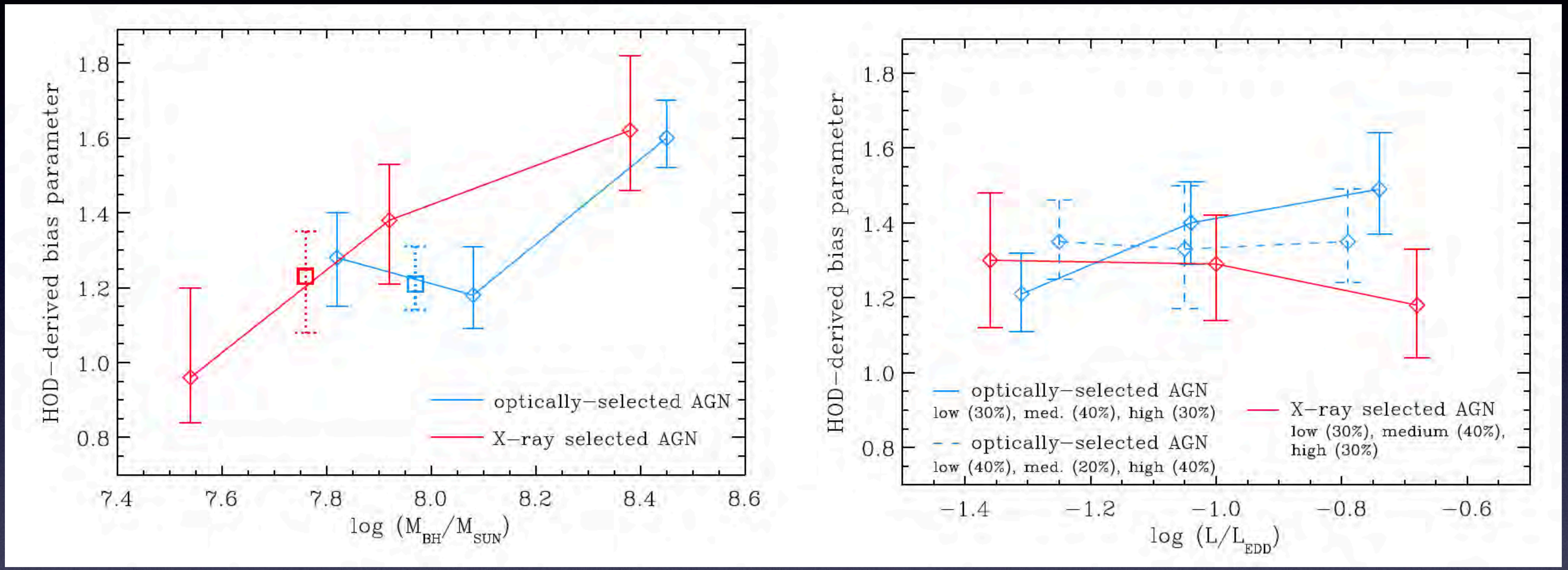
Krumpe et al. 2015

Because M_{BH} and L/L_{Edd} are correlated, need to create samples that have the same distribution in one parameter while varying the other parameter.

Here the samples have different distributions in M_{BH}, while having the same distribution in L/L_{Edd}.

Can then test clustering of high vs low M_{BH} or high vs low L/L_{Edd}, while keeping the other parameter distribution fixed.

Dependence on BH Mass + L/L_{Edd}



bias

log (M_{BH})

log (L/L_{Edd})

Krumpe et al. 2015

HOD fitting results show differences with L_X and M_{BH}, but not L/L_{Edd}. Presumably the dependence on M_{BH} is driving the weak dependence on L_X.

Dependence on AGN Obscuration

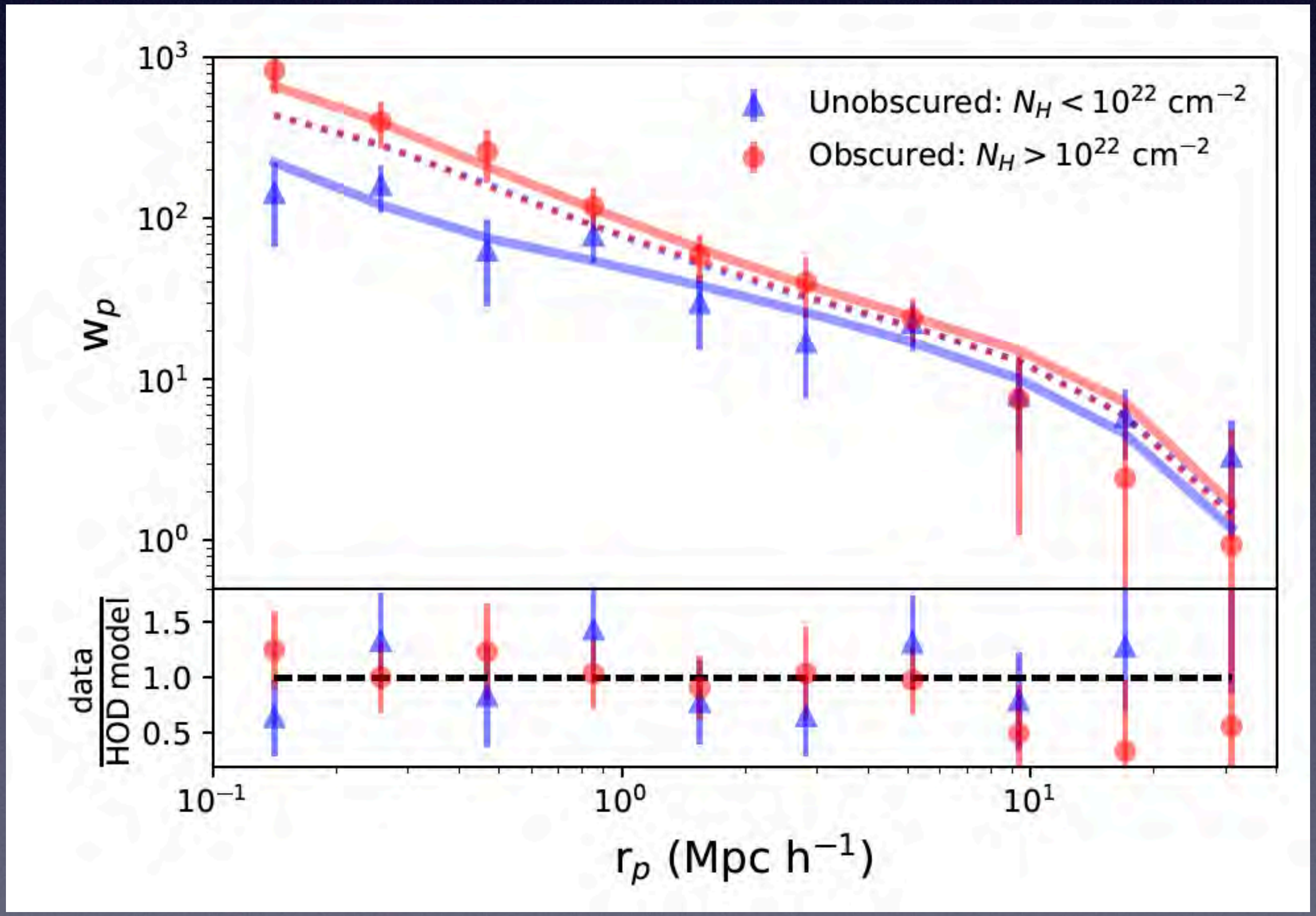
Results on differences in clustering for obscured vs unobscured AGN are mixed, and may depend on how obscuration is defined (which wavelength/method).

- optical narrow vs broad-line
- IR colors
- X-ray N_H

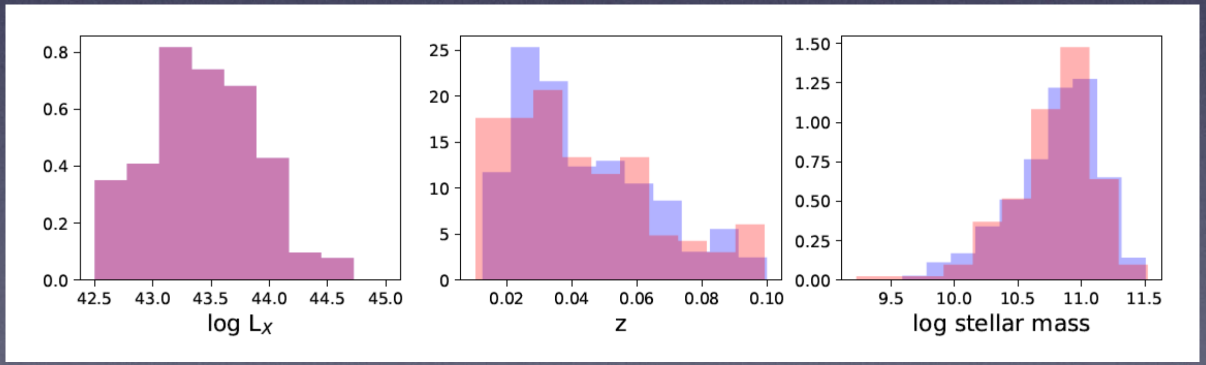
Most papers do <u>not</u> find a difference in the large-scale clustering properties of optically-selected type 1 vs type 2 AGN, using optical broad vs narrow lines (ie, Jiang et al. 2012, Krumpe et al. 2012, others). Some papers do find differences on *small* scales, with type 2 AGN having more close neighbors than type 1 AGN.

Dependence on AGN Obscuration

Using hard X-ray selected AGN samples (Swift/BAT), cross-correlated with 2MASS galaxies, obscured AGN with $N_H > 10^{22}$ cm^{-2} are more clustered than unobscured AGN on small scales:



Samples are matched in L_X, z, and stellar mass:



Powell et al. 2018 (see also Krumpe et al. 2018)

AGN Environments

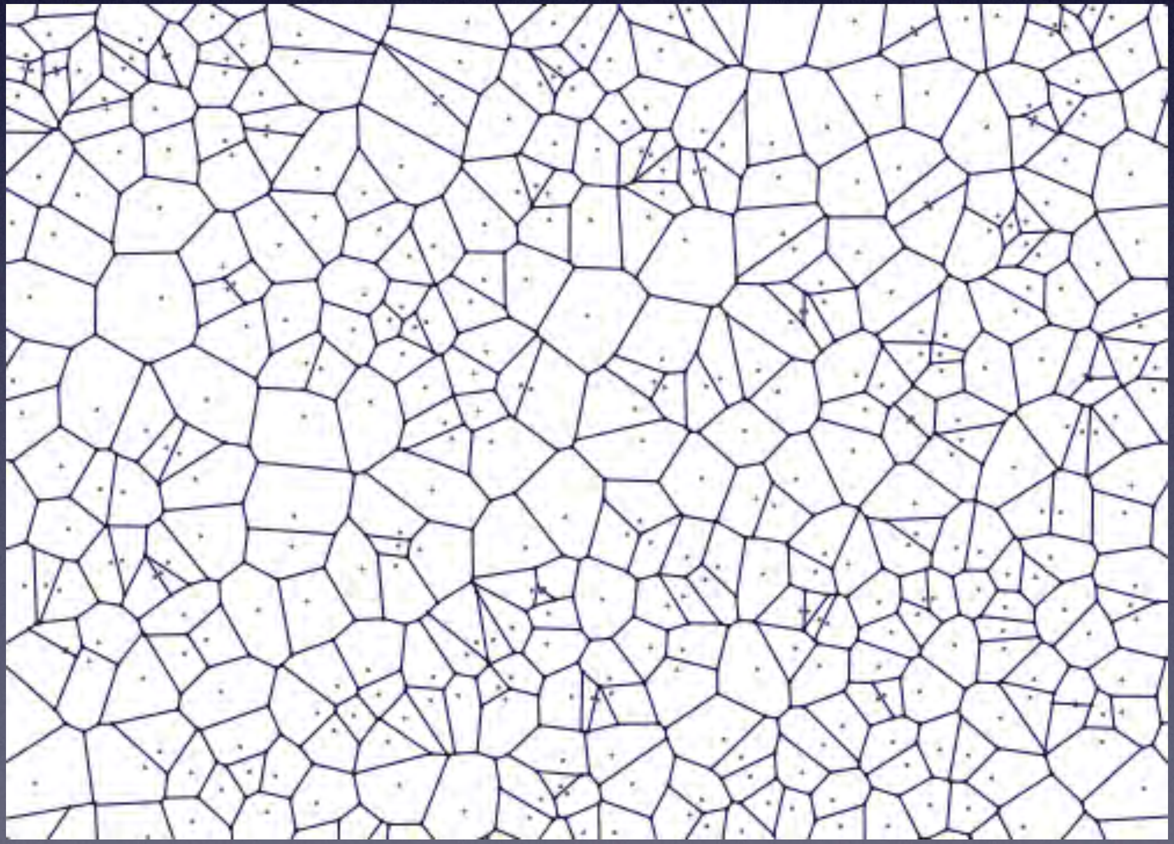
Can also measure AGN environments using group and cluster catalogs or environment density measures, ie, distance to 5th nearest neighbor.

Pros:

- use galaxies to trace cosmic web
- can identify where in halos AGN preferentially are (center vs outskirts)

Cons:

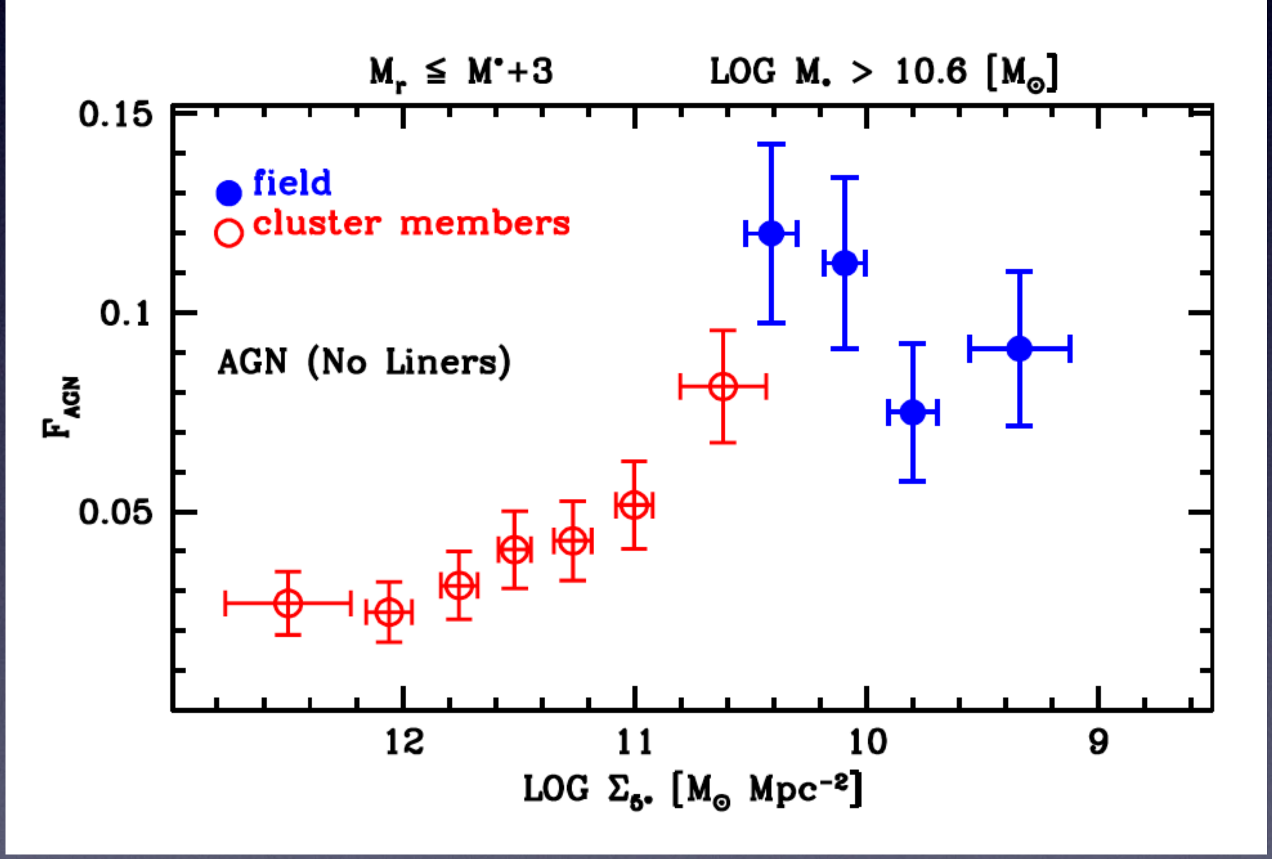
- can be a noisy measurement
- can lose scale information
- works well at low-z, not high-z



AGN Environments

Using group and cluster catalogs (at low-z) can investigate incidence and location of AGN within dark matter halos:

AGN fraction



Lopes et al. 2017

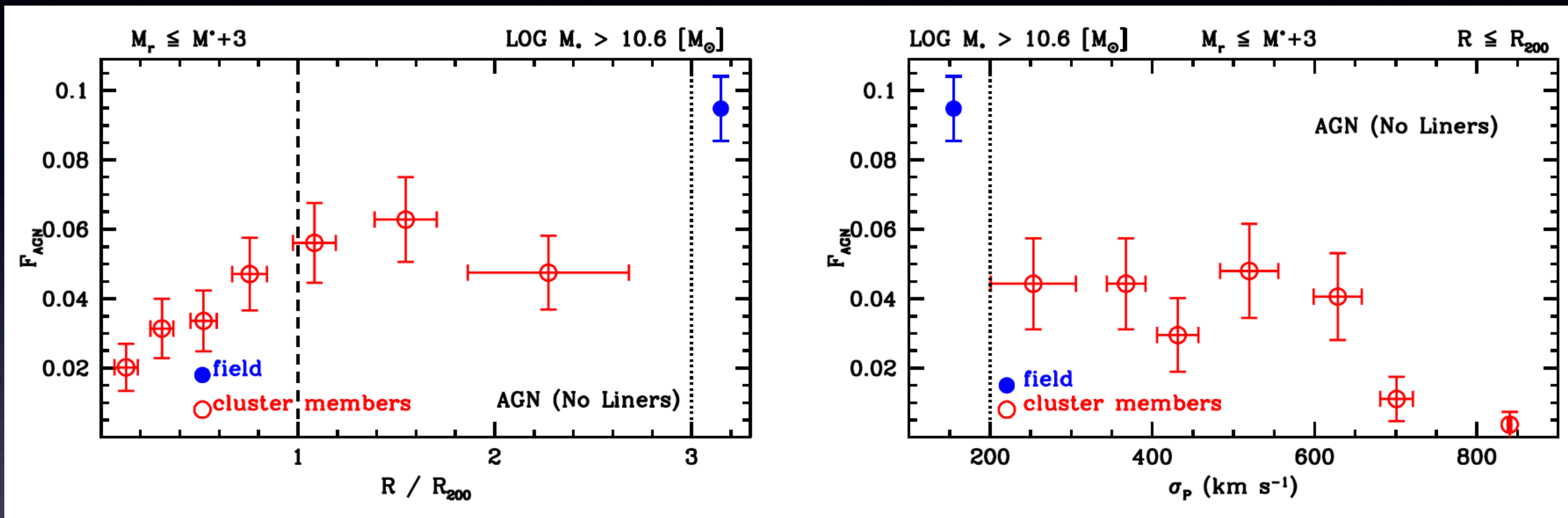
nearby stellar mass density

BPT-selected AGN from SDSS, in massive galaxies

Decline in AGN fraction towards the centers of galaxy clusters. Here using the local stellar mass density of nearby galaxies.

AGN Environments

AGN fraction



cluster-centric distance

velocity dispersion

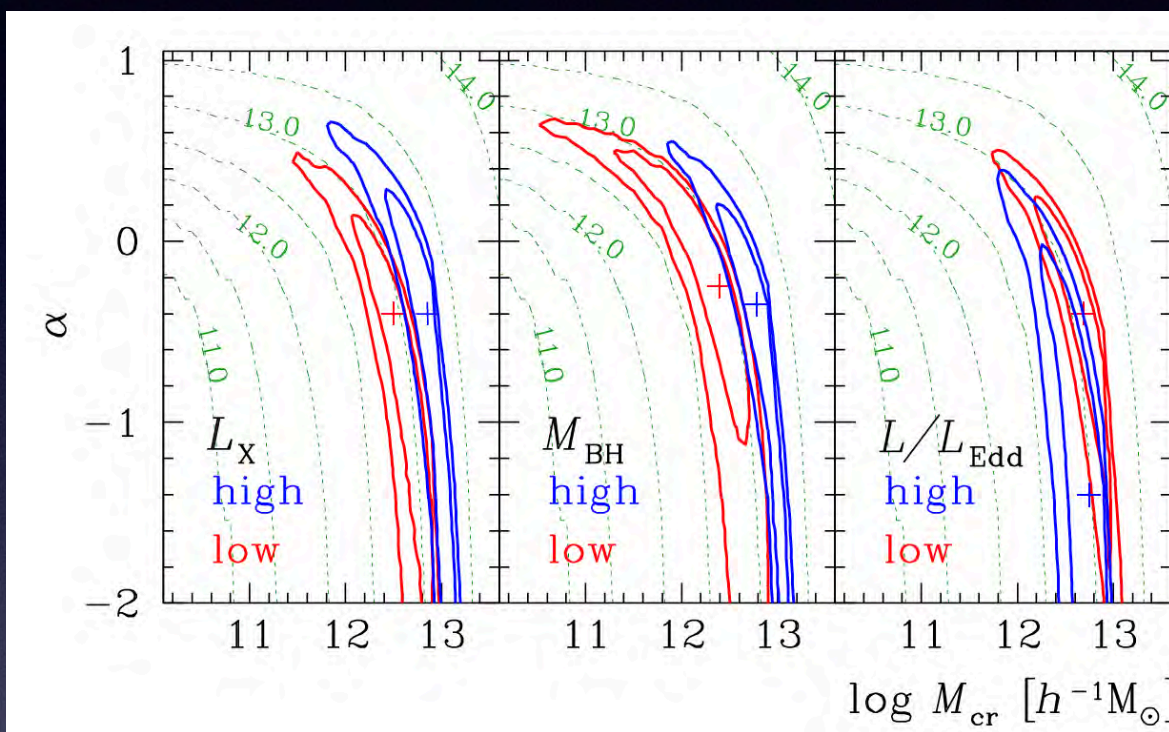
Lopes et al. 2017

BPT-selected AGN in massive galaxies

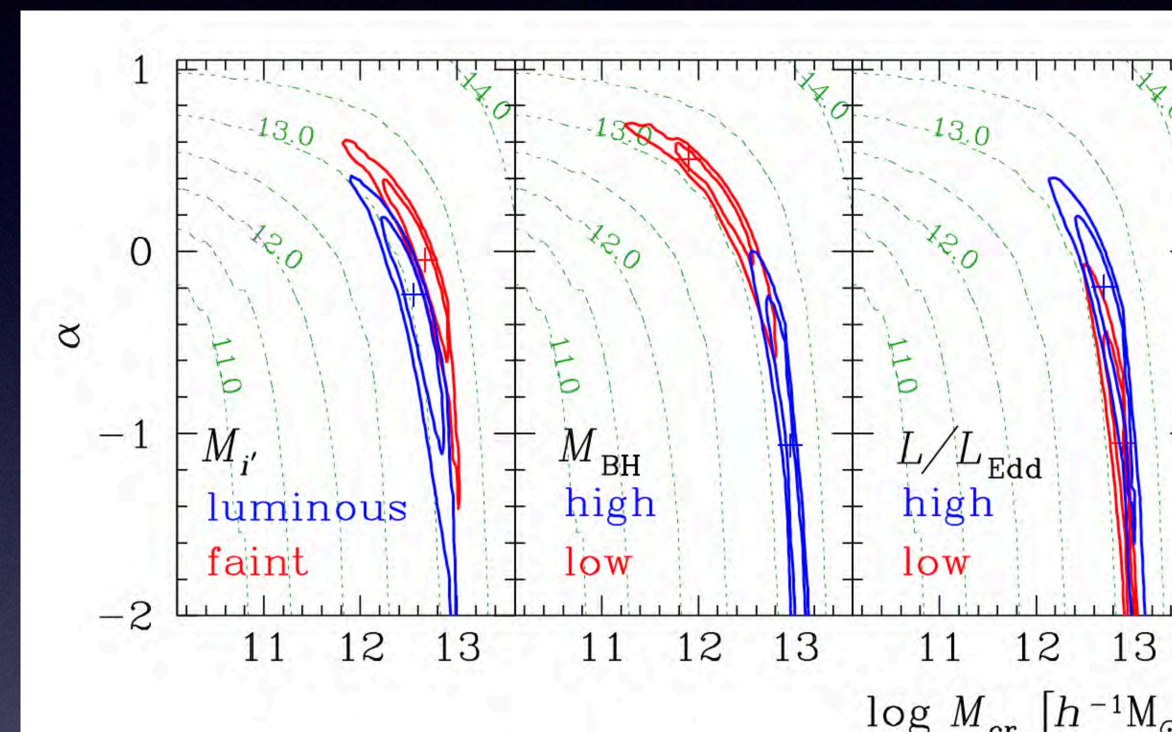
Decline in AGN fraction towards the centers of galaxy clusters using the cluster-centric distance. Also find fewer AGN in most massive clusters with high velocity dispersion (>700 km/s).

AGN in Massive Halos

X-ray AGN



Optical AGN



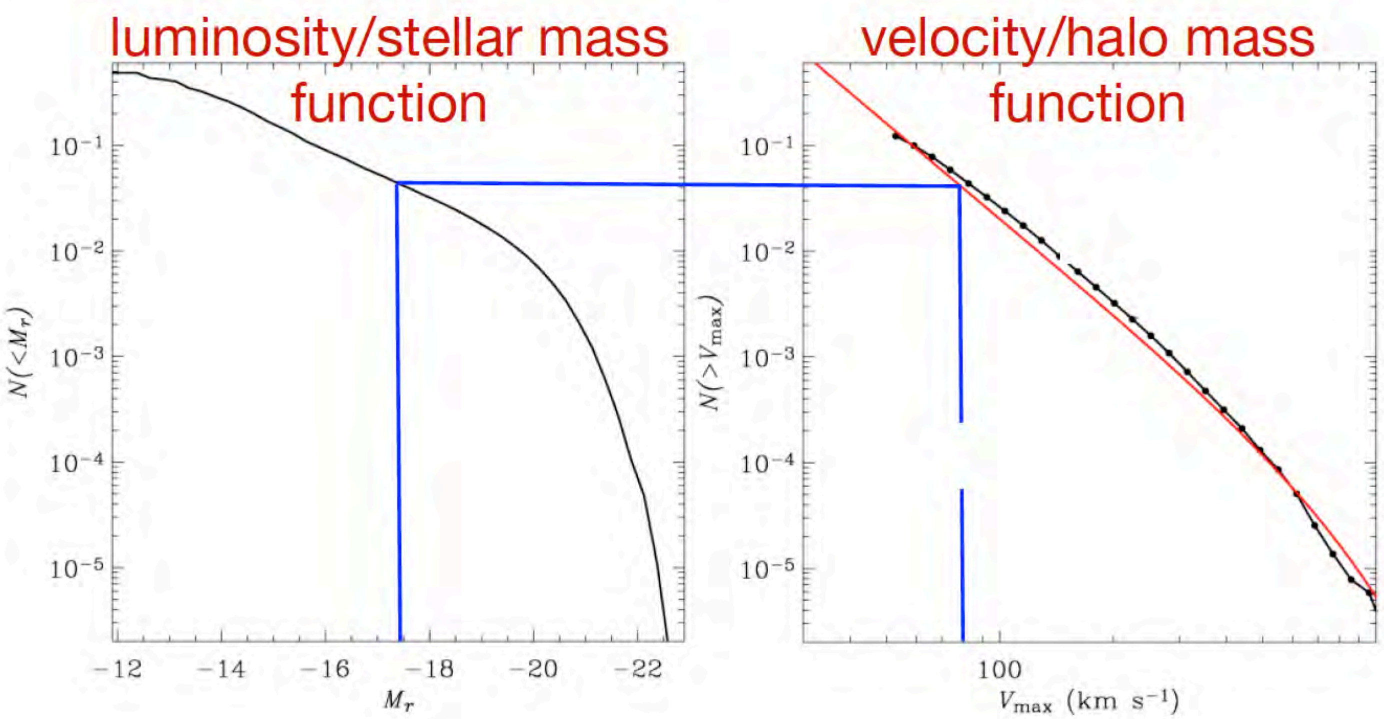
Krumpe et al. 2015

Many AGN HOD model results find that α< 1, which is not true for galaxies (where α~1). This implies fewer AGN in most massive halos, qualitatively similar to the AGN group/cluster results.

Abundance Matching

Rank order galaxies by luminosity or stellar mass and dark matter halos by mass

number density



galaxy luminosity

halo mass

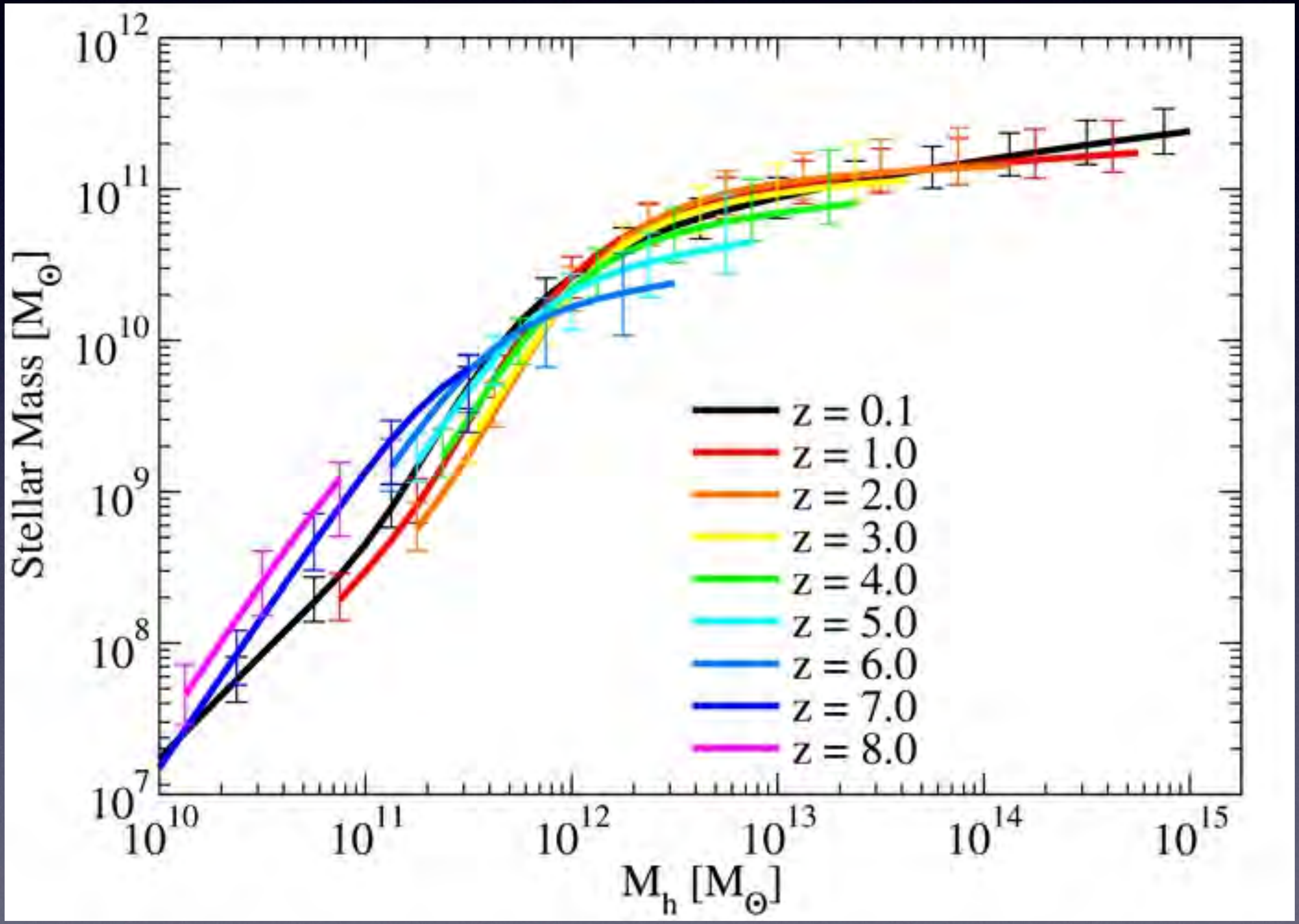
assign galaxies to halos velocities by matching n(>M*) to n(>M) (assume the most massive galaxy lives in the most massive halo)

key assumptions: one galaxy per dark matter clump; galaxy mass/luminosity tightly correlated with halo mass/velocity
required high-res cosmological simulations to properly test

Conroy, Wechsler, & Kravtsov 2006

Stellar Mass to Halo Mass Relation

Galaxy Stellar Mass



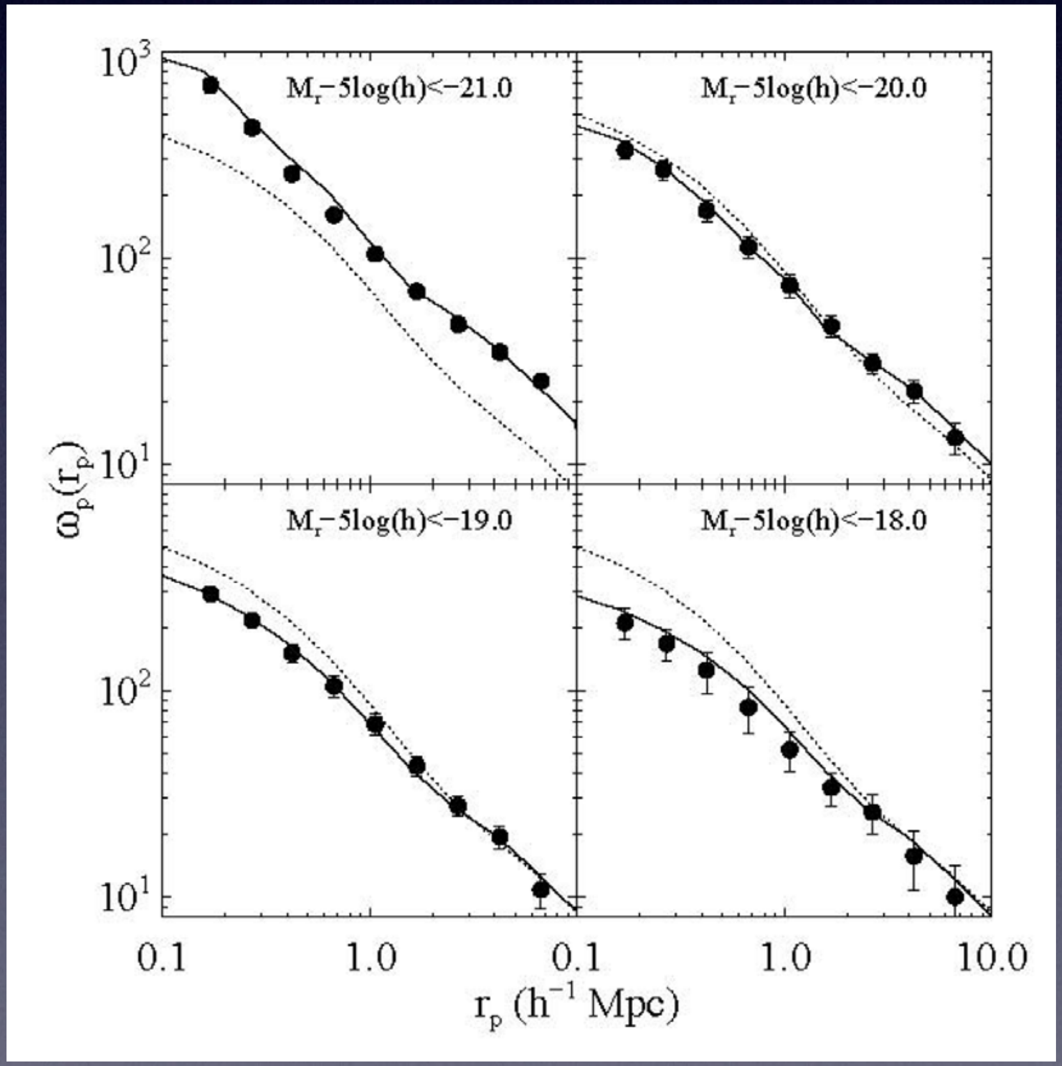
Dark Matter Halo Mass

Behroozi, Wechsler & Conroy 2013

Abundance Matching

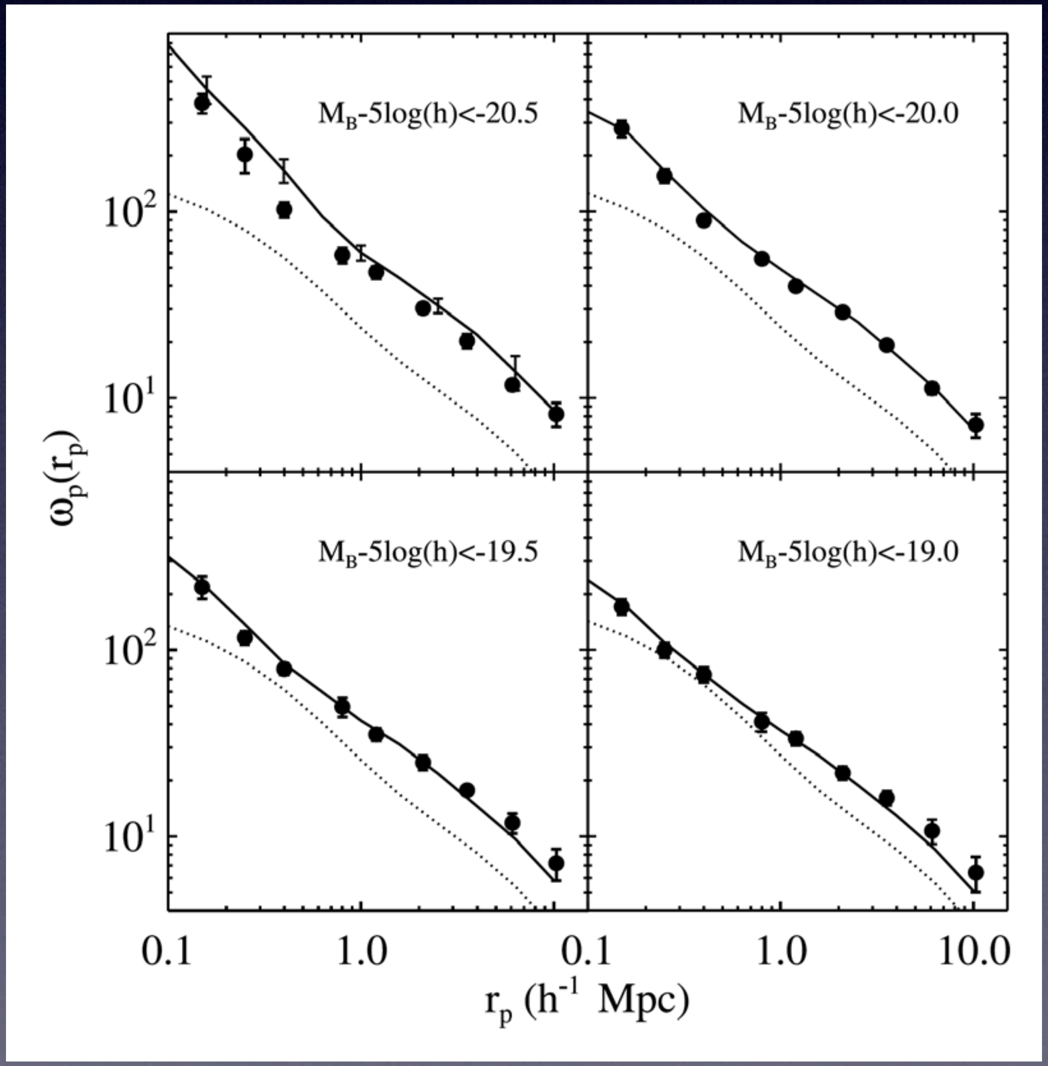
Can match galaxy clustering as a function of luminosity very well

z=0.1 SDSS



z=1 DEEP2

clustering strength



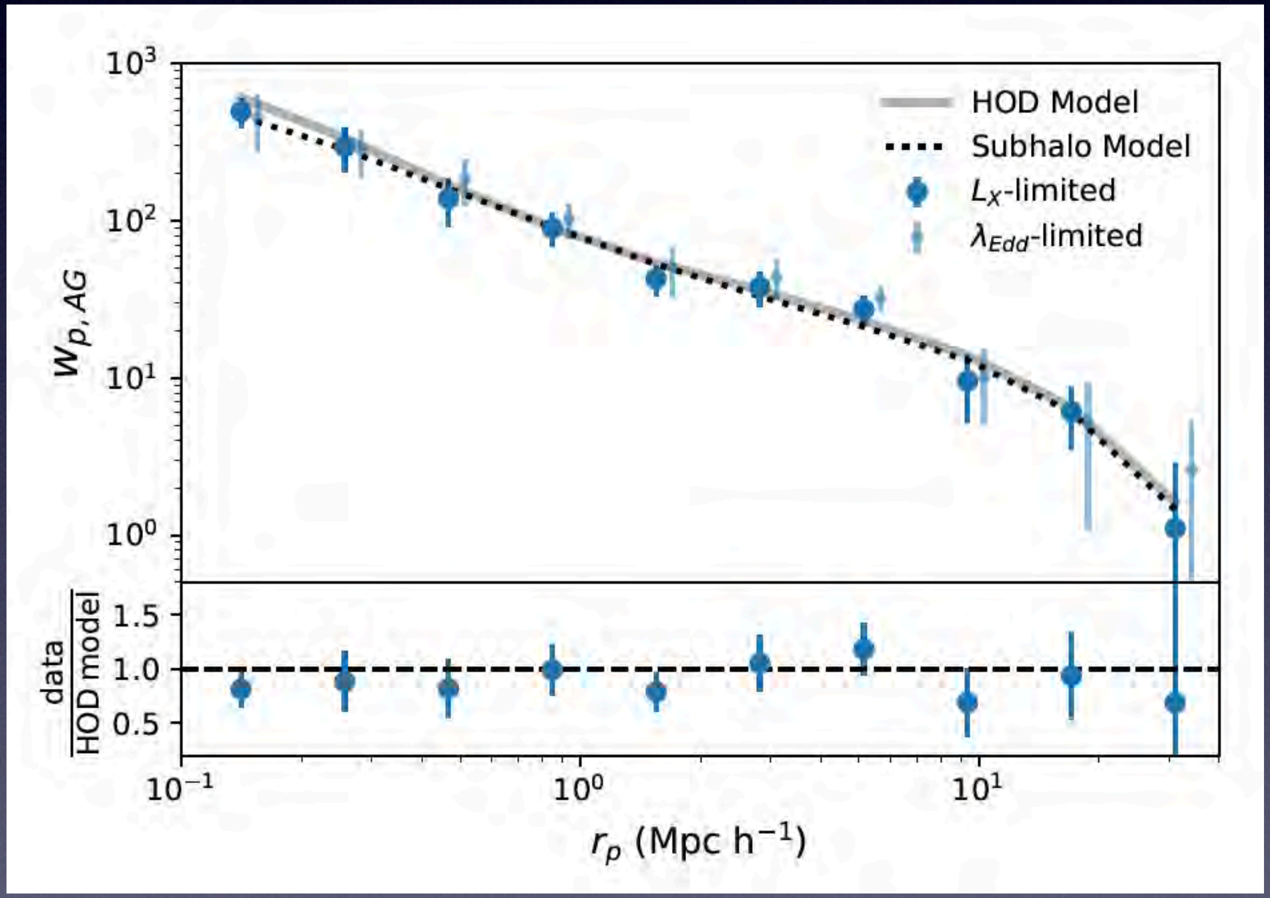
galaxy separation

Conroy, Wechsler, & Kravtsov 2006

Abundance Matching

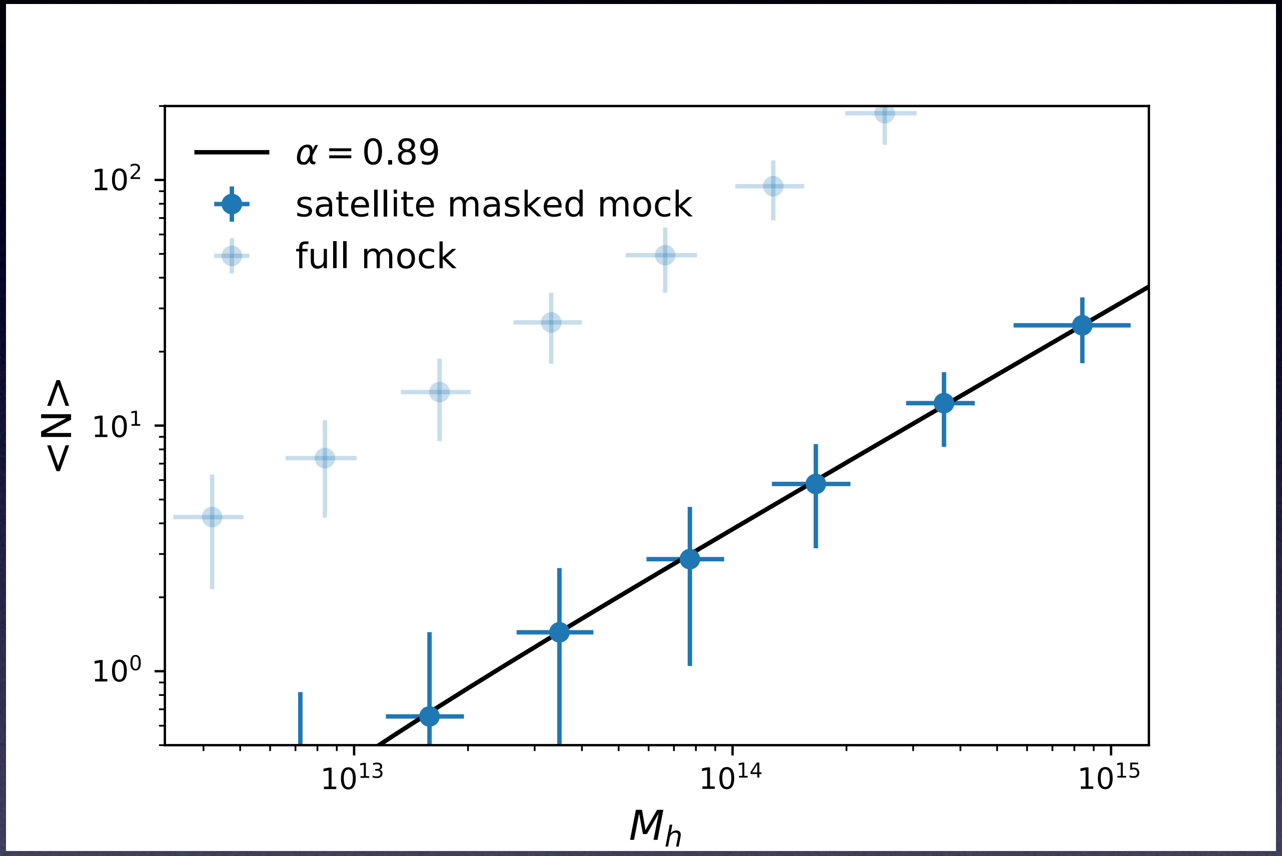
Can match X-ray AGN clustering very well!

Powell et al. 2018



The black dotted line shows a model with no free parameters, which uses the stellar mass to halo mass relation and places X-ray AGN in galaxies of a given stellar mass in halos/sub-halos of a given dark matter mass. Excellent fit!

Selection Function Effects



<N_{AGN}>

Halo Mass

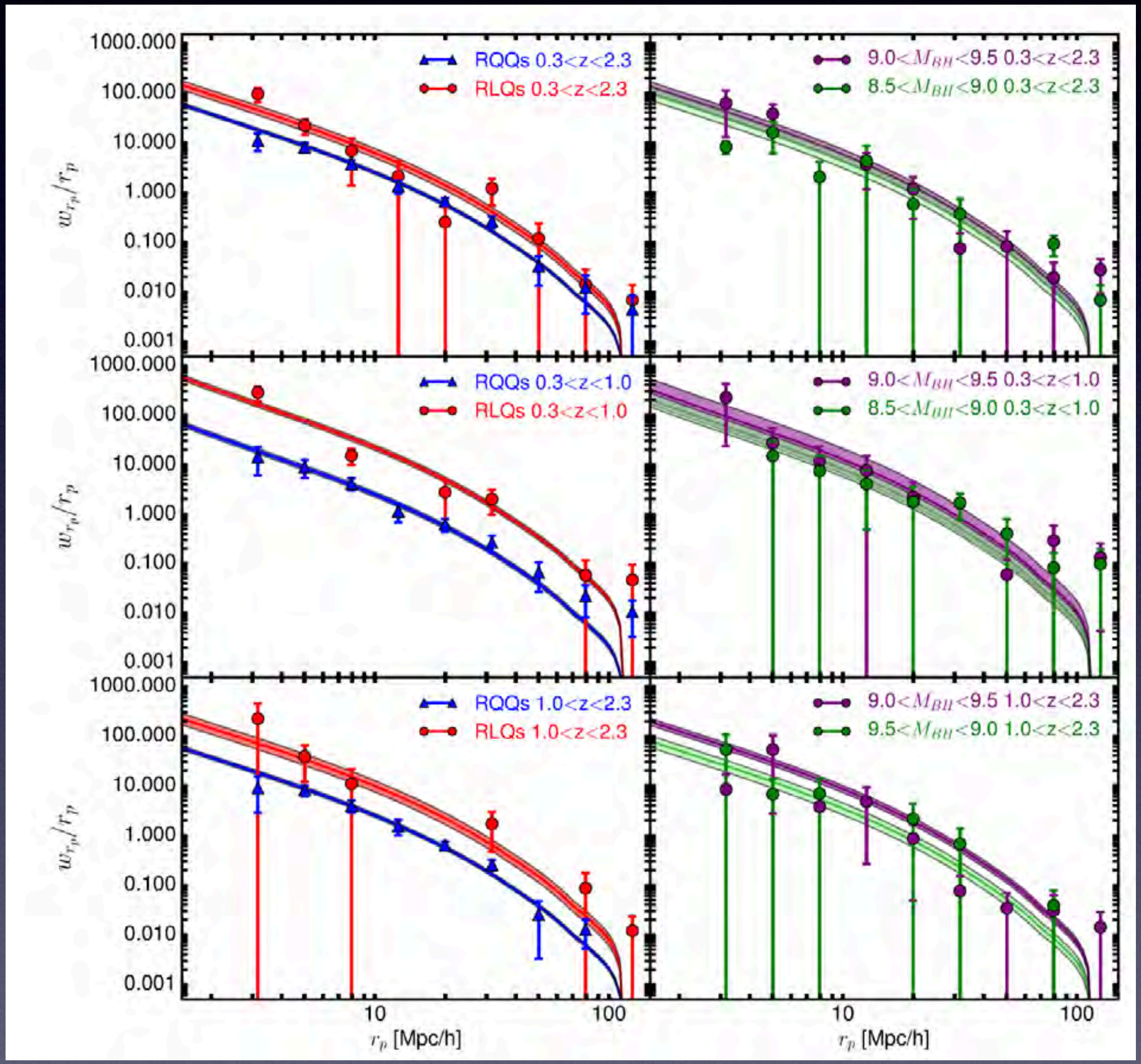
Meredith Powell (priv. comm.)

Including the AGN selection function (due to observational flux limits) can change measured α by ~10%

Here comparing an abundance matched mock catalog (light blue points, α =1) to a mock catalog that includes the AGN selection function (dark blue points, α = 0.89)

Implies that HOD results can be influenced by selection effects. Forward modeling can determine underlying true parameters.

Dependence on Radio Loudness



Using SDSS + FIRST, radio loud quasars are found to be more clustered than radio quiet quasars.

Don't have stellar masses or host properties, so haven't controlled for that.

Could be that radio loud quasars are in more massive halos, and/or could be that they are in <u>older</u> halos.

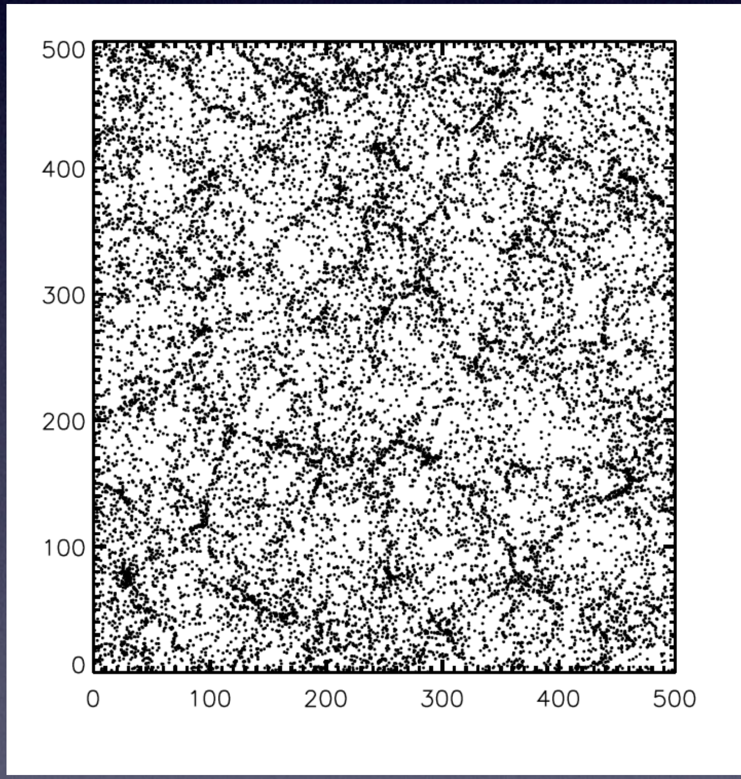
Retana-Montenegro et al. 2017

Assembly Bias

Clustering depends on halo formation time

all halos

Mpc/h



Mpc/h

for halos of a given mass

Gao, Springel & White 2005

Millenium Simulation

Assembly Bias

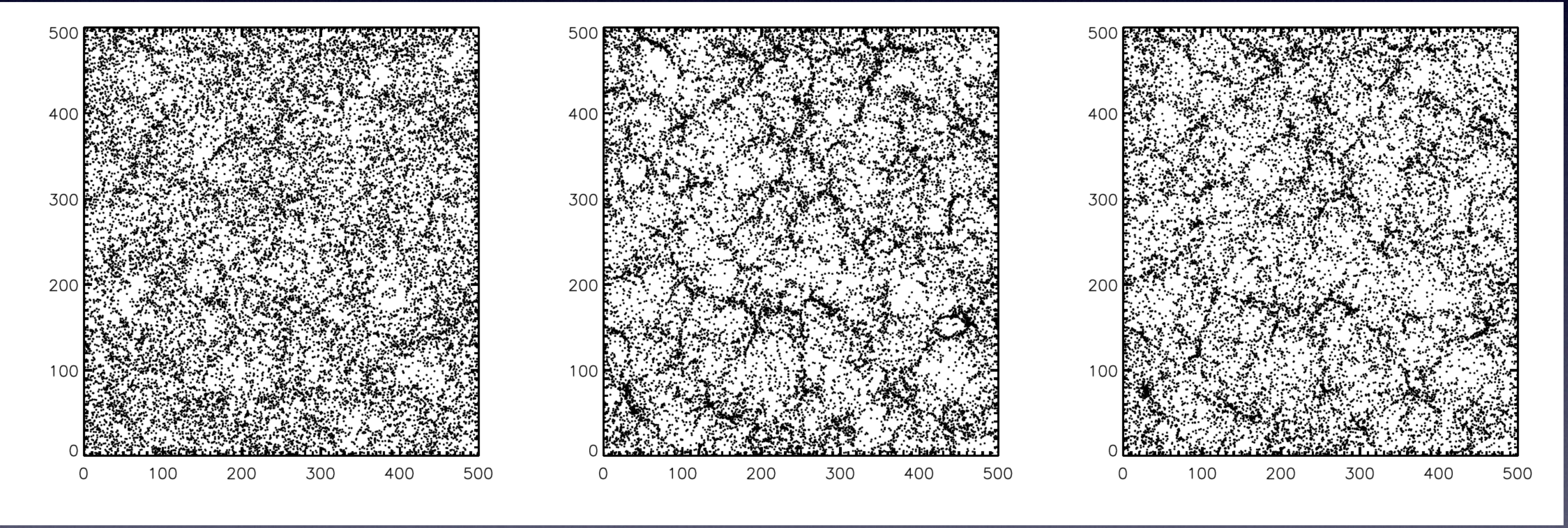
Clustering depends on halo formation time

20% youngest halos

20% oldest halos

all halos

Mpc/h



Mpc/h

for halos of a given mass

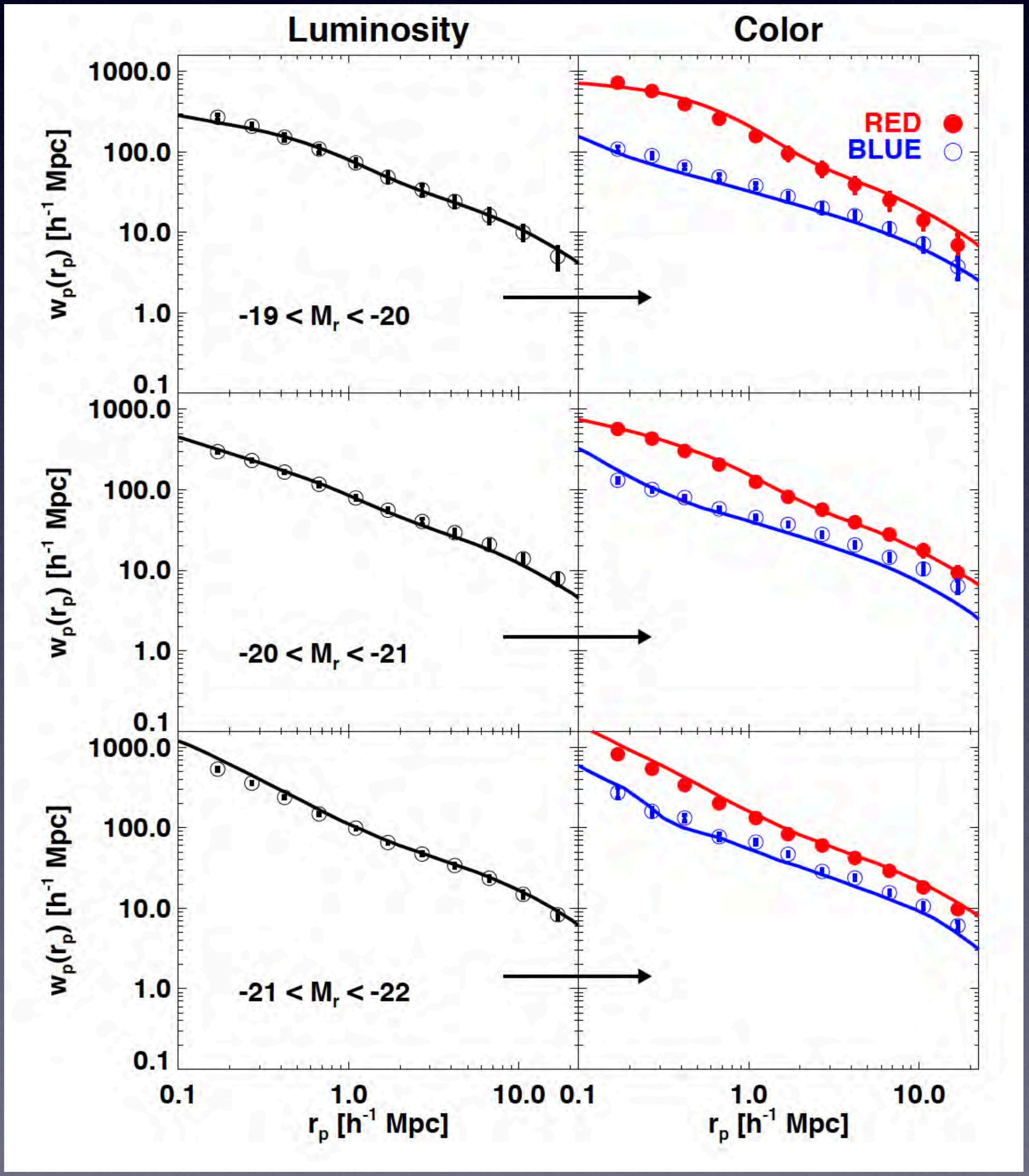
Gao, Springel & White 2005

Millenium Simulation

Age Matching

In addition to abundance matching, also rank order galaxy color and halo assembly history

This roughly places older galaxies in older halos, and allows a prediction of clustering of red and blue galaxies at a given luminosity:



Hearin & Watson 2013

z=0.1 SDSS

Age Matching

Prediction of clustering of quenched and star-forming galaxies at a given stellar mass, using an age-matched mock catalog, which takes into account assembly bias:

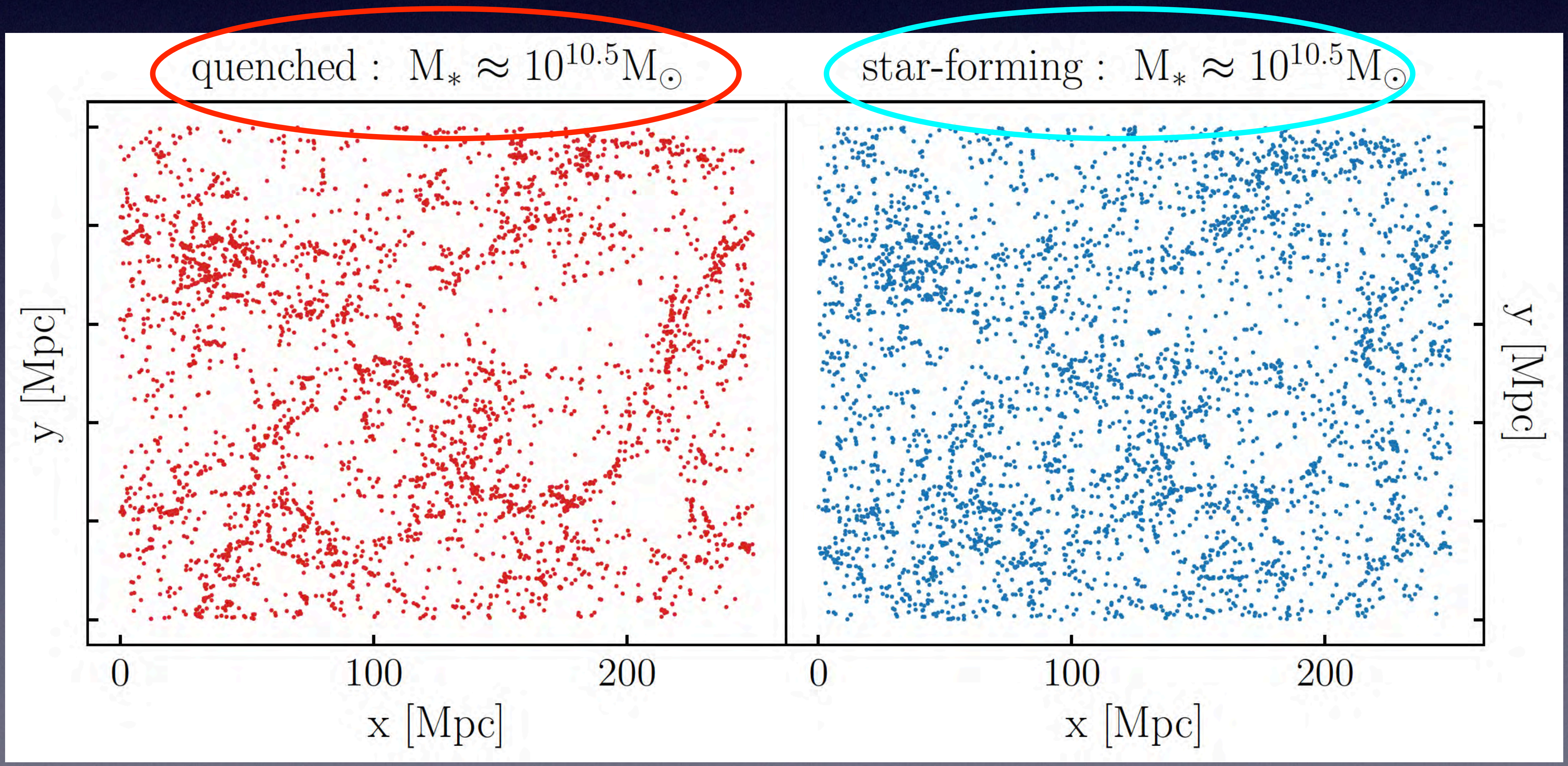


image by Andrew Hearin

Conclusions - 1

- Be careful with how you interpret measurements of AGN clustering! There is a strong bias towards high galaxy stellar mass in observed AGN samples.
- Best to compare AGN clustering with matched galaxy samples when possible, to aid interpretation - ideally match in redshift, stellar mass, and SFR.
- When comparing to matched galaxy samples, AGN have <u>same</u> clustering properties as inactive galaxies.

Conclusions - II

- Moderate-luminosity AGN are not found in special environments!
- The AGN fraction declines towards the centers of clusters and in the most massive clusters - these extreme environments don't have as much AGN activity.
- Stronger clustering doesn't necessarily mean higher halo mass - can mean older halos.
- Galaxy clustering community is moving beyond HOD modeling to more empirical, forward-modeling approaches.