What can we learn from galaxy clustering measurements II

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Introduction

Galaxy clustering has two distinct uses:

1. Large scale tracers of the cosmic web
   → Constraints on cosmological parameters

2. As a link to dark matter halo properties
   → Constraints on galaxy formation models

AGN are important in both these regards.

Outline

1. Introduction
2. AGN-Galaxy Formation Link
3. Galaxy clustering and galaxy formation
4. AGN clustering and galaxy formation
5. Galaxy Clustering and Cosmology
6. AGN clustering and Cosmology
7. Summary

AGN-Galaxy Formation link

For a galaxy actively forming stars at 10 M_{sol}/yr the SN energy coupling to the IGM is $10^{41.5}$ erg/s

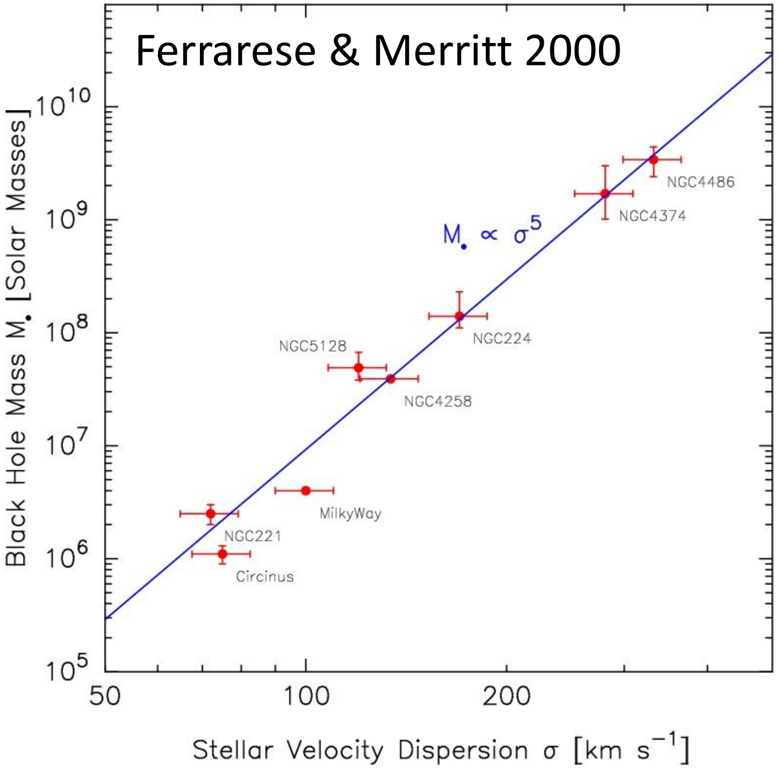
Typical AGN luminosities are $10^{44.5}$ erg/s

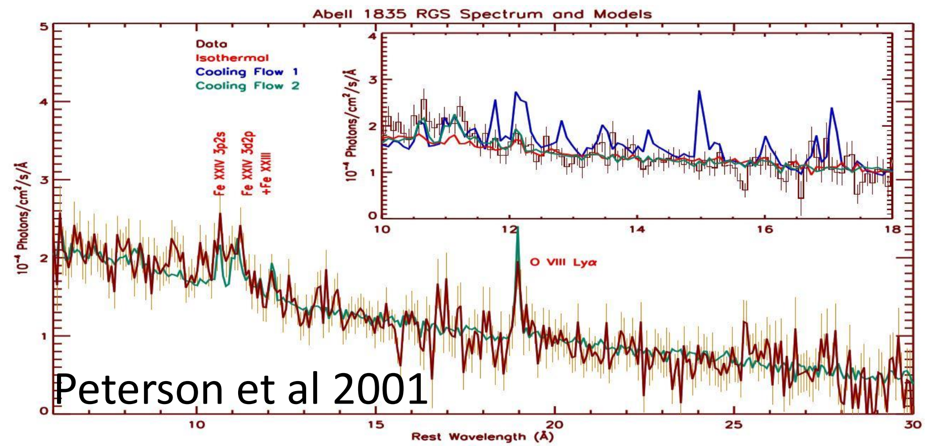
So even if AGN have ~1% duty cycles (corresponding to the relative space densities of galaxies and AGN), they dominate the average energy input into galaxies.

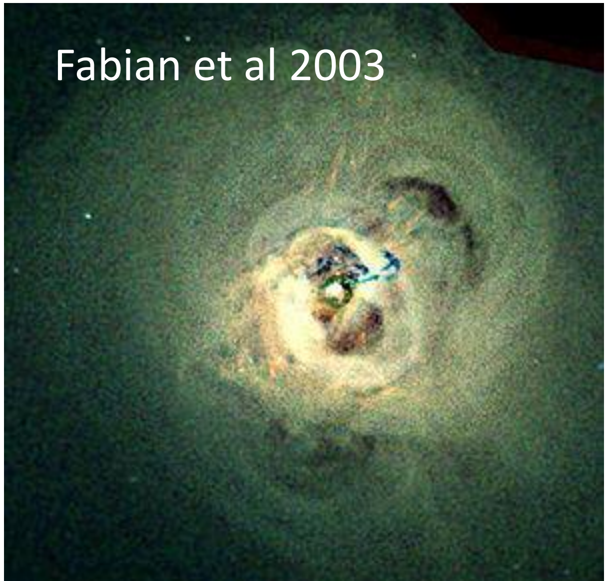
Ignored despite this due to length scale and coupling.

AGN-Galaxy Formation link

Neglect became untenable due to





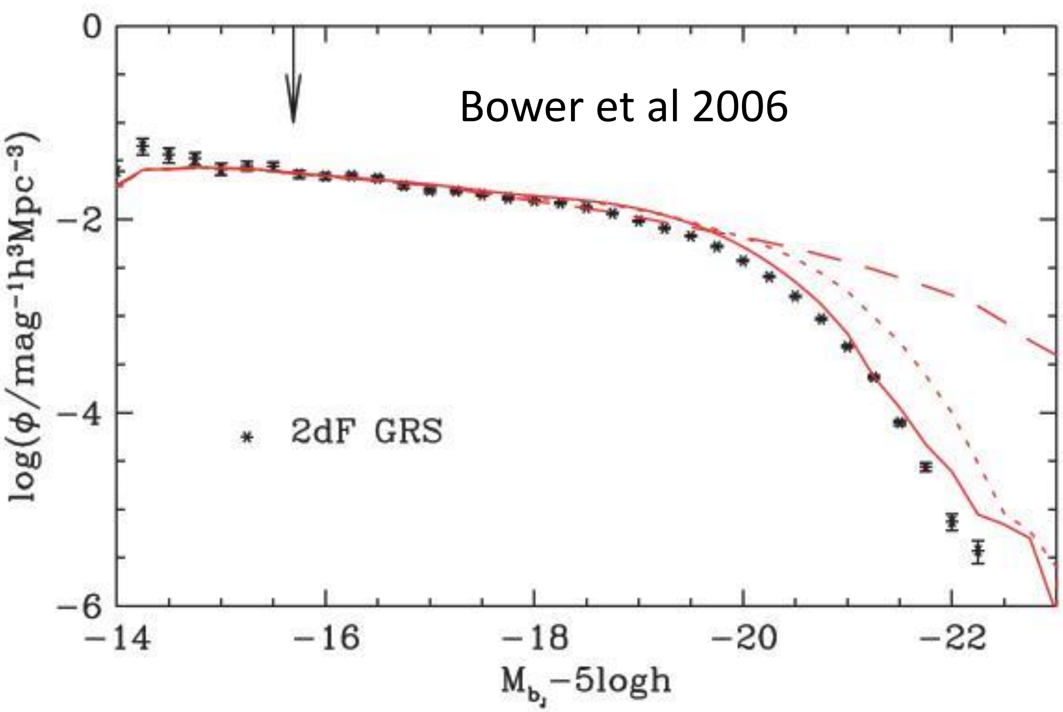


1. Intrinsic correlations between BH mass galaxy bulge
2. Evidence of AGN heating in galaxy clusters

AGN-Galaxy Formation link

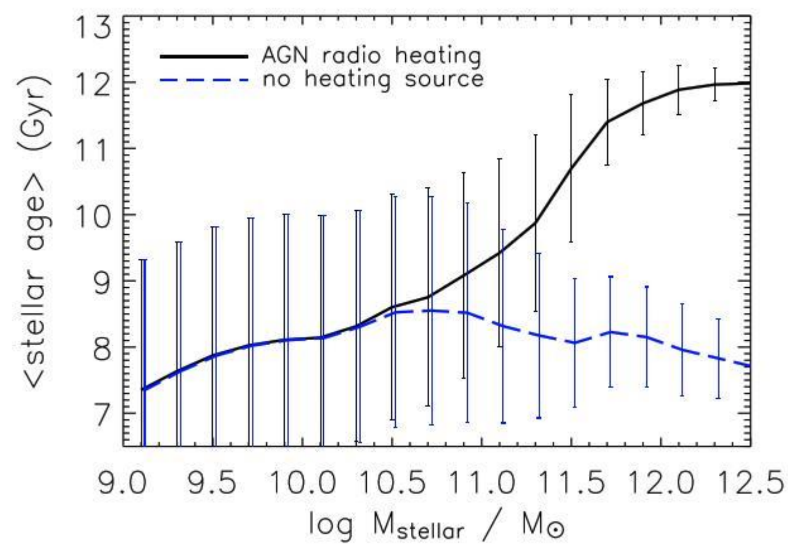
Now a central part of all galaxy formation models.

Both semi-analytic and hydrodynamic simulations.



Bower et al 2006

Croton et al 2006; De Lucia et al 2006



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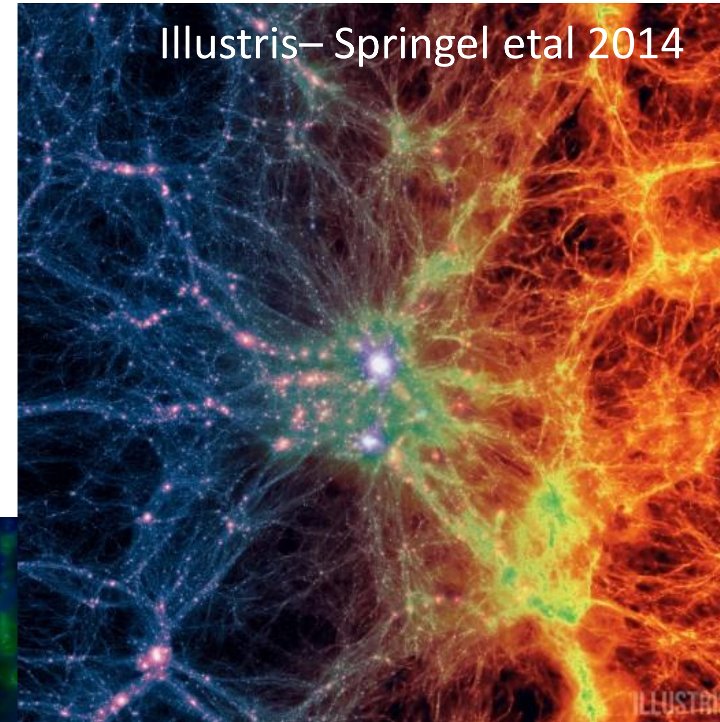
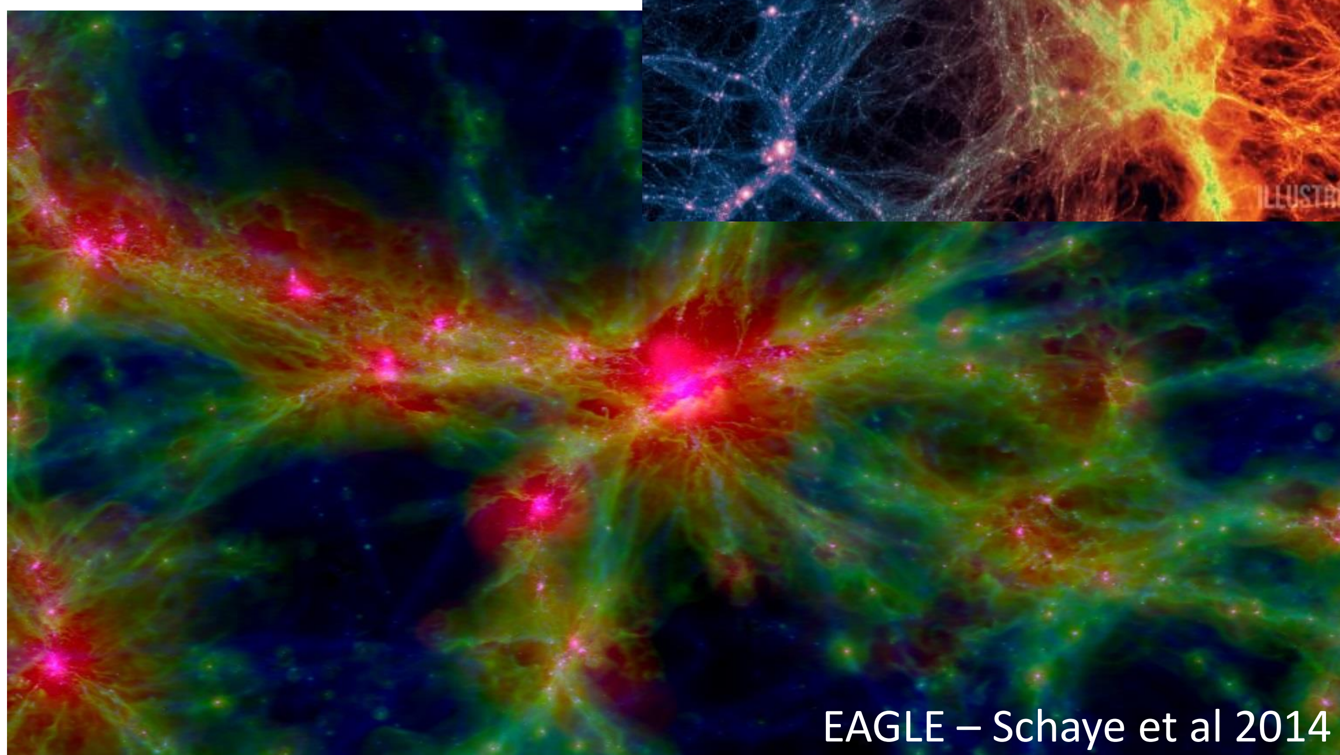
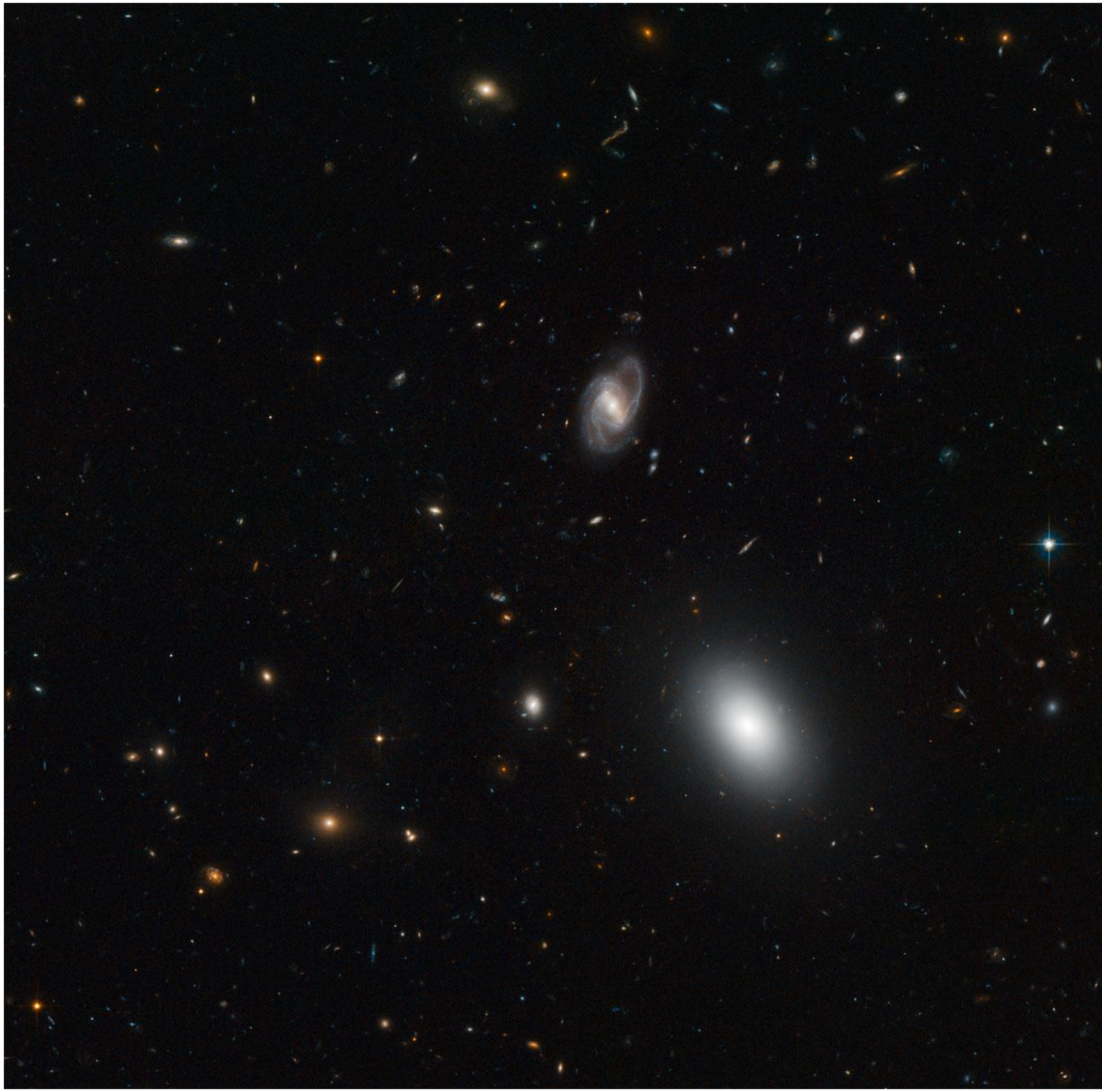




Galaxy clustering and galaxy formation

Observations at different redshifts provide snapshots of the evolving galaxy distribution, but not a direct view of evolution.

One can't observe what a given galaxy will evolve into, nor what progenitor(s) it evolved from.



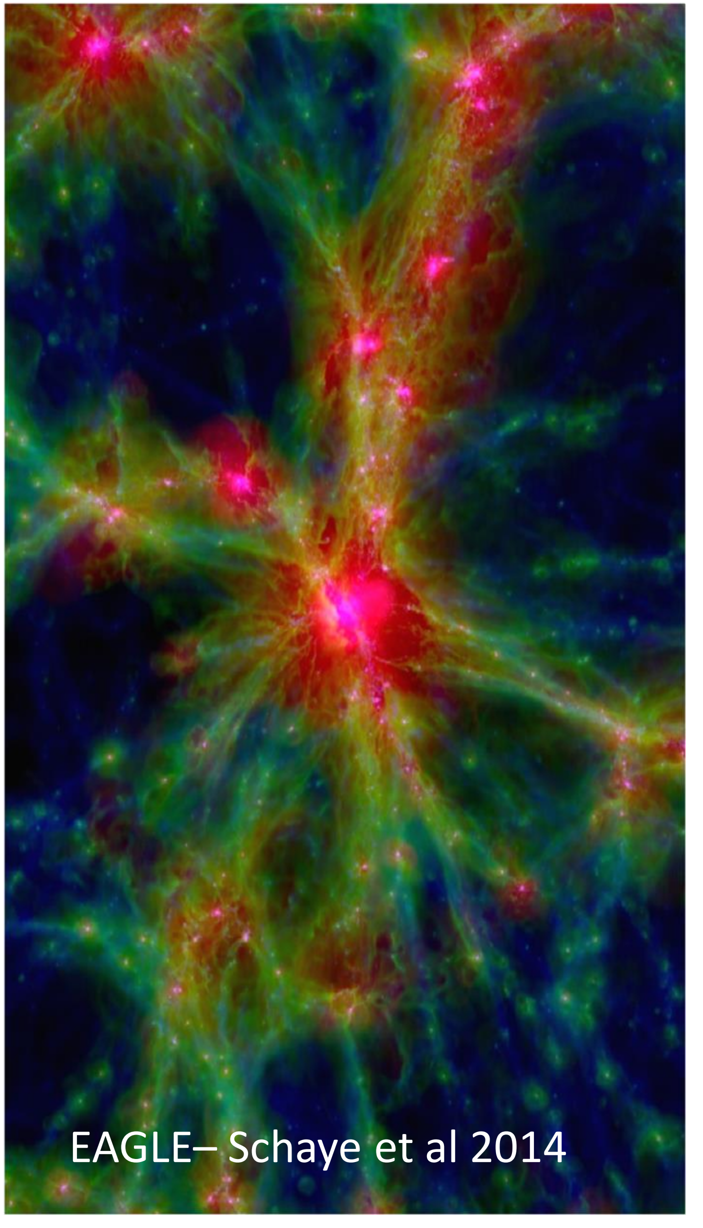
NASA HST

Galaxy clustering and galaxy formation

Full cosmological hydrodynamic simulations of galaxy formation are possible, but costly.

The physics of star formation, AGN and feedback are very complex and hence uncertain.

Hard to infer by comparing to a suite of different models.

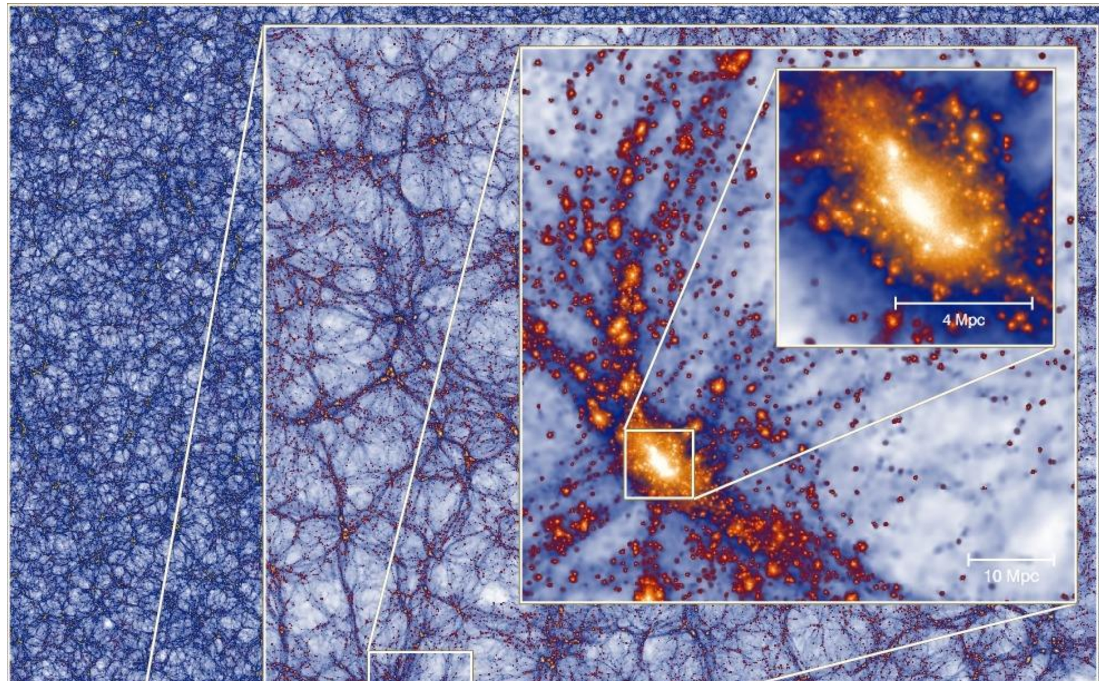


Dark matter clustering evolution

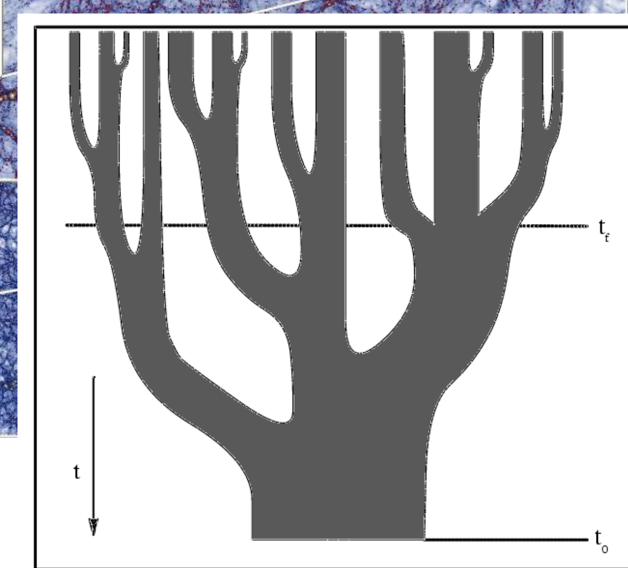
The modelling of the gravitational evolution of Dark Matter is solid.

Yields merger trees that link descendant and progenitor haloes.

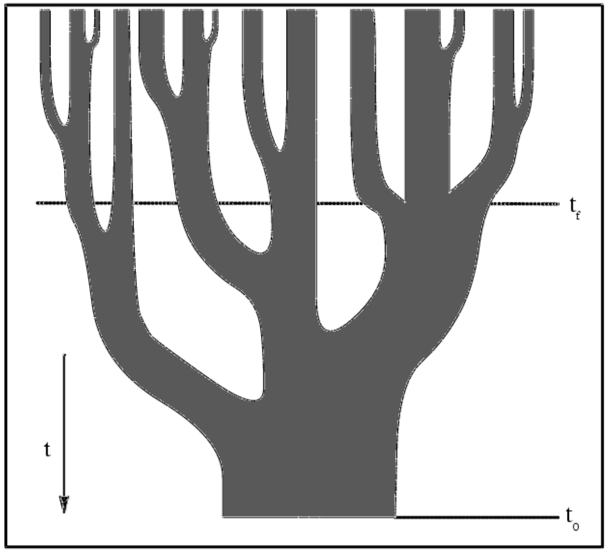
➔ If we know what mass haloes galaxies live in at different redshifts then we know (statistically) what evolves in to what.



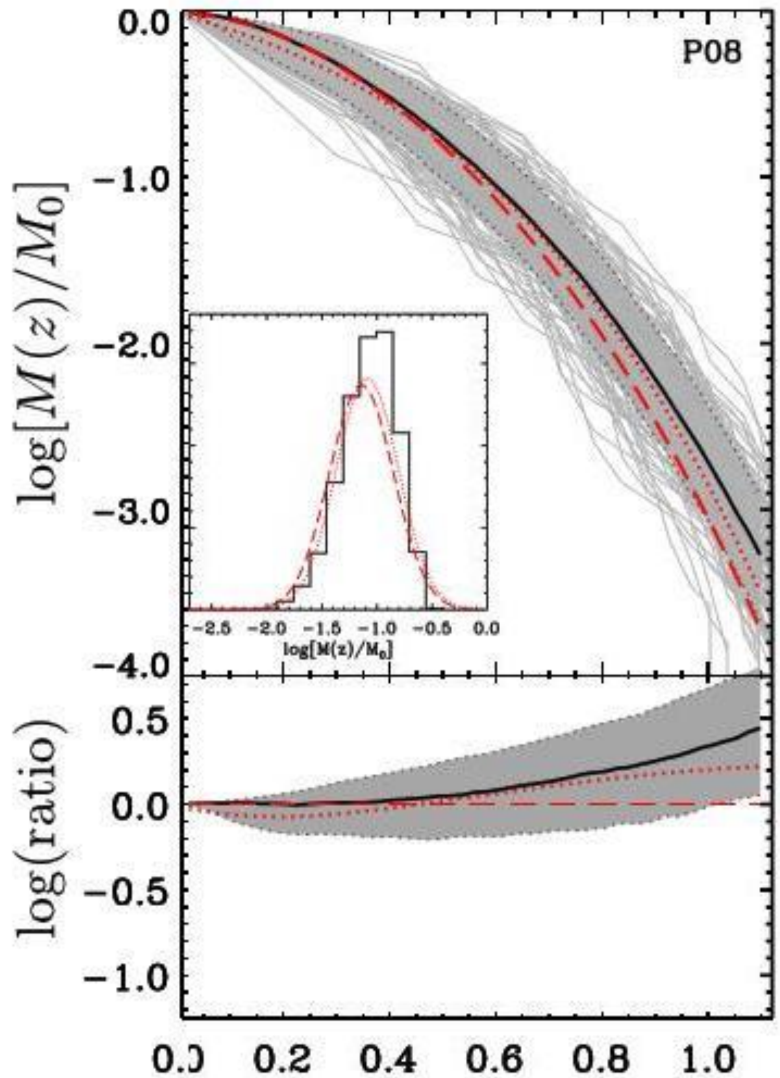
3000 Mpc box
Angulo et al 2012



Analytic hierarchical growth



Not only do we have merger trees from N-body simulations, but also analytic descriptions based on extended Press-Schechter and elliptical collapse (e.g. Parkinson et al 2008) that agree will with simulations (See Jiang & van den Bosch 2013).



Jiang & van den Bosch 2013

But also see Srisawat et al 2013

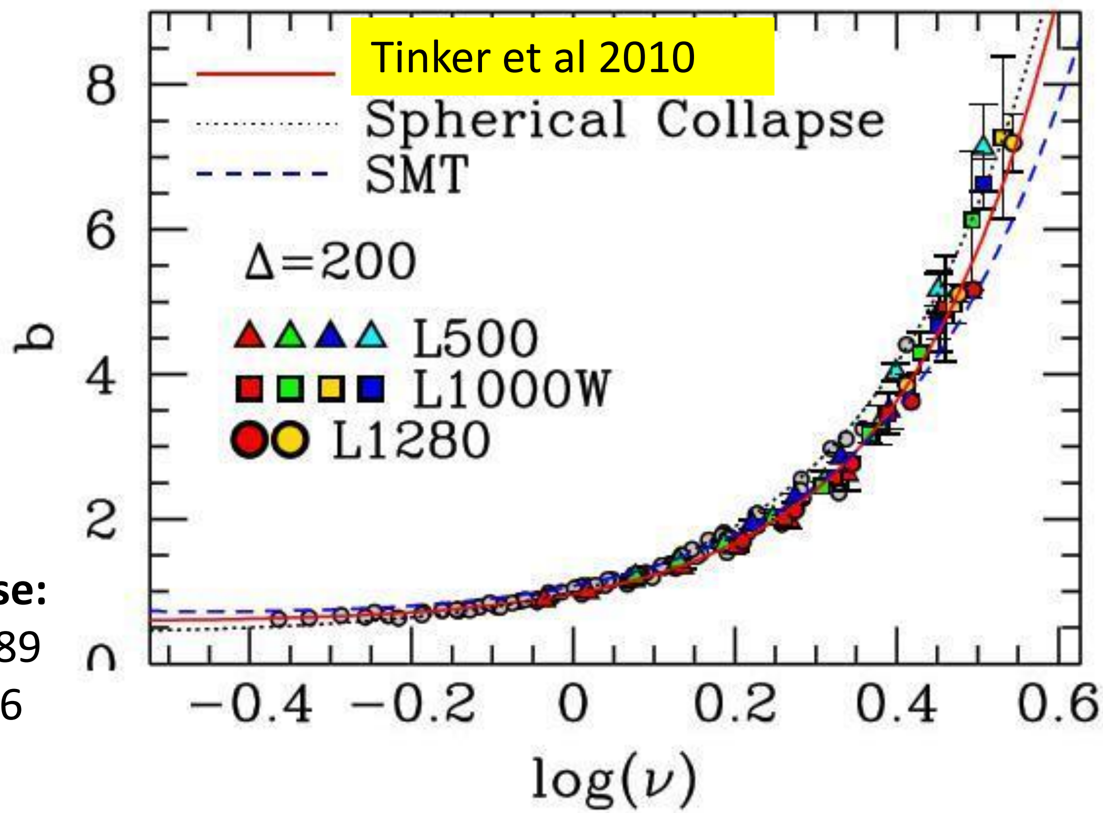
Halo clustering bias

Clustering unlocks this potential as large scale halo bias correlates well with halo mass.

$$b^2 = \xi_{\rm h}(r) / \xi_{\rm m,lin}(r)$$

$$b = 1 + \frac{\nu^2 - 1}{1.68}$$

Spherical Collapse:
Cole & Kaiser 1989
Mo & White 1996



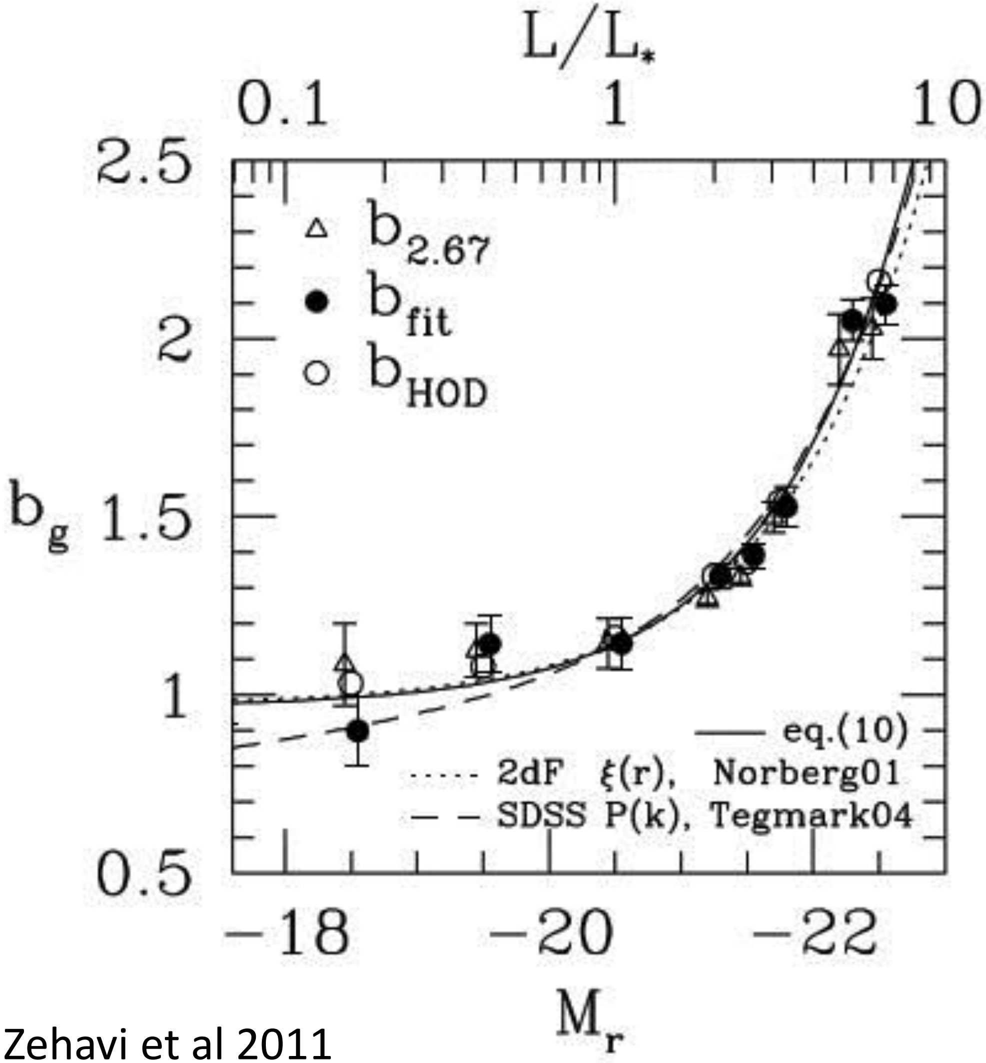
Sheth et al 2001 (**SMT**) -- analogous derivation using “elliptical collapse” mass function rather than Press-Schechter spherical collapse.

ν encodes halo mass through

$$\nu = 1.68/\sigma, \;\; \sigma^2(M) = \frac{1}{2\pi^2}\int P(k) W_M^2(k) k^2 dk$$

Tinker et al 2010 an empirical fit, b(ν), to simulation results.

Clustering as a function of X



Zehavi et al 2011

There is a wealth of observational data quantifying clustering as a function of galaxy property X
(e.g. see Alison Coil's talk)

This includes environmental dependence of galaxy properties as well as traditional correlation functions.

The choice of X is important.

SHAM illustration

Replace complicated astrophysics of galaxy formation by a simple ansatz.

Biggest galaxies form in the biggest (sub)haloes.

→ Galaxy stellar mass monotonically related to halo mass.

Note:

- There exist multiple galaxies per halo and so the mapping is between galaxies and subhaloes rather than haloes.
- The current mass of a subhalo is not the relevant quantiity as it will be tidally stripped long before its host galaxy. Hence label subhaloes by their mass at infall

$$n_{\mathrm{gal}}(>M_{\mathrm{stars}}) = n_{\mathrm{subhalos}}(>M_{subhalo})$$
$$\Rightarrow M_{\mathrm{stars}}(M_{\mathrm{subhalo}})$$

Main Development:
Kravtsov et al 2004
Vale & Ostriker 2004
Conroy et al 2006
Moster et al 2010
See also
Reddick et al 2013
Behroozi et al 2013

Aquarius, Springel et al 2008

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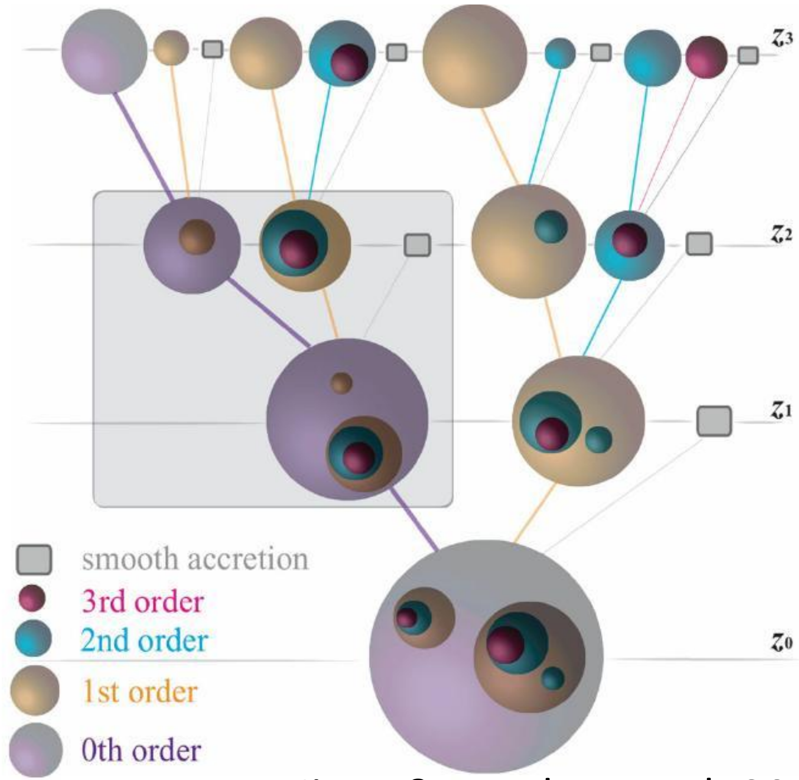
Galaxy luminosity sometimes used instead of stellar mass.
Scatter can be introduced into the relation .
Other proxies such as V_{max} exist..

SHAM illustration

Unlike HOD and CLF modelling, SHAM is making use of merger tree formation of each halo.

Also when employed in an N-body simulation it takes account of assembly bias.

The sub-haloes are a reflection of the merger tree.



Jiang & van den Bosch 2014

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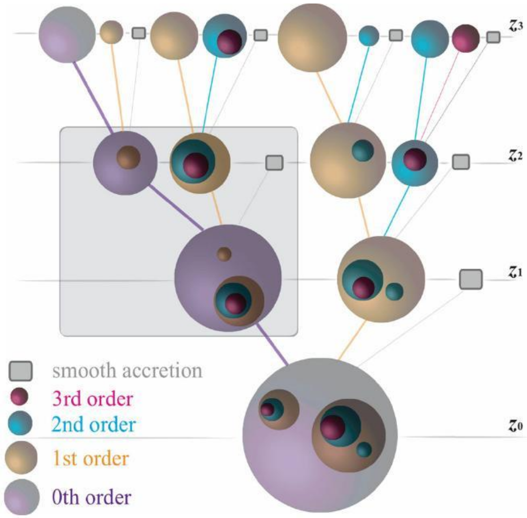

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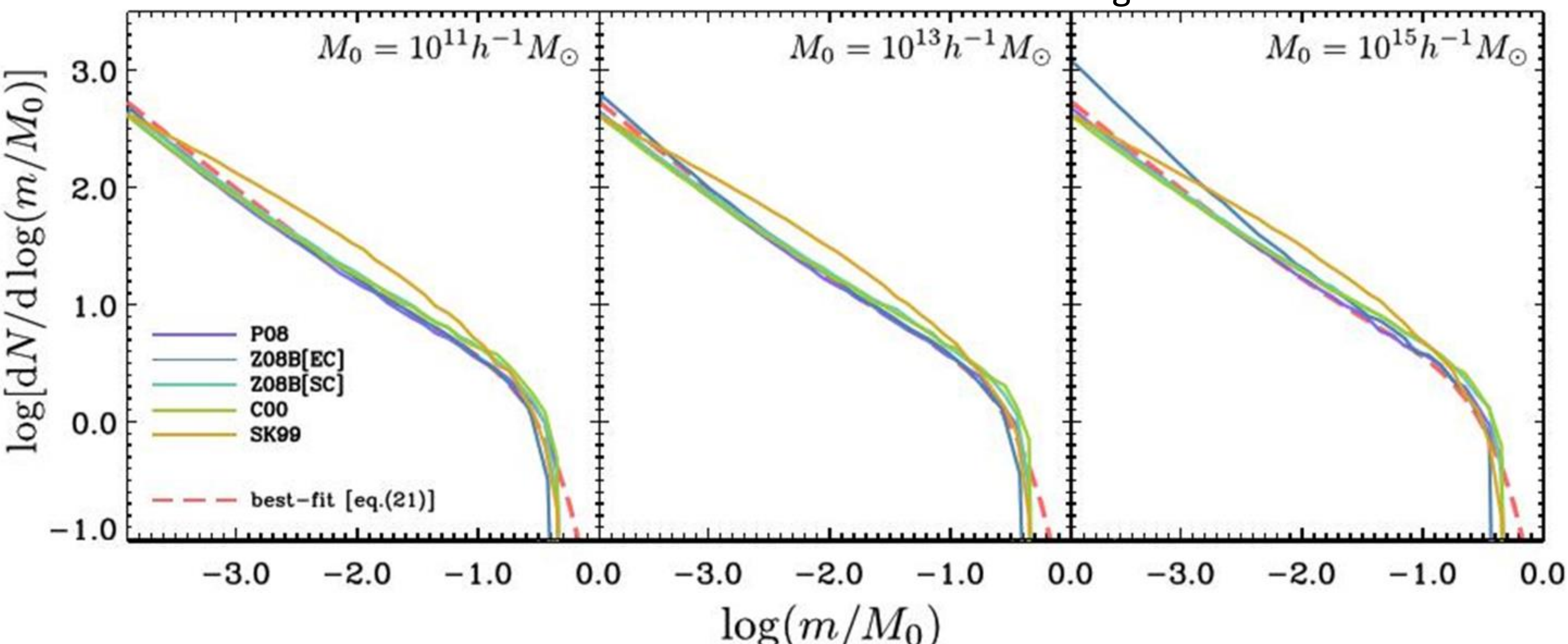
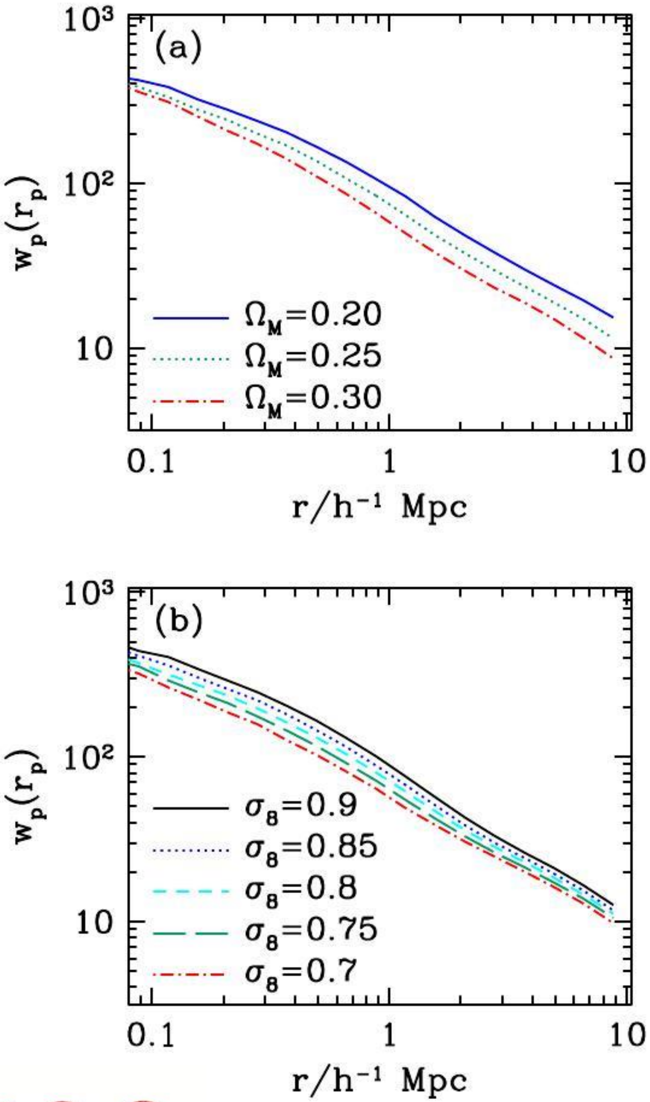


Does SHAM predict clustering?



With SHAM and dark matter only simulations we have the ingredients to predict how the clustering of a particular galaxy sample should depend on cosmological parameters.

- Choose cosmological parameters
- Rescale Millennium Simulations (Angulo & White 2010) so that input P(k) matches the linear theory (CAMB) expectation.
- Match abundances (SHAM)
- Populate the simulation
- Measure the clustering

Here we see that both decreasing Ω_m and increasing σ_8 boosts the clustering.

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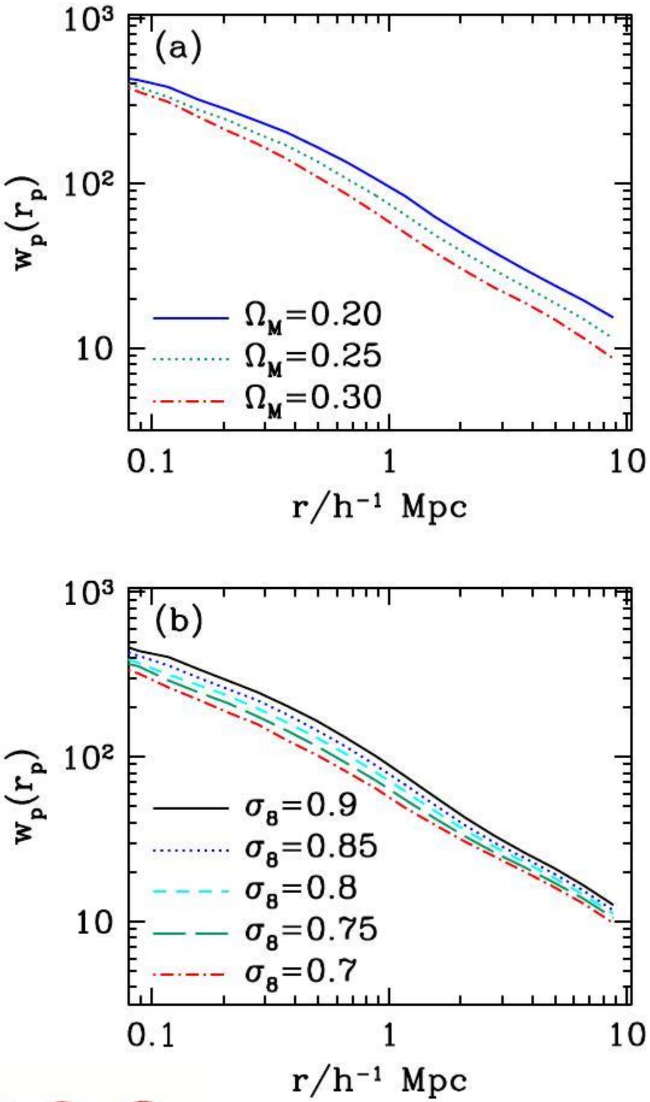

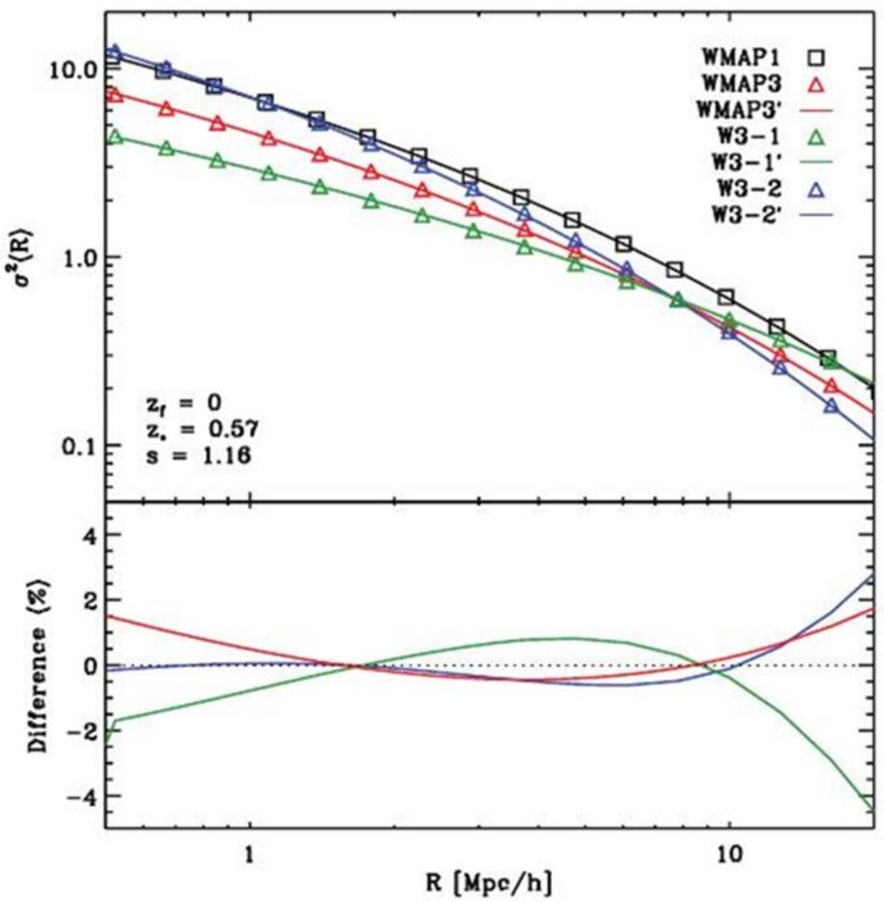

Angulo & White 2010

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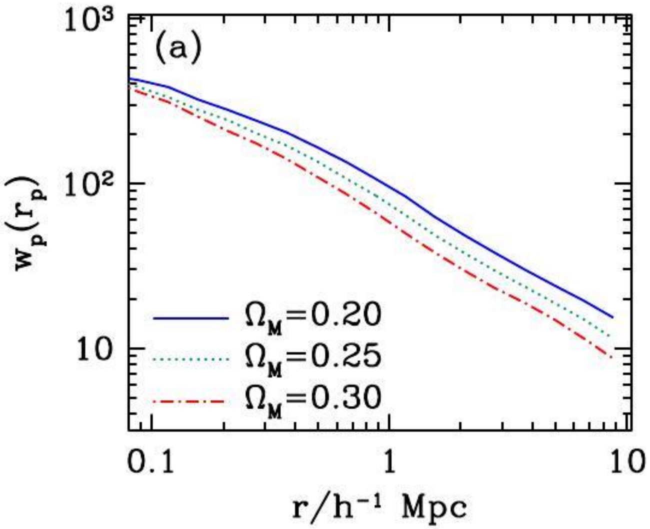

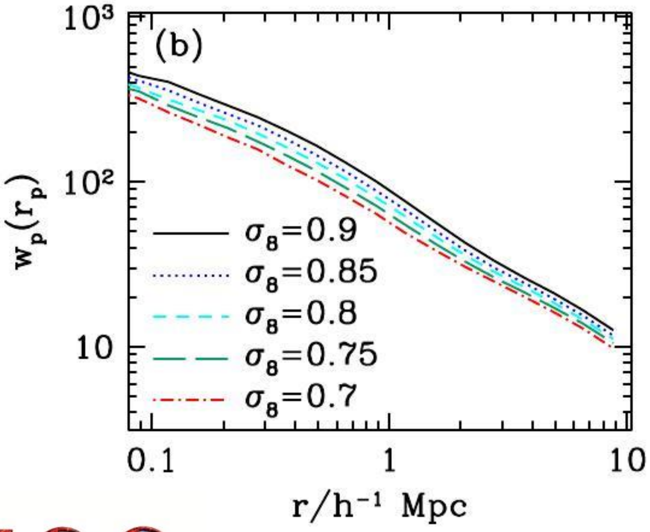

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$$w_p(r_p) = \int_{-\pi_{max}}^{\pi_{max}} \xi(r_p, \pi)\, d\pi$$

SHAM: fitted to SDSS

Take r-band volume limited SDSS sample (Zehavi et al 2011) and fit SHAM by varying $\Omega_m - \sigma_8$
and keeping all other cosmological parameters fixed

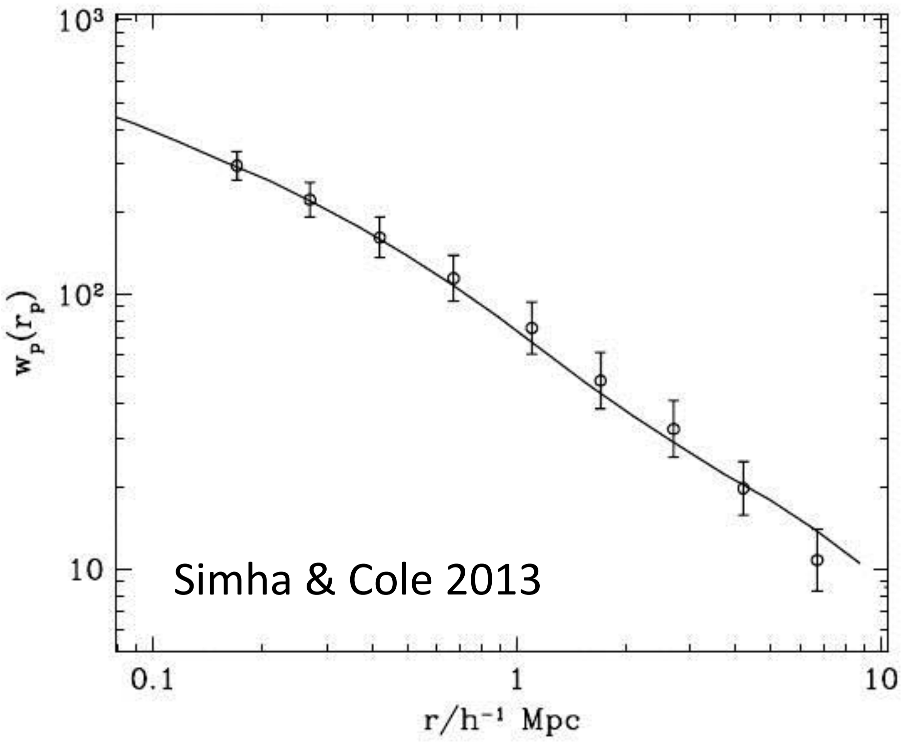


Figure 4. The solid curve is the galaxy two-point correlation function of our best-fit model with $\Omega_M = 0.275$ and $\sigma_8 = 0.86$. The points with error bars are the SDSS observed galaxy two-point correlation function from a volume limited sample of galaxies with $M_r \leq$ -18.0.

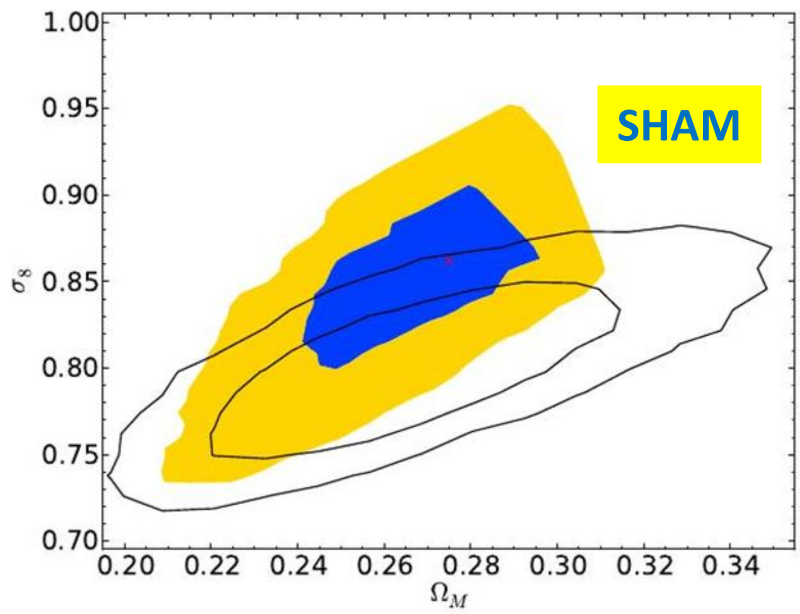


Figure 11. Joint constraint in the σ_8 - Ω_M plane. The inner contour shows the boundary of the 68% confidence region and the outer contour shows the 95% confidence region. The filled contour is the result from this work while the black solid open contours are from WMAP7 (Komatsu et al. 2011).

Predicted luminosity dependence

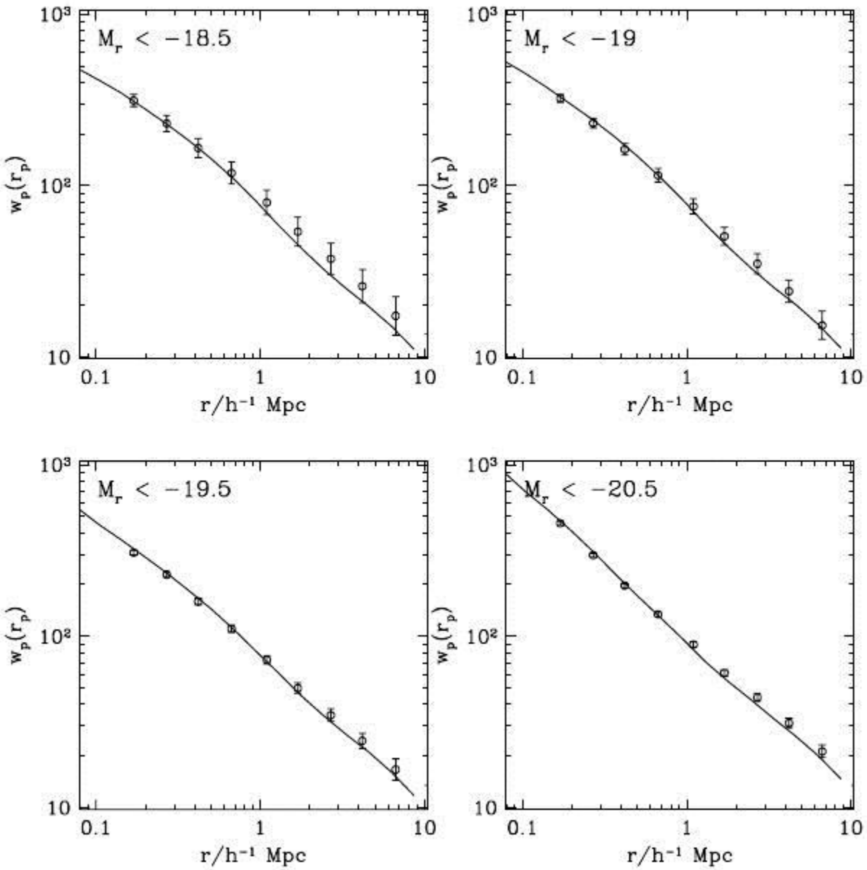


Figure 9. In each panel, the points with error bars are the SDSS observed galaxy two-point correlation function in a volume limited sample of galaxies brighter than M_r = -18.5, -19, -19.5 and -20.5. The solid curve in each panel is the galaxy two-point correlation function predicted by our best-fit model with $\Omega_M = 0.275$ and $\sigma_8 = 0.86$ for the corresponding galaxy sample.

Choice of luminosity threshold for the observational sample

All but the brightest are formally good fits.

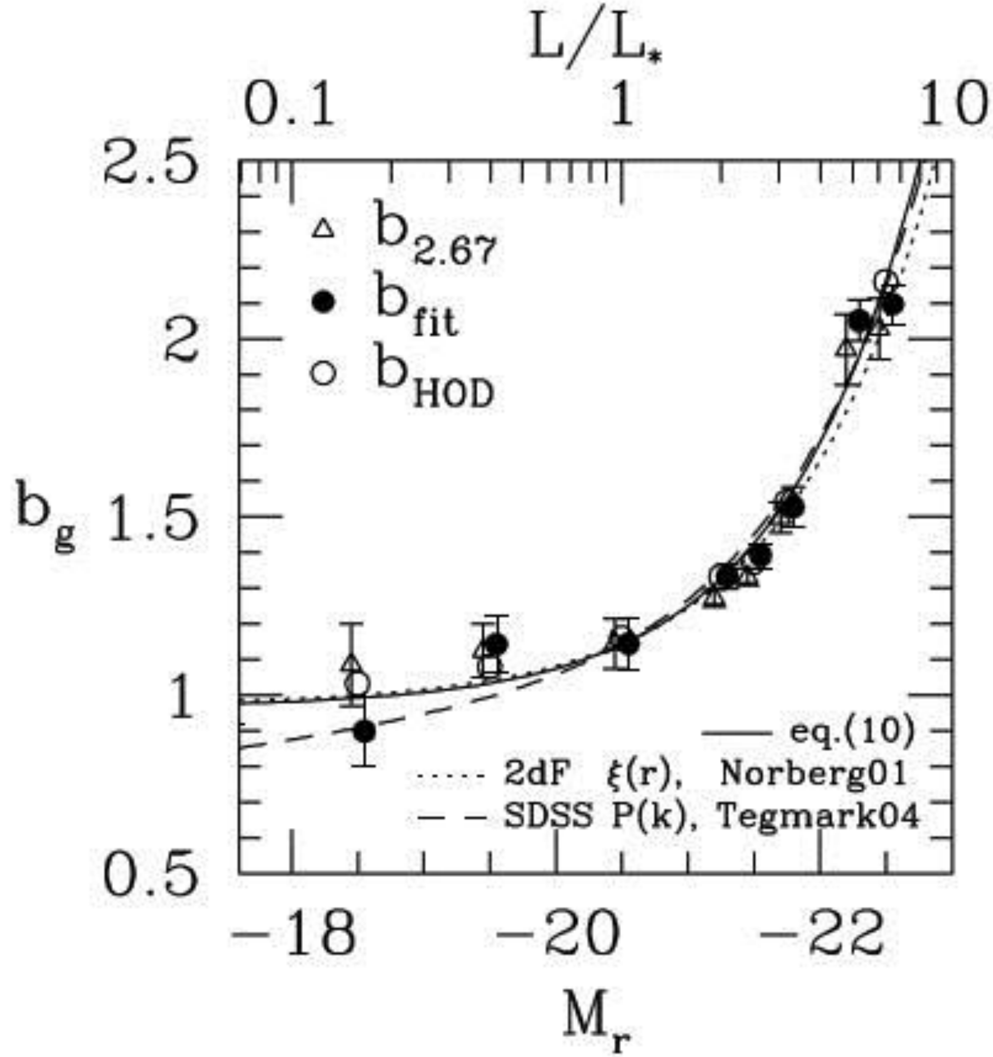
The volume of the largest sample is greater than the Millennium volume and so statistical error on the model prediction becomes important.

Simha & Cole 2013

Galaxy clustering and galaxy formation

→ Galaxy clustering as a function of galaxy properties and redshift place complementary and robust constraints on galaxy formation models.

There is a wealth of data from surveys such as 2dFGRS (Norberg et al 2001/02), SDSS (Zehavi et al 2002/05/11 and GAMA (Farrow et al 2014 in prep).



Zehavi et al 2011

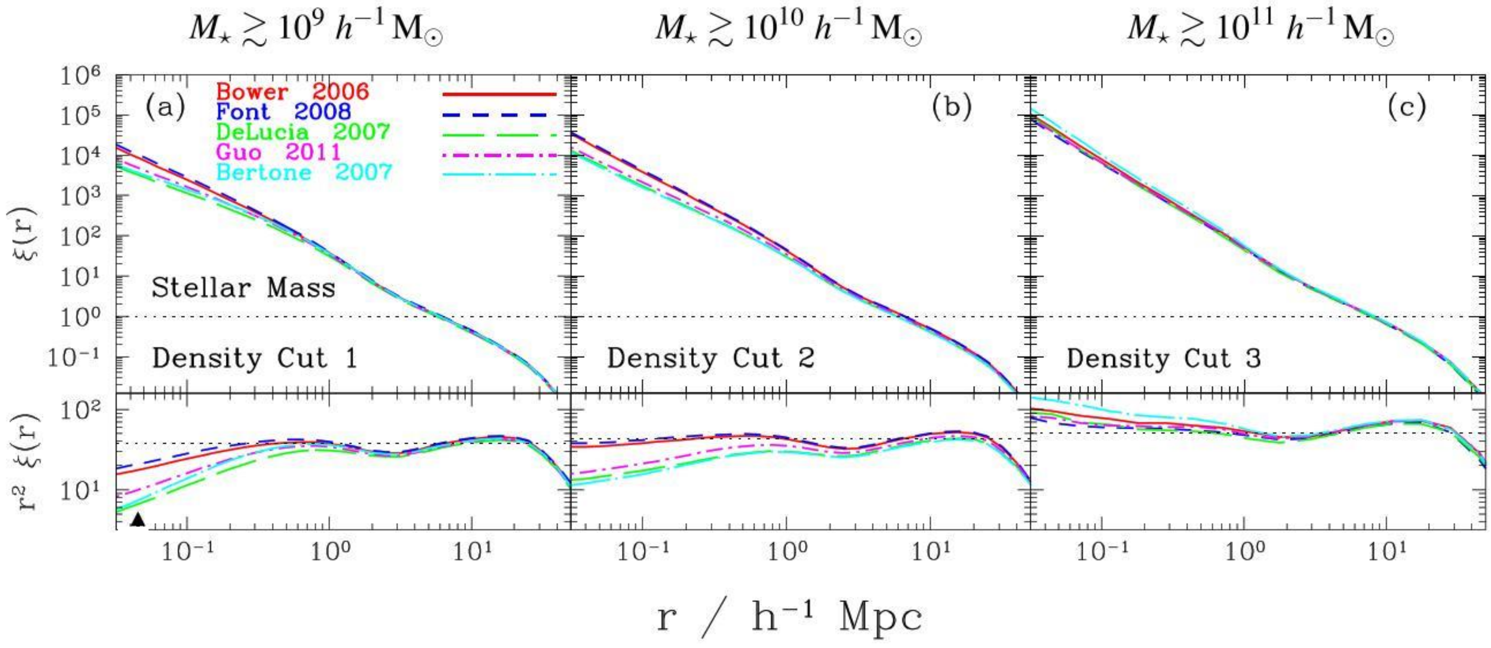
Beyond large scale bias

For a quantity that correlates well with stellar mass the success of SHAM implies large scale bias provides the same information as galaxy abundance.

$$b = \int b_{\text{halo}}(m) n(m|\text{gal}) dm / \int n(m|\text{gal}) dm$$

$$n_{\text{gal}} = \int n(m|\text{gal}) dm$$

A large variety of models produce the same large scale bias (Contreras et al 2013)

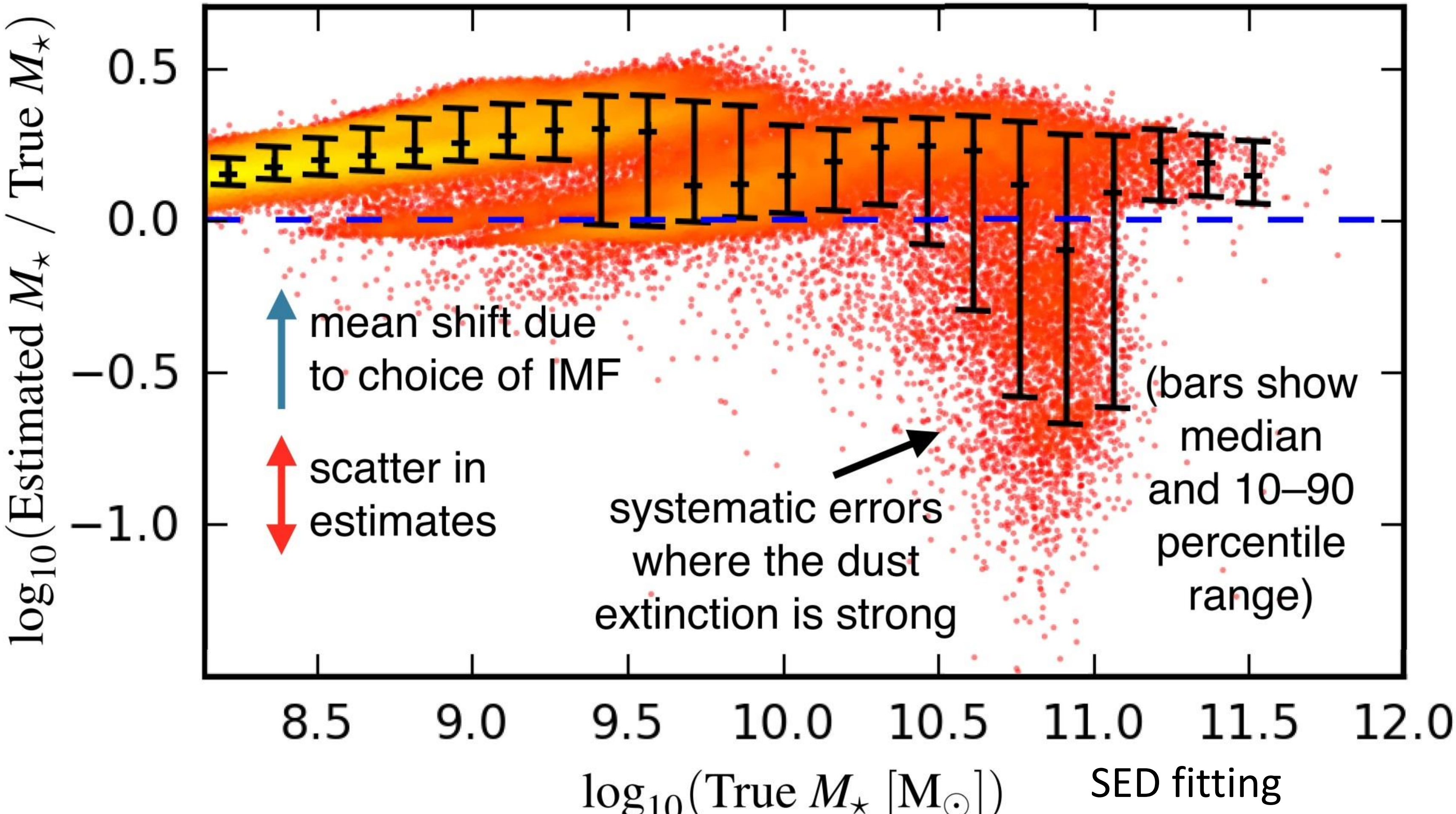


➔ Large scale bias gives information on scatter in $M_{\text{subhalo-}}$selection property

➔ Smaller scale clustering probes satellite abundance and properties

Clustering as a function of stellar mass

Insufficient to compare models selected by true stellar masses with observations selected by inferred stellar mass.
Scatter in the M_*-M_{halo} relation is important.



SED fitting
Mitchell et al 2013

Clustering as a function of stellar mass

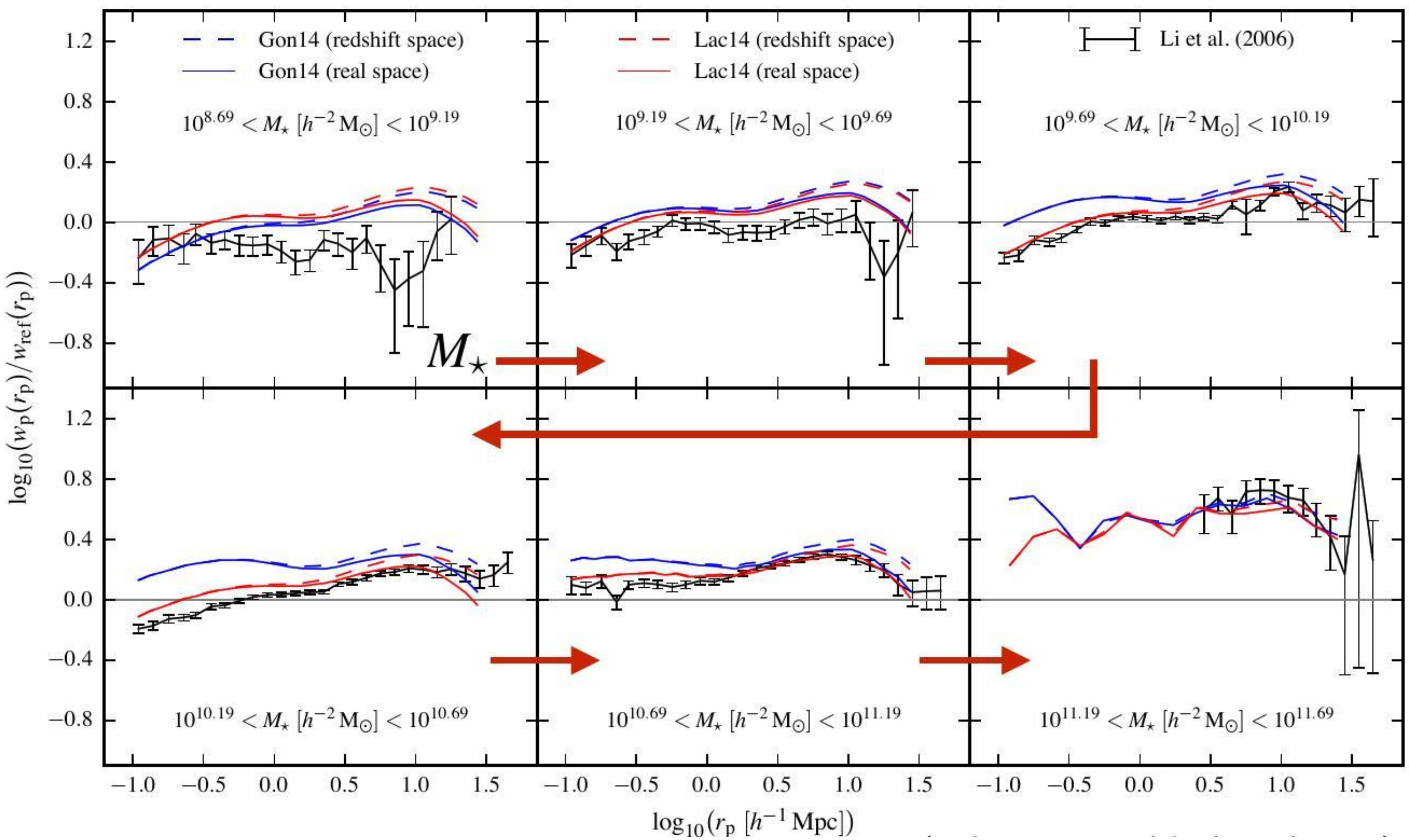
$$w_p(r_p) = \int_{-\pi_{max}}^{\pi_{max}} \xi(r_p, \pi)\, d\pi$$

for samples selected on estimated stellar mass

Galform Models:
Both WMAP7 cosmology

Gonzalez et al 2014 ("retuned" Lagos et al 2012)
Bruzual & Charlot SPS

Lacey et al 2014
Top heavy (x=0) IMF in bursts
Maraston SPS

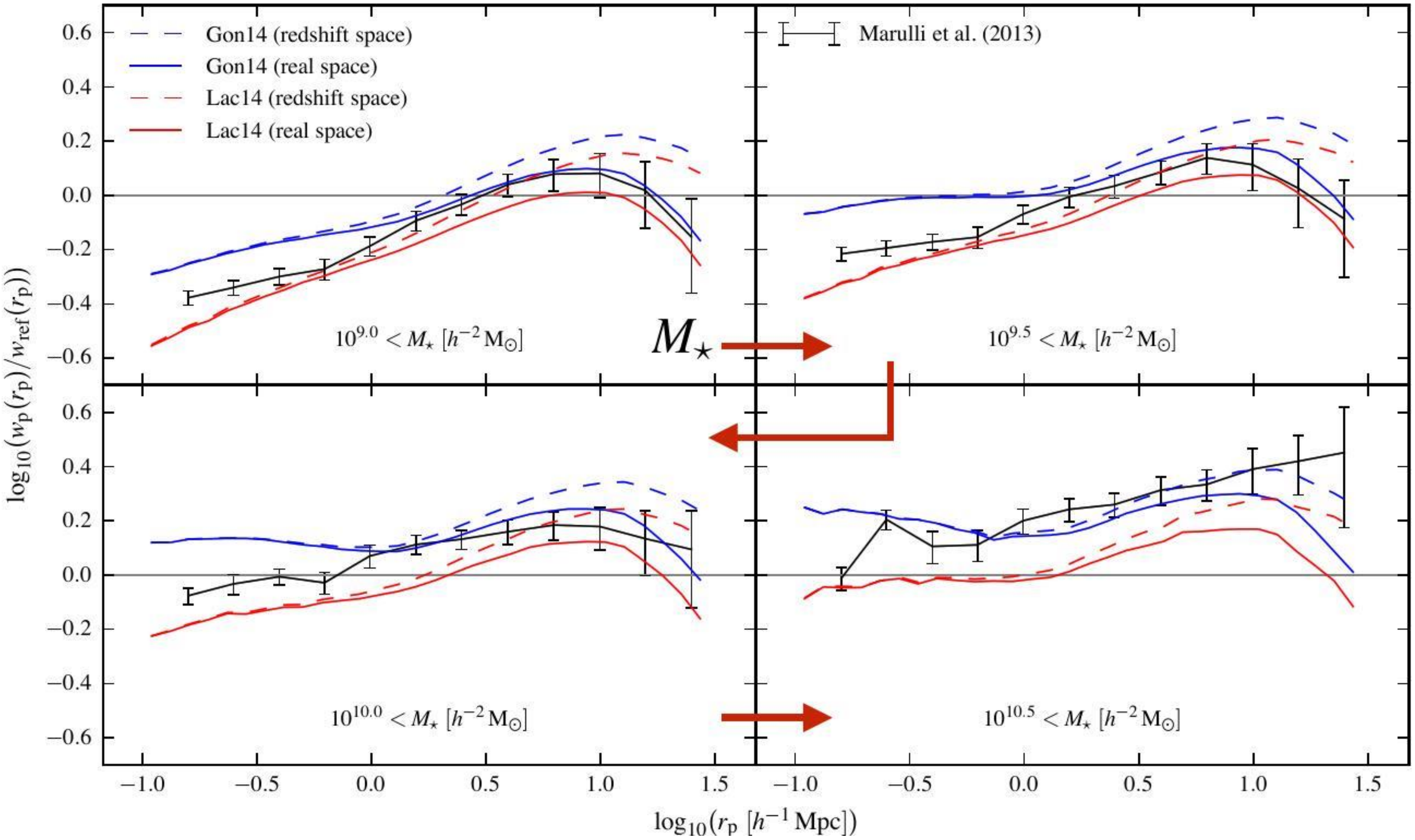


NB Boosted in redshift space as π integration limits match observations rather than extending to infinity

Campbell et al 2014 in prep
SDSS data: Li et al 2006

Clustering as a function of stellar mass

Extension to higher redshift using VIPERS
(Marulli et al 2013) at z=0.6



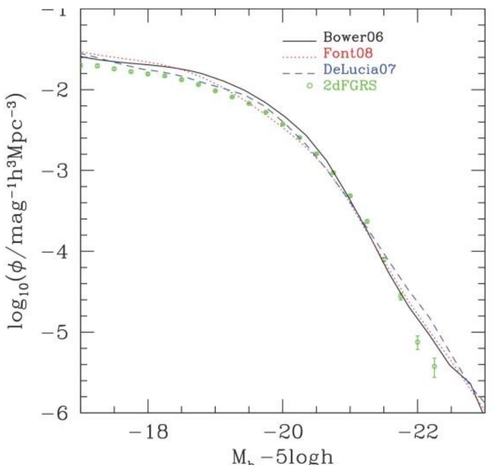
Campbell et al 2014 in prep

Luminosity dependence and satellites

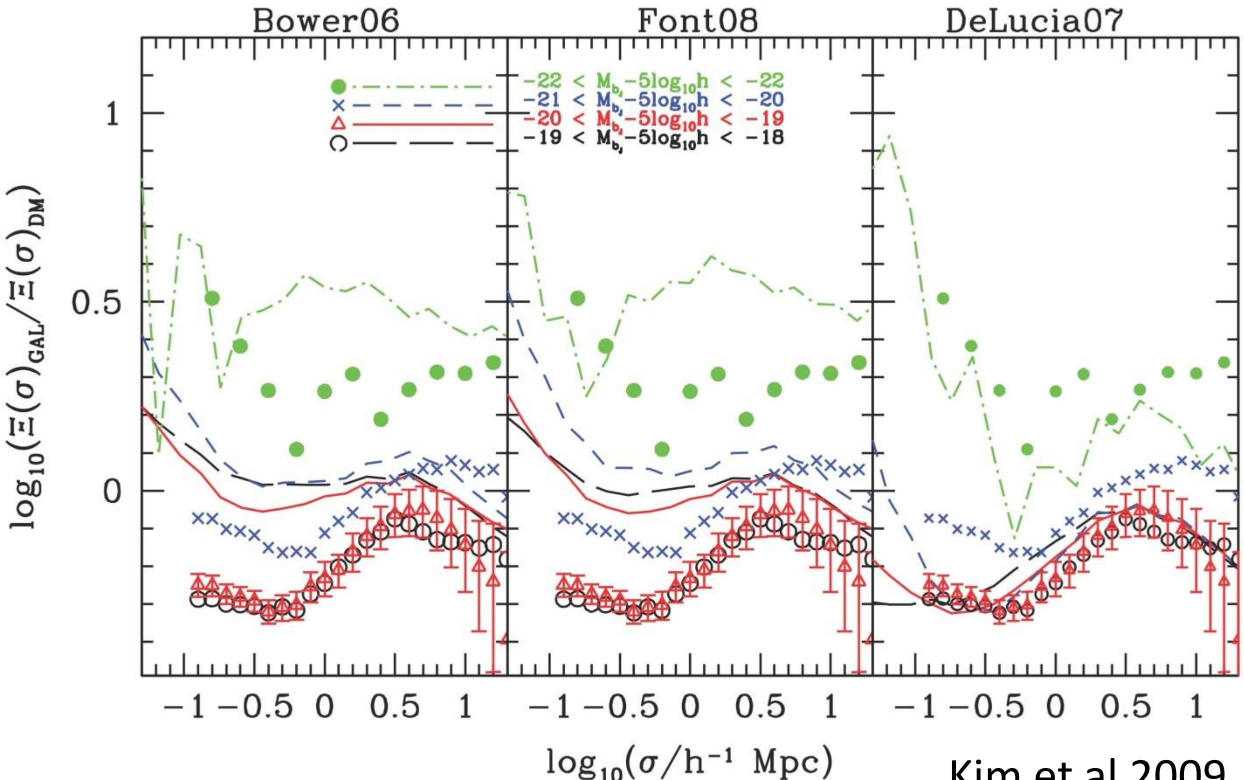
Compare a variety of semi-analytic models to the SDSS

(Zehavi et al 2005) clustering.

All models are good matches to the SDSS luminosity function



The "Munich" model produces the range of clustering but not the gradual dependence. The "Durham" models lack the range

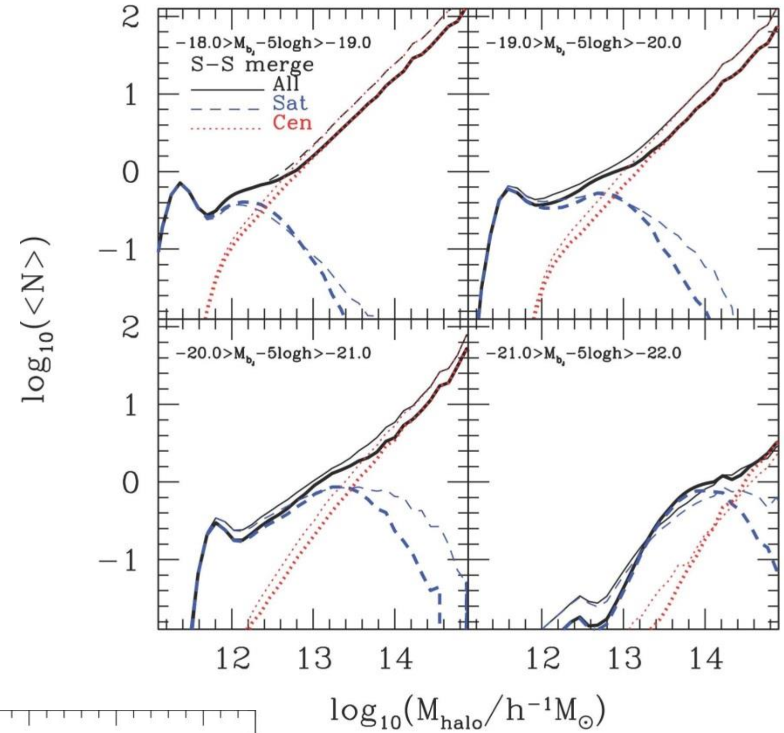


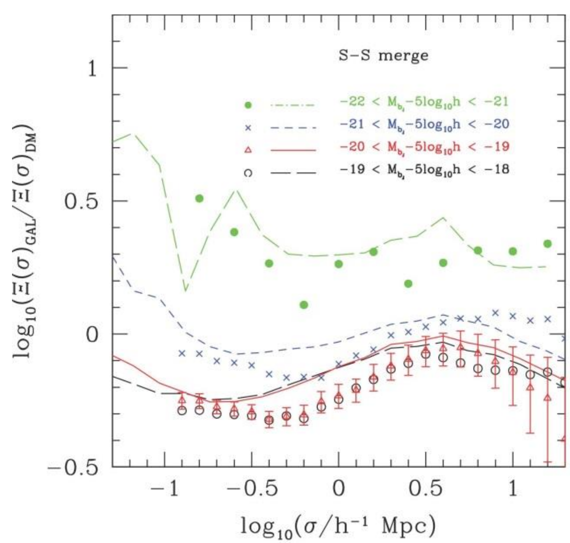
Kim et al 2009

Luminosity dependence and satellites

Kim et al (2009) found that reducing the satellite fraction in these models was key to producing a better match to the data.

This could be done by either disrupting or merging satellites.





Kim et al 2009

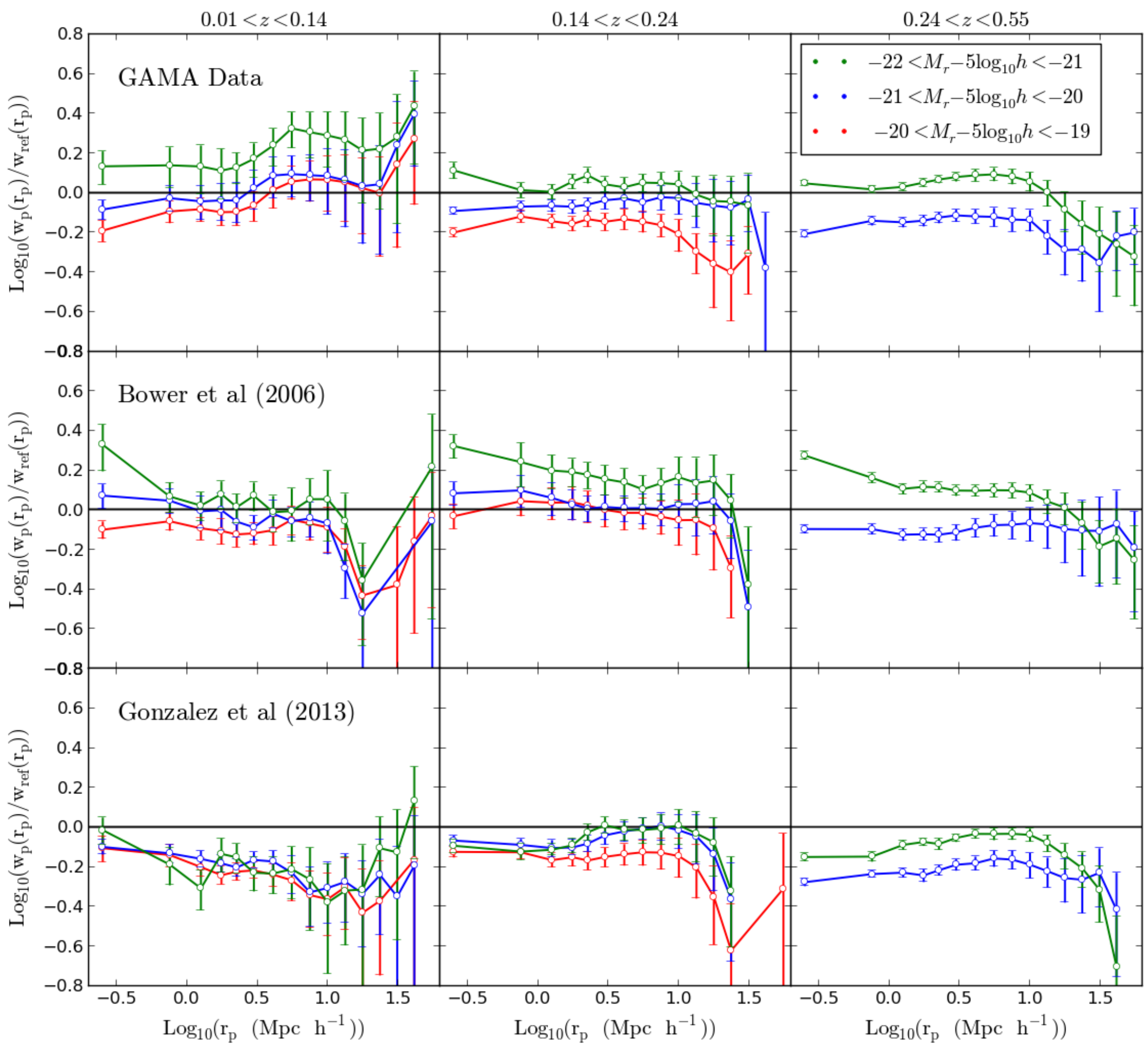
Luminosity and redshift dependence

GAMA: 3x60 sq deg to r=19.8

Projected correlation function divided by a reference power law.

All estimates from lightcone data.

Jackknife errors.

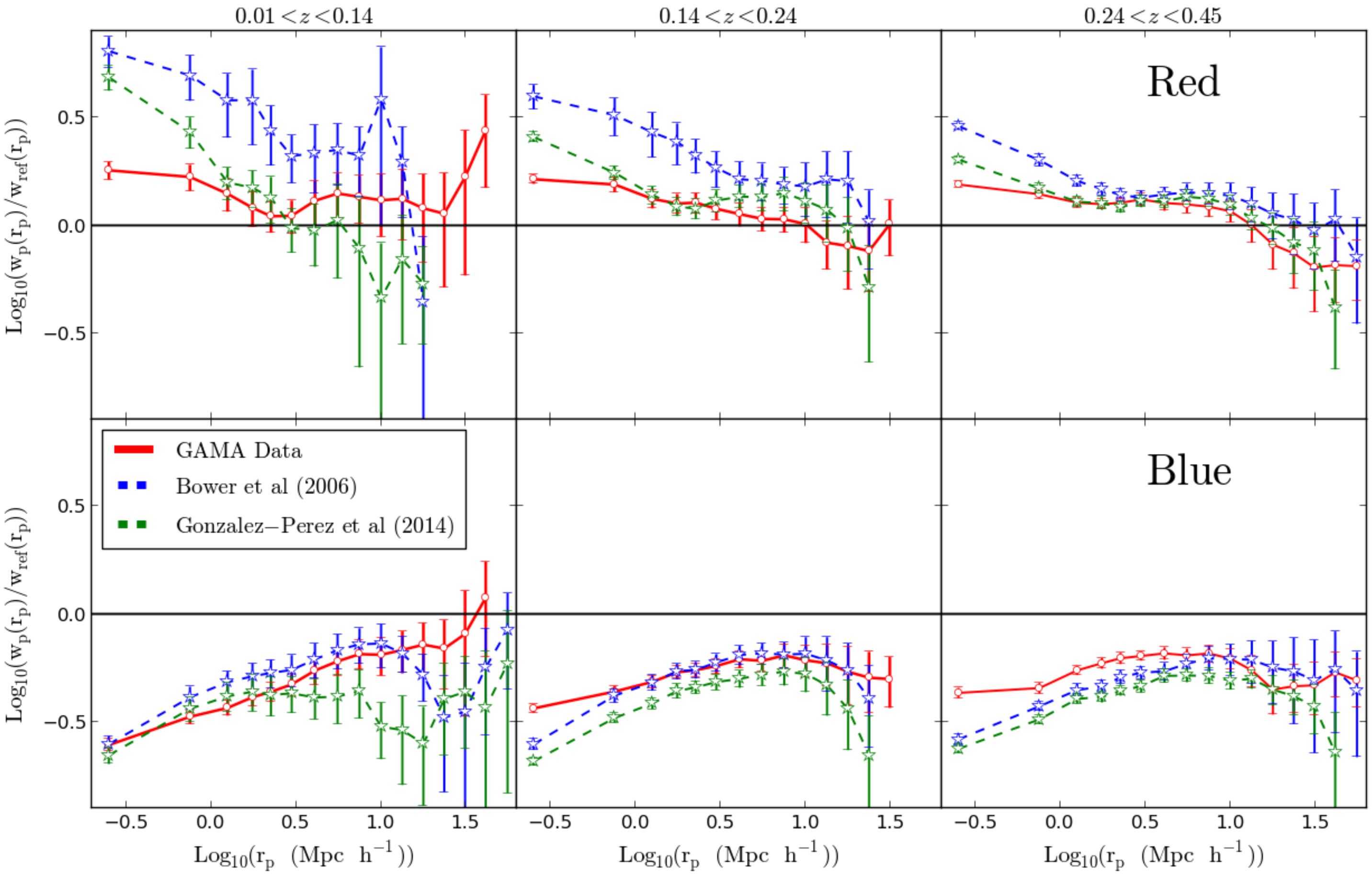


Farrow et al 2014 (Gonzalez results preliminary)

Clustering dependence on colour & z

Galaxy population split by red-blue bimodality.

Models reproduce the stronger clustering of red galaxies but with too many red satellites.



Preliminary

GAMA– Farrow et al 2014

AGN clustering and Galaxy Formation

Clustering studies of AGN can similarly constrain the mass of haloes that host the AGN.

This can be done as a function of a variety of AGN properties, X.

Again the choice of X

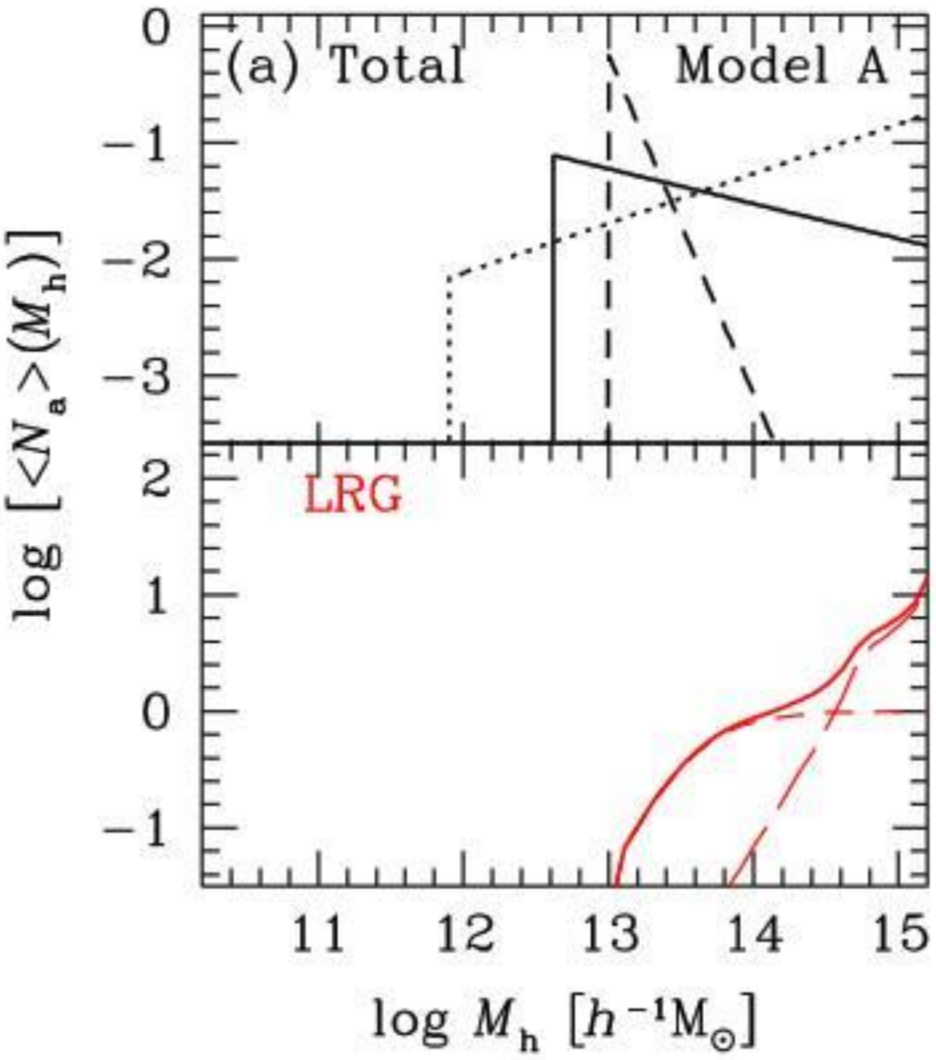
(e.g. Obscured/Unobscured,

Radio loudness, X-ray luminosity)

Is what allows you to answer interesting questions.

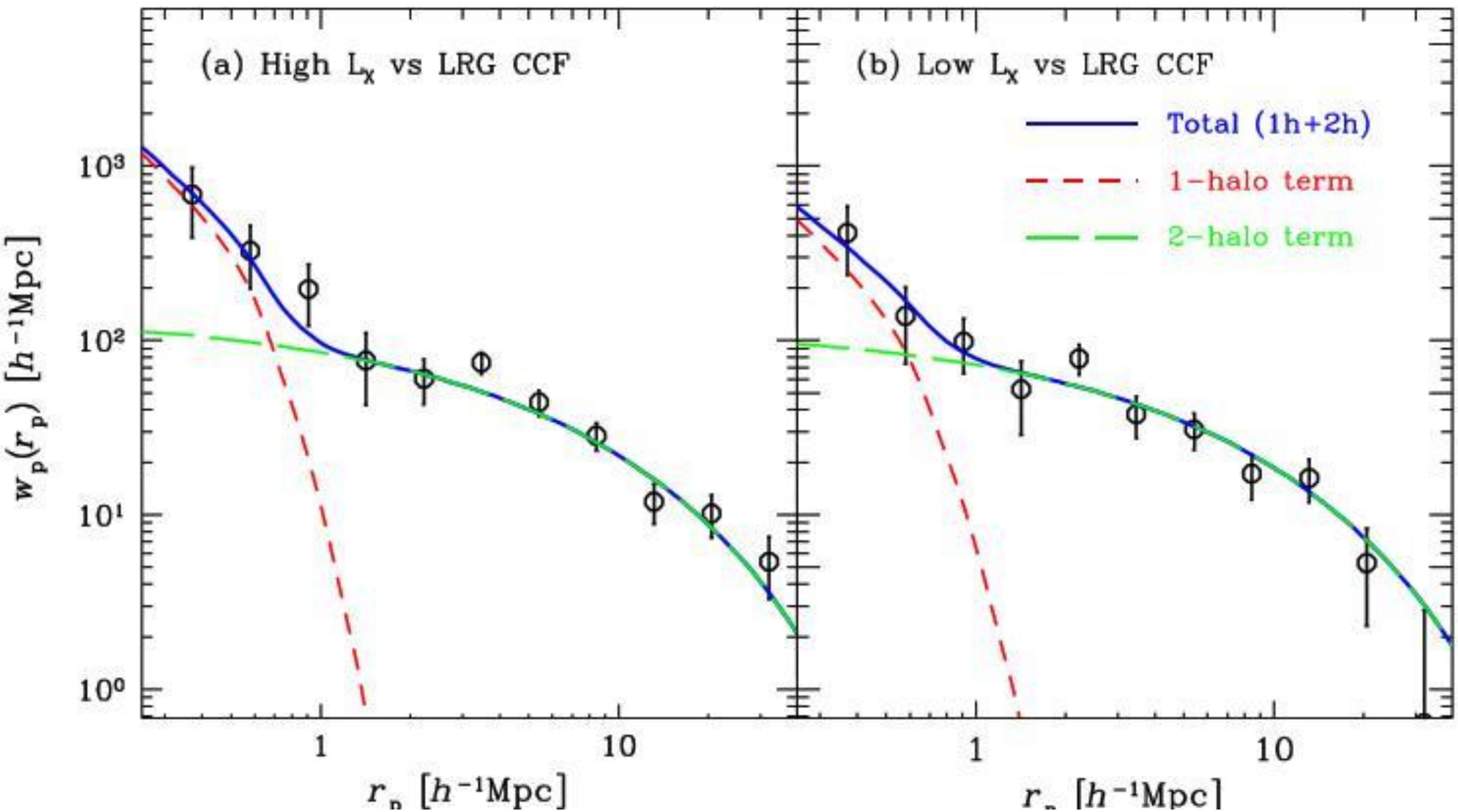
The major difference as compared to clustering as a function of galaxy stellar mass is the AGN duty cycle.

Large scale clustering strength not degenerate with abundance.



Miyaji et al 2011

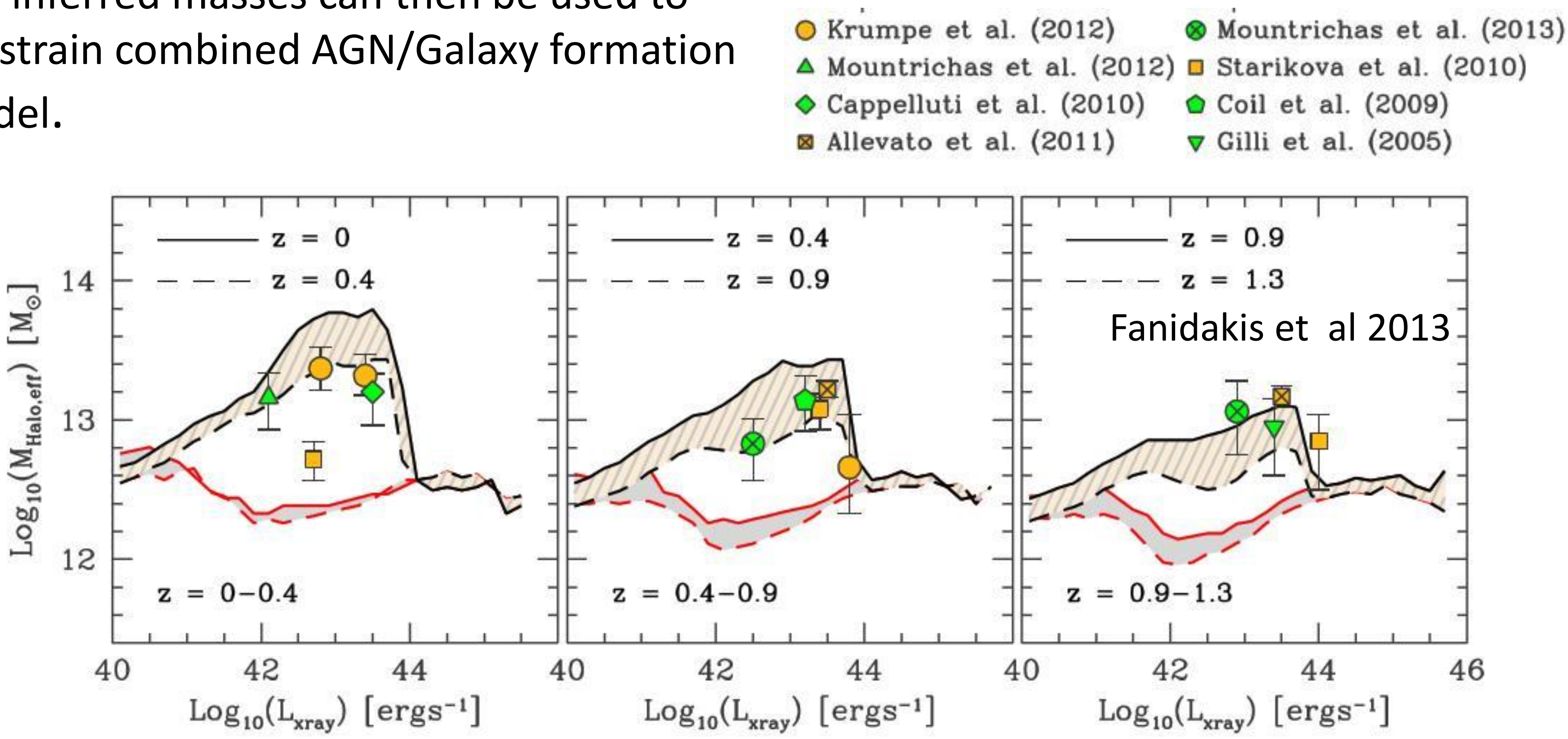
AGN projected correlation function dependence on X-ray luminosity



Miyaji et al 2011

Constraints on AGN evolution models

The inferred masses can then be used to constrain combined AGN/Galaxy formation model.



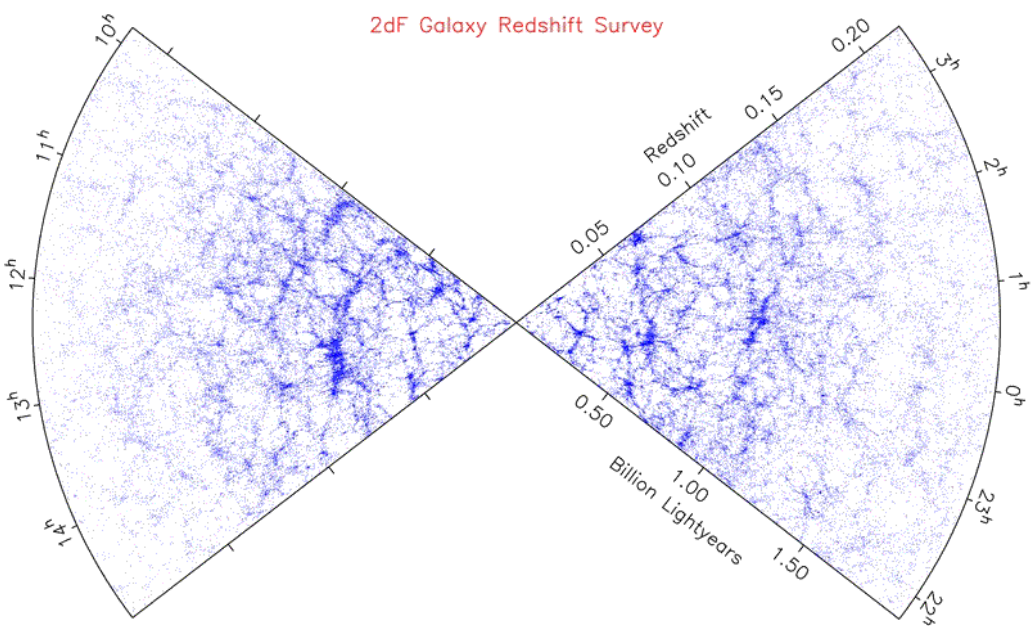
Red: AGN only accreting in starburst mode
Black: AGN also accrete from hot halo

Galaxy clustering and cosmology

Large scale probes of the linear regime

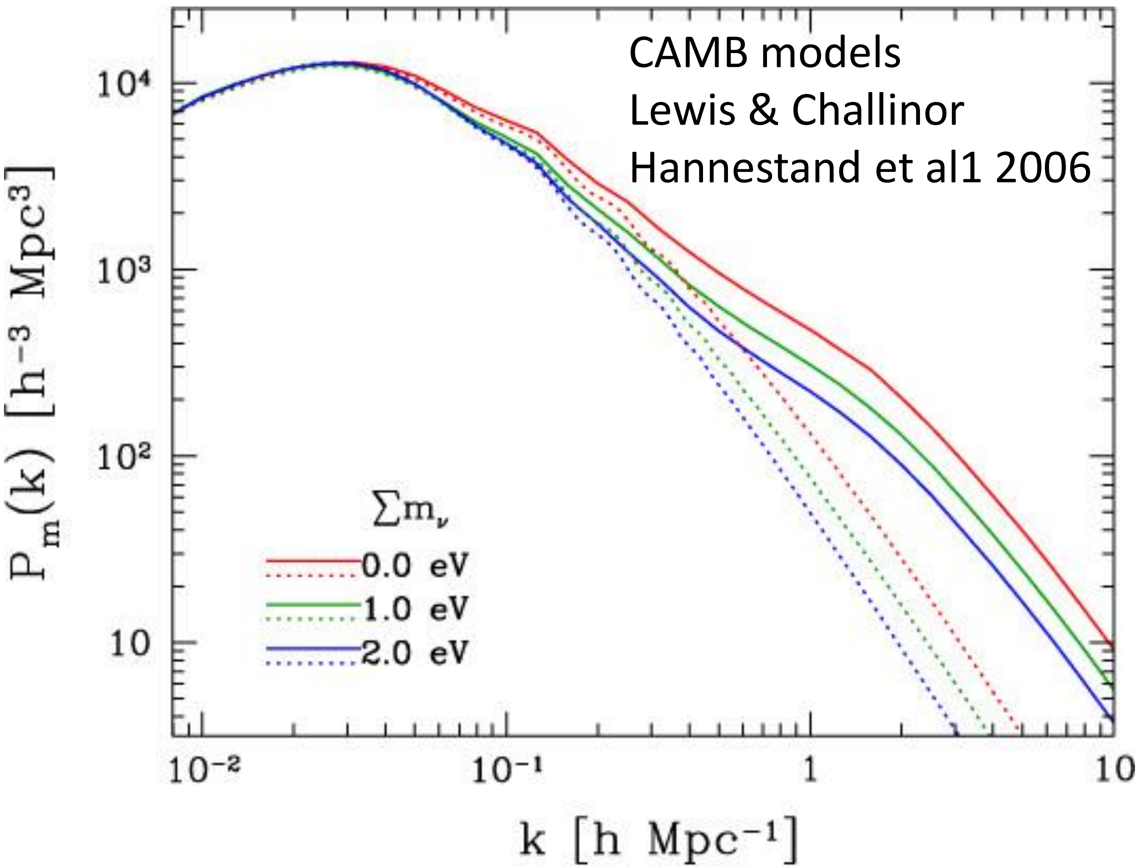
(r>100 Mpc/h, k < 0.1 h/Mpc)

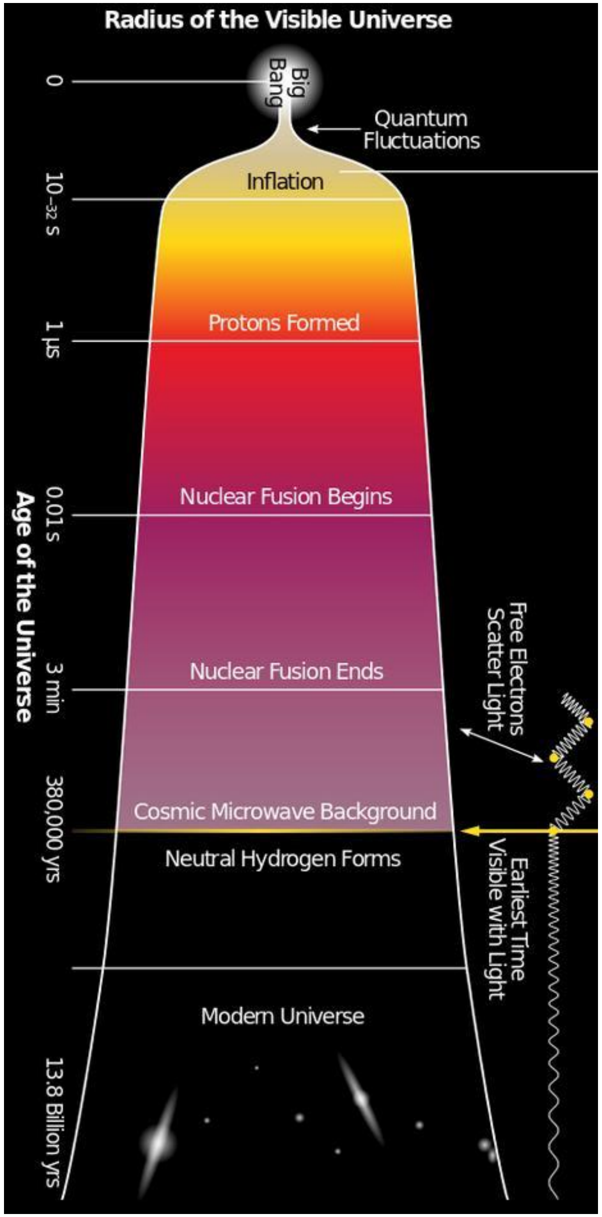
of galaxy clustering allow one to directly constrain cosmological models.



The imprint of the Early Universe

The physics of the early Universe imprints different length scales onto the fluctuation spectrum



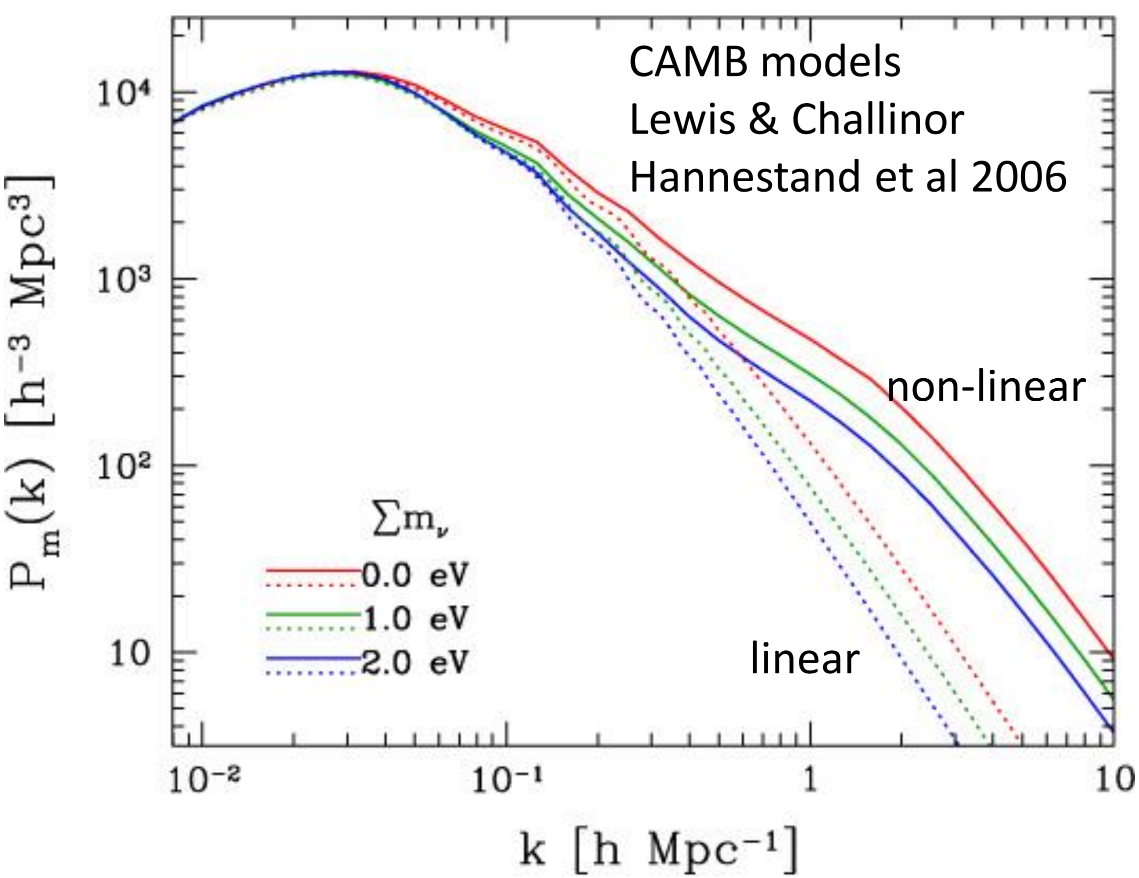


The Imprint of the Early Universe

The physics of the early Universe imprints different length scales onto the fluctuation spectrum

$$l_{eq} = \int_0^{t_{eq}} \frac{c}{a} dt \approx \frac{2ct_{eq}}{a_{eq}}$$

$$l_{eq} \rightarrow z_{eq} \rightarrow \Omega_m h$$



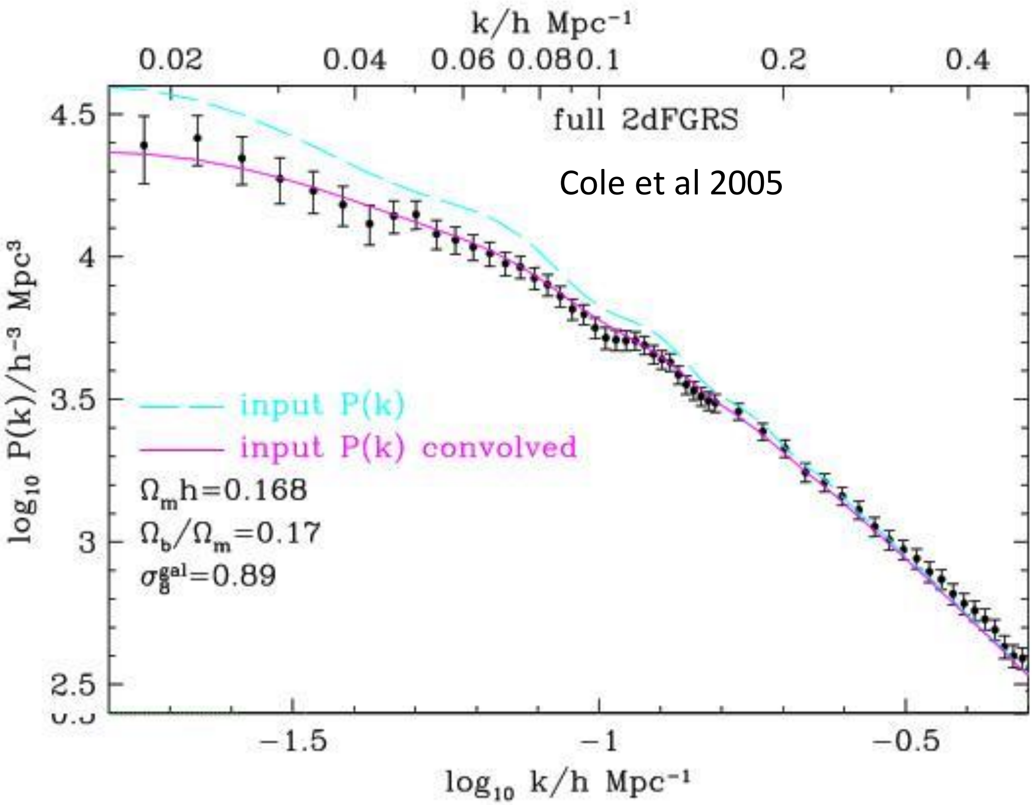
$$l_{BAO} = \int_0^{t_{rec}} \frac{c_s}{a} dt \approx \frac{ct_{rec}}{\sqrt{3} a_{rec}}$$

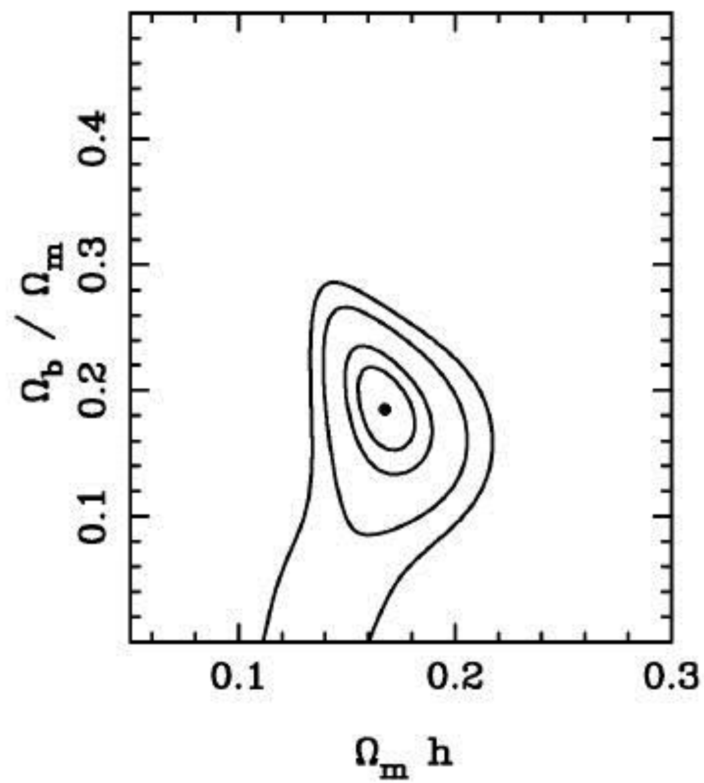
Amplitude $\rightarrow \Omega_b / \Omega_m$

Scale fixed

Cosmology from galaxy LSS

E.g. 2dFGRS galaxy power
spectrum shape constrained $\Omega_m h$ by constraining the large scale turnover and
Ω_b through the detection of BAO.



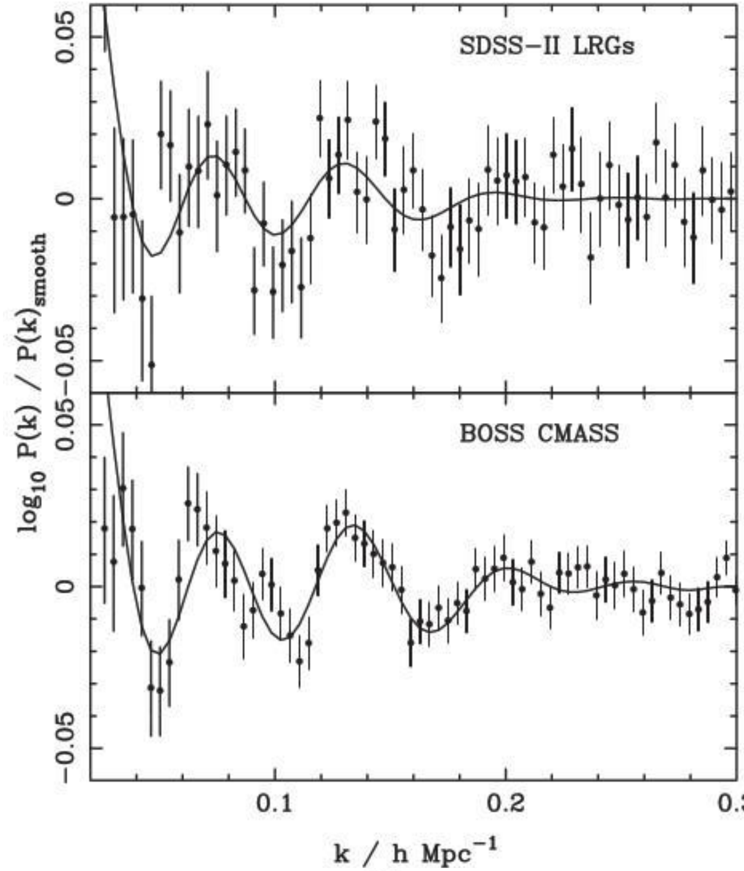


Future LSS constraints

Now the goal is to measure the BAO scale at a variety of redshifts.

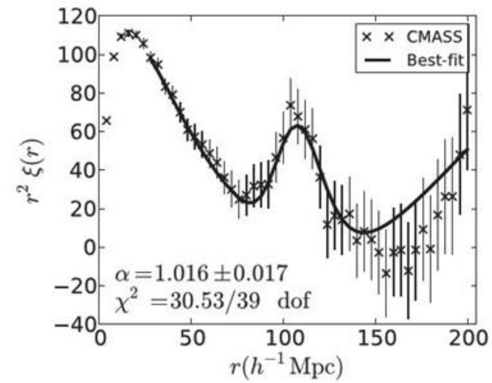
The BAO “yardstick” provides a geometric measure of distance and hence of the expansion history of the Universe.

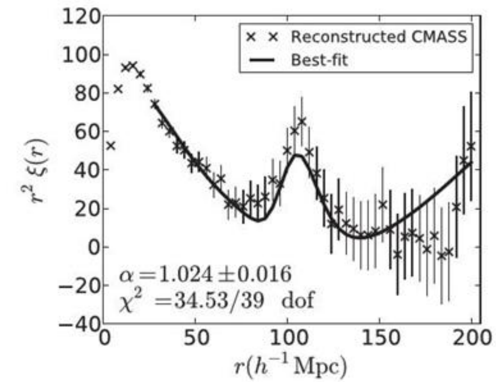
→ Constraints on Dark Energy



Since the original detection in 2dFGRS and SDSS LRGs the bar has been raised by precision measurements from BOSS.

Anderson et al 2012

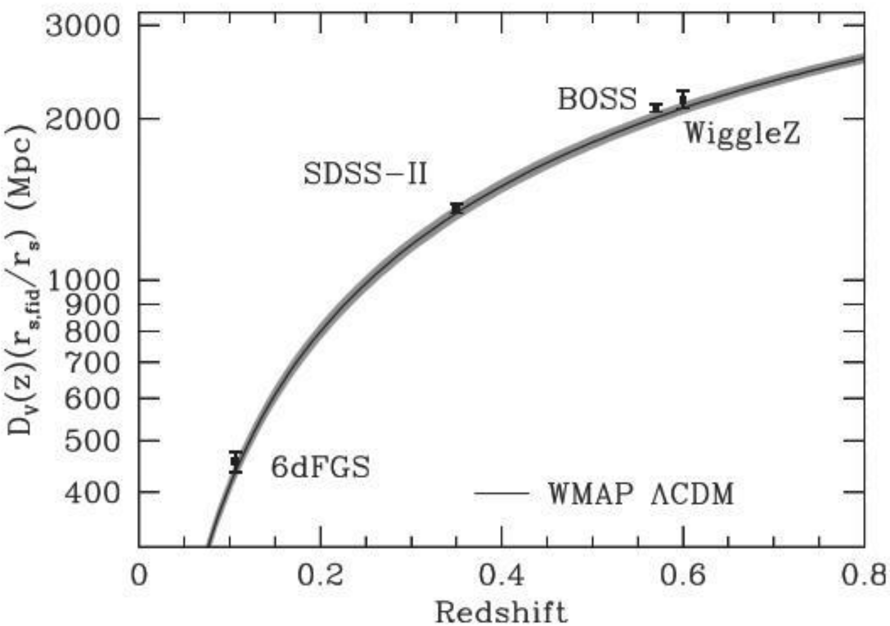


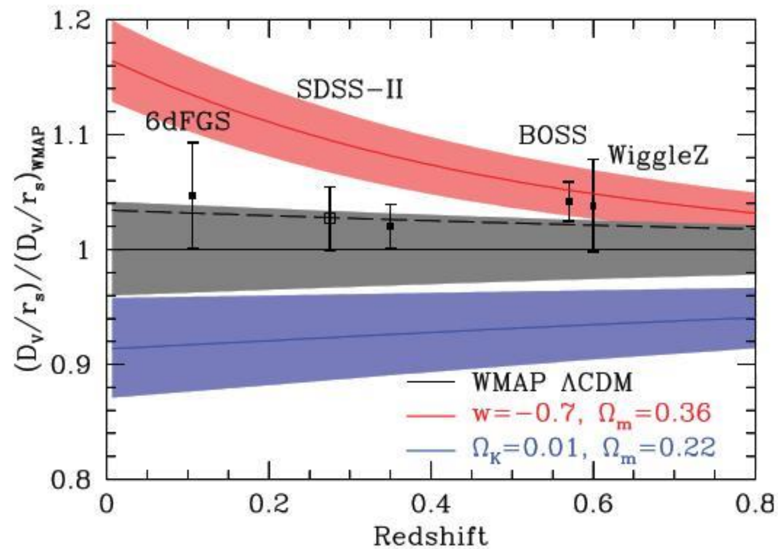


Dark Energy constraints

Constraints on the distance-redshift relation translate to parameter constraints on DE models.

$$P_{\mathrm{DE}} = w\rho_{\mathrm{DE}}c^2$$



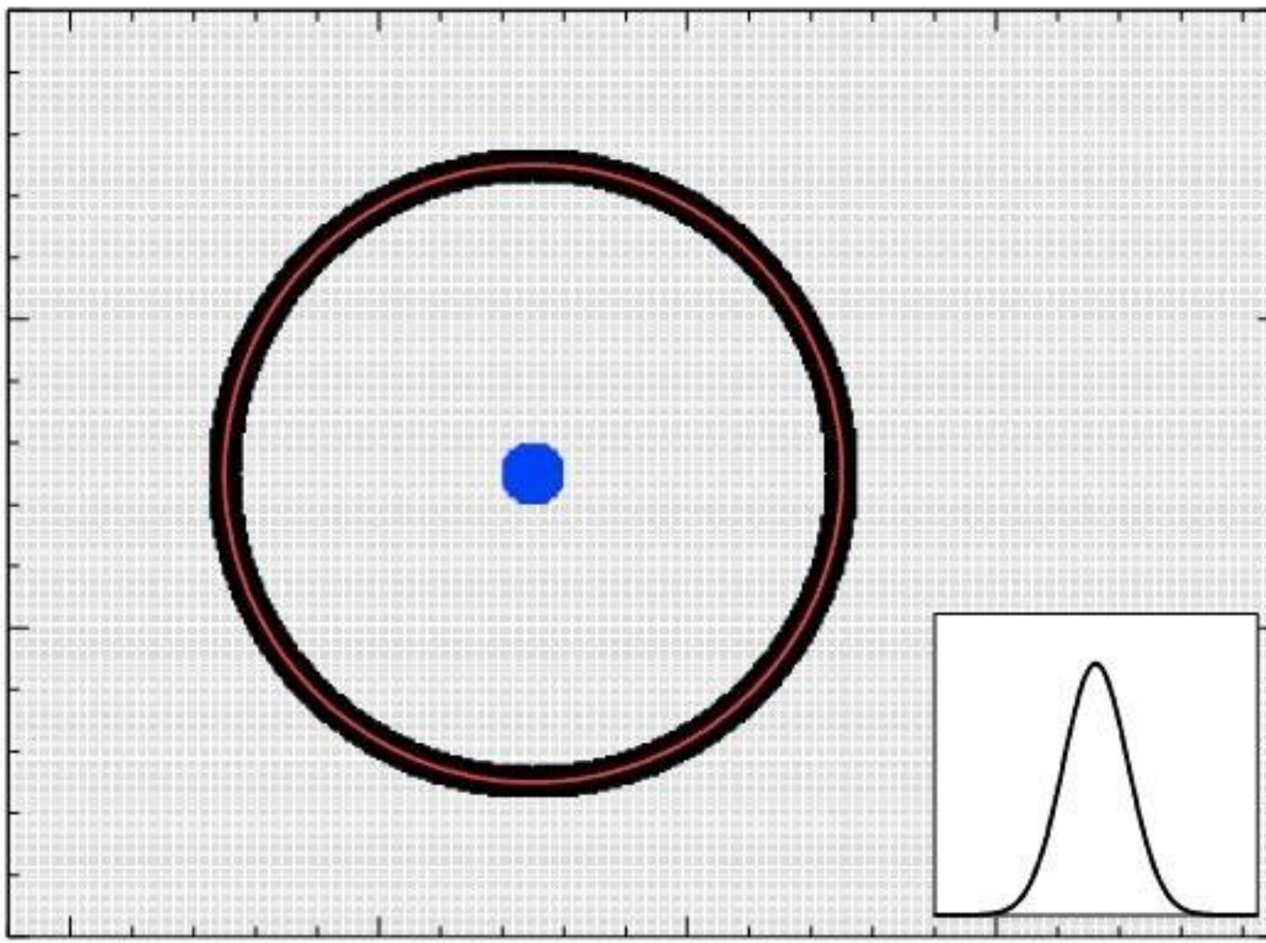


Anderson et al 2012

BAO reconstruction

One innovation in BAO measurement is reconstruction, where one attempts to undo the distortion of the BAO scale that is caused by peculiar motions.

This requires a high enough density of tracers to have a prediction of peculiar motions that is not noise dominated.



Padmanabhan et al 2012, Eisenstein et al 2007

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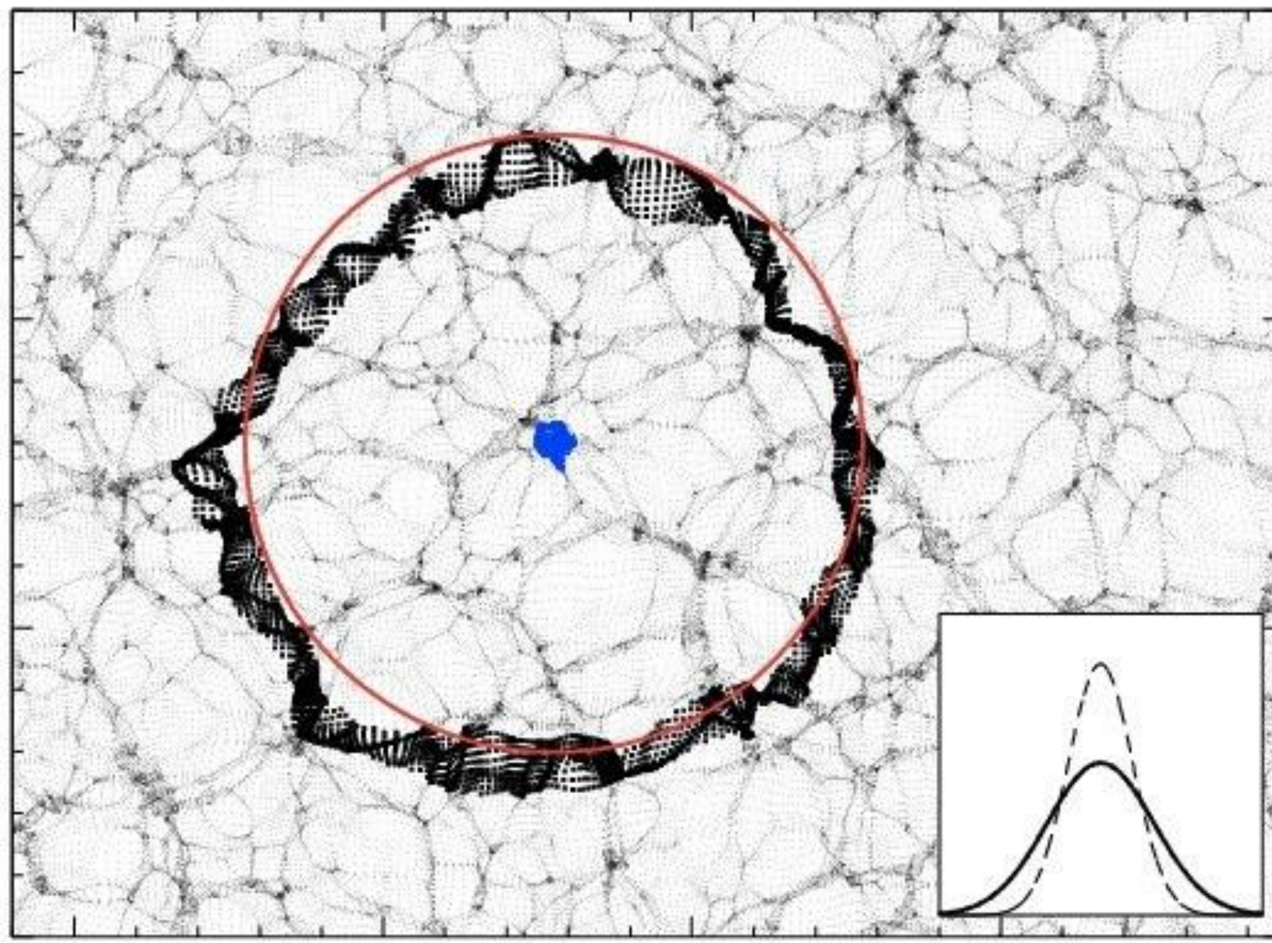

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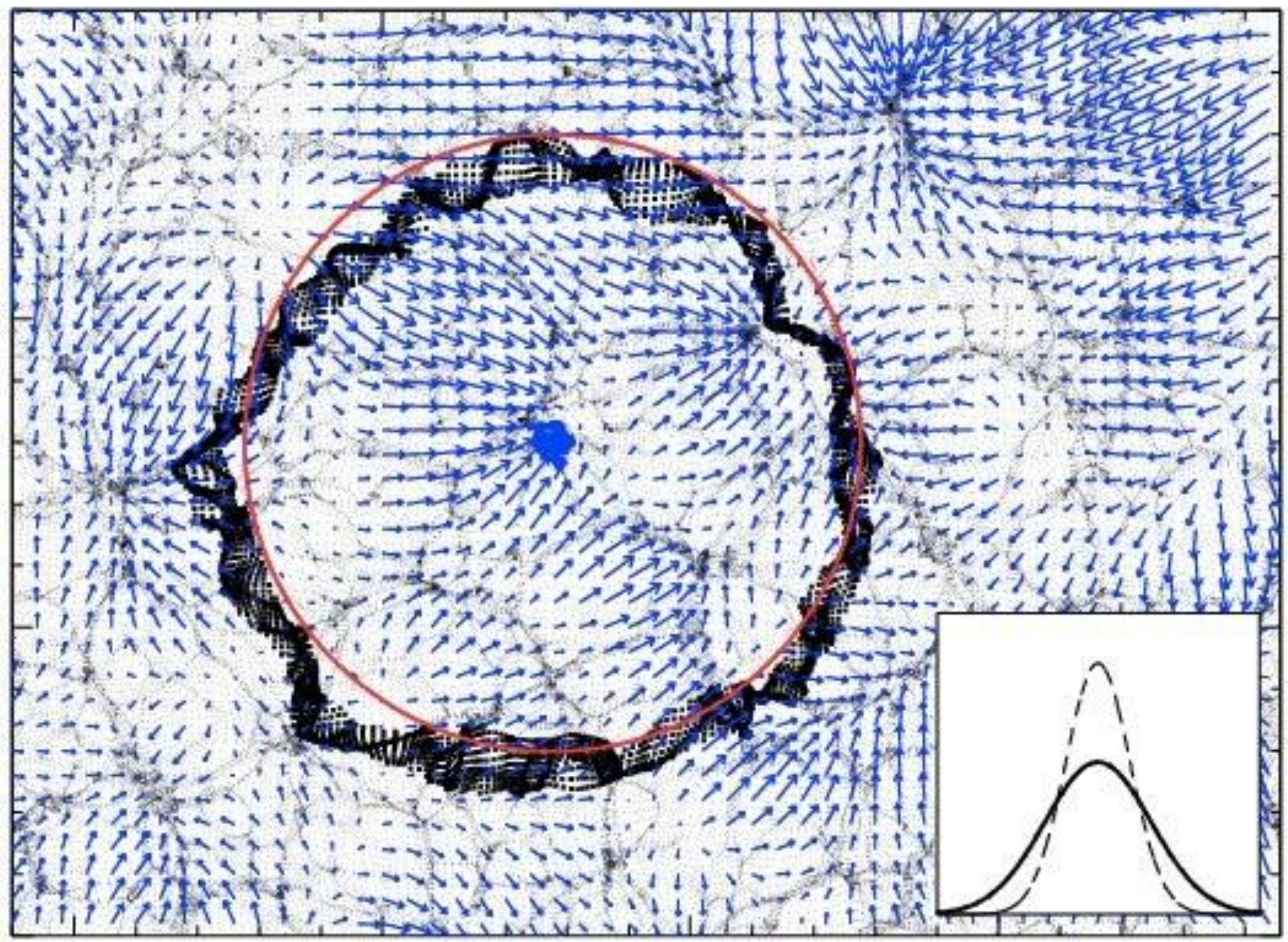

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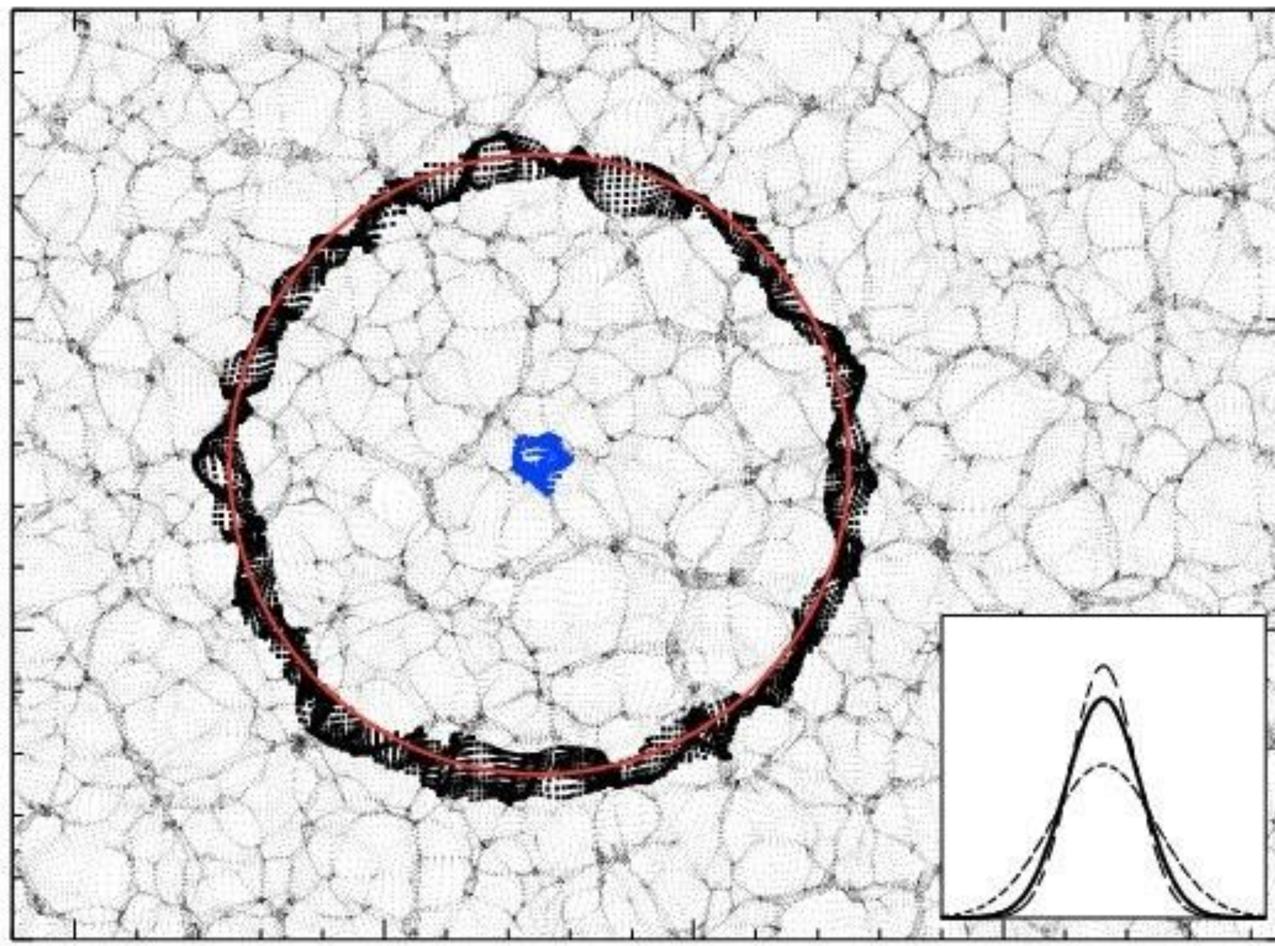

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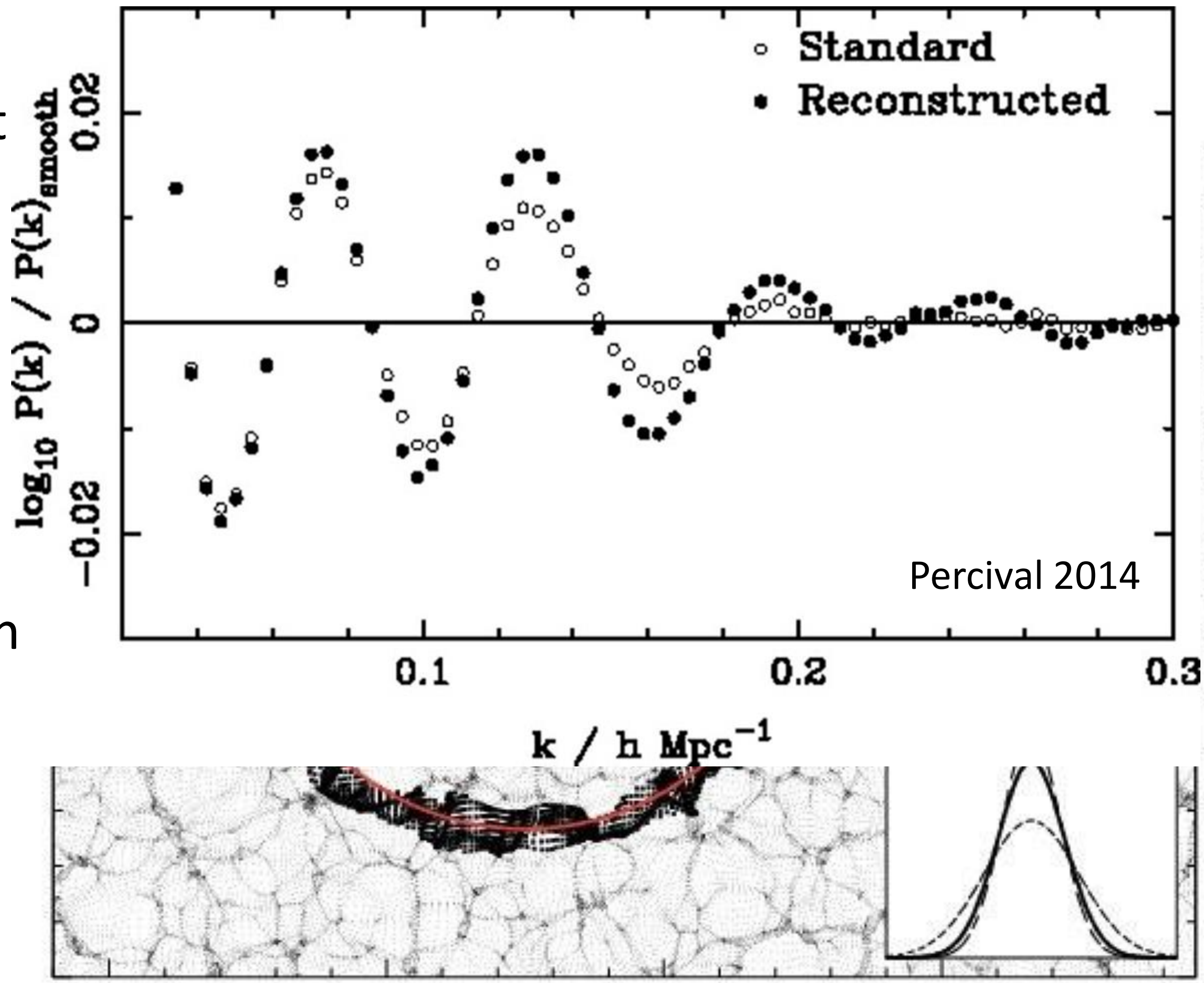


Padmanabhan et al 2012, Eisenstein et al 2007

AGN clustering and cosmology

AGN should be good tracers of the large scale mass distribution.

They are luminous and hence detectable over large volumes

Large homogeneous surveys will exist.

They can probe an unexplored redshift range.

Uniform redshift completeness is challenging.

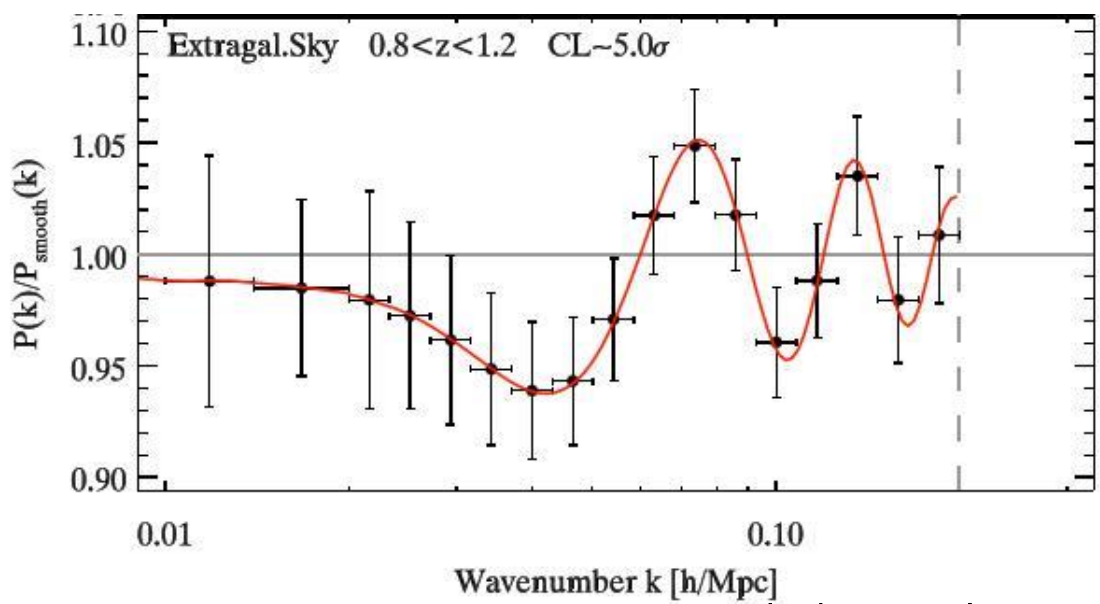
Space density insufficient for accurate reconstruction.

With eBOSS, 4MOST, MOONS, DESI, eROSITA … the future is exciting

e.g. eRASS (eROSITA All Sky Survey)

3million X-ray detected AGN

$L_{X(0.5\text{-}20keV)}$ 10^{44} erg/s



Kolodzig et al 2013

Summary

1. The evolution of galaxies and AGN are physically linked.
   (AGN feedback shapes the galaxy luminosity function!)
2. Galaxy clustering measurements provide additional robust constraints on galaxy formation models.
   (due to good theoretical understanding of hierarchical halo formation)
3. AGN clustering is harder to model, but already placing constraints of galaxy-AGN formation models.
4. Cosmological constraints from AGN clustering should be able to probe higher redshift, but are challenging.
   (relatively easy to detect at high z; follow up redshift hard; low space density hampers reconstruction)

"AGN are events, not objects" – Scott Croom, yesterday

"Galaxy formation is a process, not an event" – Simon White circa 2000

Our challenge is to determine how the events relate to the process.

The End