Halo Occupation Distribution Modeling of AGN Clustering: An Overview

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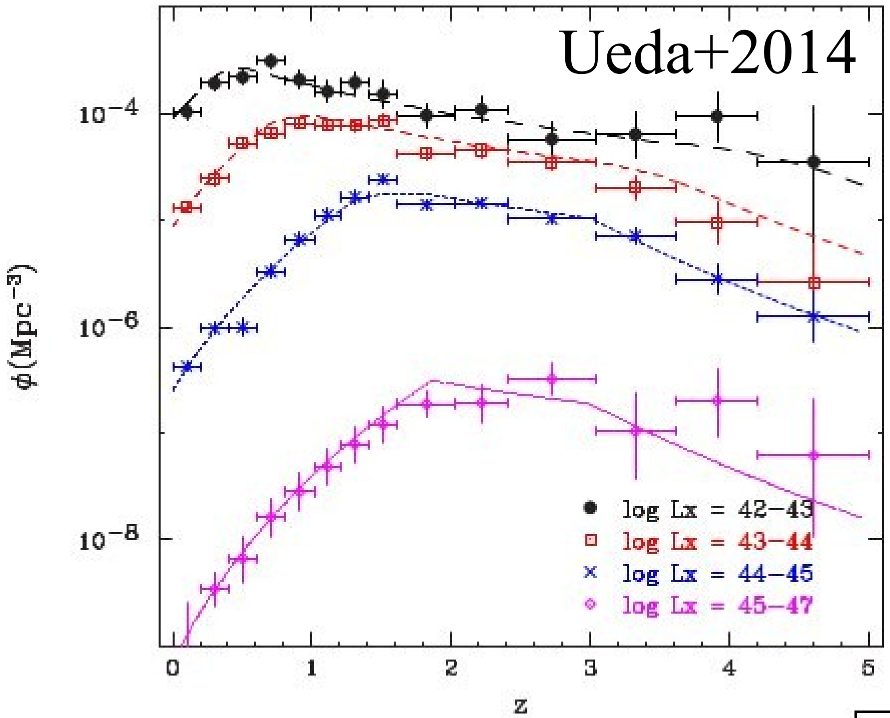
Introduction

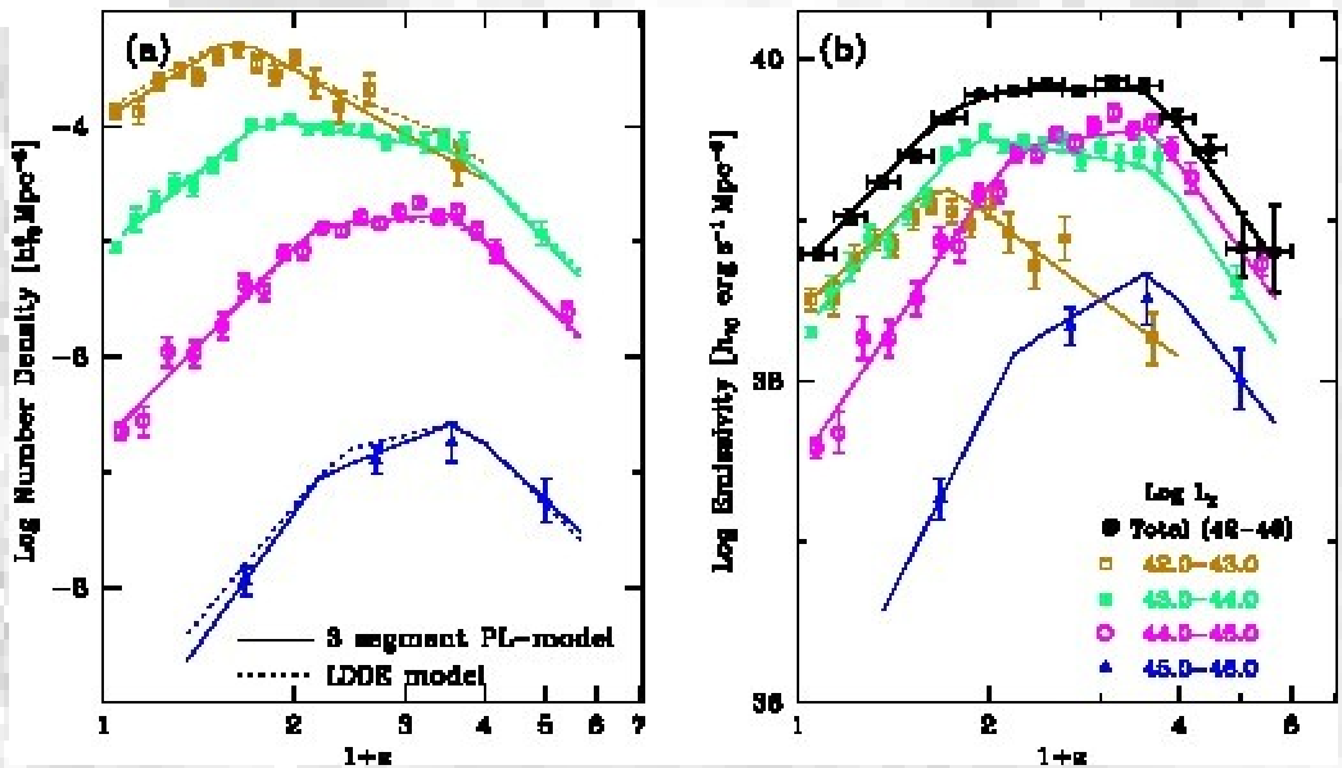
- Why AGN Clustering is important for understanding the accretion history/mechanism?
  - A small fraction of galaxies show AGN activity (It's an event!)
  - When and where, with what mechanism the SMBH accretion occurs? Statistical properties of AGNs give observational clues.
    - Merger driven?
    - Secular Evolution/Internal to galaxy?
  - Observational Clues
    - **Luminosty functions and its cosmological evolution (AGN downsizing)**
    - **Host galaxy properties (green valley, Merger remnant features).**
    - **Black Hole Demography.**
    - ***Environment*** and underlying ***large scale structure (clustering)***.



Latest determination of X-ray Luminosity Luminosity Function/Evolution

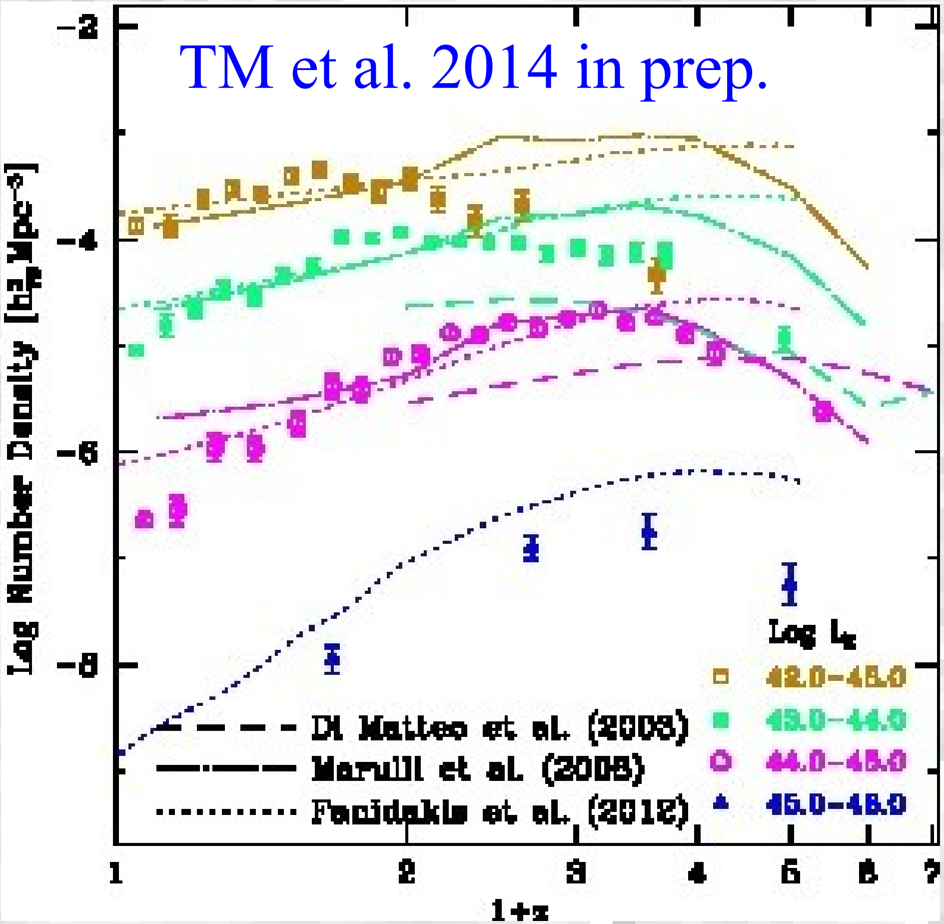
Two redshift break structure revealed.

AGN Downsizing is still strong!



TM+ to be submitted soon

Comparison with Semi-analytical models

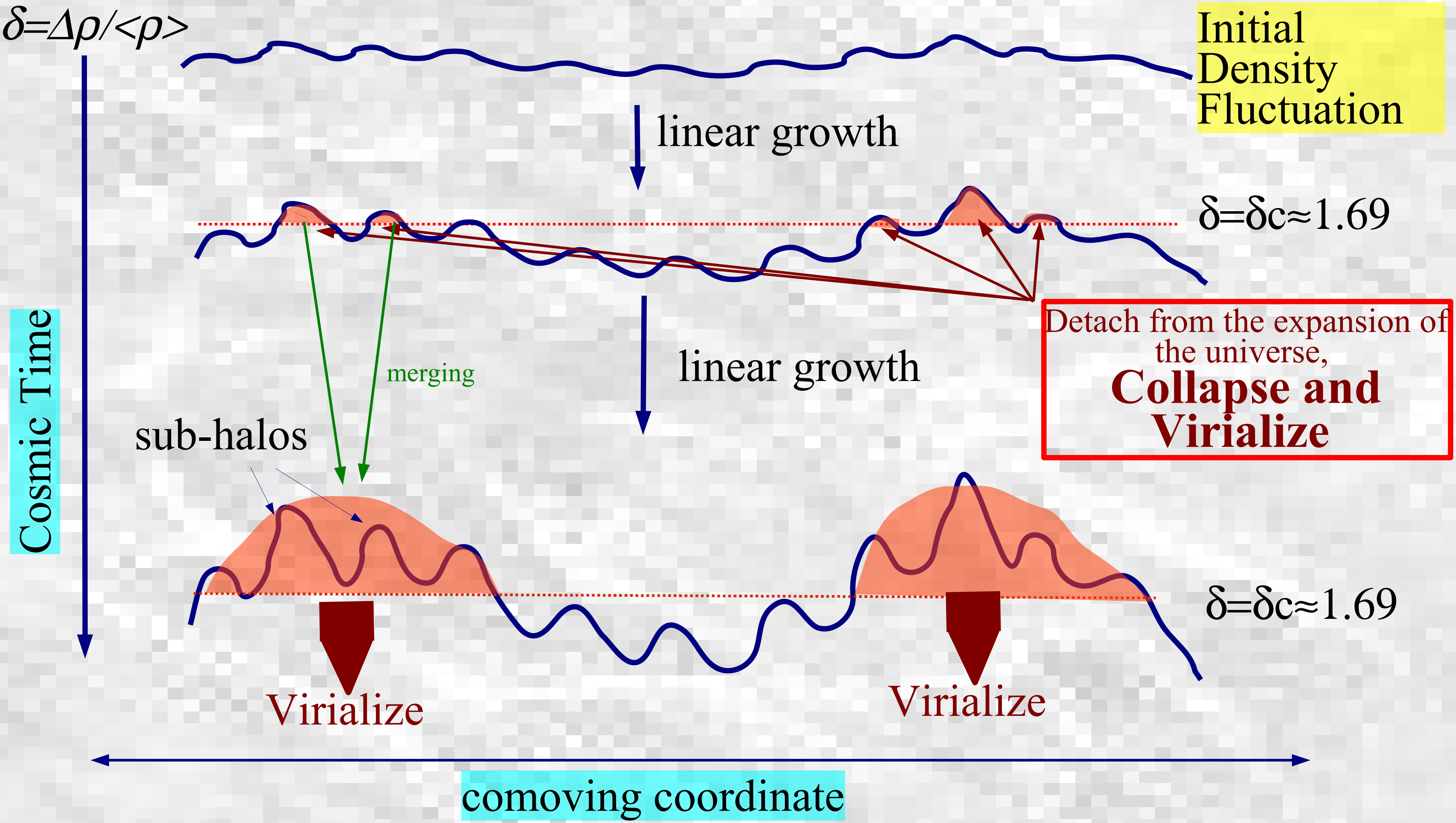


Semi-analytical models of Marulli+2005; Fanidakis+2012 overpredicts number densities of high luminosity AGNs.

Where in the Cosmic Web do AGNs occupy (accretion occurs)?

- **Observers** see the universe as galaxies, AGNs, clusters etc..
- **Theorists** see the universe as a bunch of Dark Matter Halos (DMH)--(Maybe an outdated comment!)
- How can we relate these halos with observed objects?

What are the DMHs?



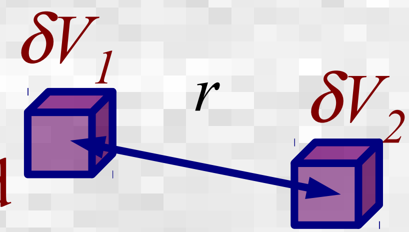
Dark Matter Halos: The collapsed & Virialized structures

Two-point Correlation Function

Excess number of pairs separated by *r* over the random distribution

- Joint probability δP of finding an object in both of the volume elements separated by r is represented by:

$$3\mathrm{D}: \delta P = n^2[1+\underline{\xi(r)}]\,\delta V_1 \delta V_2$$



$$\xi(r)=0 \quad \text{if objects are randomly distributed}$$

- In the linear biasing scheme, the two point 3-D auto correlation function (ACF) is related to bias parameter by:

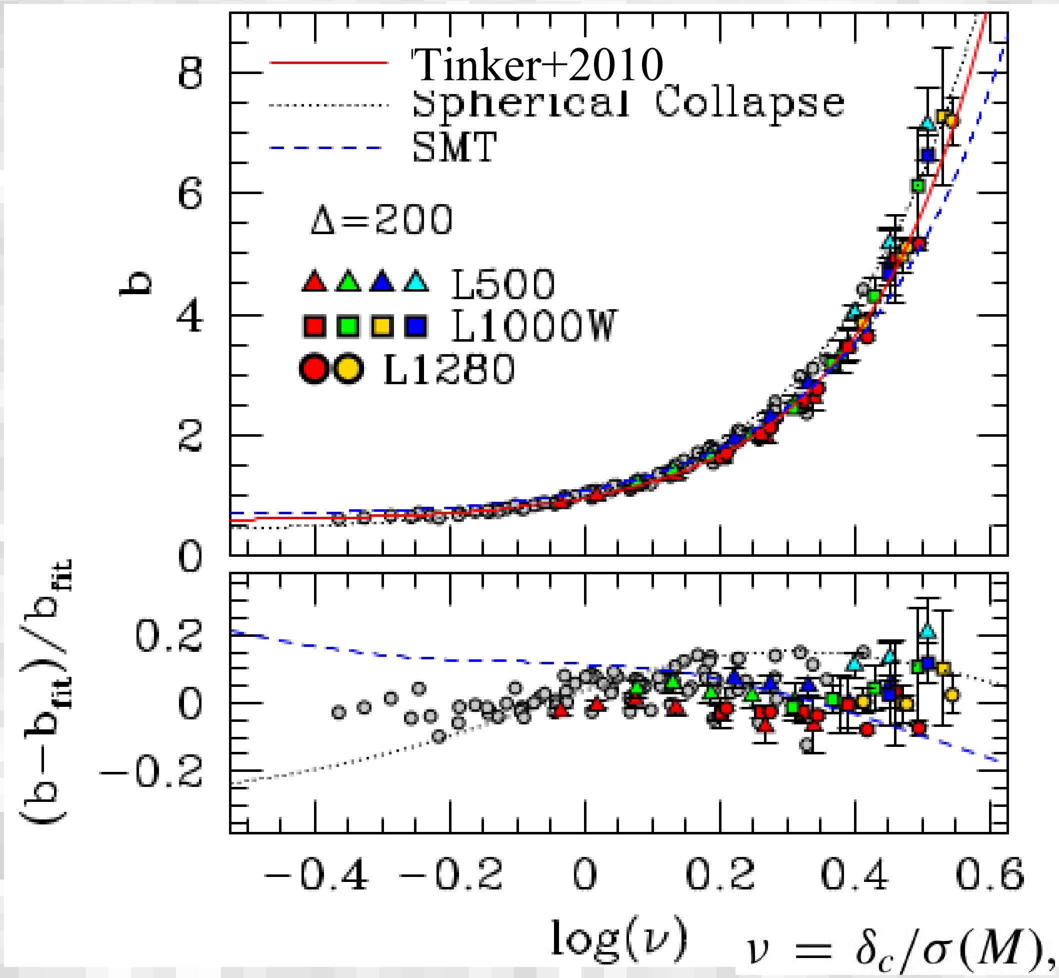
$$\xi_{\mathrm{obj}}(r)=b_{\mathrm{obj}}^{2}\,\xi_{\mathrm{mass}}(r),$$

- and two point 3-D cross-correlation function (CCF) between catalog 1 and 2 is related to the bias parameters of 1 & 2 by:

$$\xi_{12}(r)=b_2 b_1 \xi_{\mathrm{mass}}(r)$$

Clustering measurements→AGN bias

- The large-scale bias of dark matter halos depends on its mass.
- Here the "Halo mass" means the largest Virialized structure the object in question belongs to, and **NOT represents the sub-halo mass.**
- Measurements of bias of a sample of AGNs is an indicator of the "typical" mass of the DMHs that the sample is associated.

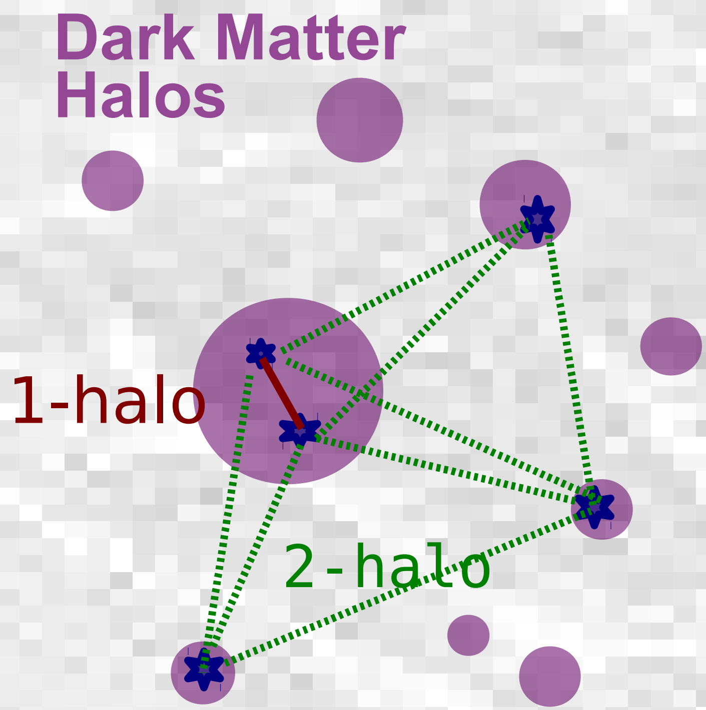


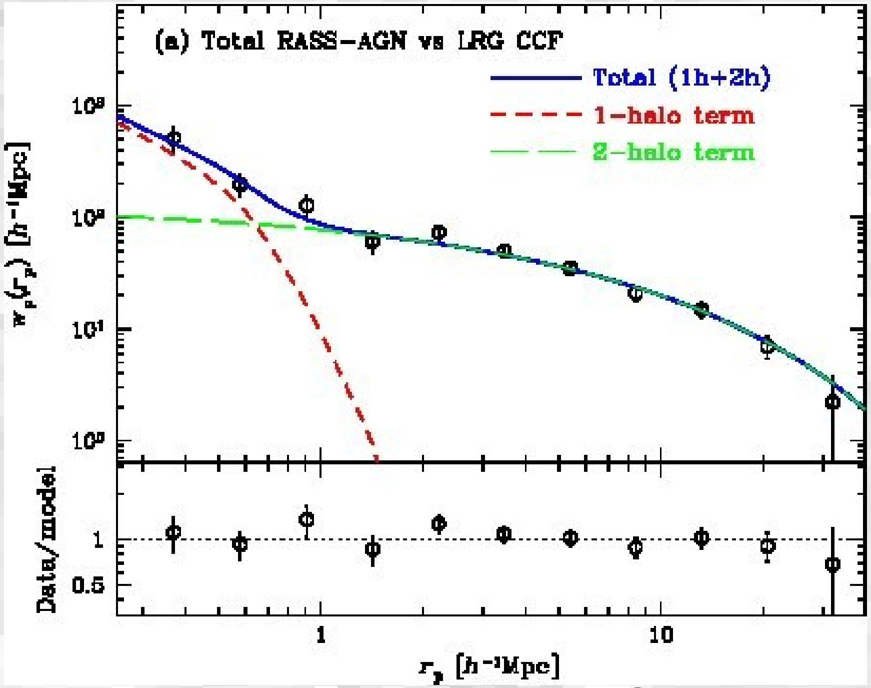
$\nu = \delta_c/\sigma(M)$,

$$b_h(\nu) = 1 + \frac{1}{\sqrt{a}\delta_c}\left[\sqrt{a}(a\nu^2) + \sqrt{a}b(a\nu^2)^{1-c} - \frac{(a\nu^2)^c}{(a\nu^2)^c + b(1-c)(1-c/2)}\right]$$

This simple relation is only valid in the linear regime ($r>\sim$1-2 h^{-1} Mpc)

Modeling of the linear and non-linear regimes with Halo Occupation Distribution (HOD)





•Model the correlation function as the sum of the contributions from pairs:

- within the same DMHs
- from different DMHs.

$$\xi(r) = \underbrace{[1+\xi_{1h}(r)]}_{\text{1-halo term}} + \underbrace{\xi_{2h}(r)}_{\text{2-halo term}}$$

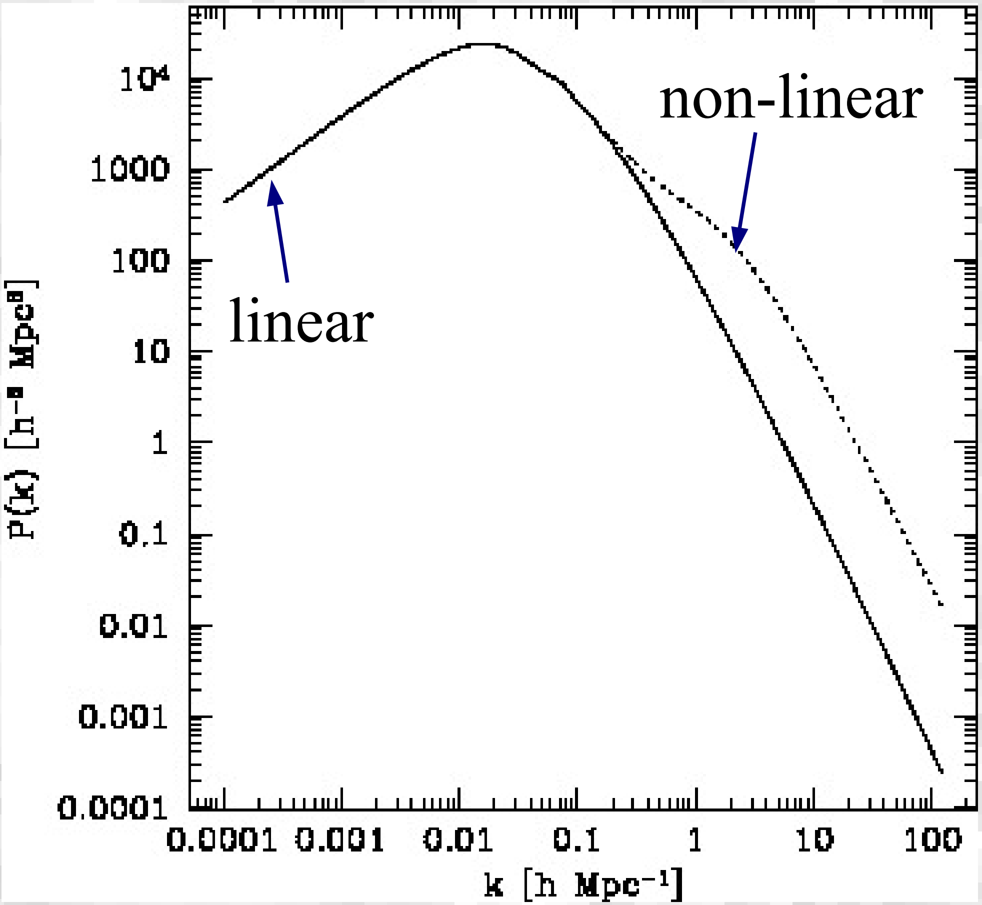
The HOD modeling is very popular in interpreting galaxy clustering

- Cooray & Sheth (2002) for classivcal review.
- Tinker+2005; 2010; van den Bosch+13 for recent theory

Application to AGN 2P Correlation Functions

- Padmanabahn+2009
  - SDSS LRG vs optically selected QSOs CCF; satellite fraction>25%
- TM, Krumpe, Coil, Aceves 2011
  - SDSS LRG vs X-ray selected AGNs CCF from ROSAT All-sky survey
- Starikova+2011
  - Chandra Boötes field. Consider both r_p and π directions. Strict upper limit on satellite fraction (<~0.1).
- Kayo & Oguri+2012 (previous talk)
- Richardson+2012,2013
  - SDSS QSOs and Allevato+11 XMM-COSMOS ACFs.
  - Full galaxy HOD-type parameterization+MCMC parameter search.

Construction of HOD models



- In the power spectrum space P(k).

Generated with "camb" (http://camb.info/)

Large Scales (approx 2-h term)

- Matter (linear) power spectrum: $P_{matter,lin}(k,z) \rightarrow \xi_{\mathrm{matter,lin}}(r,z)$
  - $P_{lin,matter}(k,z) = D(z)P_{lin,matter}(k,z=0)$; $D(\mathrm{z})$, linear growth factor
- Linear biasing (i.e. Scale independent) at large scales
  - $P_{lin,\ sample}(k,z) = b_{\mathrm{sample}}^{2}\ P_{lin,\ matter}(k,z)$
  - $\xi_{lin,\ sample}(k,z) = b_{\mathrm{sample}}^{2}\ \xi_{lin,\ matter}(k,z)$
- DMH bias $b(M_{\mathrm{h}},\mathrm{z})$ (e.g. Sheth, Mo, Tormen '01; Tinker+'05,'10)
- DMH mass function $\phi(M_{\mathrm{h}})$ (e.g. Sheth & Tormen '99; Jenkins et al. 2001;Tinker+'05)
- **$<N(M_{\mathrm{h}})>$: Halo Occupation Distribution (HOD)**
  - Mean number of sample objects per DMH as a function of M_{h}.
- The sample bias b_{sample} is the weighted mean $b(M_{\mathrm{h}},\mathrm{z})$ over DMHs
  - $b_{sample} = \int b(M_{\mathrm{h}})<N(M_{\mathrm{h}})>\phi(M_{\mathrm{h}})\mathrm{d}M_{\mathrm{h}} / \int <N(M_{\mathrm{h}})>\phi(M_{\mathrm{h}})\mathrm{d}M_{\mathrm{h}}$

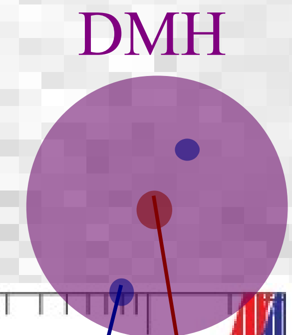
Small Scales (1-halo term)

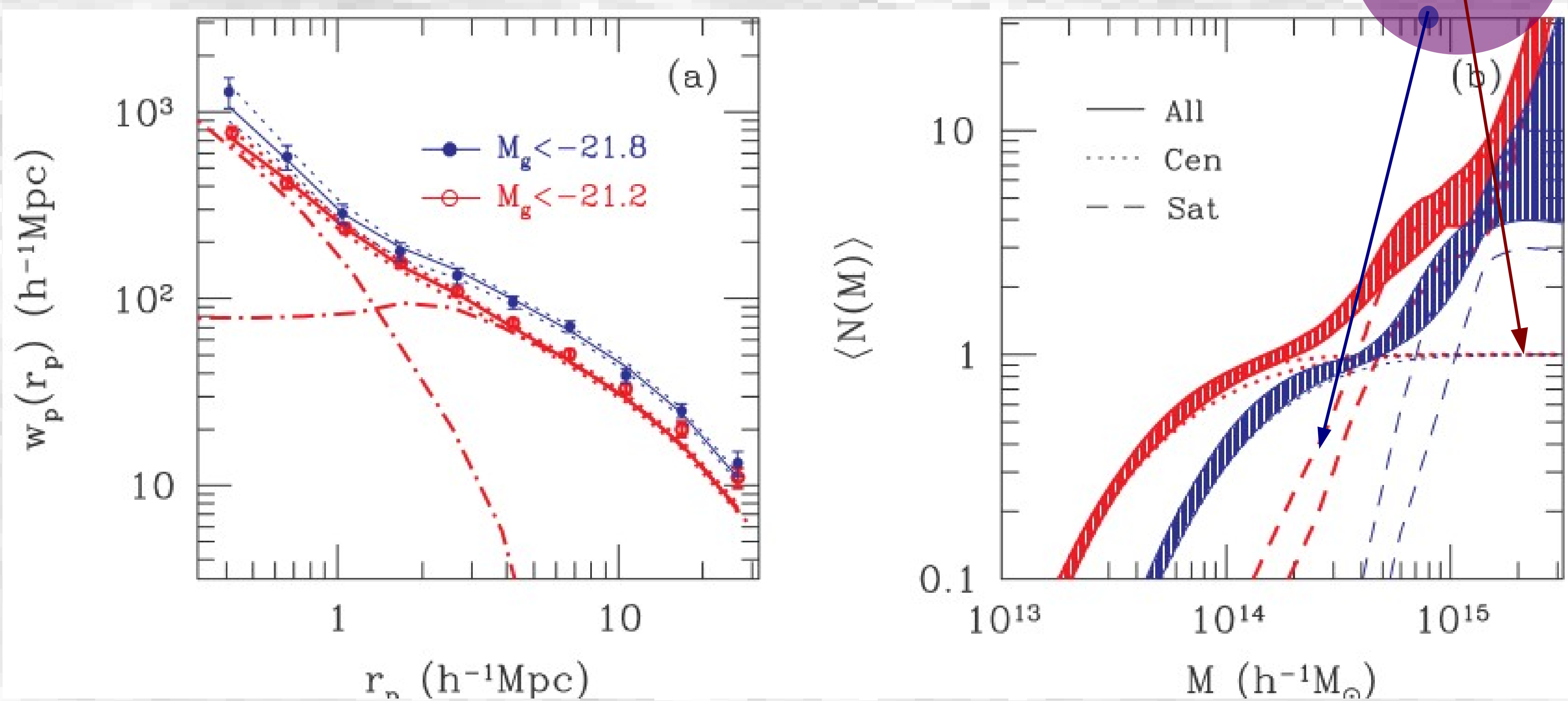
- $<N(M_h)>=<N_c(M_h)>+<N_s(M_h)>$
  - $<N_c>(M_h)$ for the objects occupying at the **center** of the host DMH.
  - $<N_s>(M_h)$ for "**satellites**", occupying non-center location of the host DMH.
- ***Assume that*** the mean radial distribution of "satellite" objects follows the mass profile of the DMH (e.g. Navarro, Frenk & White [NFW] profile).
- Contribution of the same DMH pairs to $[1+\xi_{1h}(r)]$.
  - Central-satellite pairs follow the DMH mass profile
  - Satellite-satellite pairs follows the DMH mass profile convolved by itself.
  - Central-central pairs: No such pairs.

HOD Analysis of Galaxies

Example of Luminous Red Galaxies (Zheng+2009)

$\langle N_c(M_\mathrm{h})\rangle$ center: smoothed step function saturated to 1.
$\langle N_s(M_\mathrm{h})\rangle$ satellite: power-law*$\langle N_c(M_\mathrm{h})\rangle$ or spline

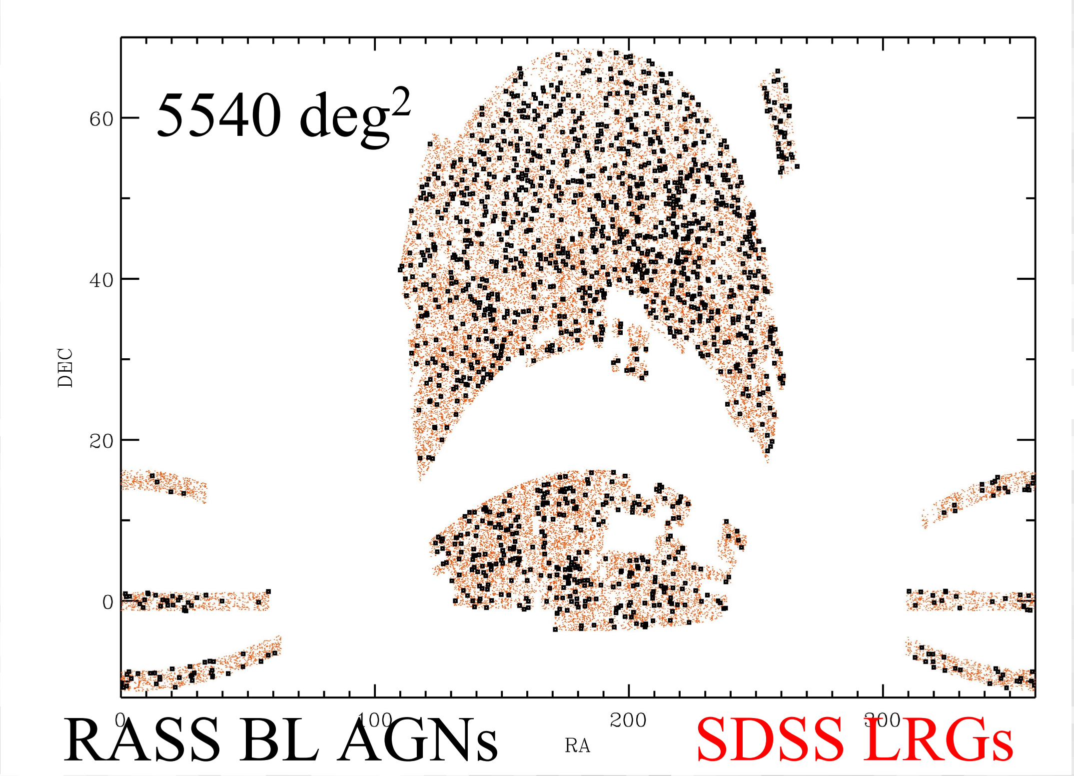




Application to SDSS Luminous Red Galaxies (LRGs) vs RASS AGNs

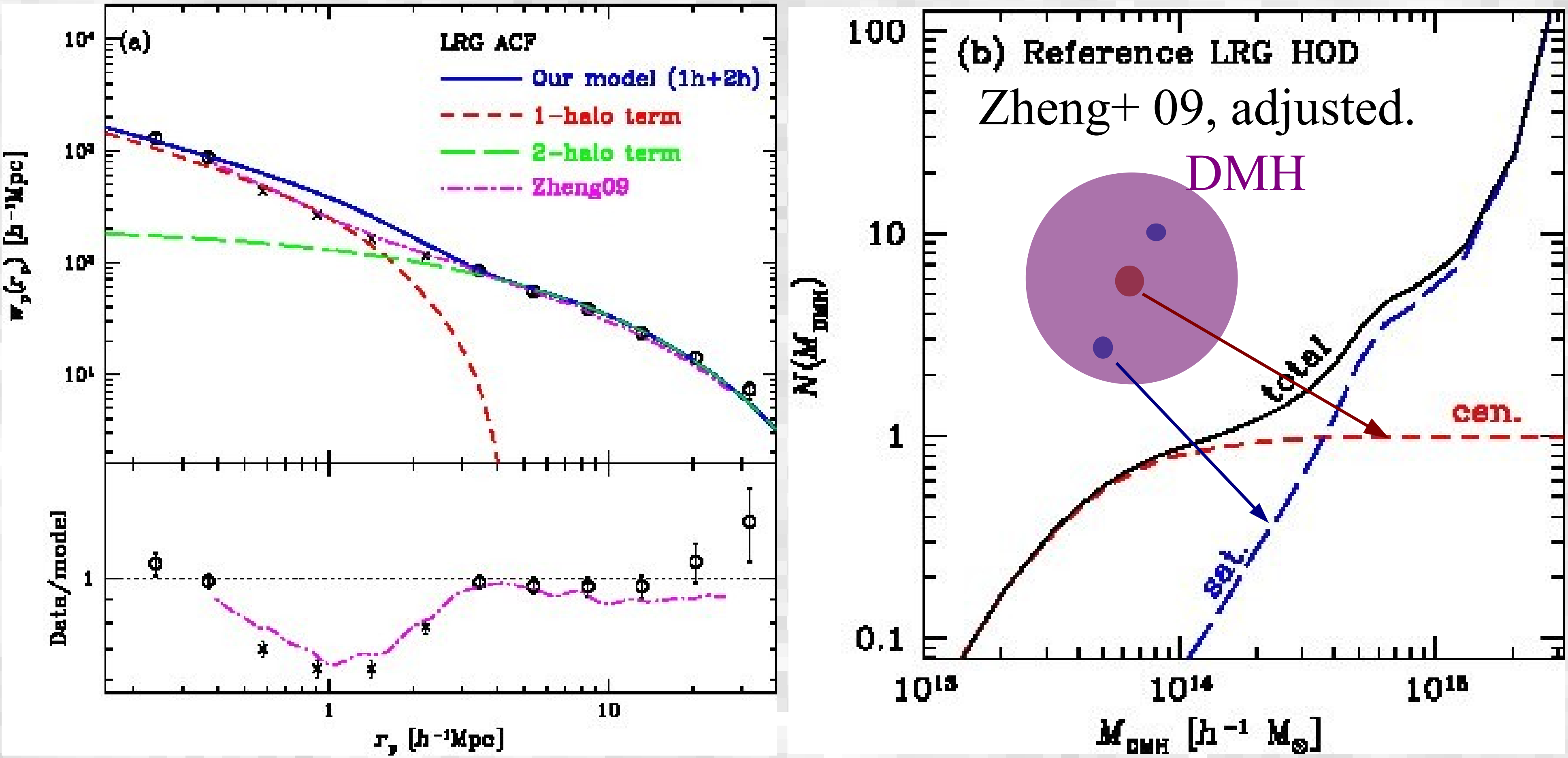
TM, Krumpe, Coil, Aceves (2011)

- Galaxy Sample
  - SDSS LRG Volume Limited Sample
  - Defined by Eisenstein et al. (2001), redrawn by us for DR4+
  - M_B<-21.2, 0.16<z<0.36
  - 45899 LRGs Galaxies
- **X-ray AGN sample:**
  - ROSAT All-Sky Survey (RASS) sources matched with the SDSS broad-line AGNs (Anderson et al. 2003; 2007).
    - 1552 AGNs in 0.16<z<0.36
  - Excluded Narrow-line AGNs.
  - Flux limited sample.



These two samples are completely separate. No common object.

HOD of LRGs as our Tracer Set



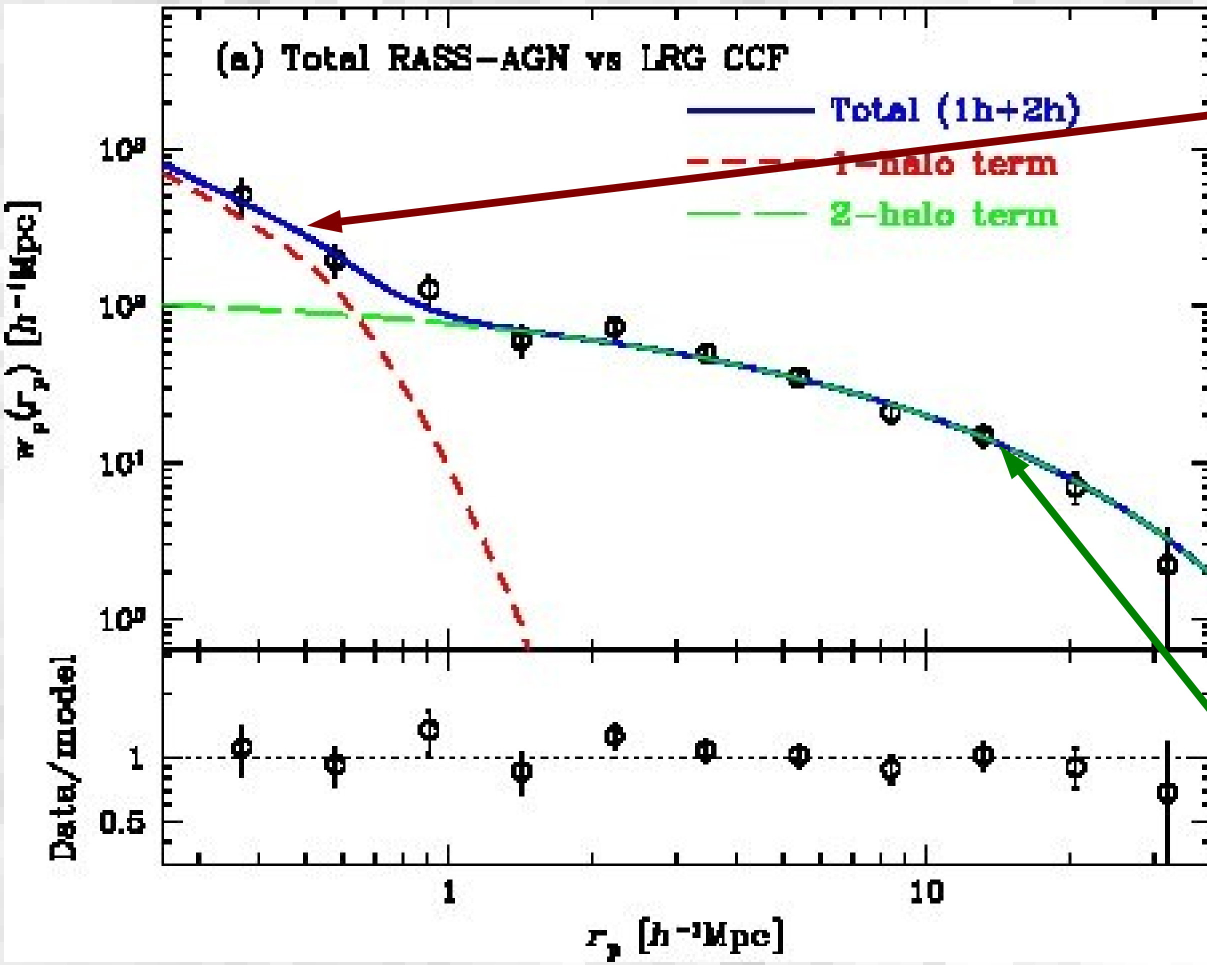
Applying HOD modeling to the AGN-LRG CCF

When modeling our CCF, we consider four HODs

- $<N_{\mathrm{LRG,c}}>(M_{\mathrm{h}})$ & $<N_{\mathrm{LRG,s}}>(M_{\mathrm{h}})$ for the central and satellite LRGs respectively.
- $<N_{\mathrm{A,c}}>(M_{\mathrm{h}})$ & $<N_{\mathrm{A,s}}>(M_{\mathrm{h}})$ and for the AGNs.
- First, we derive $<N_{\mathrm{LRG,c}}>(M_{\mathrm{h}})$ and $<N_{\mathrm{LRG,s}}>(M_{\mathrm{h}})$ using the ACF of the LRGs.
  - They can be determined with a much better statistics.
- Then, using the resulting (fixed) LRG HODS, we constrain **$<N_{\mathrm{A,c}}>(M_{\mathrm{h}})$ & $<N_{\mathrm{A,s}}>(M_{\mathrm{h}})$ by fitting to the AGN-LRG CCF.**

Model A: Simple model

Assumption:All AGNs that reside in halos containing LRGs (or contributing to the 1-h term) are satellites.



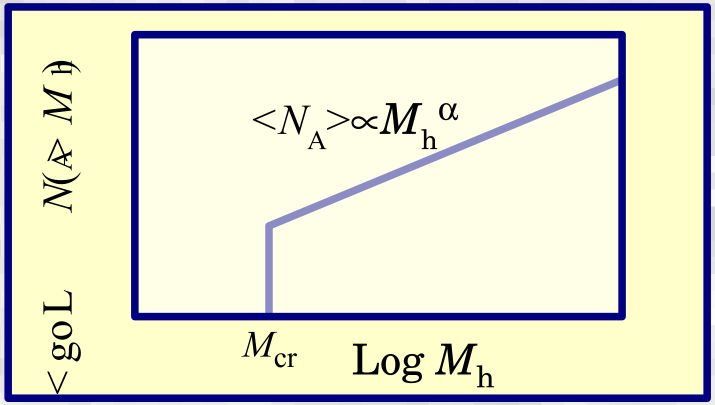
The 1-halo term is from AGN-LRG pairs in the **same DMH**.

- LRGs are in M_h>~$10^{13.5}$ M_{sol} halos.
- The 1-halo term measures AGNs in M_h>~$10^{13.5}$ M_{sol} halos.

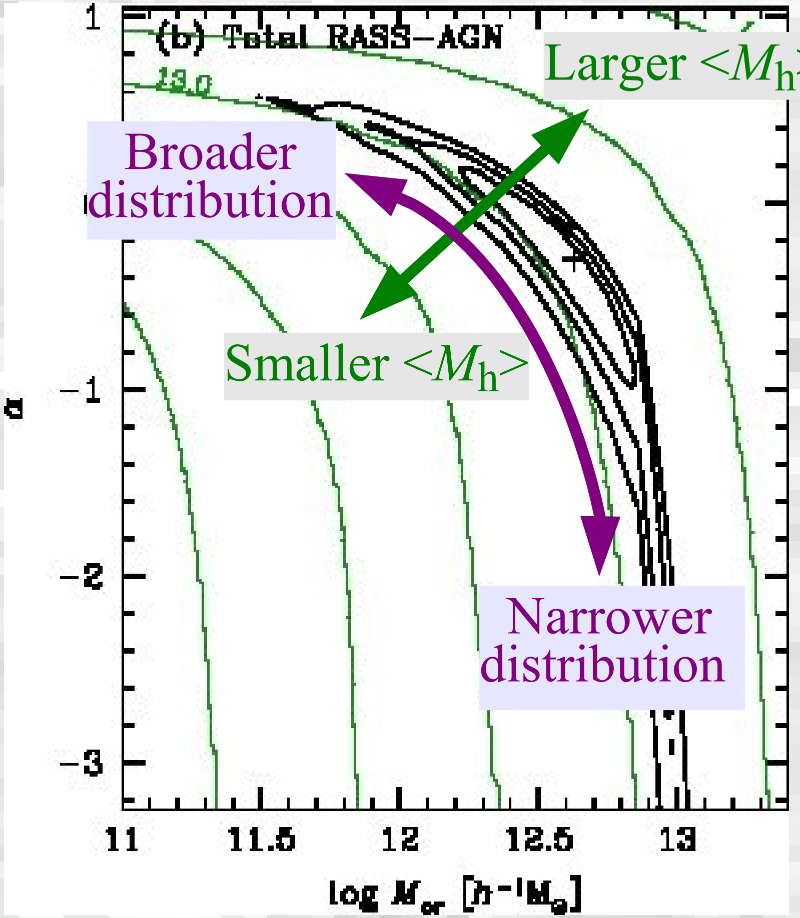
The 2-halo term $\propto b_A b_{LRG}$.

- Determines AGN bias b_A
- Indicates the mean DMH mass with AGNs.

Constraints on HODs for AGNs

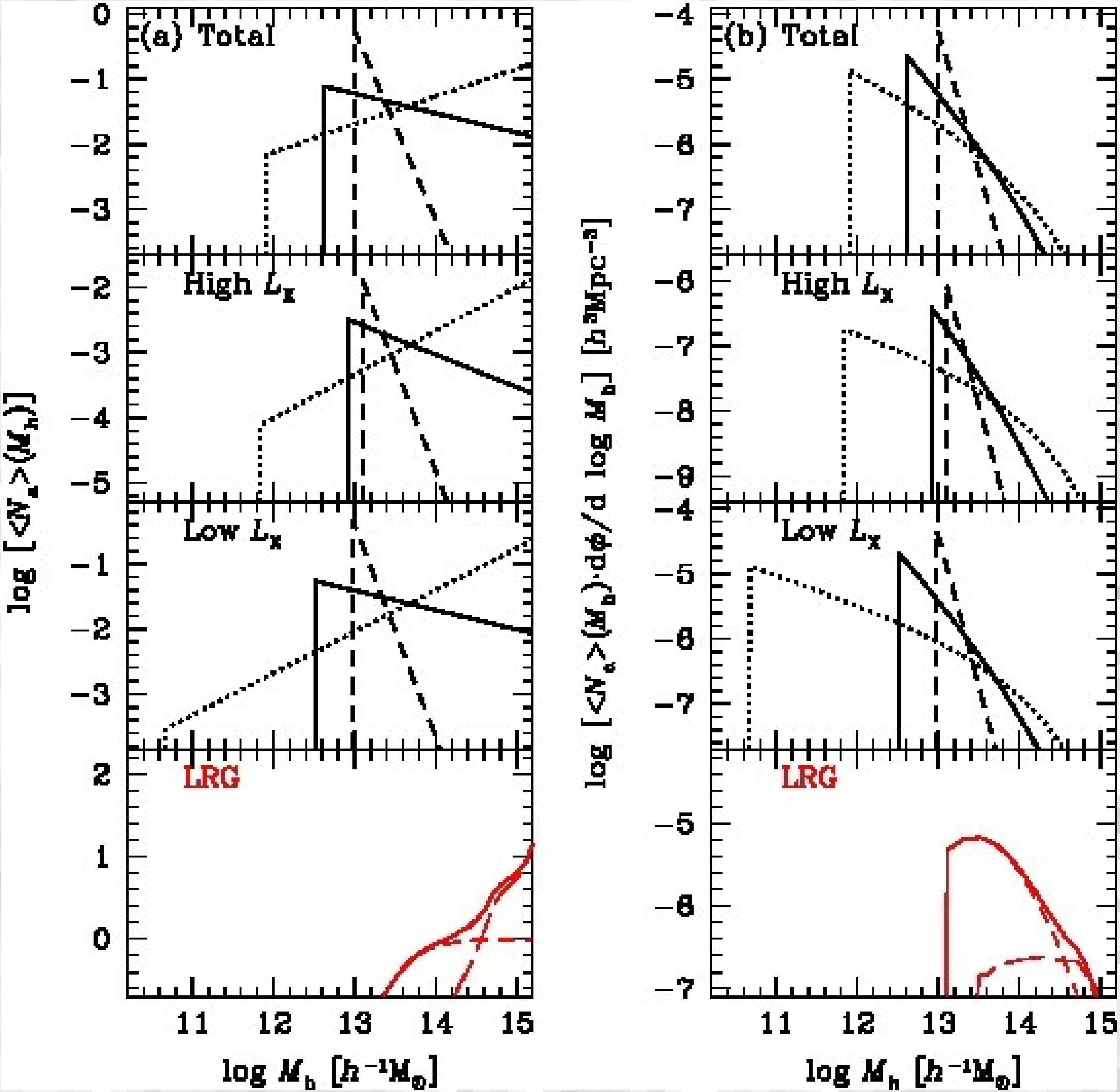


Simple HOD model for AGNs



- Constraints roughly along $<M_h>$~const.
  - Constraint from the 2-halo term (b_X)
- α<0.4 ($\Delta\chi^2$<2.3 limit)
  - Constraint from the 1-halo term

- Confidence contours (black, $\Delta\chi^2$=1;2.3;4.6)
- Mean DMH mass (green contours).



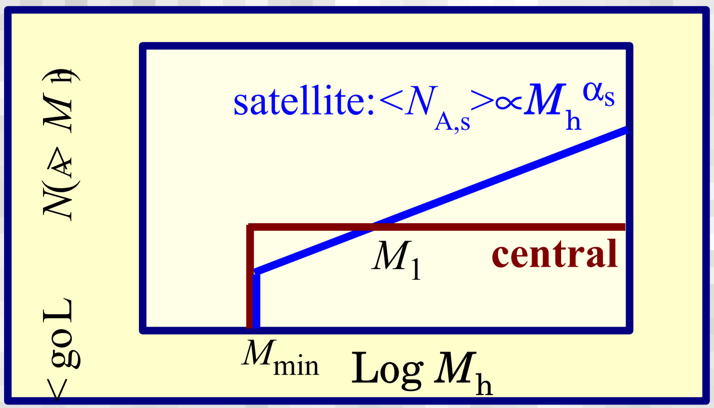
Left:
numver per halo.

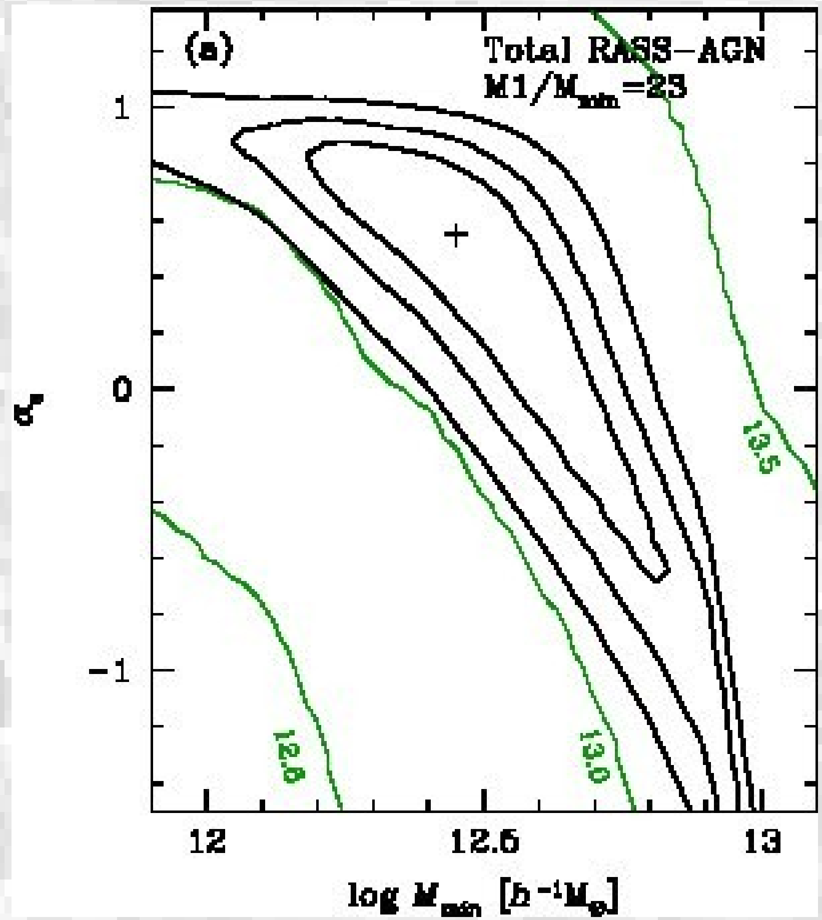
Right:
Number density

Three possible
HODs within
errors.

TM+2011

Model with separate central+satellite AGNs





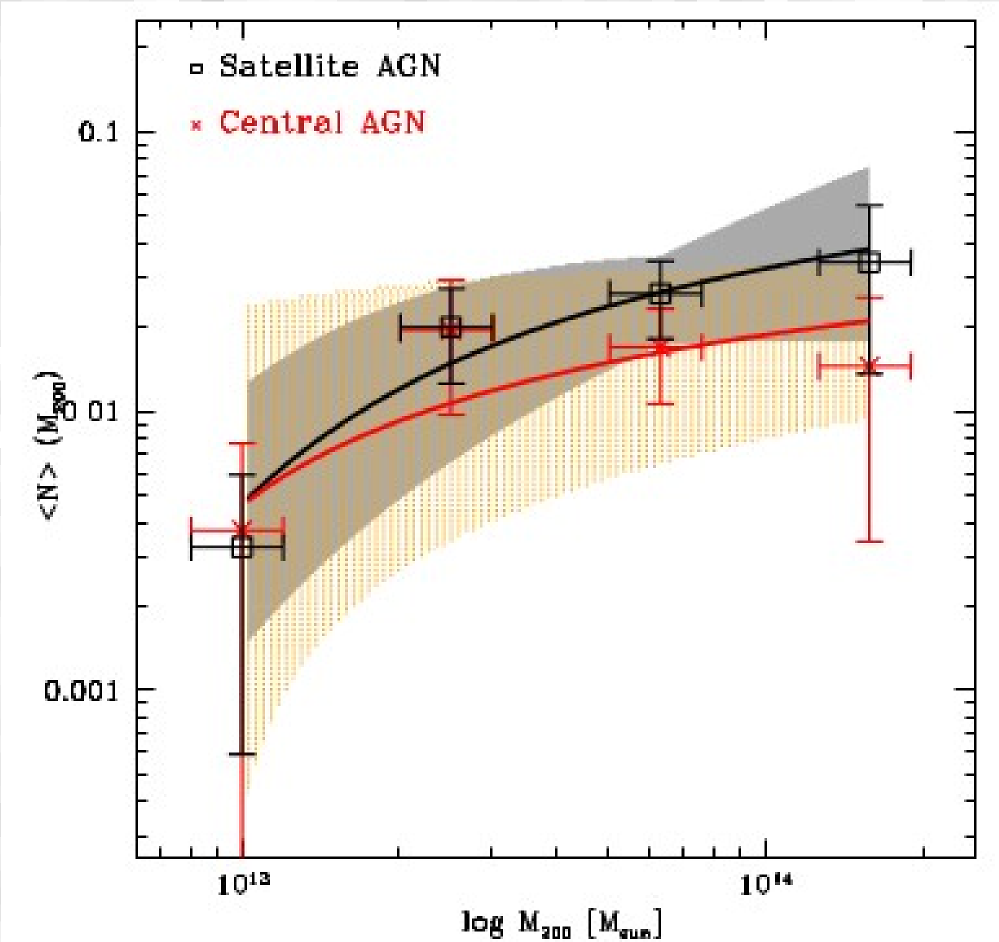
Model B:
A model with galaxy-like
central+satellite components

cf. SDSS Galaxies
(e.g. Zehavi et al. 2005)
M_1/M_{min}≈23, α≈1.2

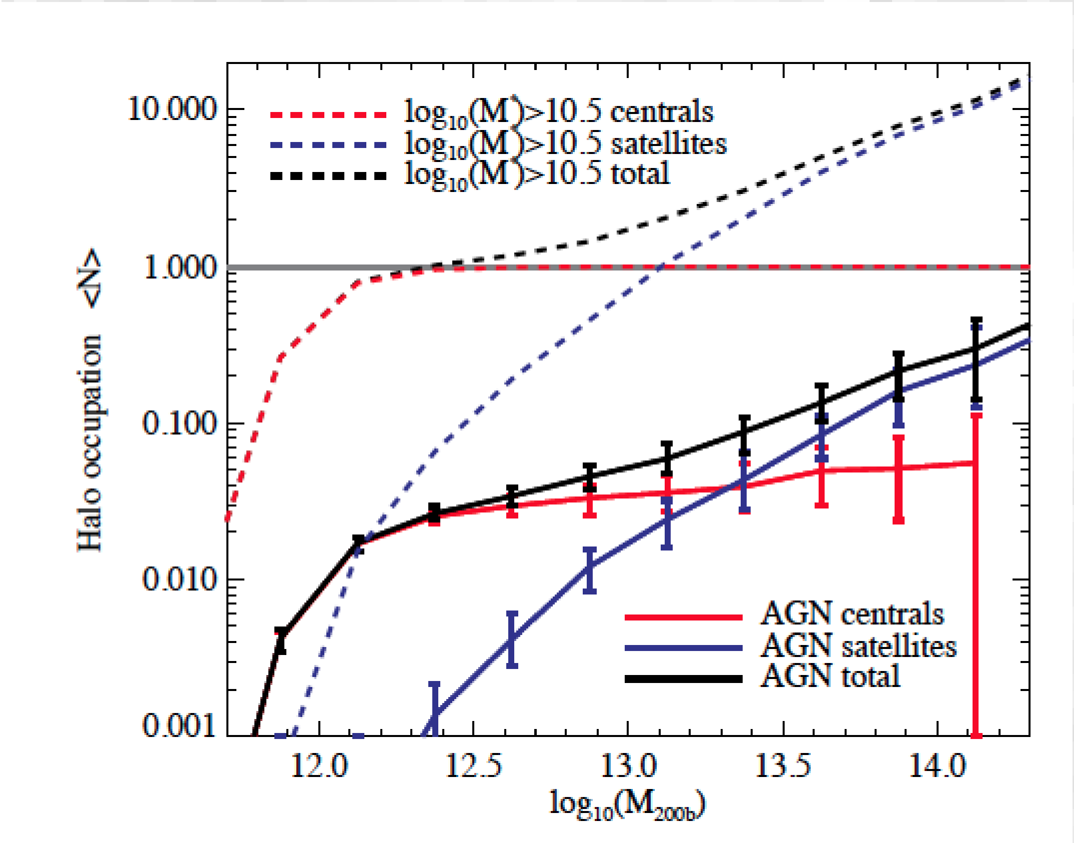
Implication of the HOD Analysis

- The limit on α_s<1 means that the number of (satellite) AGNs/Halo ***<u>grows slower than M_h</u>***.
  - The HOD of satellite **galaxies** show α~1, i.e., number/halo $\mu\, M_h$ (e.g. Zehavi et al. 2010).
  - AGN fraction (non-center) decreases with M_h.
  - Long-suggested anti-correlation of emission-line AGN fraction and cluster richness (e.g. Gisler 1978; Dressler et al. 1985).
  - Consistent with: AGN fraction anti-correlates with the velocity dispersion of clusters/groups (Popesso & Biviano 2006).
  - X-ray AGN fraction is smaller in clusters (M_h>$10^{14}M_{sol}$) than the field at low z. Higher at high z (z>~1.5), this trend reverses (Martini+13).

Trend Verified in direct couunts/Weak lensing-based HOD studies



Allevato+12, direct count
Satellite HOD slope α_s<0.63

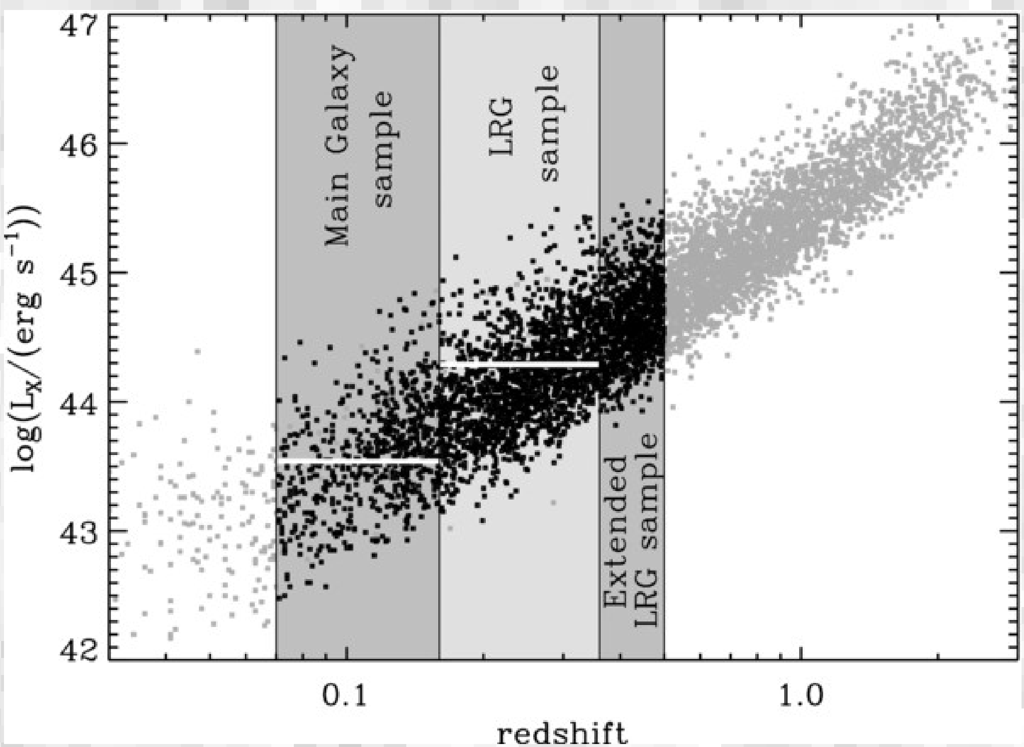


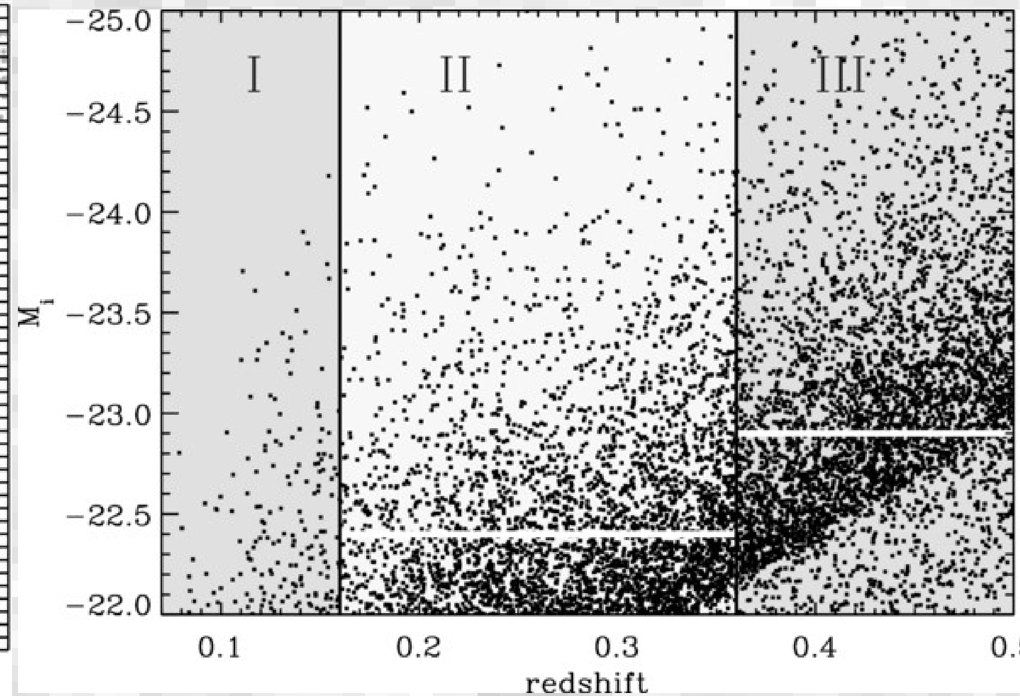
Leauthaud+2014, A. Coil's Talk

Implications -cont'd

- Possible mechanisms:
  - Merging efficiency low in high velocity encounters (Makino & Hut 1997).
  - Would AGN triggering by major merger/minor merger of **sub-halos** inside larger host halos explain the HOD behavior (Altamirano's talk)?
  - Ram pressure stripping/thermalevaporation of cold gas in galaxies in Intracluster/intragroup medium (Gunn & Gott 1972;Cowie & Songaila 1977).

Extended sample



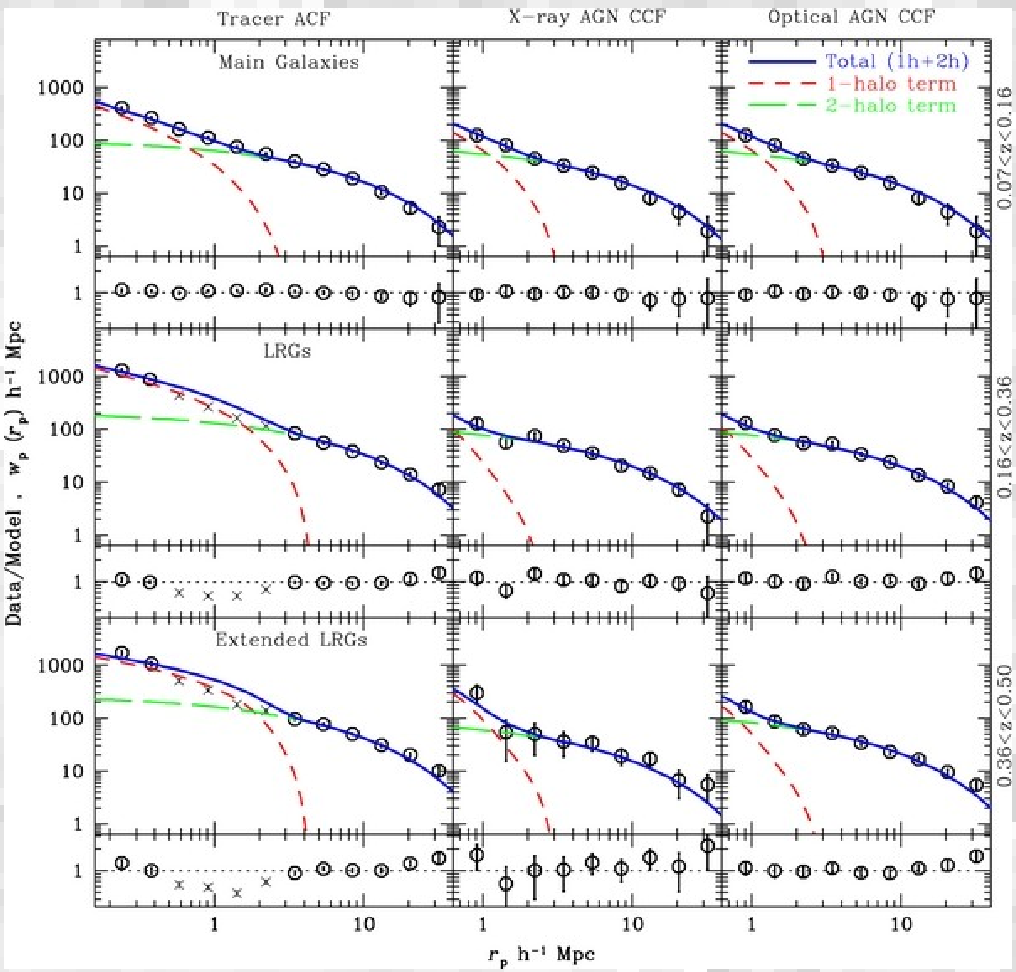


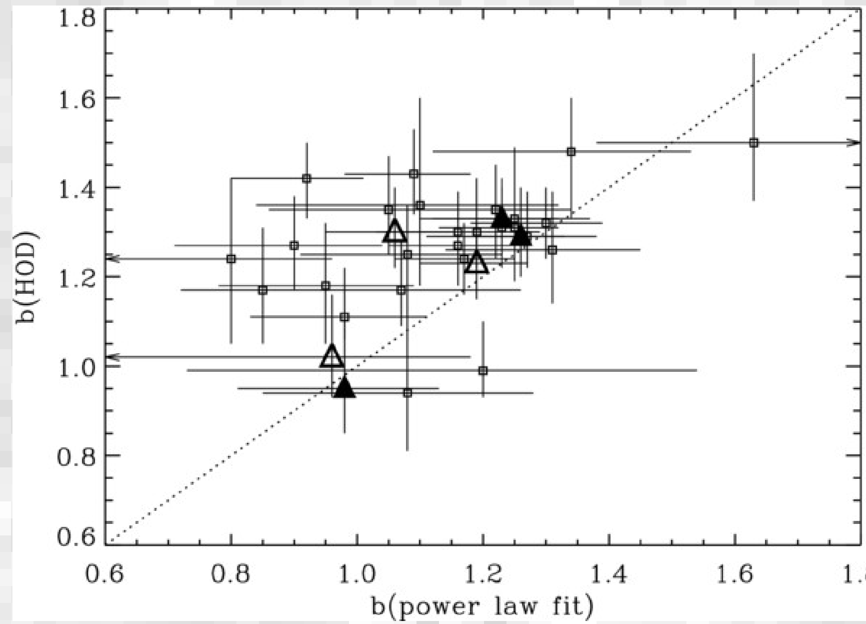
RASS-AGNs extended

Schneider et al. 2010, Optically-seleced Broad-line AGN sample

Paper III: Krumpe, TM, Coil Aceves 2012

HOD approach may be simply used for more accurate determination of linear bias paramters



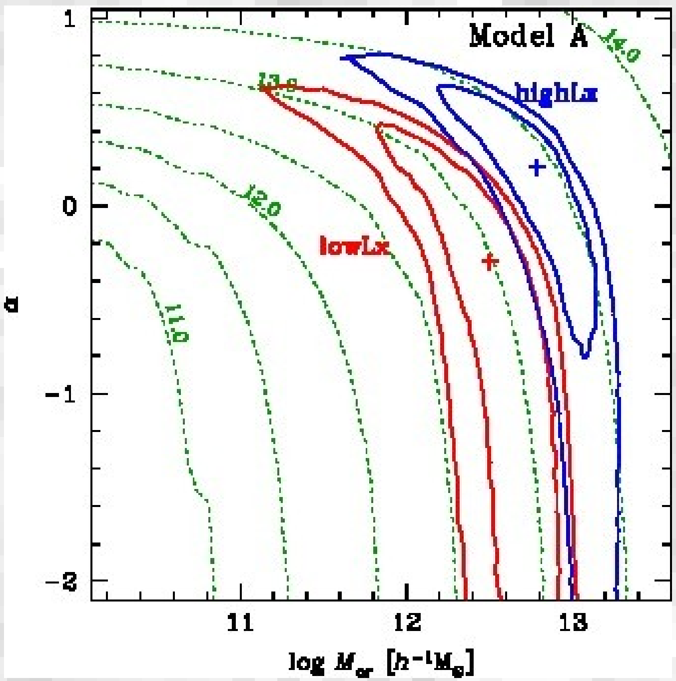


Figs: Krumpe, TM et al. (2012)

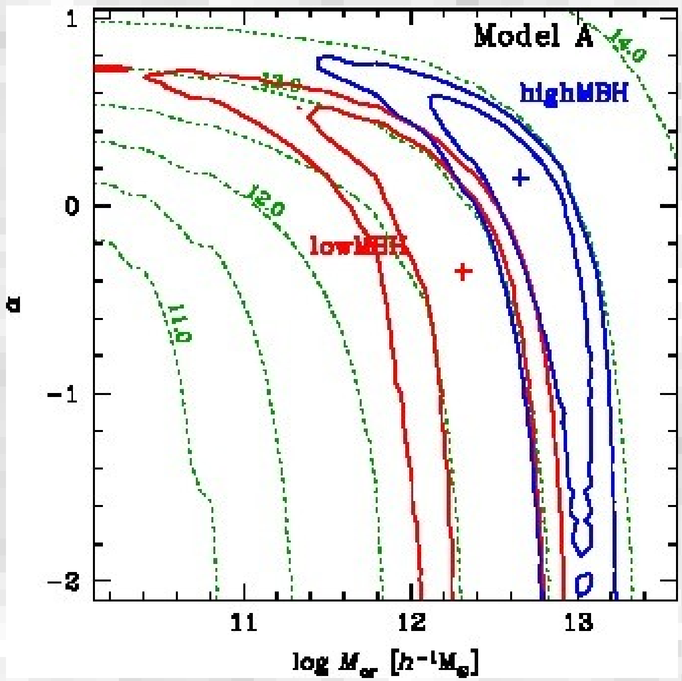
- More accurate determination of b_{lin} than power-law fits.
- Fitting 2-halo term only to r_p>1.5h^{-1}Mpc (Allevato et al. 2011,2012)
- Fitting 1 and 2-halo terms with a simple parameterized HOD model to obtain constraints on b and log <Mh> (Krumpe, TM et al. 2012, 2014).

Highlight differences between L_x, M_{BH}, & L/L_{edd} divided samples

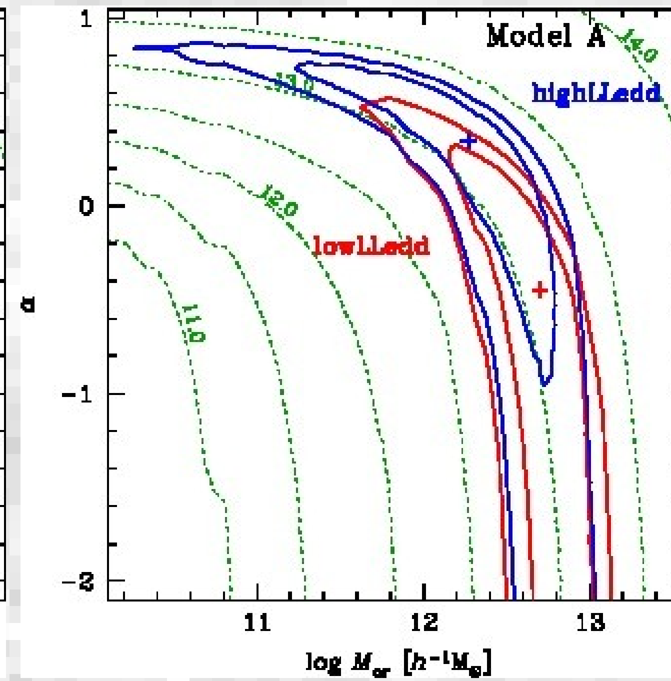
High vs low L_x



High vs low M_{BH}



High vs low L/L_{edd}

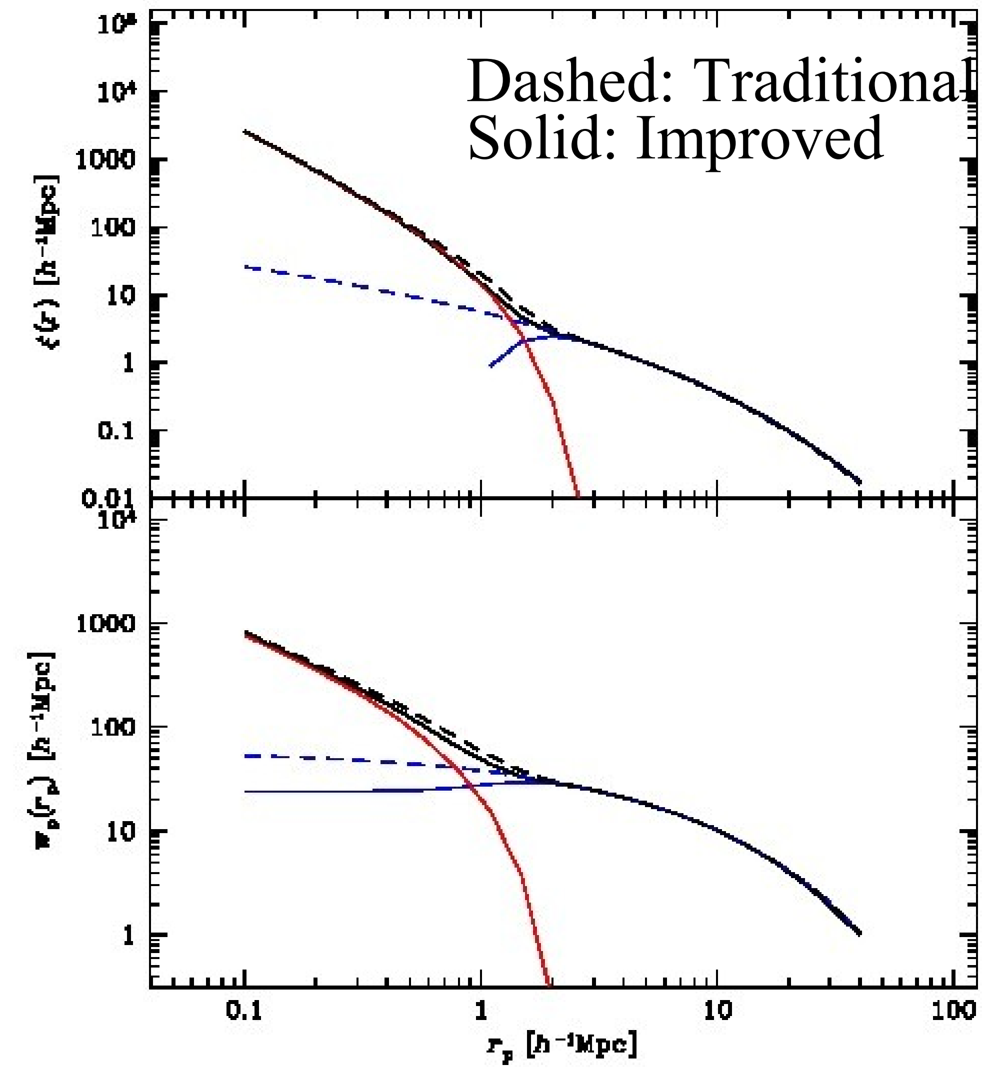


Comparing biases only use data at 2-h terms
This approach takes advantage of data at all scales.

M. Krumpe's talk yesterday

Two-halo term improvements

- Instead of simple linear PS, use non-linear PS, scale-dependent bias, and exclusion of pairs that should be counted in the 2-halo term (Zheng+'04; Tinker+'05; van den Bosch+'13)



Limitations

- Good sampling at 2-halo term (r_p>~1 Mpc)
  - Good constraint on only one parameter: linear bias
- Poor sampling at 1-halo term (r_p<~1 Mpc)
  - Poor constraint on the distribution of $N(M_h)$
  - CCF approach helps
- Degeneracy in the interpretation of the 1-halo term.
  - Central vs satellite pair or satellite-satellite pair?
- Do satellite AGNs follow DM profile?
  - The same problem with galaxy HOD studies, especially comparing blue vs red galaxy HODs.

Direct counts within resolved groups/clusters?

- QSO counts within rich clusters of galaxies (Martini et al. 2009;2013)
- DMHs with M_h>~13 h^{-1} $M_\odot$ can be cataloged as groups/clusters (e.g. X-ray selected).
  - Direct counts of AGNs in these groups/clusters are possible.
  - Combine with the CFs involving AGNs that do not belong to these groups/clusters give constraints on the minimum halo mass occupied by these HODs -> Allevato+12, **(Talk by A. Finoguenov)**
- SDSS QSOs in clusters (M_h>~14 h^{-1} $M_\odot$)

  (Talk by M. Nguyen)

Conclusions

- The HOD analysis is a strong tool to interpret correlation functions of galaxies/AGNs to scale over linear to non-linear scales.
- From HOD analysis, we can obtain not only a single “typical” host DMH mass but also constraints on how AGNs distribute among DMHs as a function of mass.
- Applying the HOD analysis to z~0.3 SDSS LRG vs RASS AGNs, we find that solutions where AGN fraction among satellite galaxies decrease with Halo mass.
- The interpretation of the HOD analysis is limited by poor sampling at small scales (especially of AGNs) and model degeneracies.
- If we have good catalog of resolved clusters/groups, direct count of AGNs in these clusters/groups can give robust HOD measures.