# Clustering of AGNs from Rosat All-Sky Survey and Halo Occupation Distribution


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Hector Aceves (IA-UNAM-E)


# This talk is based on...

- M. Krumpe, TM, A. L. Coil 2010,

  "The Spatial Clustering of ROSAT All-Sky Survey AGNs I. The Cross-correlation function with Luminous Red Galaxies"

  ApJ 713, 558

- TM, M. Krumpe, A. L. Coil, H. Aceves 2010,

  "The Spatial Clustering of ROSAT All-Sky Survey AGNs II. Halo Occupation Distribution of the Cross-Correlation Function",

  ApJ, 726, id83.

- M. Krumpe, TM, A. L. Coil, H. Aceves 2011,

  "The Spatial Clustering of ROSAT All-Sky Survey AGNs III. Expanded Sample and Comparison with Optical AGNs", almost ready to submit....

- TM et al., "The Spatial Clustering of ROSAT All-Sky Survey AGNs IV. Halo Occupation Distributions of Expanded AGN samples", ....

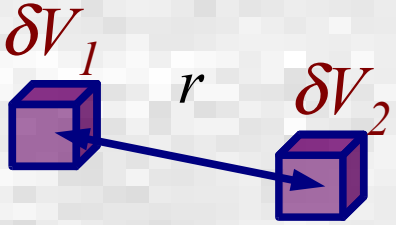
# Two-point Correlation Function

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

- Joint probability $\delta P$ of finding an object in both of the volume elements separated by r is represented by:

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

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




- **Large scale bias b**: Indicator of the mass of Dark matter halos in which they live.
- In the linear biasing scheme,

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

- For the cross-correlation function (CCF) between catalog 1 and 2:

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

# Cross-correlation function (CCF) with Galaxies Approach

- **Galaxy Clustering is usually studied with the auto-correlation function (ACF).**
- **Only a small fraction of galaxies contain an AGN**:
  - Small number statistics limit the clustering studies.
  - Cross-correlation function with numerous galaxies, e.g. from Sloan Digital Sky Survey (SDSS), improves the situation.

# RASS AGN sample

**AGN sample from** ROSAT All-Sky Survey (RASS)

(Voges et al. 1999)

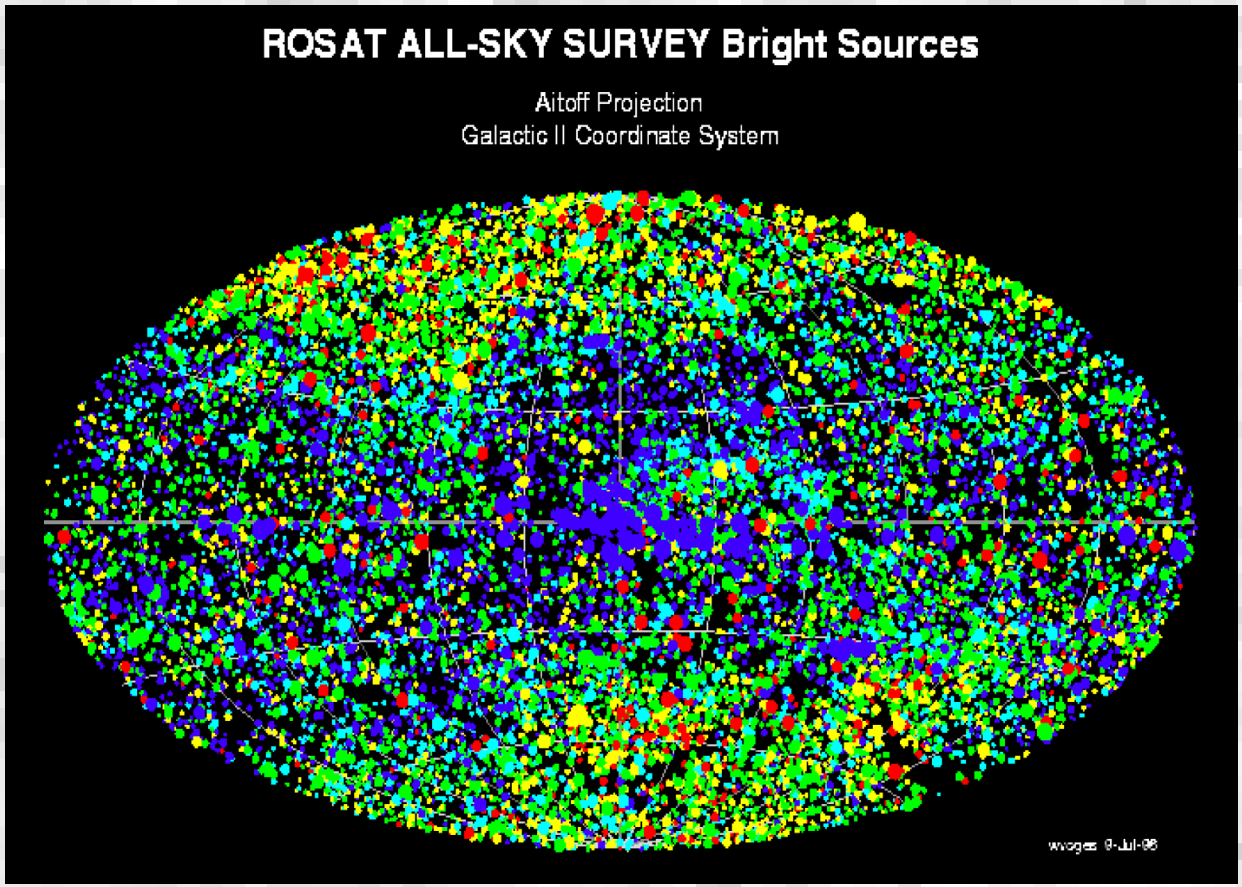



Image credits:ROSAT Mission/MPE

- Still the most sensitive all-sky X-ray survey, with ~110,000 X-ray sources.
- Sensitive in soft X-rays (0.1-2.4 keV).
- Sampled unobscured (type 1) AGNs. Not sensitive to obscured AGNs.
- SDSS spectroscopic Ids catalogued (Anderson et al. 2003;2007)

# Finding the right tracer set from the Sloan Digital Sky Survey

**tracer set:** large number & **well-defined selection!**

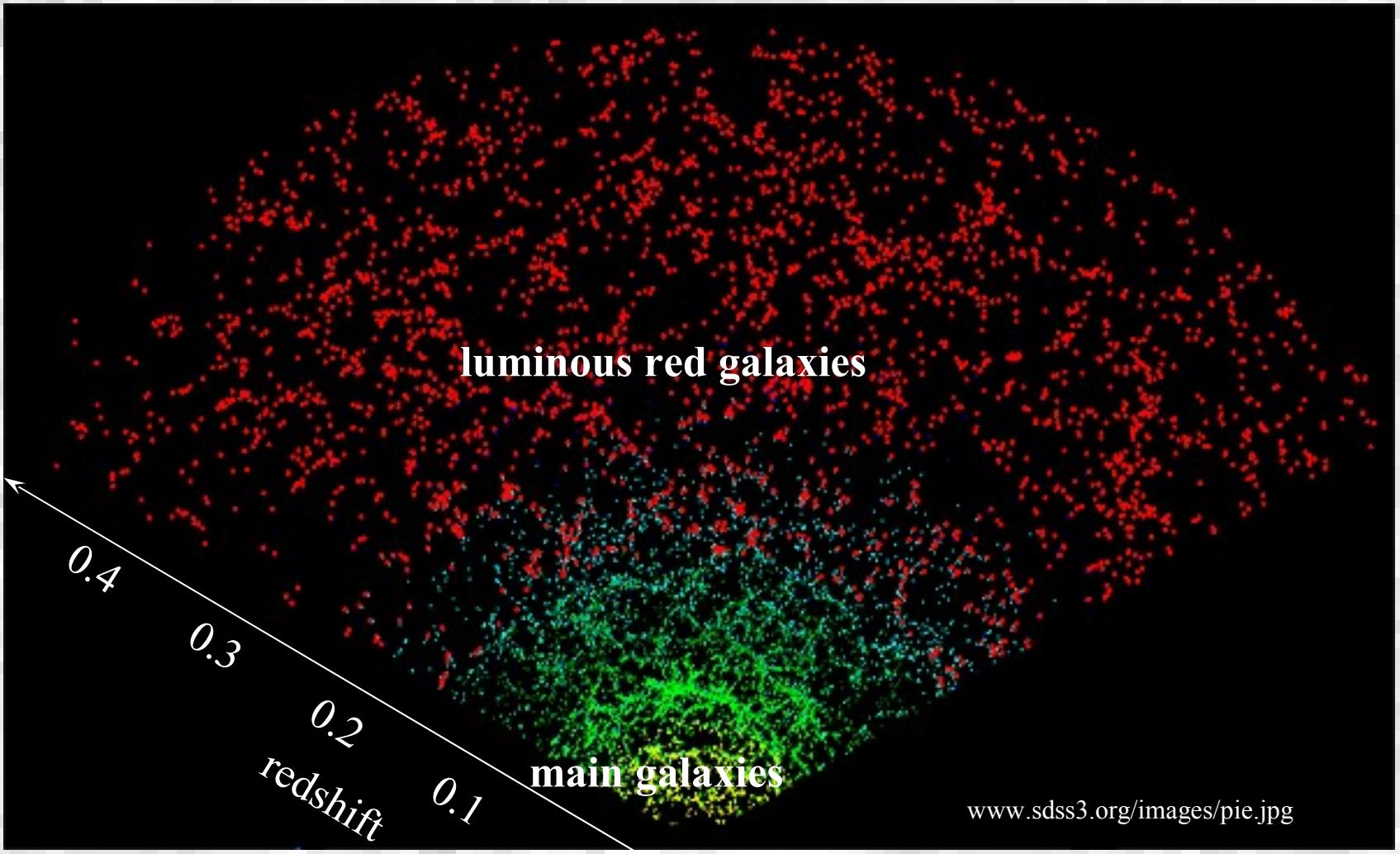
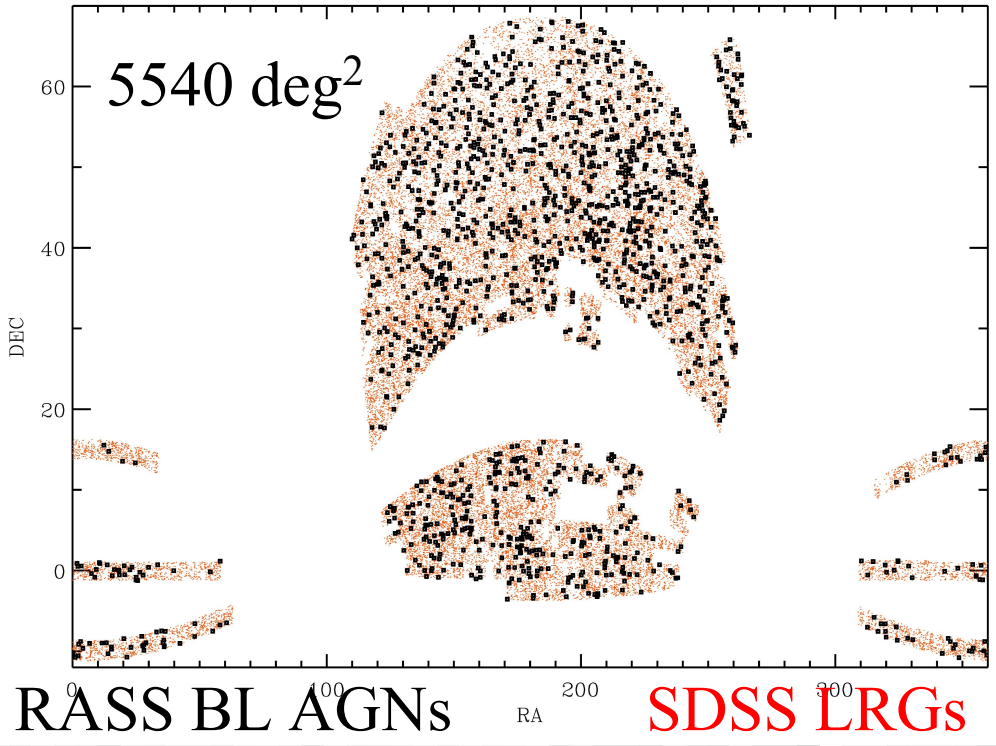



Image credit: Sloan Digital Sky Survey

# Start with SDSS Luminous Red Galaxies (LRGs) as a Tracer Set

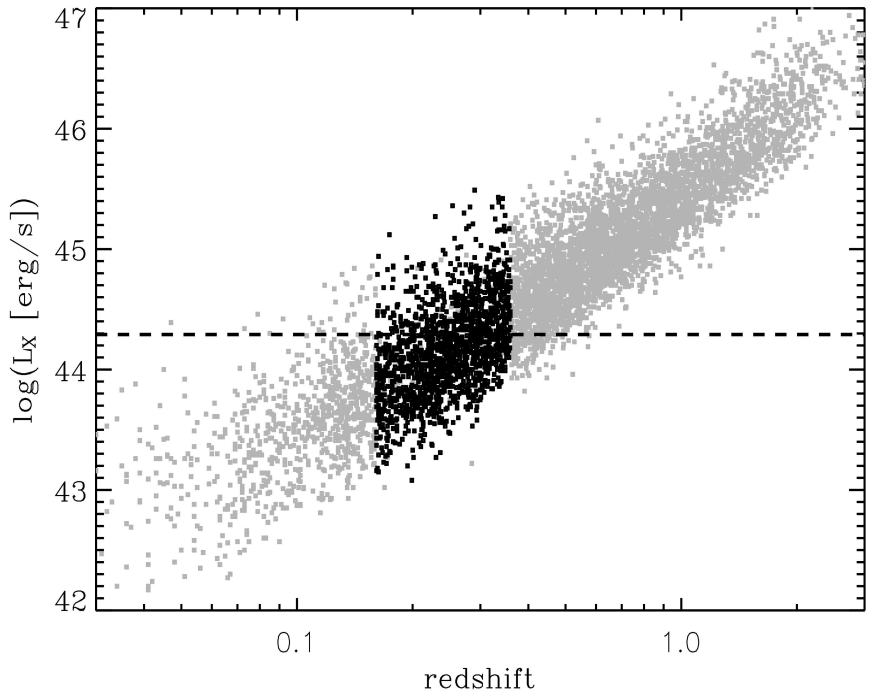
- Galaxy Sample
  - SDSS LRG Volume Limited Sample
  - Defined by Eisenstein et al. (2001), redrawn by us for DR4+
  - MB<-21.2, 0.16<z<0.36
  - 45899 LRGs Galaxies
- **X-ray AGN sample:**
  - ROSAT All-Sky Survey (RASS) sources matched with the SDSS broad-line AGNs (Anderson et al. 2003; 2007).
   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




**These two samples are completely separate. No common object.**

# First Step: SDSS LRG vs RASS AGN

- SDSS LRG sample, defined by Eisenstein et al. (2001), redrawn by us for DR4+
  - MB<-21.2, 0.16<z<0.36
  - 45899 LRGs in the DR4+ area.
  - Their ACF and HOD have been well measured (Eisenstein et al., Zehavi et al., Zheng et al. 09).
- **X-ray AGN sample:**
  - RASS sources matched with the SDSS broad-line AGNs (Anderson et al. 2003; 2007).
  - 1552 AGNs in 0.16<z<0.36

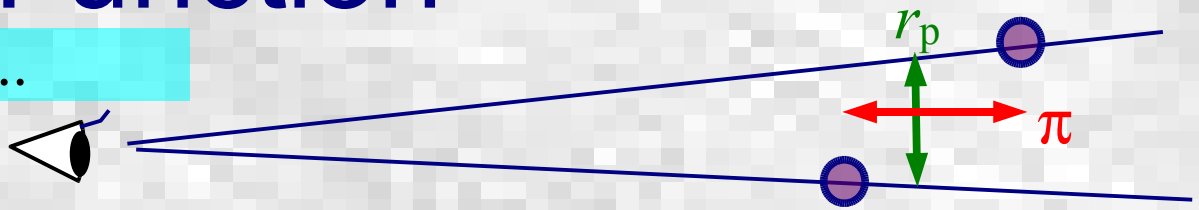



All dots: RASS-SDSS AGNs from Anderson et al. (2007)

Black dots: Used in paper I/II

# Projected Distance Correlation Function

Following a common recipe ...




- Caluculate $\xi(r_p,\pi)$
  - $r_p$: projected-distance
  - π: line-of sight separation
    - (distances from redshift --> Redshift distortion.)
- Integrate over $\pi$ —–> the projected-distance correlation function.
  - Free from the "redshift distortion".

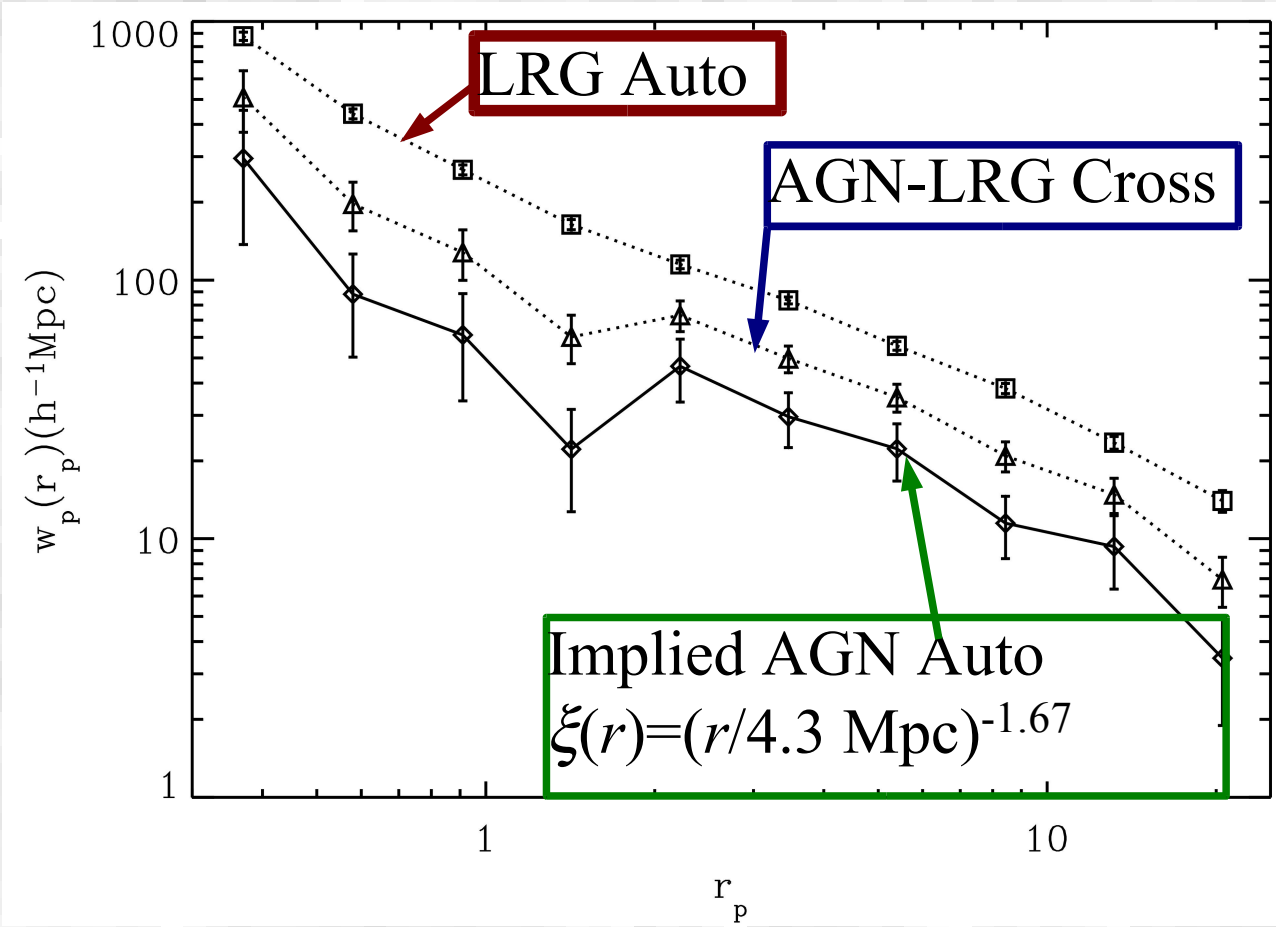
Projected Distance  Line of sight separation

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

# Implied AGN Auto-Correlation Function

Under the linear biasig approximation

$$W_{p,\text{AGN-auto}} \approx W_{p,\text{AGN-LRG}}^{2} / W_{p,\text{LRG-auto}}$$




Power-law fit:

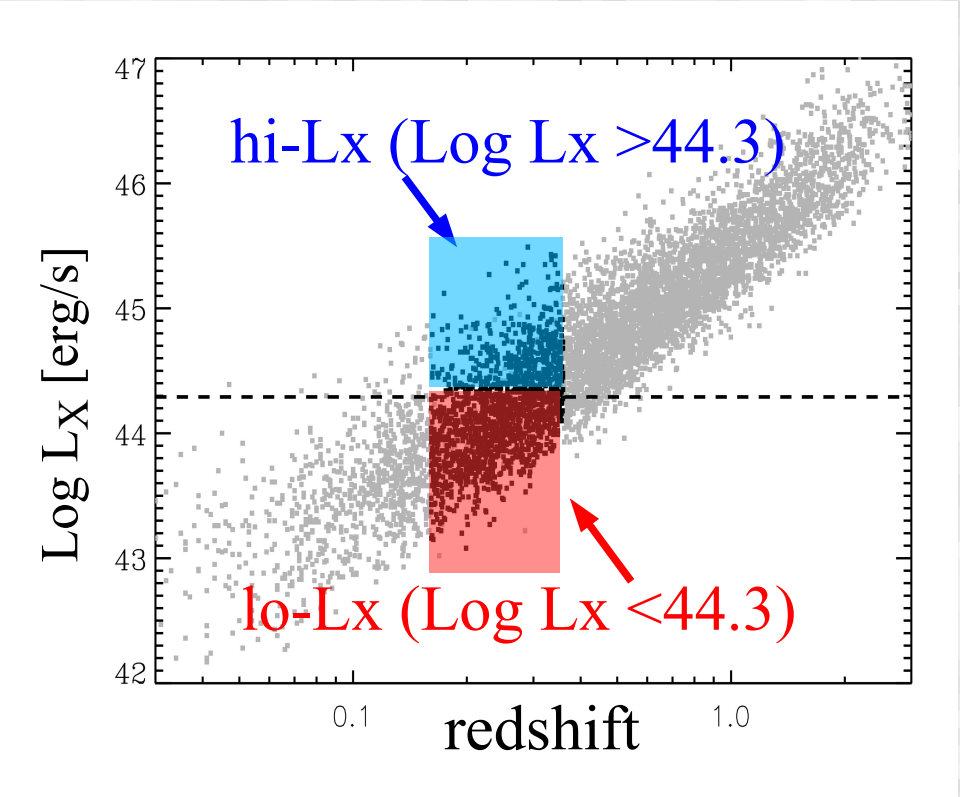
$\xi_{AGN}(r)=(r/r_c)^{-\gamma}$

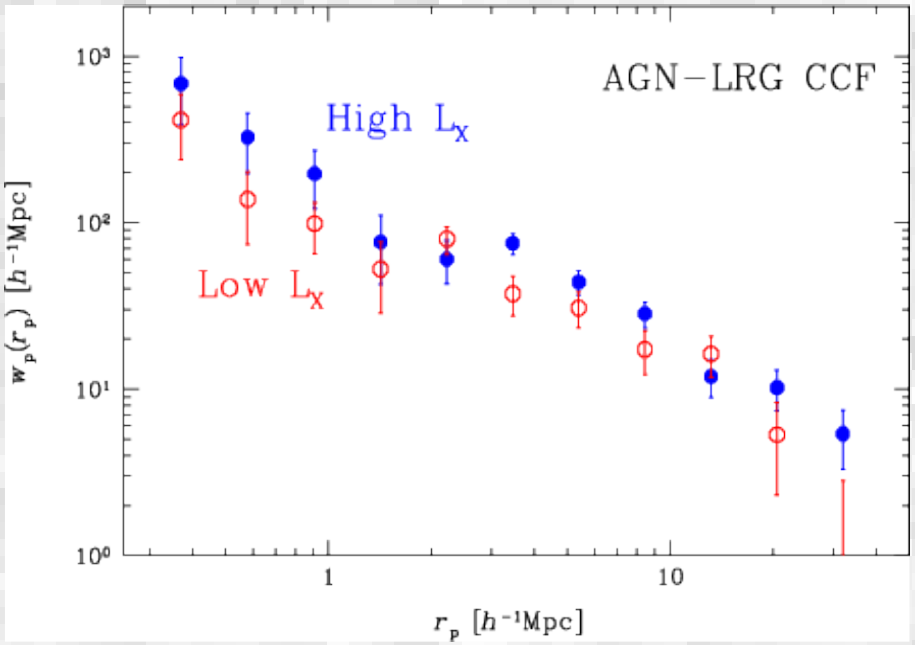
$w_{p,AGN}(r_p)=H_\gamma r_p(r_p/r_c)^{-\gamma}$

$r_c$:correlation length

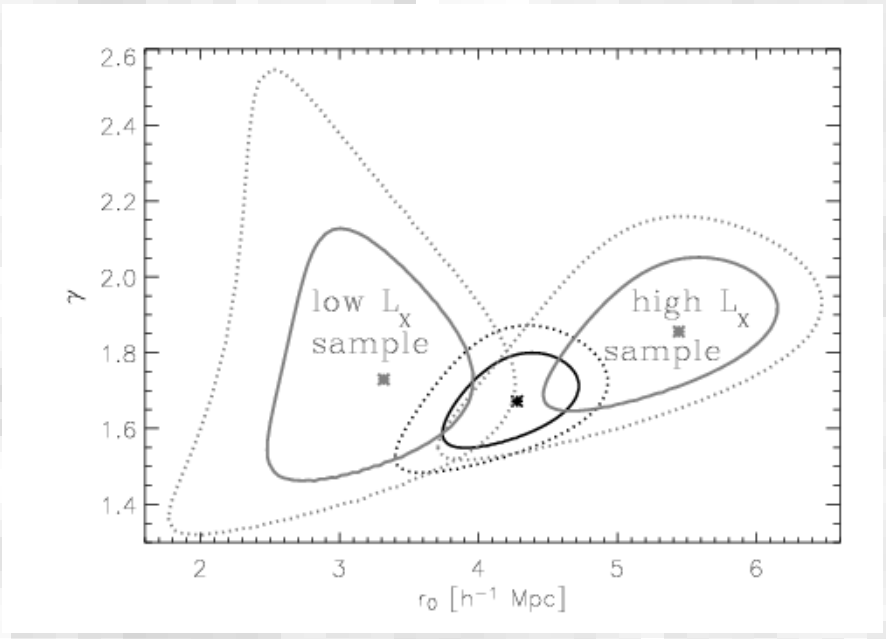
- Fit range: $0.3<r_p<15\ h^{-1}$ Mpc
- Error estimation: Jackknife-resampling of ~80 blocks.
- Correlations of errors in different bins included through the covariance matrix

# X-ray Luminosity Dependence

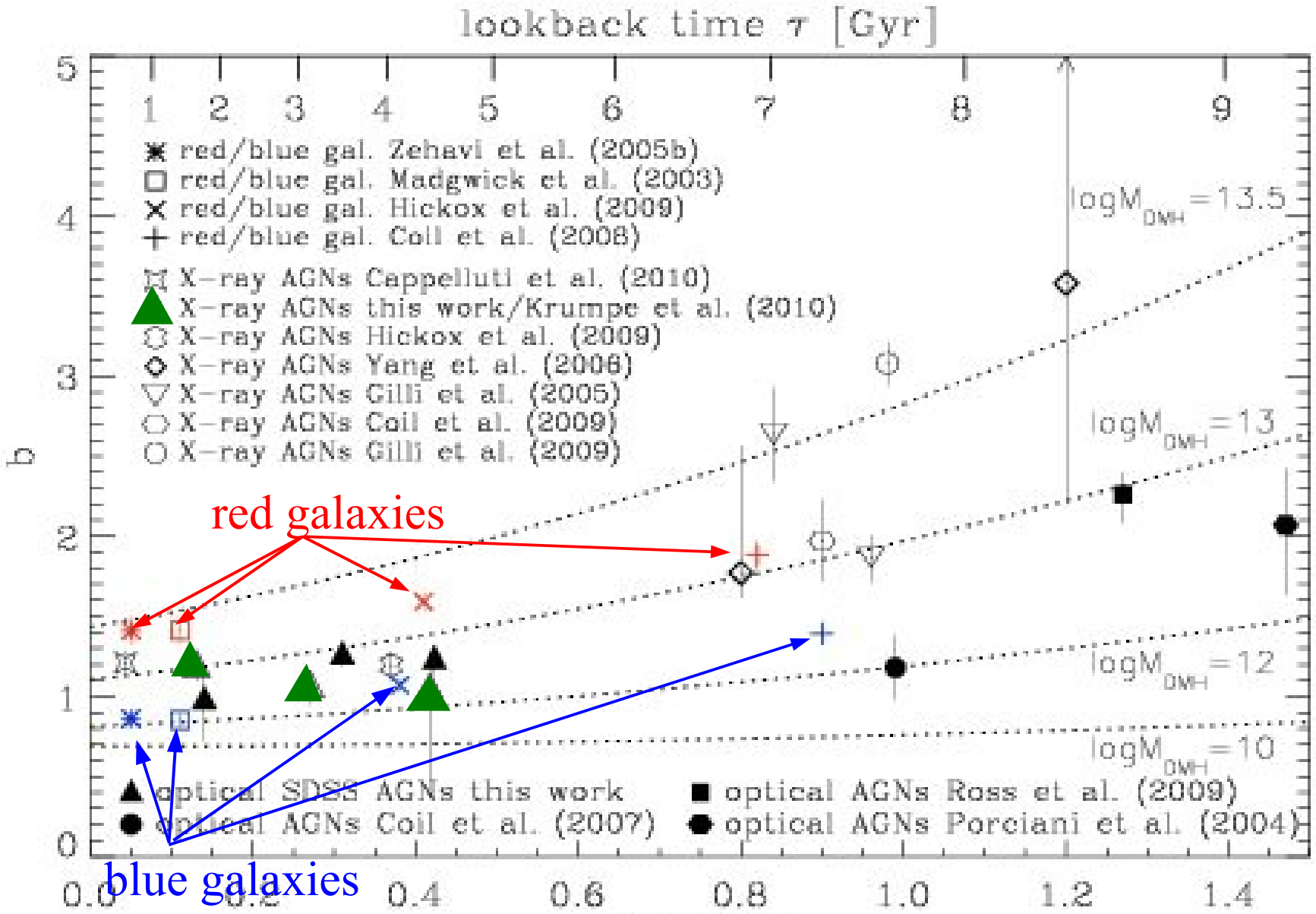



Stronger Clustering for Higher $L_X$ AGNs



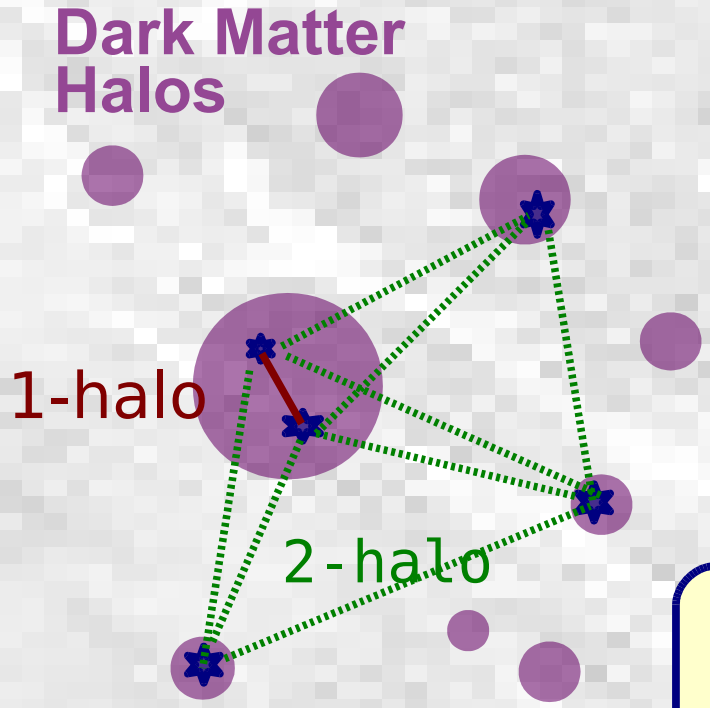
# bias ($M_{DMH}$) vs z comparisons




Krumpe et al. in prep. (paper III)

# Halo Occupation Distribution (HOD) Modeling of the AGN-LRG CCF

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




Modeling with HOD.

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

- within the same DMHs
- from different DMHs.

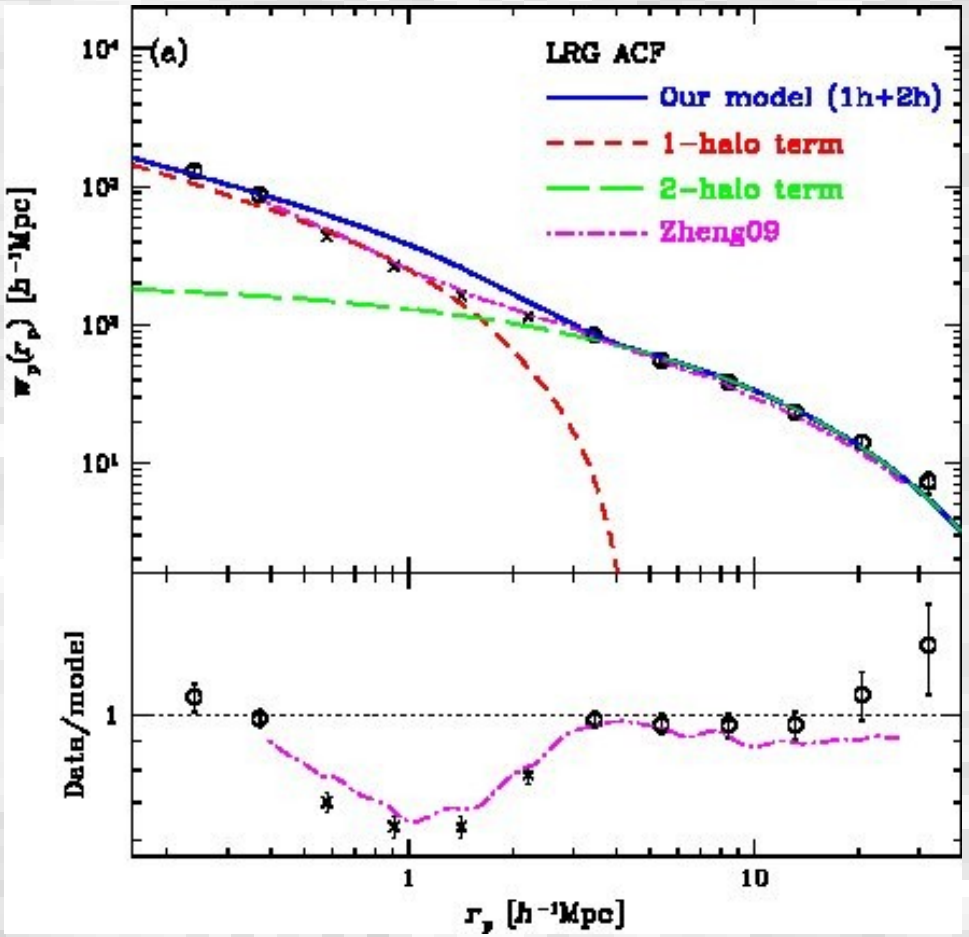
$$\xi_{\text{AGN-LRG}} = \underbrace{\xi_{\text{AGN-LRG,1h}}}_{\text{1-halo term}} + \underbrace{\xi_{\text{AGN-LRG,2h}}}_{\text{2-halo term}}$$

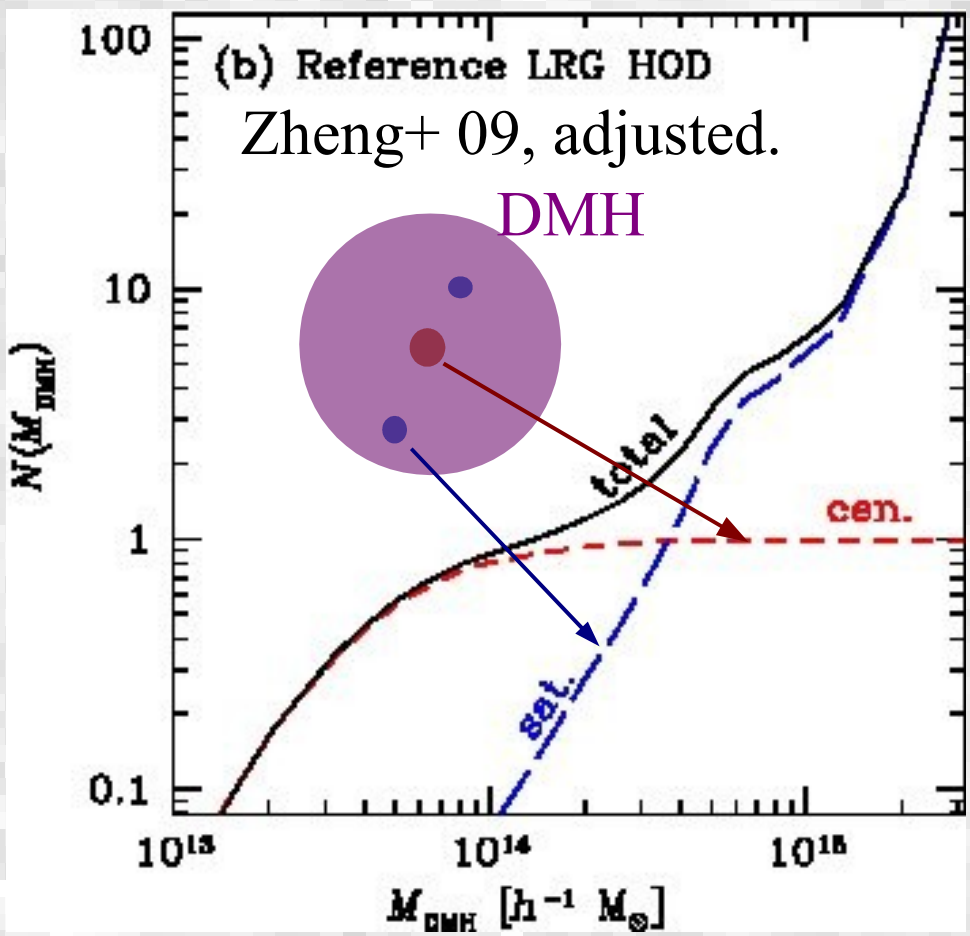
# Model Ingredients

- Matter (linear) power spectrum: $P_{lin}(k,z) \rightarrow \xi_{\mathrm{matter,lin}}(r)$
  - Used to model the two-halo term.
- DMH bias $b(M_{\mathrm{h}},z)$ (e.g. Sheth, Mo, Tormen '01; Tinker+'05)
- DMH mass function (e.g. Sheth & Tormen '99; Jenkins et al. 2001)
- DMH profile (e.g. Navarro, Frenk, White [NFW])
- **$\langle N(M_{\mathrm{h}})\rangle$**: Halo Occupation Distribution
  - mean number of sample objects per DMH as a function of $M_{\mathrm{DMH}}$, in some cases, derived separately for those at the halo centers and those not at centers (satellites).

Compute model $\xi$(r) and compare with the observation to constrain **$\langle N(M_{\mathrm{DMH}})\rangle$**

# HOD of LRGs




- The HOD for the SDSS LRGs (Zheng et al. 2009) for those at the center of a DMH (cen) and satellites (sat).

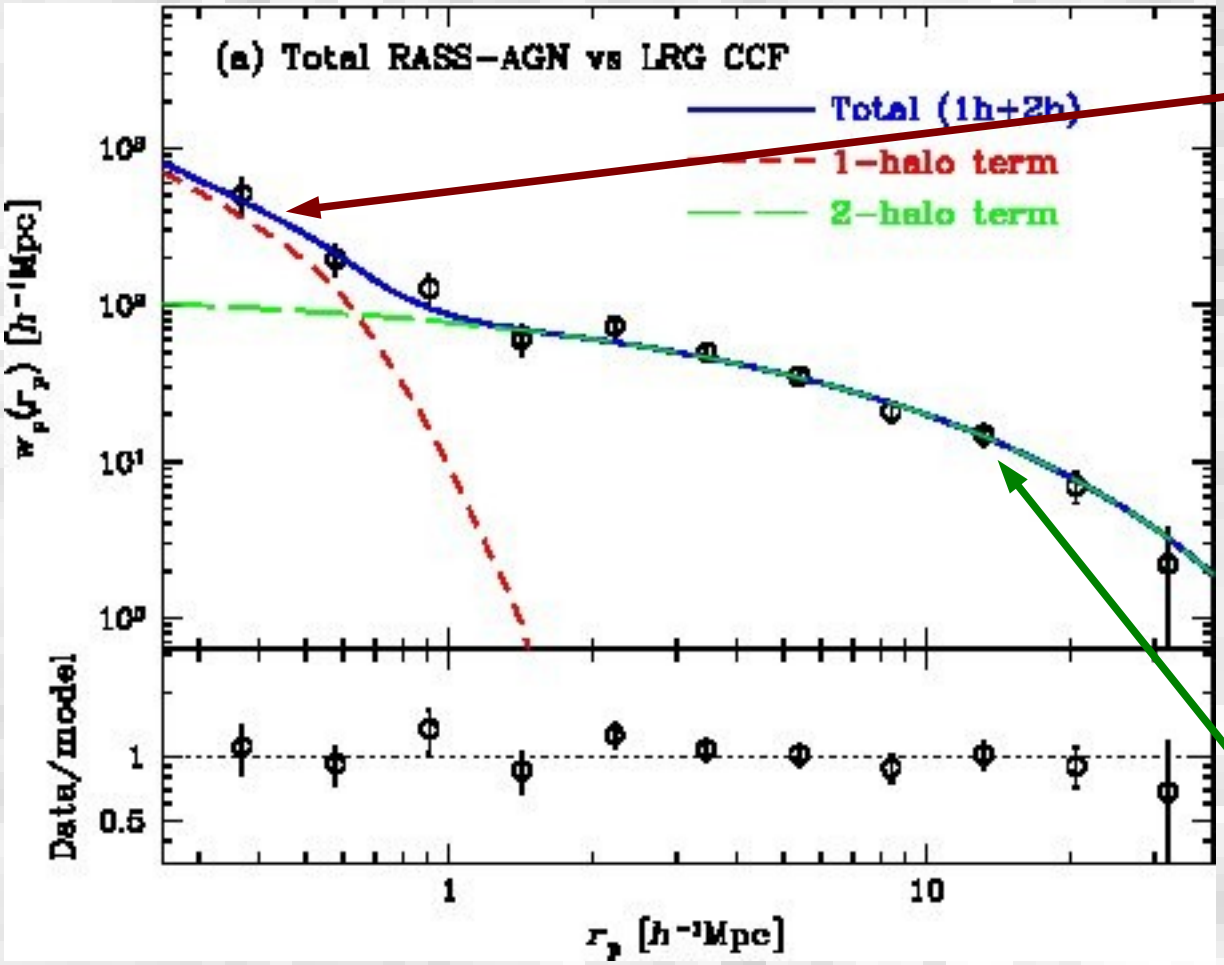
# Applying HOD modeling to the AGN-LRG CCF

When modeling our CCF, we consider three HODs

- $\langle N_{LRG,c}\rangle(M_h)$ & $\langle N_{LRG,s}\rangle(M_h)$ for the central and satellite LRGs respectively.
- $\langle N_{A,c}\rangle(M_h)$ & $\langle N_{A,s}\rangle(M_h)$ and for the AGNs.
  - First, we derive $\langle N_{LRG,c}\rangle(M_h)$ and $\langle N_{LRG,s}\rangle(M_h)$ using the ACF of the LRGs.
    - They can be determined with a much better statistics.
  - Then, using the resulting (fixed) LRG HODS, we constrain **AGN HODs (Our main interest).**

**$\langle N_{A,c}\rangle(M_h)$ & $\langle N_{A,s}\rangle(M_h)$ by fitting to the AGN-LRG CCF.**

# Model A: All AGNs that reside in halos containing LRGs are satellites.



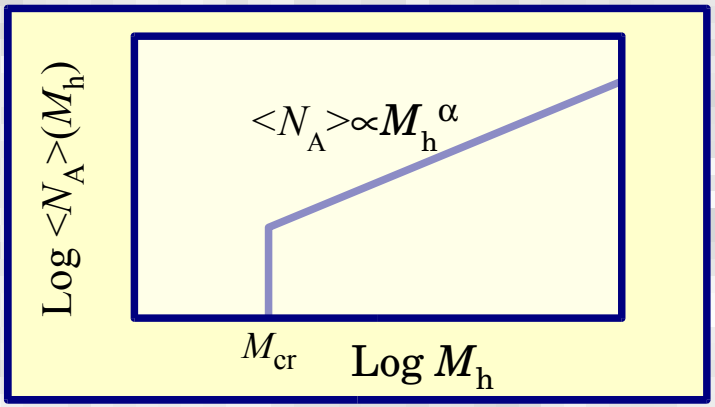

The 1-halo term is from AGN-LRG pairs in the **same DMH**.

- 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 $\propto b_A b_{LRG}$.

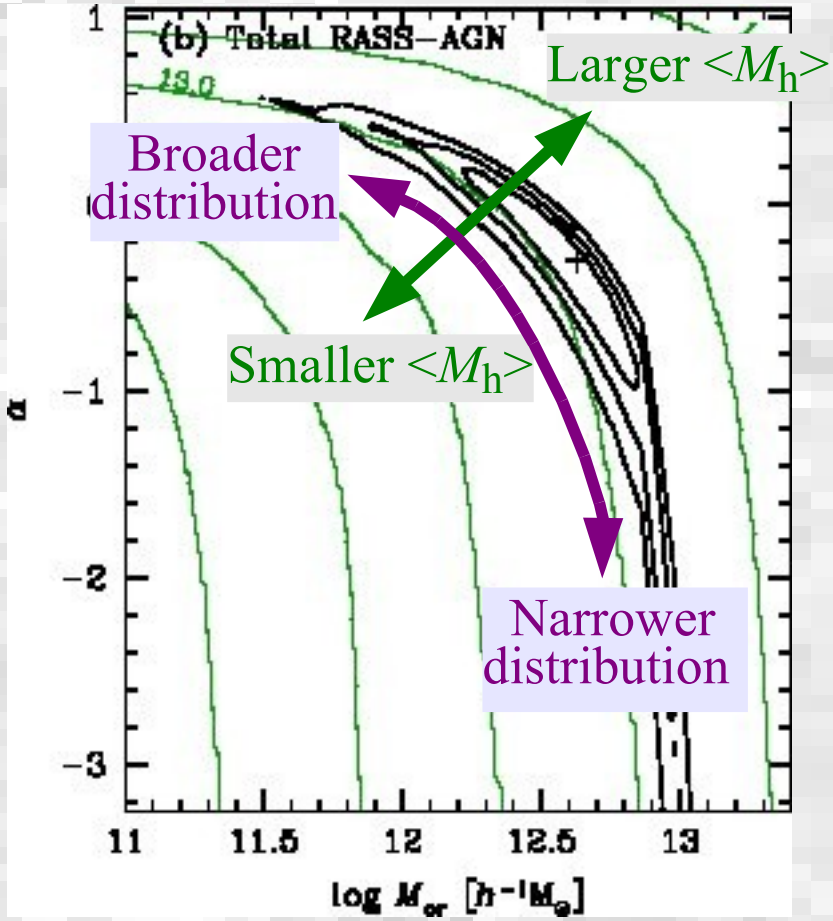
- Determines AGN bias $b_A$
- Indicates the mean DMH mass with AGNs.

# Constraints on HODs for AGNs




Simple HOD model for AGNs

- Accurate determination of $b_A$ and $\langle M_h \rangle$ than the power-law fit.
- Constraints roughly along $\langle M_h \rangle$~const.
  - Constraint from the 2-halo term ($b_X$)
- $\alpha$<0.4 ($\Delta\chi^2$<2.3 limit)
  - Constraint from the 1-halo term

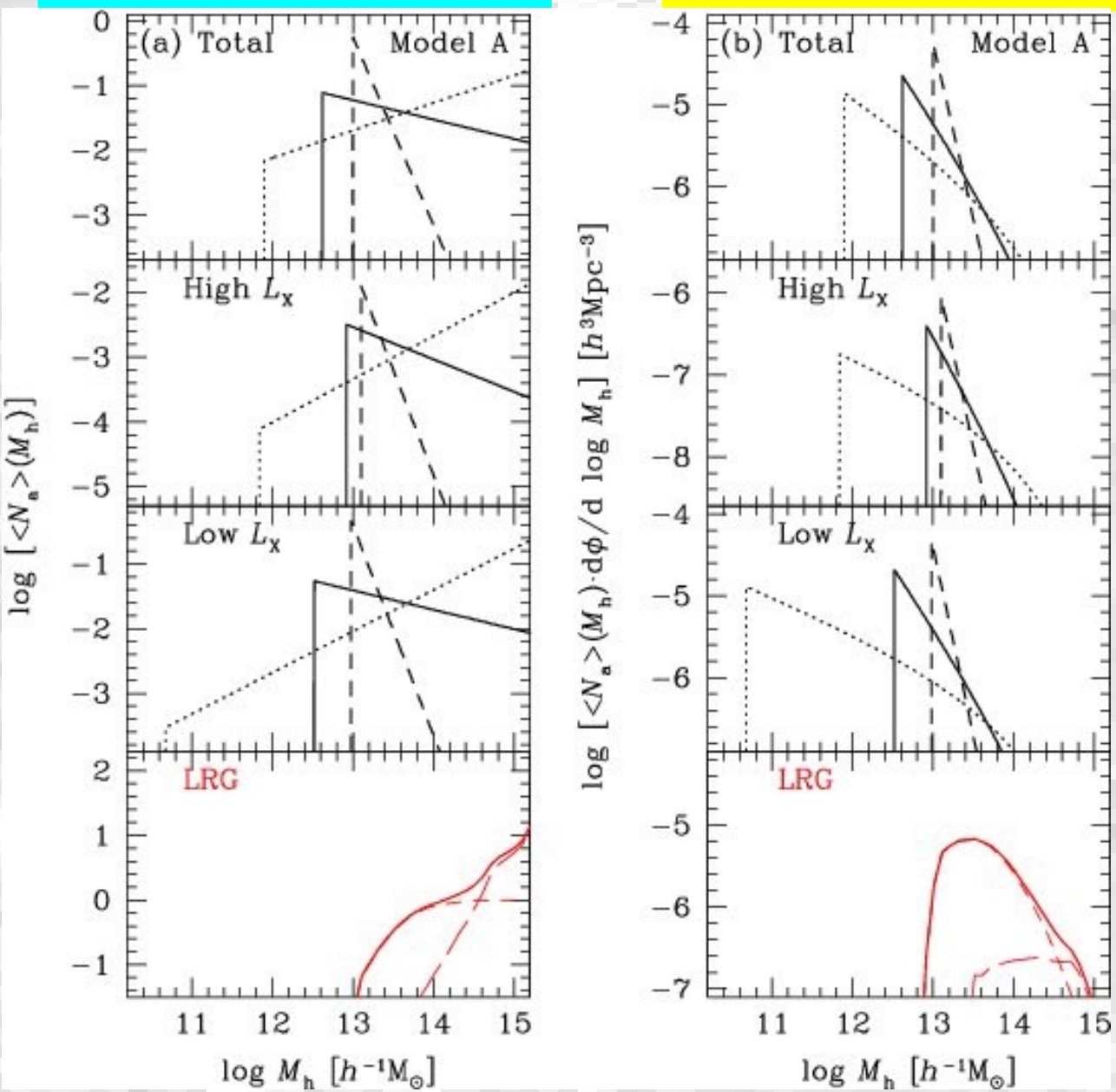



- Confidence contours (black, $\Delta\chi^2$=1;2.3;4.6)
- Mean DMH mass (green contours).

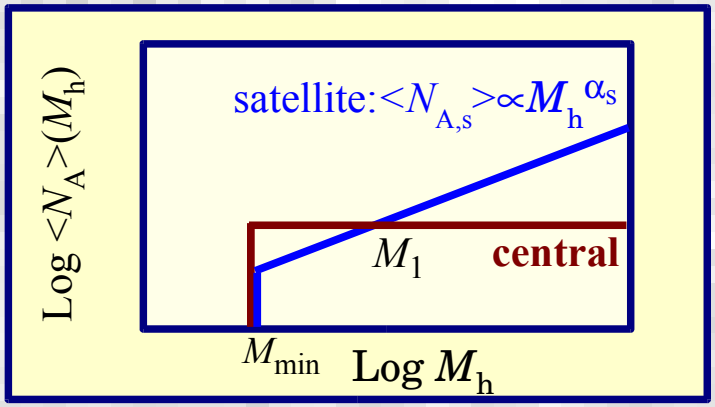
# Resulting AGN HODs (Model A)

Number per DMH (HOD)

Number Density per log $M_{DMH}$

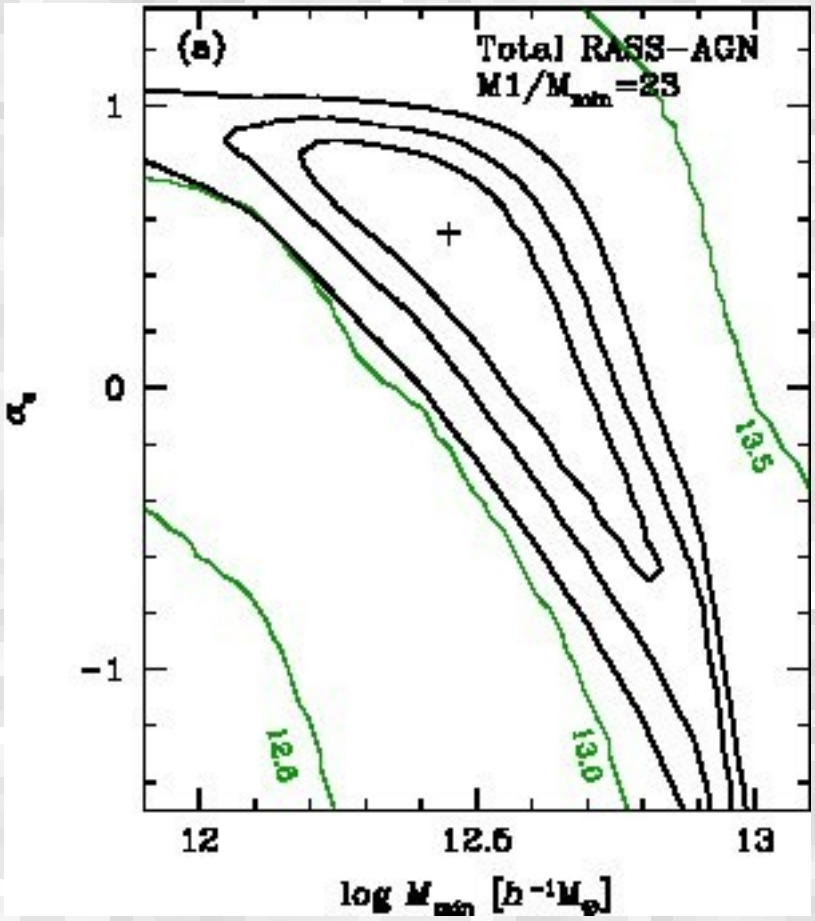


# Model with separate central+satellite AGNs




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

cf. SDSS Galaxies
(e.g. Zehavi et al. 2005)
$M_1/M_{min} \approx 23$, $\alpha \approx 1.2$



# Implication of the HOD Analysis

- The limit on $\alpha$<1 means that the number of AGNs/ Halo ***grows slower than $M_h$***.
  - The HOD of satellite **galaxies** show $\alpha$~1, i.e., number/halo $\propto M_h$ (e.g. Zehavi et al. 2010).
  - AGN fraction (non-center) decreases with $M_h$.
  - Consistent with: long-suggested anti-correlation of emission-line AGN fraction and cluster richness/velocity disperson (e.g. Gisler 1978; Dressler et al. 1985; Popesso & Biviano 2006).
- HOD analysis can probe into AGN fraction in groups/clusters without identifying individual groups/clusters.

# Implications -cont'd

- HOD analysis can probe into AGN fraction in groups/clusters without identifying individual groups/clusters.
- Possible mechanisms:
  - Merging efficiency low in high velocity encounters (Makino & Hut 1997).
  - Ram pressure stripping/thermalevaporation of cold gas in galaxies in Intracluster/intragroup medium (Gunn & Gott 1972;Cowie & Songaila 1977).

# Next Steps

- Currently working on extended redshift space using SDSS main galaxy sample ($0.07<z<0.16$) and flux-limited LRG sample ($0.16<z<0.50$). (Paper III, to be submitted soon)
- Applications of HOD modeling to expanded sample (Paper IV).
- Compare Clustering of RASS AGN subsamples sample divided based on:
  - Black hole mass ($M_\bullet$) - Eddington Ratio ($L_{bol}/L_{edd}$) space

# Summary

- We investigate the clustering of broad-line AGNs in the ROSAT All-Sky Survey using the cross-correlation function with luminous red galaxies (LRG) in SDSS in 0.16<z<0.36. The inferred AGN ACF has a correlation lengh of ~4.3 [$h^{-1}$ Mpc].
- High $L_X$ AGNs cluster more strongly (like red galaxies) than low $L_X$ ones (, which cluster like blue galaxies).
- We apply the HOD modeling to the ACF-LRG CCF directly. to constrain the distribution of AGNs among DMHs.
- For our 0.16<z<0.36 RASS-AGN sample, models where AGN fraction among satellite galaxies decreases with DMH mass are preferred.
- We are expanding our analysis to higher and lower redshifts as well as optically-selected AGNs. Stay Tuned.