Baryon oscillations in simulation

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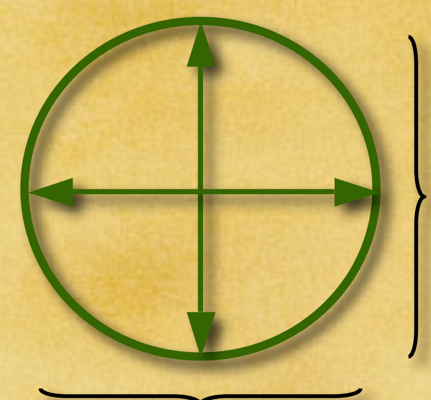
Overview

- MOTIVATION:
  - Why study baryon oscillations in galaxy power spectra?
  - Why worry about scale dependent bias?
- MODELS:
  - Scale dependent bias with the halo model
  - Other models of scale dependence
- METHODS:
  - Simulations and HODs
  - Fourier and configuration space methods
- RESULTS:
  - Halo model inspired bias model performance
  - Comparison with other model performances
- CONCLUSIONS:
  - Implications for baryon oscillation experiments
  - Unanswered questions

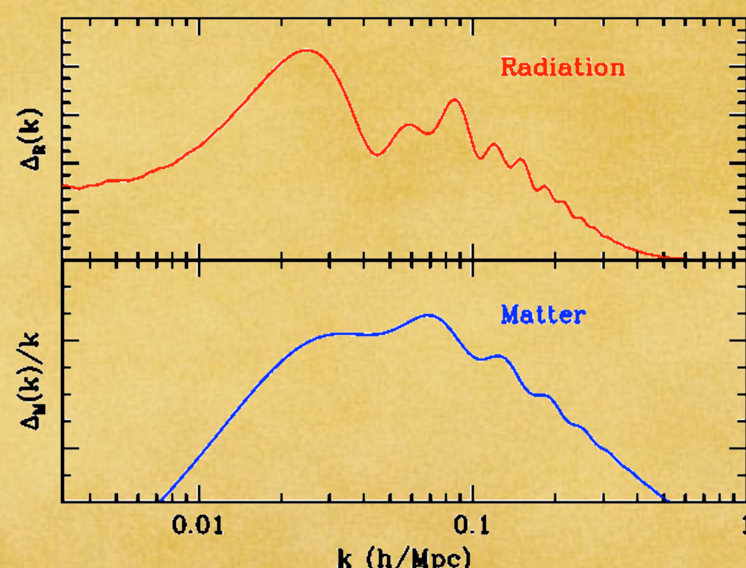
Why study baryon oscillations ?

- Models of structure formation predict Baryon (Acoustic) Oscillations, a series of features in the matter power spectrum similar to the CMB anisotropies

- The location of the peaks provide a standard ruler that probes the expansion history of the universe, and provides a sensitive new measurement of cosmological parameters



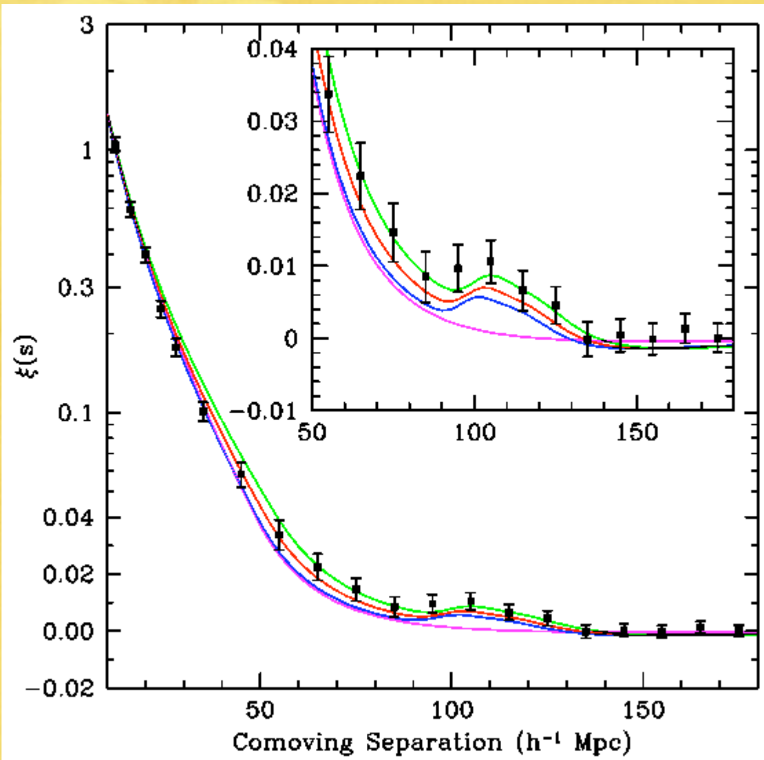
Probes distances to z~1000



Probes distances to 0<z<10

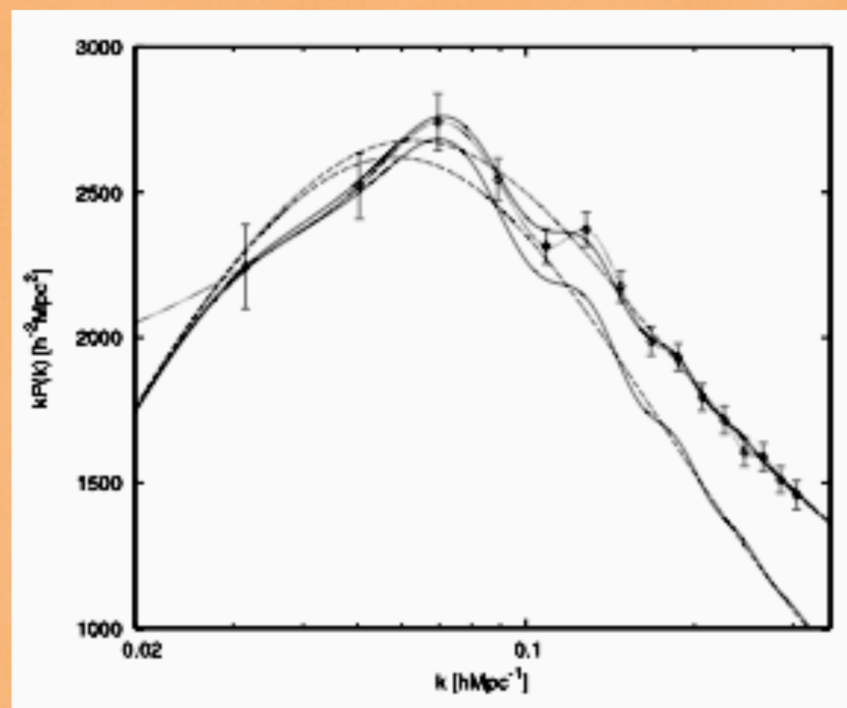
Baryon oscillations have been seen!

SDSS LRG Sample



Seo & Eisenstein (2005)

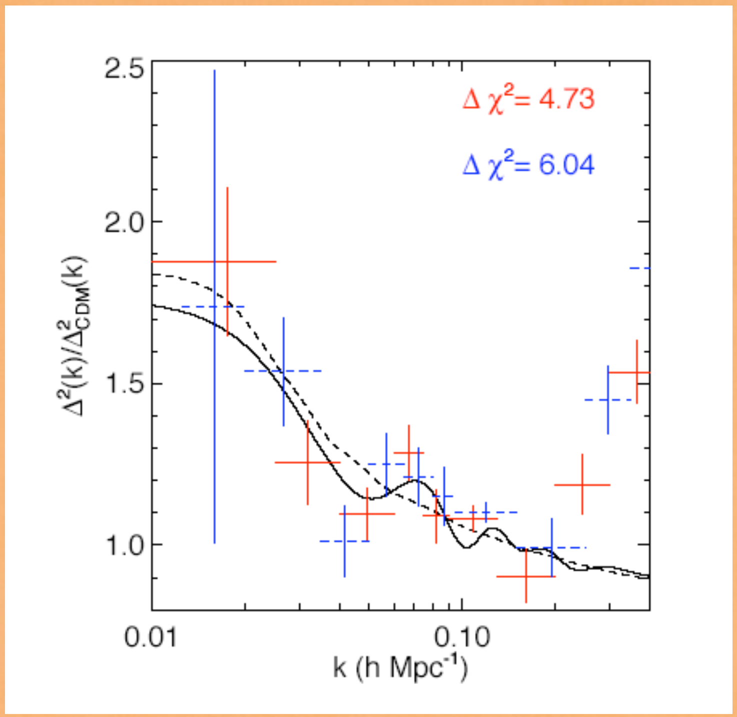
Huetsi (2005)

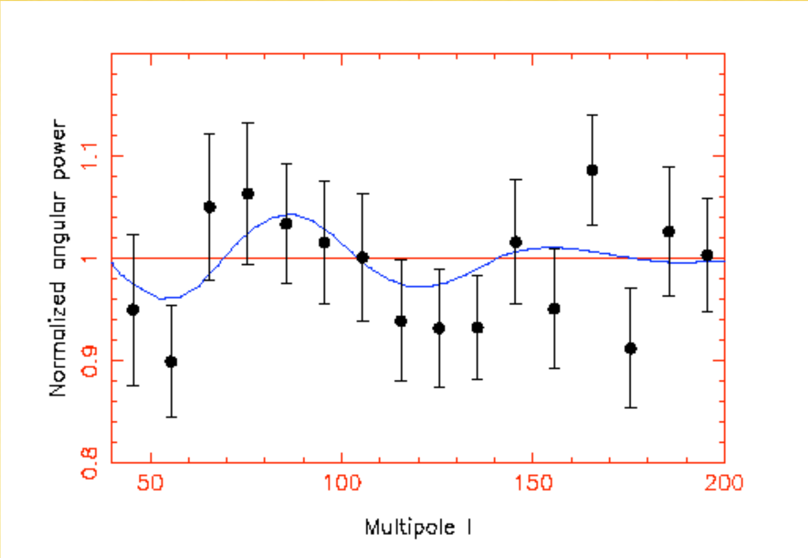


Baryon oscillations have been seen!

… and photometrically.

Padmanabhan et. al. 2006



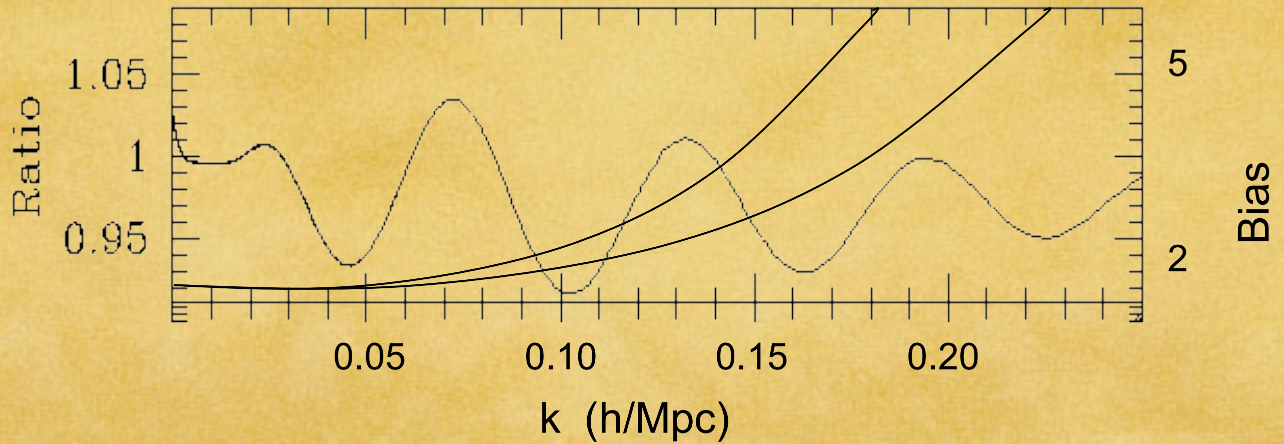


Blake et. al. 2006

Why study bias ?

- The linear dark matter power spectrum cannot be directly observed -- need galaxies
  - **Galaxy bias**
  - **Non-linear structure evolution**
  - **Redshift space distortions**

- Numerical simulations suggest that the galaxy bias has scale dependence on scales of interest
- Scale dependence in the bias can shift the relative positions of peaks and troughs in the baryon oscillations



Method: The Halo Model

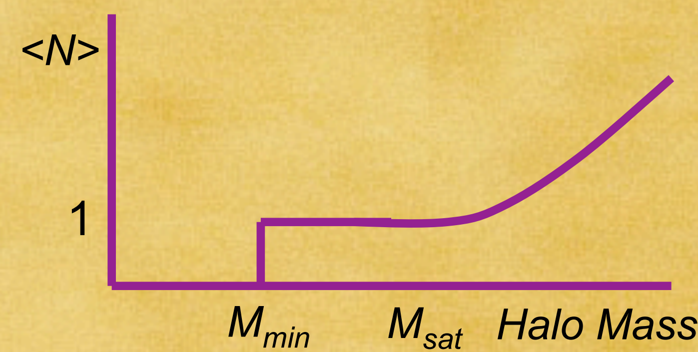
- All matter and galaxies in the universe live in virialized halos characterized by their masses
- The 2-point correlation function is the sum of inter-halo and intra-halo pair contributions
- Contribution from pairs in separate halos dominates on large scales (the 2-halo term)
- Contributions from pairs in the same halo dominate on small scales (the 1-halo term)

The Halo Occupation Distribution (HOD)

- The halo model can be extended to galaxies that act as tracers of the dark matter
  - We divide the galaxy population into central and satellite galaxies

$$\langle N_c \rangle = \Theta(M - M_{\rm min})$$

$$\langle N_s \rangle = \Theta(M - M_{\rm min}) \left(\frac{M}{M_{\rm sat}} \right)^a$$



  - The mean galaxy number density is

$$\bar{n}_{\rm gal} = \int_{M_{\rm min}}^{\infty} dM\, n_h(M) \left(1 + \left(\frac{M}{M_{\rm sat}} \right)^a \right)$$

  - Only satellites trace the halo dark matter profile

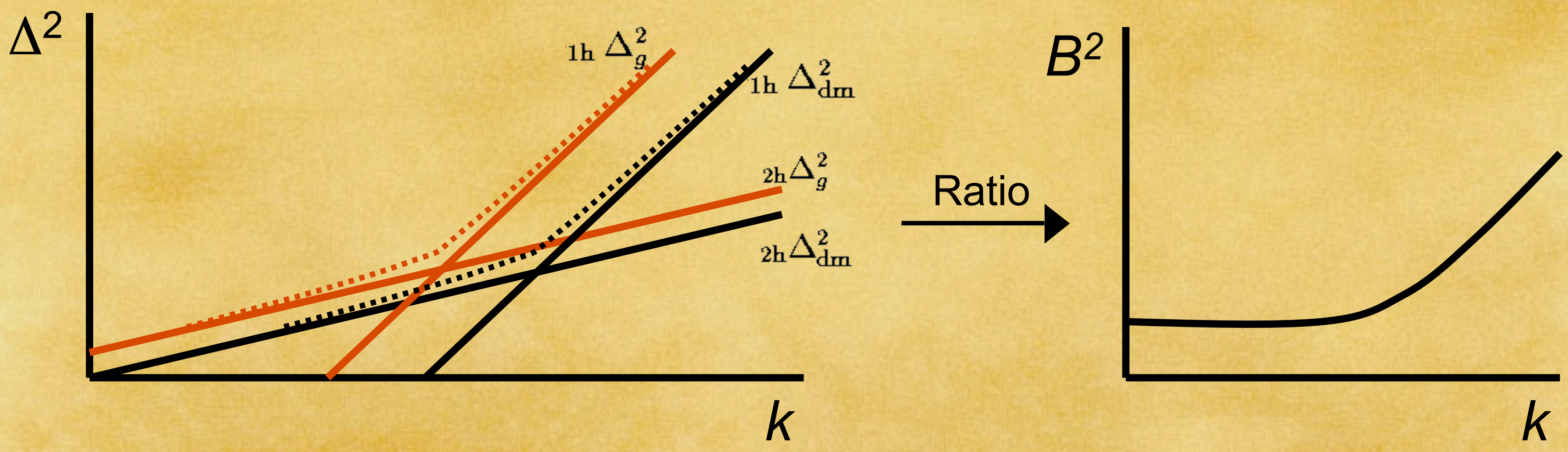
Galaxy Bias

- If we choose to define galaxy bias as the ratio of the power spectra then

$$B^2(k) \equiv \frac{{}_{2h}\Delta_g^2 + {}_{1h}\Delta_g^2}{{}_{2h}\Delta_{dm}^2 + {}_{1h}\Delta_{dm}^2}$$

Relative shift in each depends on the HOD

- In general, ${}_{2h}\Delta_g^2 > {}_{2h}\Delta_{dm}^2$ and ${}_{1h}\Delta_g^2 > {}_{1h}\Delta_{dm}^2$ but the two terms do not shift proportionally



Trends in Scale Dependence of Bias

- At fixed n_g, scale dependence increases as the tracers become more biased
- At fixed bias, scale dependence increases as n_g decreases, i.e. more scale dependance for rarer objects.
- The scale dependence is not sensitive to the distribution within the halo, only the number of galaxies per halo
- The halo model treatment suggests a more natural description of galaxy bias than B(k)

$$\Delta^2_{\rm gal}(k) = b^2 \Delta^2_{\rm lin}(k) e^{-(k/k_2)^2} + (k/k_1)^3$$

2-h

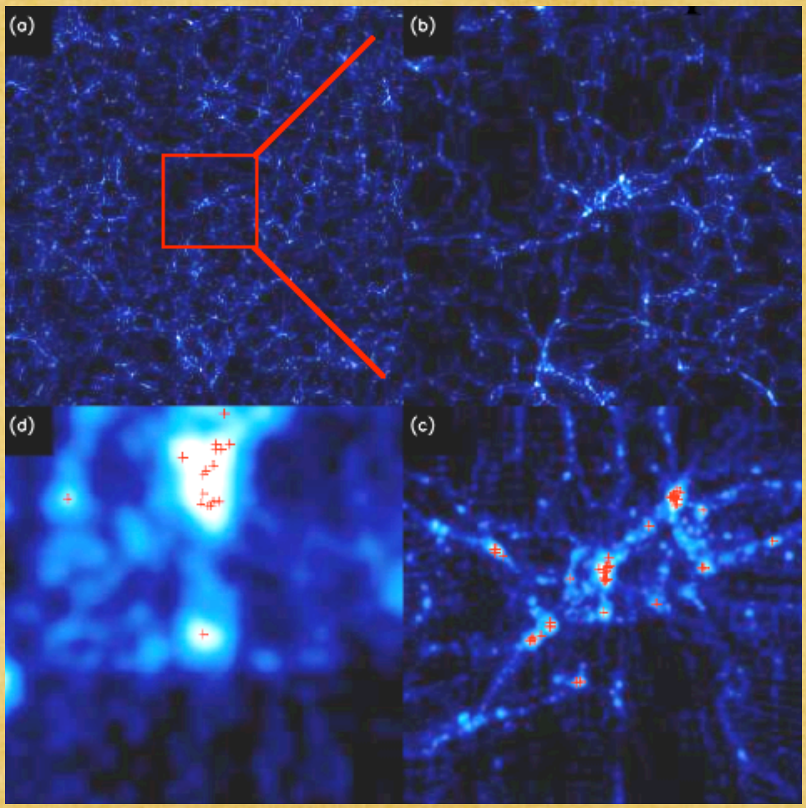
Determined by HOD parameters

Halo exclusion

1-h

N-body Simulations

- N-body simulations used to study structure formation as a function of cosmological parameters
- Some dark matter particles can be "painted" to represent galaxies
- A range of Halo Occupation Distributions (HODs) can be studied in this context (Huff, Schulz, Schlegel, Warren and White; in prep)



White 2005

An Example

•A 10 Mpc/h slice through a ~Gpc^3 simulation

•Each panel zooms in a factor of 4

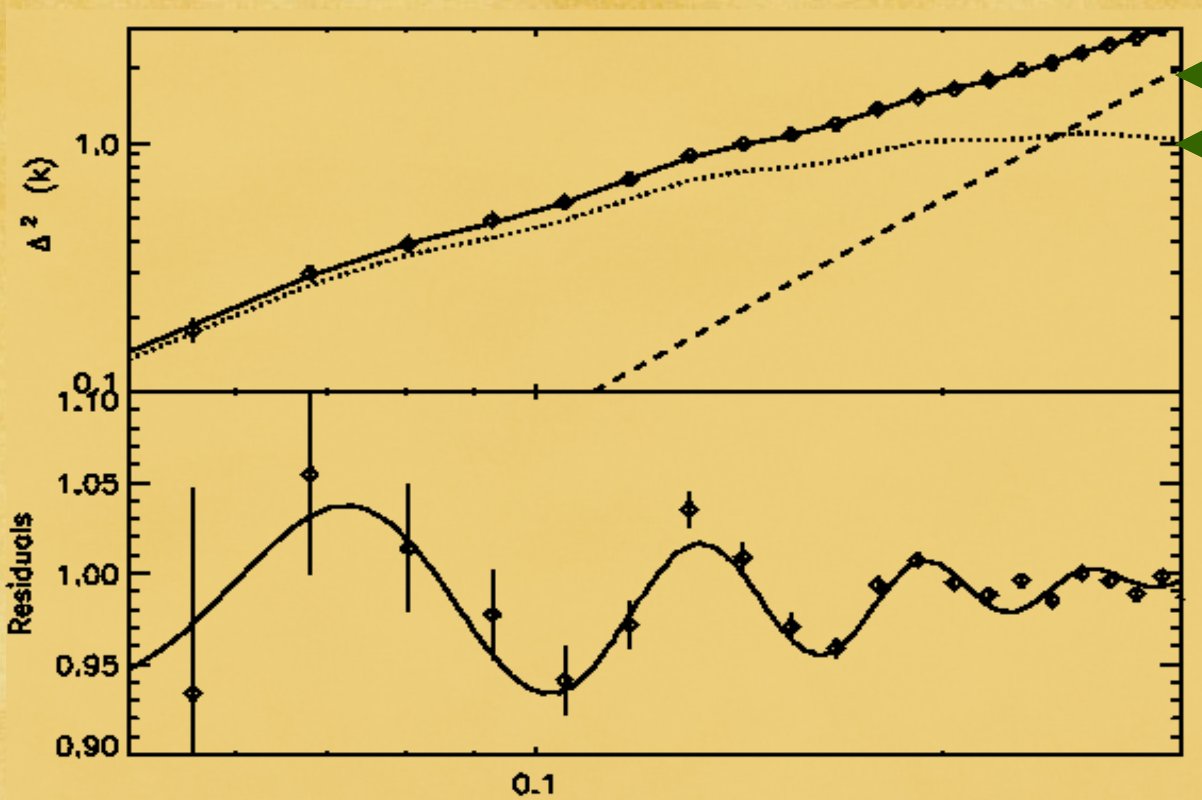
•Color scale is logarithmic, from just below mean density to 100x mean density

•Red points mark the galaxy positions

Testing the halo model inspired treatment

- This form agrees well with numerical simulations

$$\Delta^2_{\rm gal}(k) = b^2\Delta^2_{\rm lin}(k)e^{-(k/k_2)^2} + (k/k_1)^3$$



Error bars are bootstrapped from eight subdivisions of the simulation volume

Forms of galaxy bias tested

- Blake & Glazebrook

$$\Delta^2(k) = \Delta^2_{\rm ref}(k)\left[1 + Ak\exp\left\{-\left(\frac{k}{k_s}\right)^{1.4}\right\}\sin\left(\frac{2\pi k}{k_A}\right)\right]$$

- Q-model used in SDSS

$$\Delta^2(k) = b^2\,\Delta^2_{\rm lin}(k)\frac{1+Qk^2}{1+ak}$$

a=1.7 Mpc/h

- Halo Model Inspired

$$\Delta^2_{\rm gal}(k) = b^2\Delta^2_{\rm lin}(\alpha k)e^{-(\alpha k/k_2)^2} + (\alpha k/k_1)^3$$

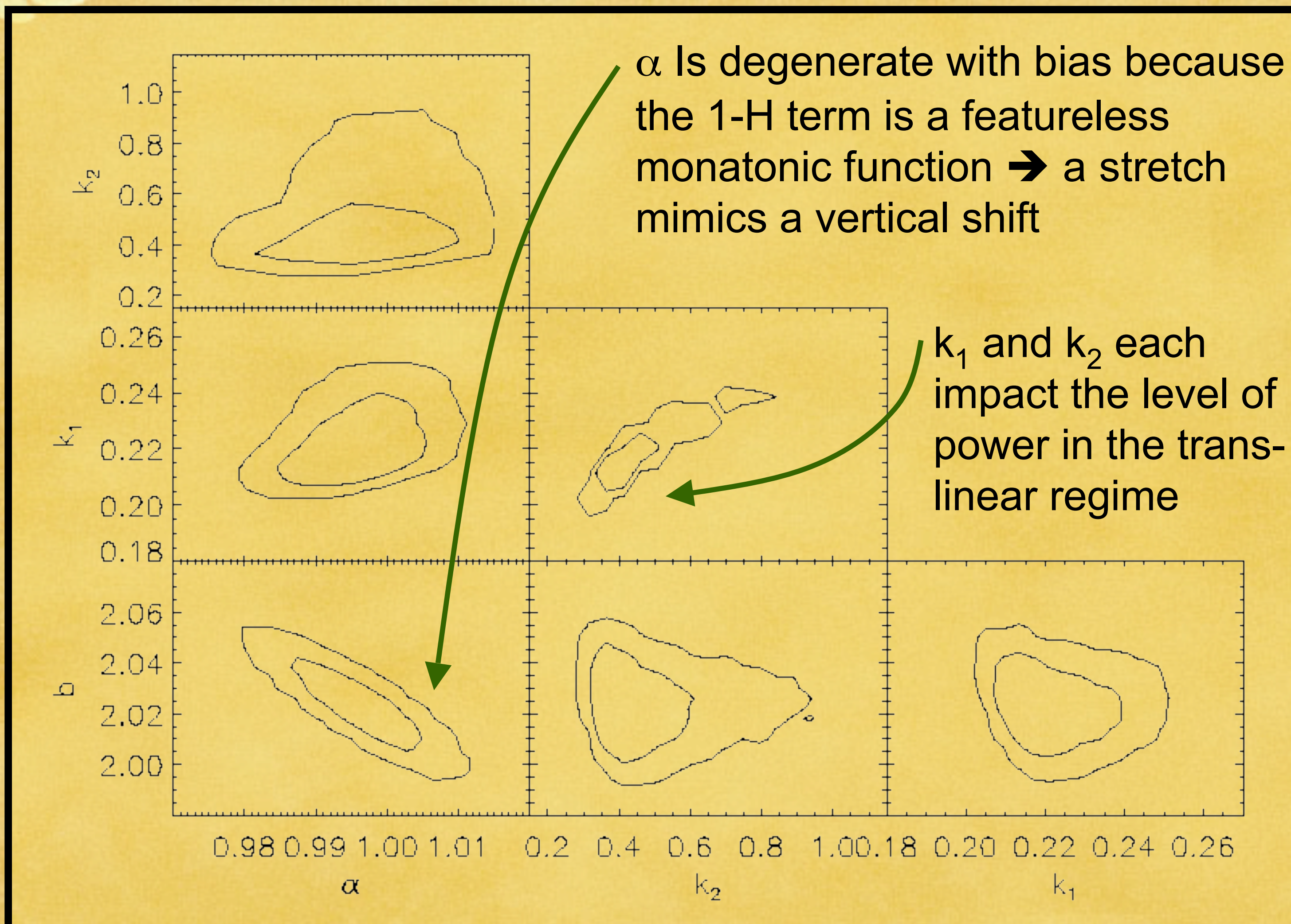
We introduce α to study the degeneracy between the model parameters and the position of the sound horizon

- Lagrangian Displacement

$$\Delta^2_{\rm gal}(k) = b^2\Delta^2_{\rm lin}(\alpha k)e^{-(\alpha k/k_2)^2} + (\alpha k/k_1)^3 + \left(1 - e^{-(\alpha k/k_2)^2}\right)b^2\Delta^2_{\rm ref}(\alpha k)$$

Degeneracy of the acoustic scale with HOD

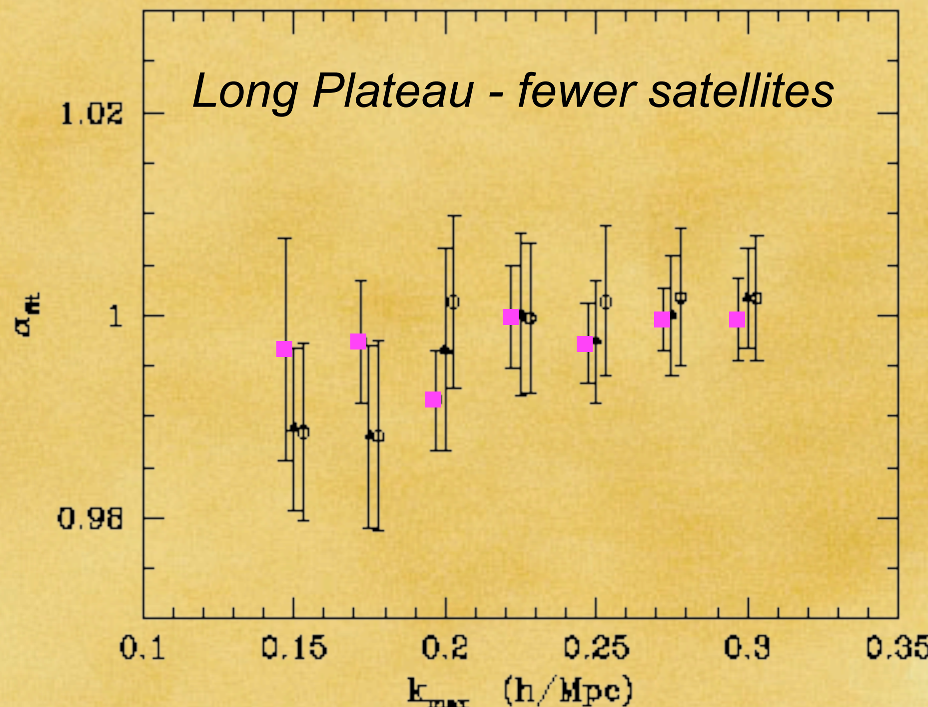
$$\Delta^2_{\rm gal}(k) = b^2 \Delta^2_{\rm lin}(\alpha k) e^{-(\alpha k/k_2)^2} + (\alpha k/k_1)^3$$



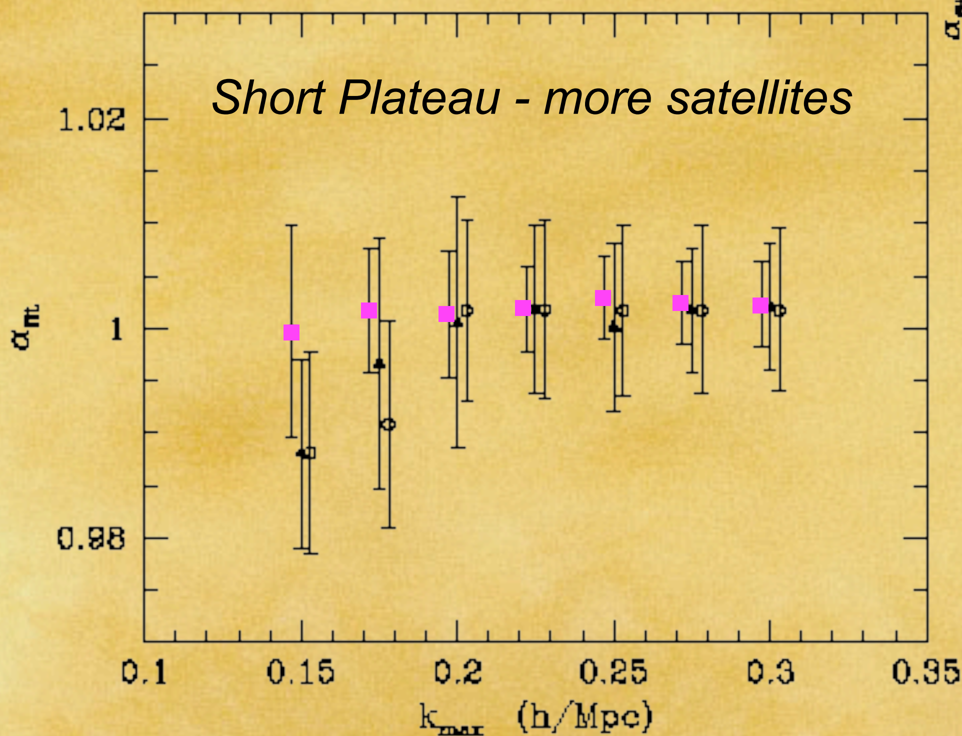
Model comparison I

- For most galaxy bias models, the recovered sound horizon is unbiased, even for fits to k_{max}=0.3
- Without treatment of scale dependant bias, models with more satellites can return up to %10 bias in α

$Log_{10}(M_{min}/M_{\odot})=12.7$ $Log_{10}(M_{1}/M_{\odot})=13.5$



$Log_{10}(M_{min}/M_{\odot})=12.8$ $Log_{10}(M_{1}/M_{\odot})=13.0$

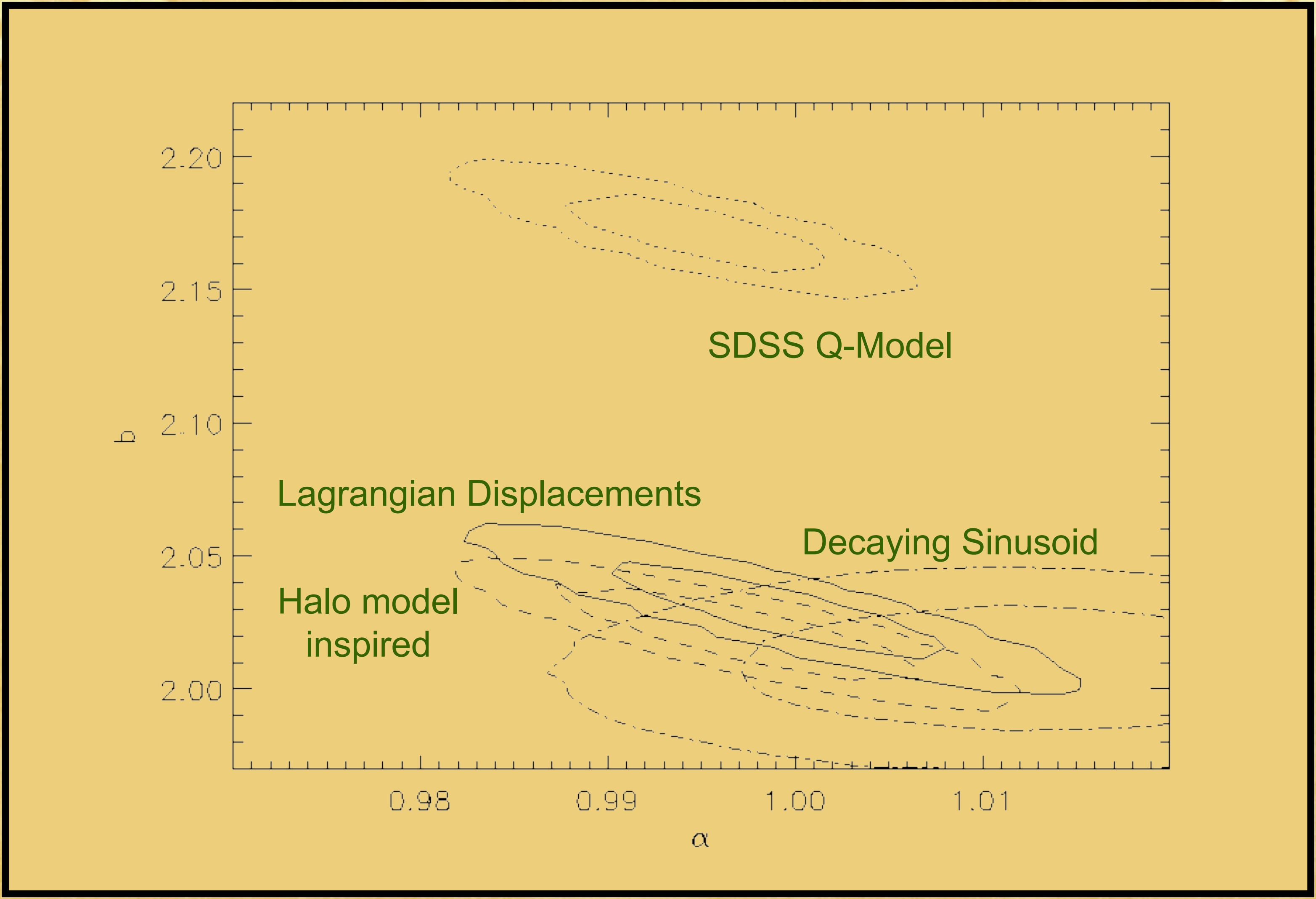


■ SDSS Q-Model

○ Halo-model inspired

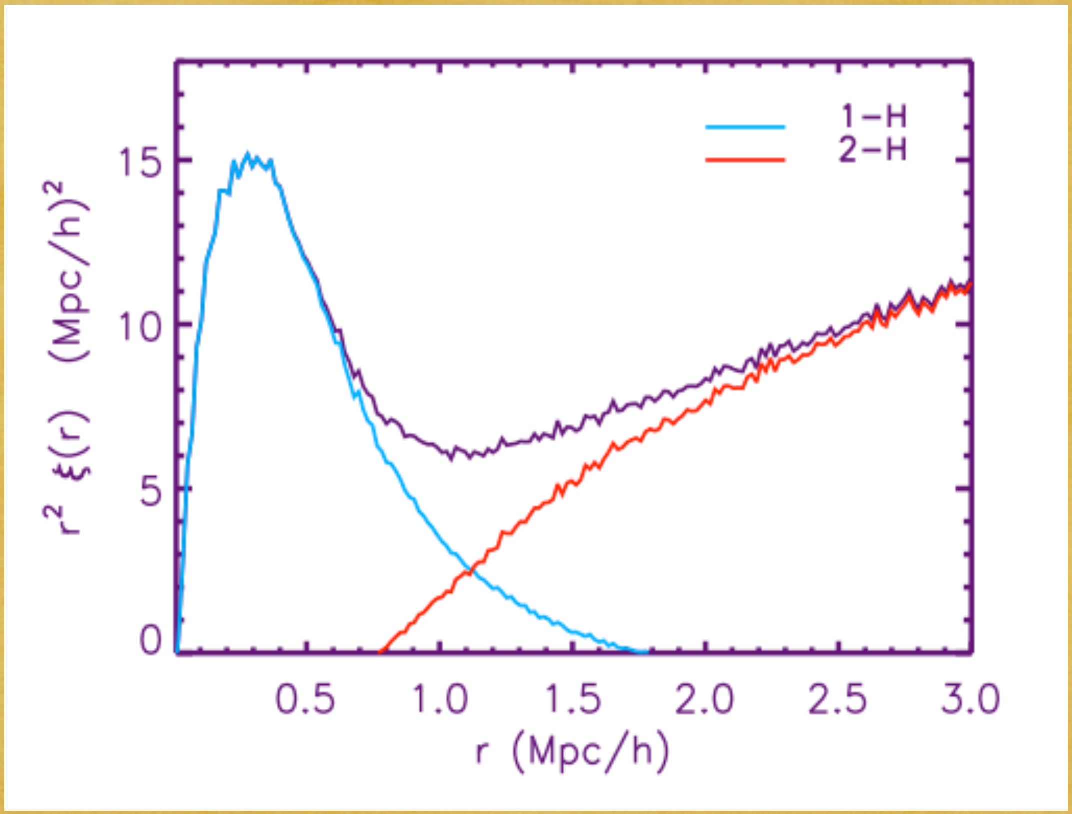
▲ Lagrangian reconstruction

Model comparison II



Virtues of the correlation function

- Studying the correlation function at ~100 Mpc/h is comparatively less scale dependent than the power spectrum
- It is often cleaner to account for irregular survey geometry
- The 1-halo term is confined to halo sized scales ~1 Mpc/h



Irritations of the correlation function

- Data in adjacent bins are very highly correlated -- error propagation difficult

- Measuring ξ in a periodic simulation can be problematic
  - sensitivity to low k modes
  - errors inherited from the mean density estimate

- In observation ξ is systematically underestimated on scales approaching the survey size -- the integral constraint

- We need an estimator that is more robust for both observations and N-body simulations

A configuration space band power estimator

- We find the following quantity to be much less sensitive while containing the same information

$$\Delta\xi(r) \equiv \bar{\xi}(<r) - \xi(r) = \frac{3}{r^3}\int_0^r x^2\,dx\;\xi(x) - \xi(r)$$

$$\Delta\xi(r) = \int \frac{dk}{k}\;\Delta^2(k)\;j_2(kr) \simeq \int \frac{dk}{k}\;\Delta^2(k)\left[\frac{(kr)^2}{15} - \frac{(kr)^4}{210} + \cdots\right]$$

- Insensitive to low k modes as compared to ξ(r)

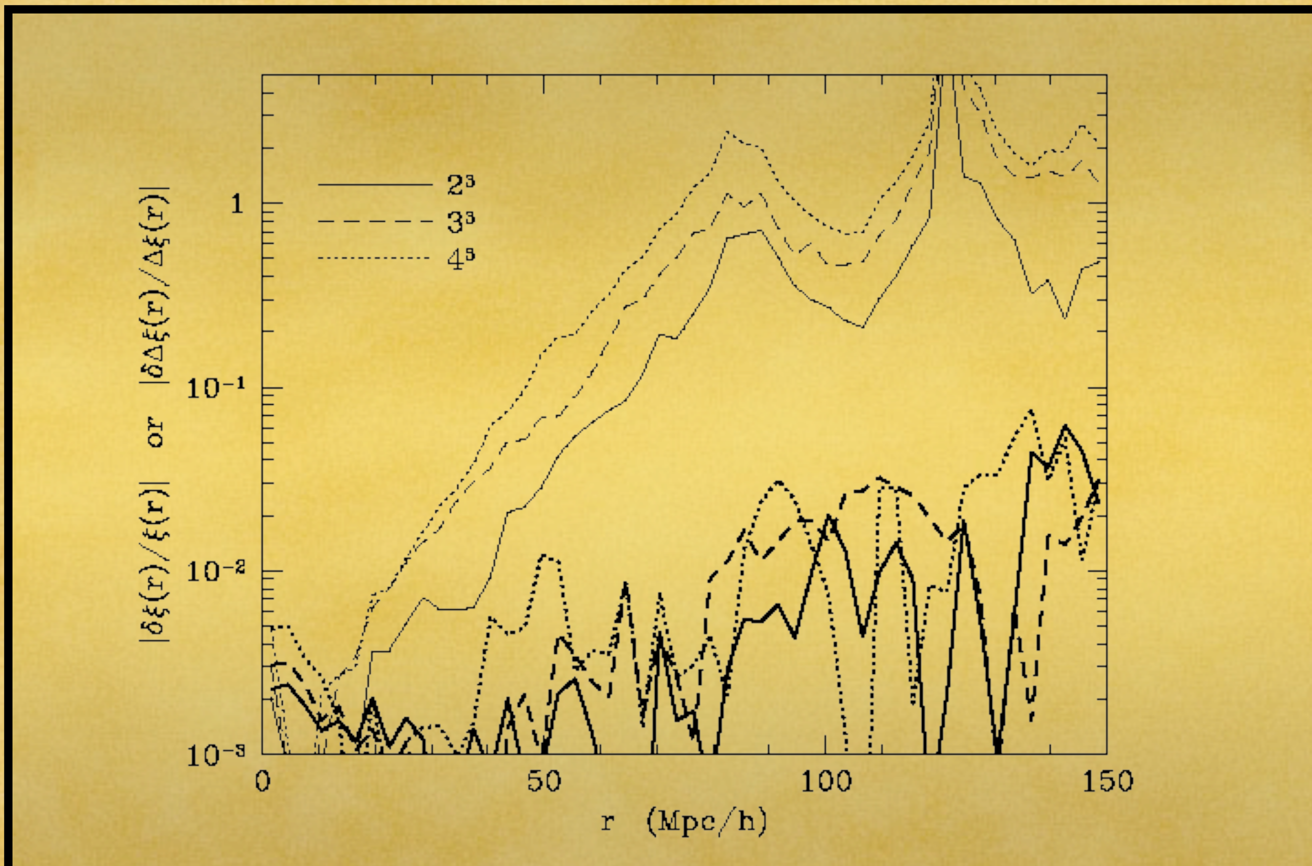
$$\xi(r) = \int \frac{dk}{k}\;\Delta^2(k)\;j_0(kr) \simeq \int \frac{dk}{k}\;\Delta^2(k)\left[1 - \frac{(kr)^2}{6} + \cdots\right]$$

- Uncertainty at large scales has been traded for uncertainty at small scales -- but we know the functional form

$$\Delta\xi(r) = \Delta\xi_{\rm model}(r) + \frac{\mathcal{A}}{r^3} \quad \text{with } \mathcal{A} \equiv 3\int_0^r r'^2 dr\;\;[\xi(r') - \xi_{\rm model}(r')]$$

The virtues of the configuration space band power estimator

- $\Delta\xi(r)$ is much less susceptible to the integral constraint problem than is $\xi(r)$

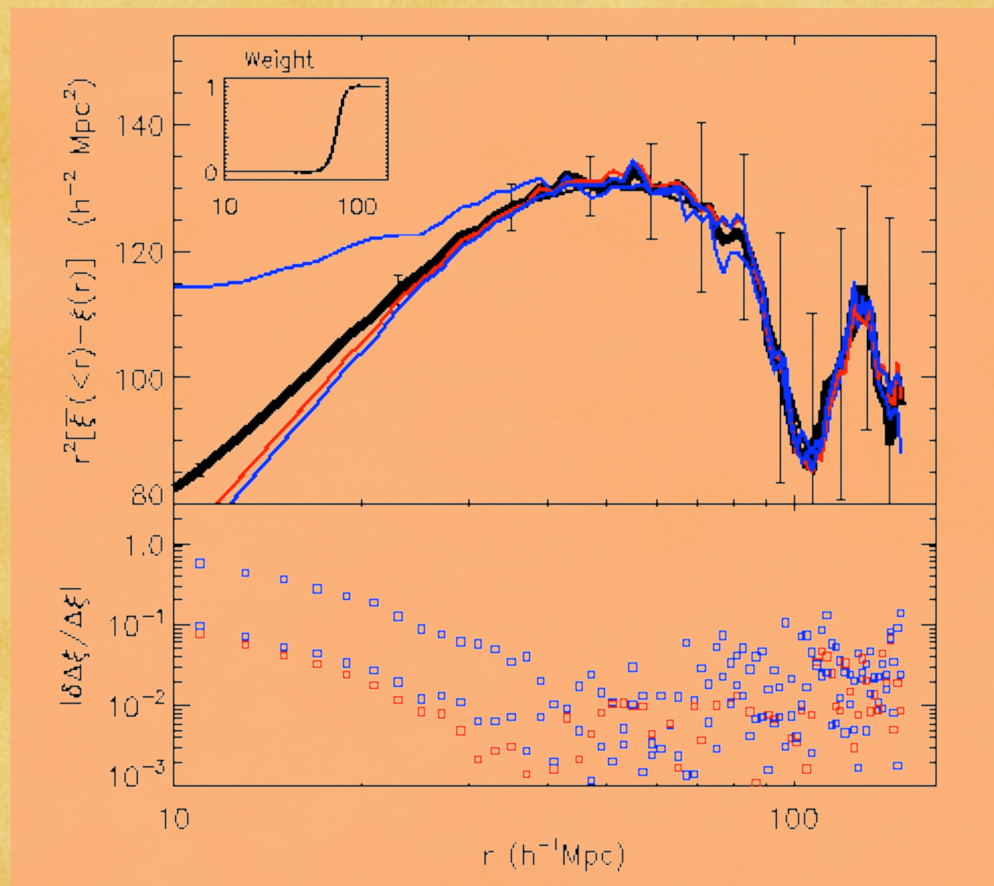


Virtues of the correlation function

- Near the baryon feature the correlation functions for different HOD models differ principally by a *constant* multiplicative bias factor

Blue, red and purple curves have been fit to the black curve in the region of the baryon feature

	M_{min}	M_{sat}	Shift
Blue	**12.83**	**13.0**	**1.81**
Black	**12.65**	**13.5**	**1.00**
Red	**12.59**	**14.0**	**0.80**
Purple	**12.58**	**14.5**	**0.73**



Conclusions

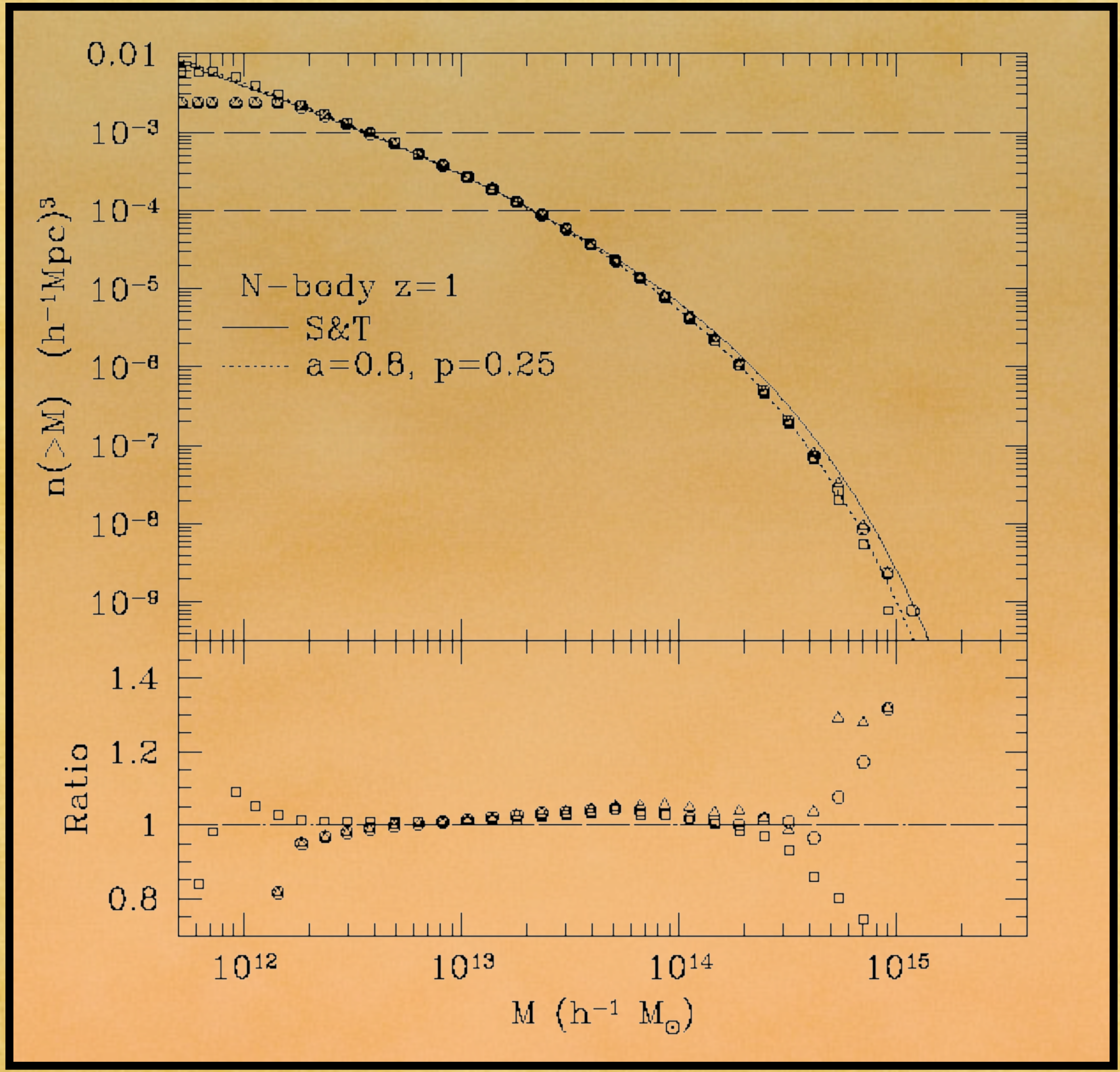
- Baryon oscillations in galaxy power spectra hold promise of a new observational handle on the expansion history of the universe
- Key to tapping this potential is the reduction of theoretical uncertainties regarding
  - Galaxy bias
  - Non-linear structure evolution
  - Redshift space distortions
- The halo model inspires an additive term in the galaxy power spectrum to account for non-linear collapse

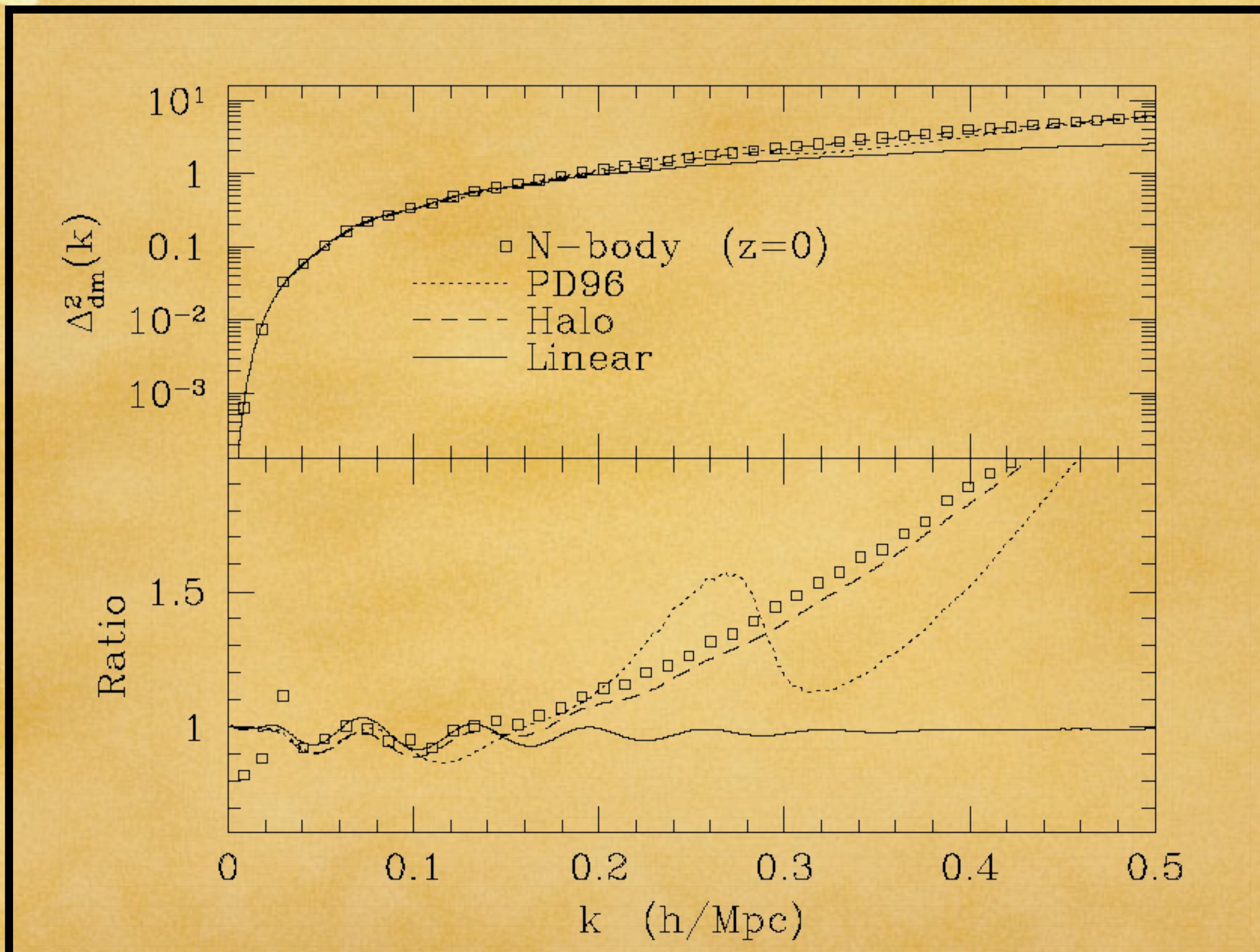
$$\Delta^2_{\mathrm{gal}}(k) = b^2 \Delta^2_{\mathrm{lin}}(k) e^{-(k/k_2)^2} + (k/k_1)^3$$

- N-body simulations have confirmed that this and other treatments of galaxy bias can be used to obtain an unbiased measure of the acoustic signature.
- We have developed an improved estimator the correlation function that can bypass many of the canonical problems by marginalizing over an known functional form
- We are close to a turn-key method of analyzing mock observations of galaxy clustering that will return an unbiased estimate of the acoustic scale

Backup Slides

The halo mass function

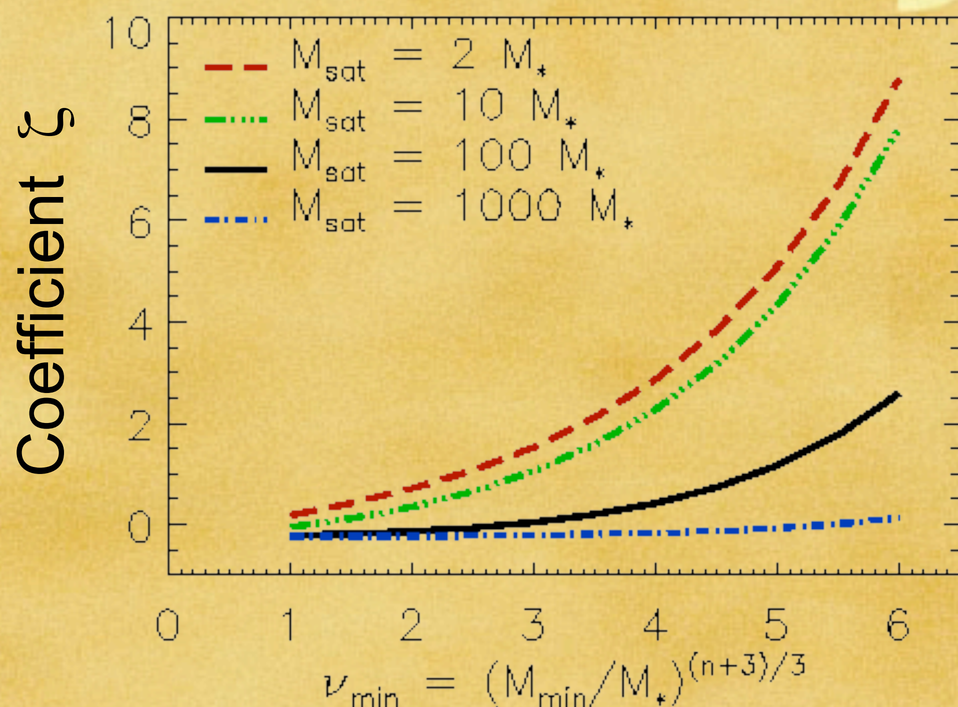




10^1
1
0.1
10^{-2}
10^{-3}
$\Delta^2_{dm}(k)$
N-body (z=0)
PD96
Halo
Linear
1.5
1
Ratio
0
0.1
0.2
0.3
0.4
0.5
k (h/Mpc)

How HOD parameters impact scale dependence

- There is a good approximation to B(k) in terms of the linear power spectrum (below)
- HODs with more satellites (red) are more scale dependant than those with few (blue)
- HODs with a higher M_{min} are also more biased



$$B^2(k) \cong b^2(1+\zeta\, P_{lin}(k)^{-1} + \ldots)$$

Determined by HOD parameters

The only scale dependent term

- Redshift space distortions for $\xi(r)$ and $\Delta\xi(r)$