Baryon Acoustic Oscillations

Alexia Schulz

Eric Huff, David Schlegel,
Mike Warren, Martin White

Overview

- MOTIVATION:
  - Dark energy and standard rulers
  - Why study baryon oscillations?
  - What are the complications when using galaxies?
- METHOD:
  - N-body simulations
  - Analytic insight: intro to the halo model
  - Bias with the halo model
- RESULTS:
  - The origin of scale dependence in large scale bias
  - The impact of changing the halo occupation distribution
  - Power spectra and correlation functions
  - Introducing redshift space distortions
- CONCLUSIONS:
  - Implications for baryon oscillation experiments
  - Unanswered questions

The universe is accelerating

- Independent observations of acceleration
  - Supernovae that behave as standard candles are further away than expected
  - The growth of structure has been slowed or halted

- Geometry is observed to be flat, but Ω_{dm} is known to be ~0.3 $\longrightarrow$ Shortfall in the energy budget!

- Serious Implications
  - Current theories of gravity wrong…or…
  - Some peculiar ingredient in the universe
    - Ultra-smooth
    - Funky unconventional equation of state $\rho+3p > 0$
    - Energy density dominance in "recent" history

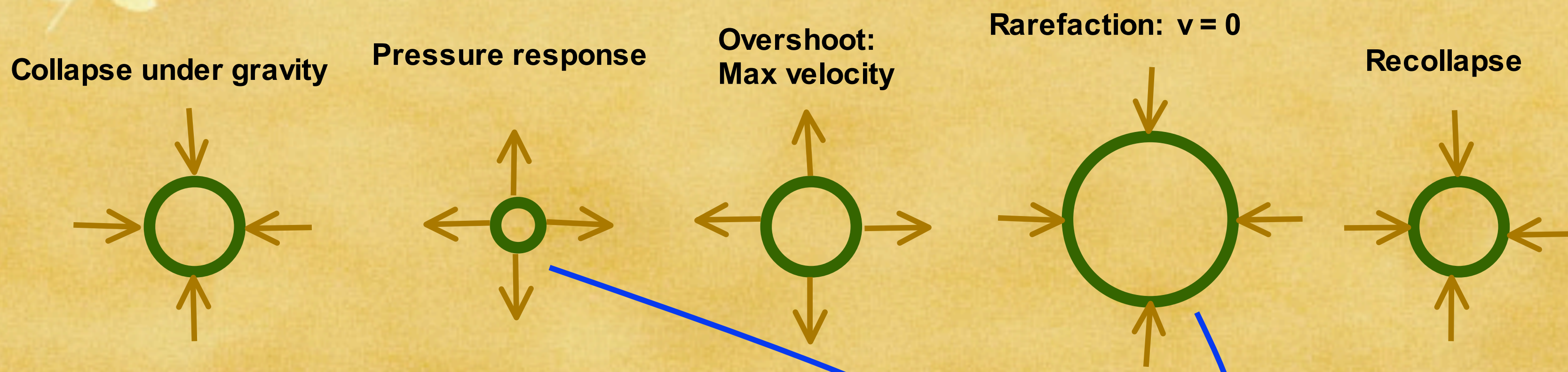
$\Omega_X > \Omega_{dm} > \Omega_b$ Roughly 70:26:4 today

Dark energy's observable influence

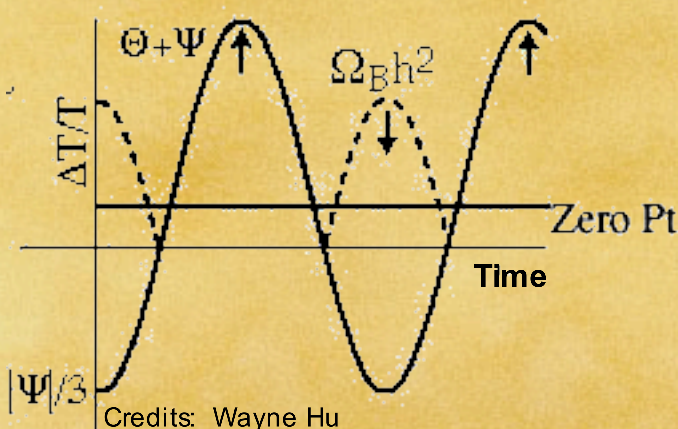
- Accelerated expansion influences the volume of the recent universe
  - Changes the expansion rate H(z)
  - Changes the physical distance to a given redshift
  - Changes observables like angular diameter distance and luminosity distance
- Tests that probe volume rely on standard candles to measure $d_L(z)$ or standard rulers to measure $d_A(z)$
- Baryon oscillations provide a calibrated standard ruler with which to measure probe the expansion

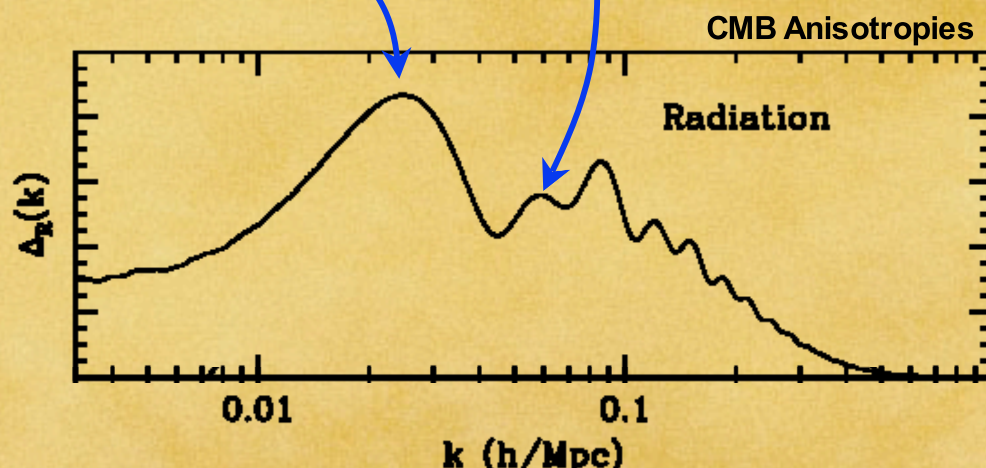
What are baryon oscillations?

- Gravity and pressure provide restoring forces for oscillations



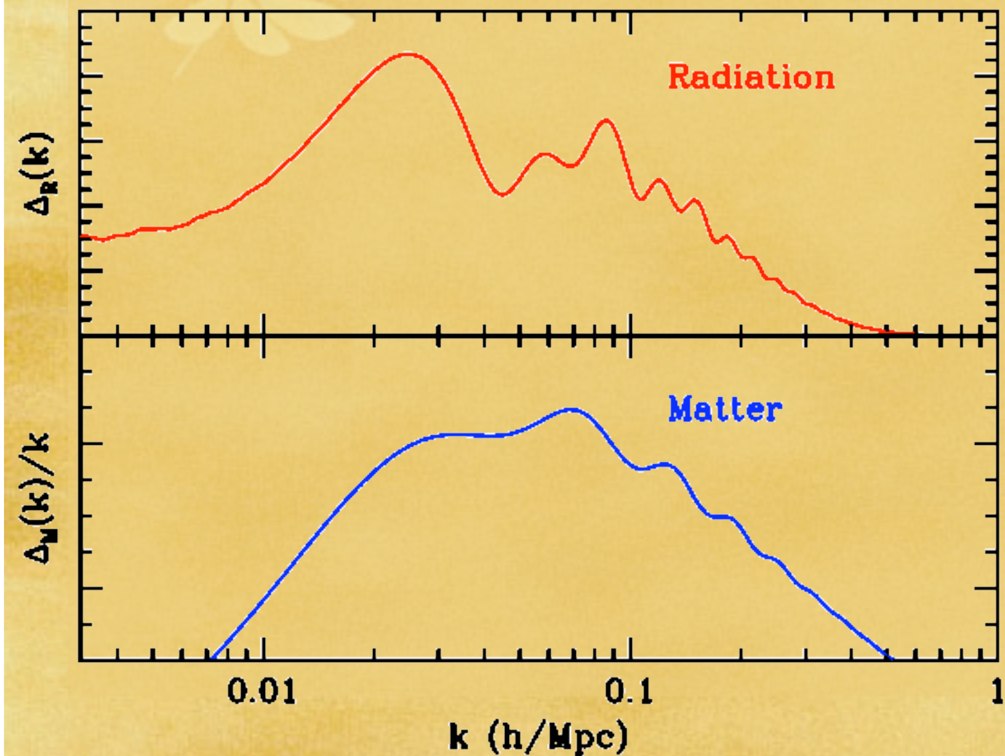
Baryon density controls the offset and influences the relative heights of overdensity and rarefaction peaks





What are baryon oscillations?

Probes distances to z~1000



Probes distances to 0<z<10

Sensitive to changes in geometry over these redshifts that tell us about the nature of dark energy

- Models of structure formation predict a series of features in the matter power spectrum similar to the CMB anisotropies
- Oscillation amplitude down by Ω_b/Ω_{dm} ~0.1 so difficult to detect
- 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
- The scale of the ruler is exquisitely calibrated by measurements of the CMB

What calibrates the standard ruler?

- The acoustic scale is sets by the sound horizon at last scattering

$$s = \int_0^{t_{\rm rec}} c_s\,(1+z)dt = \int_{z_{\rm rec}}^{\infty} \frac{c_s\;dz}{H(z)}$$

$$c_s = \left[3(1+3\rho_b/4\rho_\gamma)\right]^{-1/2}$$

- The sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB

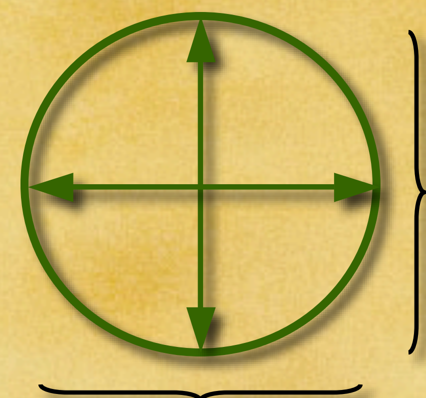
$$\begin{aligned} s &= 147 \pm 2\ \mathrm{Mpc} \\ &= (4.54 \pm 0.06) \times 10^{24}\mathrm{m} \end{aligned}$$

WMAP 1st year data

Why study baryon oscillations ?

- Measuring the acoustic scale as a function of redshift probes the volume of the universe
- Geometrical probes are clean because the expansion history depends directly on the gravitational theory
- Minimal systematics due to calibration issues suffered by other cosmological probes

Correlations along and across the line of sight give measurements of H and d_A.



Measures $H(z)$

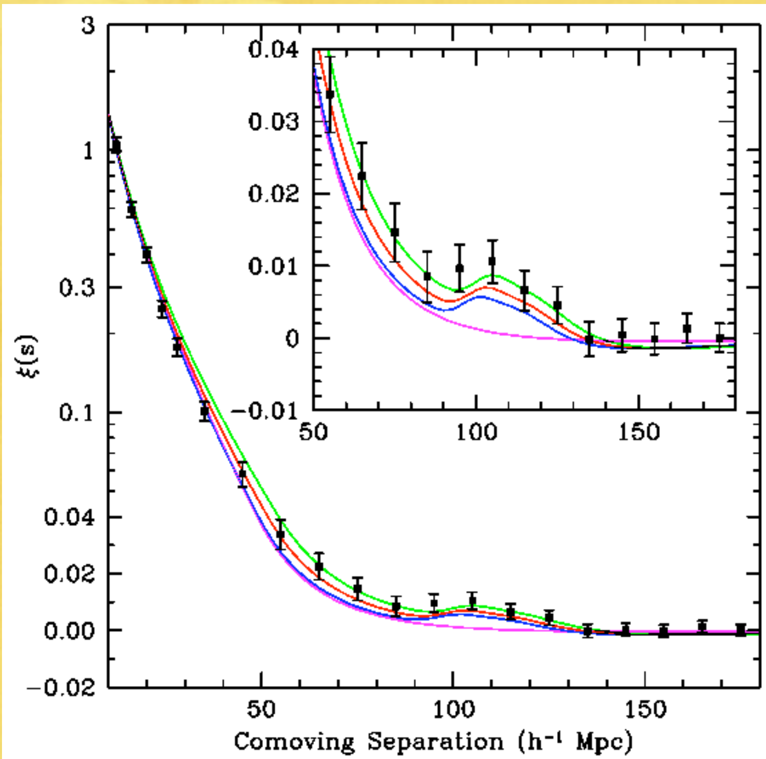
Measures d_A

Provides an internal cross check

$$d_A(z) \propto \int_0^z \frac{dz'}{H(z')}$$

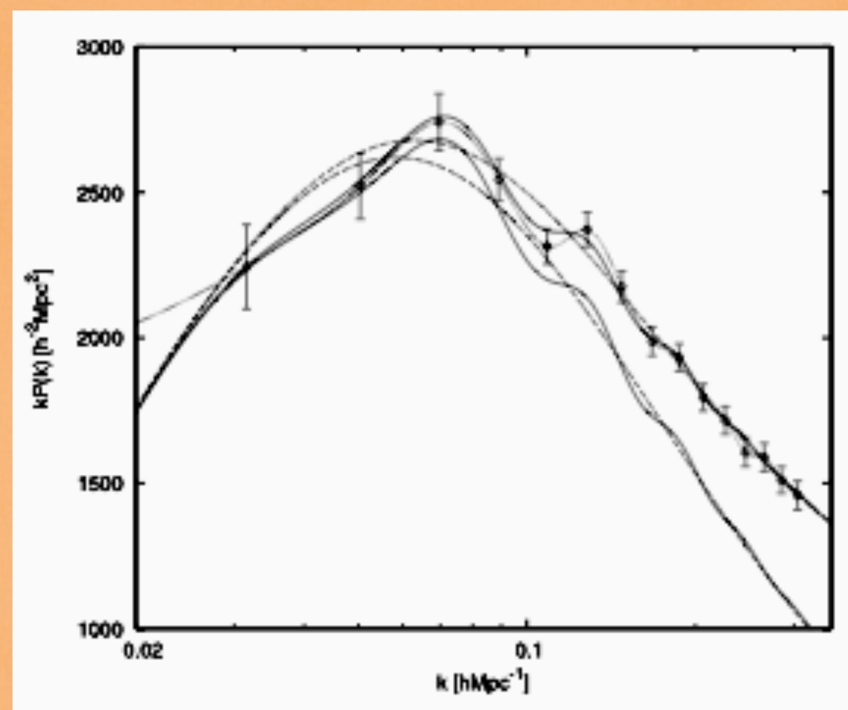
Baryon oscillations have been seen!

SDSS LRG Sample



Seo & Eisenstein (2005)

Huetsi (2005)



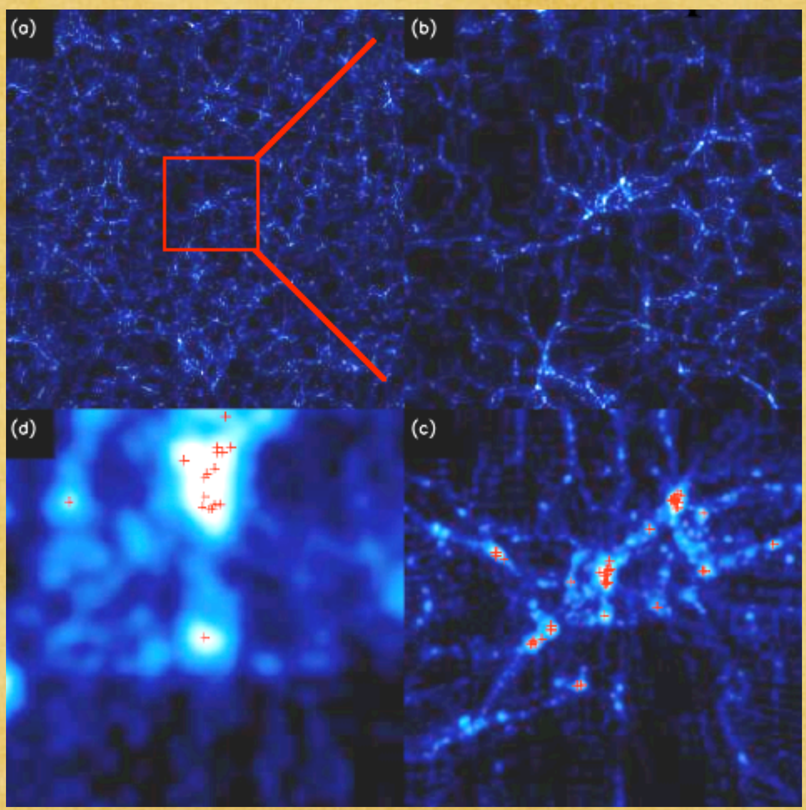
Predictions versus observables: Enter complications!

- We predict the scales of the acoustic features in the linear dark matter power spectrum
- We can't see the dark matter (*dark*!) so we have to use galaxies

- Galaxies act as biased tracers
  - Clumps clumpier
  - Voids more barren
- This requires that we develop machinery to make theoretical to predictions about the
  - Non-linear
  - Redshift space distorted
  - Galaxy power spectrum!

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

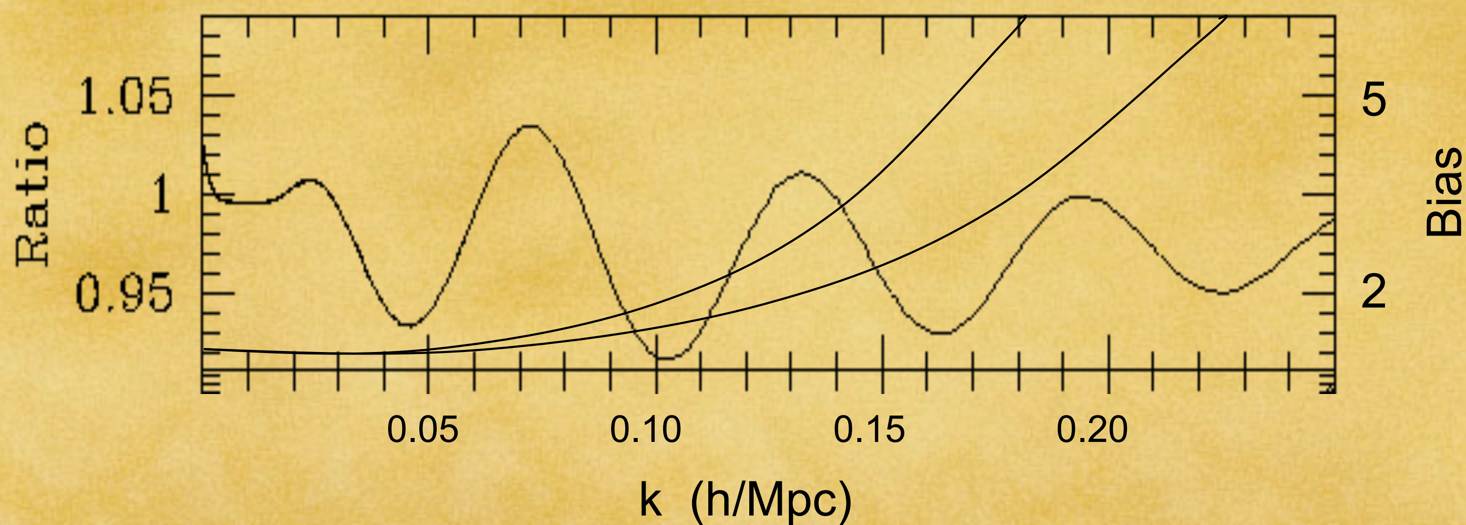
•Color scale is logarithmic, from just below mean density to 100x mean density

•Red points mark the galaxy positions

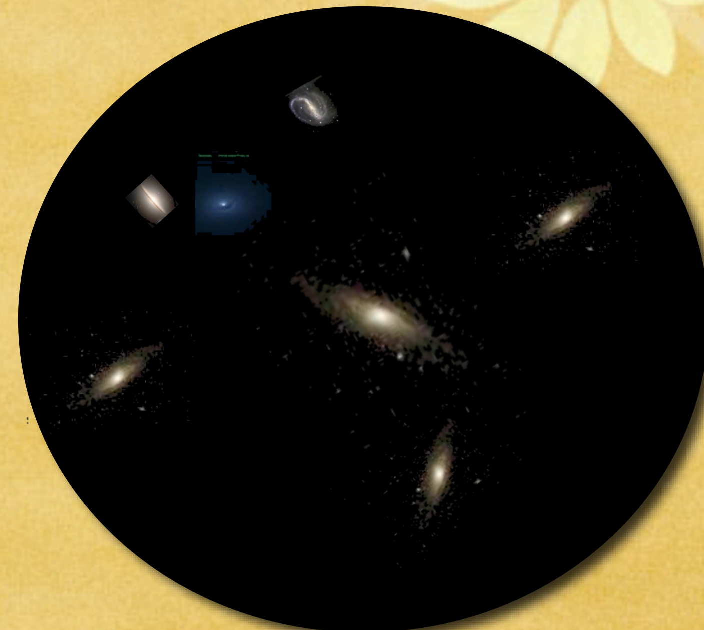
Why study bias ?

- 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

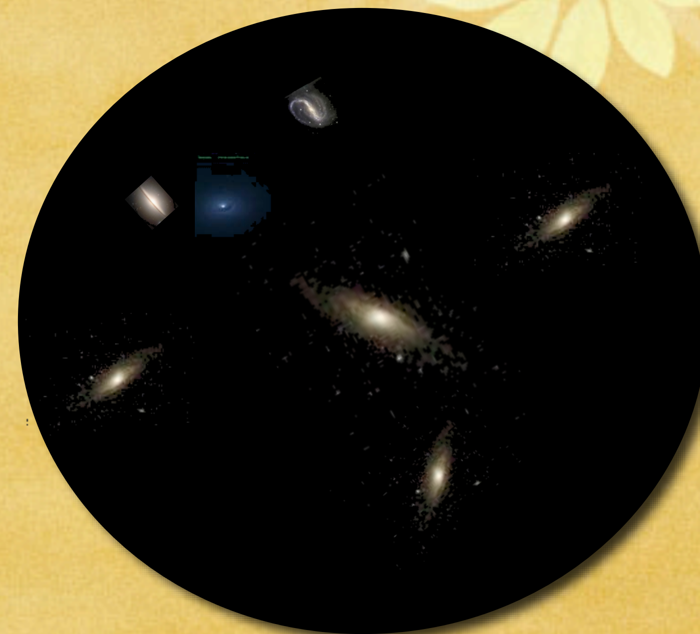


Method: The Halo Model



- All matter in the universe lives in virialized halos of various 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
- Contributions from pairs in the same halo dominate on small scales

Method: The Halo Model



- The Players:
  - Halo Mass Function - $n_h(M)$
  - Halo Bias - $b_h(M)$
  - Halo Profile - $y(M,k)$

Toy Model: Dark Matter

- The power spectrum has two contributions

$$\Delta^2_{\rm dm} \equiv \frac{k^3 \, P_{\rm dm}(k)}{2\pi^2} = {}_{\rm 1h}\Delta^2_{\rm dm} + {}_{\rm 2h}\Delta^2_{\rm dm}$$

- Pairs that live in different halos (2-halo)

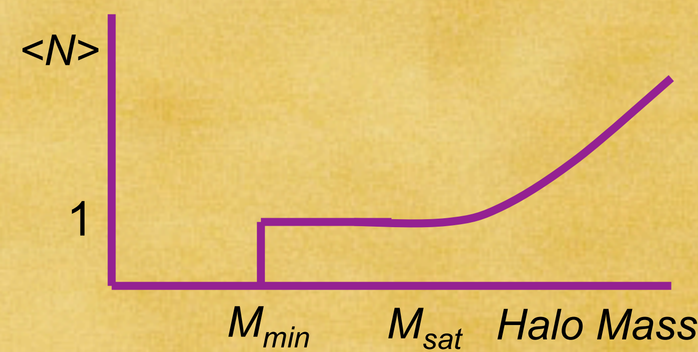
$${}_{\rm 2h}\Delta^2_{\rm dm} = \Delta^2_{\rm lin} \left[\frac{1}{\bar{\rho}} \int_0^\infty dM \; n_h(M) \, b_h(M,k) \, M \, y(M,k) \right]^2$$

- Pairs that live in the same halo (1-halo)

$${}_{\rm 1h}\Delta^2_{\rm dm} = \frac{k^3}{2\pi^2} \frac{1}{\bar{\rho}^2} \int_0^\infty dM \, n_h(M) M^2 \, |y(M,k)|^2$$

Toy Model: Galaxies

- 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



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

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

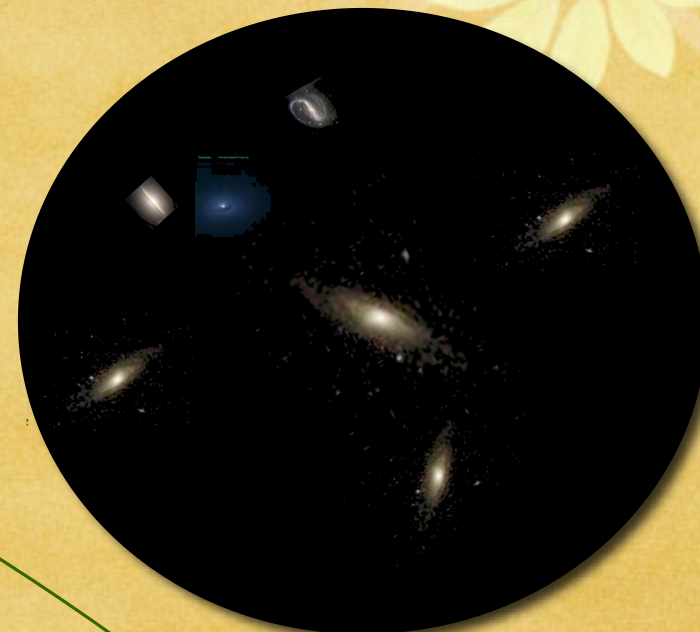
  - The mean galaxy number density is

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

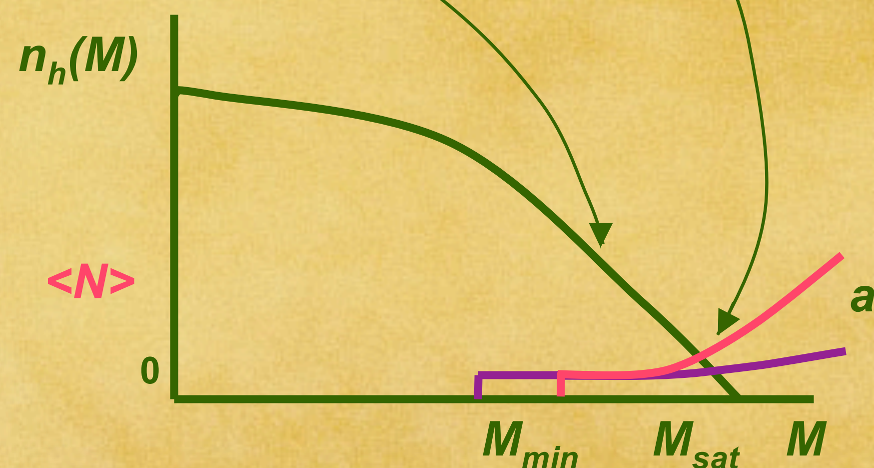
  - Only satellites trace the halo dark matter profile

What difference does an HOD make?

- More massive halos are rarer and much more biased



- Halos are weighted by <N> rather than their mass M
- M_{min} influences how biased is the galaxy 2-halo term
- The 1-halo term will be more biased than the 2-halo term, as determined by M_{sat} and a



Galaxy extension to halo model

- 2-halo term

$\bar{n}_{\rm gal}$

Number and distribution of galaxies in a halo of mass *M*

$$_{\rm 2h}\Delta^2_{\rm dm} = \Delta^2_{\rm lin}\left[\frac{1}{\bar{\rho}}\int_0^\infty dM\; n_h(M)\, b_h(M,k)\, M\, y(M,k)\right]^2$$

- 1-halo term

$$_{\rm 1h}\Delta^2_{\rm dm} = \frac{k^3}{2\pi^2}\frac{1}{\bar{\rho}^2}\int_0^\infty dM\, n_h(M)\, M^2\, |y(M,k)|^2$$

$\bar{n}^2_{\rm gal}$

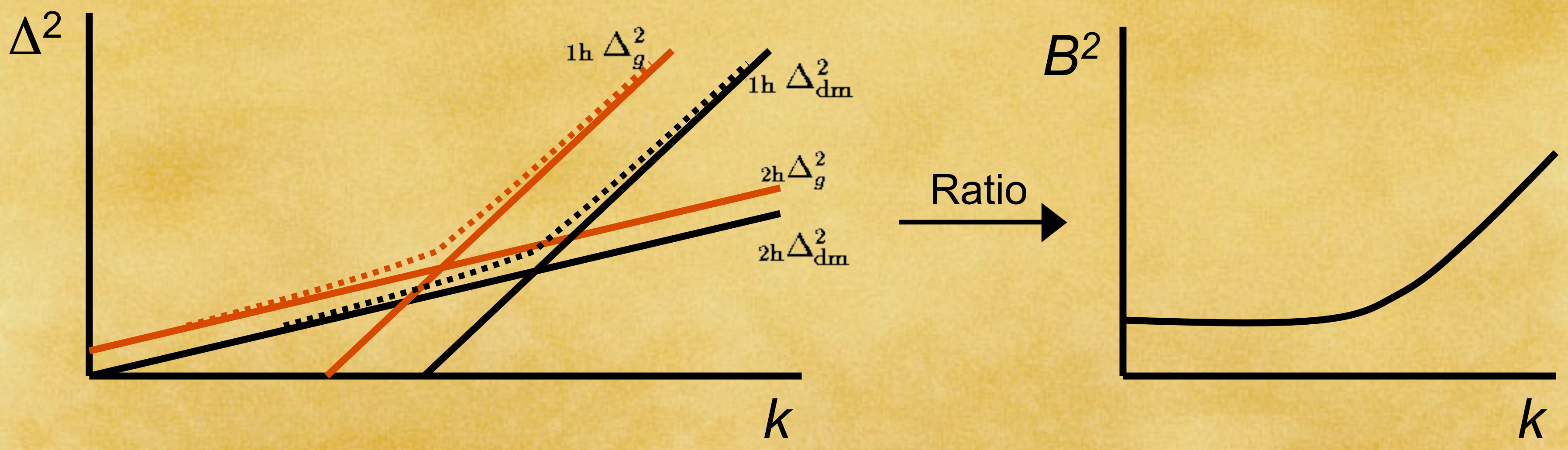
All central-satellite and satellite-satellite pairs in a halo of mass *M*

Galaxy Bias

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

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

- 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

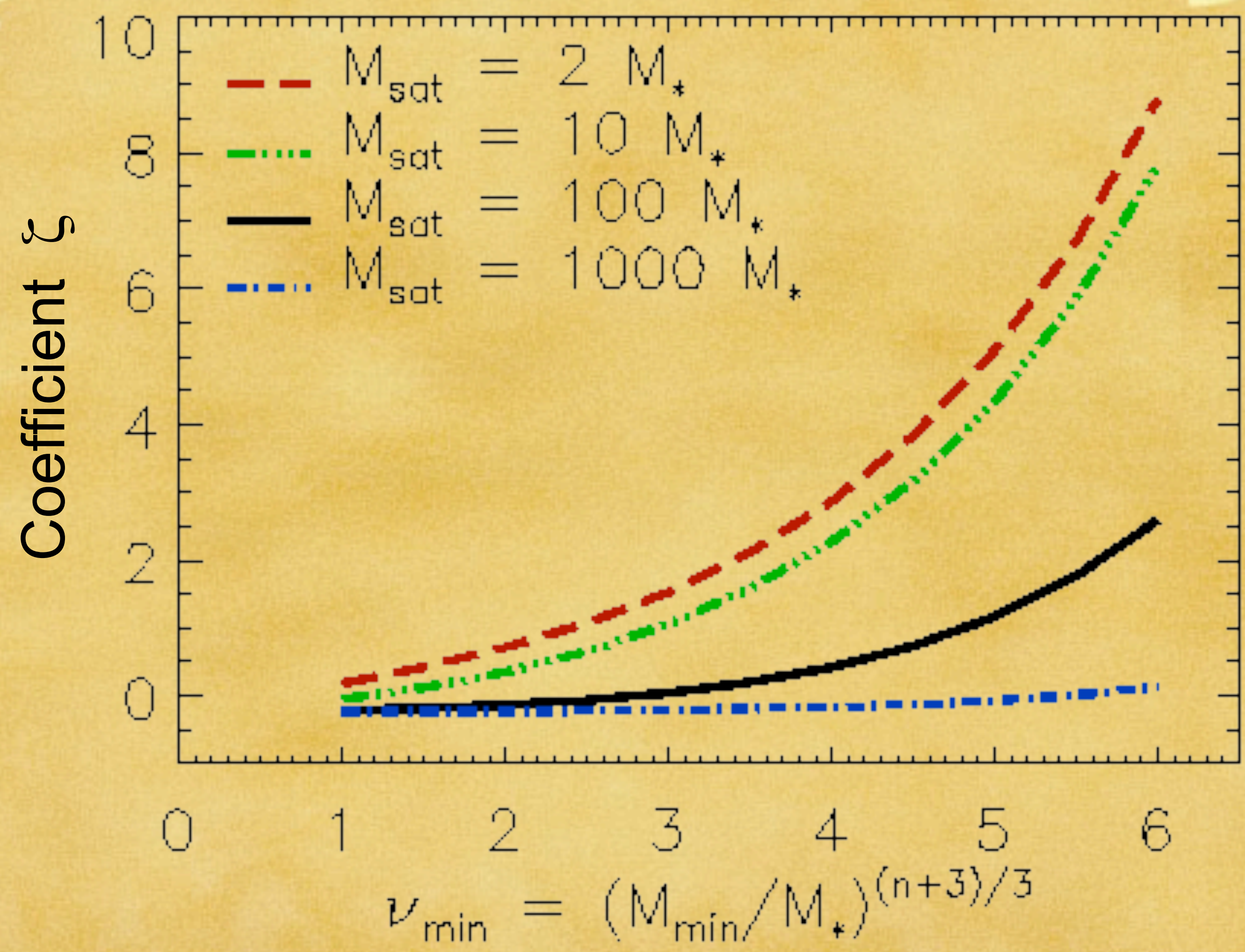
- At fixed n_g, scale dependence increases as the tracers become more biased
- At fixed bias, scale dependence increases as n_g decreases, i.e. more scale dependance for rarer objects.
- The scale dependence is not sensitive to the distribution within the halo, only the number of galaxies per halo
- For large scales, there is a very good approximation for $B^2(k)$ given by

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

Determined by HOD parameters

The only scale dependant term

How HOD parameters impact scale dependence

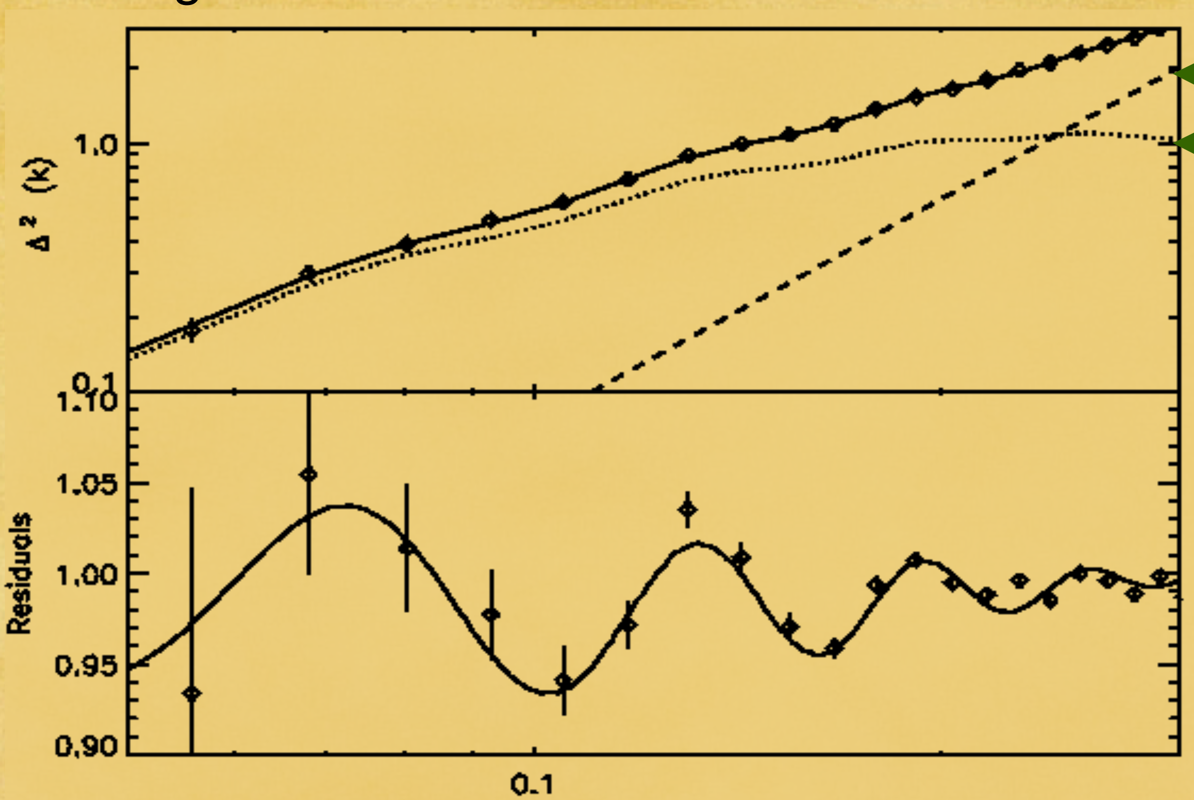


A sensible new description of galaxy bias

- In light of these insights, we are led to recast the parameterization of galaxy bias

$$\Delta^2_{\rm gal}(k) = b^2 \Delta^2_{\rm lin}(k)\left[1 - \varepsilon k^2 + \cdots\right] + (k/k_1)^3$$

- Similar functional form as in Seo & Eisenstein (2005)
- Agrees well with numerical simulations



1-halo term

2-halo term

1+2 (the model)

N-body data

Error bars are bootstrapped from eight subdivisions of the simulation volume

Eric Huff

Virtues of the correlation function

- Studying the correlation function at ~100 Mpc/h is comparatively less scale dependent than the power spectrum
- The 1-halo term is confined to halo sized scales ~1 Mpc/h

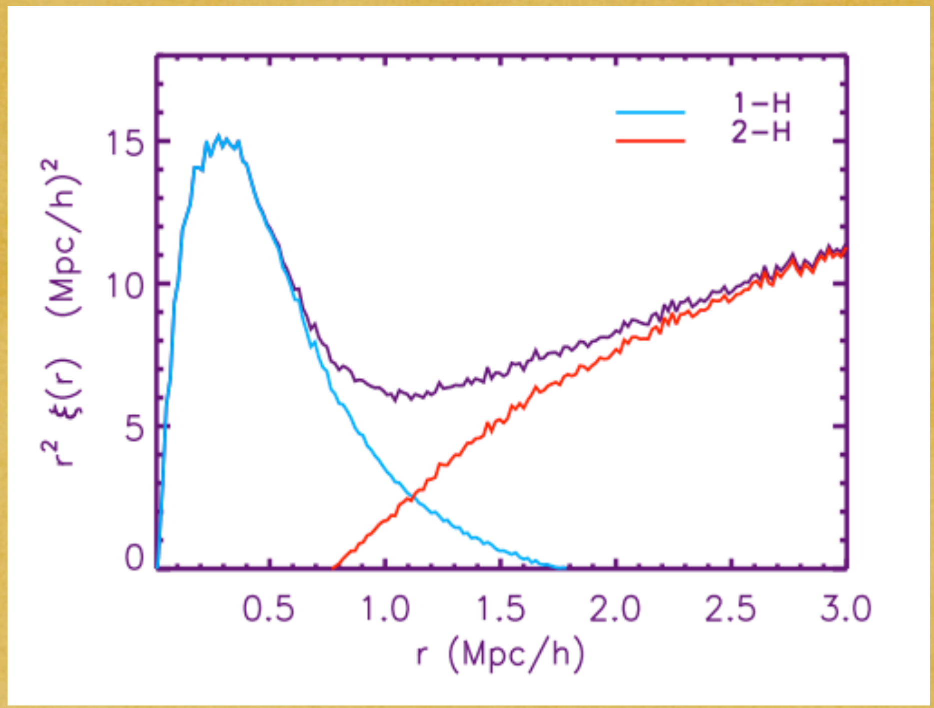
Measuring ξ in a periodic box can be problematic

-sensitivity to low k modes

-errors inherited from the mean density estimate

We find the following quantity to be much less sensitive

$$\Delta\xi(r) \equiv \bar{\xi}(<r) - \xi(r)$$

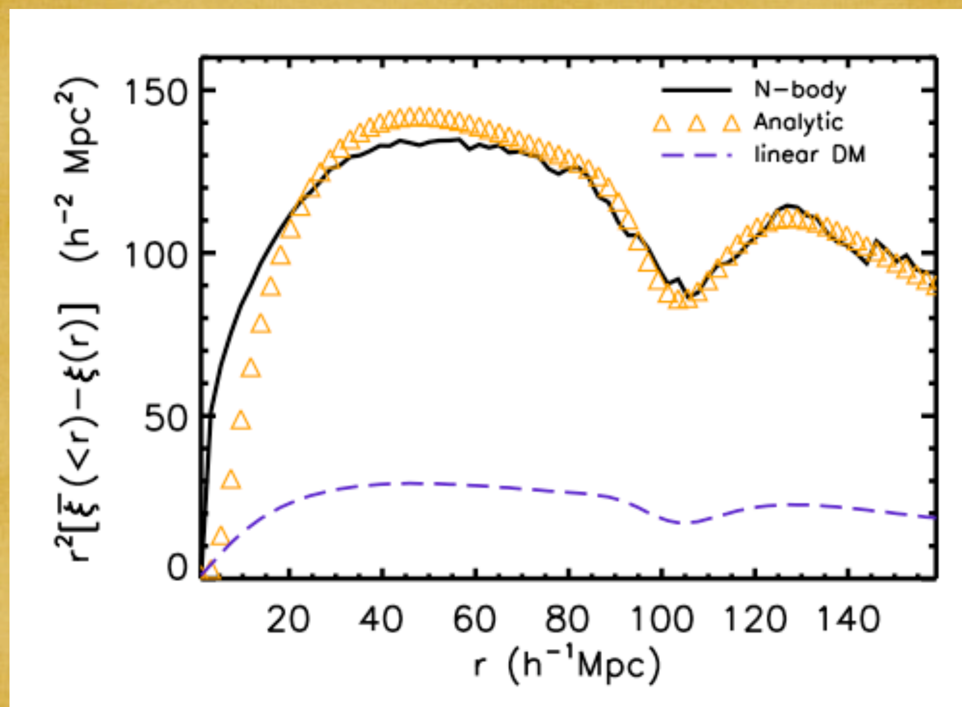


Halo model analytic form fits correlation function well

- $\Delta\xi$ can be obtained by integrating the power spectrum

$$\Delta\xi(r) = \int \frac{dk}{k}\, \Delta^2(k)\, j_2(kr)$$

The analytic model (yellow triangles) is completely insensitive to the value of the parameter k_1.

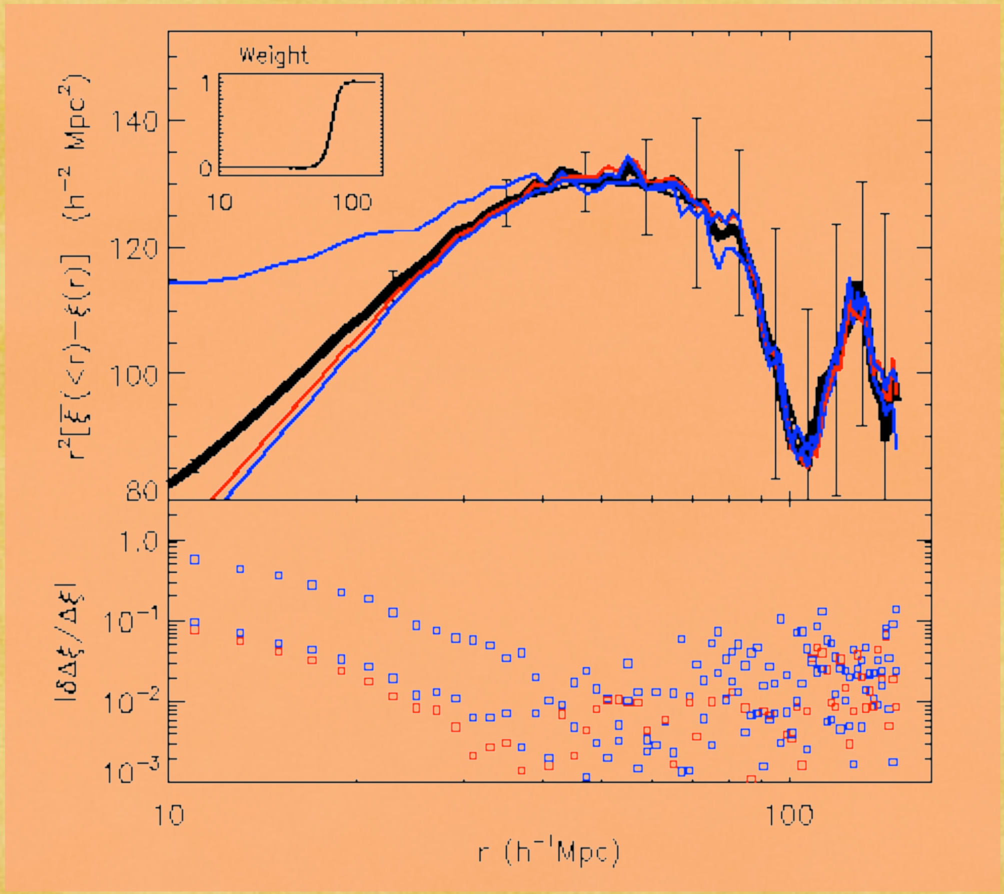


Virtues of the correlation function

- 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**



What happens in redshift space?

- Velocity Dispersion (Fingers of God):
  - Impacts small scales, satellites only

$$y(M,k) \longrightarrow y_s(M,k) = y(M,k)\ e^{-(k\sigma_v\mu)^2/2}$$

Where $\mu = \hat{r}\cdot\hat{k}$ and $\sigma^2_{v,\mathrm{sat}} = GM/2r_{\mathrm{vir}}$

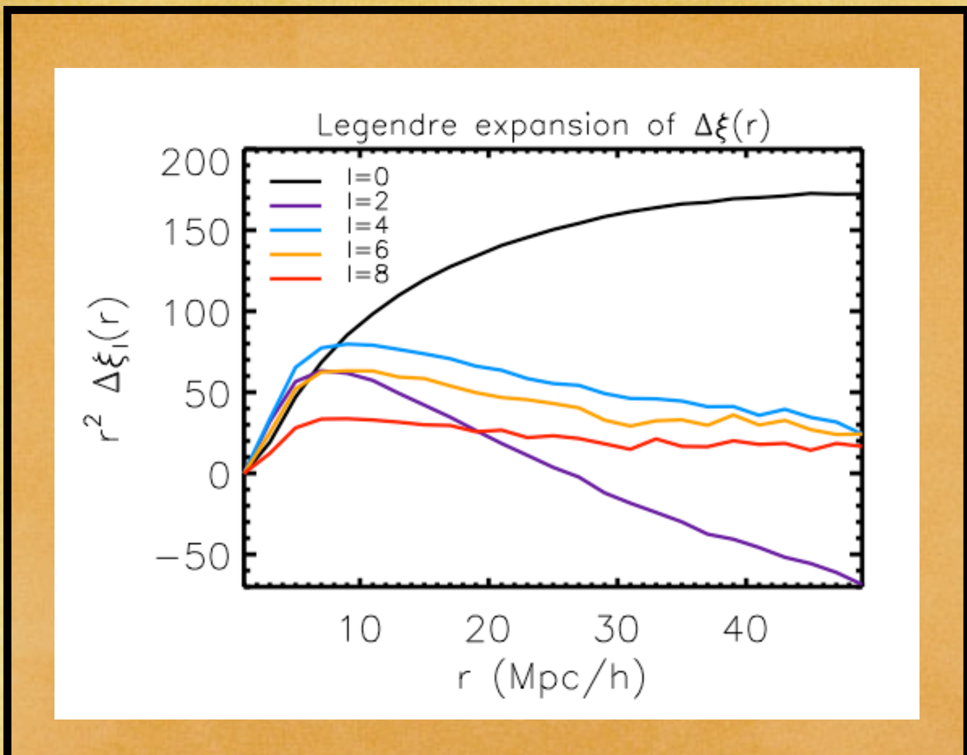
- Coherent Infall
  - Impacts large scales, 2-halo term only
  - Caused by ***dark matter*** in other halos that induces coherent velocity flow in the members of a halo

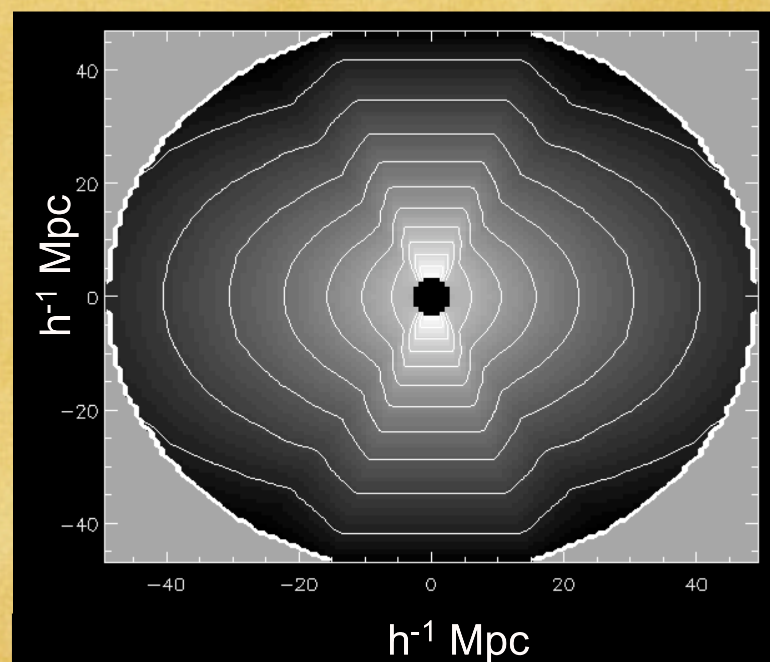
$$_{2h}\Delta^2_g = \Delta^2_{\mathrm{lin}}\left[\frac{1}{\bar{n}_{\mathrm{gal}}}\int_0^\infty dM\ n_h(M)\, b_h(M,k) <N> y_s(M,k)\ + \ldots \right.$$
$$\left. \ldots + \ f\mu^2\int_0^\infty dM\ n_h(M)\, b_h(M,k)\, (M/\rho)\, y_s(M,k)\right]^2$$

Redshift space distortions in N-body

- The correlation function as a function of angle from the line of sight
- Method: Use N-body simulations to predict Legendre coefficients and their dependence on HOD

Hopefully, the model will not require very many terms in the expansion.





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 toy analytic model provides a pedagogical complement to complex numerical simulations
- The functional form of the bias suggested by study of the toy model quantitatively fits the results of N-body simulations

$$\Delta^2_{\rm gal}(k) = b^2 \Delta^2_{\rm lin}(k)\left[1 - \varepsilon k^2 + \cdots\right] + (k/k_1)^3$$

Conclusions II

- The analytic model has revealed several important insights about galaxy bias
  - The origin in the bias at large scales comes from the relative shift in the 1 and 2-halo terms compared to the dark matter
  - The scale dependence of the bias cares about the number of galaxies in a halo, but not about their distribution inside the halo
  - The amplitude of the scale dependence on large scales depends on the HOD parameters
  - Scale dependence increases with increasingly biased tracers, and is larger the rarer the object
- Constraining dark energy with the acoustic signature requires sophisticated understanding of structure and galaxy formation-- a profound challenge for theorists!
- 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