Astrophysical Probes of Dark Energy

A thesis presentation by

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to

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Talk Overview

- Motivation and Background
  - Observational evidence for dark energy
  - Impact on geometry of the universe
  - Impact on growth of Large Scale Structure
  - Summary of astrophysical probes
- Baryon Acoustic Oscillation research
  - Introduction
    - What they are
    - Why we study them
  - Methods
    - The Halo Model
    - Numerical Simulations
  - Results
    - A model of galaxy bias in the power spectrum
    - A configuration space approach
- Conclusions

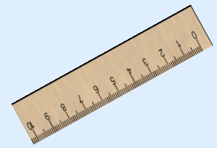
Lexicon of terms

We Live in an Expanding Universe

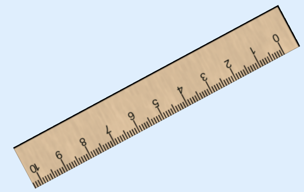
- Redshift

$$\frac{\lambda_{\text{observed}}}{\lambda_{\text{emitted}}} = 1 + z$$

L(last week)=a L(today)



L(today)



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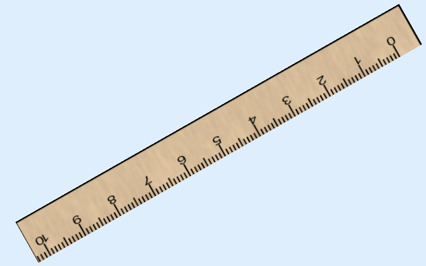


- Scale Factor

$$a = \frac{1}{1+z}$$

- FRW Cosmology (time-time and space-space parts of EEs)

$$H(a) = \frac{\dot{a}}{a} = \frac{8\pi G}{3}(\rho_m + \rho_b + \rho_r + \rho_\nu + \rho_X)$$

(Flat Space)

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right)$$

- Critical Density

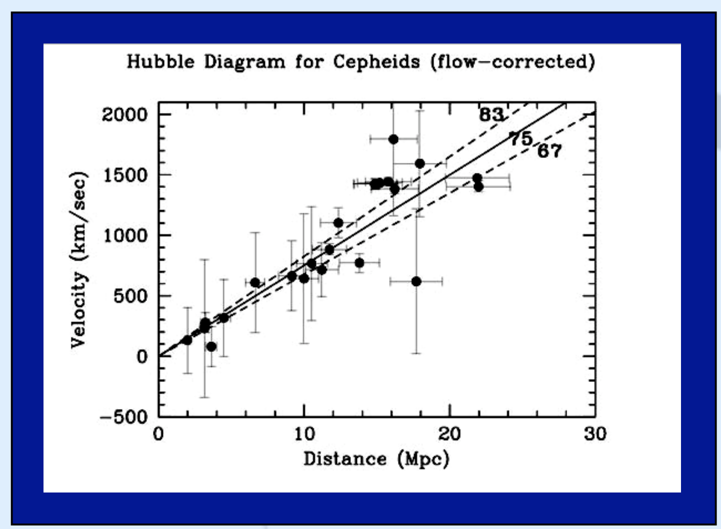
$$\rho_{\text{crit}} \equiv \frac{3H_0^2}{8\pi G}$$

- Ingredient Densities

$$\Omega = \frac{\rho}{\rho_{\text{crit}}}$$

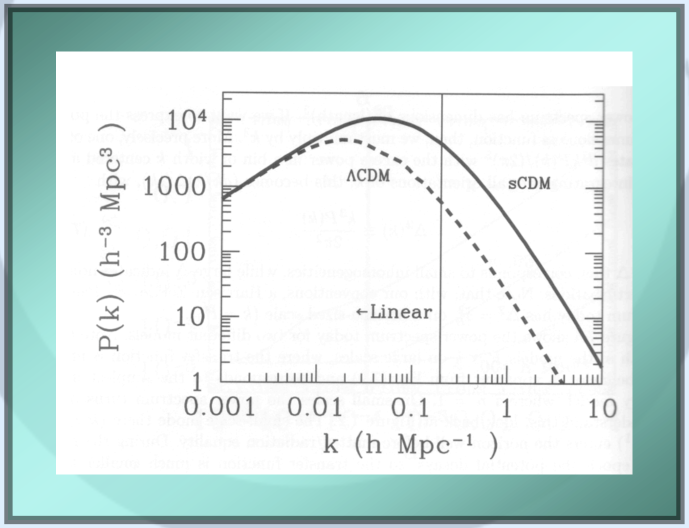
- Equation of state

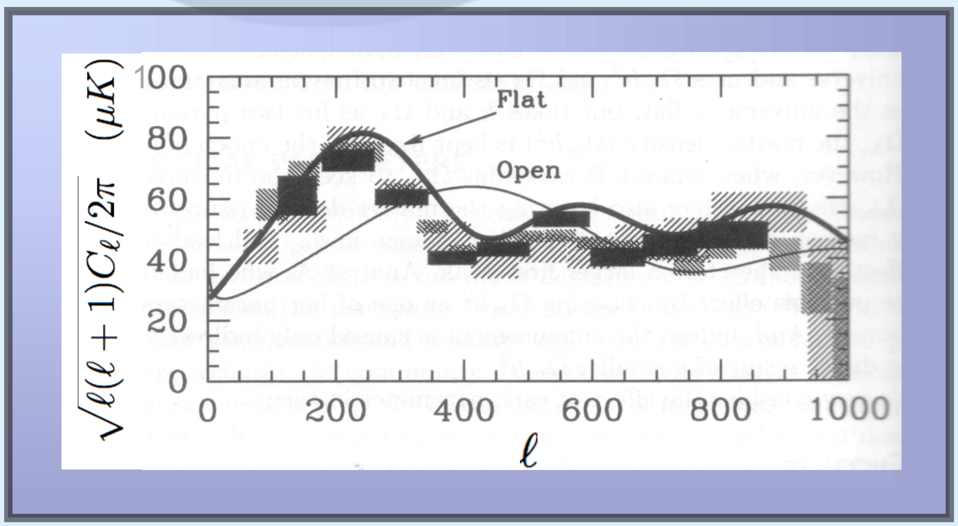
$$w_X = \frac{P_X}{\rho_X}$$



Credits: E. Hubble

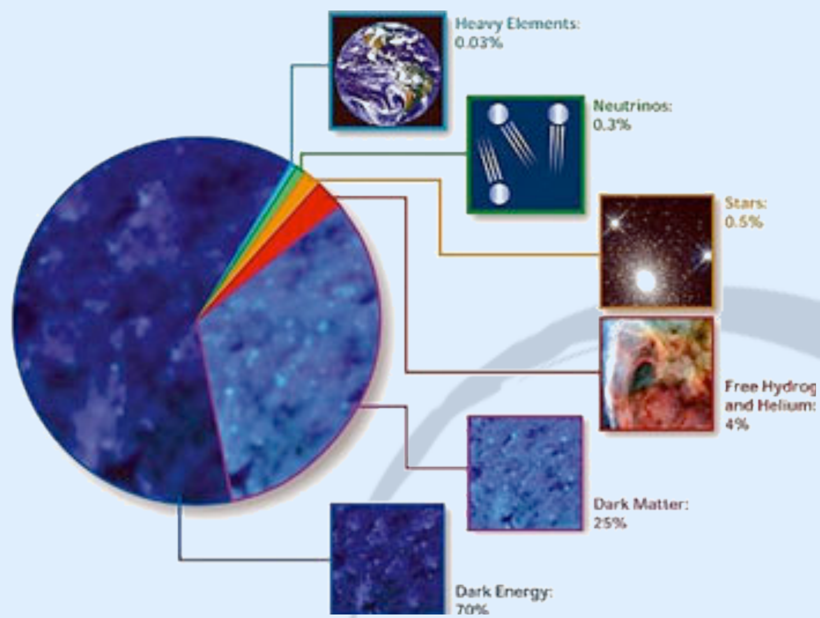
The universe is flat





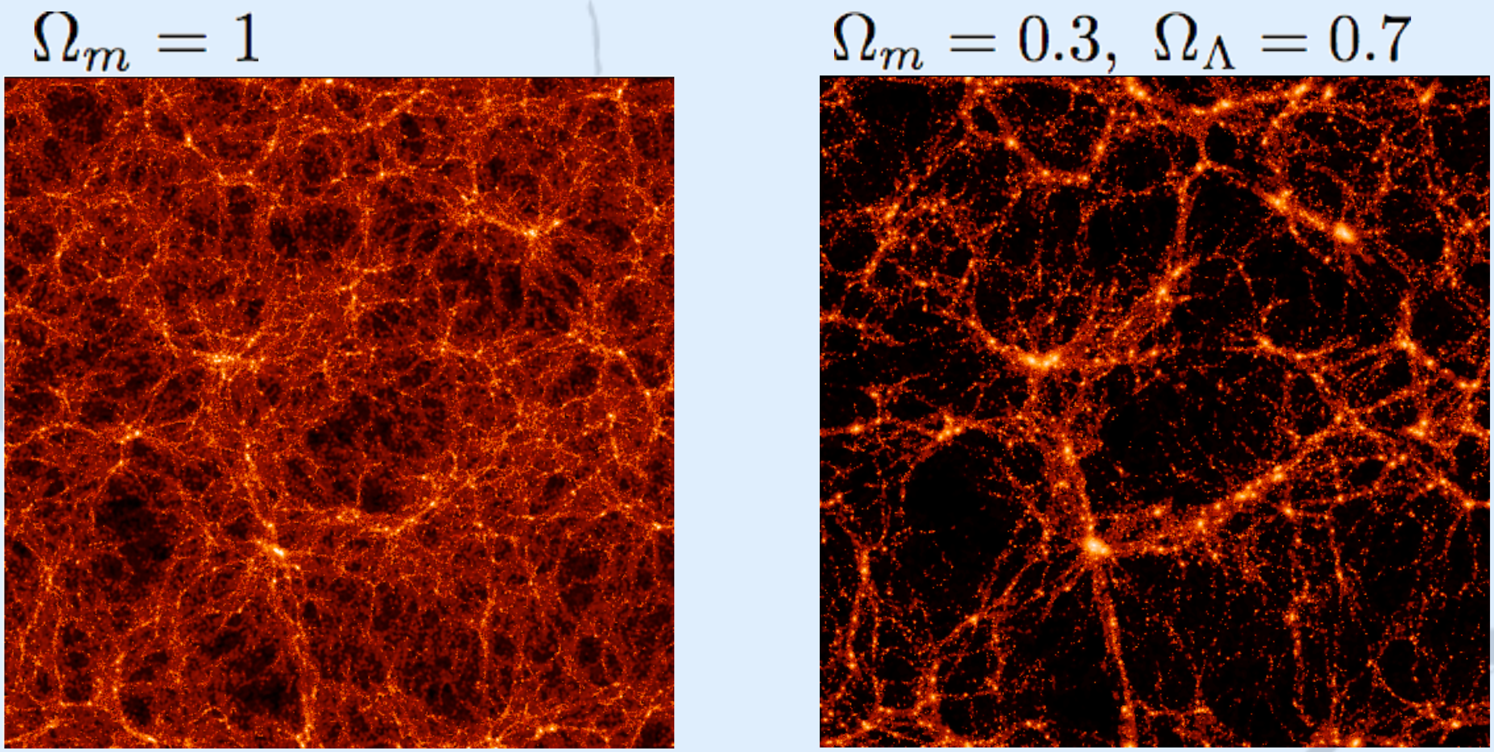
Credits: Scott Dodelson and Wikipedia

- Geometry is observed to be flat with $\Omega_{tot}=1$, but
- Ω_m is known to be ~0.3 Shortfall in the energy budget!



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

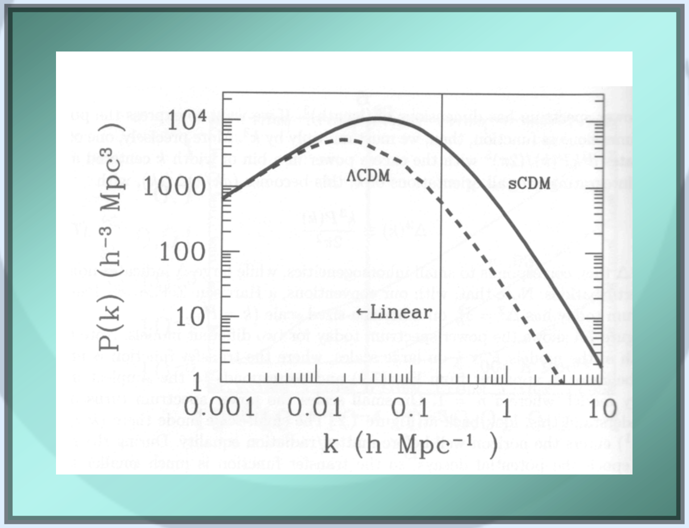
Too much structure in an Ω_{dm}=1 universe

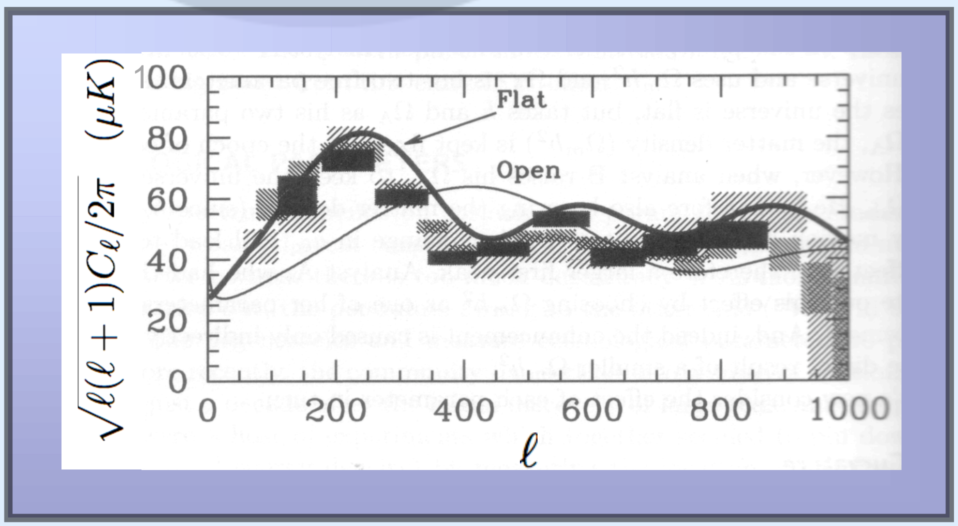


Credits: Hubble Volume, MPA Garching

- Astronomers have known for decades that the matter density must be low

The universe is flat





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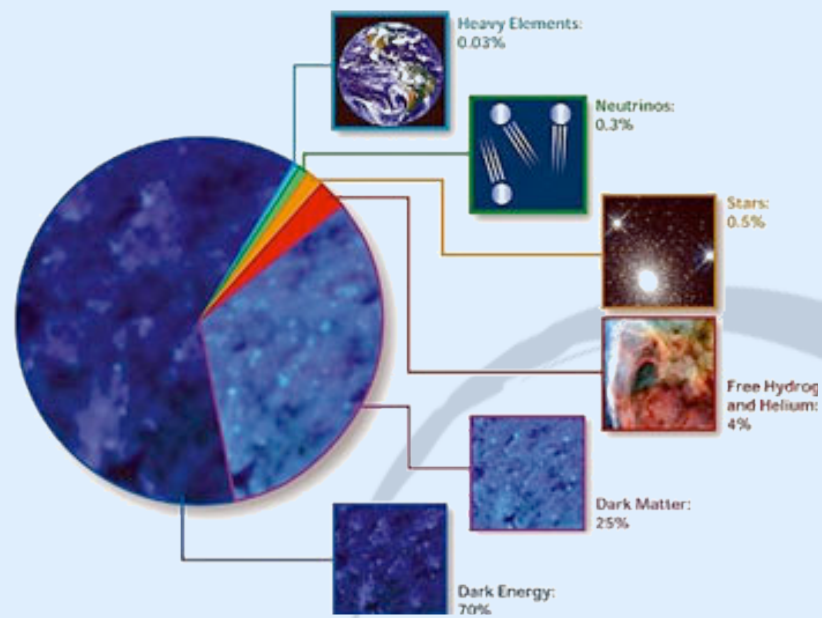
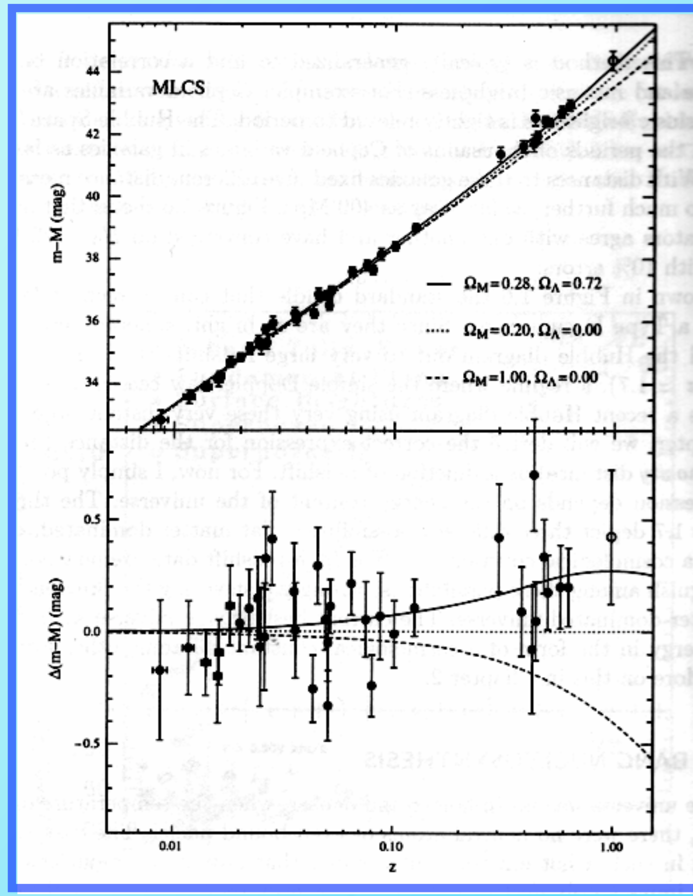


$\Omega_X > \Omega_{dm} > \Omega_b$ Roughly 70:26:4 today

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



Dark energy's observable influence

- Accelerated expansion influences the volume of the recent universe
  - Changes the expansion rate H(z)

$$H(z) = H_0\sqrt{\Omega_m(1+z)^3 + \Omega_X(1+z)^{3(1+w)} + (1-\Omega_m-\Omega_X)(1+z)^2}$$

  - Changes the distance to a given redshift

$$\chi(z) = \int_0^z \frac{c\,dz}{H(z)}$$

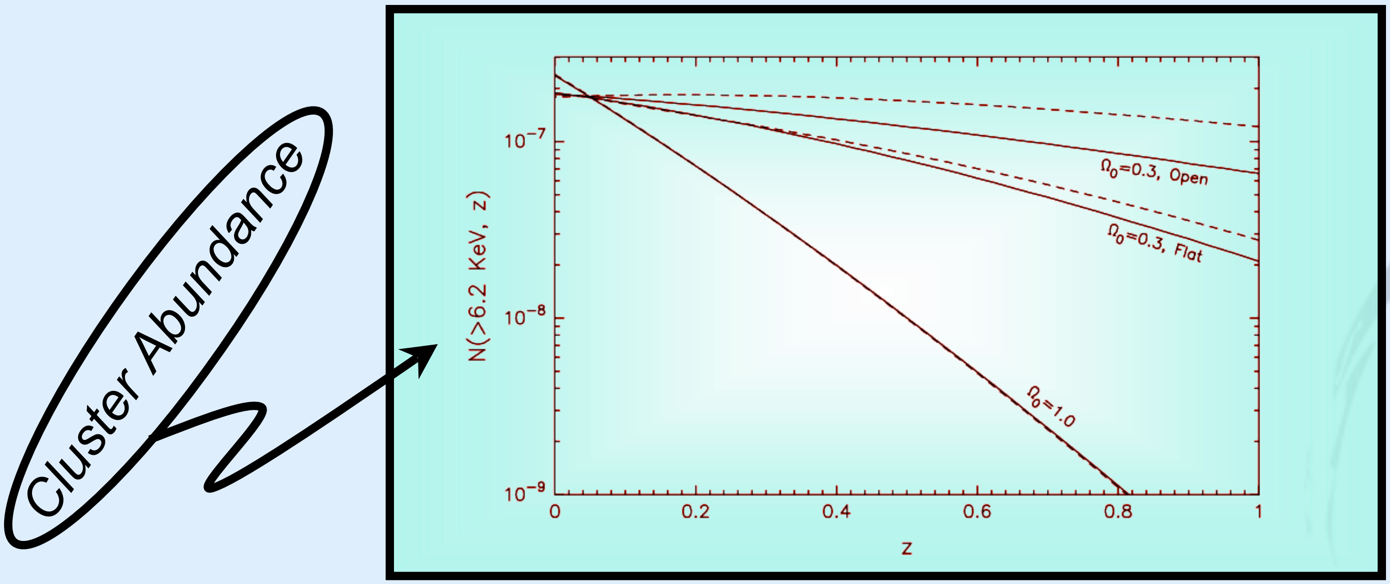
  - Changes observables like angular diameter distance and luminosity distance

$$d_L = \chi(z)(1+z) \qquad d_A = \frac{\chi(z)}{1+z}$$

- Tests that probe volume rely on standard candles to measure $d_L(z)$ or standard rulers to measure $d_A(z)$

Dark energy's observable influence

- Accelerated expansion influences the rate of structure growth
- Structure formation is a competition between the gravitational collapse and the expansion
- An accelerated expansion in the recent past implies that structures form more slowly
- Given a fixed level of structure today, models with dark energy will have more structure in place at high redshift



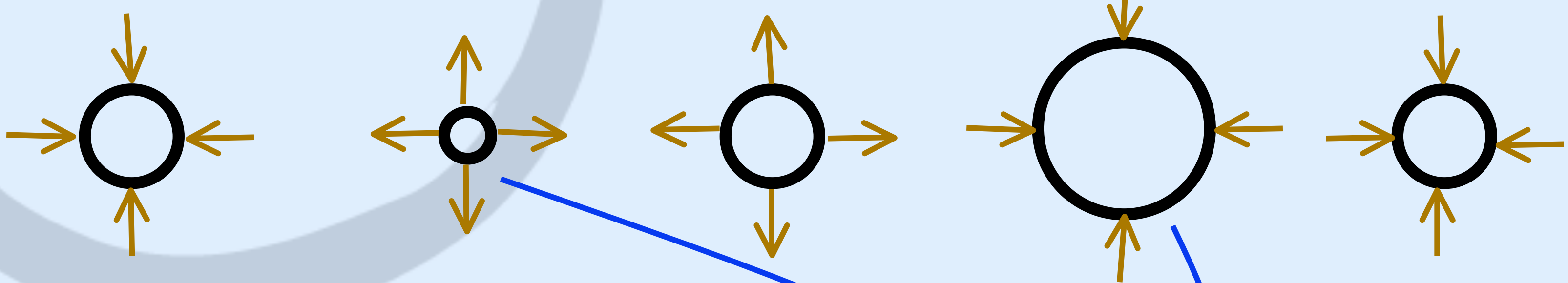
Astrophysical Probes

- Geometric Probes
  - Distance Redshift Relation
  - Alcock-Pascynski Test
  - Gravitational Lensing
- Probes of Structure Growth
  - Cluster Abundance vs.redshift
  - Integrated Saches Wolfe Effect
  - Gravitational Lensing

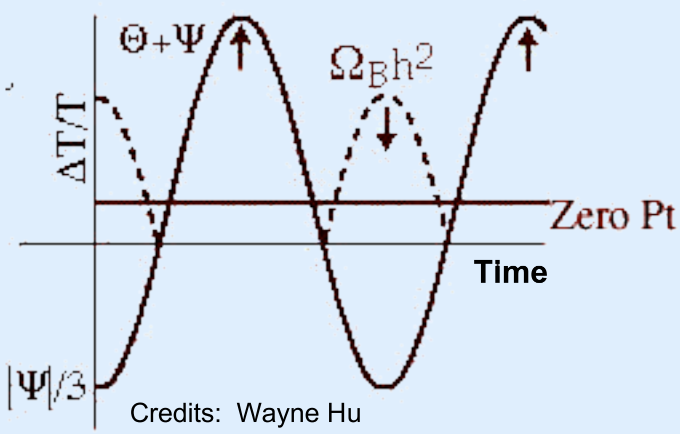
What are baryon oscillations?

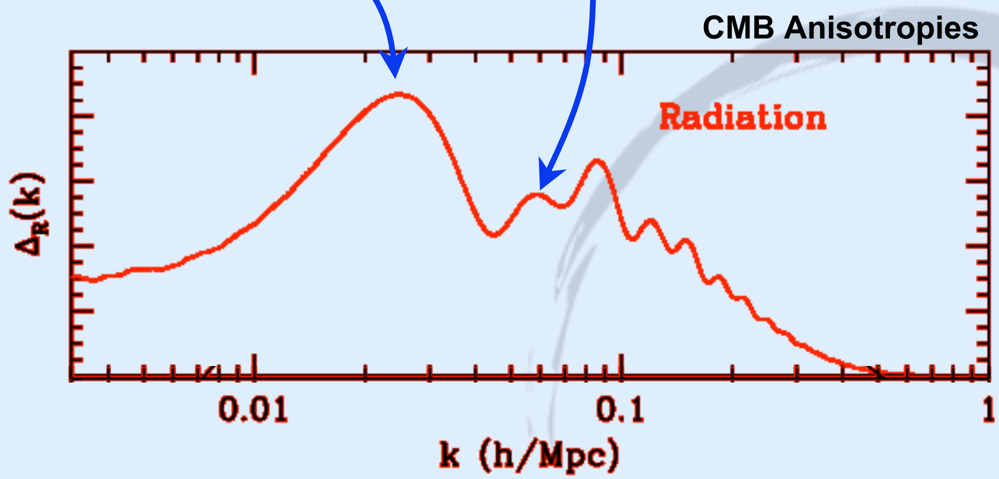
- Gravity and pressure provide restoring forces for oscillations

Collapse under gravity | **Pressure response** | **Overshoot: Max velocity** | **Rarefaction: v = 0** | **Recollapse**



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

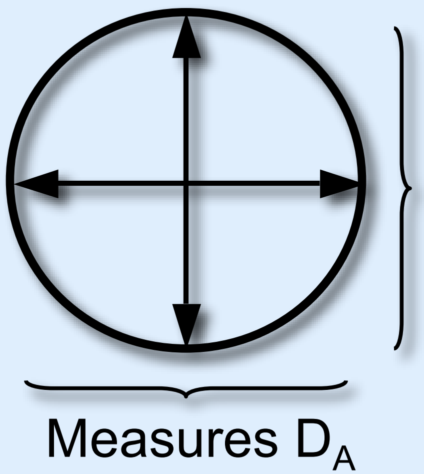




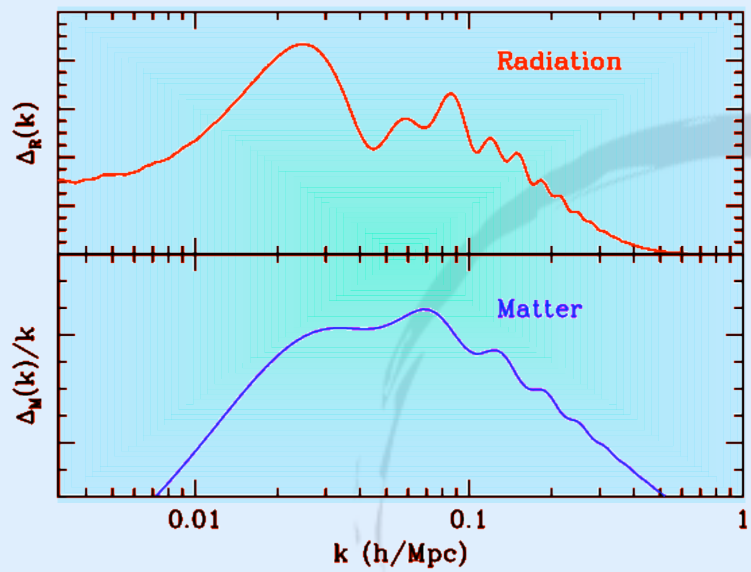
Why study baryon oscillations ?

- 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



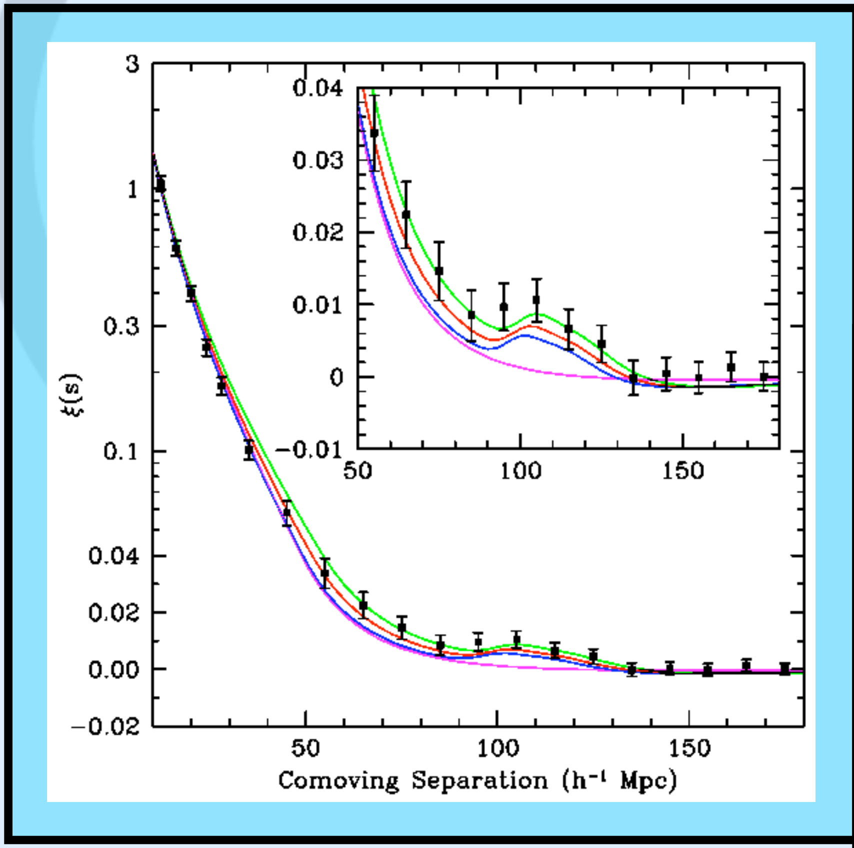
Probes distances to z~1000



Probes distances to 0<z<10

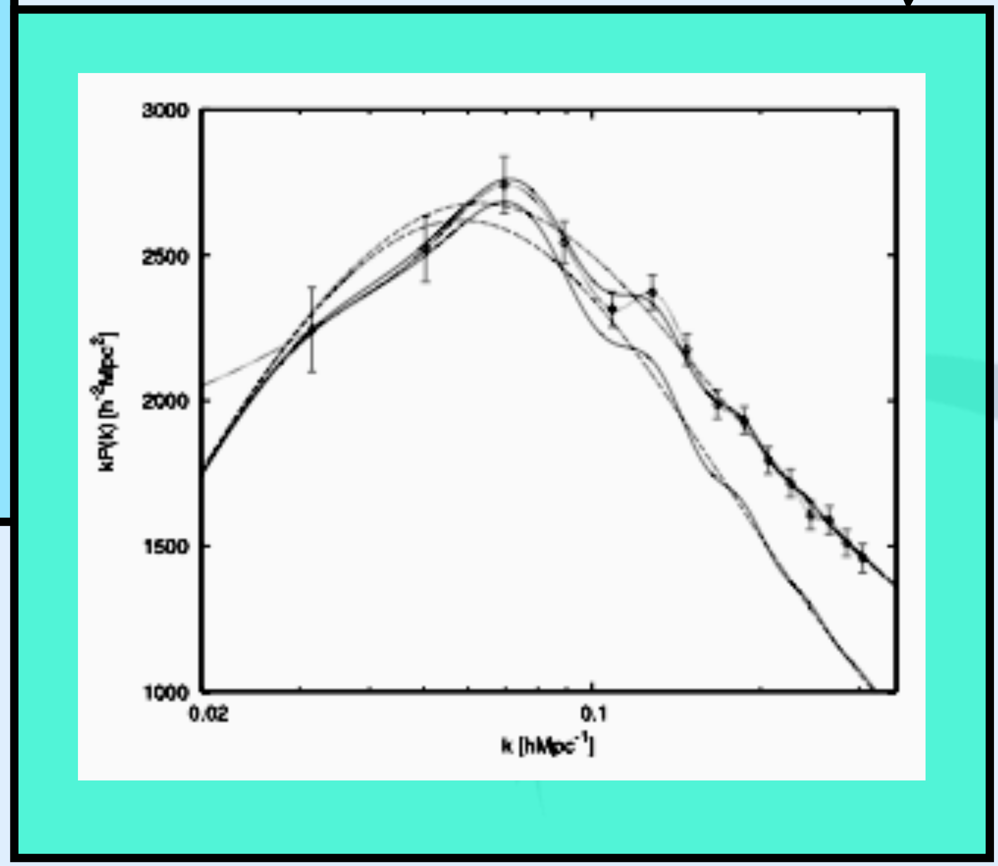
Baryon oscillations have been seen!

SDSS LRG Sample



Seo & Eisenstein (2005)

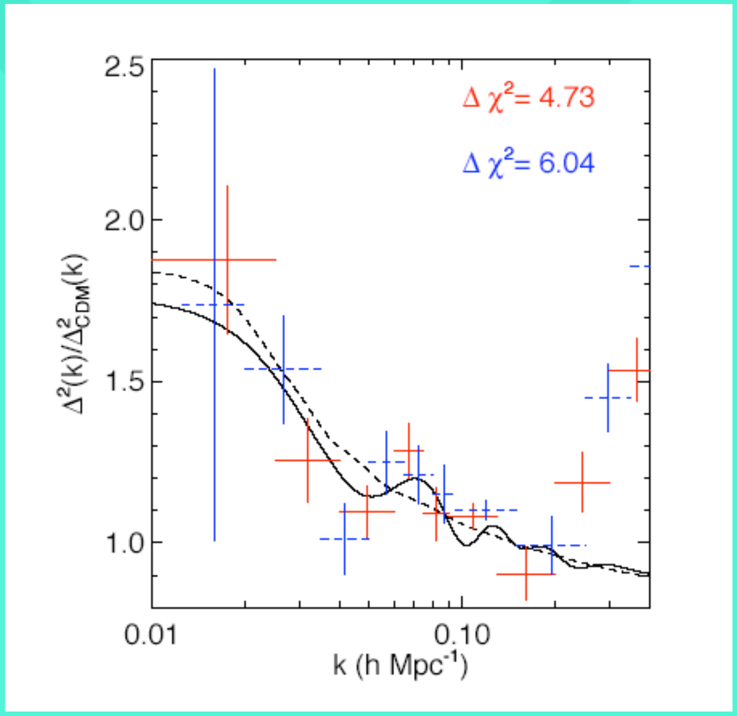
Huetsi (2005)

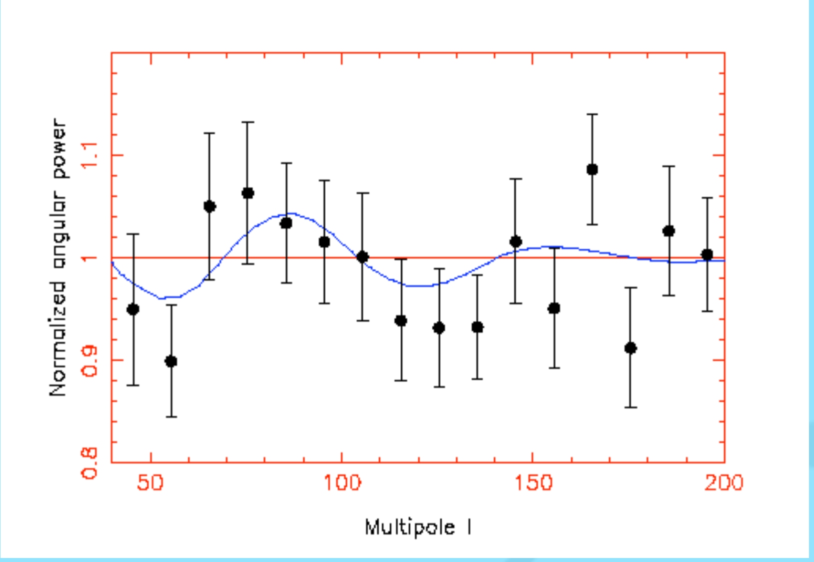


Baryon oscillations have been seen!

… and photometrically.

Padmanabhan et. al. 2006



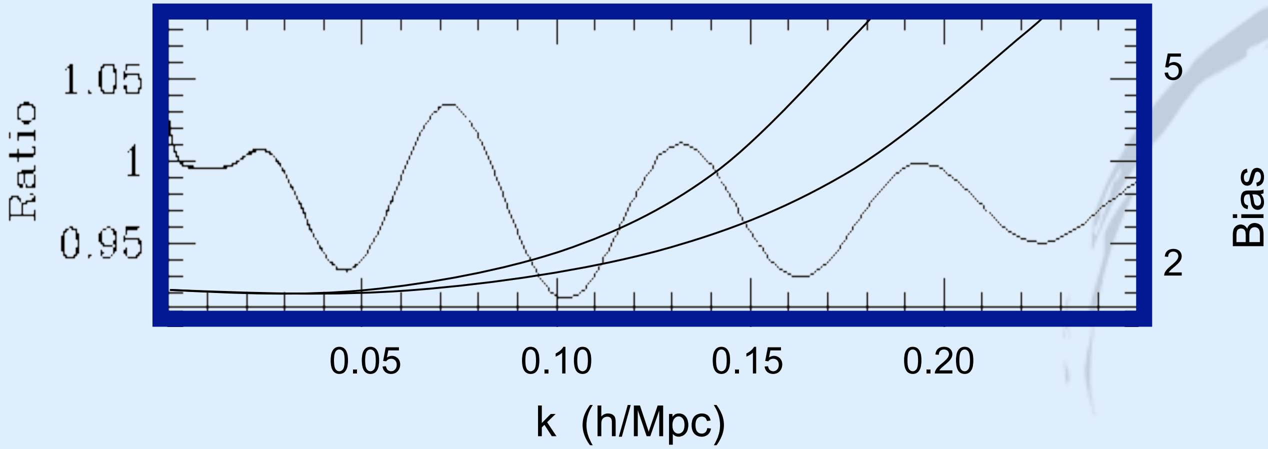


Blake et. al. 2006

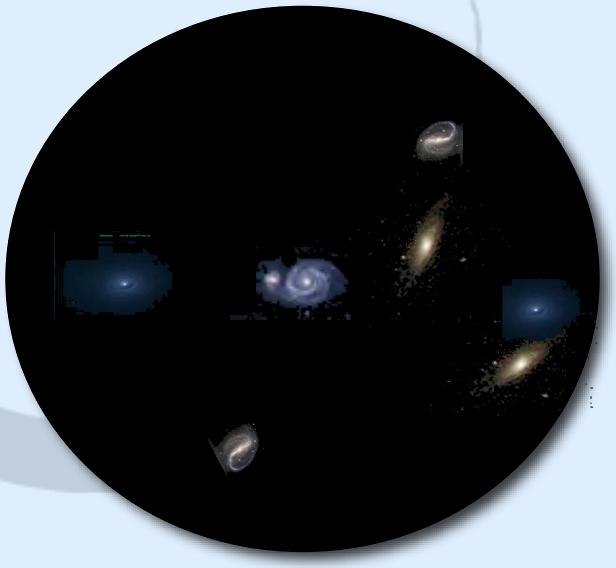
Why study bias ?

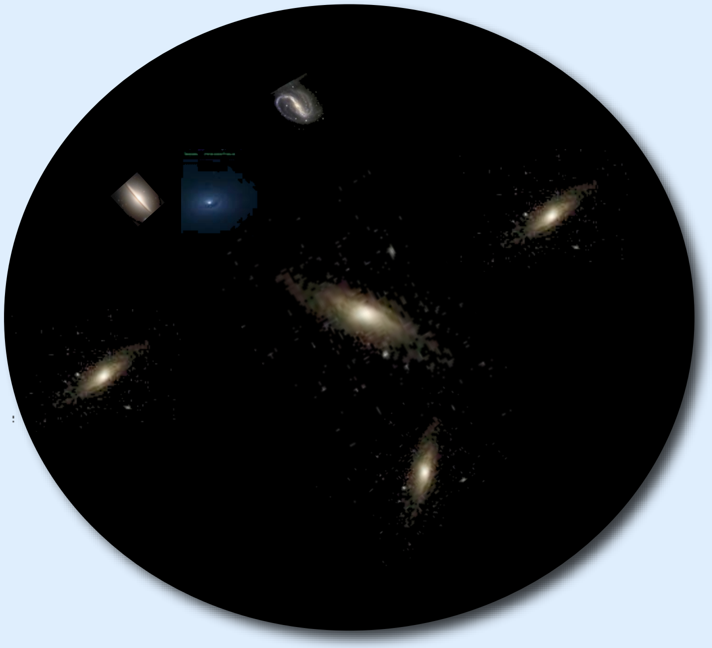
- The linear dark matter power spectrum cannot be directly observed -- need galaxies
  - **Galaxy bias**
  - **Non-linear structure evolution**
  - **Redshift space distortions**

- 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

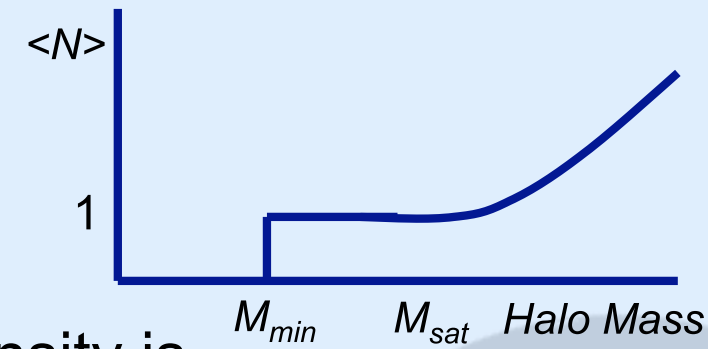




- All matter and galaxies in the universe live in virialized halos characterized by their masses
- The 2-point correlation function is the sum of inter-halo and intra-halo pair contributions
- Contribution from pairs in separate halos dominates on large scales (the 2-halo term)
- Contributions from pairs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

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

  - Only satellites trace the halo dark matter profile

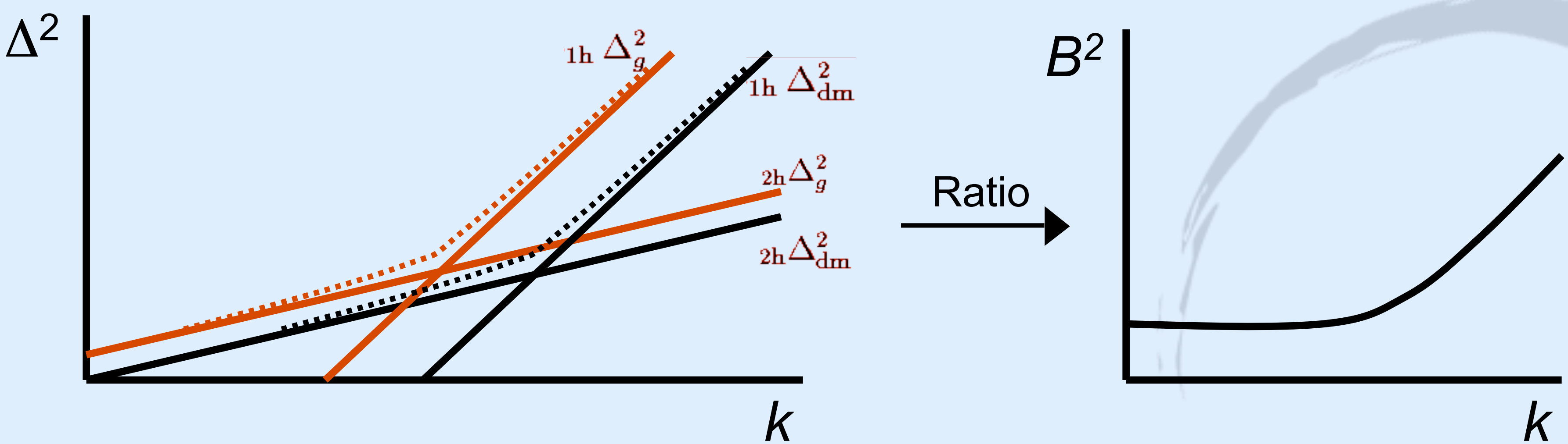
Galaxy Bias

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

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

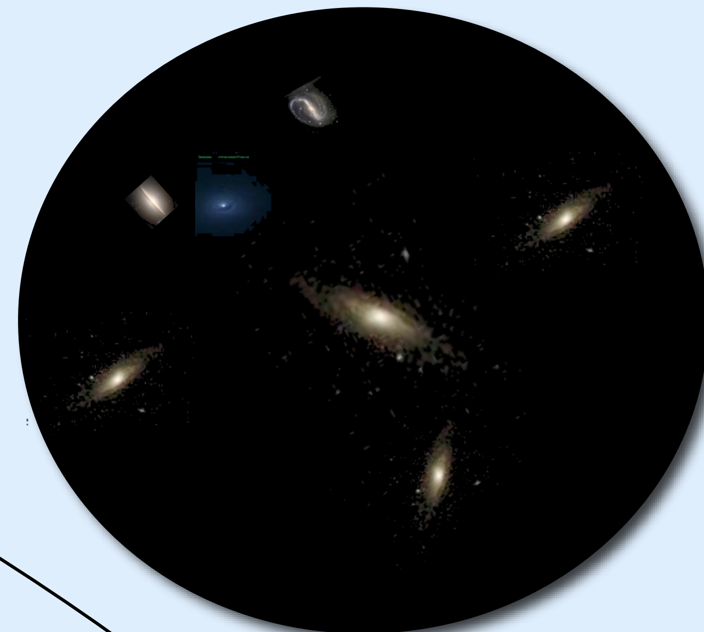
Relative shift in each depends on the HOD

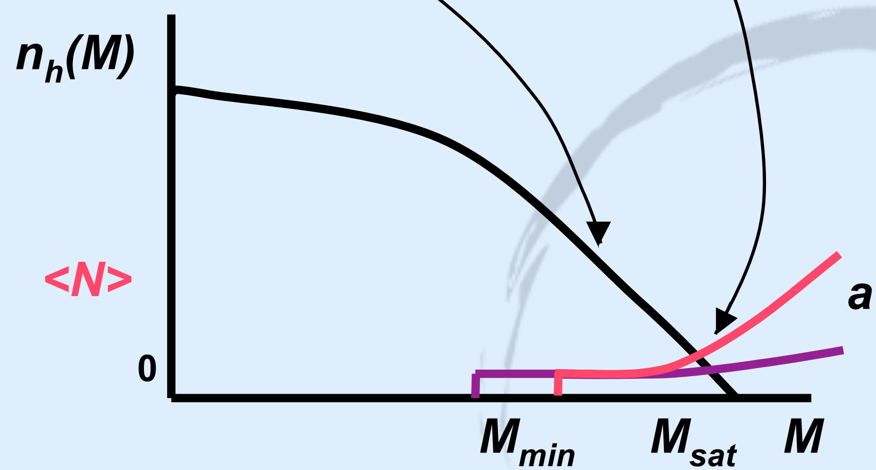
- In general, ${}_{2h}\Delta_g^2 > {}_{2h}\Delta_{dm}^2$ and ${}_{1h}\,\Delta_g^2 > {}_{1h}\,\Delta_{dm}^2$ but the two terms do not shift proportionally



What difference does an HOD make?

- More massive halos are rarer and much more biased



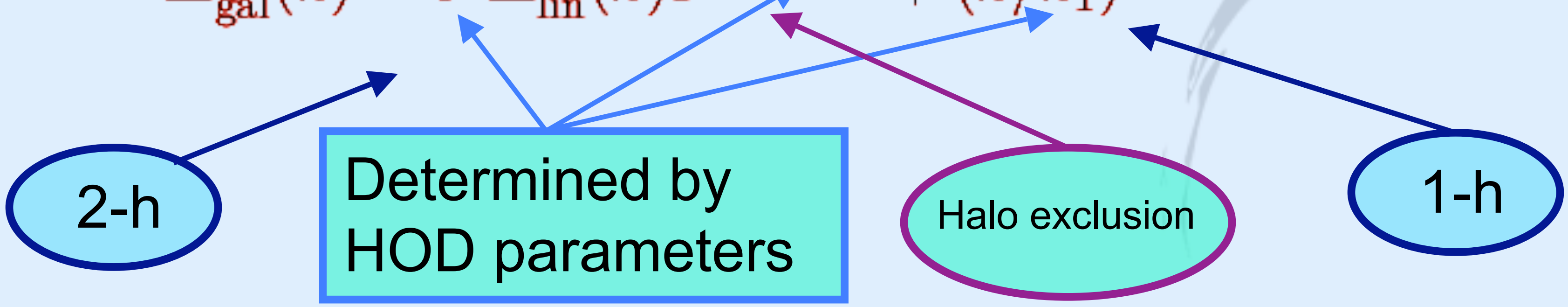


- Halos are weighted by <N> rather than their mass M
- M_{min} influences how biased is the galaxy 2-halo term
- The 1-halo term will be more biased than the 2-halo term, as determined by M_{sat} and a

Trends in Scale Dependence

- Fixed n_g: scale dependence increases as the tracers become more biased
- 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)

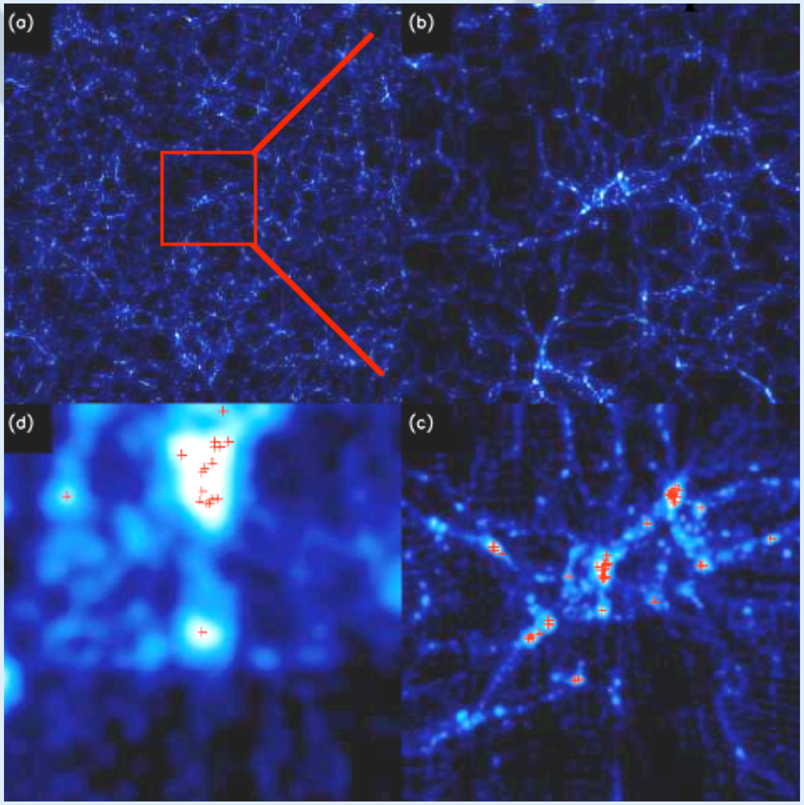
$$\Delta^2_{\rm gal}(k) = b^2 \Delta^2_{\rm lin}(k) e^{-(k/k_2)^2} + (k/k_1)^3$$



Does it work? ⇒ 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; astro-ph/0607061)



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

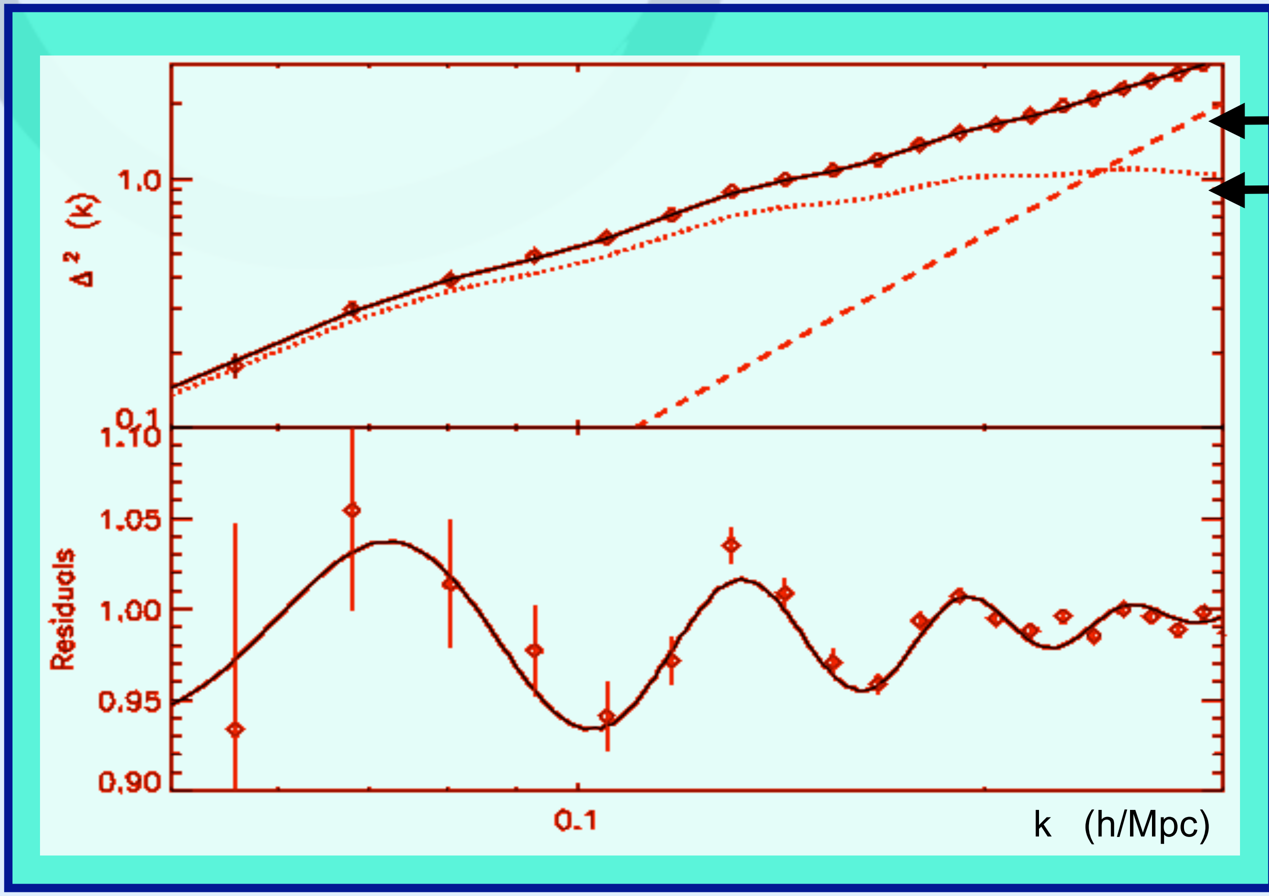
•Red points mark the galaxy positions

White 2005

Testing the halo model inspired treatment

- This form agrees well with numerical simulations

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



1-halo term

2-halo term

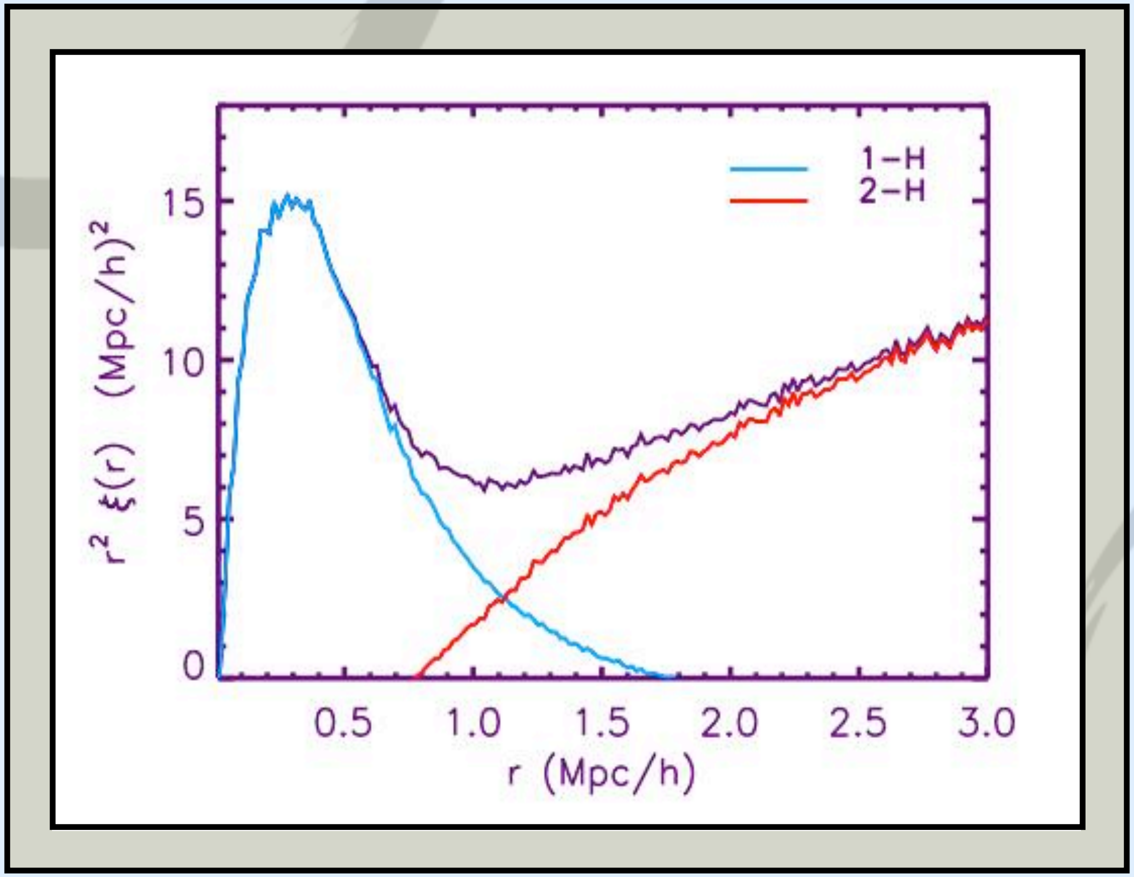
1+2 (the model)

N-body data

Error bars are bootstrapped from eight subdivisions of the simulation volume

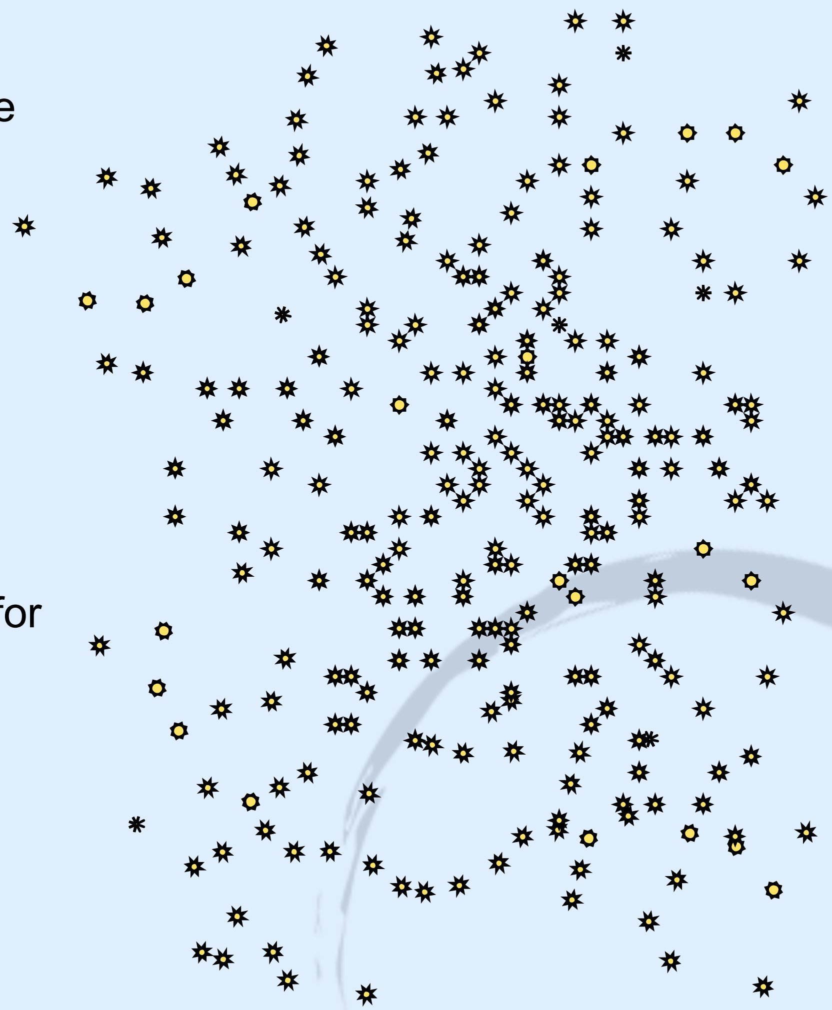
Virtues of the correlation function

- Studying the correlation function at ~100 Mpc/h is comparatively less scale dependent than the power spectrum
- Accounting for irregular survey geometry is often cleaner
- 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



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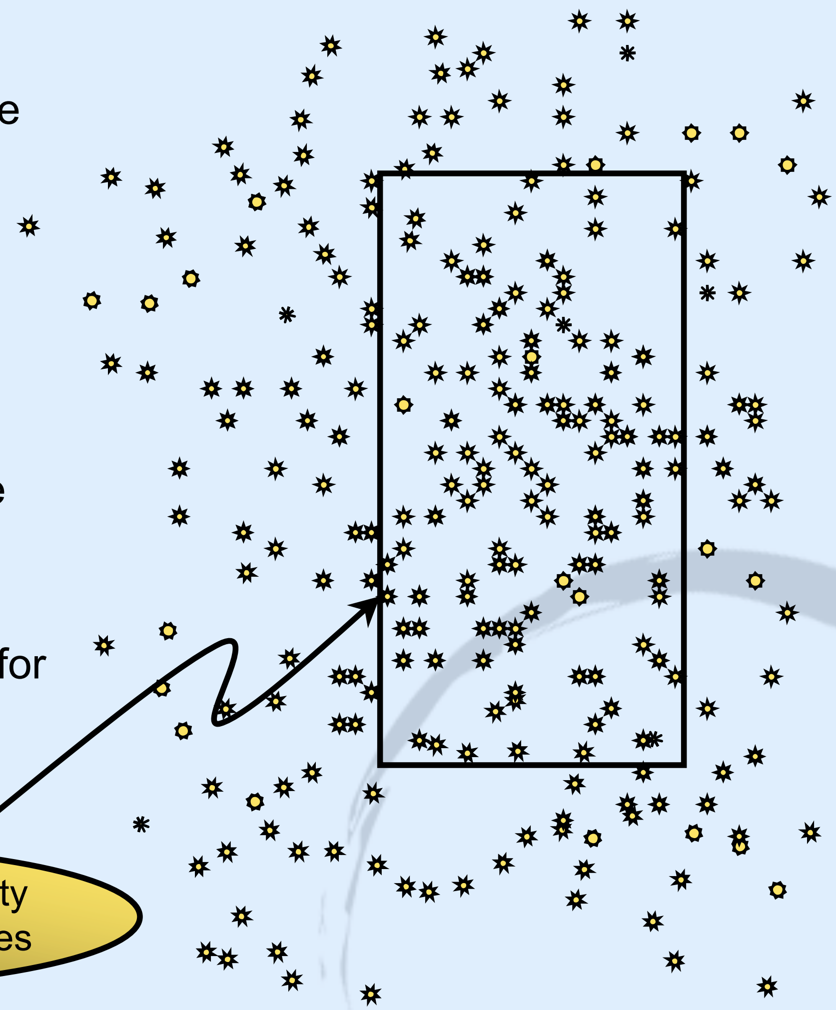


A configuration space band power estimator

- 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 $\xi(r)$

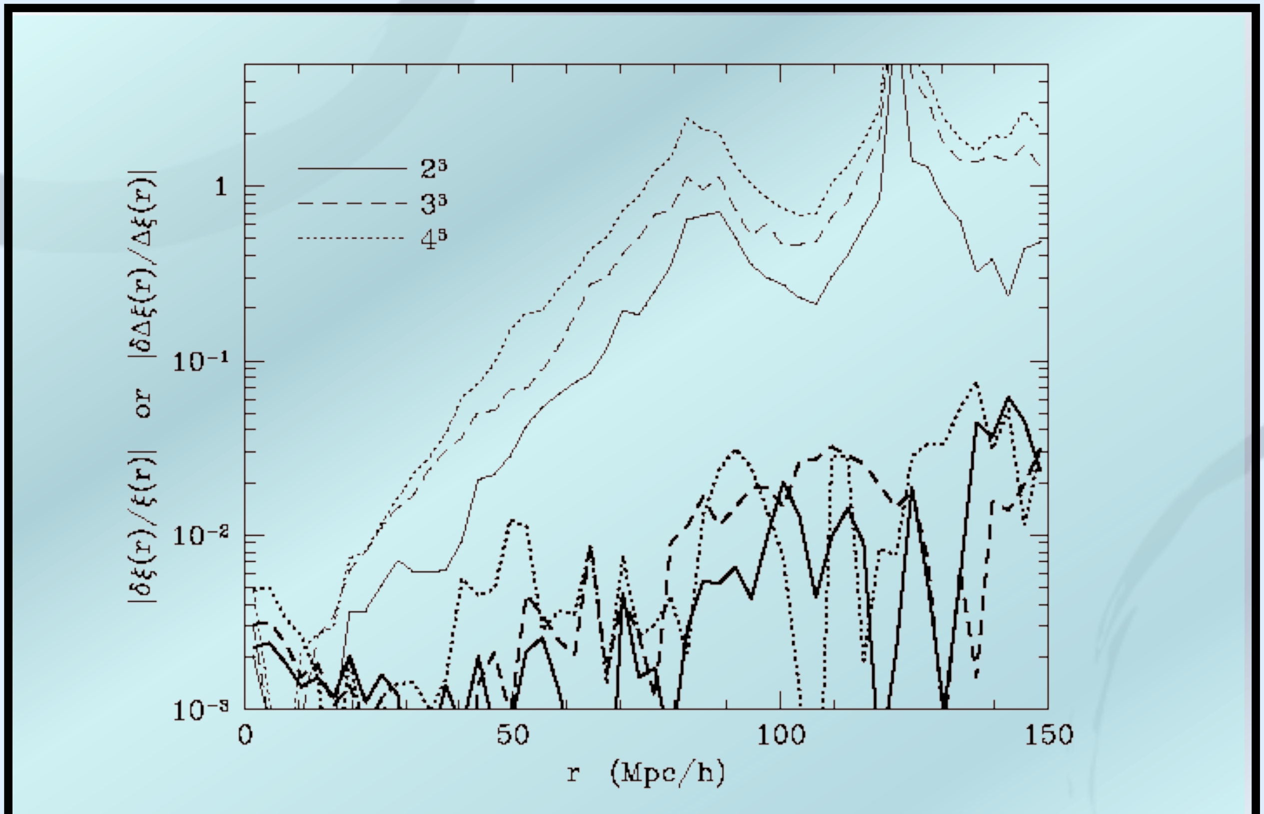
$$\xi(r) = \int \frac{dk}{k}\,\Delta^2(k)\,j_0(kr) \simeq \int \frac{dk}{k}\,\Delta^2(k)\left[1 - \frac{(kr)^2}{6} + \cdots\right]$$

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

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

The virtues of the configuration space band power estimator

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

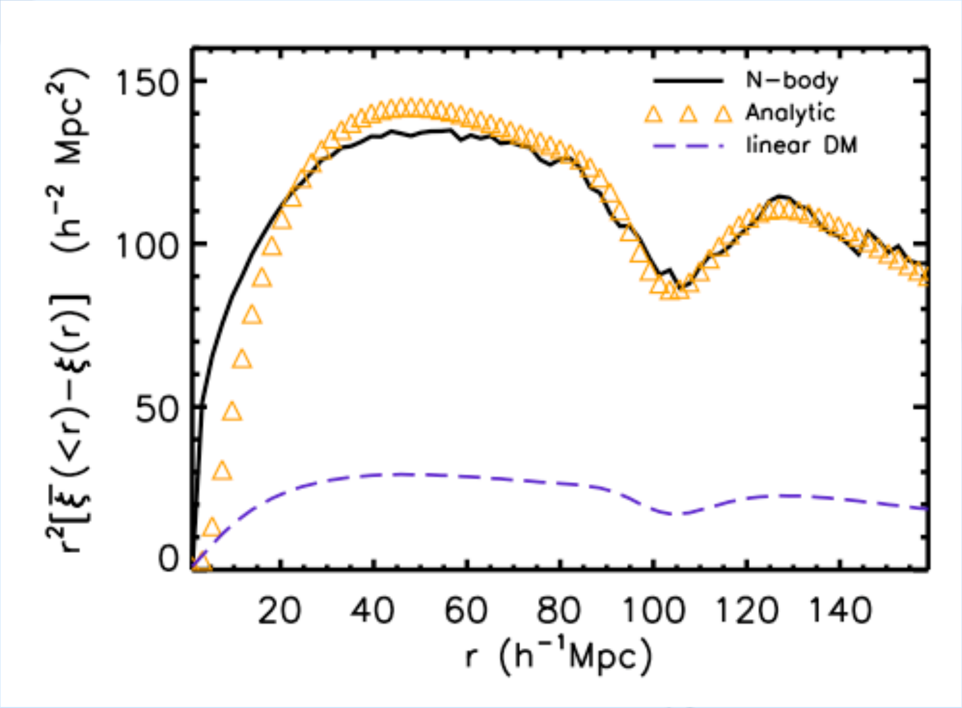


Halo model analytic form fits correlation function well

- $\Delta\xi$ 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.

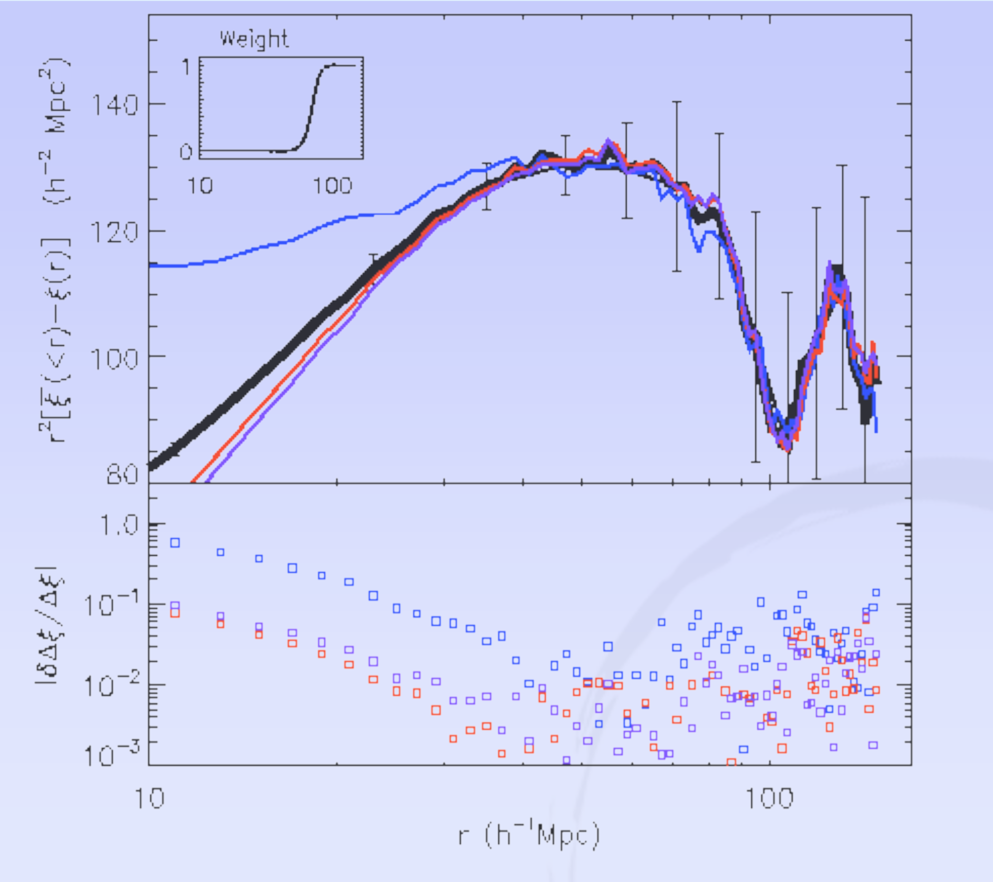


Virtues of the configuration space band power estimator

- 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**



To do:

- HOD expected to change with redshift
  - Observationally: Galaxy selection function varies
  - In the model: Unknown galaxy formation physics
    - ⟨N(M)⟩ may evolve (depend on halo age)
    - Color distribution in mass M halo may evolve (older--redder)
    - ⟨N(M)⟩ and colors may depend on local environment
    - ⟨N(M)⟩ and colors may depend on host halo merger history
- With high volume surveys it will be possible to study halo merger statistics through the observation of close halo pairs
- There is scatter in N(M) relation, and it may evolve
  - Based on sub-halo statistics, scatter in number of satellite halos is expected to be nearly Poisson
  - This assumption has not been tested for high mass sub-halos (expected to house galaxies) in the highest mass hosts (<5e14)
  - Deviations from Poisson scatter, or systematic evolution of the scatter could impact clustering and scale-dependent bias

To do:

- Redshift space
  - Different information is contained in line-of-sight and plane-of-sky correlations
    - Line-of-sight: Expansion H(z)
    - Plane-of-sky: Angular diameter distance D_A
  - Line-of-sight correlations more sensitive to changes in cosmological parameters
  - Redshift errors distort only the line-of-sight
  - Methods to date:
    - Angular average of signal
    - Projection of signal along line of sight
    - Projection along line of sight in wide z-bins
  - An end-to-end pipeline needs to be developed to better exploit the three-dimensional nature of the data
  - Photo-zs require a careful balance
    - Coarser z binning required by line-of-sight scatter
    - Coarser binning ➜ loss of information
  - Techniques to reconstruct the degradation of wiggles due to non-linearity at lower z's should be extended (if possible) to address photometric surveys

Conclusions

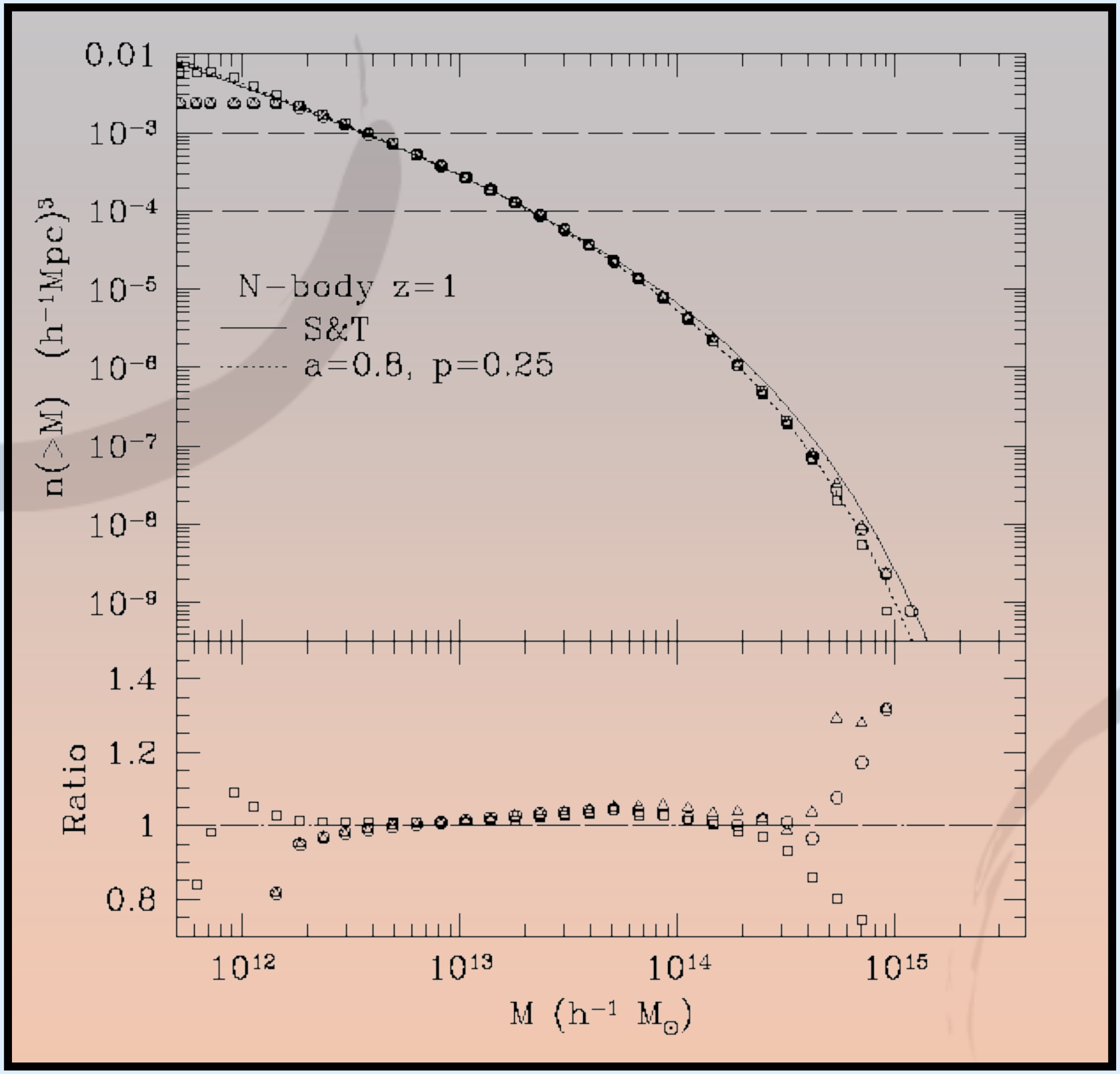
- Baryon oscillations in galaxy power spectra hold promise of a new observational handle on the expansion history of the universe
- Key to tapping this potential is the reduction of theoretical uncertainties regarding
  - Galaxy bias
  - Non-linear structure evolution
  - Redshift space distortions
-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

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

- We have developed an improved estimator of the correlation function that can bypass many of the canonical problems by marginalizing over a 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



What calibrates the standard ruler?

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

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

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

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

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

WMAP 1st year data

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)

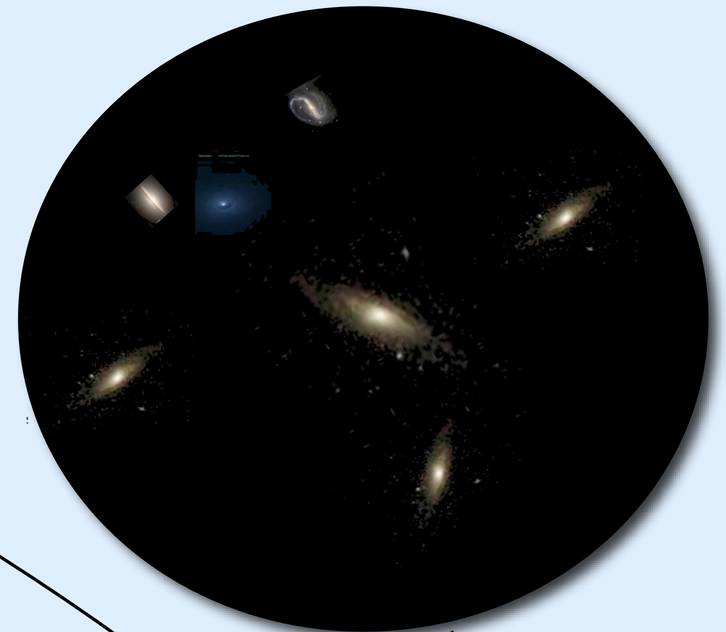
$${}_{\rm 2h}\Delta^2_{\rm dm} = \Delta^2_{\rm lin} \left[\frac{1}{\bar\rho} \int_0^\infty dM \; n_h(M) \, b_h(M,k) \, M \, y(M,k) \right]^2$$

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

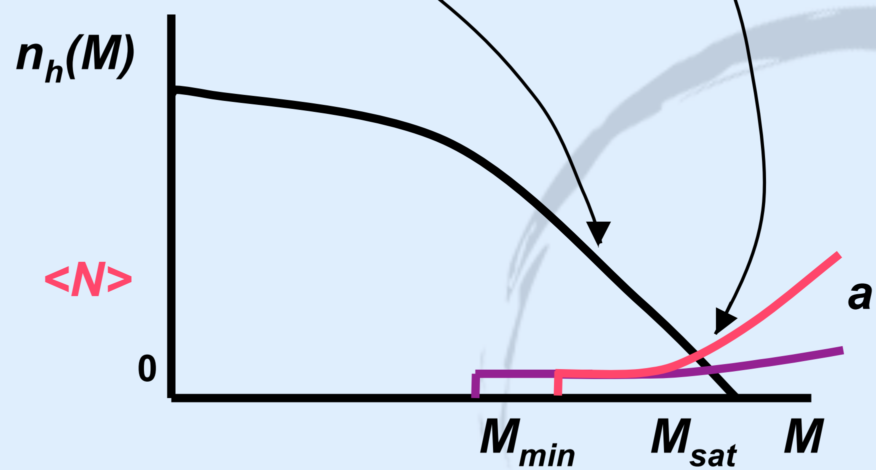
$${}_{\rm 1h}\Delta^2_{\rm dm} = \frac{k^3}{2\pi^2} \frac{1}{\bar\rho^2} \int_0^\infty dM \, n_h(M) M^2 \, |y(M,k)|^2$$

What difference does an HOD make?

- More massive halos are rarer and much more biased

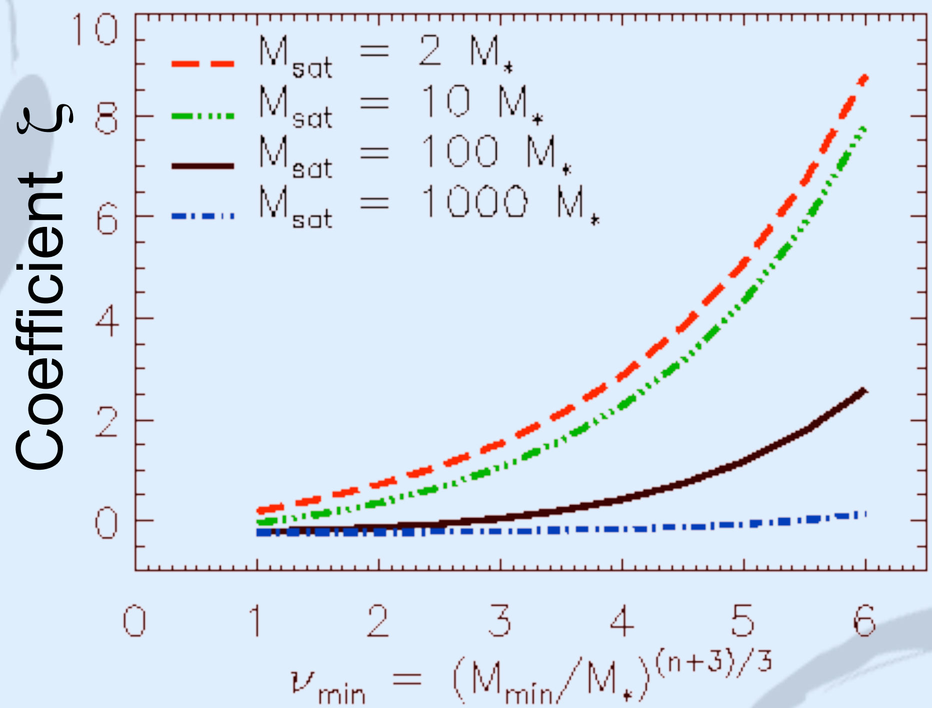


- Halos are weighted by <N> rather than their mass M
- M_{min} influences how biased is the galaxy 2-halo term
- The 1-halo term will be more biased than the 2-halo term, as determined by M_{sat} and *a*



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



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

Determined by HOD parameters

The only scale dependent term

Galaxy extension to halo model

- 2-halo term

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

$\bar{\rho}$ → $\bar{n}_{gal}$

$M\,y(M,k)$: Number and distribution of galaxies in a halo of mass *M*

- 1-halo term

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

$\bar{\rho}^2$ → $\bar{n}^2_{gal}$

$M^2\,|y(M,k)|^2$: All central-satellite and satellite-satellite pairs in a halo of mass *M*

Forms of galaxy bias tested

- Decaying Sinusoid

Blake & Glazebrook, ApJ 594, 665 (2003)

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

k_s=0.1 h Mpc^{-1}

- Q-model used in SDSS

Cole et al. MNRAS 362, 505 (2005)
Padmanabhan, astro-ph/0605302

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

a=1.7 Mpc/h

- Halo Model Inspired

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

Schulz & White, Astropart. Phys. 25, 172 (2006)

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

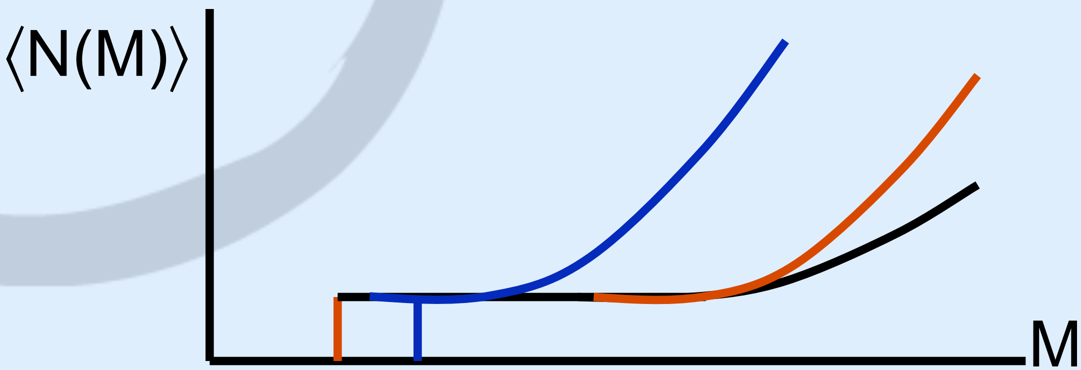
- Lagrangian Displacement

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

Eisenstein, Seo & White, ApJ in press, astro-ph/0604361

Model testing methodology

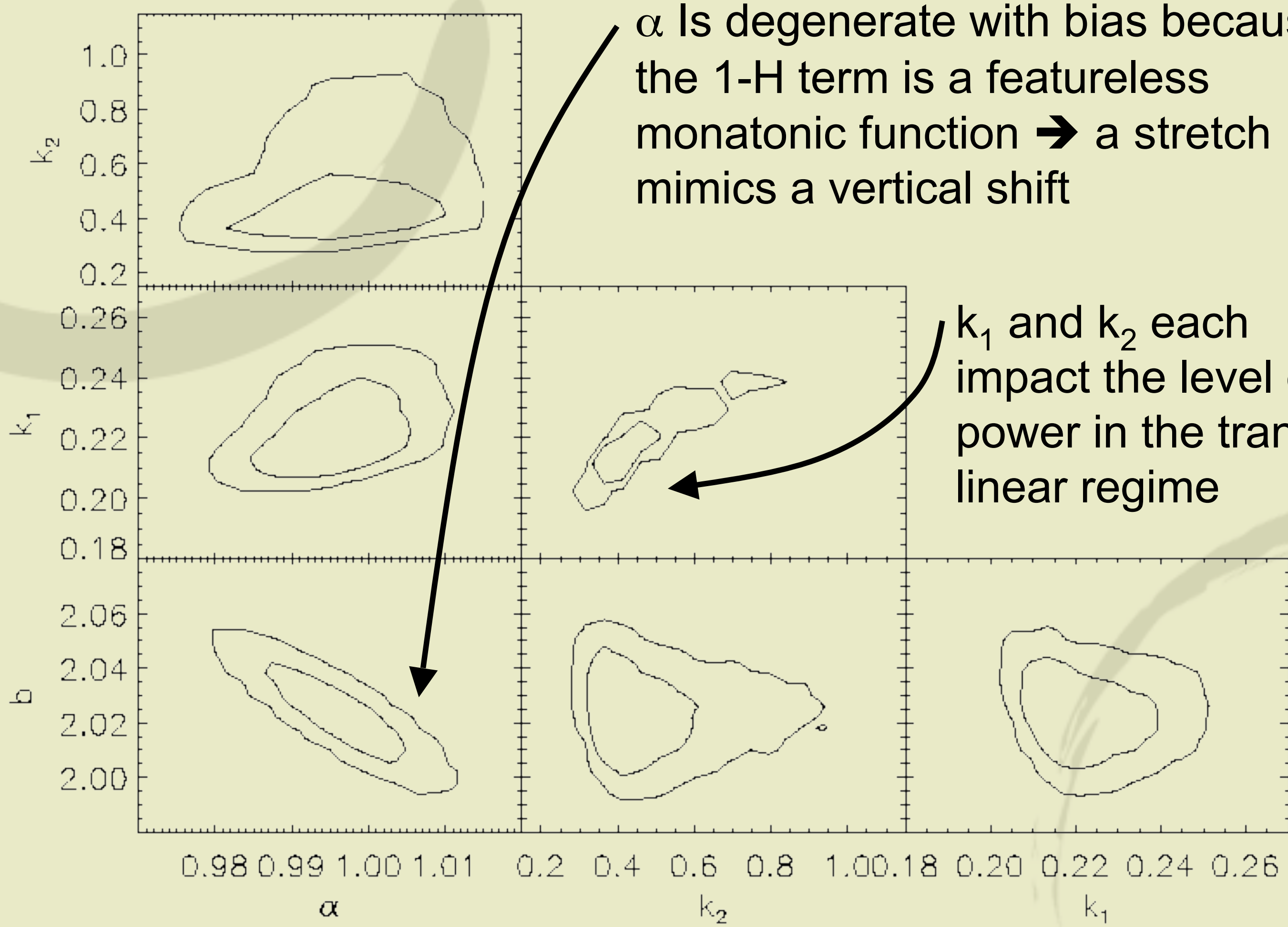
- Populate three independent 1 Gpc^3/h simulation volumes at z=1 with 36 different HOD prescriptions
- HODs span expected range of behaviors



- Perform MCMC fits to $\Delta(k)$ using mode counting error bars
- Marginalize over HOD parameters to get error on the horizon scale
- Translates to dark energy errors approximately as $d\alpha/\alpha \approx 5\, dw/w$ for constant w

Degeneracy of the acoustic scale with HOD

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



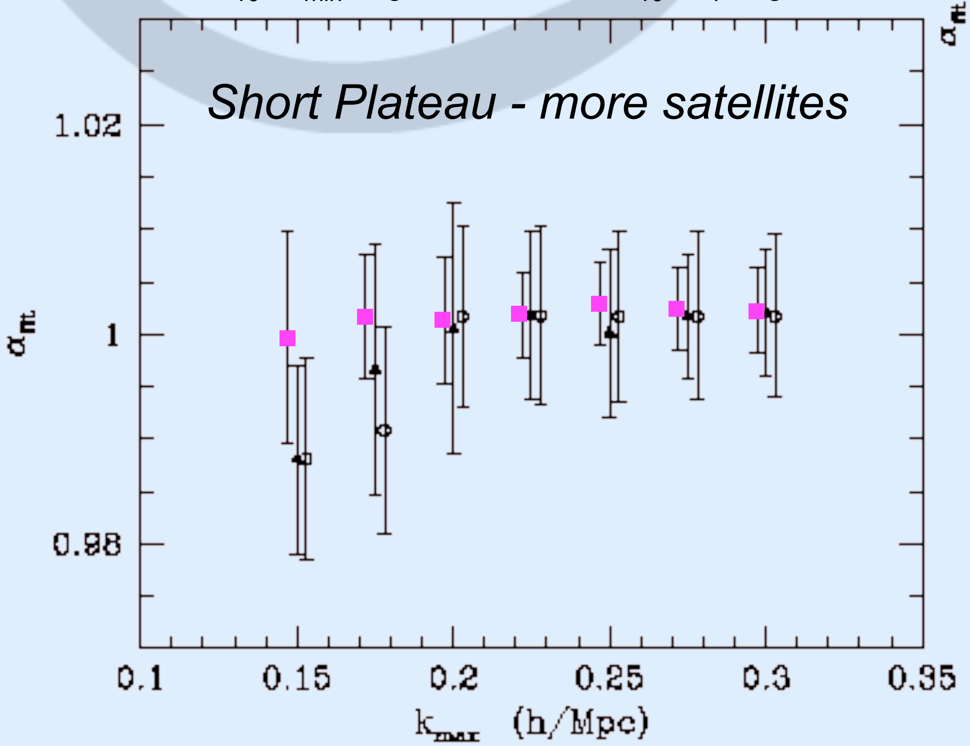
α Is degenerate with bias because the 1-H term is a featureless monatonic function ➔ a stretch mimics a vertical shift

k_1 and k_2 each impact the level of power in the trans-linear regime

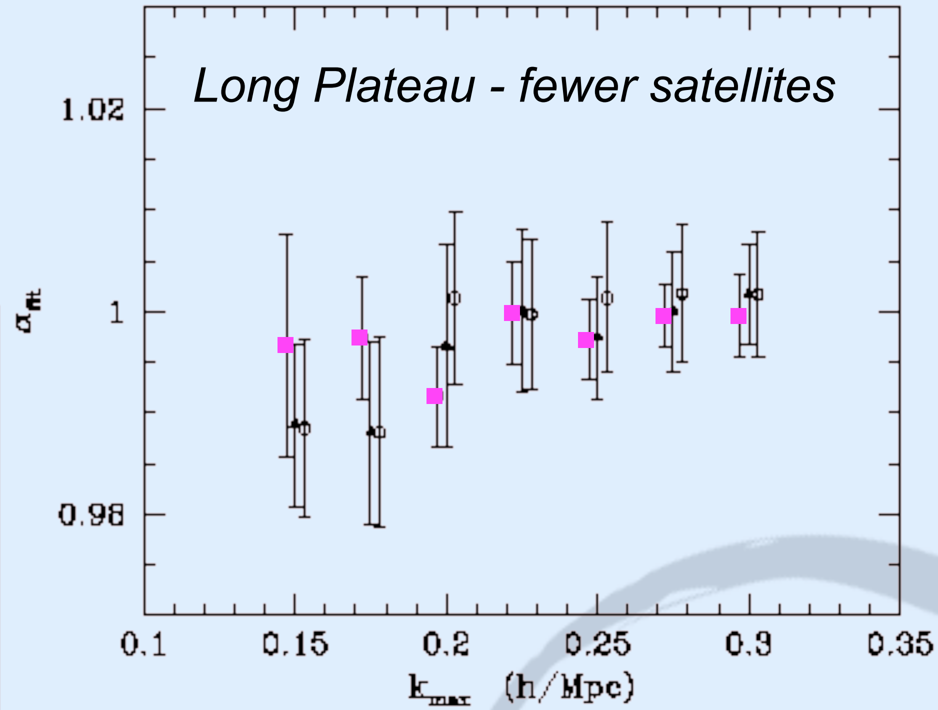
Model comparison I

- 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

$Log_{10}(M_{min}/M_{\odot})$=12.8 $Log_{10}(M_1/M_{\odot})$=13.0

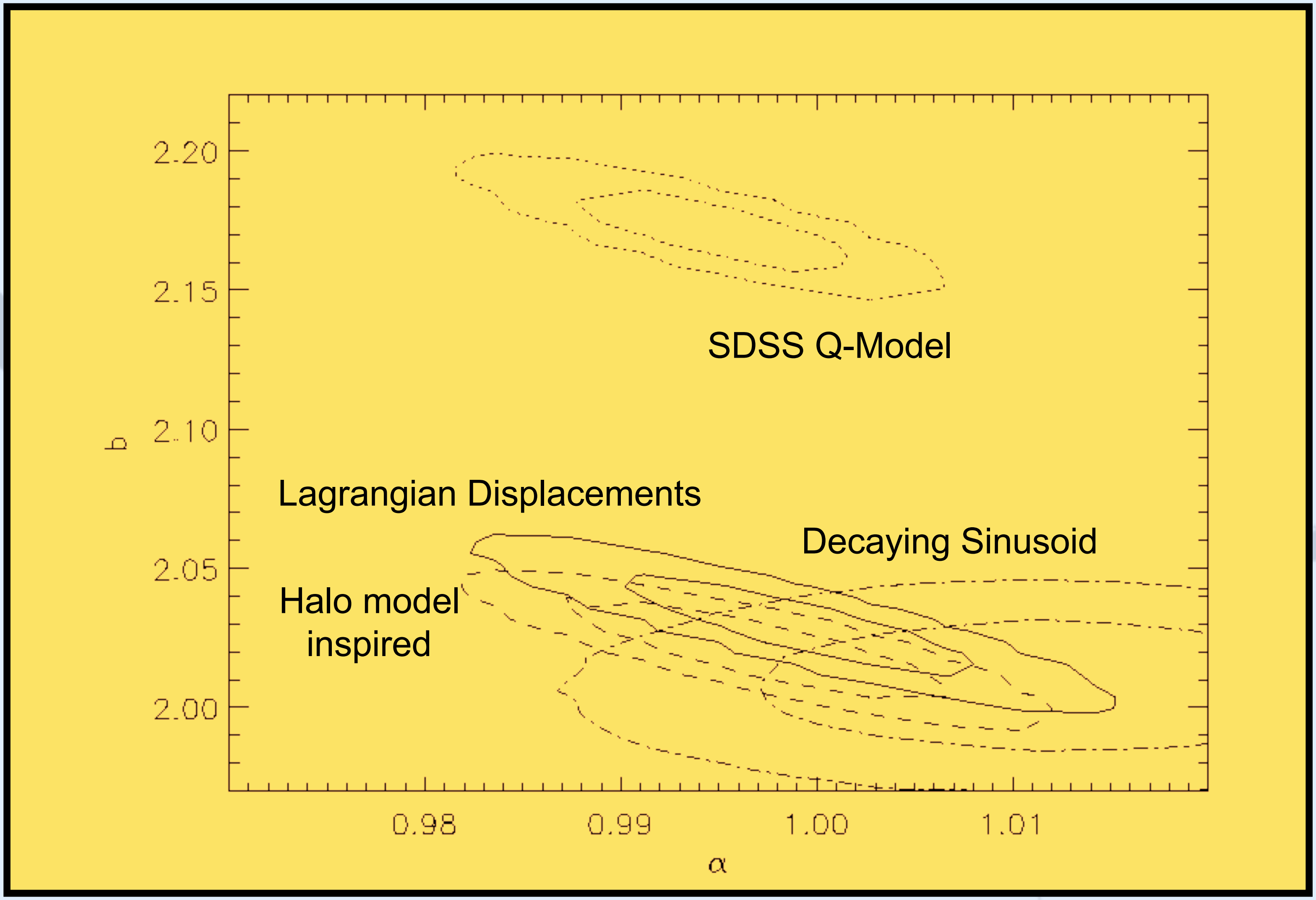


$Log_{10}(M_{min}/M_{\odot})$=12.7 $Log_{10}(M_1/M_{\odot})$=13.5



- ■ SDSS Q-Model
- ○ Halo-model inspired
- ▲ Lagrangian reconstruction

Model comparison II



What happens in redshift space?

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

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

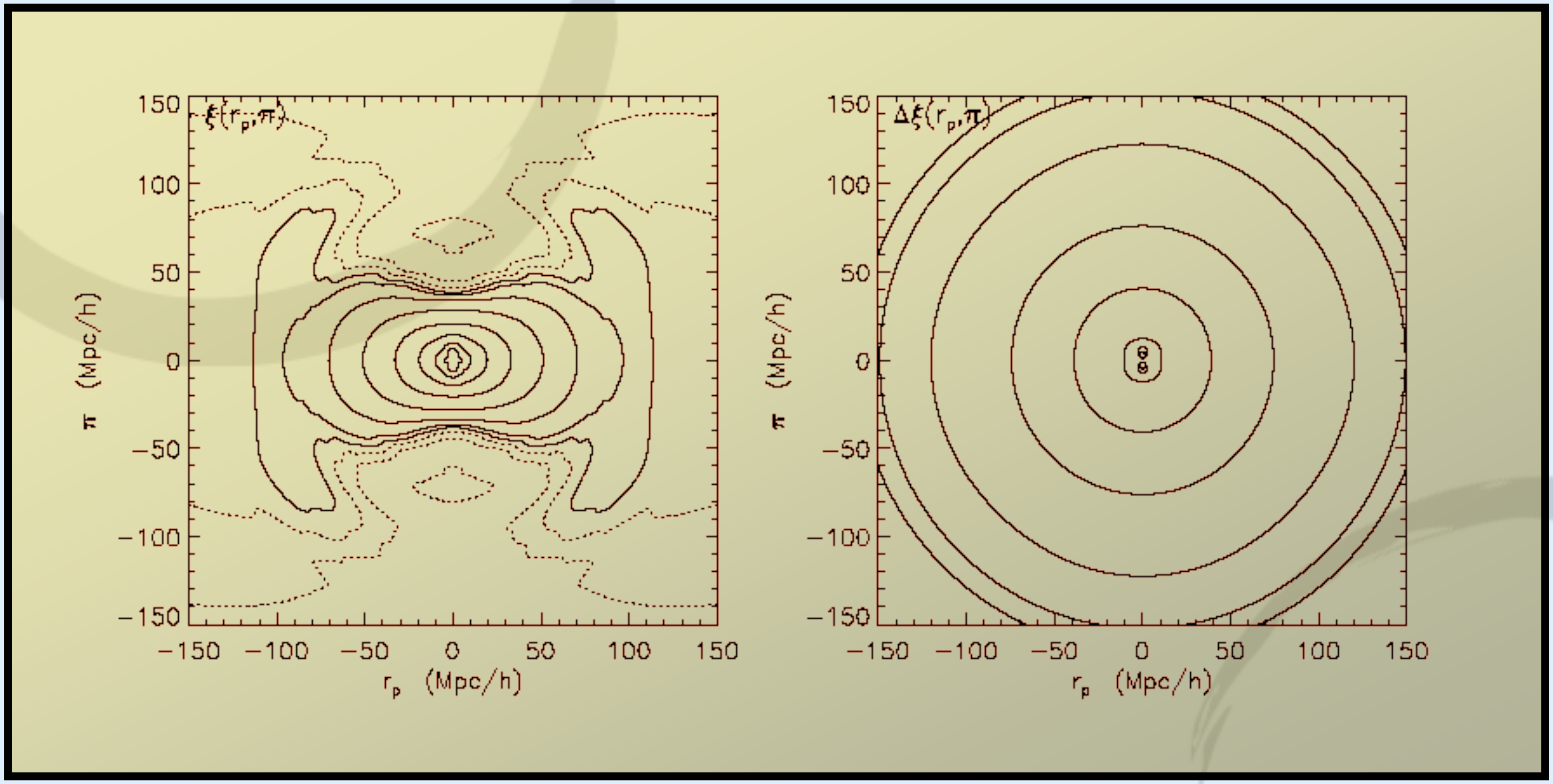
Where $\mu = \hat{r}\cdot\hat{k}$ and $\sigma^2_{v,\rm sat} = GM/2r_{\rm vir}$

- 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

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

Δξ is Rounder than ξ in Redspace

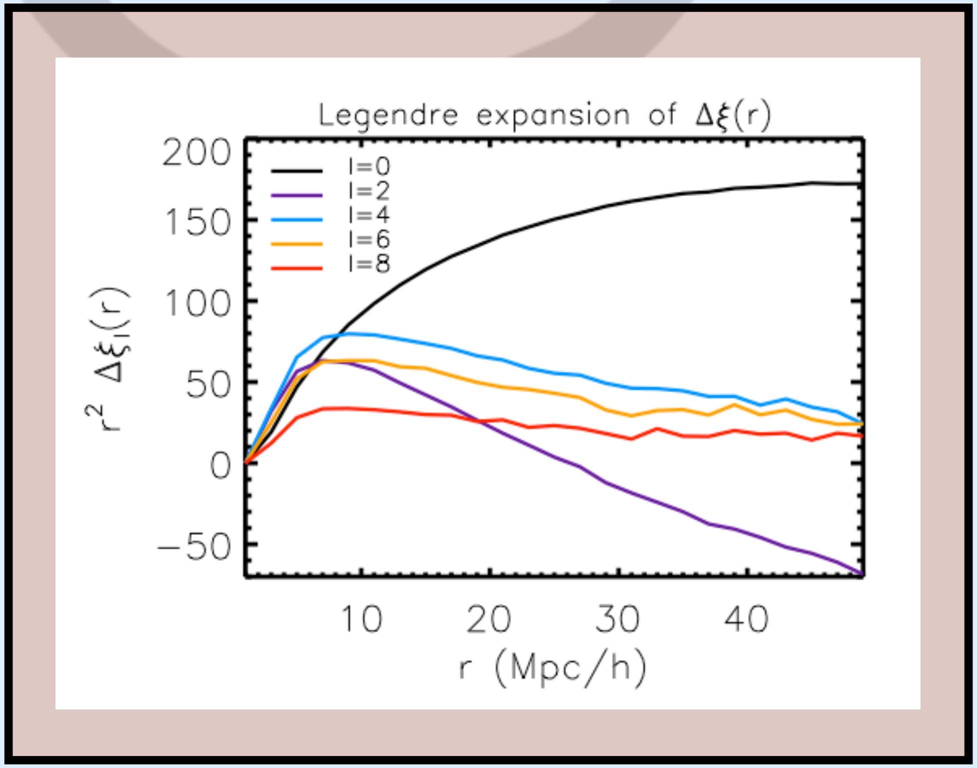
- Redshift space distortions for ξ(r) and Δξ(r)

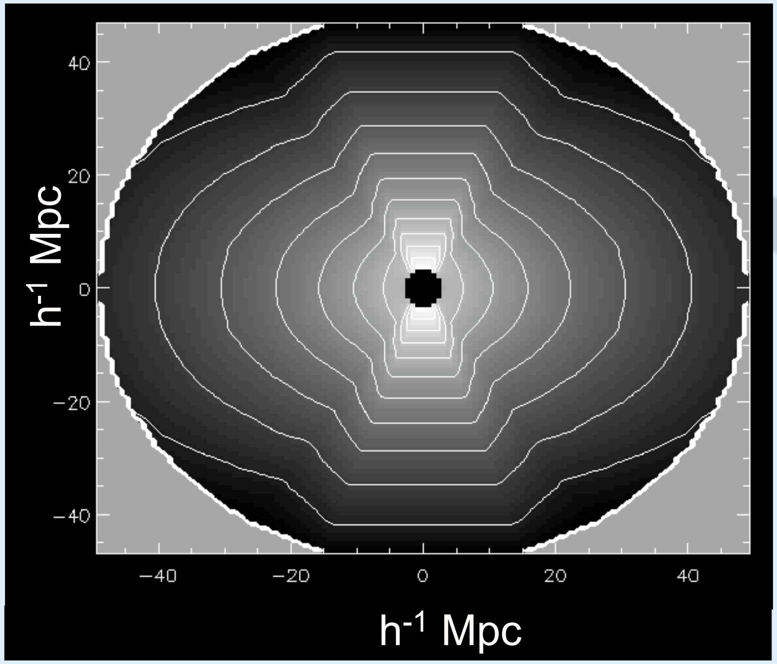


Redshift space distortions in N-body

- 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.

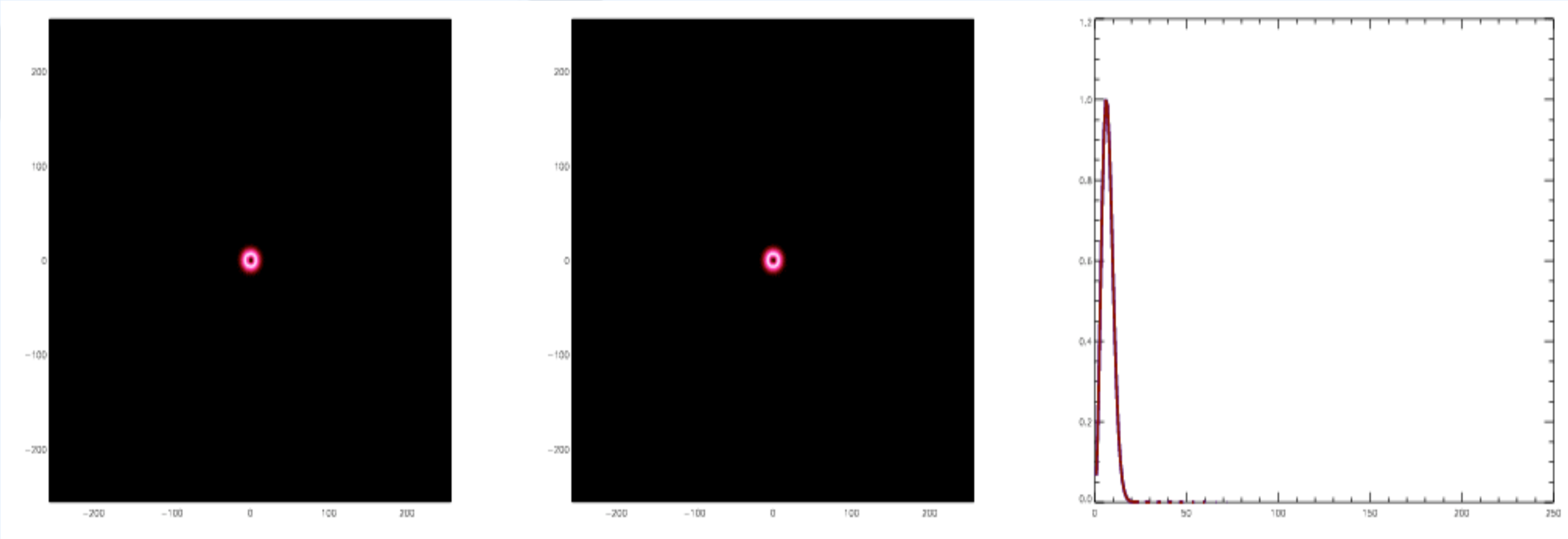




The acoustic wave

Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin.

High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.

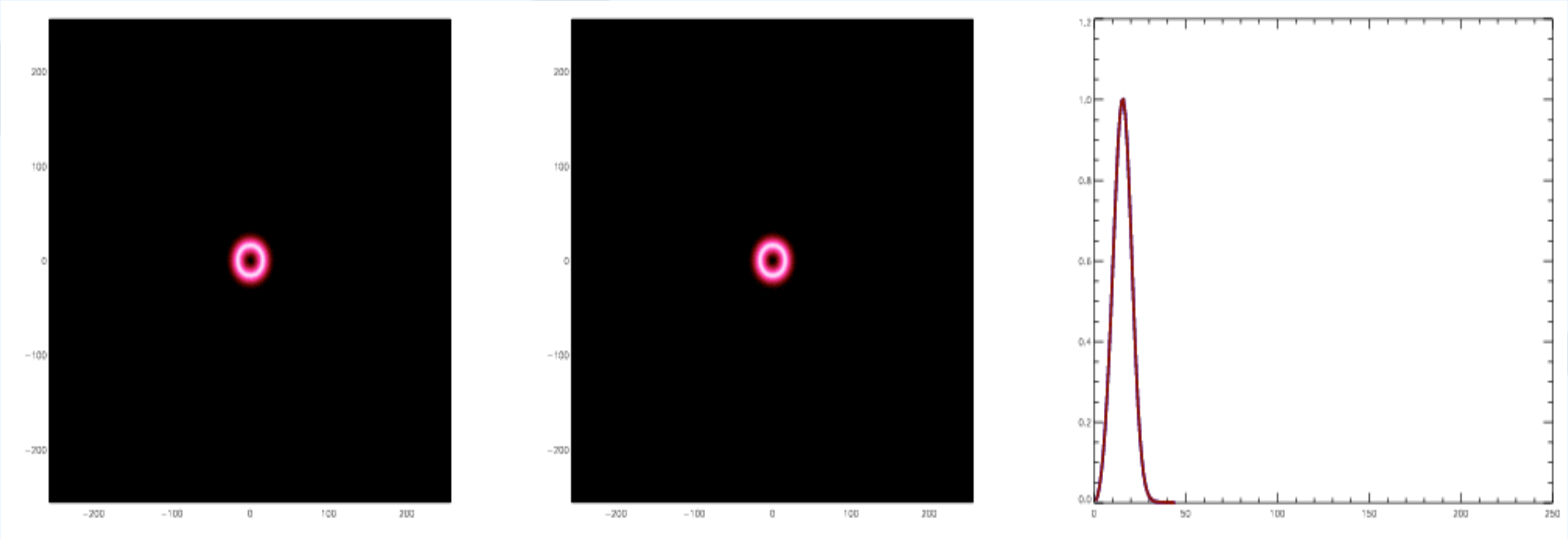


Baryons   Photons   Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.

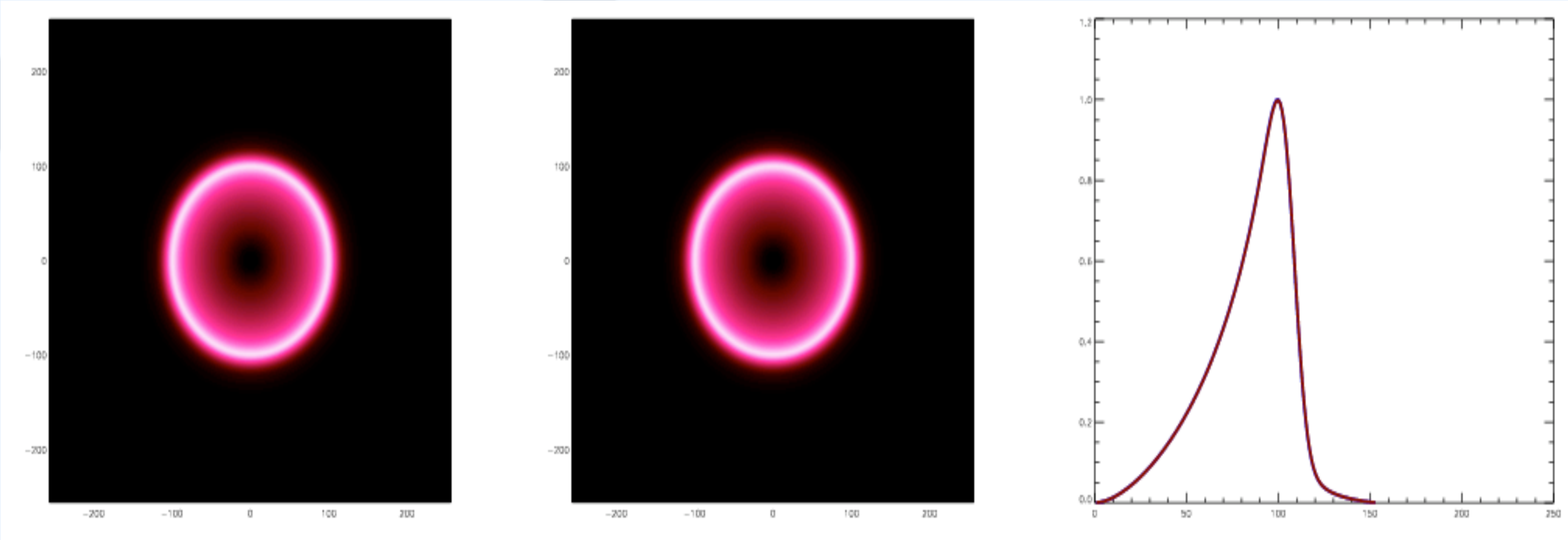


Baryons Photons Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

This expansion continues for 10^5 years



Baryons

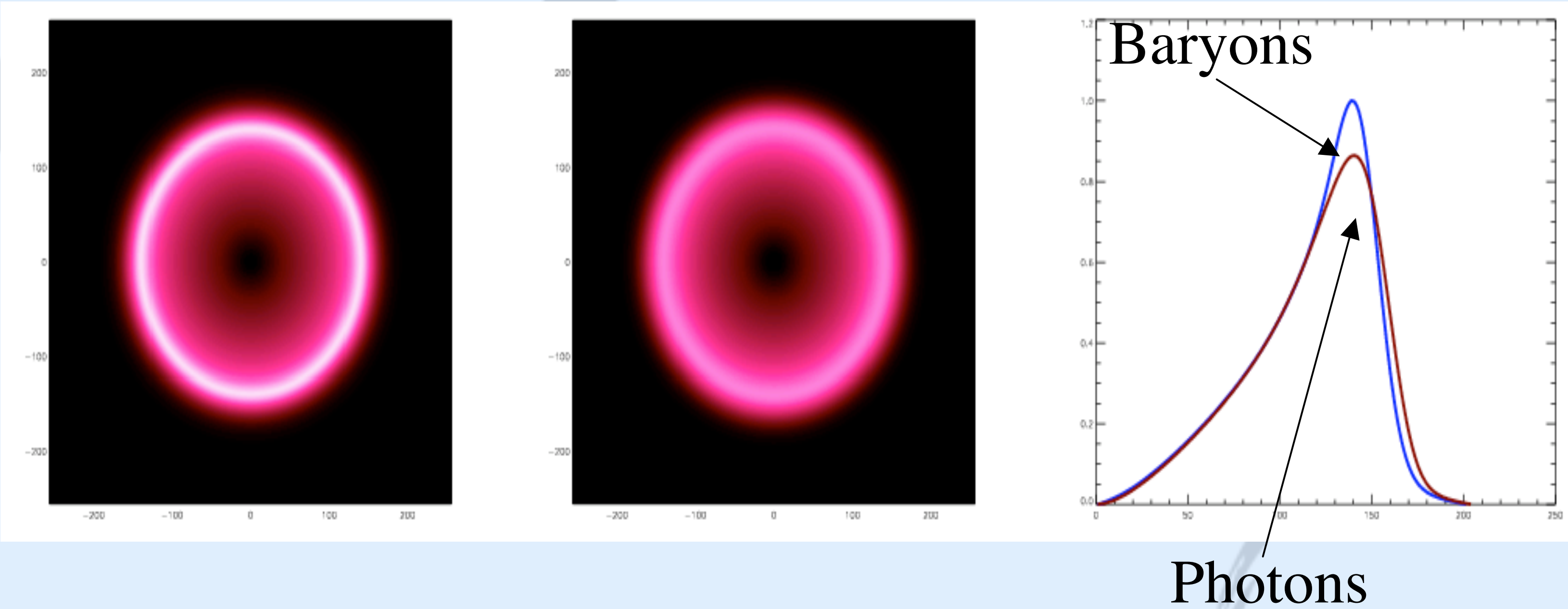
Photons

Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.

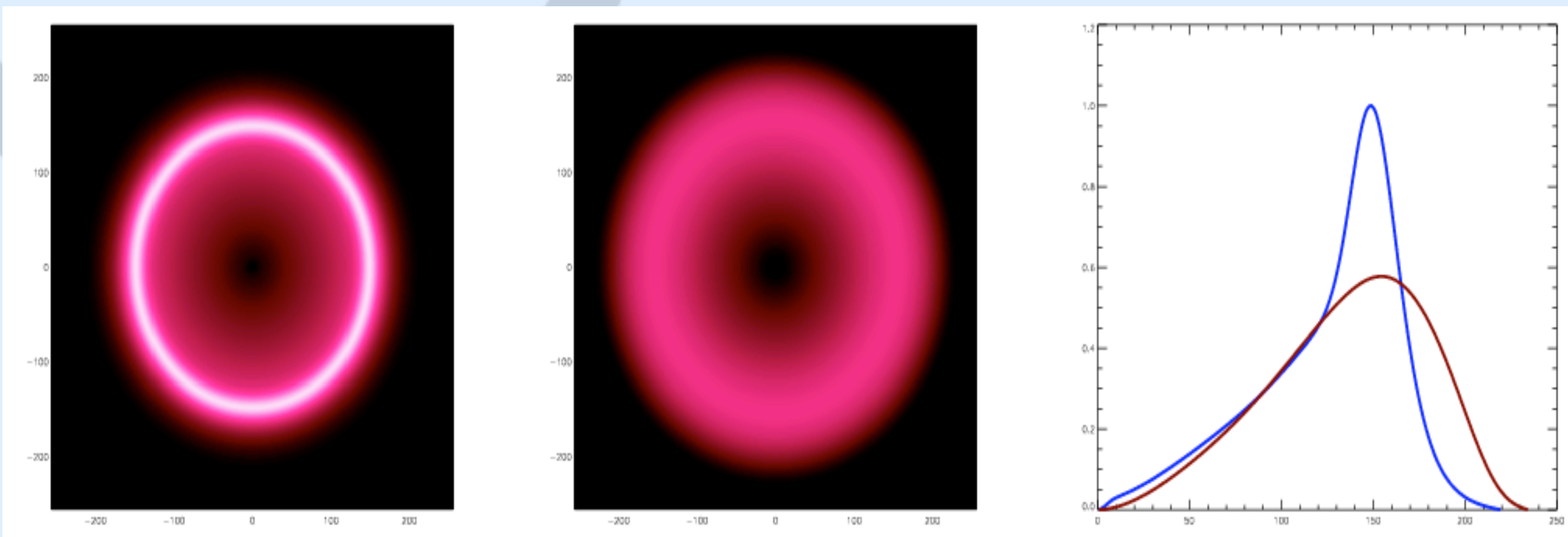


Baryons Photons Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

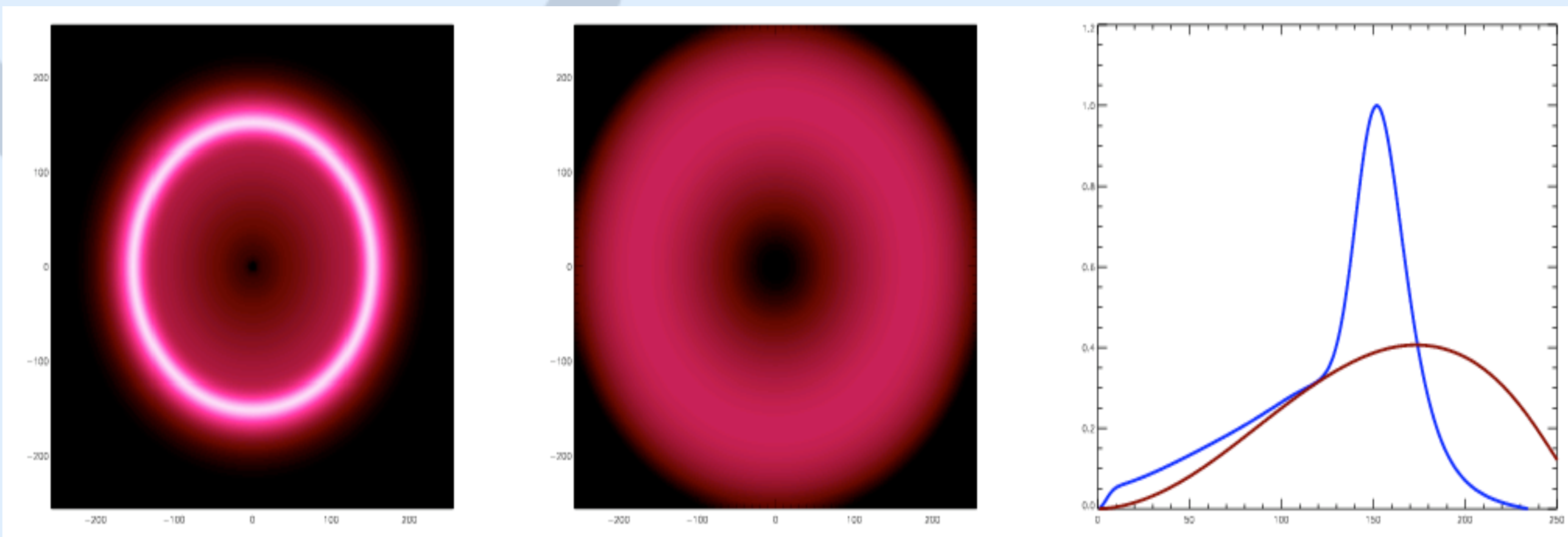
The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.



Baryons | Photons | Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave



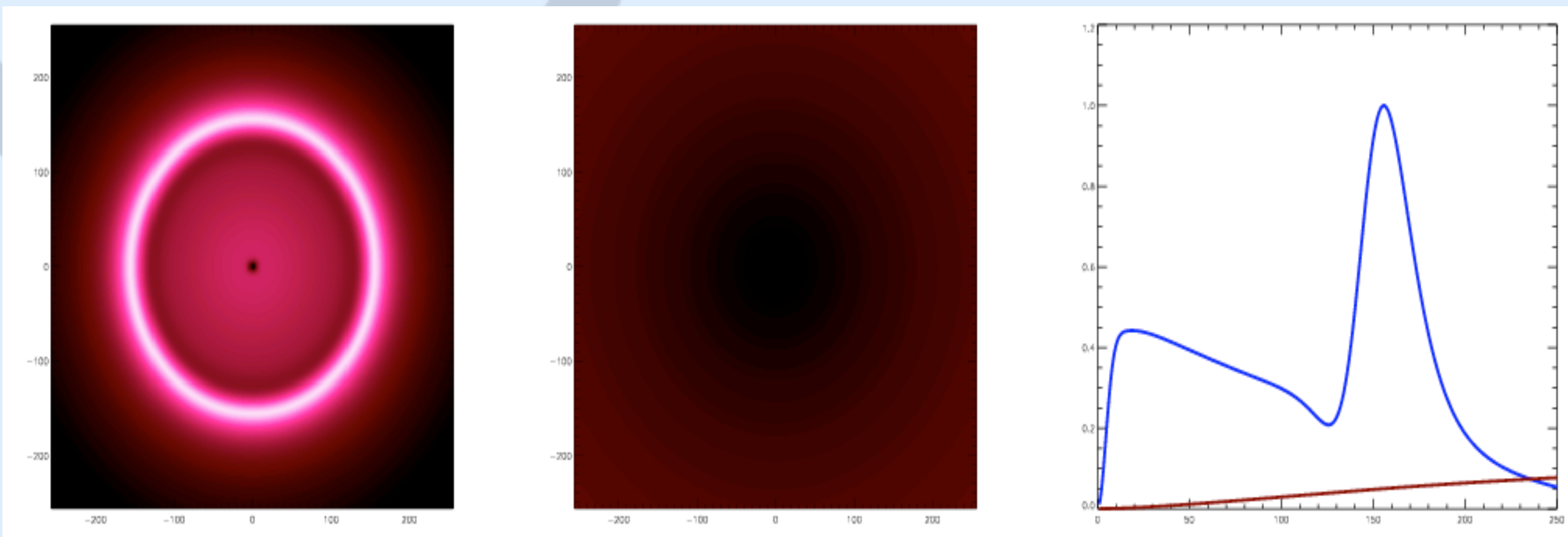
Baryons Photons Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius.

In addition, the large gravitational potential well which we started with starts to draw material back into it.



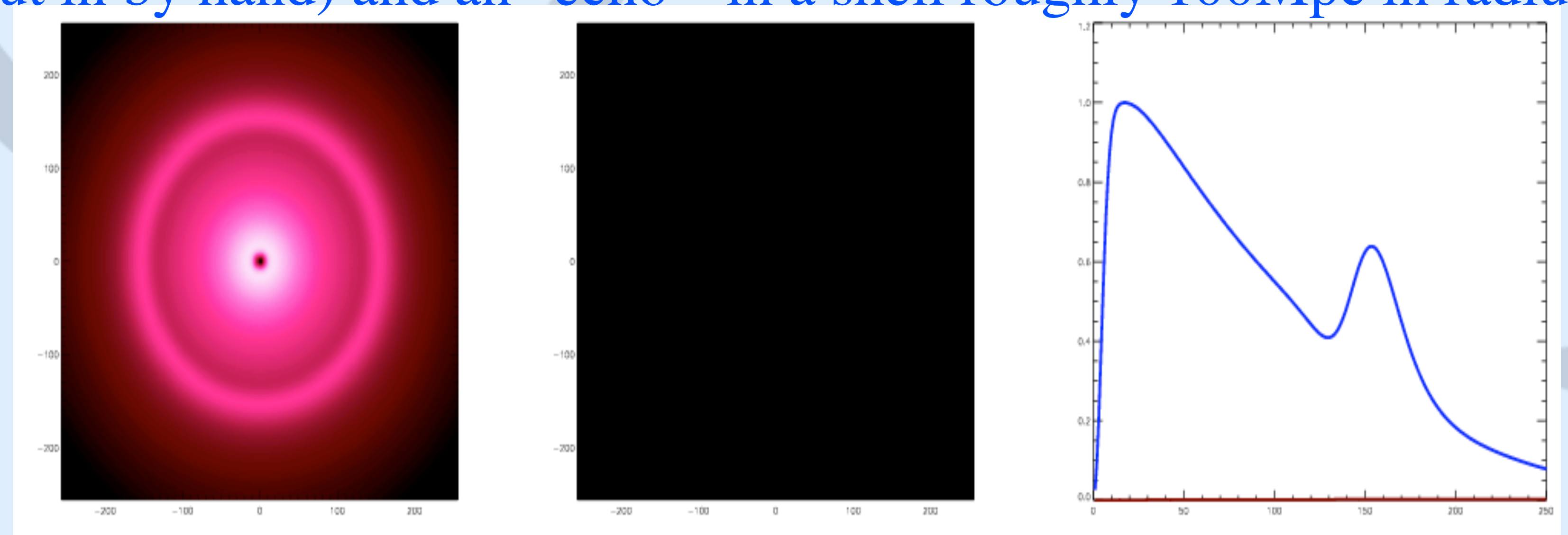
Baryons Photons Mass profile

Eisenstein, Seo & White (2006)

The acoustic wave

As the perturbation grows by ~10^3 the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m.

The final configuration is our original peak at the center (which we put in by hand) and an “echo” in a shell roughly 100Mpc in radius.



Further (non-linear) processing of the density field acts to broaden and very slightly shift the peak -- but galaxy formation is a local phenomenon with a length scale ~10Mpc, so the action at r=0 and r~100Mpc are essentially decoupled.