Title: Observational Probes of Early Universe Cosmology - Lecture 2

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Abstract:

An Introduction to Observational Cosmology

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Lect 1: Dynamics of the Universe as probed by distance measurements (SNe)
Lect 2: Baryonic Acoustic Oscillations
Lect 3: Dark matter clustering and galaxy surveys
Lect 4: Gravitational lensing
Lect 5: The cosmic microwave background radiation

With material from
Sarah Bridle and Martin White

This lecture:
Baryonic acoustic oscillation

- Dark energy and standard rulers
- Cosmic sound: baryon acoustic oscillations
- Current state-of-the-art
- Future experiments
- More on theoretical issues
- Prospects and conclusions.

Dark Energy

- Dominate the current energy budget of the Universe
- Causes accelerated expansion
- Modifies growth of structures
- Unknown origins
- Most prosaic "explanation" is a cosmological constant
- Well established originally (as e.g. with SNe)

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Equation of state

- What distinguishes different model is their equation of state, $w=p/\rho$ that fixes the time evolution of ρ_{DE}
- A cosmological constant has $w=-1$
- Most DE model have $w>-1$ and are time evolving
- The goal of DE observations is to demonstrate that $w\neq-1$ at some time

DE and Cosmology

- We probed DE via its evolution on the expansion rate of the Universe, e.g. the Friedman equation

$$\mathrm{H}^2(z) = \frac{8\pi G}{3}\sum_i \rho_i(z)$$

- 3 different approaches
  - –Luminosity distance measurements, D_L (e.g. with SNe Ia), an integral of H(z)
  - –Angular diameter distance measurements, D_A (e.g. with BAO and CMB), an integral of H(z)
  - –Growth of structures (clustering of dark matter, see next lectures)

Standard rulers

- Suppose we had an object whose length is known (in meters) and we knew it as a function of cosmic epoch

- By measuring the angle (θ) subtended by this ruler ($r=\Delta D$) as a function of redshift we map out the angular diameter distance D_A

$$\Theta = \frac{r}{D_A(z)} \qquad D_A(z) = \frac{D_L}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

- By measuring the redshift interval (Δz) associated with this distance, we map out the Hubble parameter $H(z)$

$$\mathrm{c}\Delta z = H(z)\Delta D$$

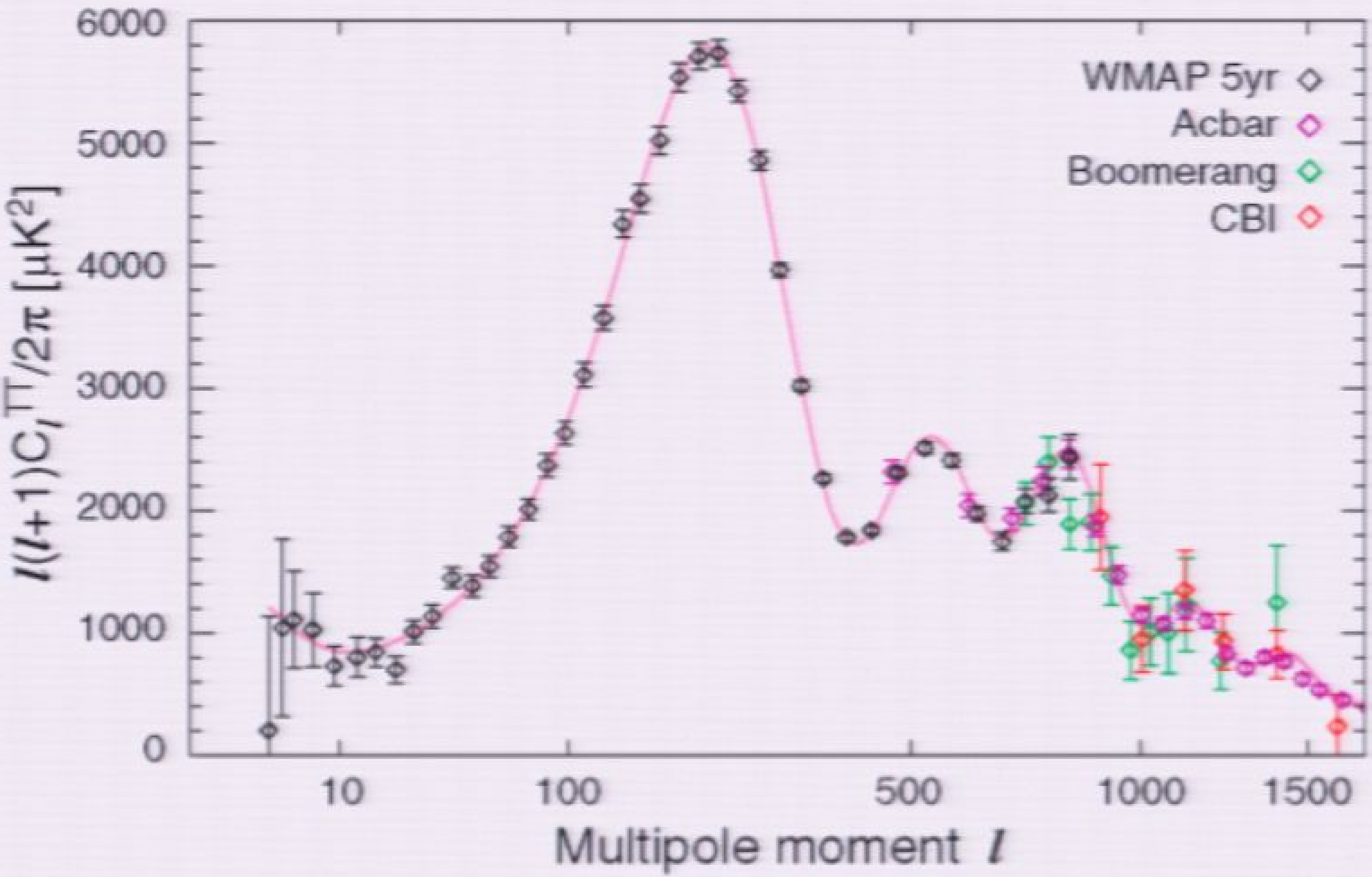
Ideal property of the rulers?

- We need to be able to calibrate the ruler accurately over most of the age of the Universe
- We need to be able to measure the ruler over much of the volume of the universe
- We need to be able to make ultra-precise measurements of the ruler
- To get competitive constraints on dark energy we need to be able to see changes in H(z) at the 1% level -- this would give us "statistical" errors in DE equation of state w ~10%.

Where do we find such a ruler?

- Cosmological objects (clusters, galaxies, ...) can probably never be uniform enough
- We believe that the laws of physics haven't changed over the relevant time scales
  - Use features arising from physical processes in the early Universe
- Use statistics of the large-scale distribution of matter and radiation
  - If we work on large scales or early times perturbative treatment is valid and calculations under control.

CMB Power spectrum



Nolta et al. 08

- The current CMB data are in excellent agreement with the LCDM model

Simple picture

- At early times, the Universe was hot, dense and ionized. Photons and baryons were tightly coupled by Thomson scattering.
- The mean free path of photons is much smaller than the horizon and allows fluid approximation
- Initial fluctuations in density and gravitational potential drive acoustic waves in the fluid: compressions and rarefactions with $\delta_{photons} \propto \delta_b$
- These perturbations show up at temperature fluctuations in the CMB
- Since $\rho \propto T^4$ a harmonic wave will be for one comoving mode k

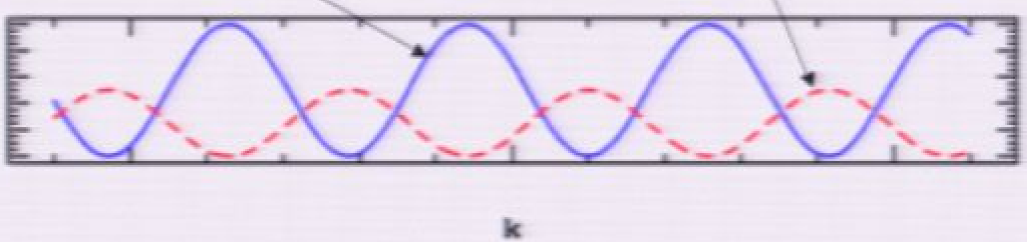
$$\Delta T \simeq \delta\rho_\gamma^{1/4} \simeq A(k)cos(kc_st)$$

- Plus a component due to the velocity of the fluid (Doppler effect)

A simple picture

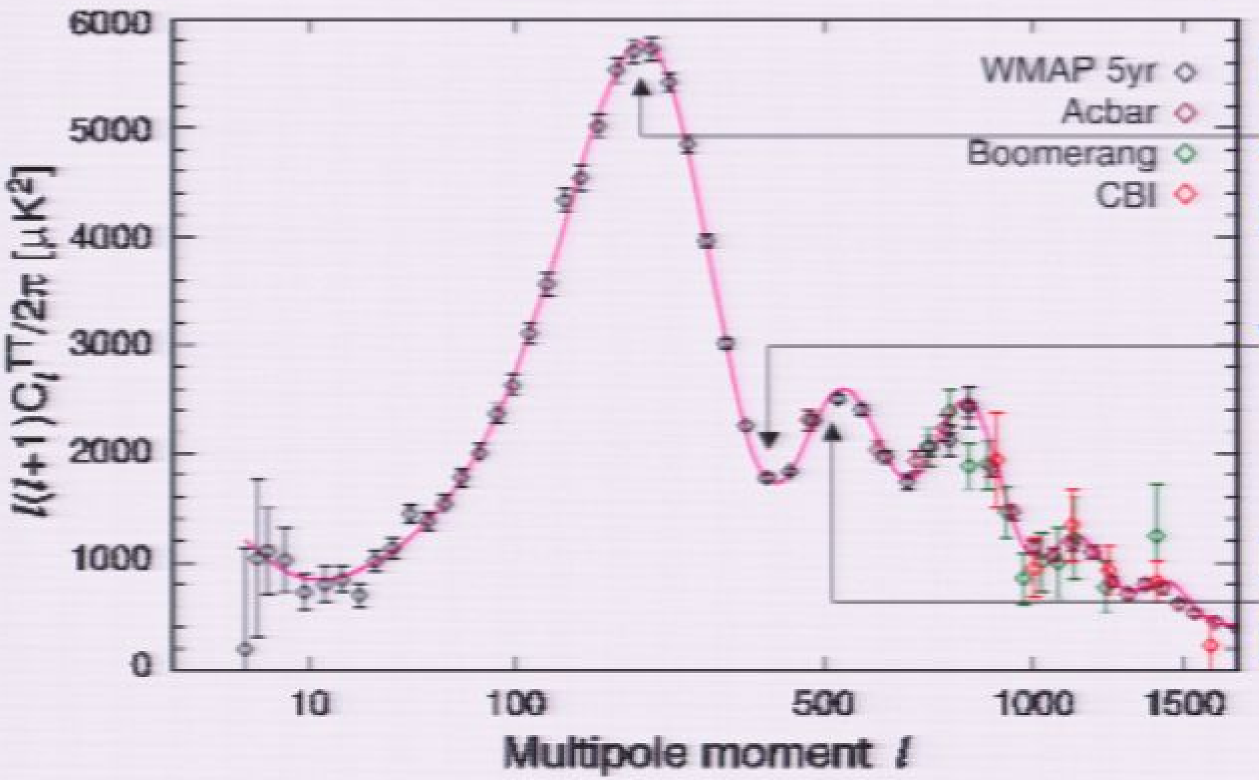
- A sudden recombination decouples the radiation and matter giving us a snapshot of the fluid at last scattering

$$(\Delta T)^2_{\rm ls} \sim \cos^2(kc_s t_{\rm ls}) + \text{velocity terms}$$



- The fluctuations are projected on the sky as $\lambda \sim D_A(ls)\theta$ or $l \sim kr_{ls}$

Acoustic oscillations in the CMB



First "compression", at $kc_st_{ls}=\pi$. Density maxm, velocity null.

Velocity maximum

First "rarefaction" peak at $kc_st_{ls}=2\pi$

Acoustic scale is set by the *sound horizon* at last scattering: $s = c_s t_{ls}$

CMB calibration

- Not coincidentally the sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB.

$$
\begin{aligned}
s &= 146.8 \pm 1.8 \text{ Mpc} \\
&= (4.53 \pm 0.06) \times 10^{24} \text{m}
\end{aligned}
$$

WMAP 5th yr data

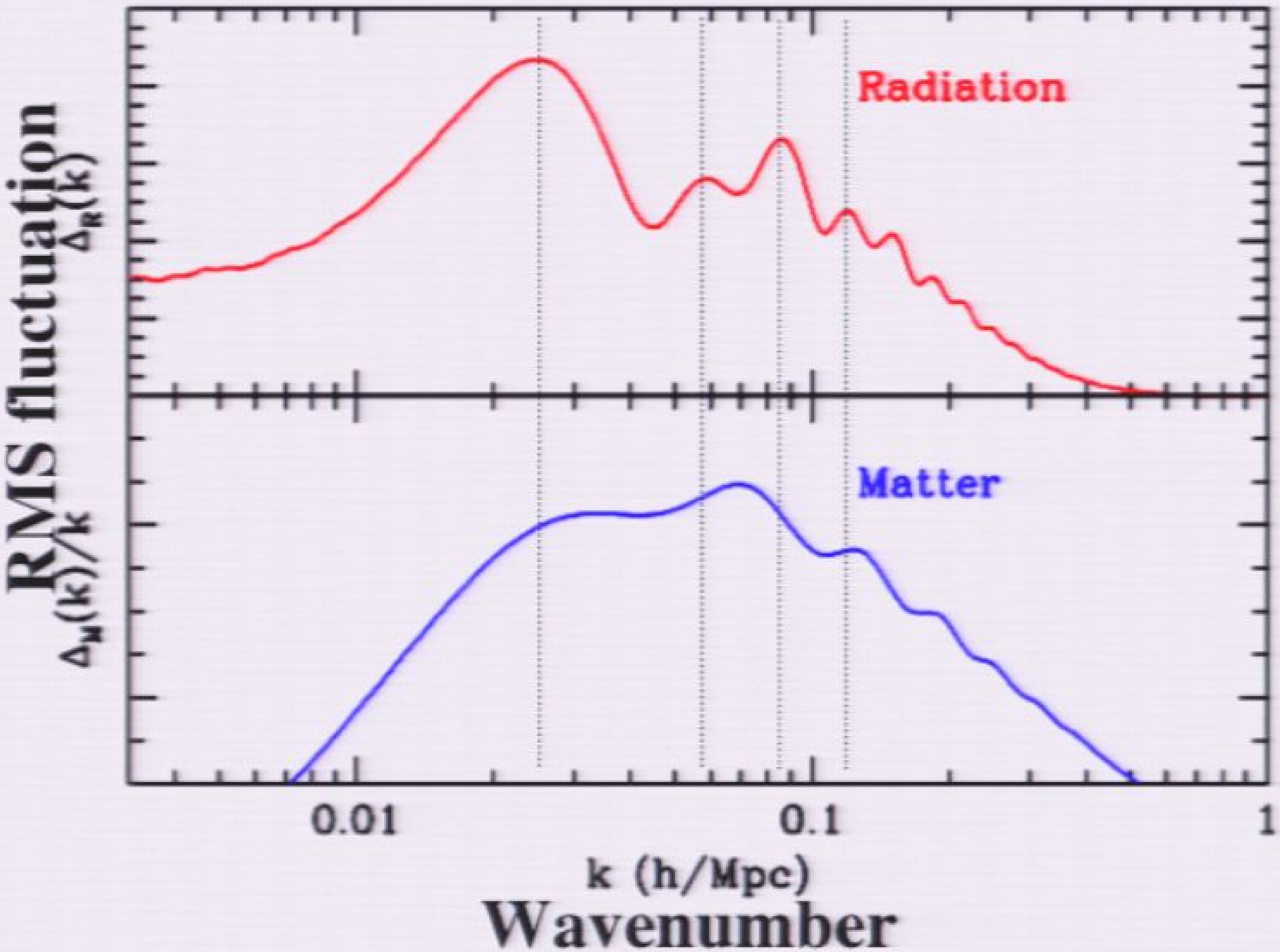
↑

Dominated by uncertainty in ρ_m from poor constraints near 3rd peak in CMB spectrum. (Planck will nail this!)

Baryon oscillations in $P(k)$

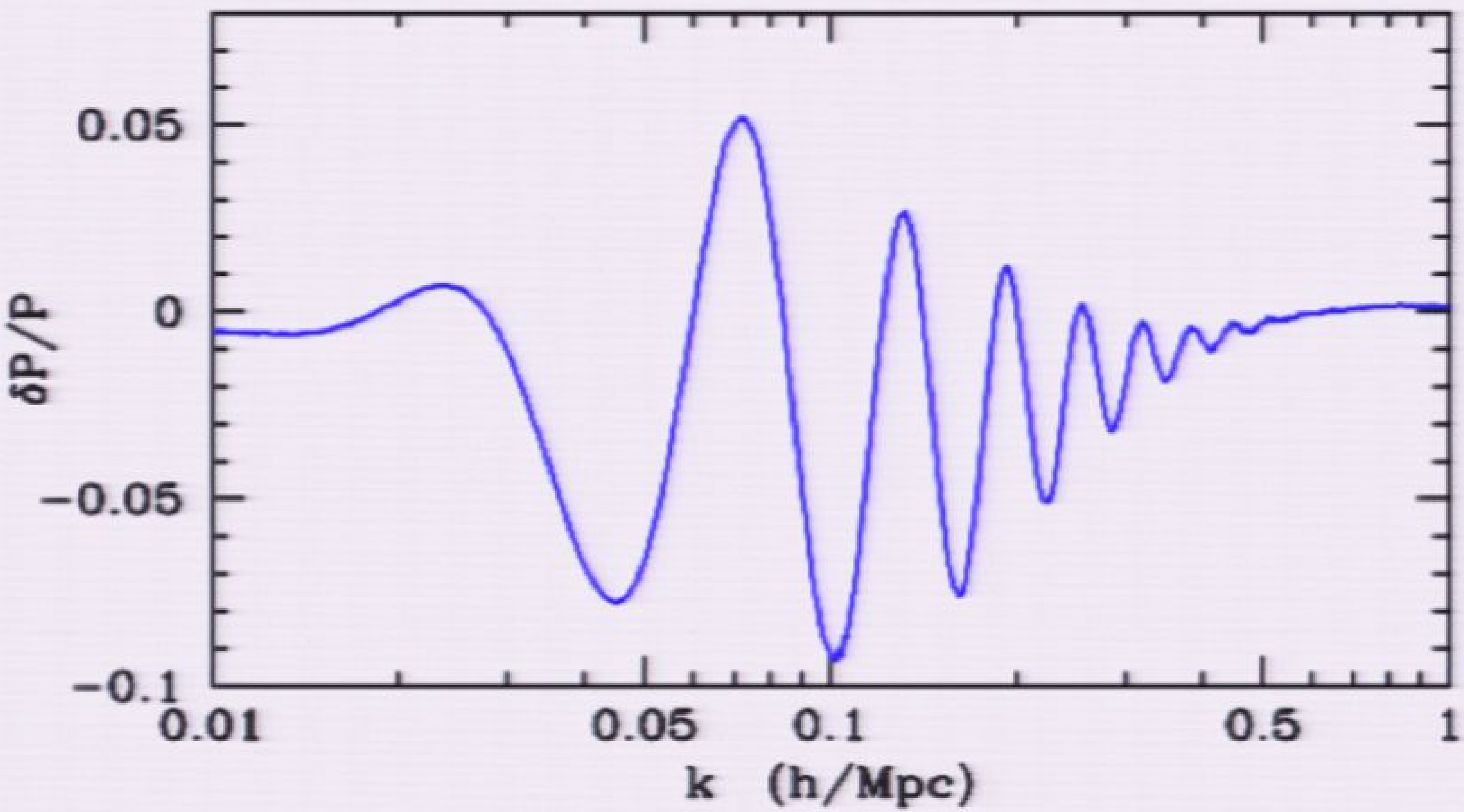
- Since the baryons contribute ~15% of the total matter density, the total gravitational potential is affected by the acoustic oscillations with scale set by *s*.
- This leads to small oscillations in the matter power spectrum *P*(*k*).
  - No longer order unity, like in the CMB, now suppressed by $\Omega_b/\Omega_m \sim 0.1$
- **Note:** all of the matter sees the acoustic oscillations, not just the baryons.

Baryon (acoustic) oscillations



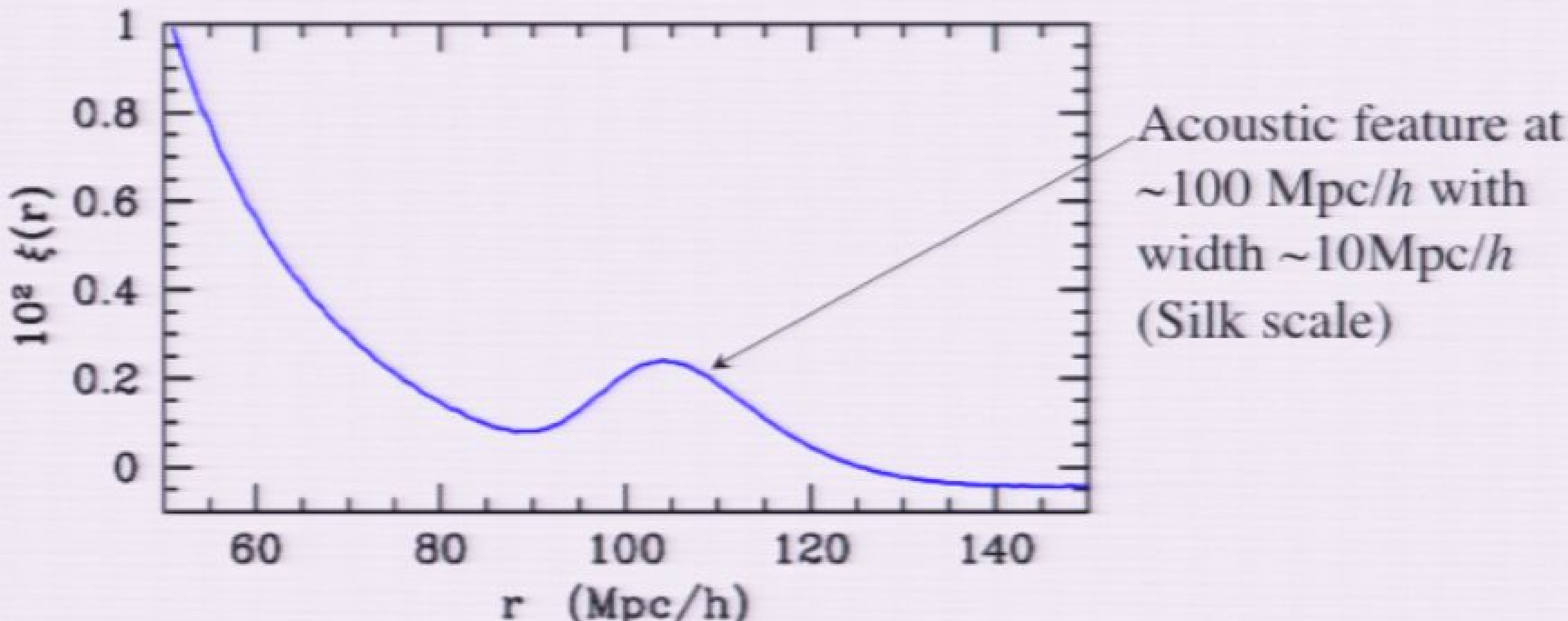
Divide out the gross trend …

A damped, almost harmonic sequence of "wiggles" in the power spectrum of the mass perturbations of amplitude $O(10\%)$.



In configuration space

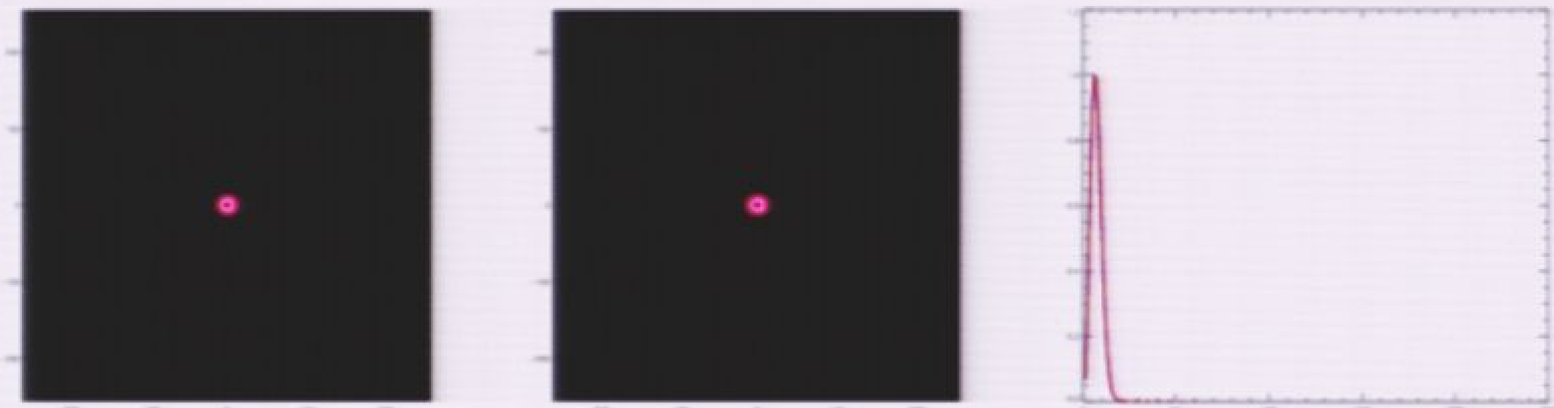
- The configuration space picture offers some important insights,and will be useful when we consider non-linearities and bias.
- In configuration space we measure not power spectra but correlation functions: $\xi(r)=\int\Delta^2(k)j_0(kr)\,d\ln k$.
- A harmonic sequence would be a δ-function in r, the shift in frequency and diffusion damping broaden the feature.



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.

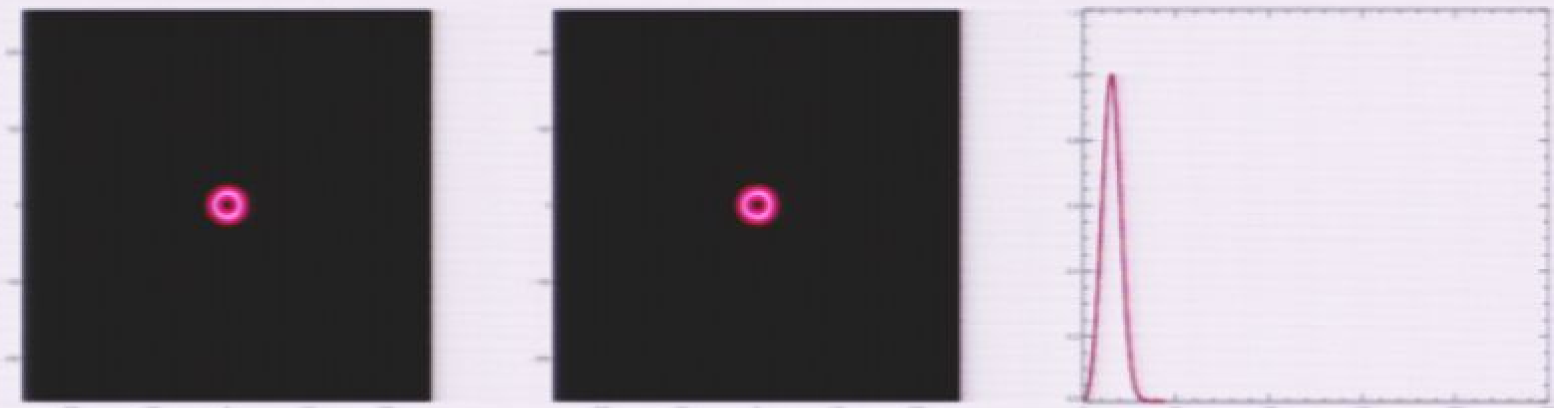


Baryons Photons Mass profile

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.



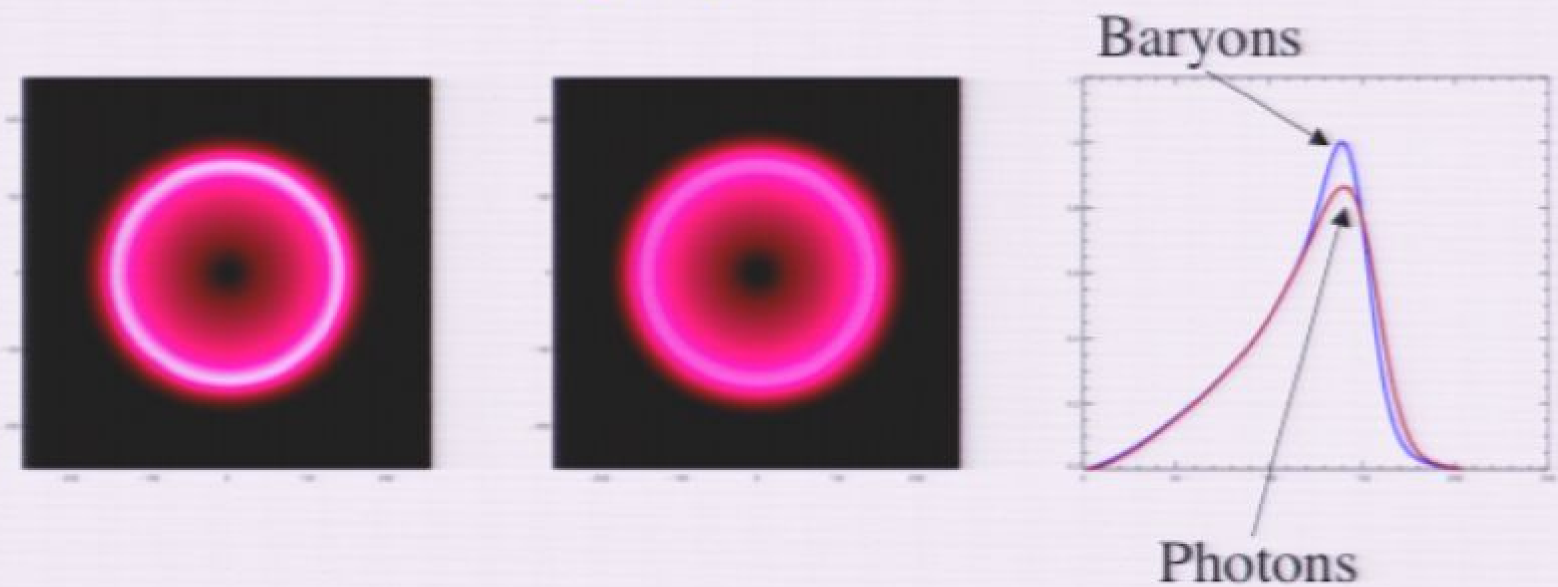
Baryons Photons

The acoustic wave

This expansion continues for 10^5 years

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.



The acoustic wave

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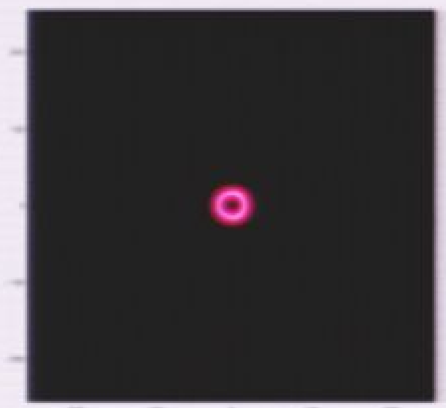
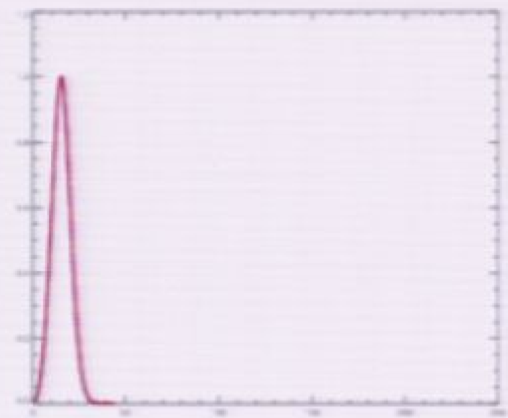
Baryons



Photons



The acoustic wave

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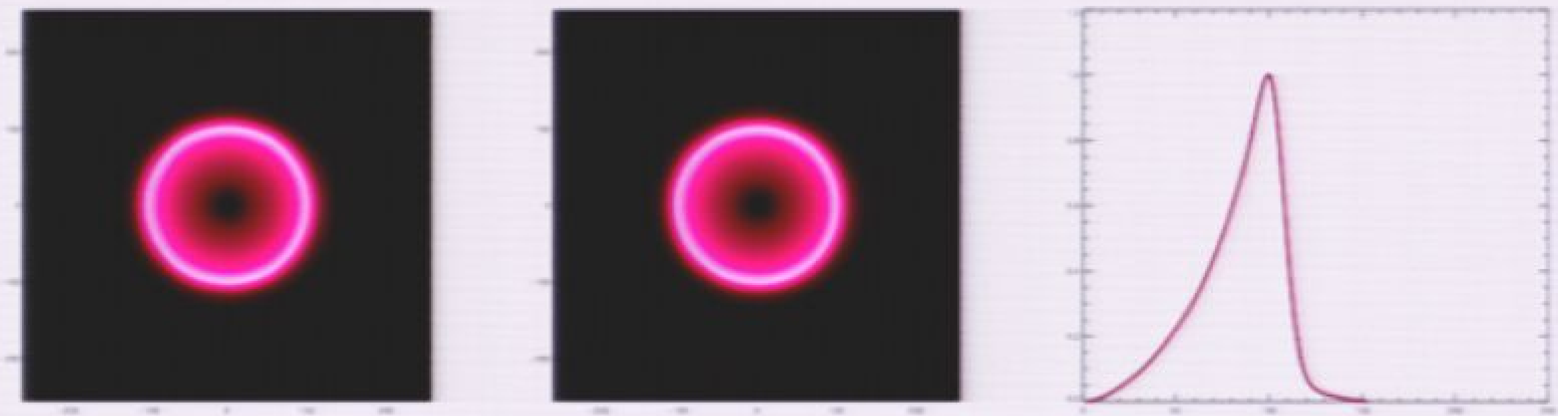

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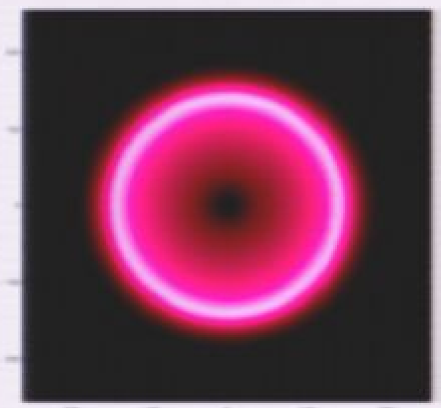
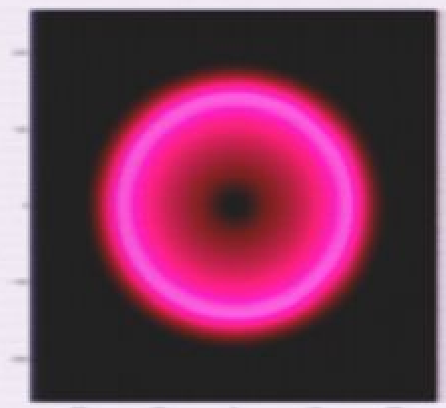
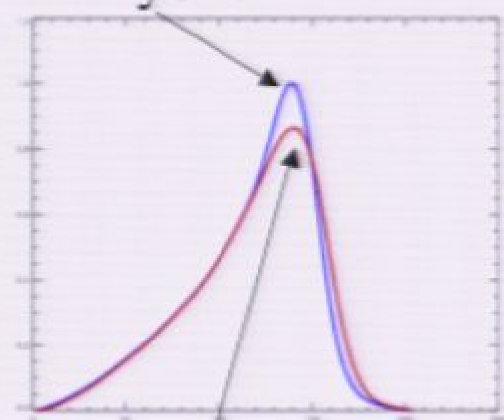
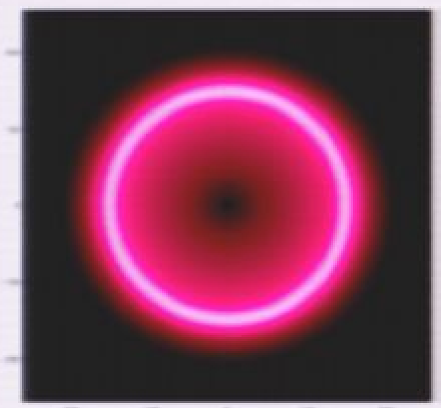


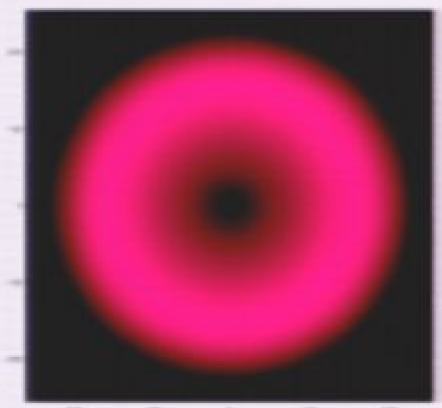


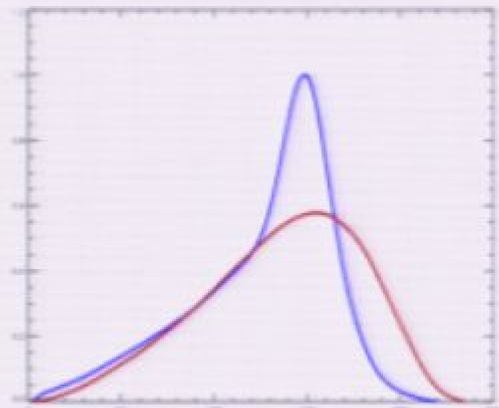


The acoustic wave

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



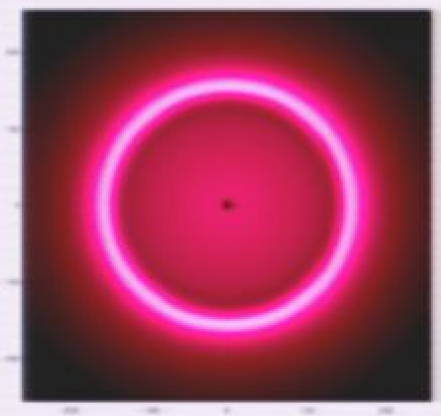


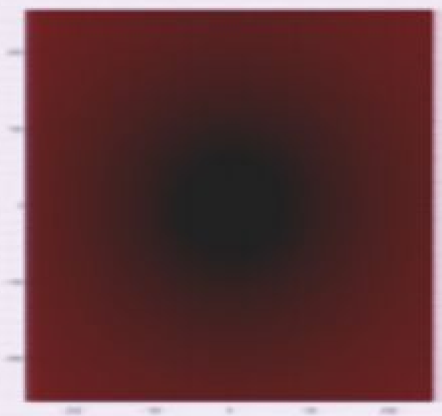


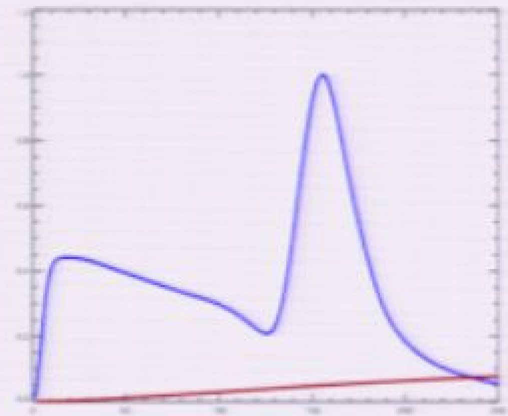
The acoustic wave

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.



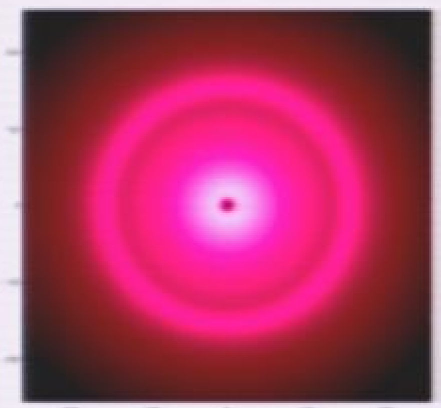


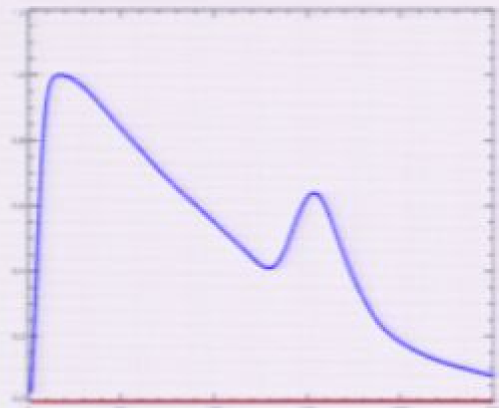


The acoustic wave

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.



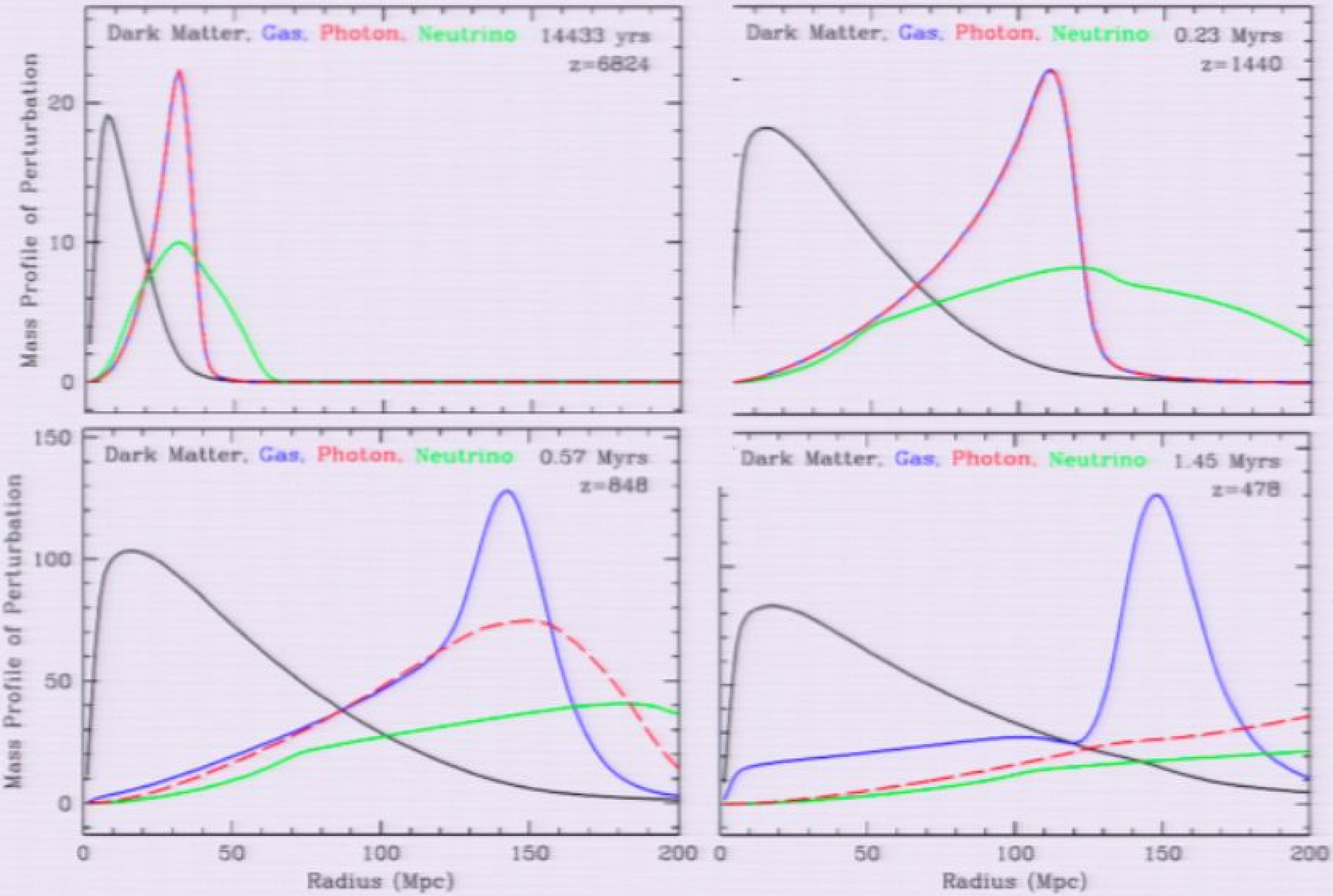


Further (non-linear) processing of the density field acts to broaden and very slightly shift the peak -- but galaxy formation is a local phenomenon with a length scale ~10Mpc, so the action at r=0 and r~100Mpc are essentially decoupled. We will return to this …

Features of baryon oscillations

- Firm prediction of models with $\Omega_b>0$
- Positions well predicted once (physical) matter and baryon density known - calibrated by the CMB.
- Oscillations are "sharp", unlike other features of the power spectrum.
- Internal cross-check:
  - d_A should be the integral of $H^{-1}(z)$.
- Since have $d(z)$ for several z's can check spatial flatness: "$d(z_1+z_2) = d(z_1)+d(z_2)+O(\Omega_K)$"
- Ties low-z distance measures (e.g. SNe) to absolute scale defined by the CMB (in Mpc, not h^{-1}Mpc).
  - Allows ~1% measurement of h using trigonometry!

Shape of $P(k)$ in pictures



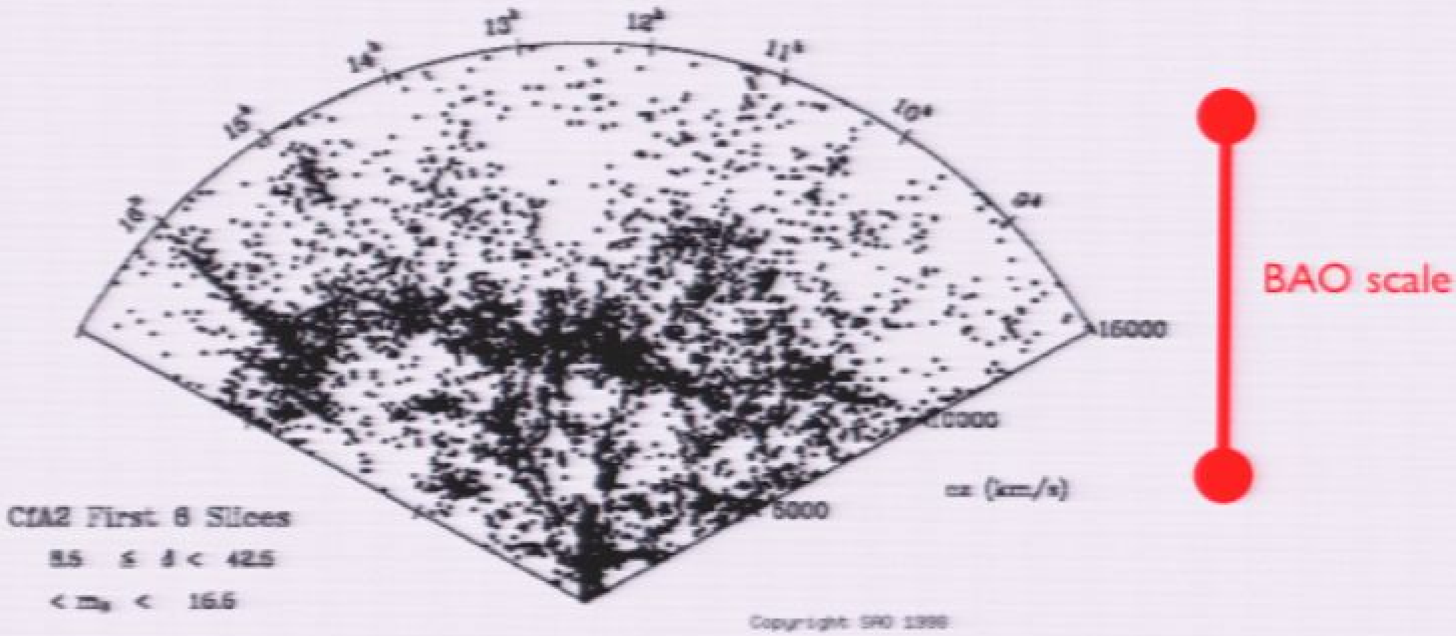
Eisenstein, Seo & White (2007)

The program

- Find a tracer of the mass density field and compute its 2-point function.
- Locate the features in the above corresponding to the sound horizon, *s*.
- Measure the $\Delta\theta$ and Δz subtended by the sound horizon, *s*, at a variety of redshifts, *z*.
- Compare to the value at $z \sim 10^3$ to get d_A and $H(z)$
- Infer expansion history, DE properties, modified gravity.

But ruler inconveniently large …

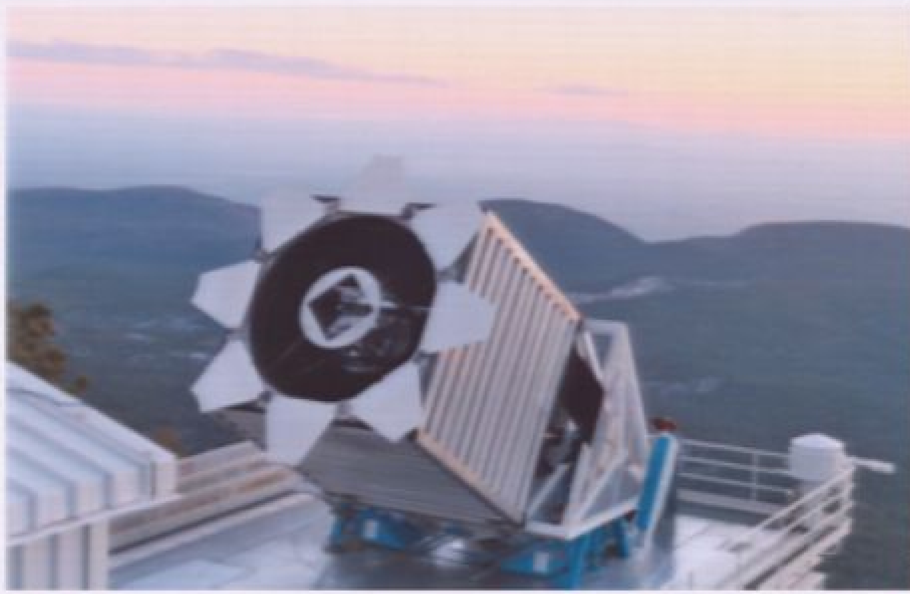
Early surveys too small

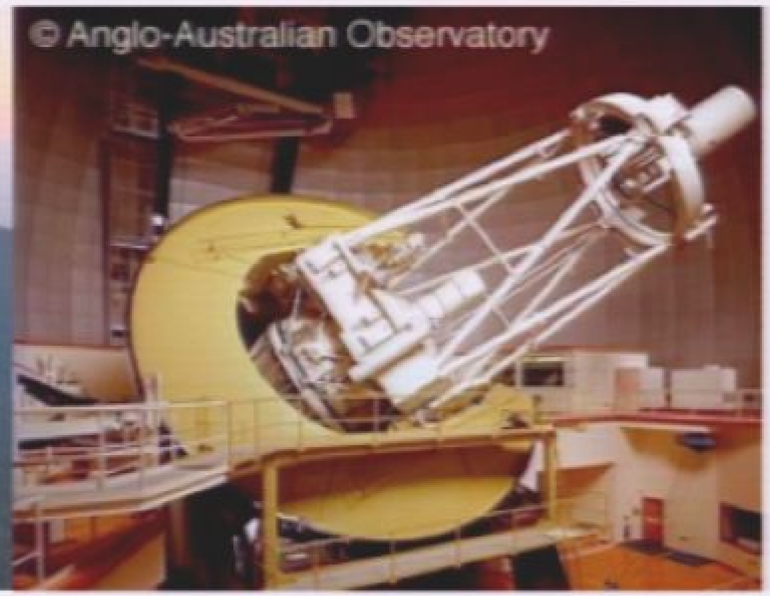


CfA2 redshift survey (Geller & Huchra 1989)
Formally, this could "measure" BAO with a ~0.05σ detection

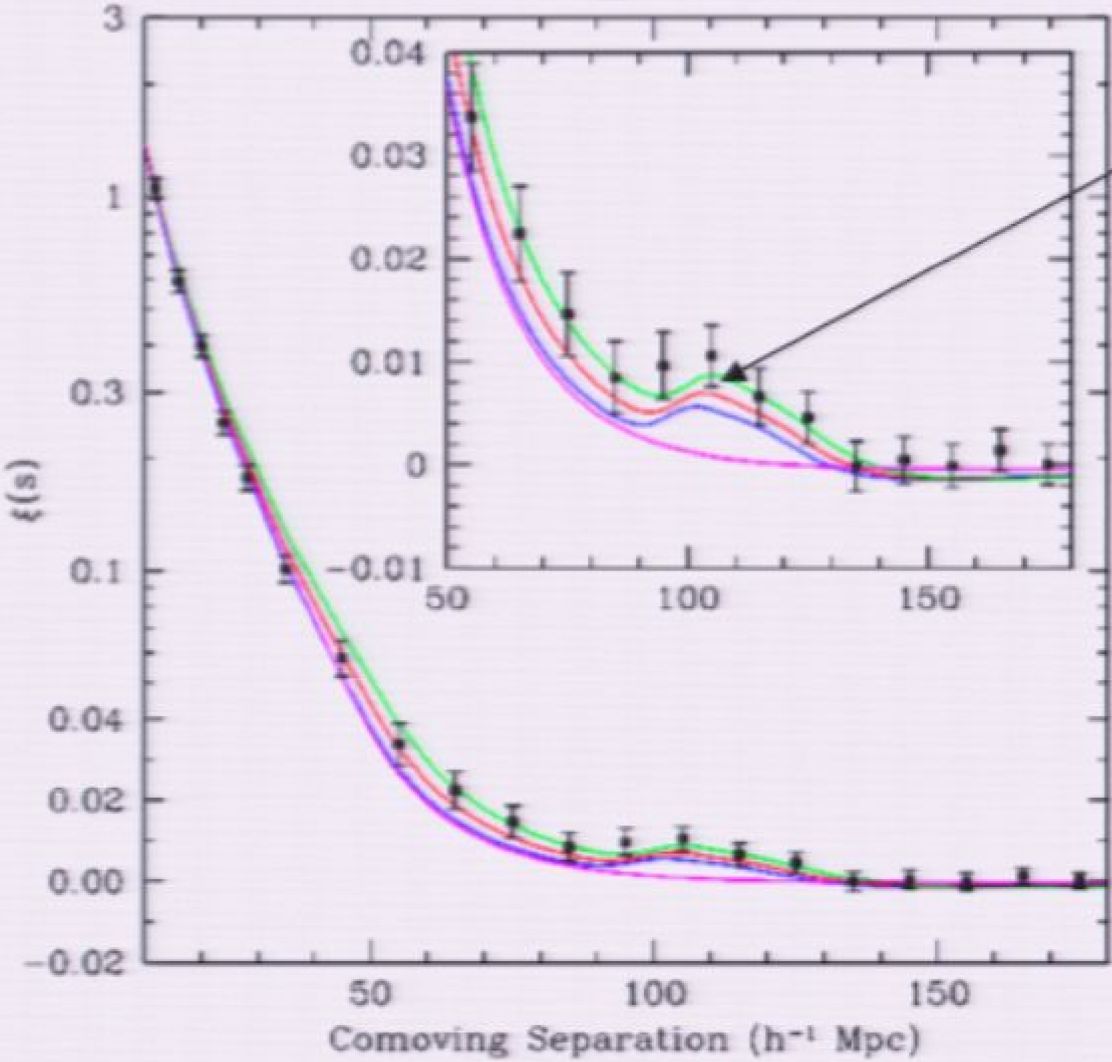
Finally technically possible

SDSS and 2dF surveys allow detection of BAO signal …





Another prediction verified!!



Eisenstein et al. (2005) detect oscillations in the SDSS LRG ξ(r) at z~0.35! Knowing ***s*** determines D(z=0.35).

About 10% of the way to the surface of last scattering!

Constraints argue for the existence of DE, but do not strongly constrain its properties.

Current state of the art

1. Eisenstein et al 2005
   - 3D map from SDSS
   - 46,000 galaxies, 0.72 $(h^{-1}\ Gpc)^3$

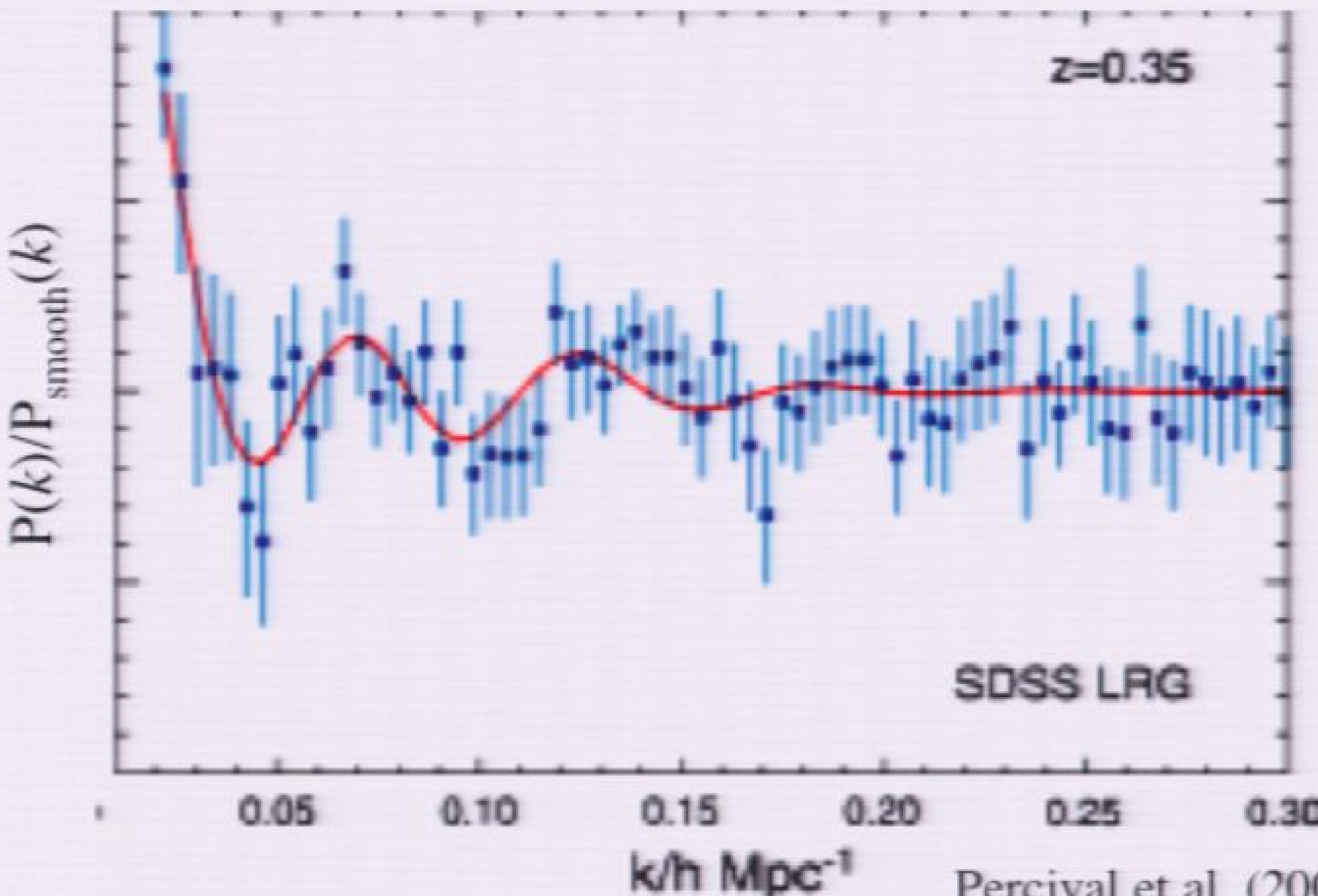
   (spectro-z)
   4% distance measure
2. Cole et al 2005
   - 3D map from 2dFGRS at AAO
   - 221,000 galaxies in 0.2 $(h^{-1}Gpc)^3$

   (spectro-z)
   5% distance measure
3. Hutsi (2005ab)
   - Same data as (1).
4. Padmanabhan et al 2007
   - Set of 2D maps from SDSS
   - 600,000 galaxies in 1.5 $(h^{-1}Gpc)^3$

   (photo-z)
   6% distance measure
5. Blake et al 2007
   - (Same data as above)
6. Percival et al 2007
   - (Combination of SDSS+2dF)
7. Okumura et al 2007
   - (Anisotropic fits)
8. Gaztanaga et al. 2008a
   - (3pt function)

   (spectro-z)
   Detection
9. Gaztanaga et al. 2008b
   - (measure of H)

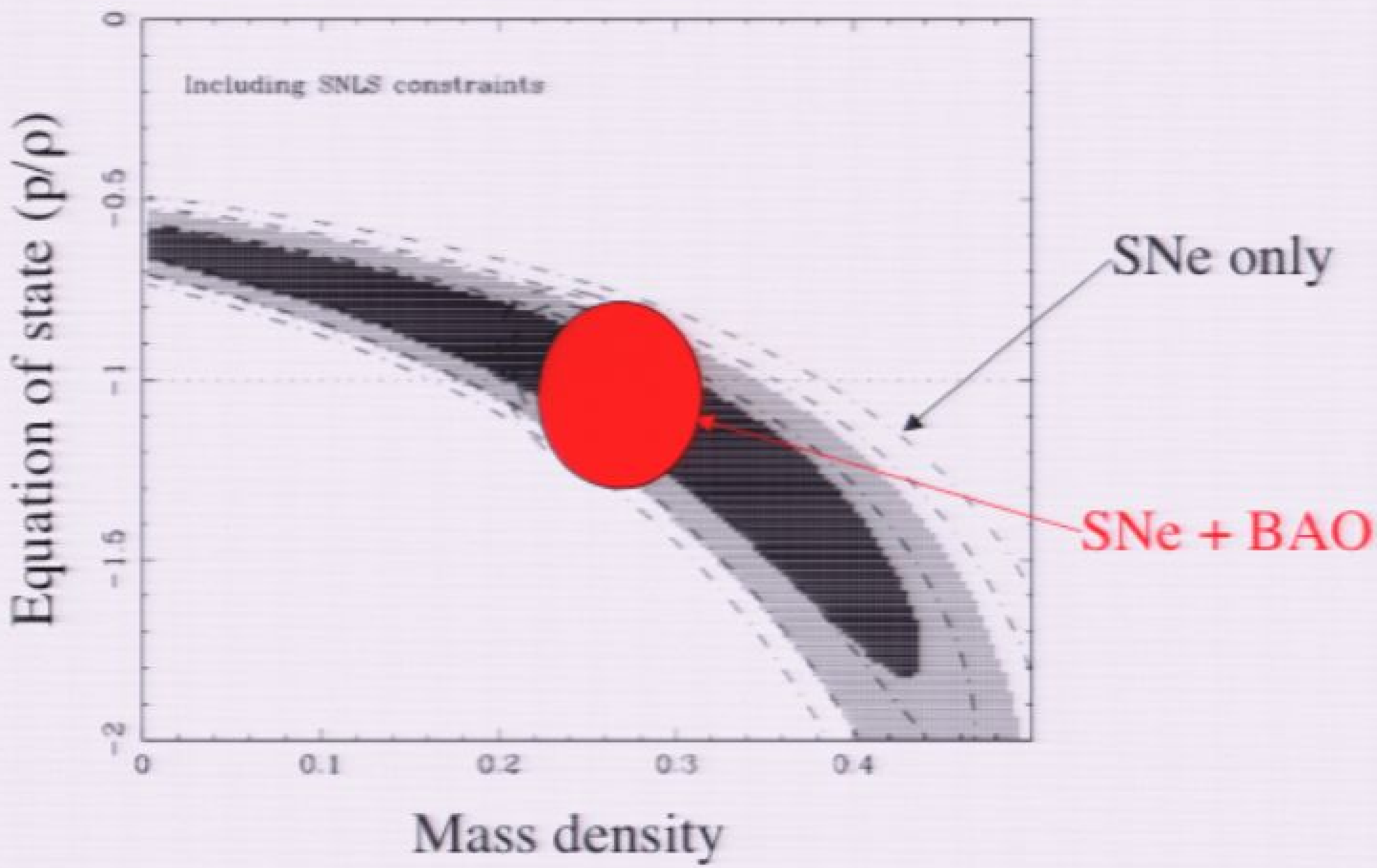
Current combined constraints



Percival et al. (2007);

Dunkley et al. (2008)

… on cosmological parameters



From Percival et al. (2007)

The next step?

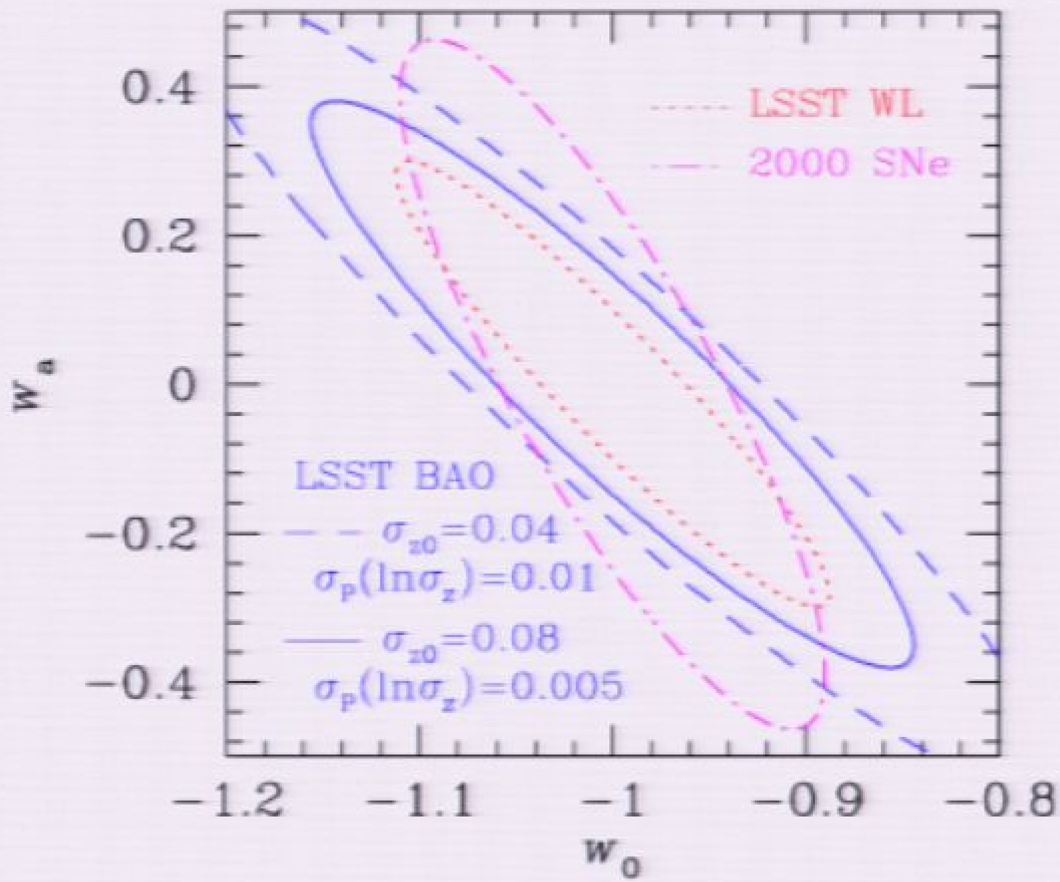
- We need a much more precise measurement of *s* at more redshifts to constrain DE.
- To measure *P(k)* or $\xi(r)$ well enough to see such subtle features requires many well defined modes
  - More than a Gpc^3 volume.
  - Million(s) of galaxies.
  - Systematic errors need to be controlled to high precision.

The next generation

- There are now proposals for several next-generation BAO surveys, both spectroscopic and photometric.
  - Photometric surveys generally deeper and wider.
  - Not a requirements driver if already doing weak lensing.
  - More susceptible to systematic errors in *z* determination.
  - Generally takes 3-10x as much sky for same constraints as a spectro survey (# modes in 2D vs 3D).
  - Cannot make use of “reconstruction”.
- Future surveys should be able to measure d_A and H to ~1%, giving competitive constraints on DE
- Eventually a space-based, all-sky BAO survey could measure distances to ~0.1% over most of the redshift range of interest for DE.

Parameter constraints, forecasts

$$w(z) = w_0 + (1-a)w_a$$



Zhan & Knox 05

$$\omega = \omega_0 + (1-a)\,\omega_a$$

$\sim 10^{2c}$

5

$$\omega = \omega_0 + (1-a)\omega_a$$

$$\sim 10^{20}_{5}$$

Parameter constraints, forecasts

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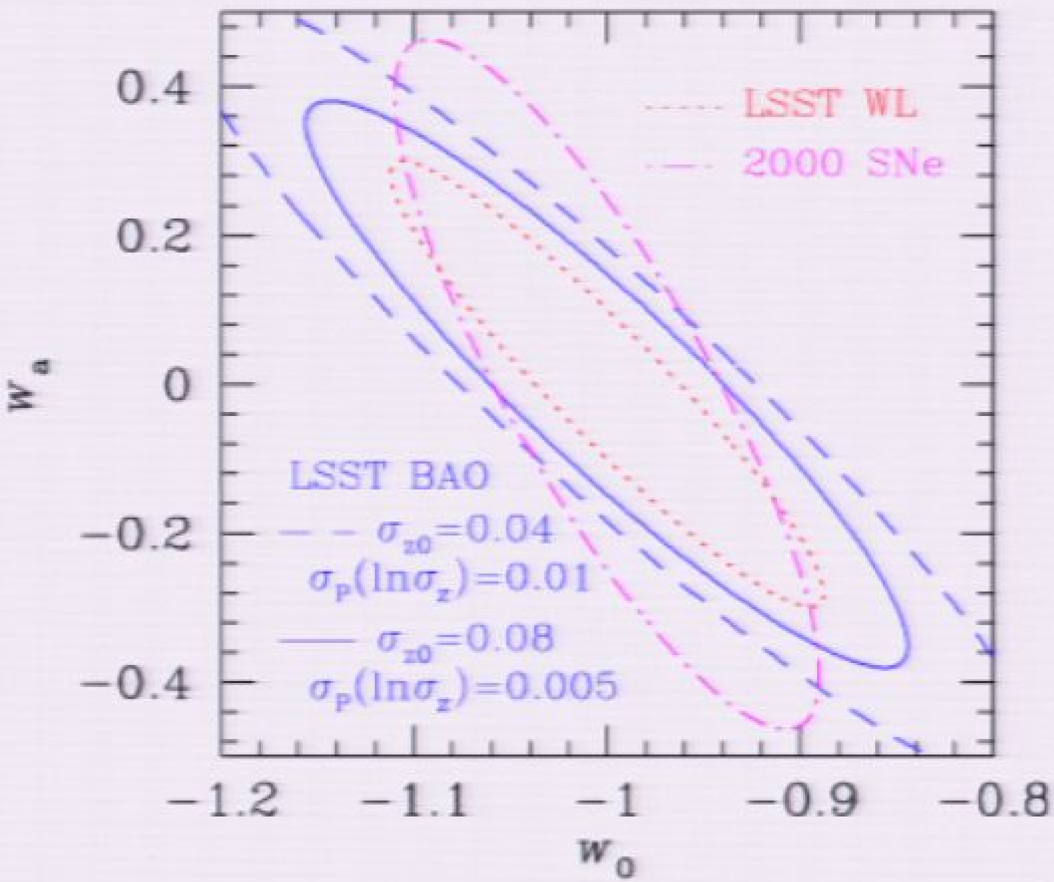
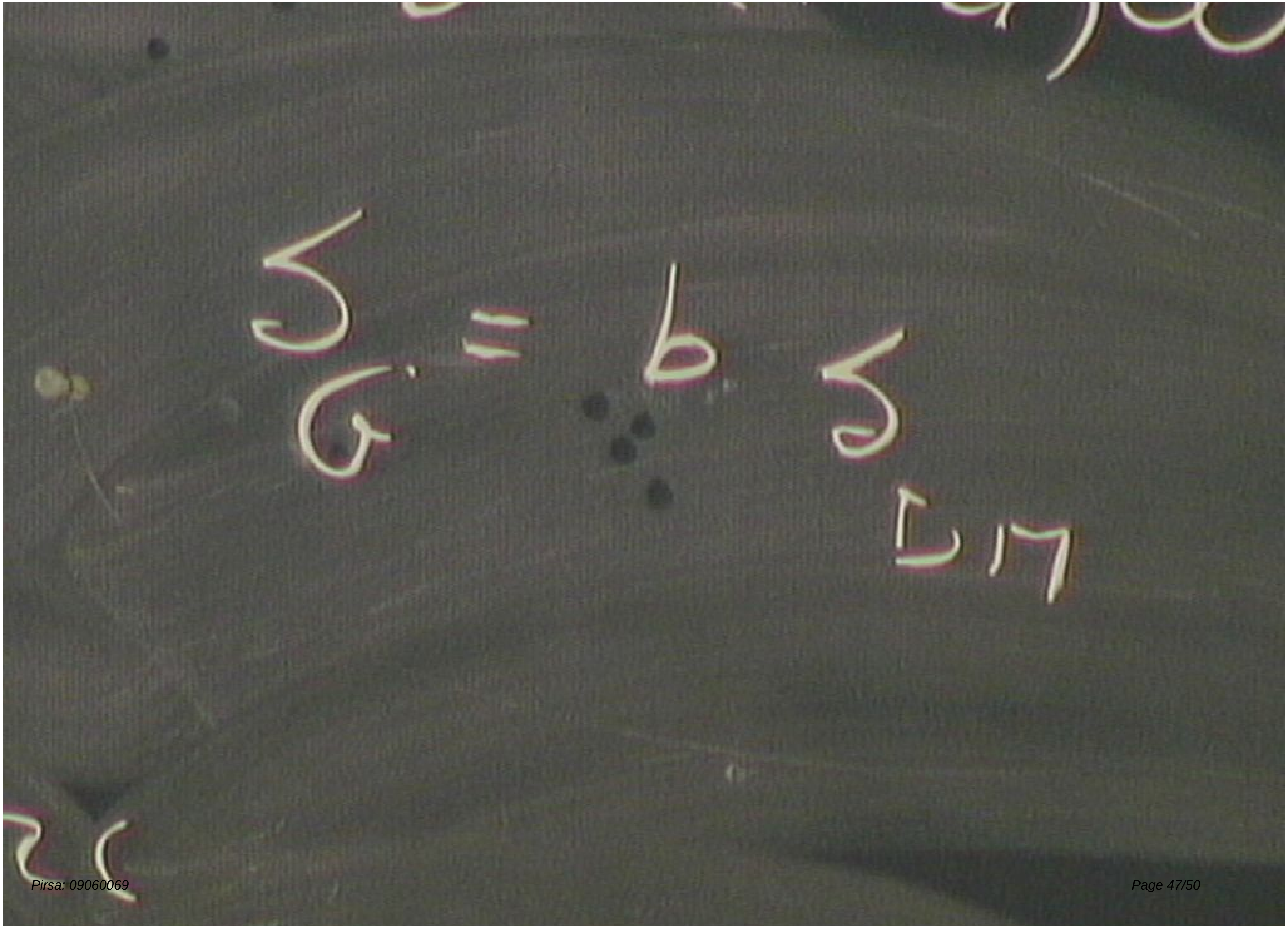


Zhan & Knox 05

Those pesky details …

- Unfortunately we don't measure the linear theory matter power spectrum in real space.
- We measure:
  - the non-linear
  - galaxy power spectrum
  - in redshift space
- How do we handle this?



Those pesky details …

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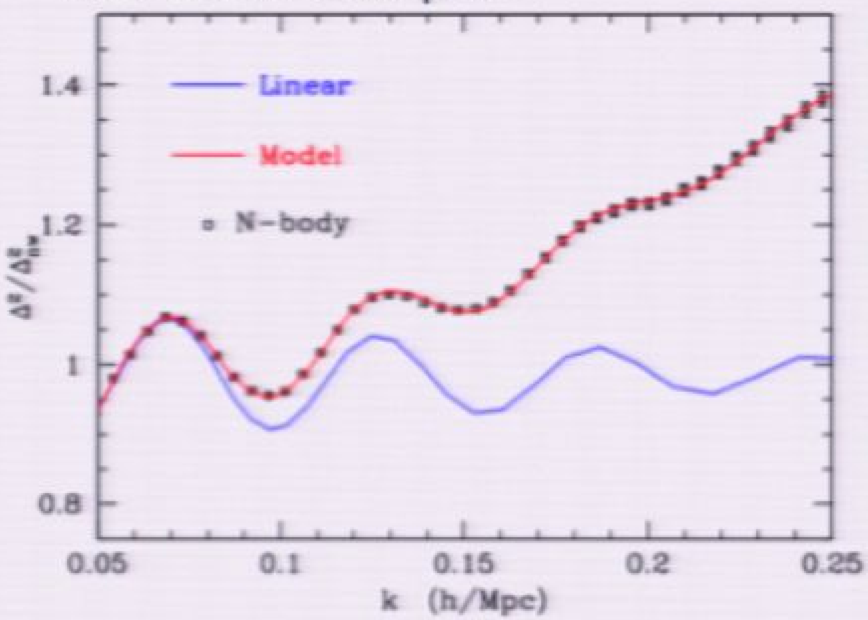
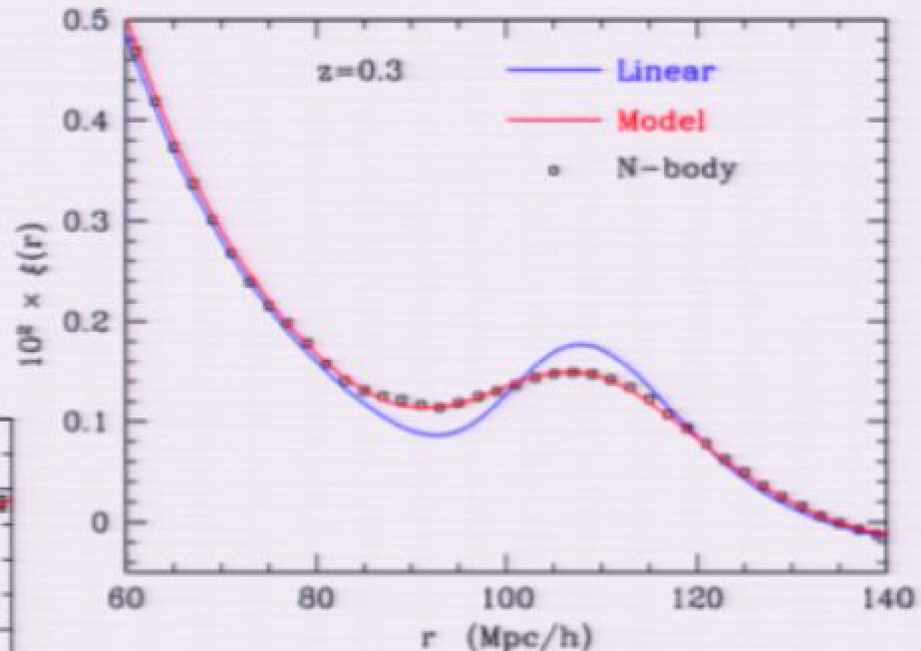
Non linearities smear the peak

Loss of contrast and excess power from non-linear collapse.





Broadening of feature due to Gaussian smoothing and ~0.5% shift due to mode coupling.

This lecture: Baryonic acoustic oscillation

- Baryonic acoustic oscillations provide robust and tested standard ruler
- Allows to constrain the properties of Dark Energy through measurements of D_a
- Both the CMB (high z) and the imprints of on low z galaxies have been predicted and detected
- Much more to come especially at low z
- How do we related dark matter and galaxies?
- What are the limitations?
- Stay one more hour...