The Echo of Einstein's Greatest Blunder

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Outline

- Dark energy and standard rulers.
- Cosmic sound: baryon acoustic oscillations.
- Theoretical issues.
- Modeling issues.
- Prospects and conclusions.

cdm.berkeley.edu/doku.php?id=baopages

cmb.as.arizona.edu/~eisenste/acousticpeak/

mwhite.berkeley.edu/BAO/

Probing DE via cosmology

- We "see" dark energy through its effects on the expansion of the universe:

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

- Three (3) main approaches
  - – Standard candles
    - measure d_L (integral of H^{-1})
  - – Standard rulers
    - measure d_A (integral of H^{-1}) and $H(z)$
  - – Growth of fluctuations.
    - Crucial for testing extra ρ components vs modified gravity.

Standard rulers

- Suppose we had an object whose length (in *meters*) we knew as a function of cosmic epoch.
- By measuring the angle ($\Delta\theta$) subtended by this ruler ($\Delta\chi$) as a function of redshift we map out the angular diameter distance d_A

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)} \qquad d_A(z) = \frac{d_L(z)}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

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

$$c\Delta z = H(z)\ \Delta\chi$$

Ideal properties 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 of ~10%.

- 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.

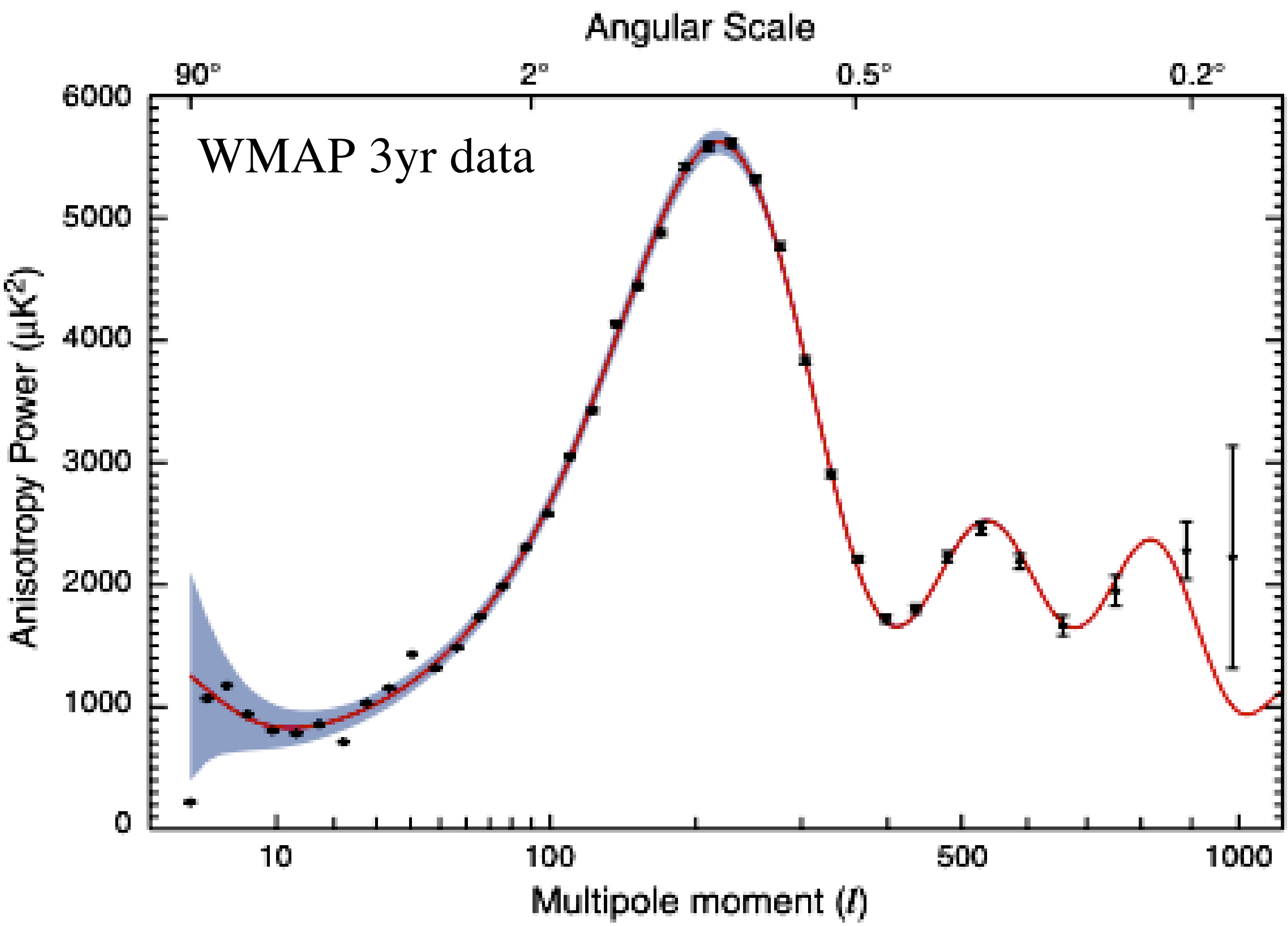
Where do we find such a ruler?

- Cosmological objects can probably never be uniform enough.
- 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.
- Preferred length scales arising from physics of the early universe are imprinted on the distribution of mass and radiation and form time-independent “rulers”.

Sunyaev & Zel’dovich (1970); Peebles & Yu (1970); Doroshkevitch, Sunyaev & Zel’dovich (1978); …; Cooray, Hu, Huterer & Joffre (2001); **Eisenstein** (2003); Seo & Eisenstein (2003); Blake & Glazebrook (2003); Hu & Haiman (2003); …

Back to the beginning …

The CMB power spectrum



The current CMB data are in excellent agreement with the theoretical predictions of a ΛCDM model.

The cartoon

- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
  - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the fluid: compressions and rarefactions.

$$\frac{d}{d\tau}\left[m_{\rm eff}\frac{d\delta_b}{d\tau}\right]+\frac{k^2}{3}\delta_b=F[\Psi] \qquad m_{\rm eff}=1+3\rho_b/4\rho_\gamma$$

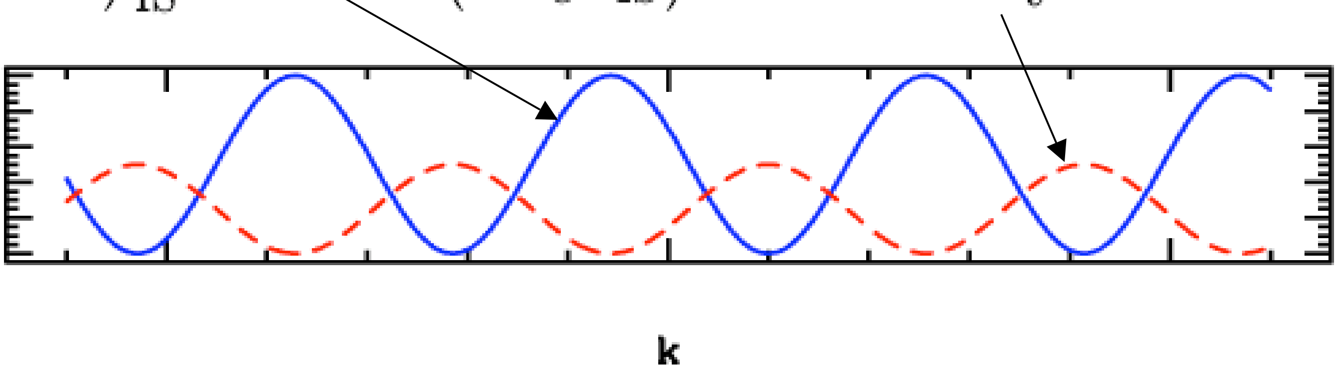
- These show up as temperature fluctuations in the CMB

$$\Delta T\sim\delta\rho_\gamma^{1/4}\sim A(k)\cos(kc_st) \qquad \text{[harmonic wave]}$$

The cartoon

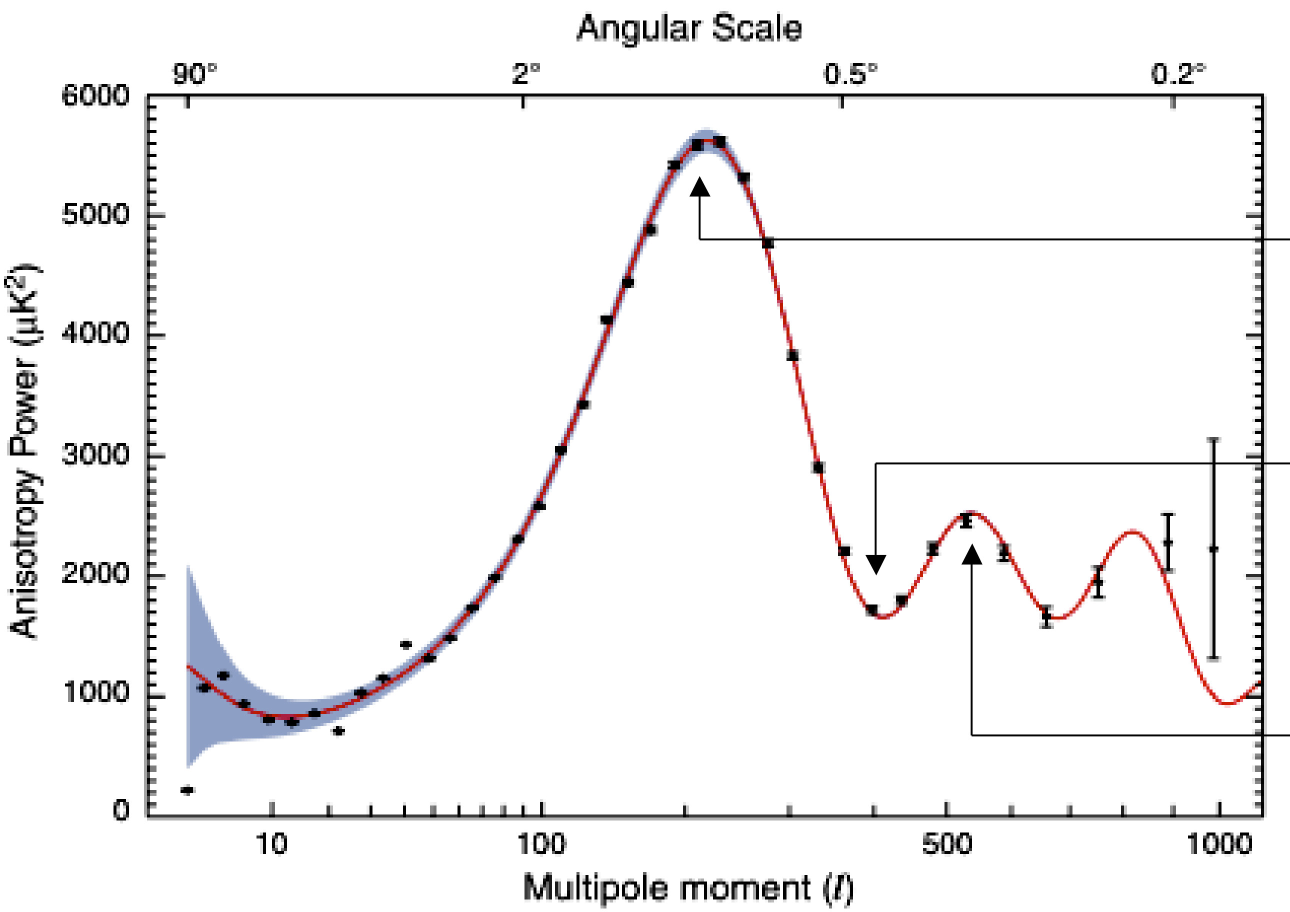
- A sudden "recombination" decouples the radiation and matter, giving us a snapshot of the fluid at "last scattering".

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



- These fluctuations are then projected on the sky with $\lambda \sim r_{ls}\theta$ or $l \sim k\, r_{ls}$

Acoustic oscillations seen!



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: $s = c_s t_{ls}$

Sound horizon more carefully

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

- Depends on
  - – Epoch of recombination
  - – Expansion of universe
  - – Baryon-to-photon ratio (through c_s)

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

Photon density is known exquisitely well from CMB spectrum.

CMB calibration

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

$$s = 147.8 \pm 2.6 \text{ Mpc}$$
$$= (4.56 \pm 0.08) \times 10^{24}\text{m}$$

WMAP 3rd yr data

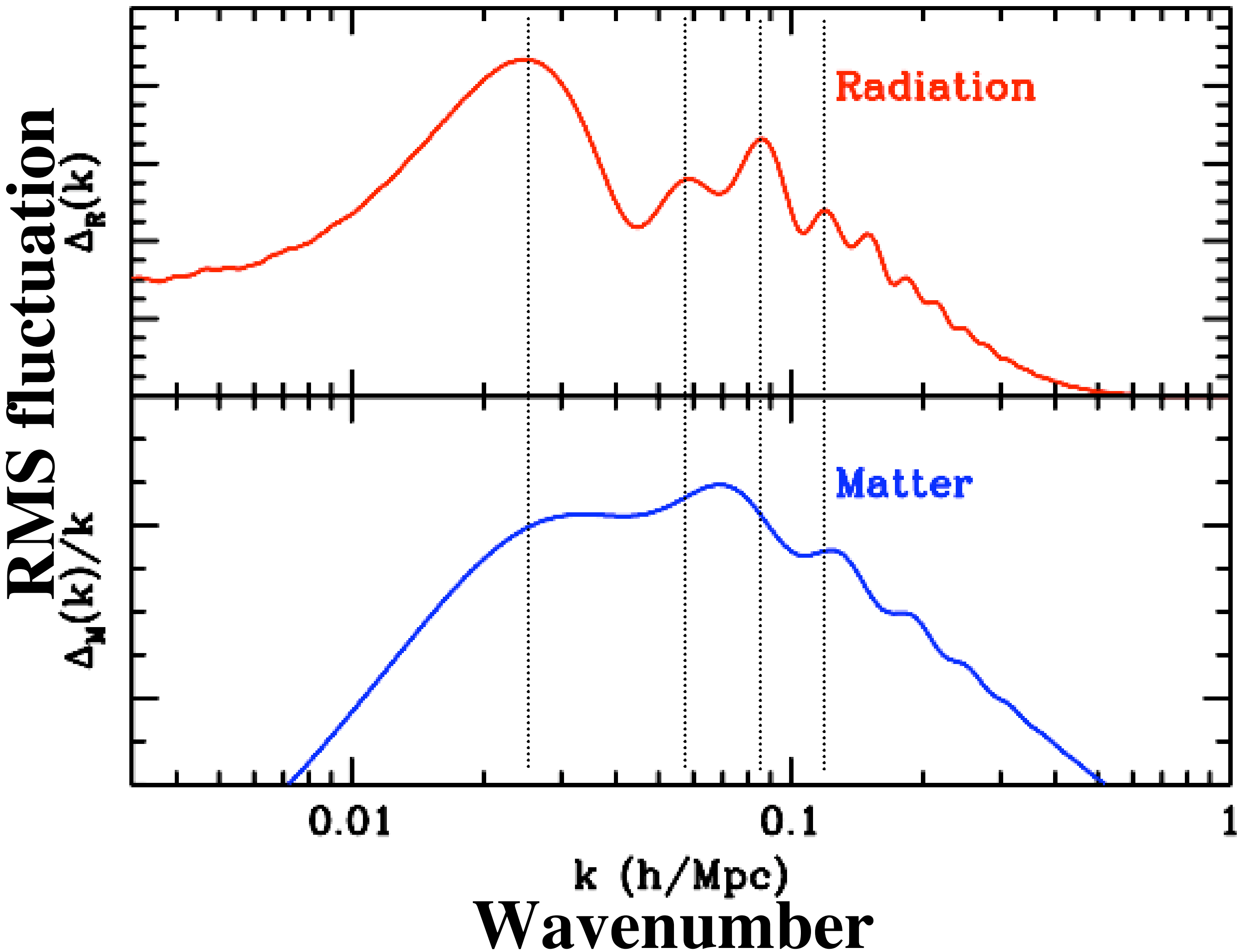
↑

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

Baryon oscillations in $P(k)$

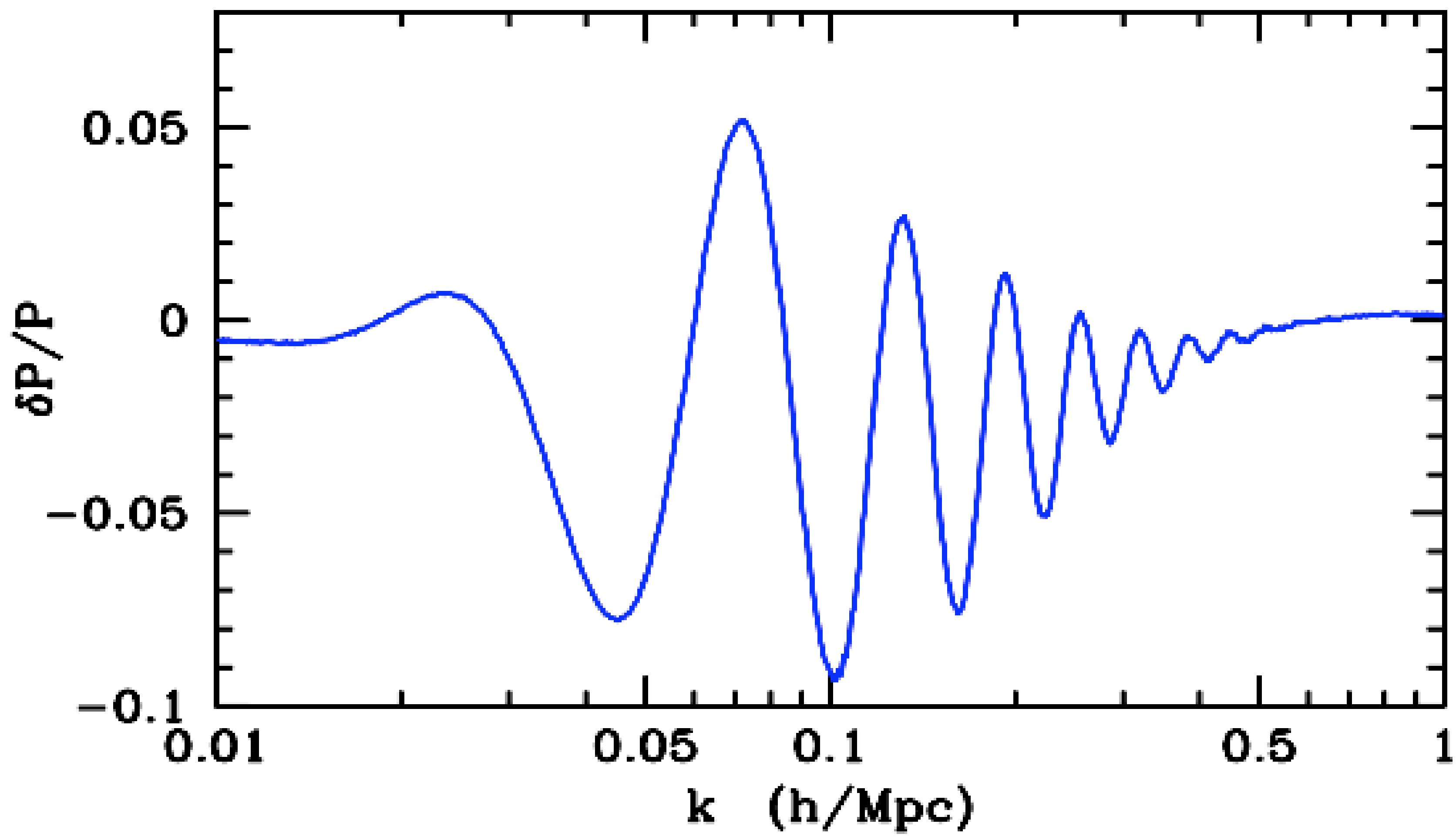
- Since the baryons contribute ~15% of the total matter density, the total gravitational potential is affected by the acoustic oscillations with scale set by *s*.
- This leads to small oscillations in the matter power spectrum $P(k)$.
  - No longer order unity, like in the CMB, now suppressed by $\Omega_b/\Omega_m \sim 0.1$

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 $O(10\%)$.



Higher order effects

- The matter and radiation oscillations are not in phase, and the phase shift depends on k.
- There is a subtle shift in the oscillations with k due to the fact that the universe is expanding and becoming more matter dominated.
- The finite duration of decoupling means photons can diffuse out of over-densities smaller than a certain scale, leading to damping of the oscillations on small scales.
- But regardless, the spectrum is calculable and s can be inferred!

These features are frozen into the mass power spectrum, providing a known length scale that can be measured as a function of z.

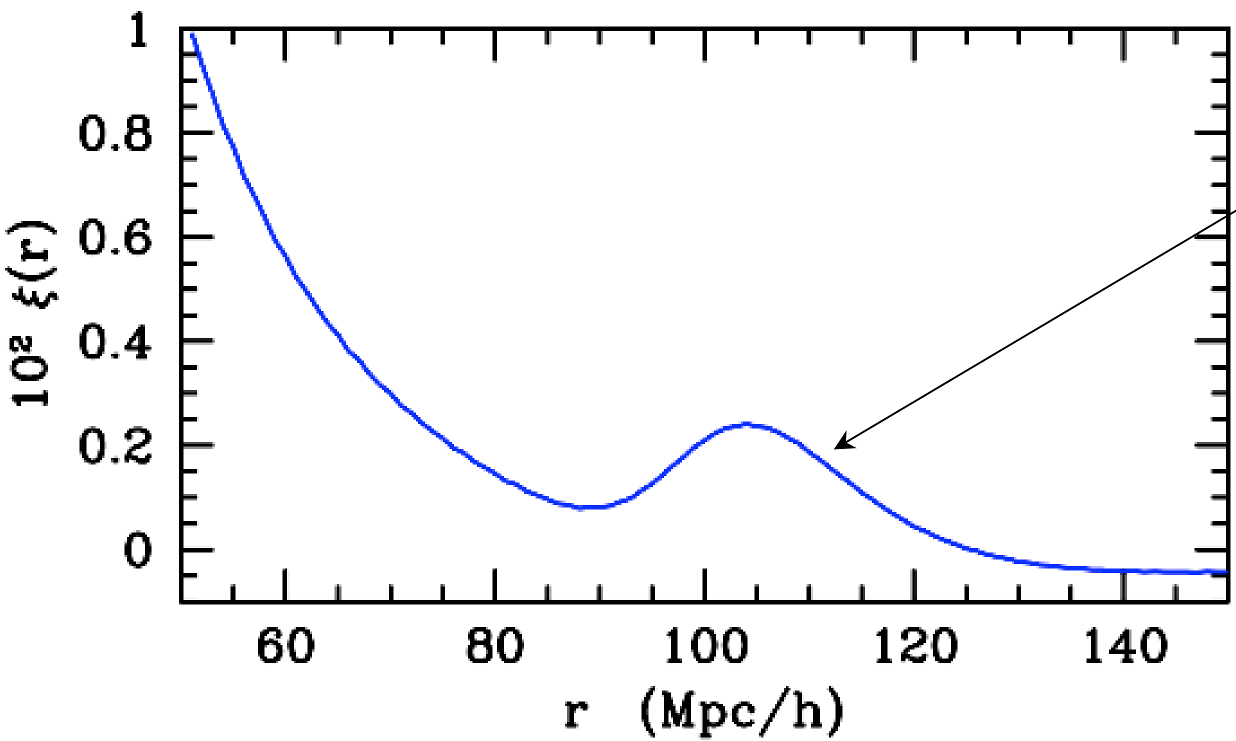
DE or early universe weirdness?

- Key to computing ***s*** is our ability to model CMB anisotropies.
- Want to be sure that we don't mistake an error in our understanding of $z \sim 10^3$ for a property of the DE!
- What could go wrong in the early universe?
  - Recombination.
  - Misestimating c_s or ρ_B/ρ_γ.
  - Misestimating $H(z>>1)$ (e.g. missing radiation).
  - Strange thermal history (e.g. decaying ν).
  - Isocurvature perturbations.
  - ….
- It seems that future measurements of CMB anisotropies (e.g. with Planck) constrain ***s*** well enough for this measurement even in the presence of odd high-*z* physics.

Eisenstein & White (2004); White (2006)

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
- A harmonic sequence would be a δ-function in *r*, the shift in frequency and diffusion damping broaden the feature.



Acoustic feature at ~100 Mpc/*h* with width ~10 Mpc/*h* (Silk scale)

Configuration space

While the CMB/LSS calculations are traditionally done in Fourier space there is no reason why one can't use a Green's function method to solve them in configuration space.

To linear order Einstein's equations look similar to Poisson's equation relating ϕ and δ, but upon closer inspection one finds that the equations are hyperbolic: they describe traveling waves.

[effects of local stress-energy conservation, causality, …]

In general the solutions are unenlightening, but in some very simple cases you can see the main physical processes by eye:

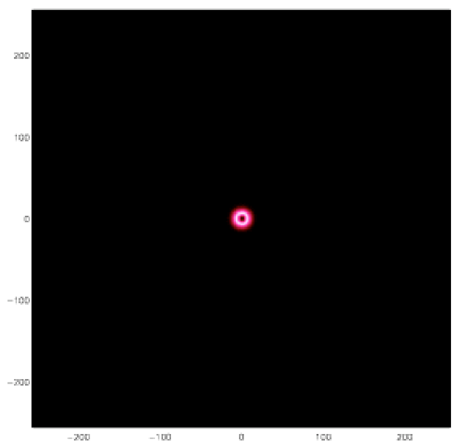
$$G_{\Phi}^{RD} \propto (c_s\tau)^{-3}\,\theta(c_s\tau - r)$$

Bashinsky & Bertschinger (2000)

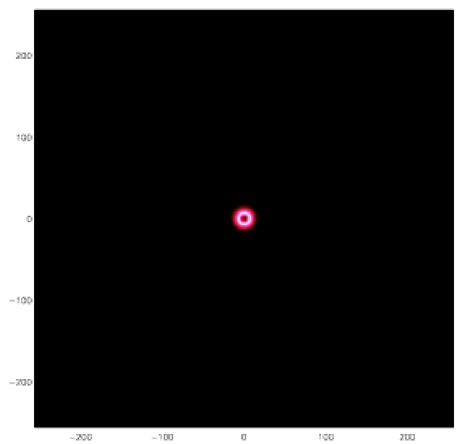
The acoustic wave

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

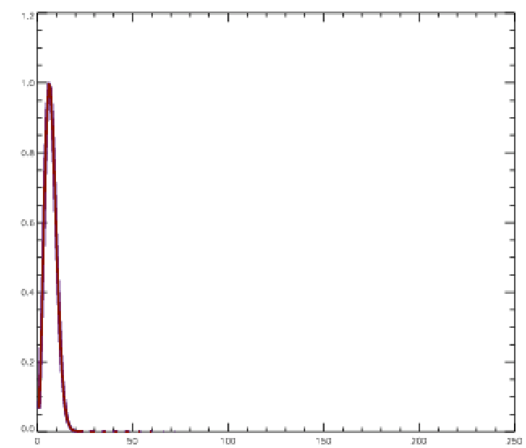
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Baryons



Photons

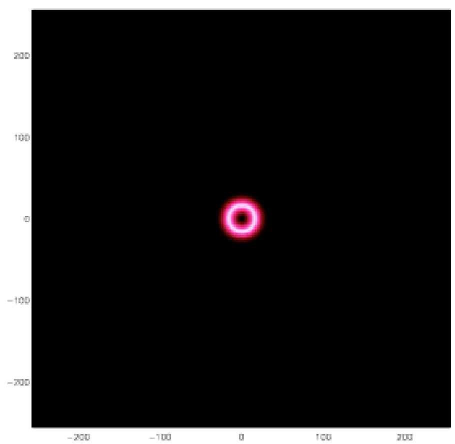


Mass profile

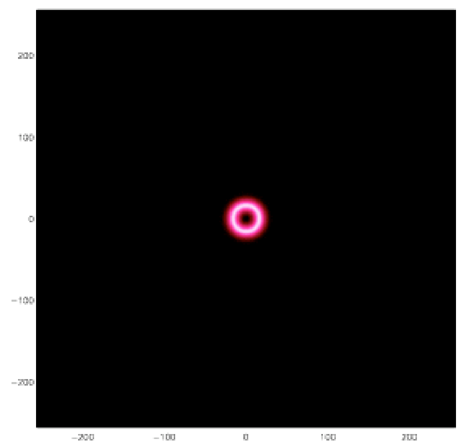
Eisenstein, Seo & White (2006)

The acoustic wave

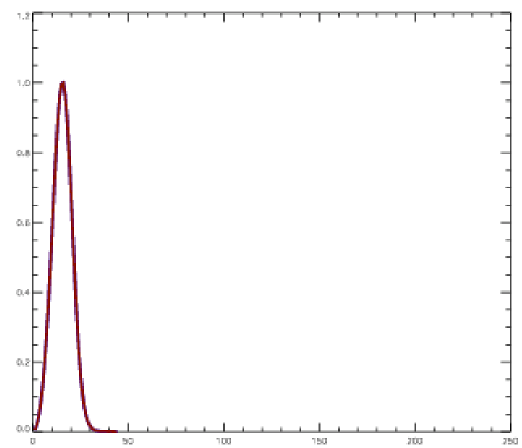
Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



Baryons

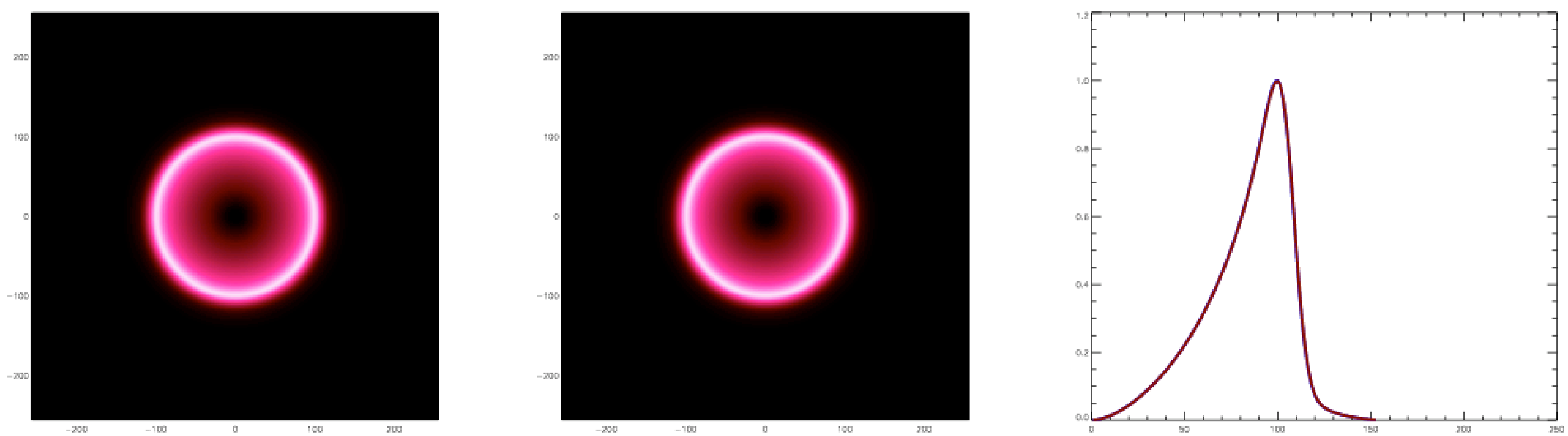


Photons



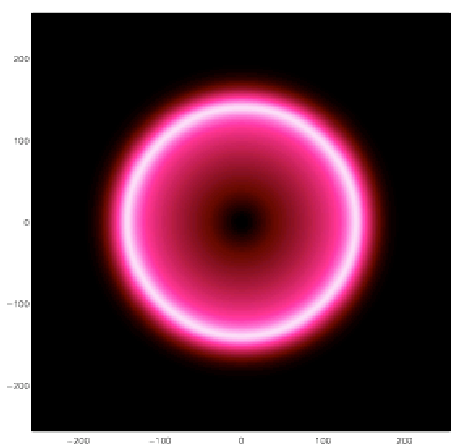
The acoustic wave

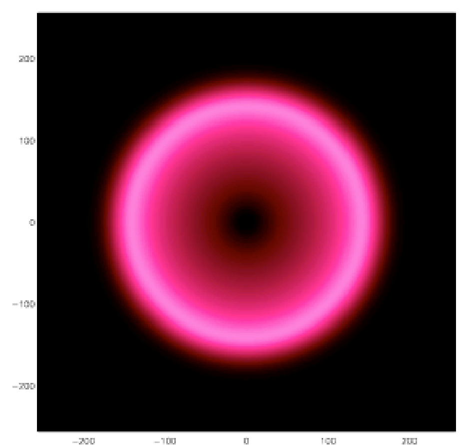
This expansion continues for 10^5 years

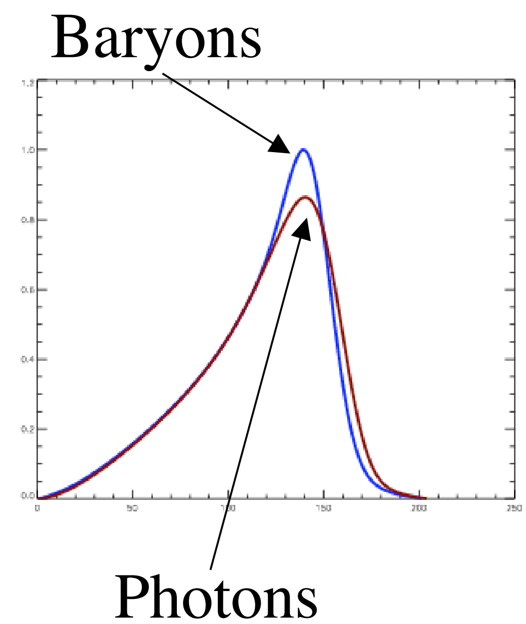


The acoustic wave

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.

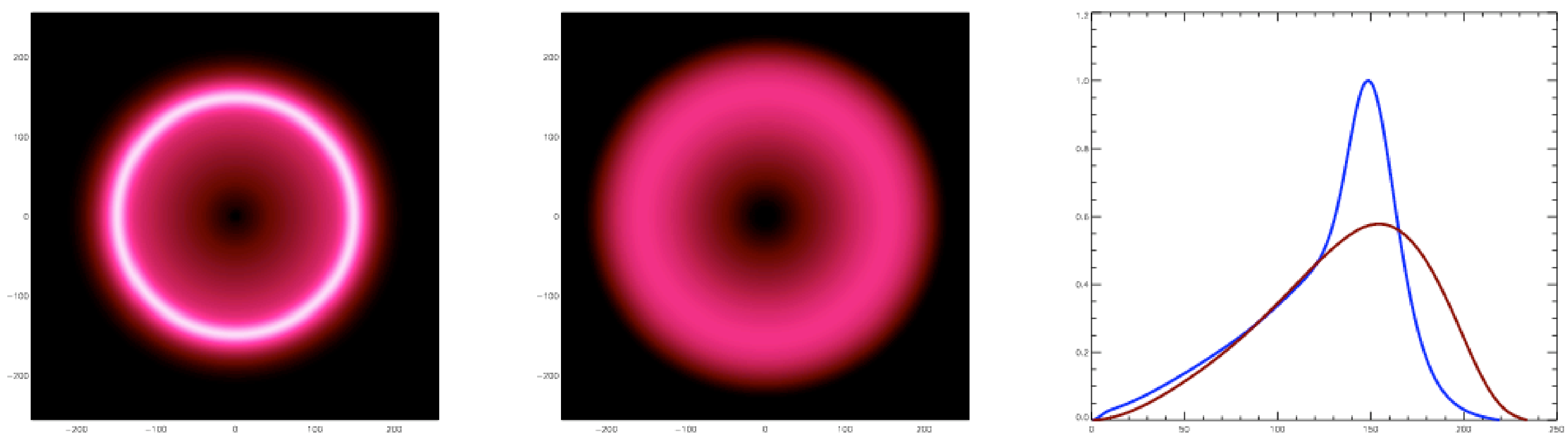




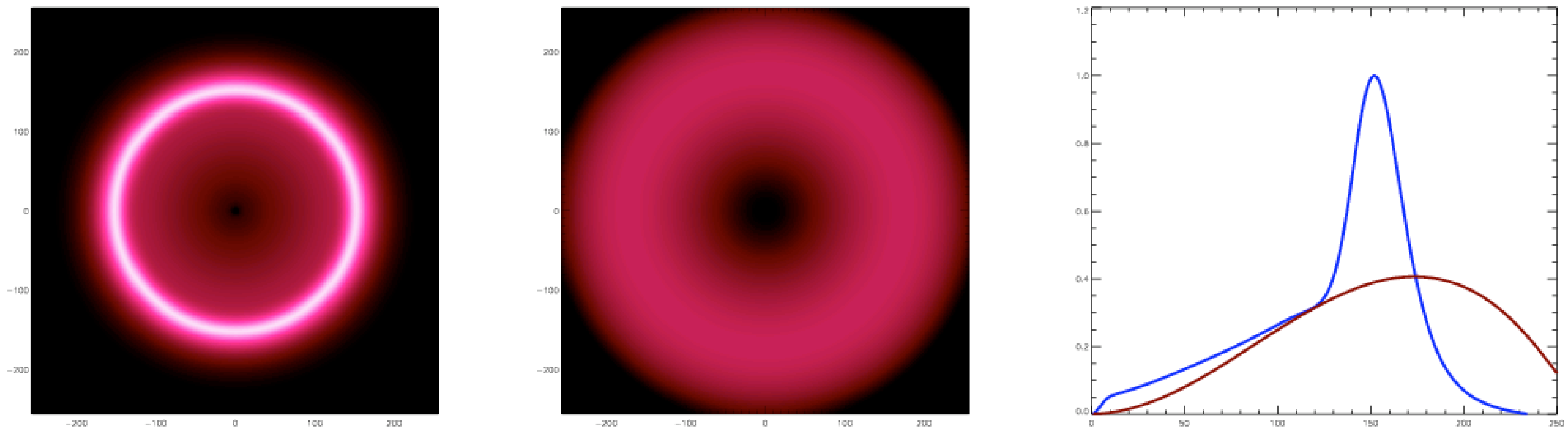


The acoustic wave

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



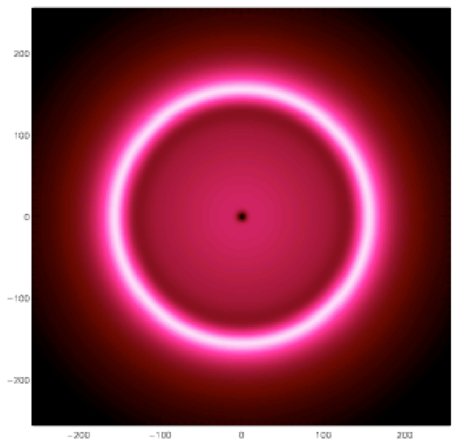
The acoustic wave

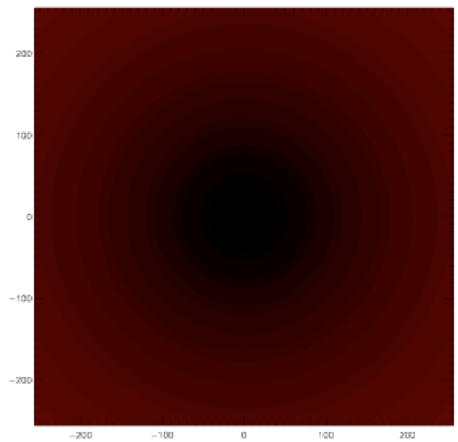


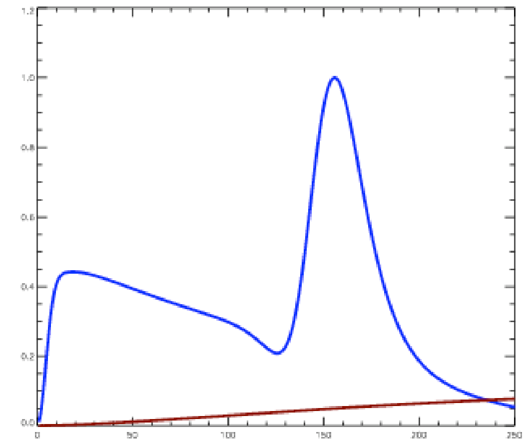
The acoustic wave

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.



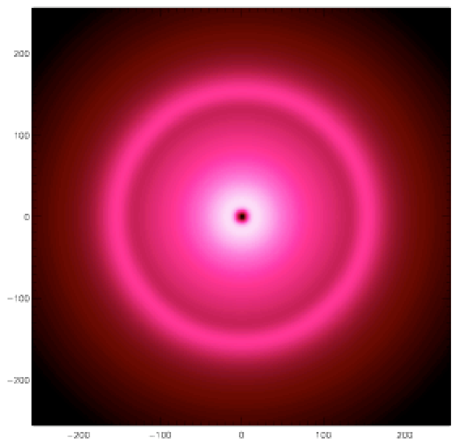


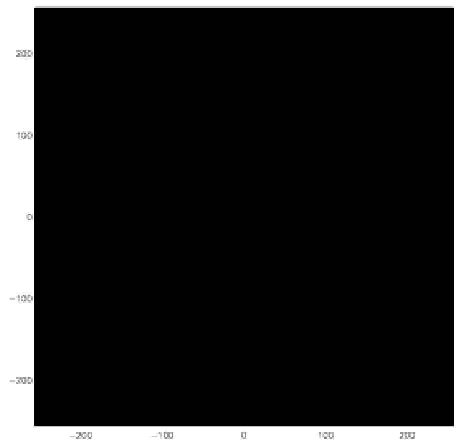


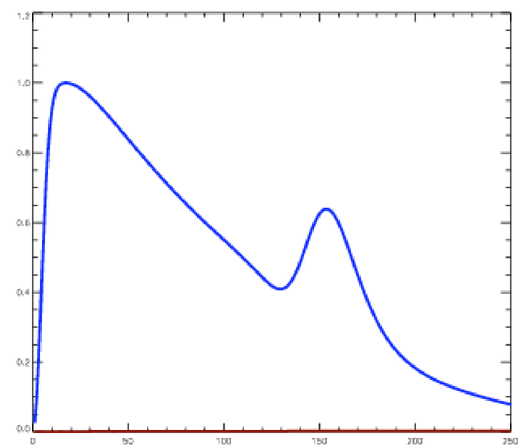
The acoustic wave

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 with width ~10%.







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 …

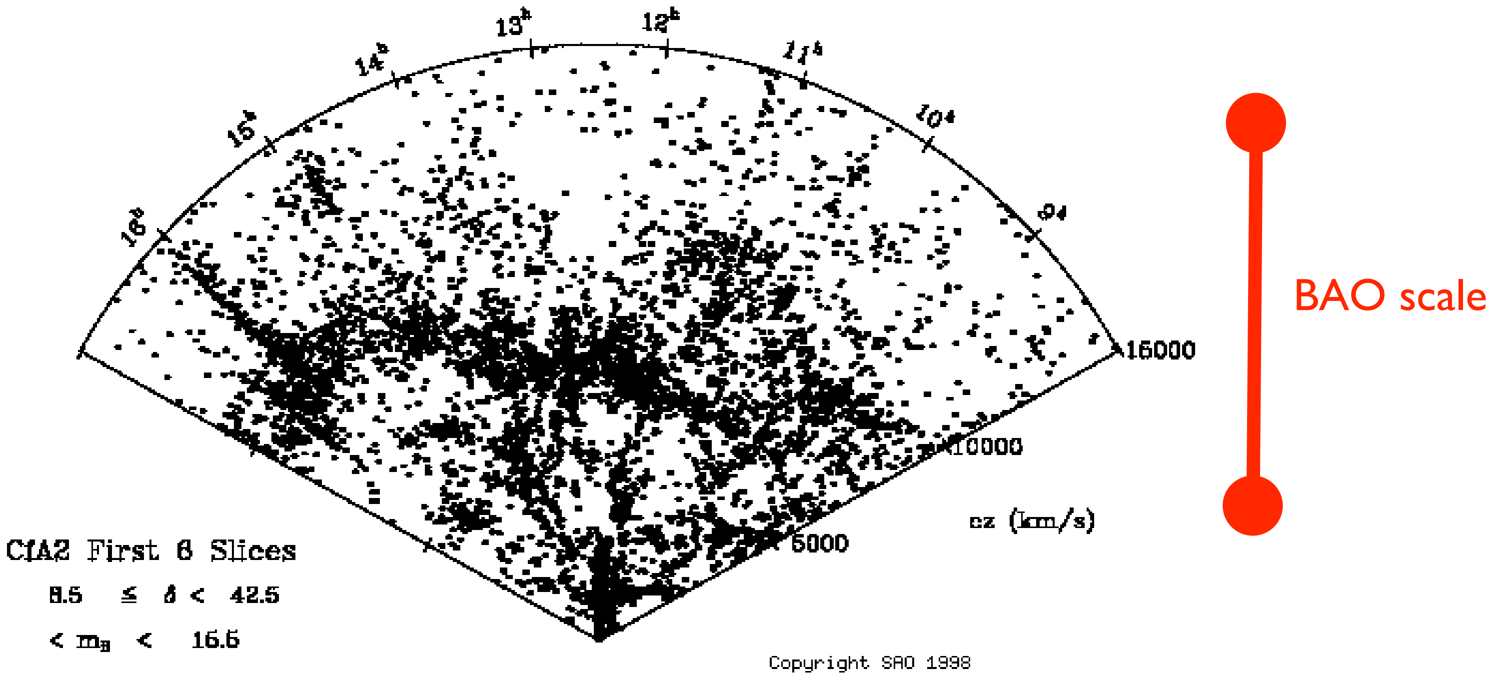
Features of baryon oscillations

- 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.

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.

Early surveys too small

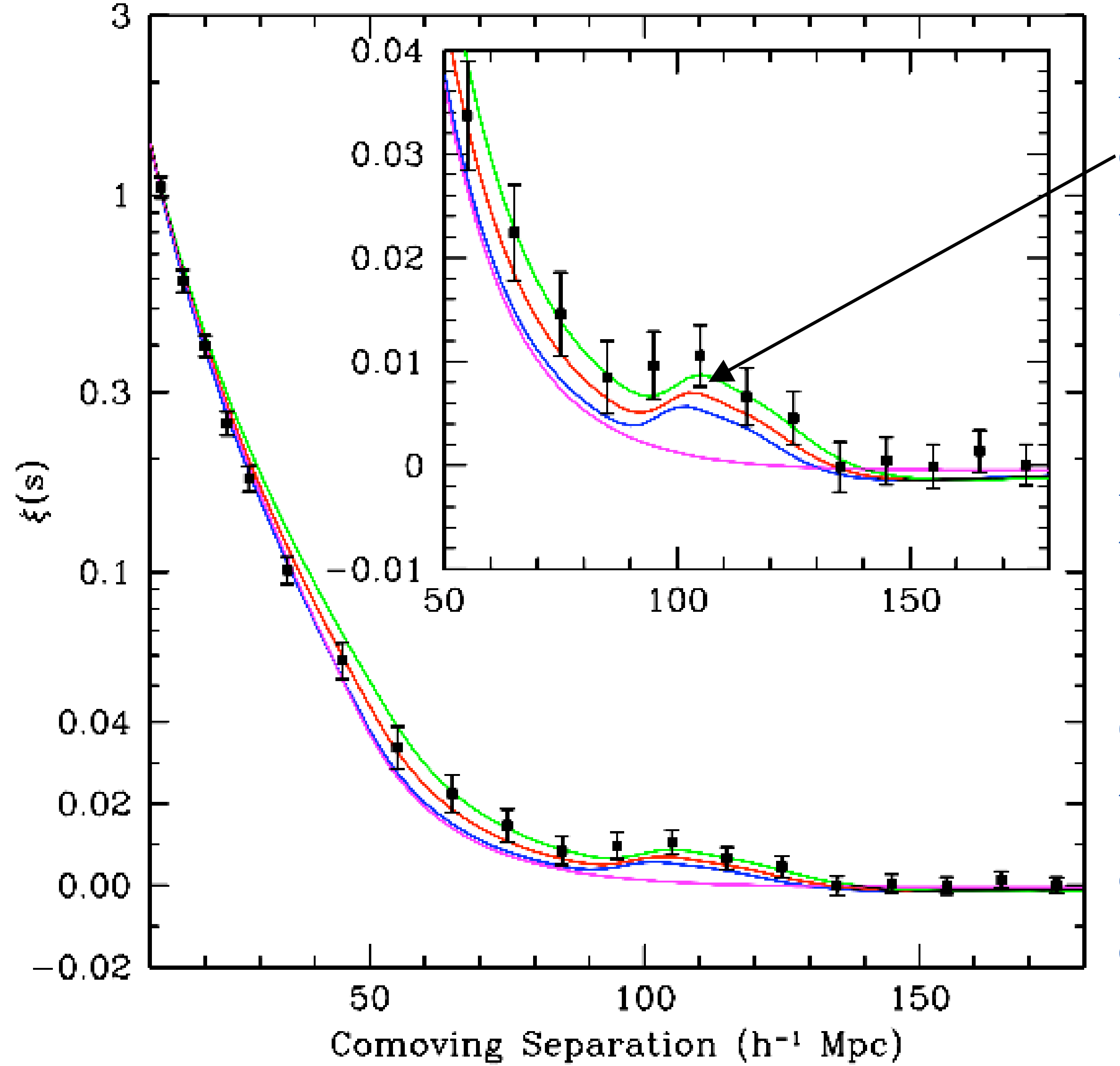


CfA2 redshift survey (Geller & Huchra 1989)
Formally, this could “measure” BAO with a ~0.05σ detection

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)
   3% distance measure

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

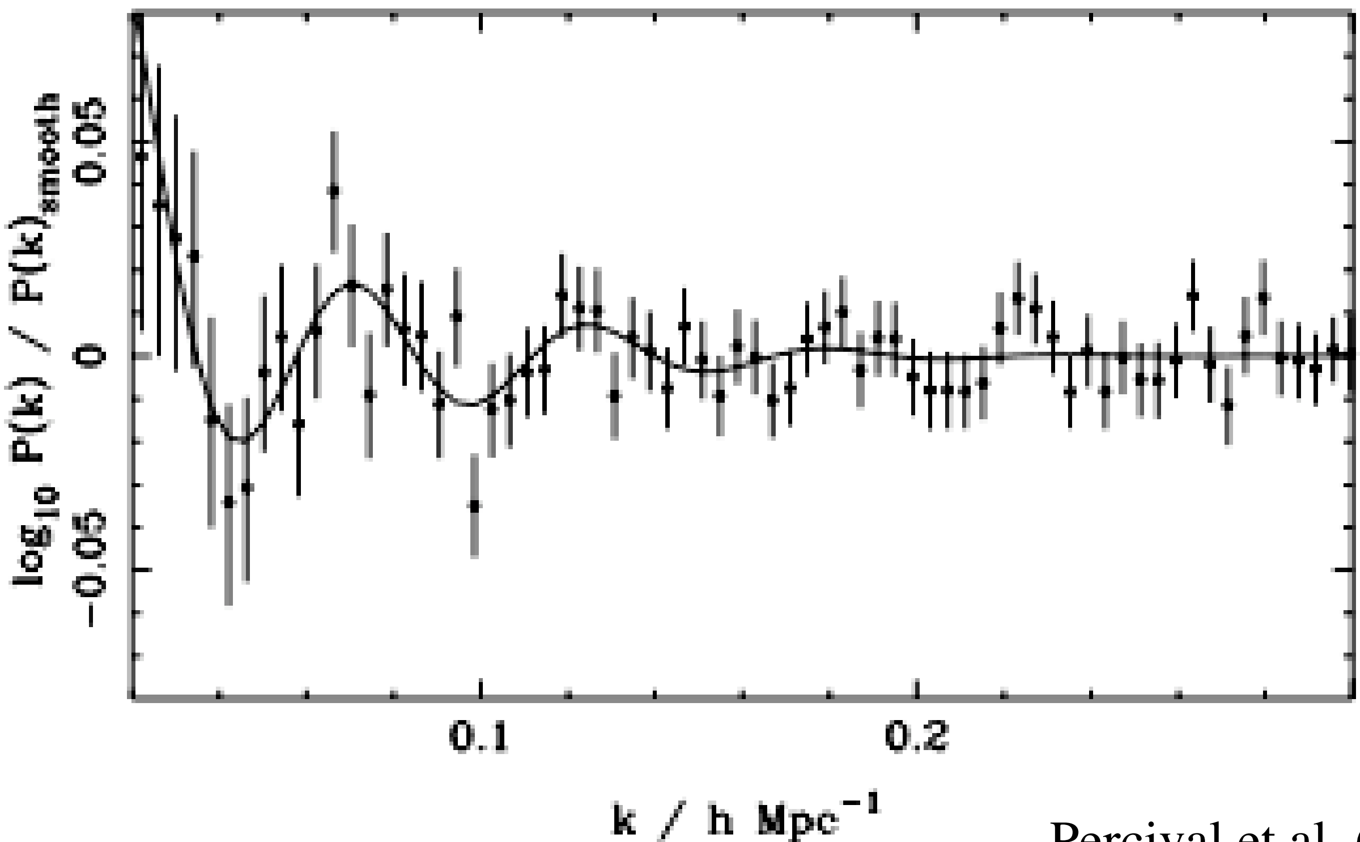
   (spectro-z)
   5% distance measure

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)
   5% distance measure

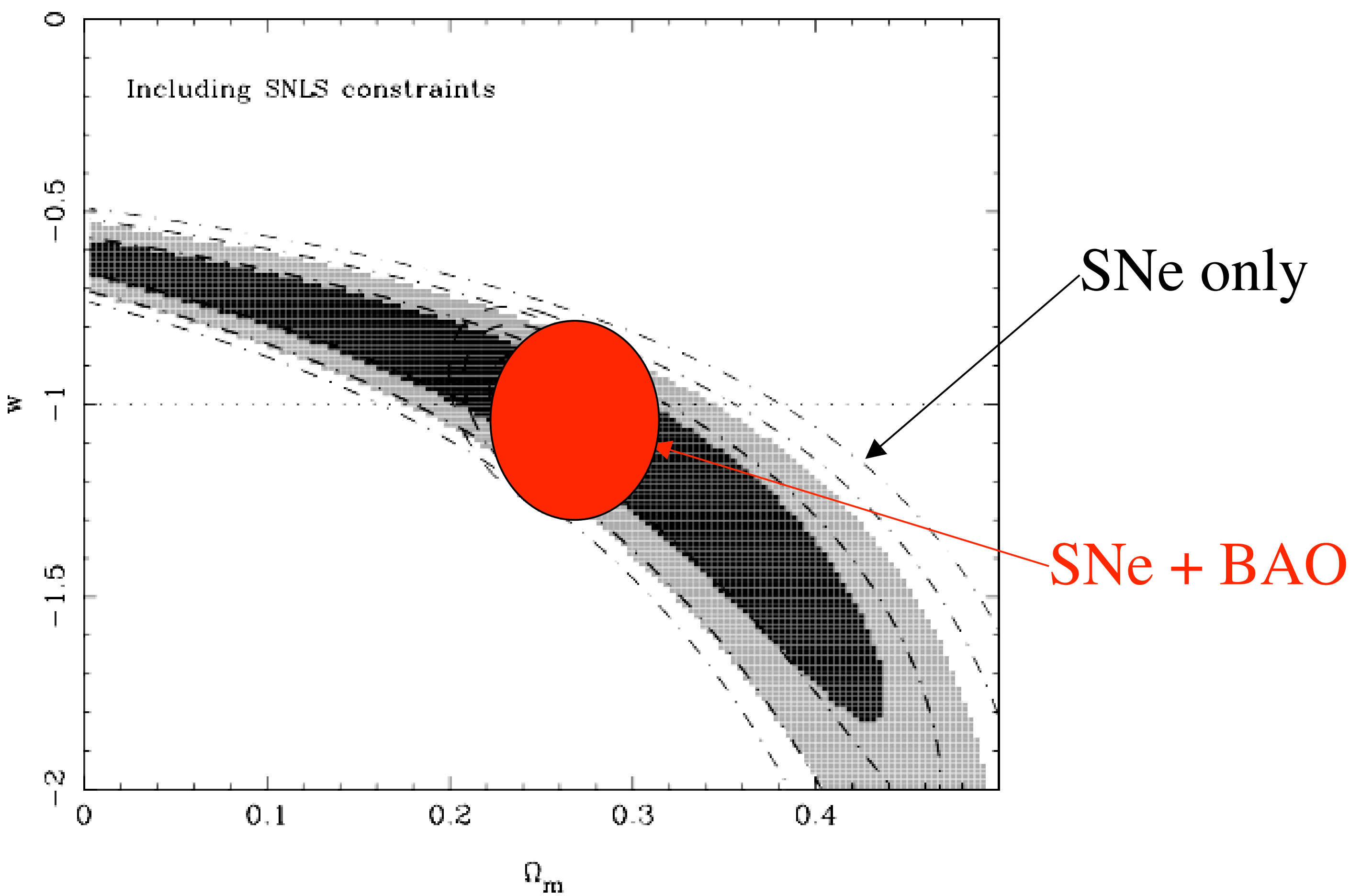
5. Blake et al 2007
    - (Same data as above)
6. Percival et al 2007
    - (Combination of SDSS+2dF)

Current combined constraints



Percival et al. (2007)

On cosmology



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 ξ(r) well enough to see such subtle features requires many well defined modes
  - a Gpc^3 volume.
  - Million(s) of galaxies.
- To keep higher order terms small we need to work at "high" *z* where the density contrast is small.
  - A survey at z ~ 1.
  - Model out the non-linearities.
- Do the equivalent of the SDSS at *z*~0-3!

Current and proposed spectroscopic BAO surveys

Project	Redshift	Area (sq. deg.)	n (10^{-4})	FoM
Stage II	-	-	-	53.4
WiggleZ	0.4-1.0	1,000	3.0	66.52
HETDEX	2.0-4.0	350	3.6	70.08
WFMOS	0.5-1.3, 2.3-3.3	2000, 300	5.0	94.84
BOSS LRG	0.1-0.8	10,000	3.0	86.38
+QSO	+ 2.0-3.0	+ 8000		122.22
+Stage III		-		331.03

Photometric BAO surveys

- As has been mentioned previously, we are now entering the era of large photometric surveys.
- While these surveys cannot do line-of-sight correlations, they can provide constraints on d_A from angular clustering.
- Generally a photometric survey takes ~5-10x as much sky area as a spectroscopic one to obtain similar constraints on $d_A(z)$.
  - This just comes from counting the measurable modes in 2D vs. 3D.
- Pan-STARRS, DES, LSST, etc. will all provide constraints on DE through BAO.

BOSS (Baryon Oscillation Spectoscopic Survey)

July 2006	Competitive proposal to use (upgraded) SDSS telescope for next-generation BAO experiment
Nov 2006	BOSS proposal selected (from 7) for all dark+grey time for 5 of 6 years
Nov 2006	First BOSS collaboration meeting
Feb 2007	DOE R&D proposal for upgrading SDSS spectroscopic system
2007-	Funding requests expected to Sloan Foundation, NSF, and DOE
2009-2014	BOSS spectroscopic survey

http://cosmology.lbl.gov/BOSS/

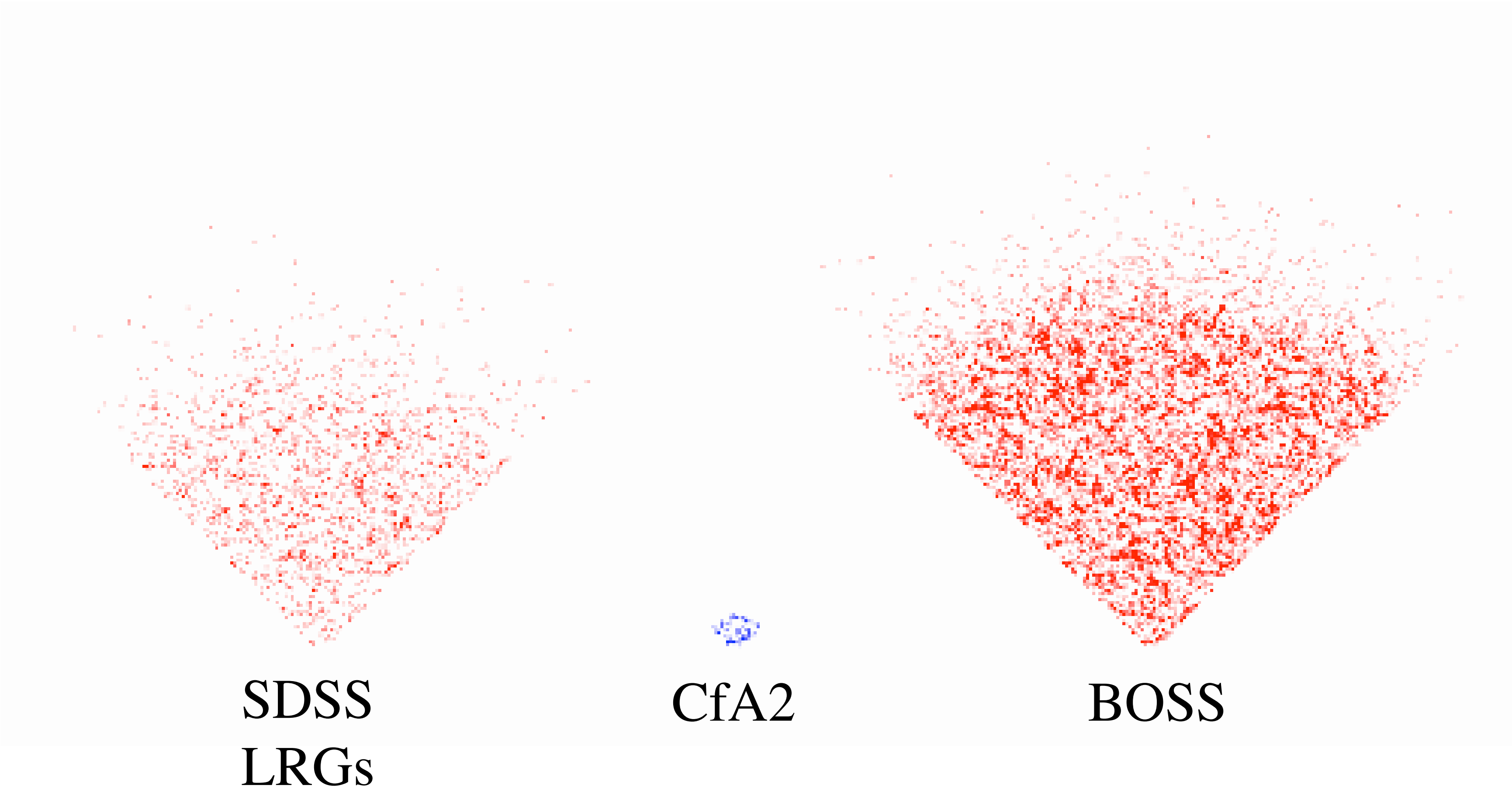
BOSS in a nutshell

- Image additional 2000 deg^2 in Fall by end of 2008
- BOSS will then have:
  - 8500 deg^2 footprint in Spring
  - 2500 deg^2 footprint in Fall
- Upgrade spectrographs in summer 2008 or 2009
  - Replace 640x 3-arcsec fibres with 1000x 2-arcsec fibers in cartridges
  - Replace CCDs with (larger/better) Fairchild & LBNL CCDs
  - Increase wavelength range to 3700-9800A (R=2400)
- Replace ruled gratings with VPH grisms

- (Milky Way program 2008-2009)

- Only spectroscopy from 2009-2013
  - 1.5 million LRGs $i<20$, $z<0.8$, over 10,000 deg^2 (dark+grey time)
  - 160,000 QSOs $g<22$, $2.3<z<3$, over 8,000 deg^2 (dark time)

BOSS by comparison

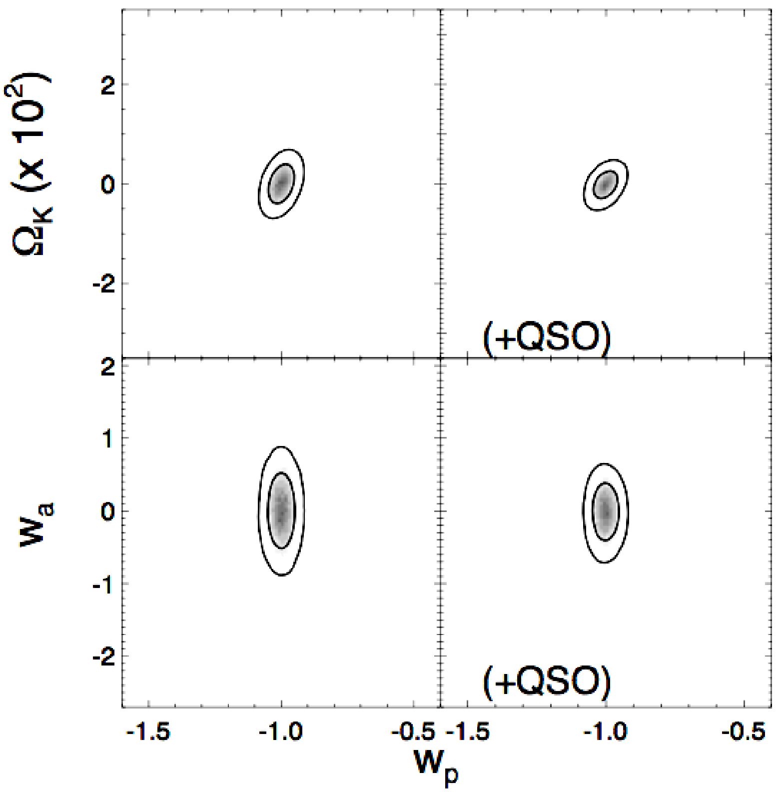


BOSS science

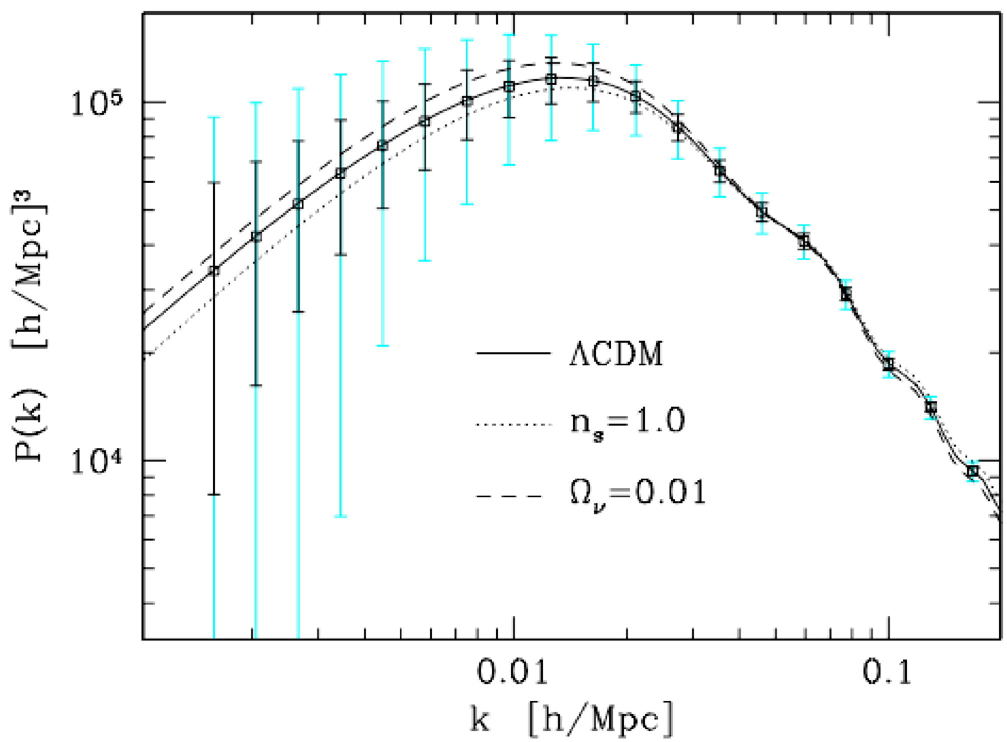
Like SDSS-I and II, BOSS will provide a rich scientific return including:

- DE constraints
- A 1% H_0 measurement
- A 0.2% Ω_K measurement
- Large scale structure constraints (250,000 modes at $k<0.2$)
- A S/N=200 measurement of ξ_{gm} from galaxy-galaxy lensing
- Constraints on galaxy formation: evolution of massive galaxies
- QSO science (piggy-back program doubles N_{QSO} with $z>3.6$)
- Galaxtic structure (C stars)
- Loads of other stuff …

BOSS science II



Dark energy



Large-scale structure

Findings of the Dark Energy Task Force

(Reporting to DOE, NASA & NSF; chair Rocky Kolb)

- Four observational techniques for studying DE with baryon oscillations:
- “Less affected by astrophysical uncertainties than other techniques.”
- **BUT**
- “We need…Theoretical investigations of how far into the non-linear regime the data can be modeled with sufficient reliability and further understanding of galaxy bias on the galaxy power spectrum.”

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?
- We don't have a "turn-key" method for reliably going from measured galaxy positions to sound horizon constraints.
  - Hard to propagate systematics
  - Hard to do trade-off studies
  - Hard to investigate sample selection effects

BAO surveys are *always* in the sample variance dominated regime. Cannot afford to take a large "hit" due to theoretical uncertainties!

Numerical simulations

- Our ability to simulate structure formation has increased tremendously in the last decade.
- Simulating the dark matter for BAO:
  - Meiksin, White & Peacock (1999)
    - 10^6 particles, 10^2 dynamic range, ~1Gpc^3
  - Springel et al. (2005)
    - 10^{10} particles, 10^4 dynamic range, 0.1Gpc^3
- Our understanding of galaxy formation has also increased dramatically.

Numbers vs Insight

- Trying to learn from these simulations
  - What range of behaviors do we see?
  - Which D/A algorithms work best?
  - How do we parameterize the effects?
- Can we gain an analytic understanding of the issues?
- Are there shortcuts for describing the complexities?
  - e.g. the Lagrangian displacement distribution (ES&W '07)
- Can we push further into the non-linear regime?
  - Reconstruction (Eisenstein et al. 2007).

Effects of non-linearity

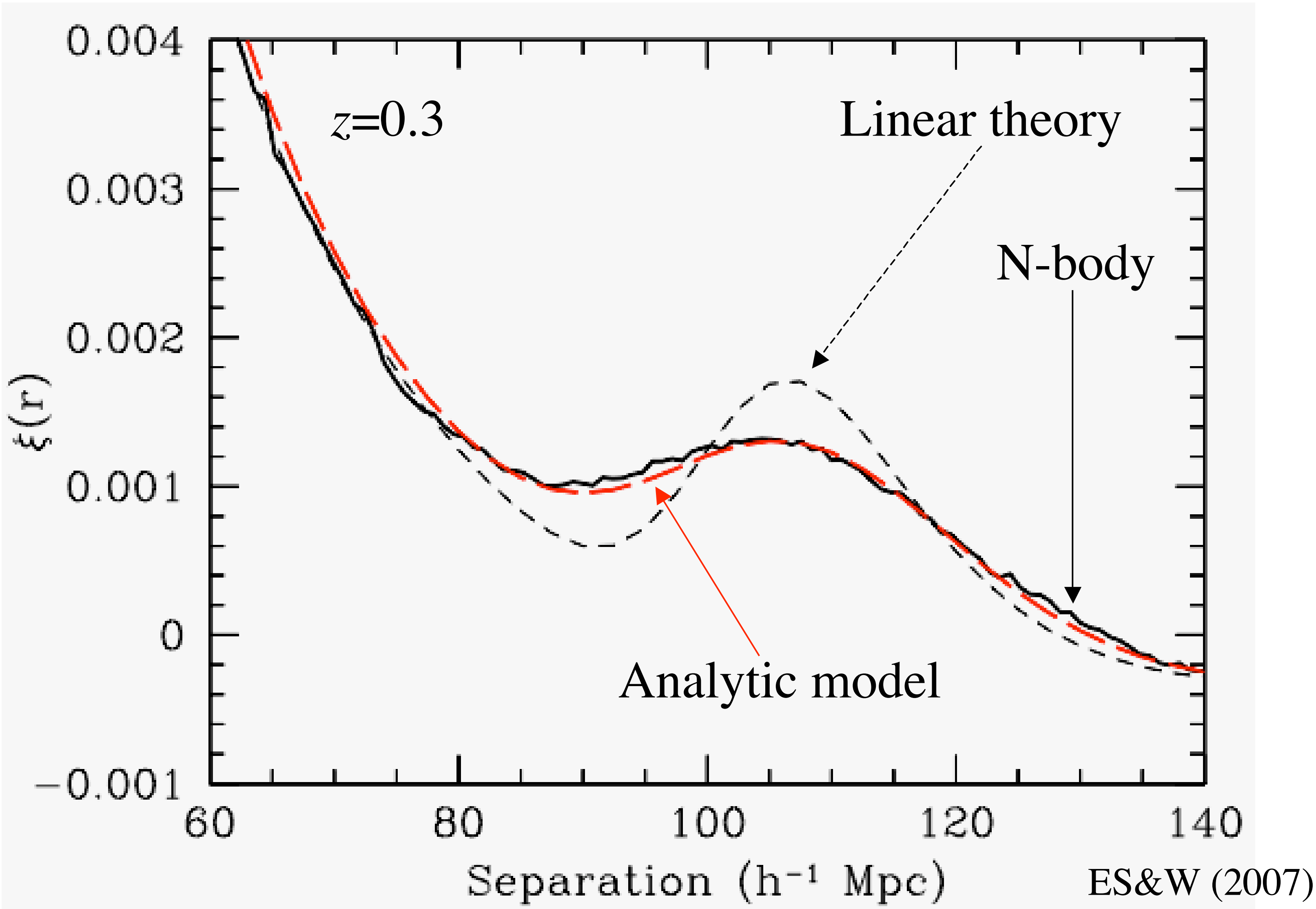
As large-scale structure grows, neighboring objects “pull” on the baryon shell around any point. This super-clustering causes a broadening of the peak [and additional non-linear power on small scales]. From simulations or PT find:

$$\Delta^2(k) = \Delta^2_{\rm lin}(k) \exp\left[-k_{||}^2\Sigma_{||}^2 + k_\perp^2\Sigma_\perp^2\right] + \cdots$$

This does a reasonable job of providing a “template” low-z spectrum, and it allows us to understand where the information lives in Fourier space.

Eisenstein, Seo & White (2007)
Smith, Scoccimarro & Sheth (2007)
Eisenstein et al. (2007)

Non-linearities smear the peak



Information on the acoustic scale

- For a Gaussian random field $Var[x^2]=2Var[x]^2$, so our power spectrum errors are go as the square of the (total) power measured.
  - Measured power is $P+1/n$
- For a simple 1D model

$$\sigma_{\ln s}^{-2} = \frac{V}{2}\int \frac{d^3k}{(2\pi)^3}\left(\frac{\partial P/\partial \ln s}{P+\bar{n}^{-1}}\right)^2$$

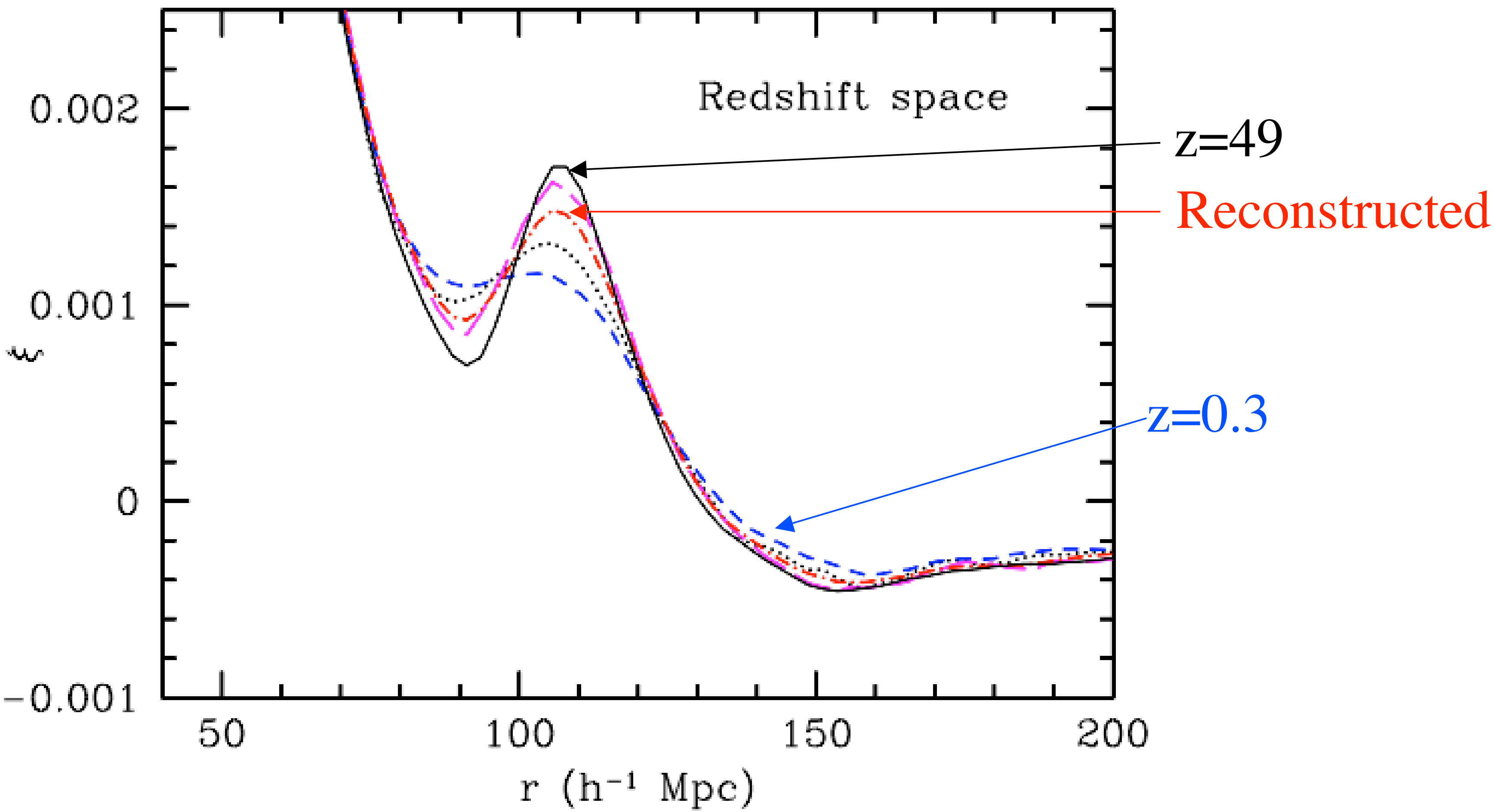
Seo & Eisenstein (2006)

- Note that $\delta P/\delta \ln s$ depends only on the wiggles while $P+1/n$ depends on the whole spectrum.
- The wiggles are (exponentially) damped at high k.

Reconstruction

- The broadening of the peak comes from the "tugging" of large-scale structure on the baryon "shell".
- We measure the large-scale structure, and hence the gravity that "tugged".
- Half of the displacement in the shell comes from "tugs" on scales > 100 Mpc/h
- Use the observations to "undo" non-linearity
  - Measure $\delta(x)$, infer $\phi(x)$, hence displacement.
  - Move the galaxies back to their original positions.
- Putting information from the phases back into $P(k)$.
- There were many ideas about this for measuring velocities in the 80's and 90's; but not much of it has been revisited for reconstruction (yet).

Reconstruction: simplest idea



From Eisenstein et al. (2007)

Musings on non-linearity

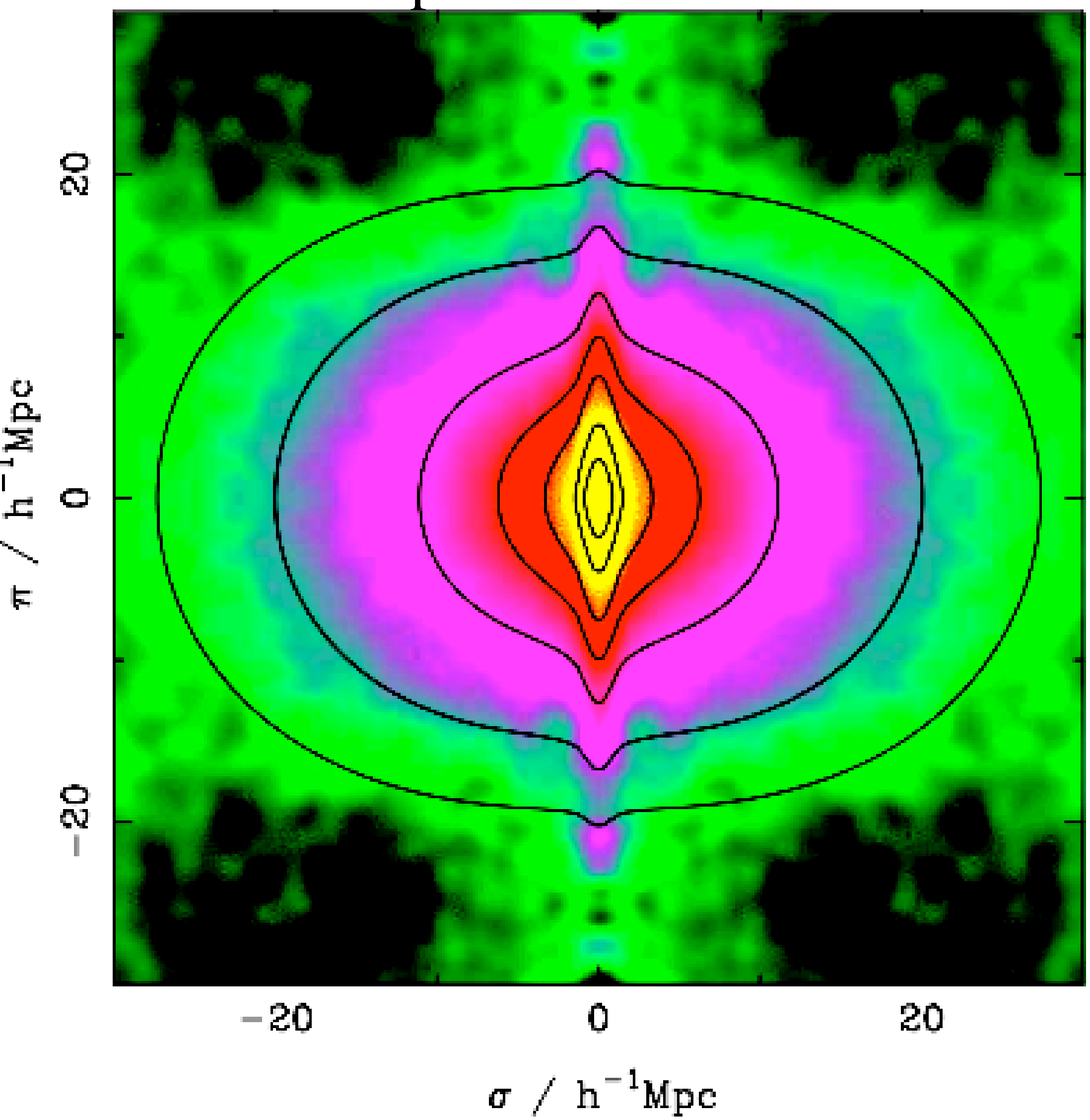
- Fourier space
  - Excess power on small-scales.
  - Mode coupling erases oscillations at high *k*
  - Non-linearities appear to encroach on signal.
  - Unclear whether acoustic scale is shifted.
- Configuration space
  - Non-linearities "smear" initial peak by ~10Mpc
  - Smearing decreases contrast (lower S/N).
  - Existence of collapsed halos increases ξ variance even at 100Mpc -- decreasing S/N.
  - A bias/shift in peak position can be estimated. At *z*=0:

$$\frac{\Delta r_{12}}{r_{12}} \equiv r_{12}^{-1} \frac{\langle u_{12}\delta_{g,1}\delta_{g,2}\rangle}{\langle \delta_{g,1}\delta_{g,2}\rangle} \simeq -2J_3(r_{12})\ \frac{\langle \nu^2\nu_g\rangle}{\sigma} < 1\%$$

Decreases roughly as growth factor squared at fixed *n*.

Redshift space distortions

Anisotropic correlation function



2d*F*GRS, Peacock et al.

Inhomogeneities in Φ lead to motion, so the observed *v* is not directly proportional to distance:

$$v_{\rm obs} = Hr + v_{\rm pec}$$

These effects are still difficult to model with high accuracy.

Redshift space distortions II

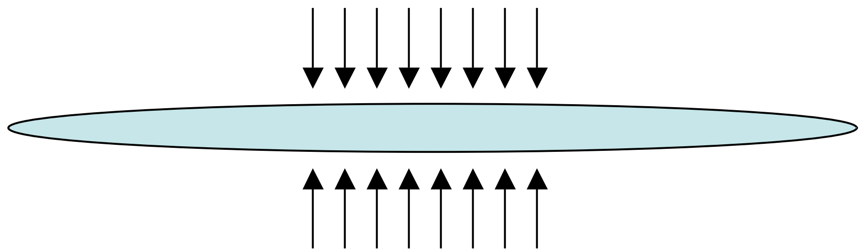
$$1+\xi_s(\pi,\sigma)=\int\frac{dr\,d\gamma}{2\pi}e^{-i\gamma(r-\pi)}\left\langle e^{if\gamma(u-u')}\left[1+\delta\right]\left[1+\delta'\right]\right\rangle$$

The distortions depend on non-linear density and velocity fields, which are correlated.

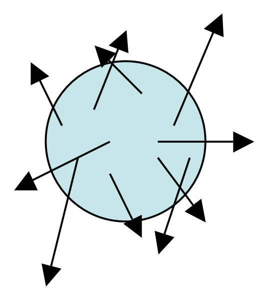
Velocities enhance power on large scales and suppress power on small scales.

The transition from enhancement to suppression occurs on the scale of the baryon oscillations.

Coherent infall

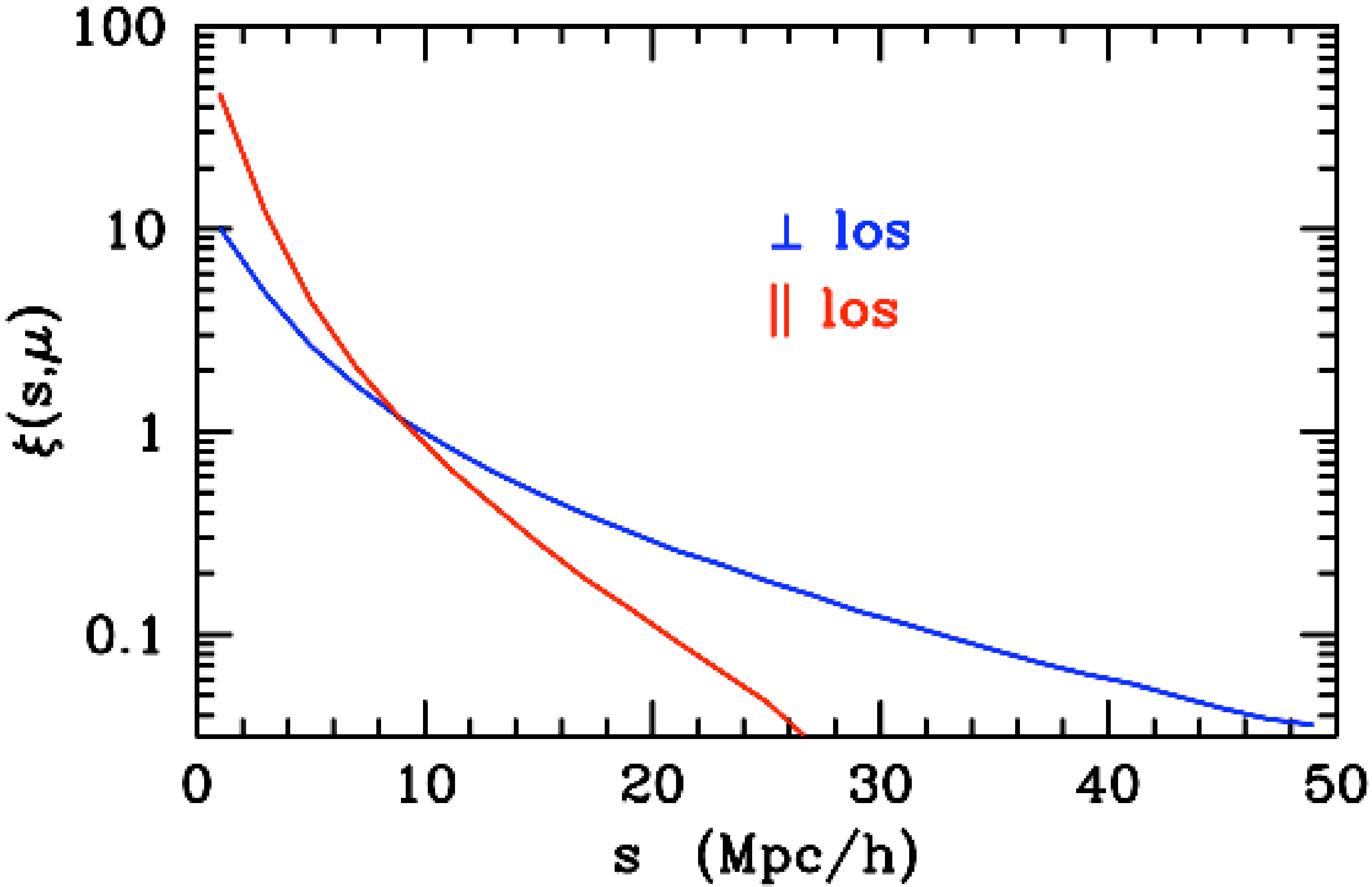


Random (thermal) motion

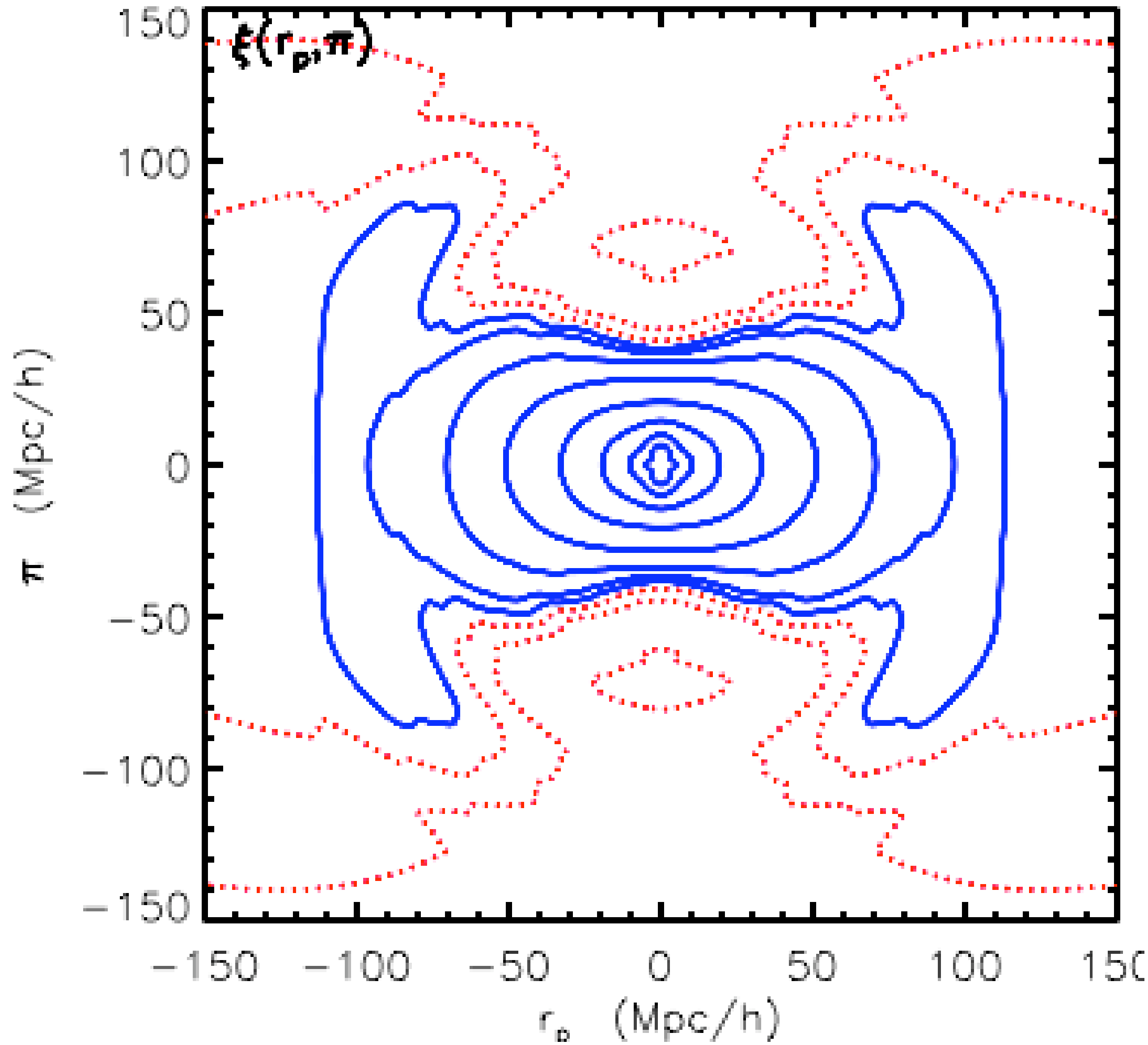


Modeling this?

Fortunately it is a smooth variation on the scales of interest.



And can be simulated



Galaxy bias

- The hardest issue is galaxy bias.
  - Galaxies don't faithfully trace the mass
- ... but galaxy formation "scale" is << 100Mpc so effects are "smooth".
  - In $P(k)$ effect of bias can be approximated as a smooth multiplicative function and a smooth additive function.
- Work is on-going to investigate these effects:
  - Seo & Eisenstein (2005)
  - White (2005)
  - Schulz & White (2006)
  - Eisenstein, Seo & White (2007)
  - Huff et al. (2007)
  - Angulo et al. (2007)
  - Smith et al. (2007)
  - Padmanabhan et al. (20XX)

$$\Delta^2_g(k) = B^2(k)\,\Delta^2(k) + C(k)$$

Rational functions or polynomials

Statistics

- Extracting science from surveys always involves a comparison of some statistic measured from the data which can be computed reliably from theory.
  - Theory probably means simulations.
- Significant advances in statistical estimators in the last decade (CMB and SDSS)
- Open questions:
  - Which space should we work in?
    - Fourier or configuration space?
  - What is the best estimator to use?
    - $P(k)$, $\xi(r)$, $\Delta\xi(r)$, $\omega_l(r_s)$, … ?
  - How do we estimate errors?
    - Assume Gaussian, mock catalogs, …

Conclusions

- Baryon oscillations are a firm prediction of CDM models.
- The acoustic signature has been detected in the SDSS!
- With enough samples of the density field, we can measure $d_A(z)$ and $H^{-1}(z)$ to the percent level and thus constrain DE.
- Require "only" a large redshift survey - we have a >20 years of experience with redshift surveys.
- Linear theory is under control if have *Planck* CMB data.
- We are close to a "turn-key" method for analyzing mock observations which returns unbiased estimates of *s*.
- It may be possible to "undo" non-linearity.
- Understanding structure and galaxy formation to the level required to maximize our return on investment will be an exciting and difficult challenge for theorists!

Further reading

- `cdm.berkeley.edu/doku.php?id=baopages`
- `cmb.as.arizona.edu/~eisenste/acousticpeak/`
- `mwhite.berkeley.edu/BAO/`
- Eisenstein D., 2005,
  - Dark energy and cosmic sound,
  - New Astronomy Reviews, 49, 360
- Glazebrook K., et al., 2005
  - WFMOS white paper to the DETF
  - astro-ph/0507457