Baryon Acoustic Oscillations: A standard ruler method for determining the expansion rate of the Universe.

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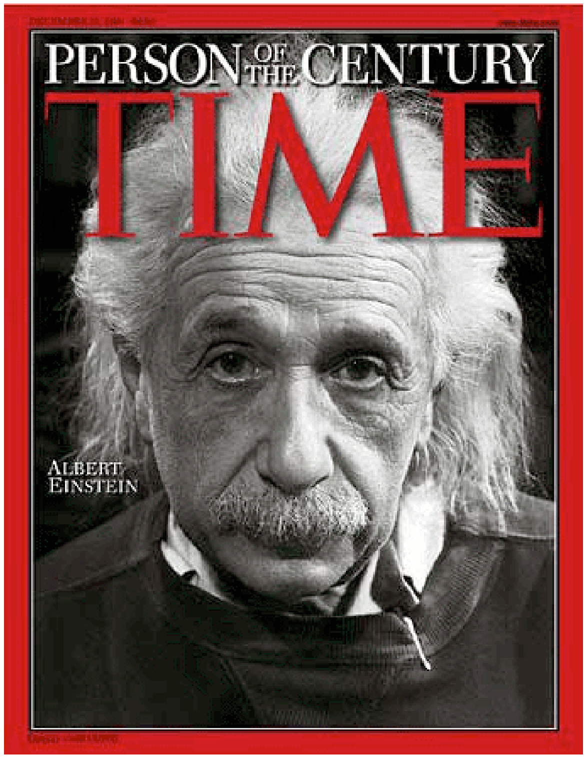
Outline

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

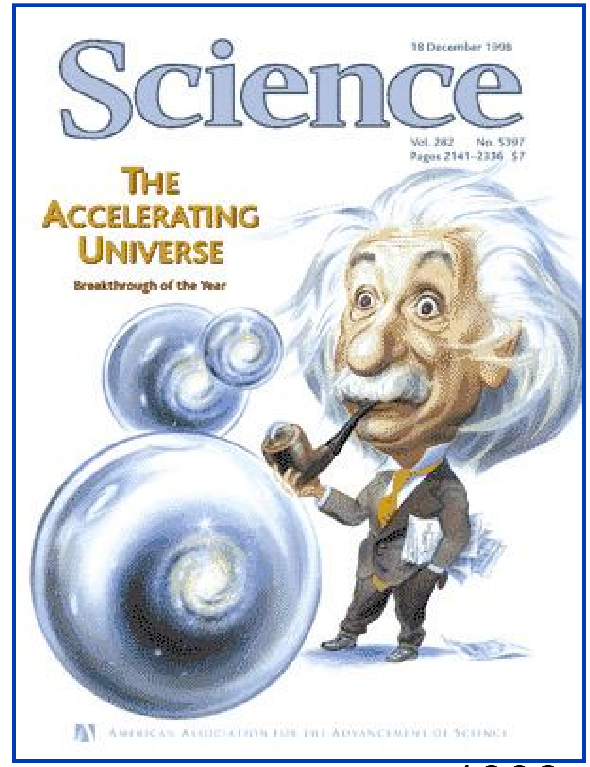
Eisenstein, New Astronomy Reviews, 49, 360, 2005
http://cmb.as.arizona.edu/~eisenste/acousticpeak/
http://cdm.berkeley.edu/doku.php?id=baopages

Beyond Einstein?



1919

Our theories of the Universe are based upon General Relativity which, like Newton's theory, predicts that gravity is an attractive force which would act to slow any existing expansion.



1998

The discovery that the expansion of the Universe is currently accelerating was heralded as the "Breakthrough of the year" by *Science* in 1998.

Dark energy

- There are now several independent ways to show that the expansion of the Universe is accelerating.
- This indicates that:

a) Our theory of gravity (General Relativity) is wrong.
b) The universe is dominated by a material which violates the strong energy condition: $\rho+3p>0$.

- If (b) then it cannot be any fluid we are familiar with, but some weird "stuff" which dominates the energy density of the Universe (today). We refer to it as "dark energy".
- The most prosaic explanation is Einstein's cosmological constant, which can be interpreted as the energy of empty space.

Dark energy equation of state

- The amount of dark energy is actually quite well constrained by present data:

  $\rho_{DE} = (1.43 \pm 0.09) \times 10^{-29}$ g/cm^3
- What distinguishes models is the time-evolution of ρ_{DE}
- This is usually described by the equation of state: $w = p/\rho$.
  - A cosmological constant, vacuum energy, has w=-1.
  - Many (most) dark energy models have w>-1, and time evolving.
- So the "holy grail" of DE research is to demonstrate that $w \neq -1$ at any epoch.

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 (w=p/ρ) 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.

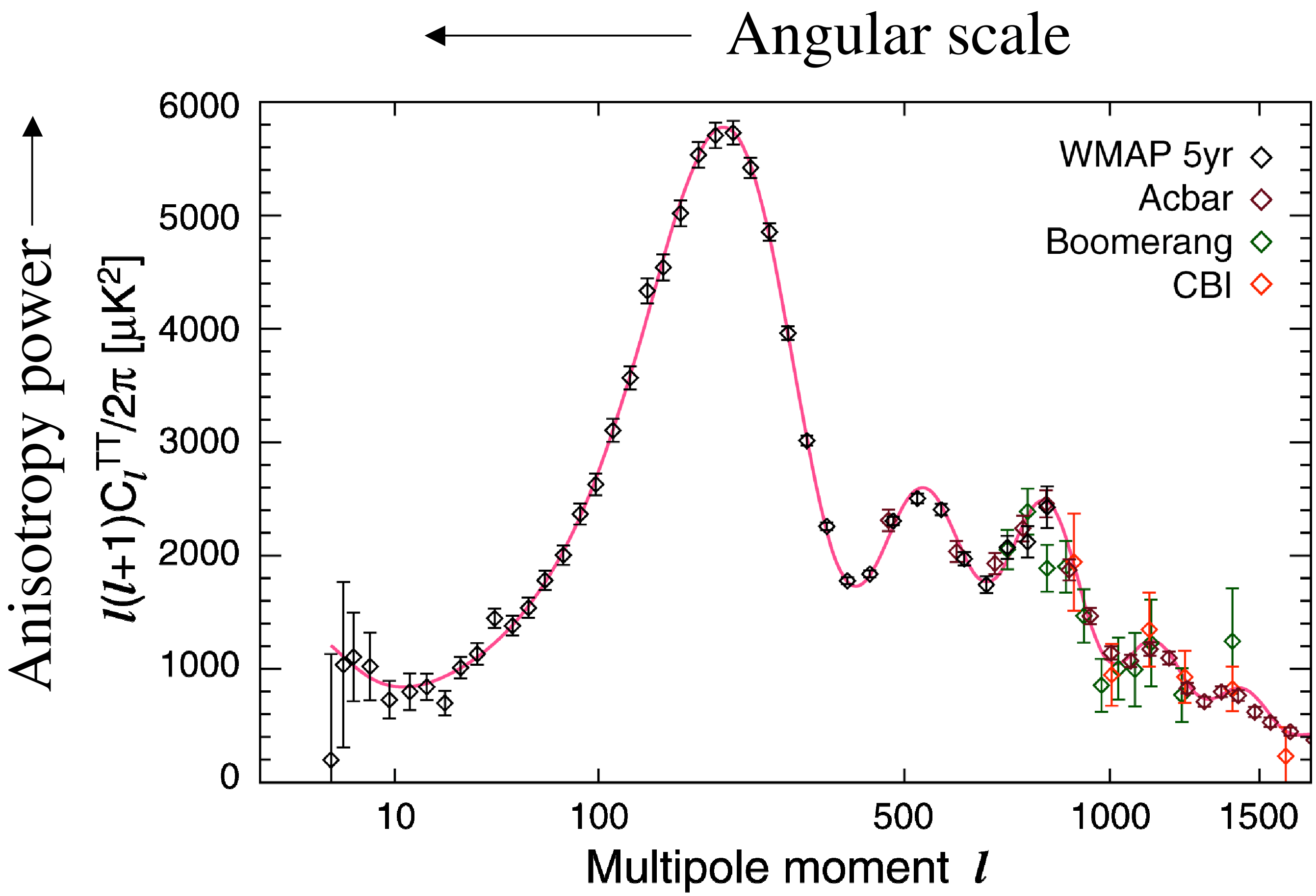
Where do we find such a ruler?

- Cosmological objects can probably never be uniform enough.
- 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.

Sunyaev & Zel'dovich (1970); Peebles & Yu (1970); Doroshkevitch, Sunyaev & Zel'dovich (1978); …; Hu & White (1996); 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.

Hinshaw et al. (2008)

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 with $\delta_\gamma \propto \delta_b$.
- Consider a (standing) plane wave perturbation of comoving wavenumber *k.*
- If we expand the Euler equation to first order in the Compton mean free path over the wavelength we obtain

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

The cartoon

- These perturbations show up as temperature fluctuations in the CMB.
- Since $\rho \sim T^4$ for a relativistic fluid the temperature perturbations look like:

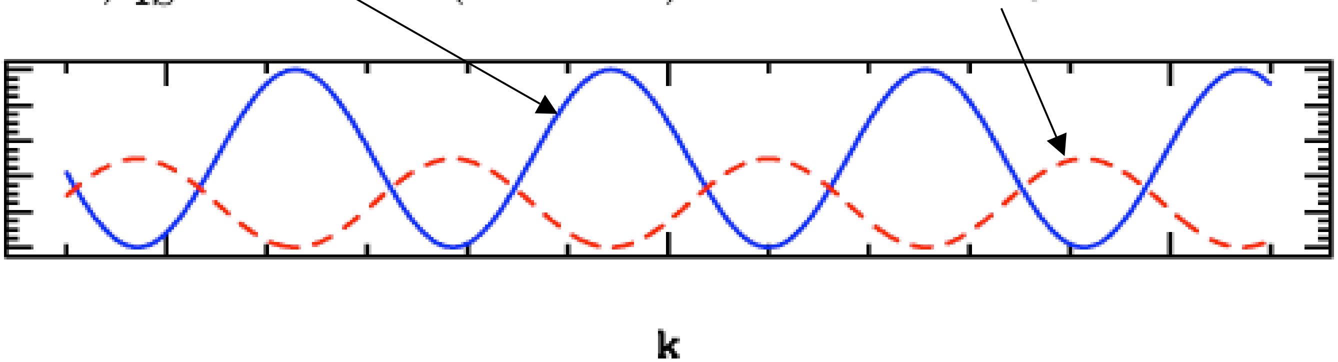
$$\Delta T \sim \delta\rho_\gamma^{1/4} \sim A(k)\cos(kc_s t)$$ [harmonic wave]

- … plus a component due to the velocity of the fluid (the Doppler effect).

The cartoon

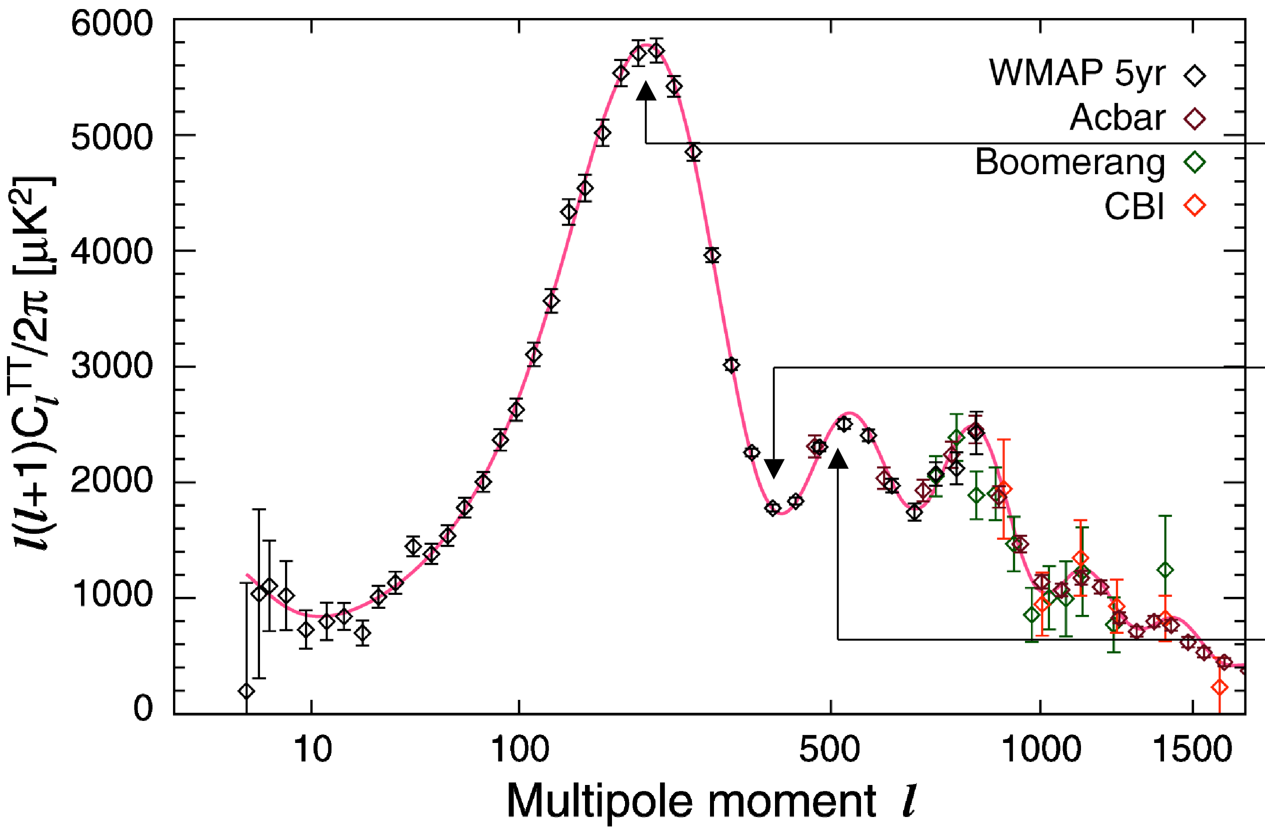
- A sudden “recombination” decouples the radiation and matter, giving us a snapshot of the fluid at “last scattering”.

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



- 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 $kc_s t_{ls}=\pi$. Density maxm, velocity null.

Velocity maximum

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

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.

$$s = 146.8 \pm 1.8 \text{ Mpc}$$ WMAP 5th yr data

$$= (4.53 \pm 0.06) \times 10^{24}\text{m}$$

↑

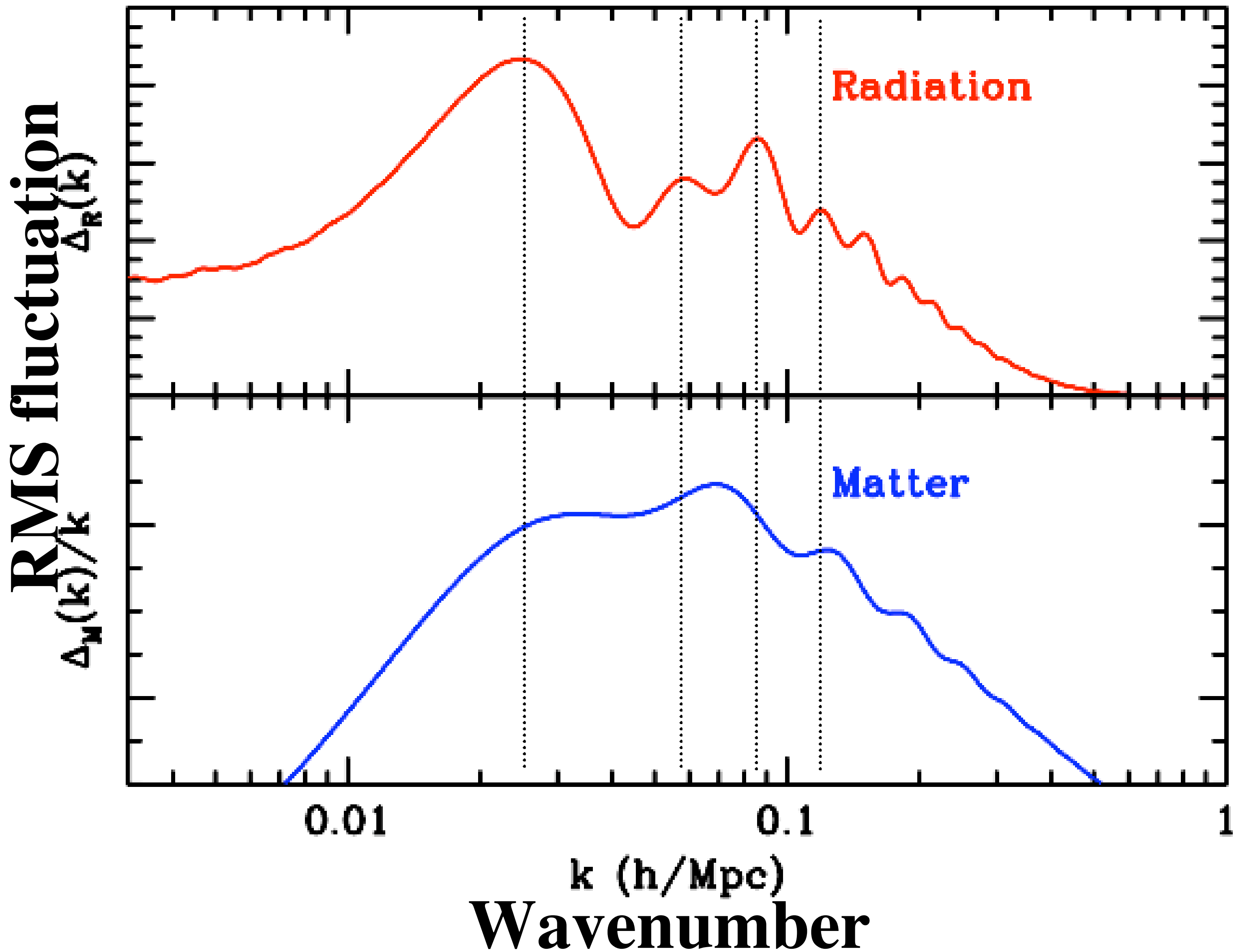
Dominated by uncertainty in ρ_m from poor constraints near 3rd peak in CMB spectrum. (Planck will nail this!)

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 $\Omega_b/\Omega_m \sim 0.1$

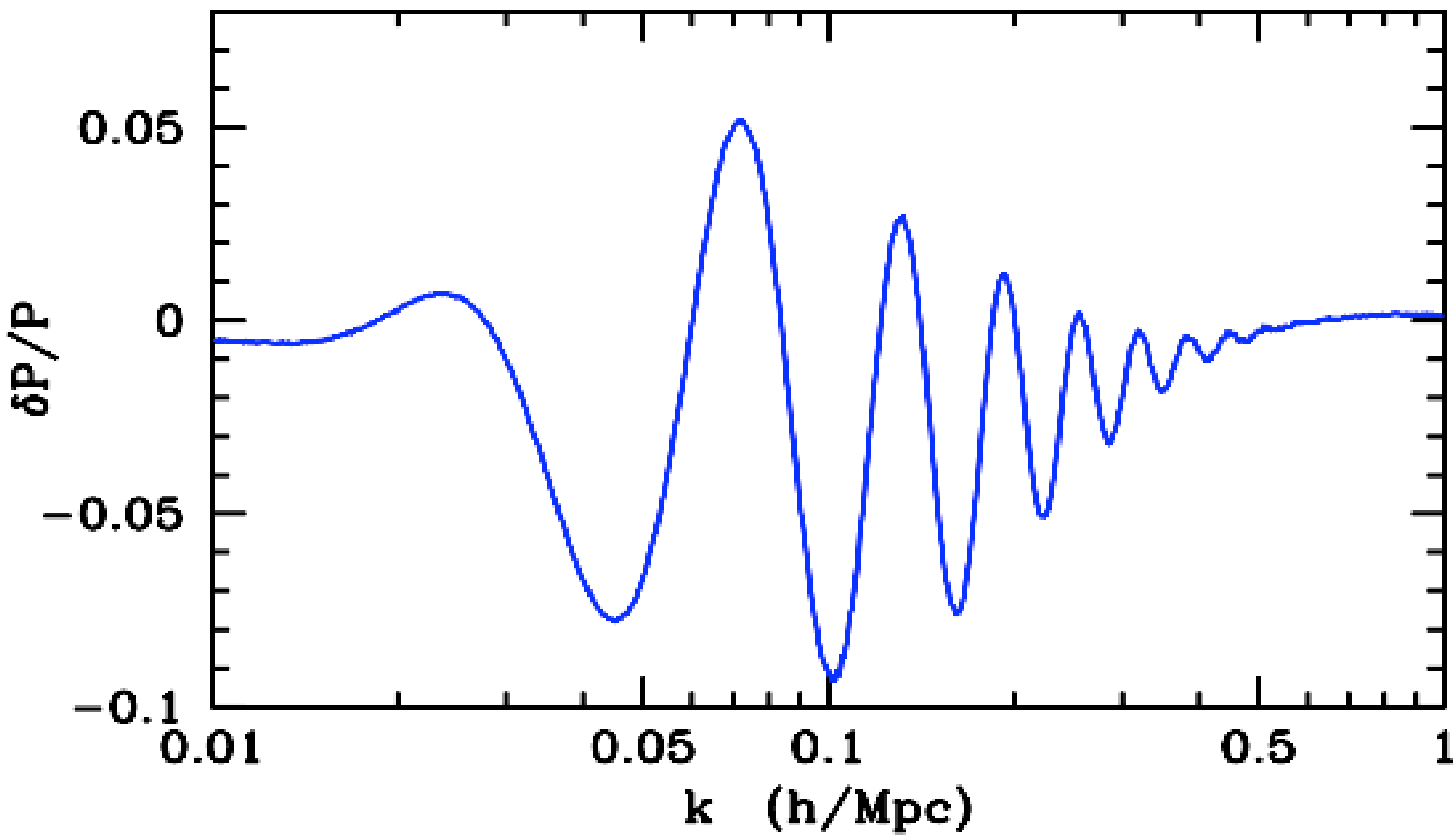
- **Note:** all of the matter sees the acoustic oscillations, not just the baryons.

Baryon (acoustic) oscillations



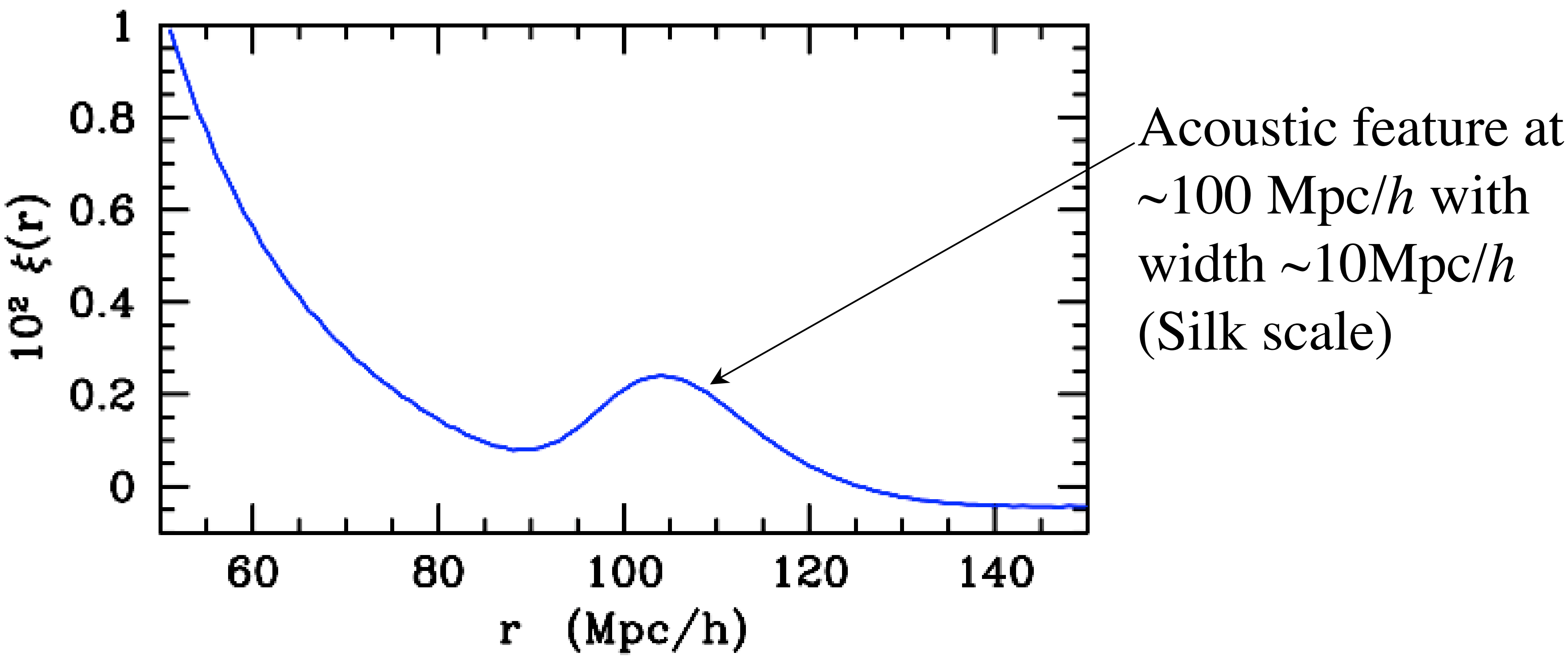
Divide out the gross trend …

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.



Configuration space

In configuration space on uses a Green's function method to solve the equations, rather than expanding *k*-mode by *k*-mode. (Bashinsky & Bertschinger 2000)

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, …]

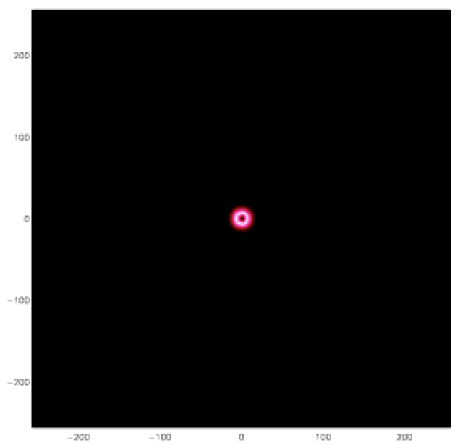
In general the solutions are unenlightening, but in some very simple cases you can see the main physical processes by eye, e.g. a pure radiation dominated Universe:

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

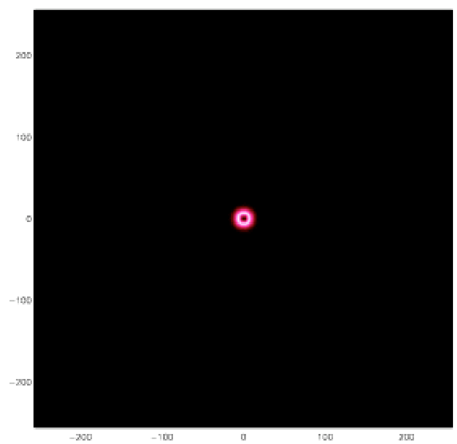
The acoustic wave

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

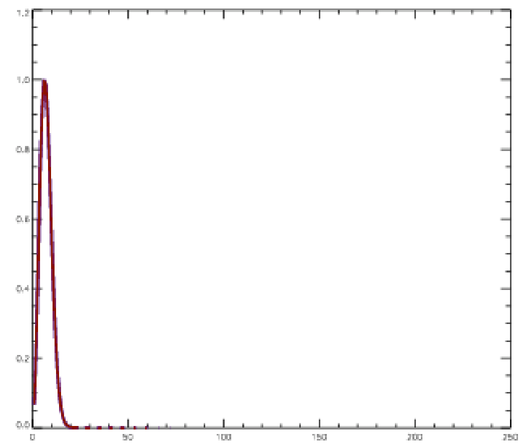
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Baryons



Photons

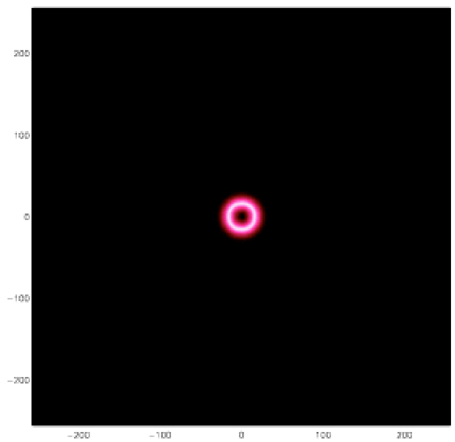


Mass profile

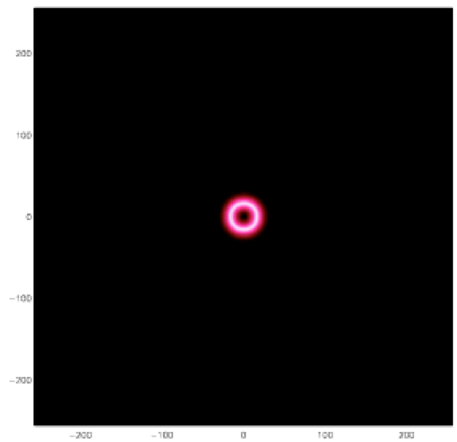
Eisenstein, Seo & White (2006)

The acoustic wave

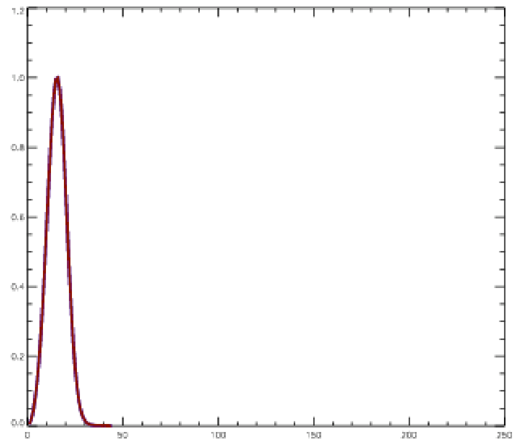
Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



Baryons

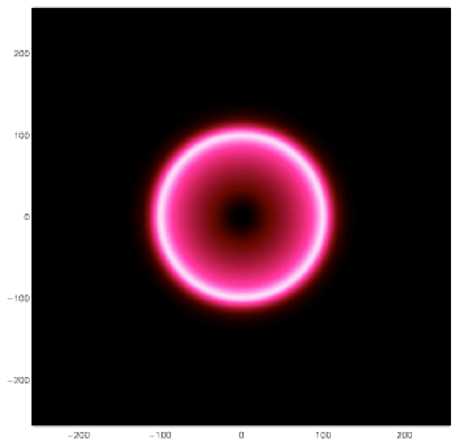


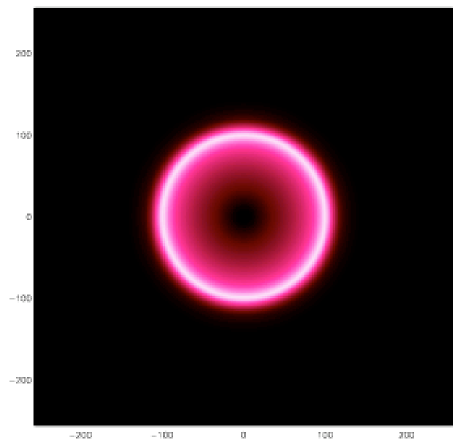
Photons

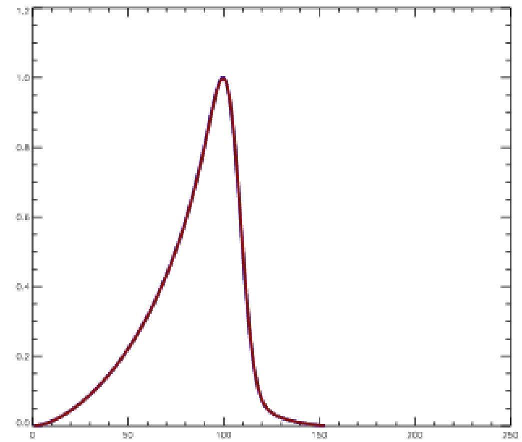


The acoustic wave

This expansion continues for 10^5 years

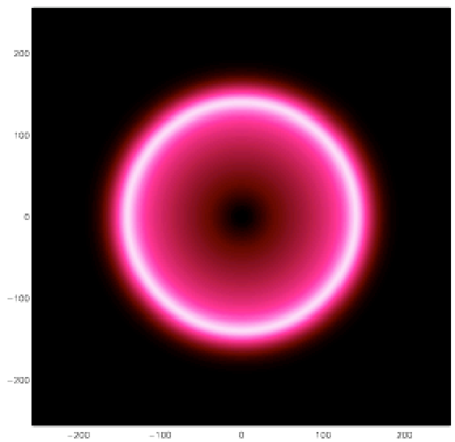


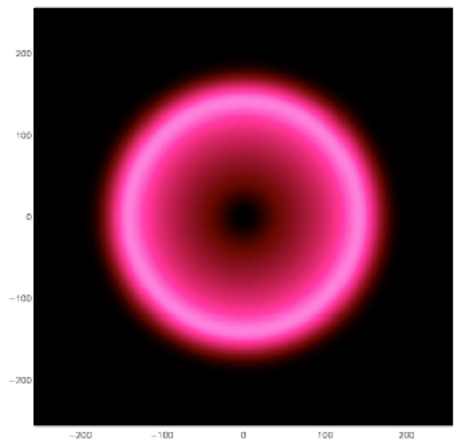


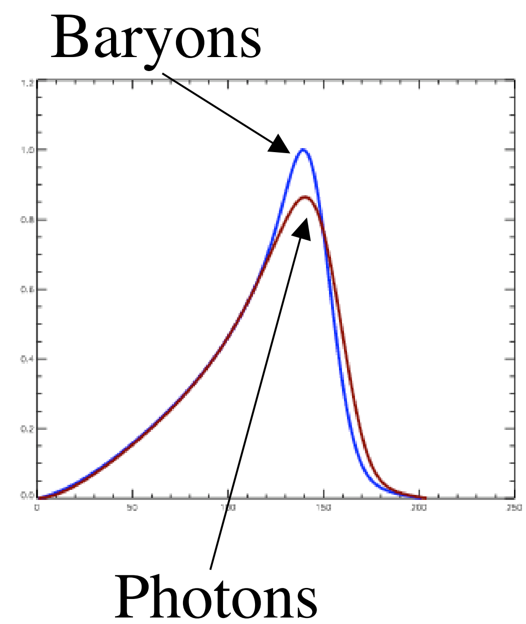


The acoustic wave

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.

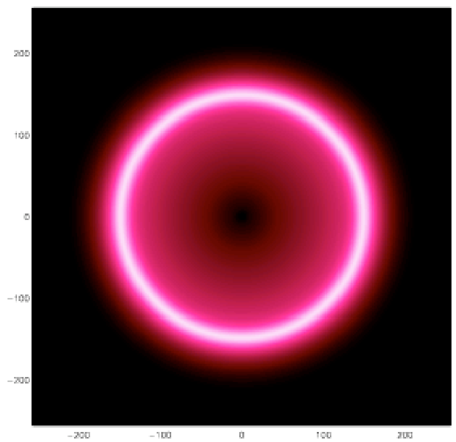


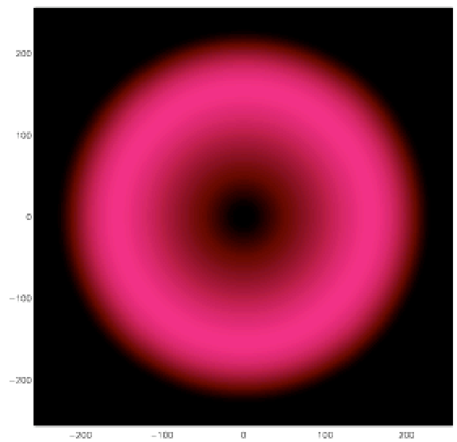


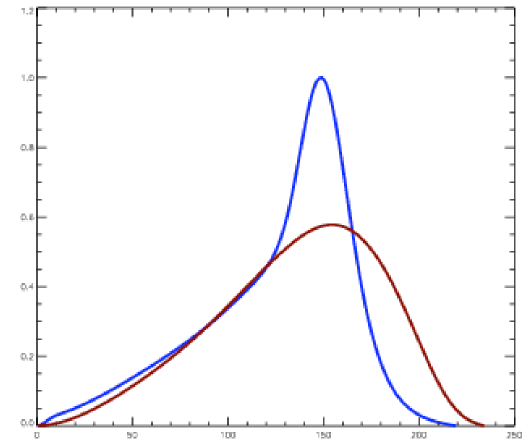


The acoustic wave

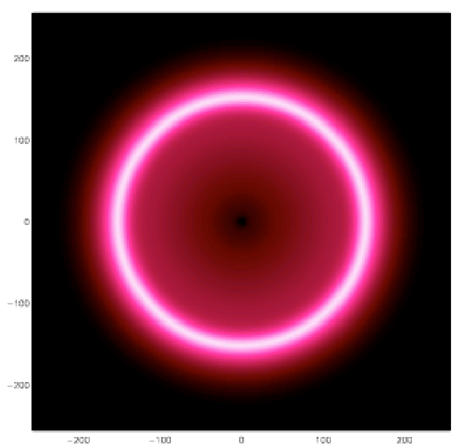
The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.

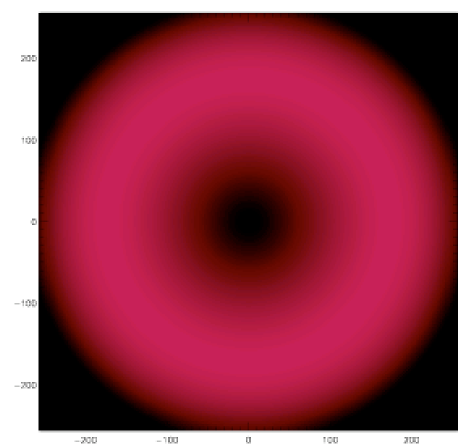


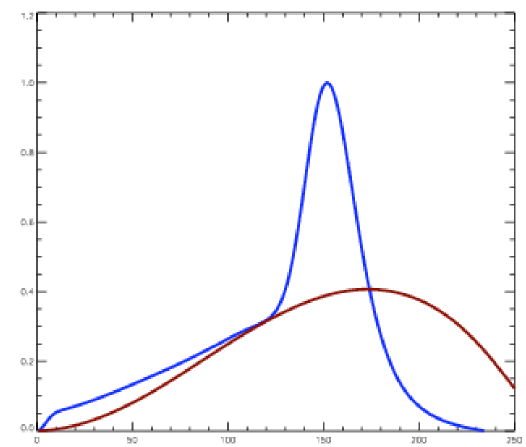




The acoustic wave



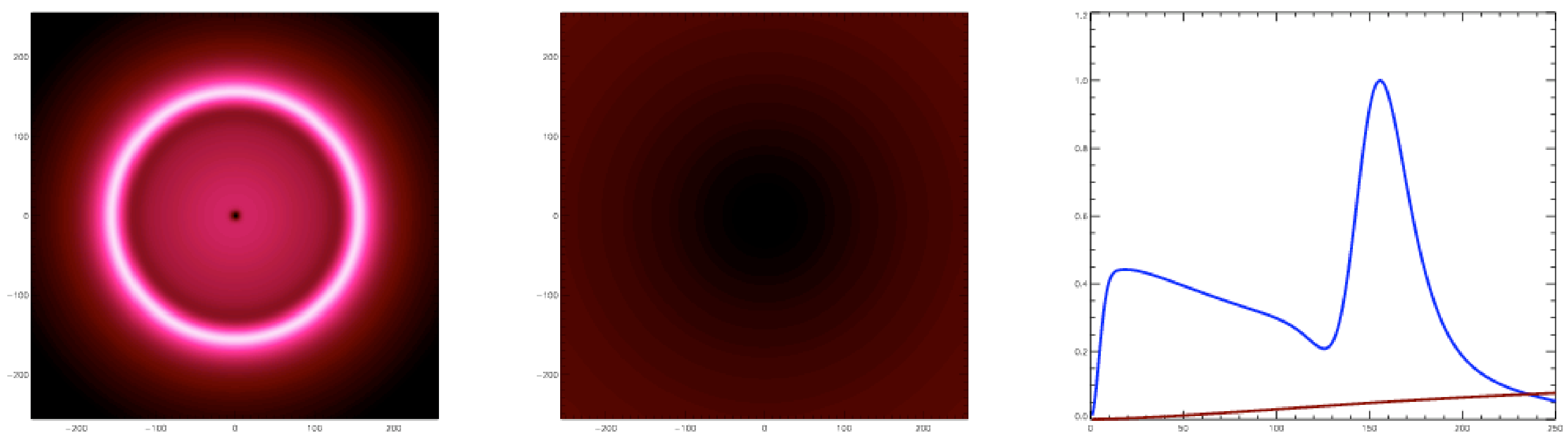




The acoustic wave

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

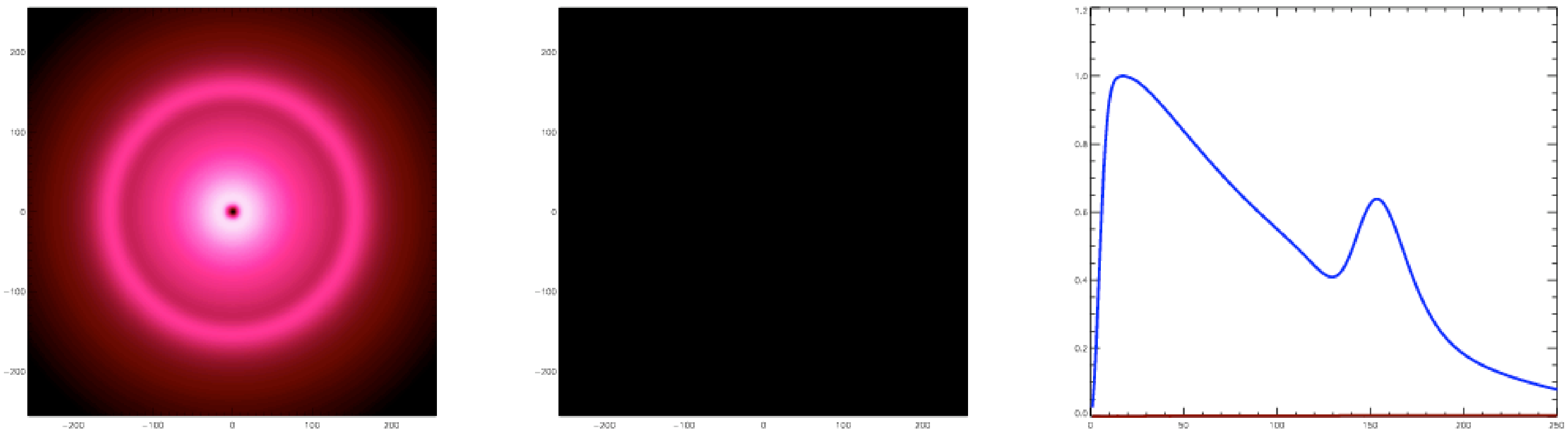
In addition, the large gravitational potential well which we started with starts to draw material back into it.



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.



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 …

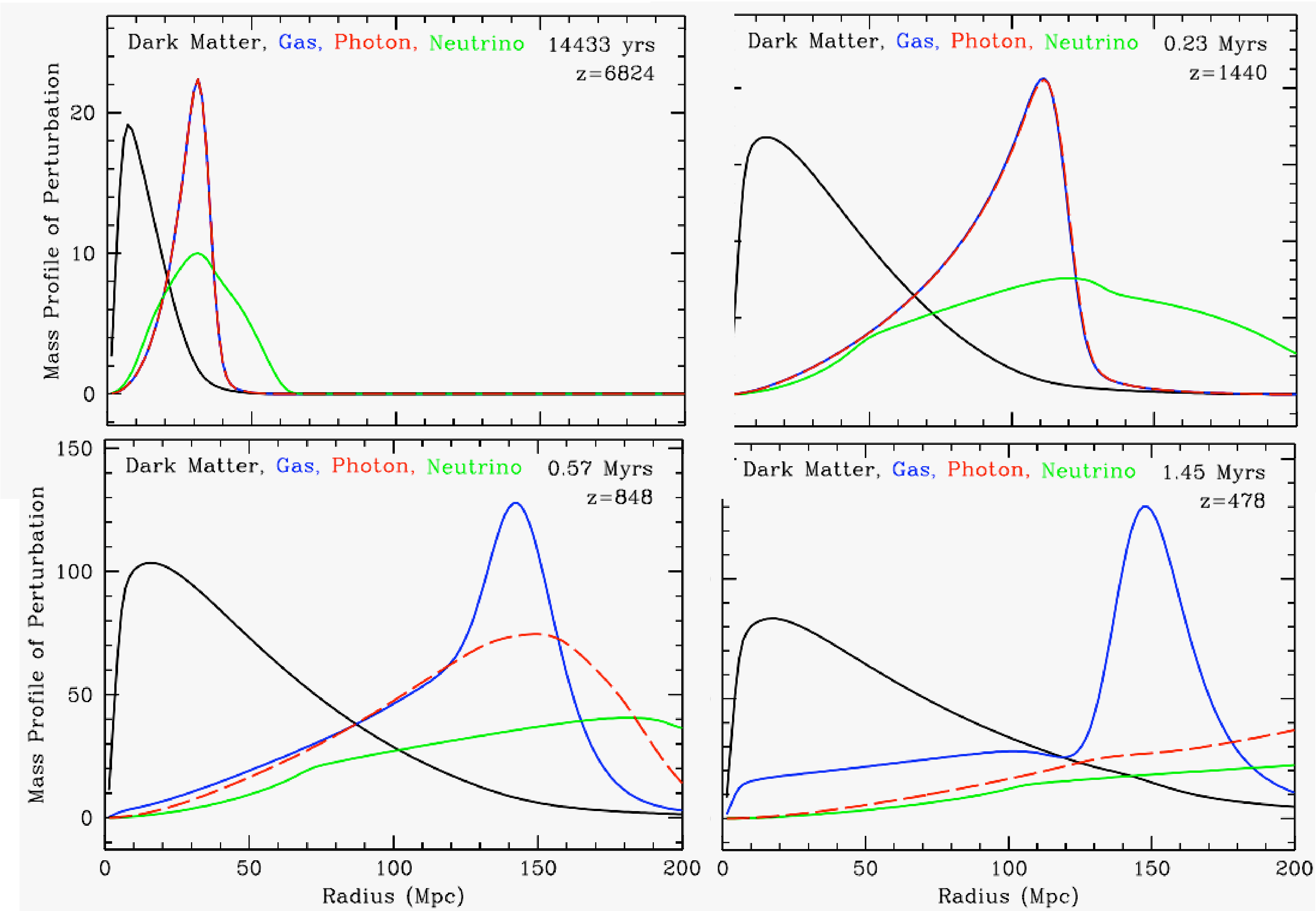
Features of baryon oscillations

- 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!

Aside:broad-band shape of *P(k)*

- This picture also allows us a new way of seeing why the DM power spectrum has a “peak” at the scale of M-R equality.
- Initially our DM distribution is a δ-function.
- As the baryon-photon shell moves outwards during radiation domination, its gravity “drags” the DM, causing it to spread.
- The spreading stops once the energy in the photon-baryon shell no longer dominates: after M-R equality.
- The spreading of the δ-function $\rho(r)$ is a smoothing, or suppression of high-*k* power.

Shape of $P(k)$ in pictures



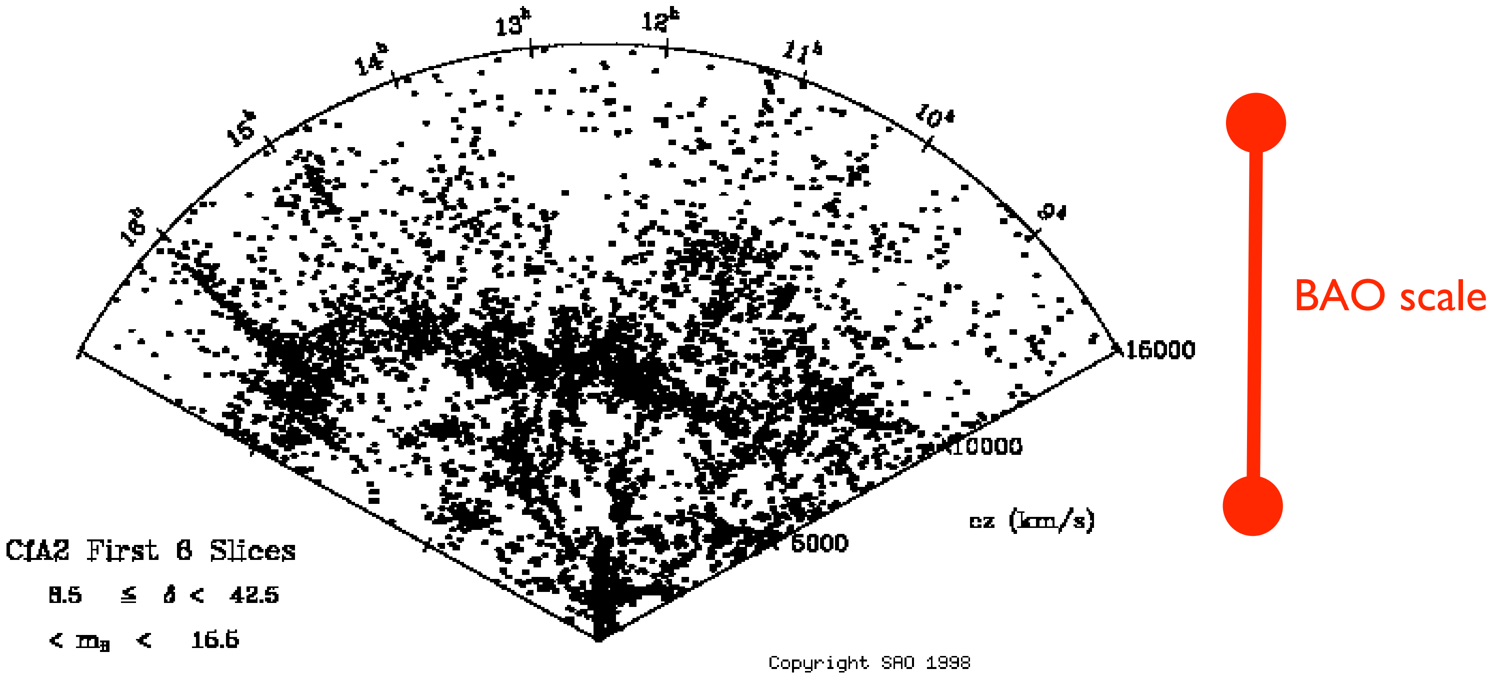
Eisenstein, Seo & White (2007)

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

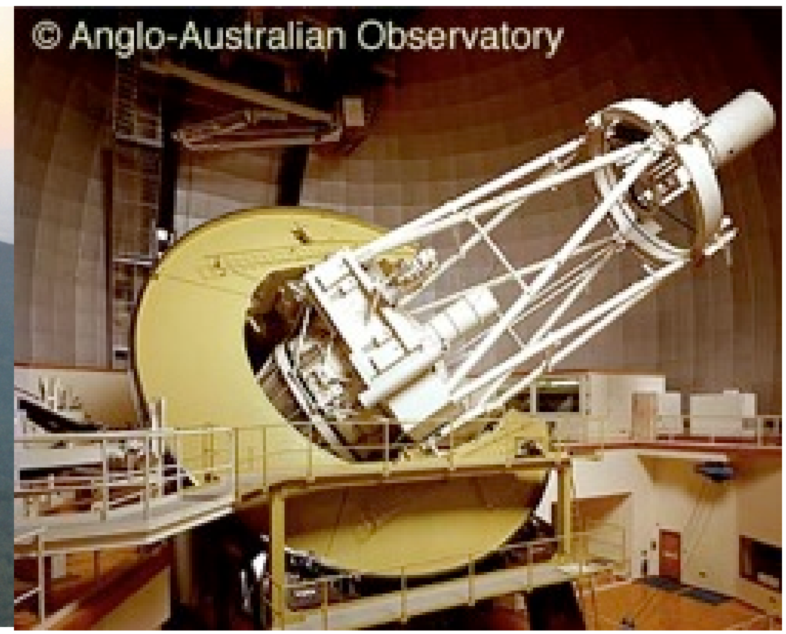


CfA2 redshift survey (Geller & Huchra 1989)

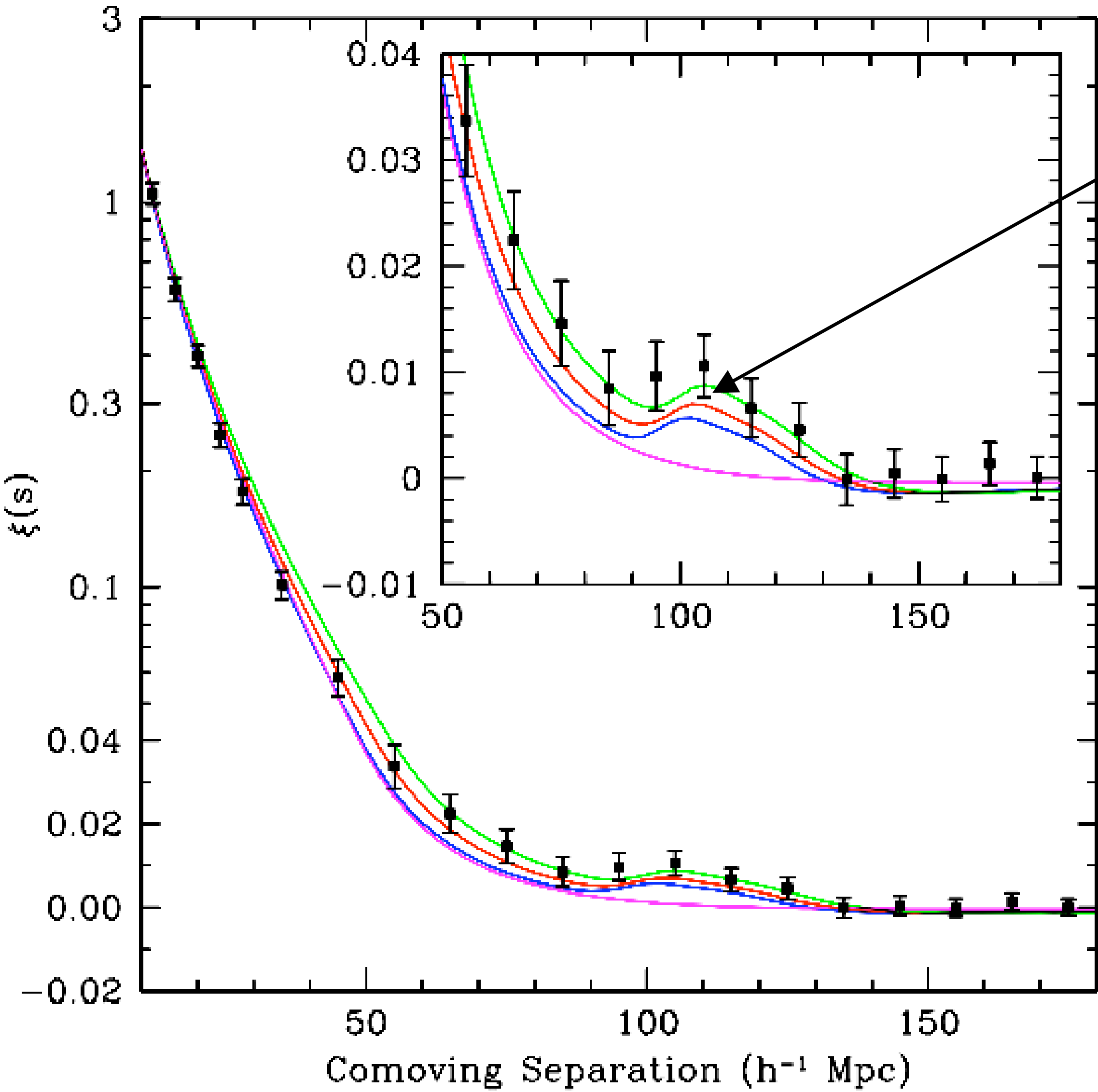
Formally, this could “measure” BAO with a ~0.05σ detection

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 $(h^{-1}\ Gpc)^3$
2. Cole et al 2005
   - 3D map from 2dFGRS at AAO
   - 221,000 galaxies in 0.2 $(h^{-1}Gpc)^3$
3. Hutsi (2005ab)
   - Same data as (1).
4. Padmanabhan et al 2007
   - Set of 2D maps from SDSS
   - 600,000 galaxies in 1.5 $(h^{-1}Gpc)^3$
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)
9. Gaztanaga et al. 2008b
   - (measure of H)

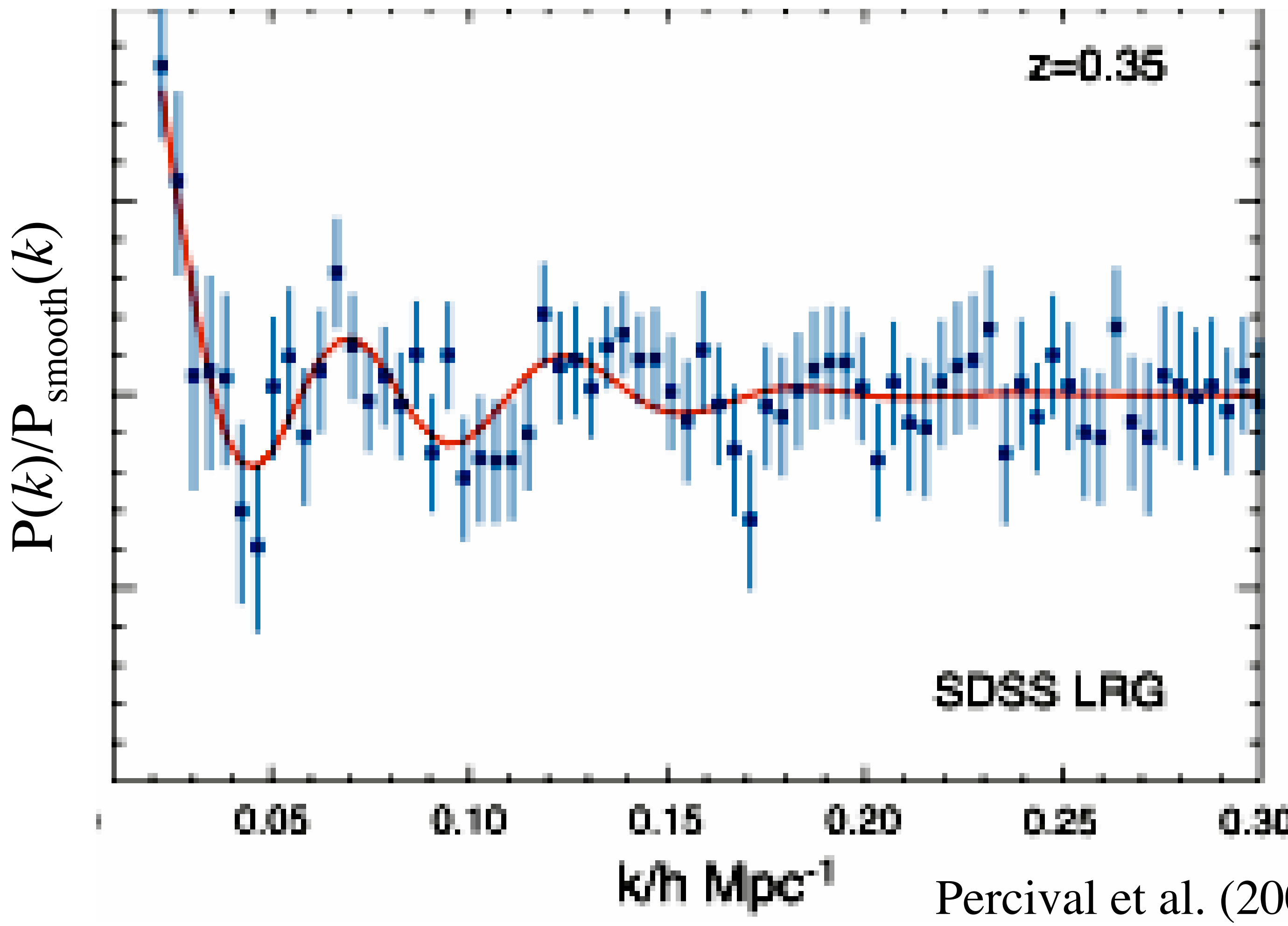
(spectro-z)
4% distance measure

(spectro-z)
5% distance measure

(photo-z)
6% distance measure

(spectro-z)
Detection

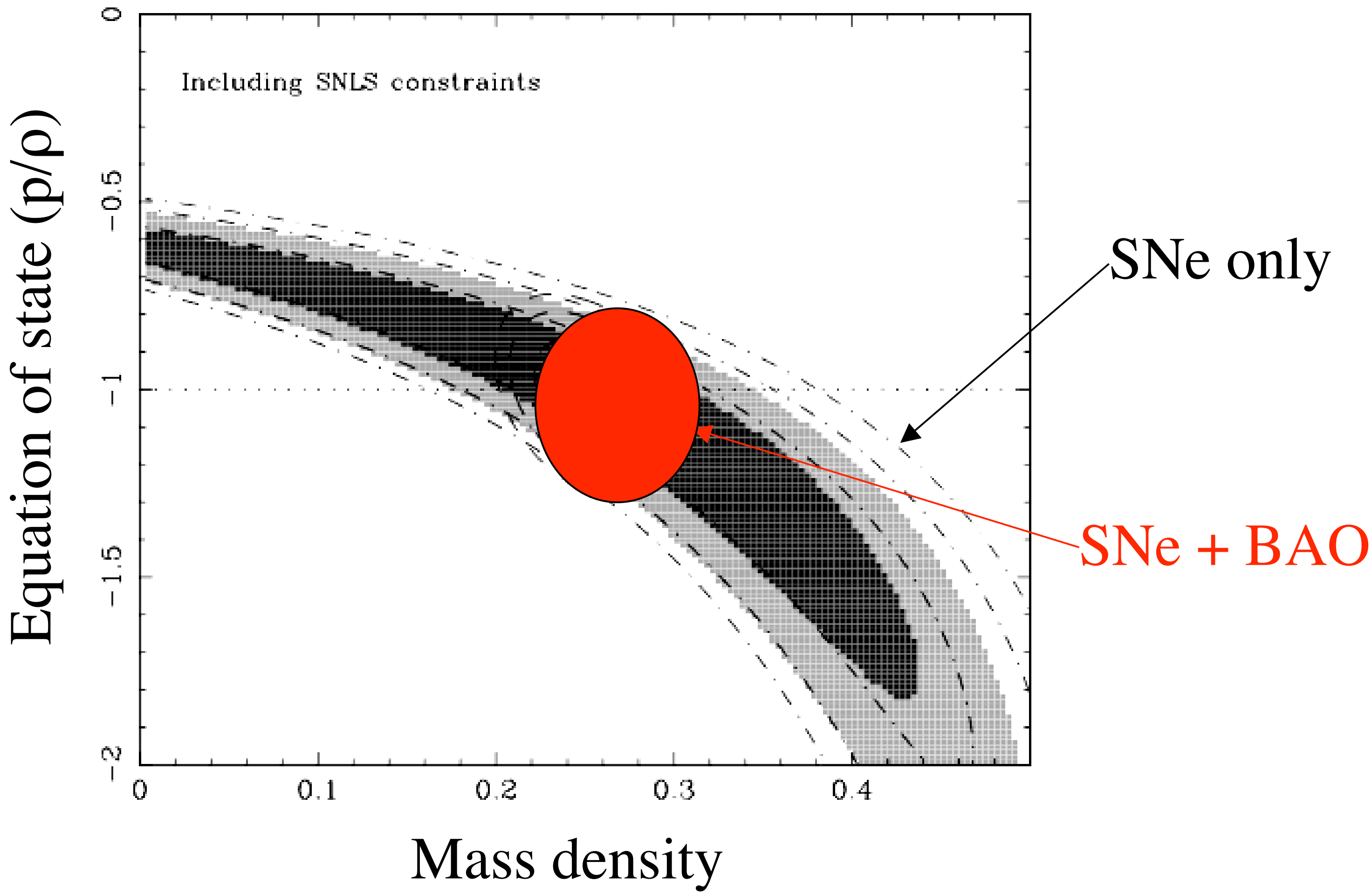
Current combined constraints



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

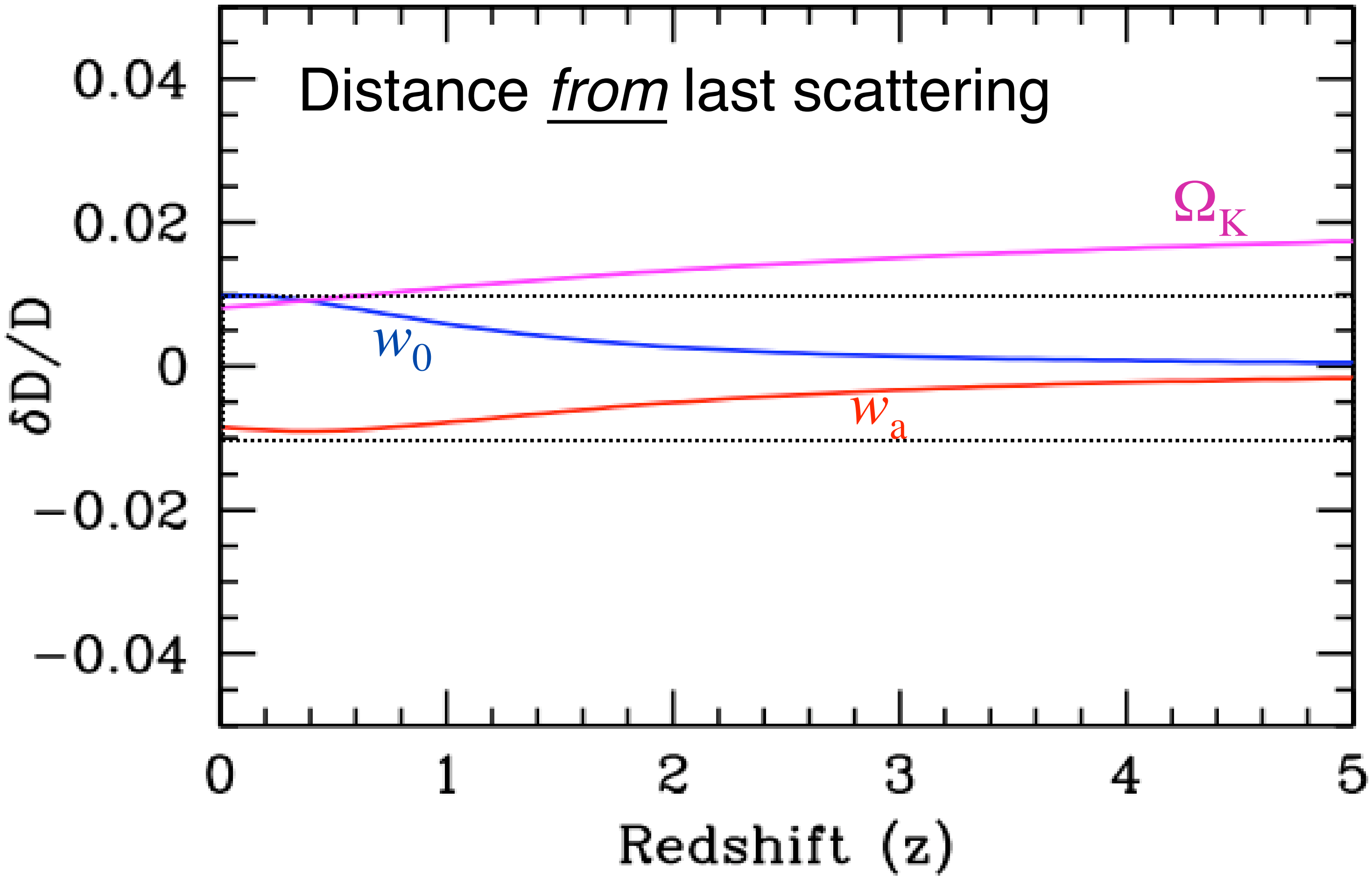
- There are now proposals for several next-generation BAO surveys, both spectroscopic and photometric.
  - Photometric surveys generally deeper and wider.
  - Not a requirements driver if already doing weak lensing.
  - More susceptible to systematic errors in *z* determination.
  - Generally takes 3-10x 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.

The landscape

- It’s difficult to do BAO at very low z, because you can’t get enough volume.
- BAO surveys “turn on” around z~0.3 and can go as high as z~3.
- A point at high z constrains Ω_K
  - Allowing focus on w_0 and w_a at lower z.
- Lower z very complementary to SNe.
  - Completes distance triangle, constrains curvature.
  - Ground BAO+Stage IV SNe (opt), FoM ↑~6x.
- Tests of GR?
  - Can do lensing from BAO, but weak constraint.
  - Assuming GR, distances give $\delta(z\sim1)/\delta(z\sim10^3)$ to <1%.
  - A spectroscopic survey that does BAO can use redshift space distortions to measure the temporal metric perturbations (c.f. WL which measures sum of temporal and spatial) and hence constrain dD/dln(a).

Distances

In the standard parameterization the effects of DE are confined to low *z*, and are (partially) degenerate with curvature. A high *z* measurement can nail down the curvature, removing the degeneracy.



Not-so-next-generation surveys

While the final round of data (DR7) from SDSS-I & II hasn't been analyzed yet the "next" generation of surveys is already underway.

Project	Redshift	Area (sq. deg.)	n (10^{-4})
WiggleZ	0.4-1.0	1,000	3.0
HETDEX	2.0-4.0	350	3.6
SDSS-III (BOSS)	0.1-0.8 + 2.0-3.0	10,000 + 8,000	3.0
Pan-STARRS*	0-1	20,000	10

With more waiting in the wings …

BOSS in a nutshell

BOSS is part of SDSS-III which started July 2008

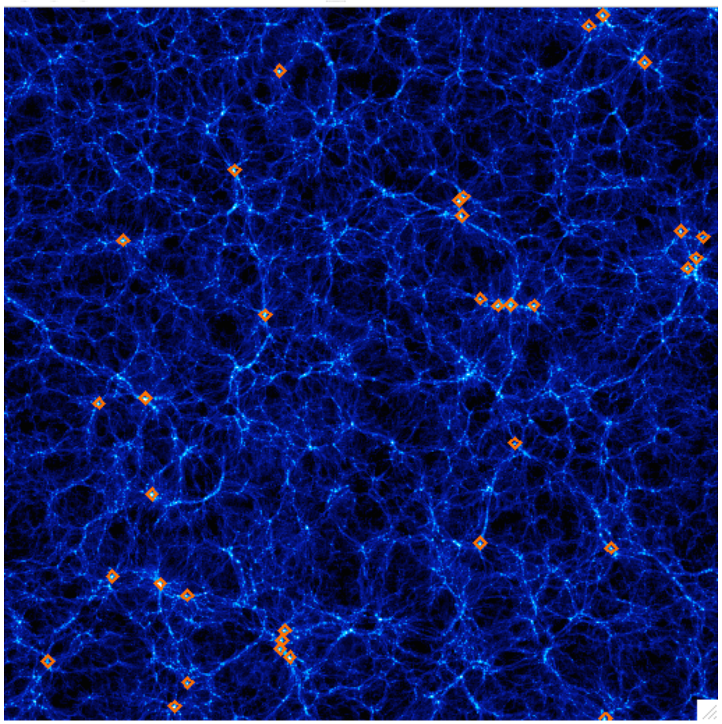
- Image additional 2000 deg^2 in Fall by end of 2008
- BOSS will then have:
  - 8500 deg^2 footprint in Spring
  - 2500 deg^2 footprint in Fall
- Upgrade spectrographs in summer 2008 or 2009
  - Replace 640x 3-arcsec fibres with 1000x 2-arcsec fibers in cartridges
  - Replace CCDs with (larger/better)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

- 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)

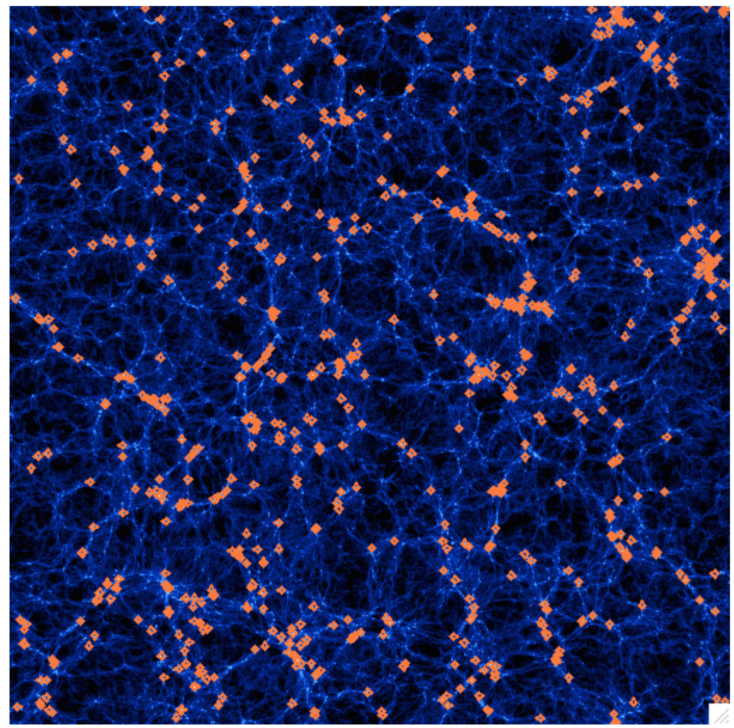
http://www.sdss3.org/

Tracing large-scale structure

The cosmic web at z~0.5, as traced by luminous red galaxies



SDSS



BOSS

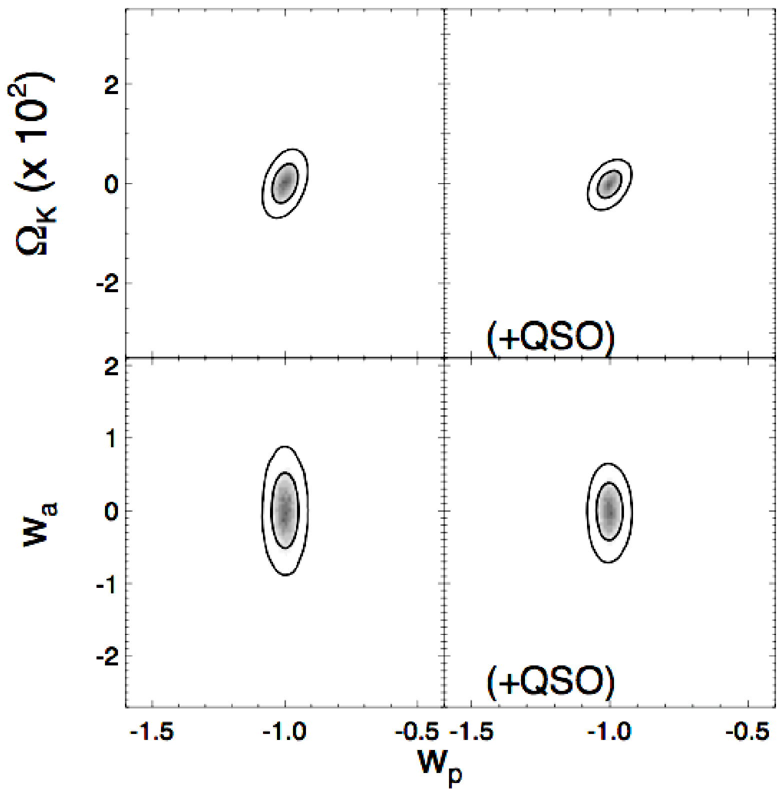
A slice 500h^{-1} Mpc across and 10 h^{-1} Mpc thick

BOSS science

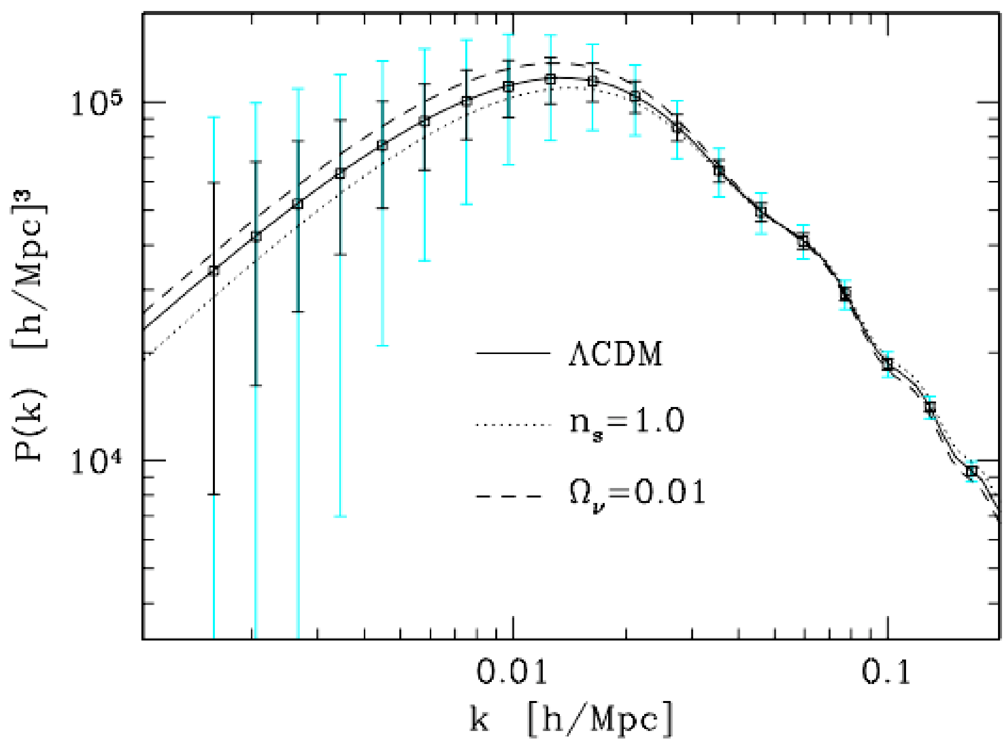
Like SDSS-I and II, BOSS will provide a rich scientific return including:

- DE constraints
- A 1% H_0 measurement
- A 0.2% Ω_K measurement
- Strong constraints on primordial non-Gaussianity (f_{NL}~10)
- Large scale structure constraints (250,000 modes at k<0.2)
- A S/N=44 measurement of $f\sigma_8$ from redshift space distortions.
- 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 approx. doubles N_{QSO} with z>3.6)
- Galactic structure (C stars)
- Loads of other stuff …

BOSS science II



Dark energy



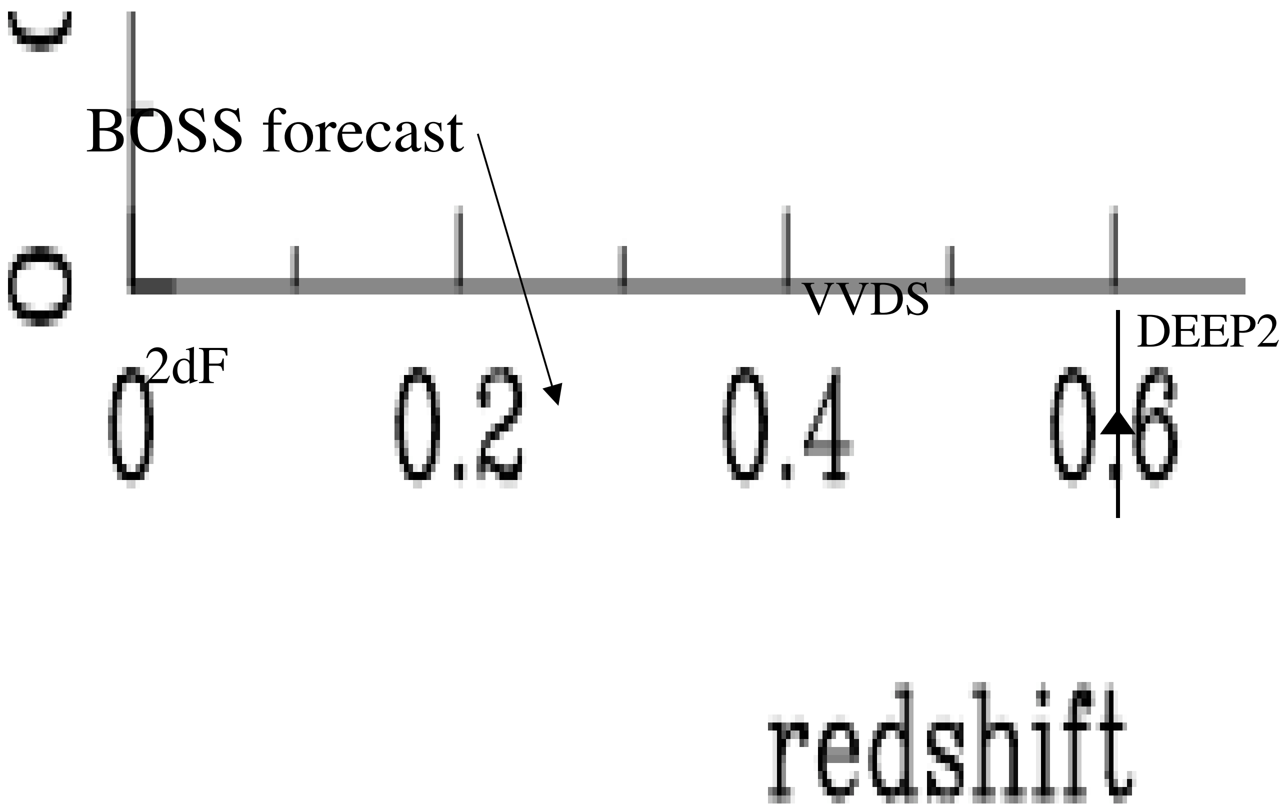
Large-scale structure

δh~0.008, δw_p(z~0.2)~0.03, δw_a~0.3

x1/2 if can model broad-band power!

Growth of structure

Modeling of redshift space distortions allows us to constrain the growth rate of structure, $f\sigma_8 \sim dD/d\ln(a)$.



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?

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 -- or at least our ability to describe -- galaxy formation has also increased dramatically.

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 (of various flavors) find:

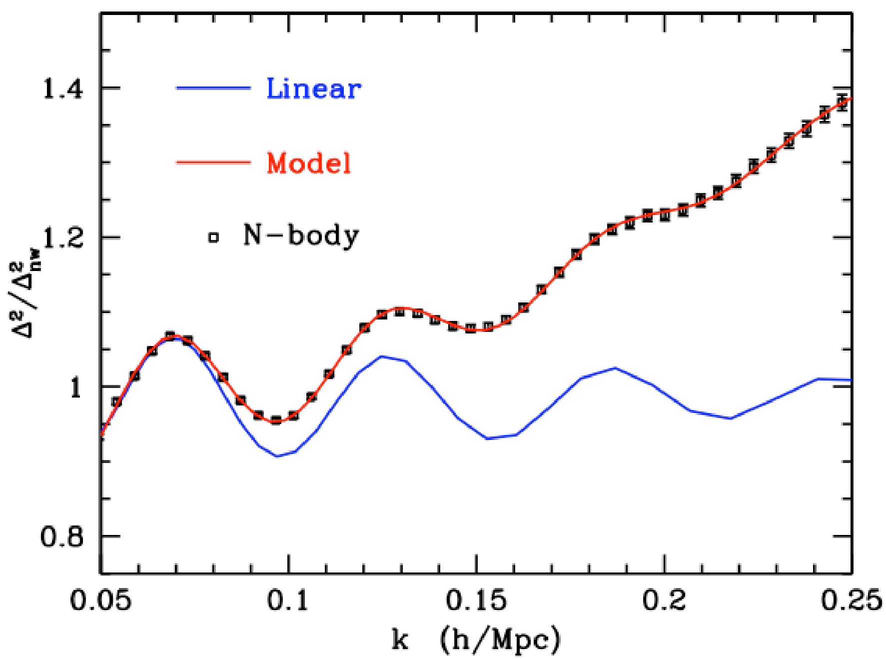
$$\Delta^2(k) = \left\{\Delta^2_{\rm lin}(k) + \cdots\right\} \exp\left[-k_{||}^2\Sigma_{||}^2 - k_\perp^2\Sigma_\perp^2\right] + \Delta^2_{22} + \cdots$$

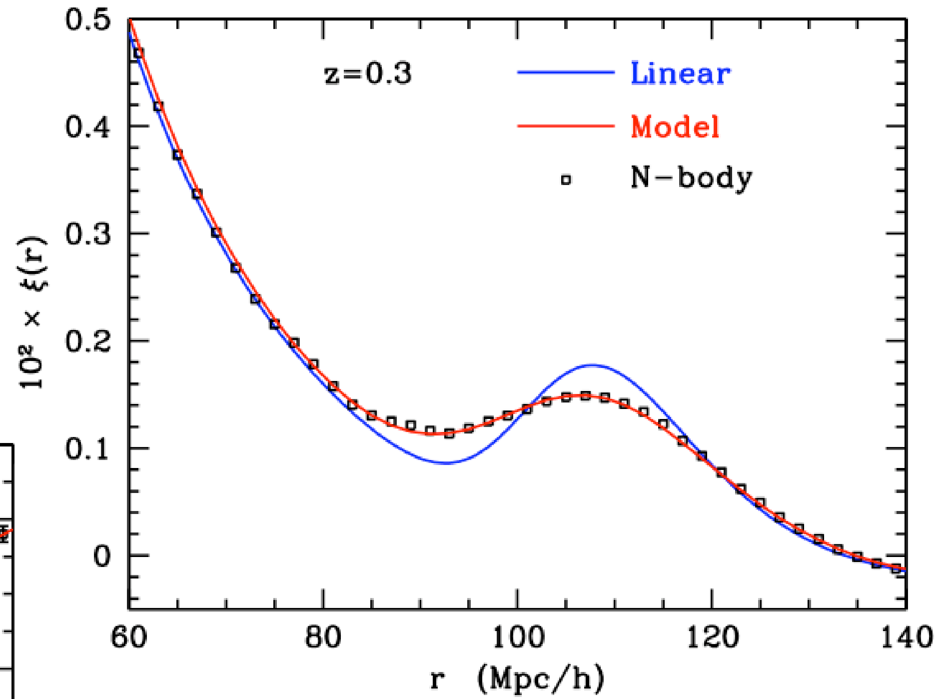
This does a reasonable job of providing a "template" low-z spectrum, and it allows us to understand where the information lives in Fourier space [forecasting].

Eisenstein, Seo & White (2007)
Smith, Scoccimarro & Sheth (2007)
Eisenstein et al. (2007)
Matsubara (2007, 2008)
Padmanabhan et al. (2008)

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.

Information on the acoustic scale

- For a Gaussian random field $\mathrm{Var}[x^2]=2\mathrm{Var}[x]^2$, 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 the error on the sound horizon, s, is:

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

- 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.
- So an optimal survey has a large V, and sets 1/n such that it is less than P for $k<\Sigma^{-1}$

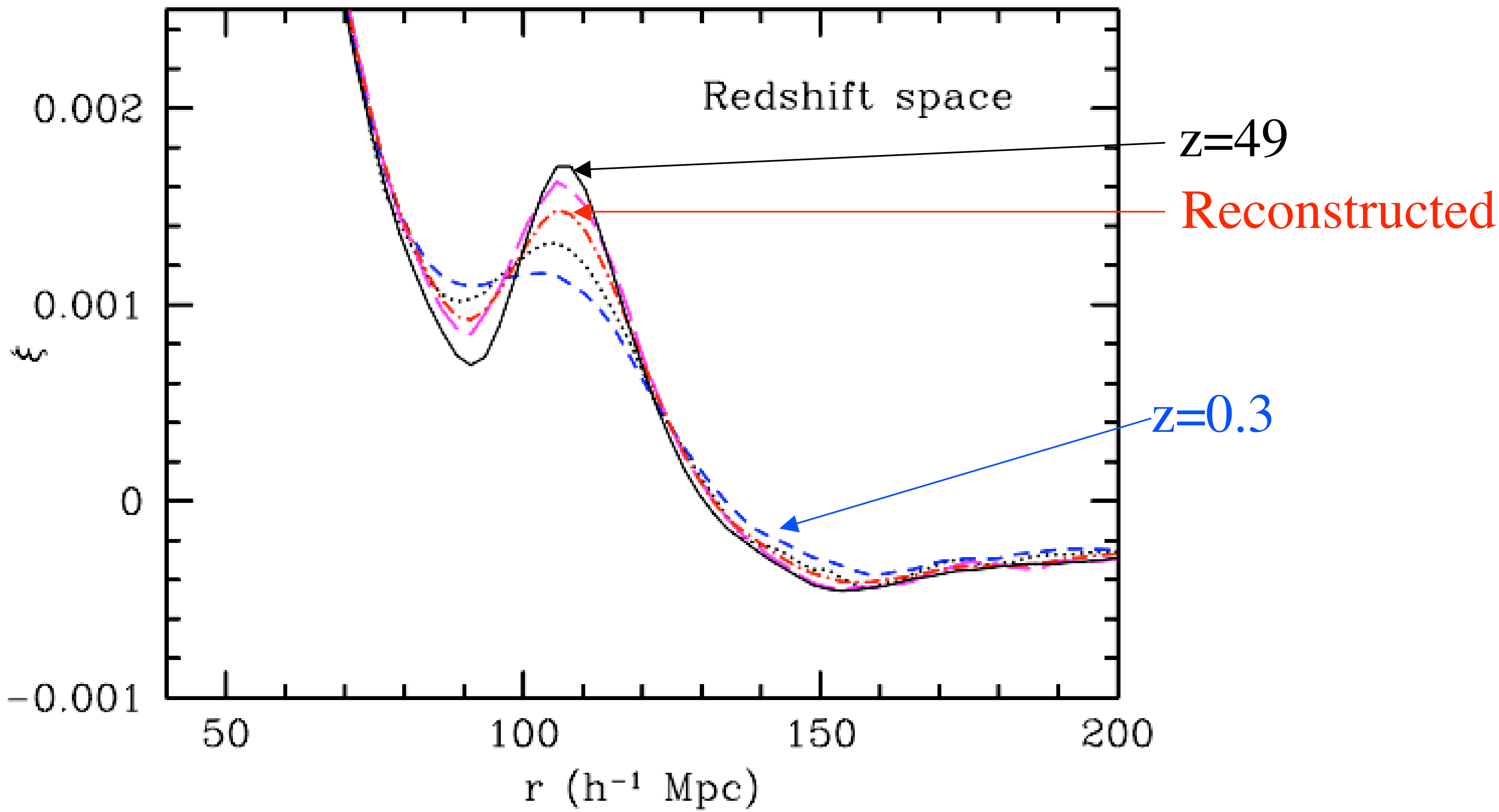
Seo & Eisenstein (2006)

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 $P(k)$.
  - Reconstruction effectively reduces Σ, recovering high k information.
- 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).

Eisenstein et al. (2007)
Huff et al. (2007)
Seo et al. (2008)

Reconstruction: simplest idea



From Eisenstein et al. (2007)

Mode coupling

- BAO may be one of the few places where perturbation theory really helps.
- In perturbation theory I can expand $\delta=\delta_1+\delta_2+\delta_3+\ldots$ where δ_n is n^{th} order in δ_1.
- Under some (not completely justified) assumptions, it is straightforward to write δ_n as integrals over *n* δ_1s:

  $\delta_n(k) = \int\prod dp_j\, \delta^{(D)}(k-\sum p)\, F_n(p_1\ldots p_n)\, \delta_1(p_1)\ldots\delta_n(p_n)$
- The F_n are simply ratios of dot products of the p_n, and can be derived by a simple recurrence relation.
- The power spectrum looks like: $P(k)=P_{11}(k)+P_{13}(k)+P_{22}(k)+\ldots$

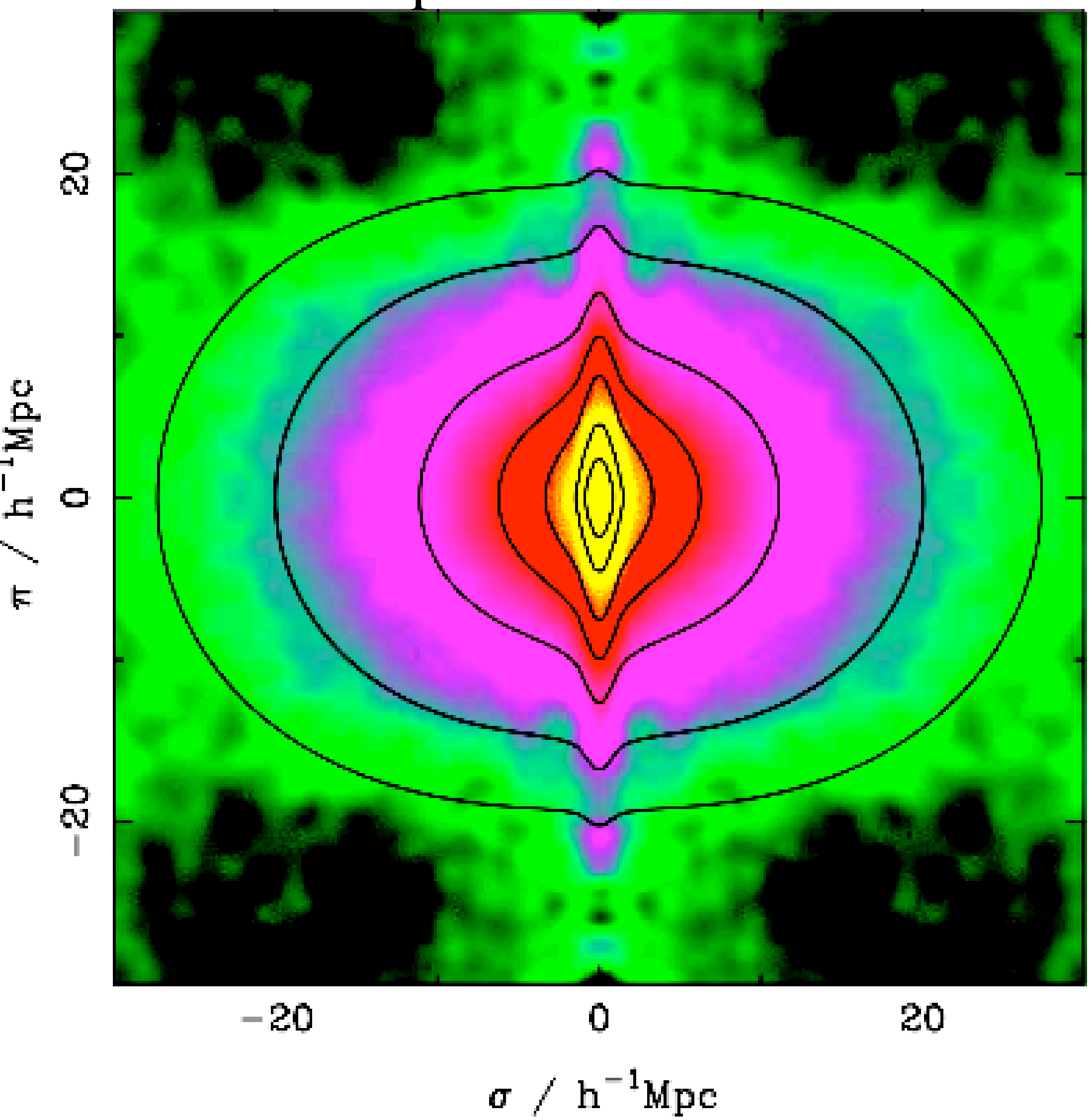
Juszkiewicz (1981); Vishniac (1983); Fry (1984); Goroff et al. (1986); Makino et al. (1992); Jain & Bertschinger (1994); etc.

Mode coupling

- The term P_{13} looks like P_{11} times an integral over P_{11} with a broad kernel.
- Terms of the form P_{1n} give the exponential damping, though "standard" PT over-estimates the strength of the damping.
  - This is essentially the "random" Zel'dovich displacement of particles from their initial positions.
  - rms Zel'dovich displacement at 100Mpc $\neq$ that for infinite displacement.
- The term P_{22} is a true convolution-like integral of P_{11}, times the square of F_2.
- Since F_2 has a strong peak for $p_1=p_2$, the "mode coupling" term P_{22} has wiggles out of phase with P_{11} and gives a shift in the acoustic scale.
- Reconstruction appears to remove this shift.
- These arguments can be generalized to halos & galaxies.

Redshift space distortions

Anisotropic correlation function



2dFGRS, 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 describe with high accuracy analytically, but they can be simulated.

Redshift space distortions II

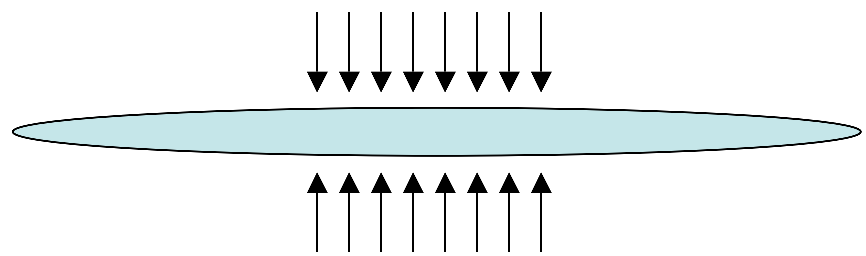
$$1 + \xi_s(\pi, \sigma) = \int \frac{dr\,d\gamma}{2\pi} e^{-i\gamma(r-\pi)} \left\langle e^{if\gamma(u-u')} [1+\delta][1+\delta'] \right\rangle$$

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

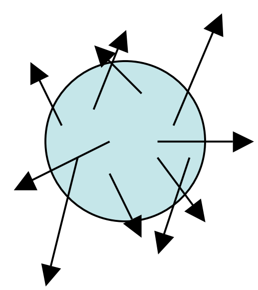
Velocities enhance power on large scales and suppress power on small scales.

The transition from enhancement to suppression occurs on the scale of the baryon oscillations but does not introduce a “feature”.

Coherent infall



Random (thermal) motion



Galaxy bias

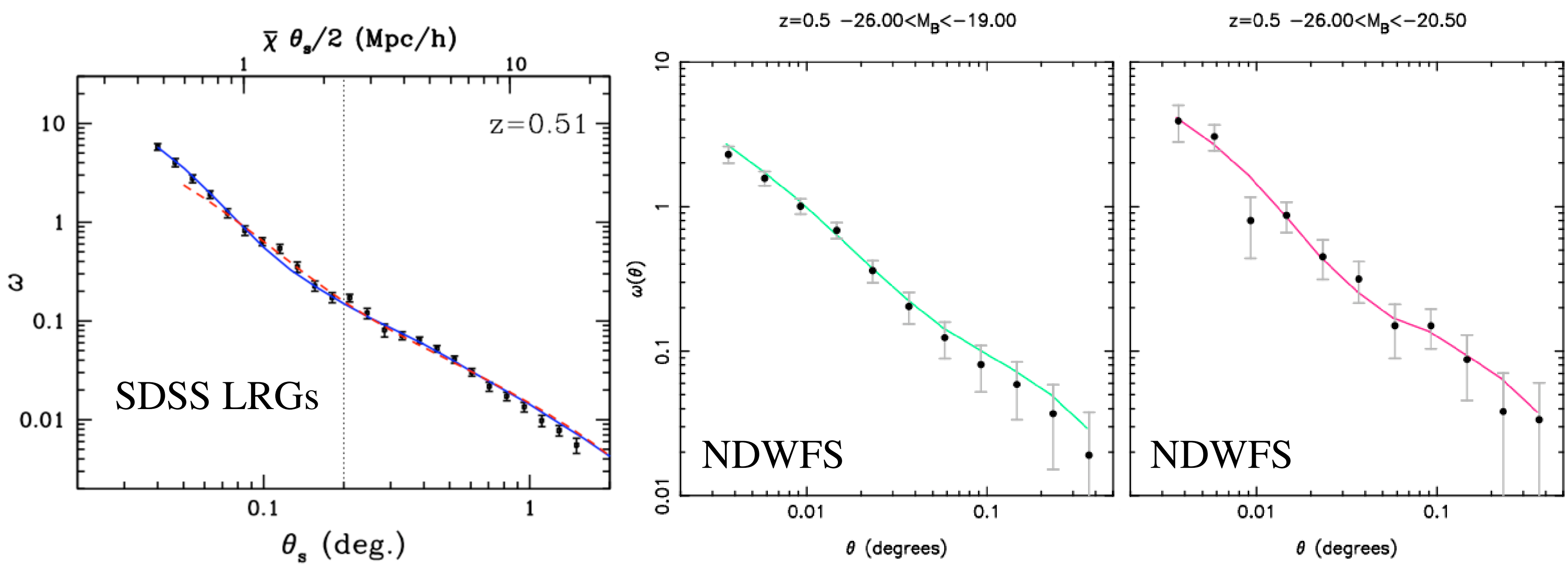
- The hardest issue is galaxy bias.
  - Galaxies don't faithfully trace the mass
- ... but galaxy formation "scale" is << 100Mpc so effects are "smooth".
  - In $P(k)$ effect of bias can be approximated as a smooth multiplicative function and a smooth additive function.
- Work is on-going to investigate these effects:
  - Seo & Eisenstein (2005)
  - White (2005)
  - Schulz & White (2006)
  - Eisenstein, Seo & White (2007)
  - Percival et al. (2007)
  - Huff et al. (2007)
  - Angulo et al. (2007)
  - Smith et al. (2007)
  - Padmanabhan et al. (2008)
  - Seo et al. (2008)
  - Matsubara (2008)

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

Rational functions or polynomials

Modeling red galaxies

Recent advances in our ability to model (understand?) red galaxies as a function of luminosity in the range 0<*z*<1:



Padmanabhan et al. (2008); Brown et al. (2008); …

This small-scale understanding aids our models of large-scale effects.

Ongoing work

- Templates for fitting data, able to account for non-linearity, redshift space distortions and galaxy bias.
- New estimators optimized for large-scale signals calibrated by numerical simulations.
- Models for the covariance matrices, calibrated by simulations.
- More sophisticated reconstruction algorithms.
- Some “new” ideas, and experimental approaches …

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, …

Lensing

Hui, Gaztanaga & LoVerde have analyzed the effects of lensing on the correlation function. For next-generation experiments the effect is small, but it may eventually be measurable. Template is known:

$$\xi_{\mathrm{obs}}(R, z) = \xi\left(\sqrt{R^2 + z^2}\right) + f(R)z + g(R)$$

For normal galaxy parameters fractional peak shift on isotropic spectrum is below 0.1% out to z~2 or so.

A new way of doing BAO at z~2-3

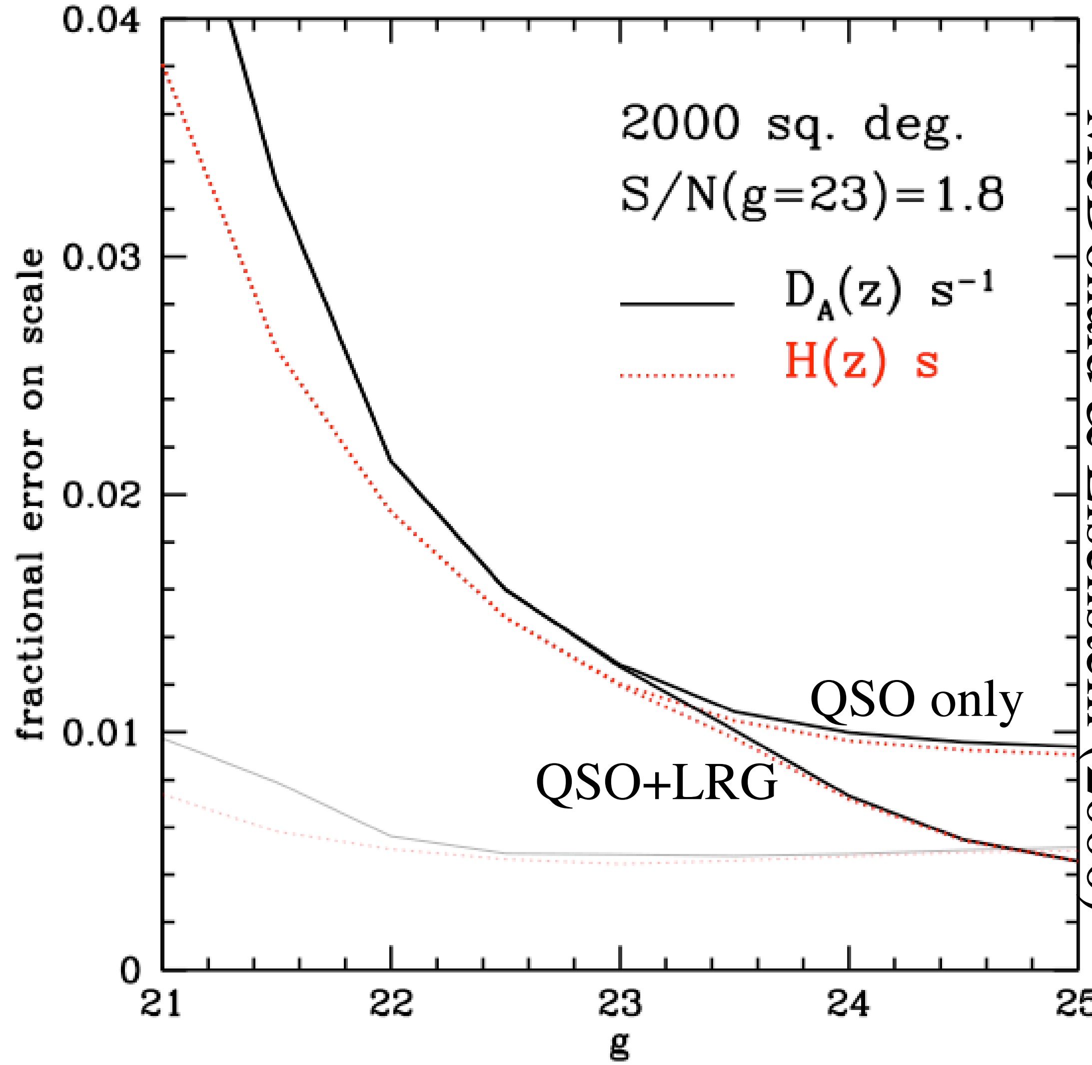
- One requires less sky area per unit volume at high z, but it becomes increasingly expensive to obtain spectra (and imaging) of high z galaxies.
- Quasars can be seen to high z "easily".
- Their light is filtered by the IGM along the line-of-sight
  - The fluctuations in the IGM can be seen in QSO spectra.
  - The fluctuations contain the BAO signature.
- Thus a dense grid of QSO spectra can (in principle) be used to measure BAO at high z.
  - This has little impact on instrument design, but could dramatically alter survey optimization.
- A very promising idea which needs to be further investigated (theoretically & observationally).

White (2003)
McDonald & Eisenstein (2006)

QSO constraints

BOSS (an example):

- 8000 sq. deg. to g=22
- 1.5% measure of both d_A and H
- Comparable to other high *z* measurements, but with a 2.5m telescope!



McDonald & Eisenstein (2006)

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~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)

Conclusions

- Baryon oscillations are a firm prediction of CDM models.
- Method is "simple" geometry, with few systematics.
- 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.
  - Was Einstein right?
- Require "only" a large redshift survey - we have >20 years of experience with redshift surveys.
- Exciting possibility of doing high z portion with QSO absorption lines, rather than galaxies.
- It may be possible to "undo" non-linearity.
- Much work remains to be done to understand structure and galaxy formation to the level required to maximize our return on investment!

The End