Baryon acoustic oscillations A standard ruler method to constrain dark energy

Martin White

University of California, Berkeley

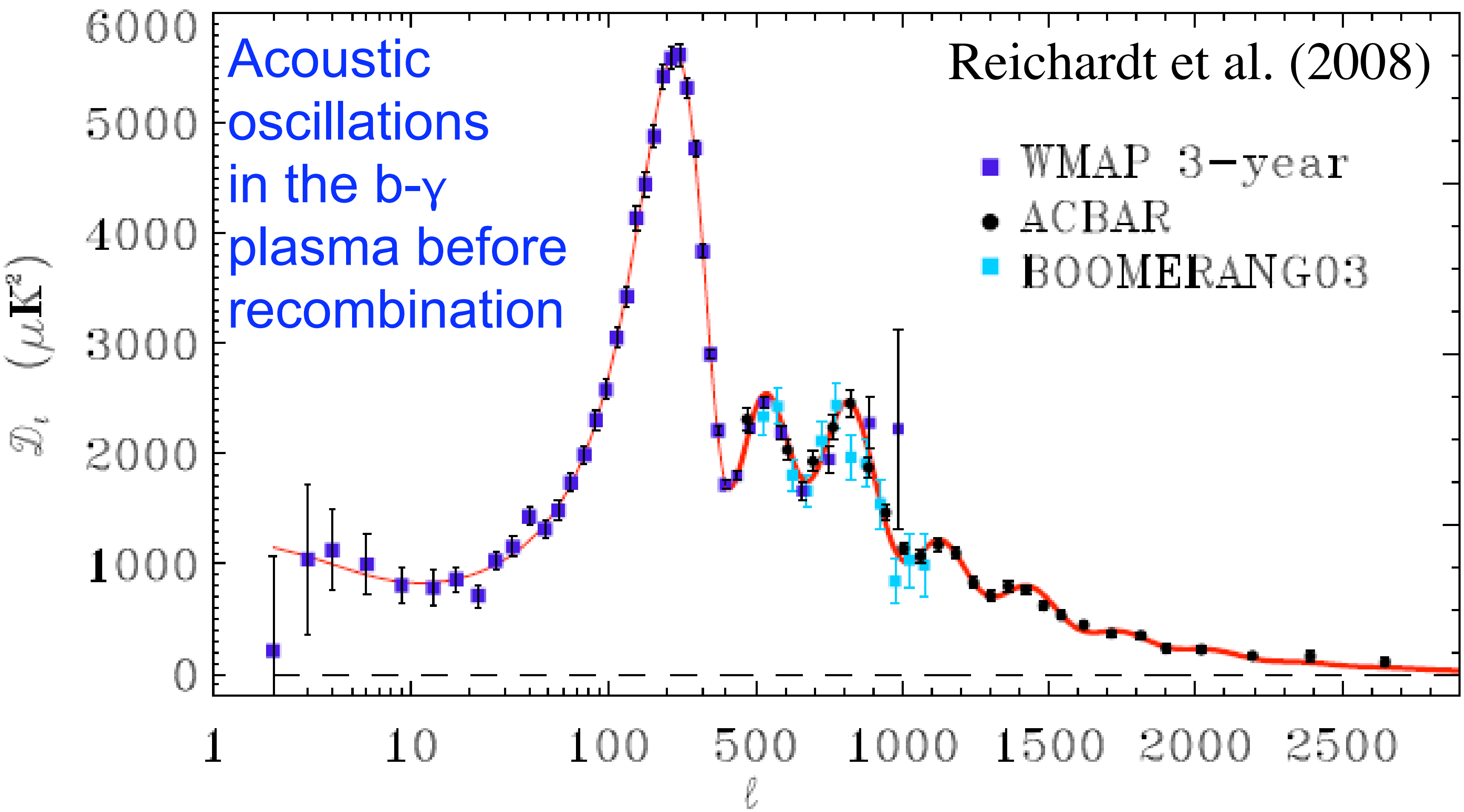
Lawrence Berkeley National Laboratory

... with thanks to Nikhil Padmanabhan for help preparing figures and Tables.

BAO basics

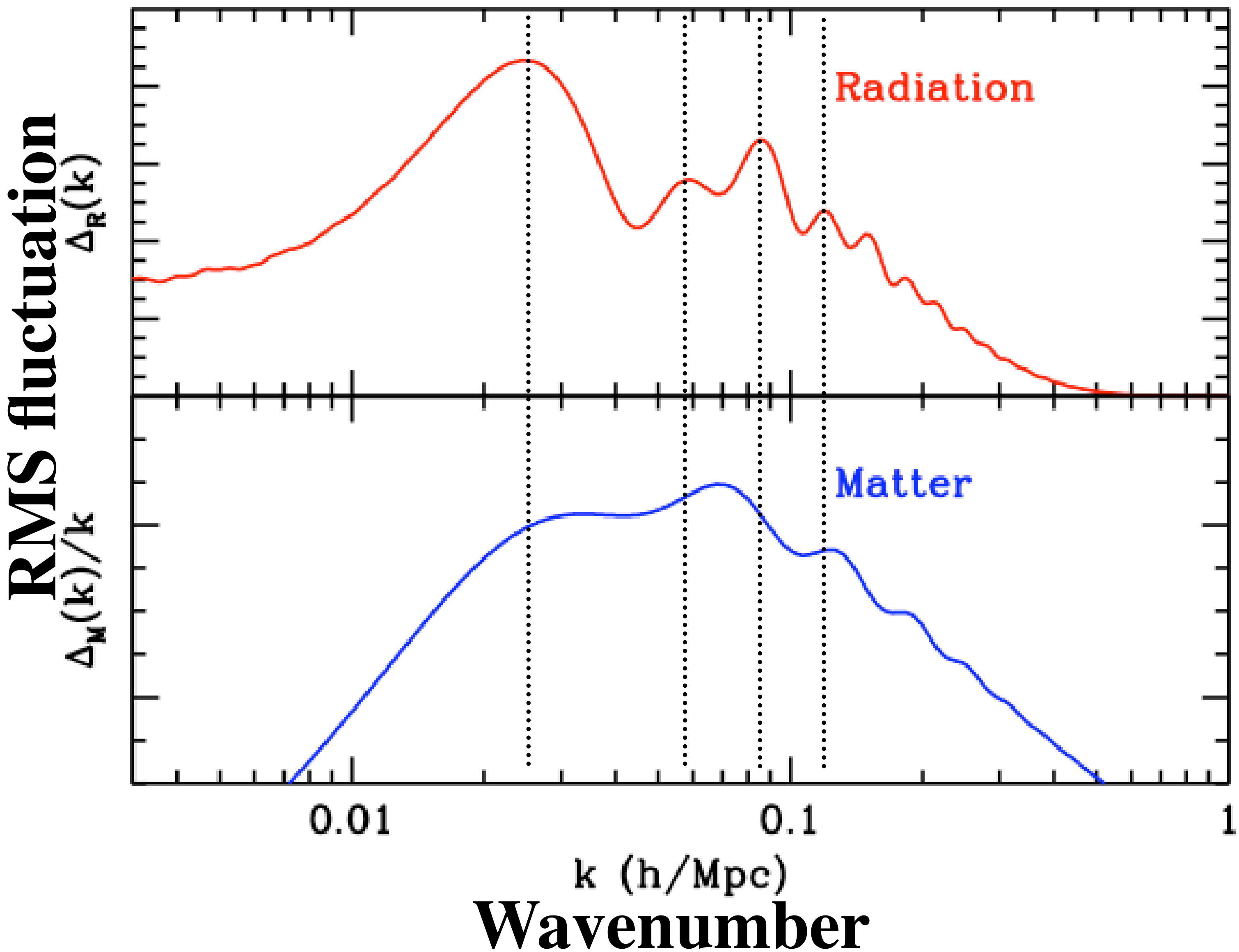
- Sound waves that propagate in the opaque early universe imprint a characteristic scale in the clustering of matter, providing a “standard ruler” whose length can be computed using straightforward physics and parameters that are tightly constrained by CMB observations.
- Measuring the angle subtended by this scale determines a distance to that redshift and constrains the expansion rate.
- The detection of the acoustic oscillation scale is one of the signature accomplishments of the SDSS, and even this moderate signal-to-noise measurement substantially tightens constraints on cosmological parameters.
- “*Method least affected by systematic uncertainties and for which we have the most reliable forecasts of the resources required to accomplish a survey of chosen accuracy*”. (report of the Dark Energy Task Force)
- ***But***, very large surveys are required to attain high statistical precision.

The CMB power spectrum



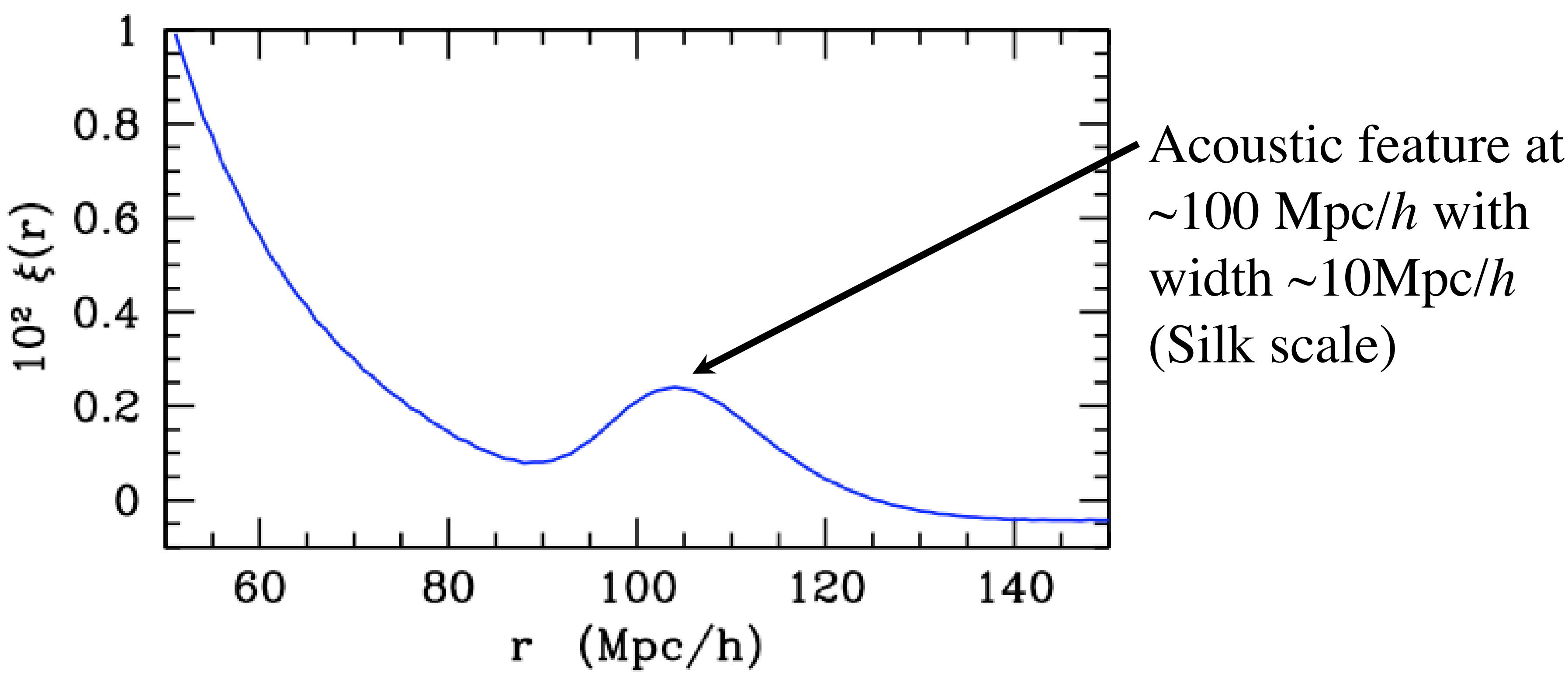
Location of peaks set by sound horizon ($s \sim c_s t_{ls}$) at last scattering. Highly precise measurement, but unfortunately only at one *z*.

Baryon (acoustic) oscillations



In configuration space

- These features are frozen into the matter power spectrum and provide a known length scale (standard ruler) with which to measure $d_A(z)$ and $H(z)$ as a function of z. Both d_A and H constrain DE.
- In Fourier space, a damped (almost) harmonic series of peaks in *P(k)*.
- In configuration space a narrow feature in $\xi(s)$ at the sound horizon



Systematics

- All methods have systematics, but not all methods have systematics of the same size ...
- BAO feature generated & frozen in at high *z*
  - Linear physics, well tested by CMB.
- Any non-linear effects are mild on large scales (~100Mpc)
  - These are "easy" to solve and we do so routinely.
- Galaxy bias not degenerate with signal, and we will have loads of data to help us constrain it.
- Method intrinsically differential.
  - Spectroscopy is differential (hence "easy" requirements).
  - Clustering is differential (hence "easy" requirements).
  - Acoustic peak is differential within clustering & not degenerate with radial or tangential errors.

Current state of the art

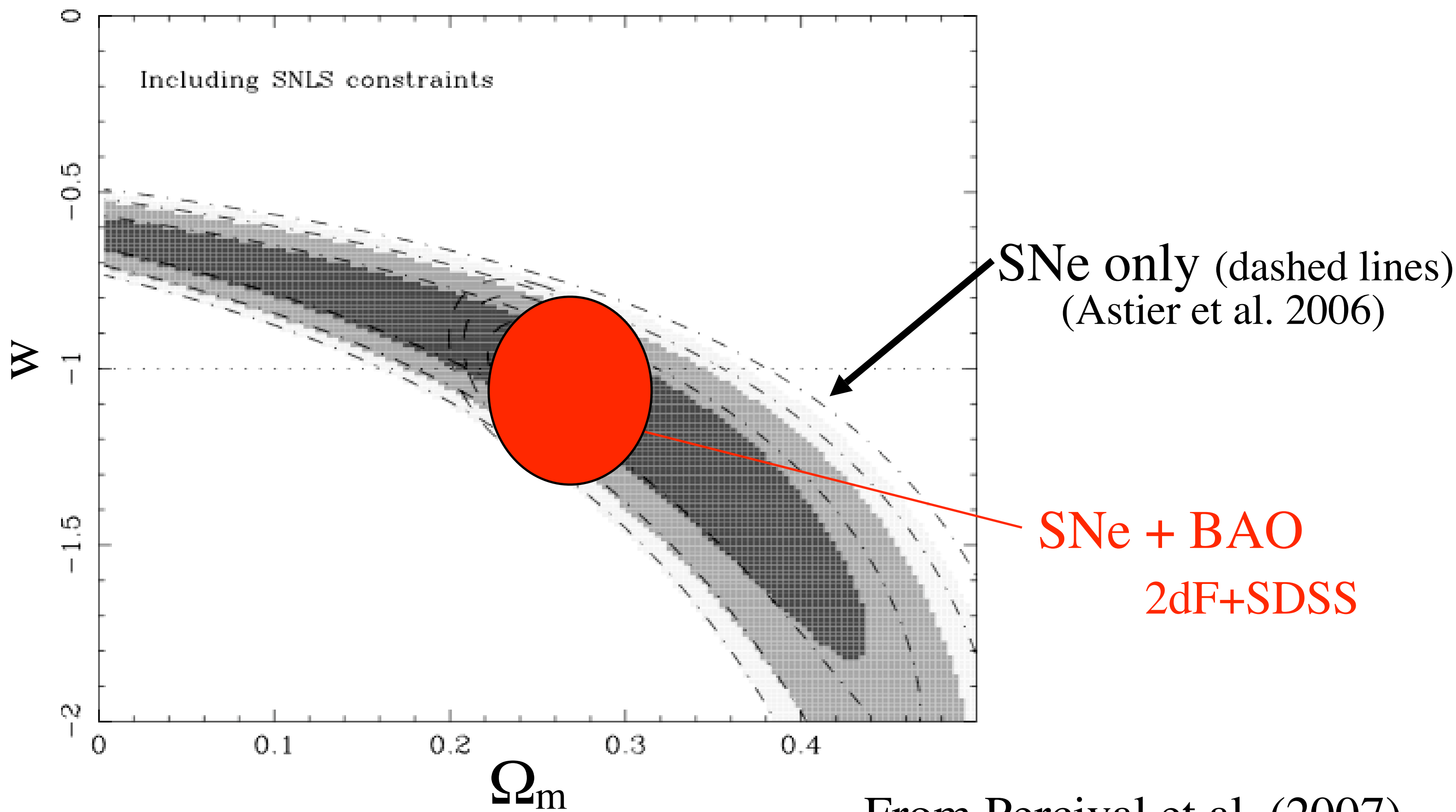
1. Eisenstein et al 2005
   - 3D map from SDSS
   - 46,000 galaxies, 0.72 $(h^{-1}\ \mathrm{Gpc})^3$
2. Cole et al 2005
   - 3D map from 2dFGRS at AAO
   - 221,000 galaxies in 0.2 $(h^{-1}\mathrm{Gpc})^3$
3. Hutsi (2005ab)
   - Same data as (1).
4. Padmanabhan et al 2007
   - Set of 2D maps from SDSS
   - 600,000 galaxies in 1.5 $(h^{-1}\mathrm{Gpc})^3$
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)

(spectro-z)
4% distance measure

(spectro-z)
5% distance measure

(photo-z)
6% distance measure

Current constraints

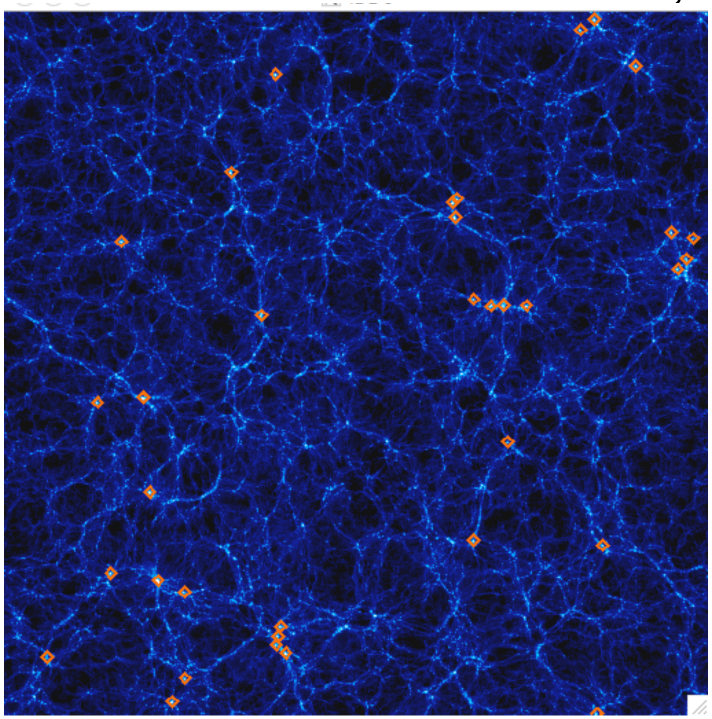


From Percival et al. (2007)

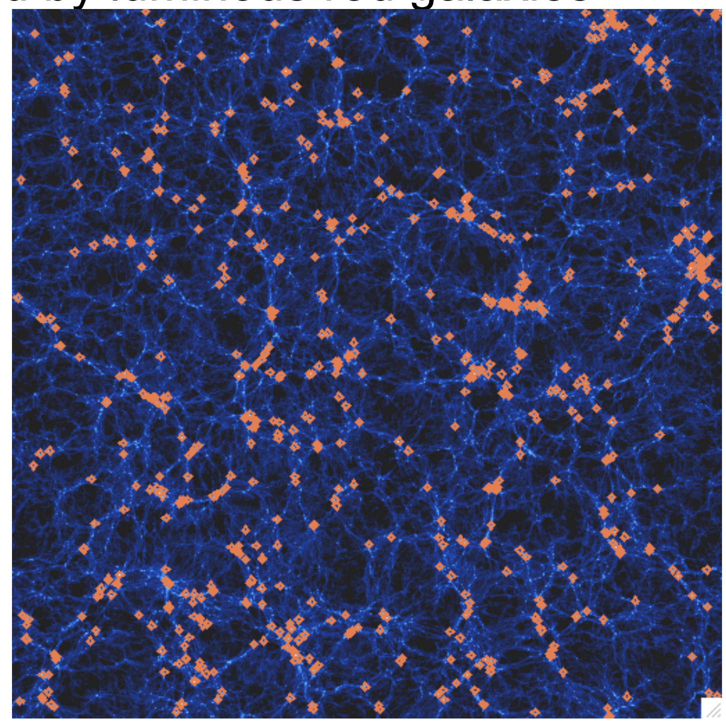
The march of technology ...

The instruments which made these detections are more than a decade old, and it is straightforward to upgrade the performance. By focussing on one goal, we can dramatically improve the reach.

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



SDSS



BOSS

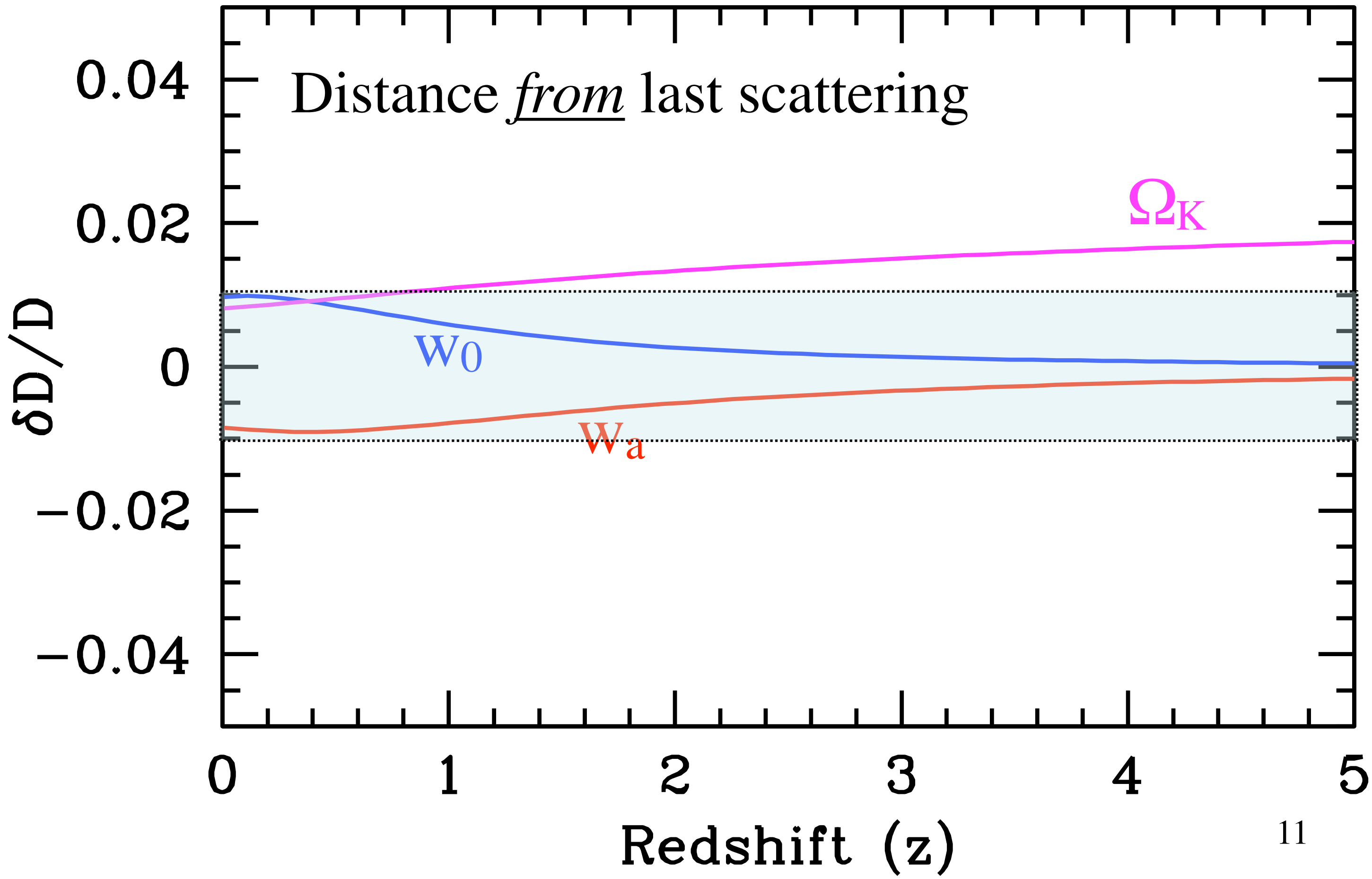
A slice 500h^{-1} Mpc across and 10 h^{-1} Mpc thick

The landscape

- We need a much more precise measurement of *s* at more redshifts to constrain DE.
- A point at high z constrains Ω_K
  - allowing focus on w_0 & 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%.
- Ground vs. Space
  - Going to space gets you high *z* and all sky.
    - Best possible BAO measurement.
  - Like CMB much *can* be done from ground ...

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.



Current and proposed spectroscopic BAO surveys

Project	Redshift	Area (sq. deg.)	n (10^{-4})	FoM
Stage II	-	-	-	53
WiggleZ	0.4-1.0	1,000	3.0	67
HETDEX*	2.0-4.0	350	3.6	70
WFMOS*	0.5-1.3, 2.3-3.3	2,000, 300	5.0	95
BOSS LRG	0.1-0.8	10,000	3.0	86
+QSO	+ 2.0-3.0	+ 8,000		122
LRG+QSO +Stage III		-		331
"Best"	0-2	30,000	10	~600

*Specs taken from published work, not optimized

Current and proposed photometric BAO surveys

Project	Redshift	Area (sq. deg.)	n (10^{-4})	FoM
Stage II	-	-	-	53
Pan-STARRS	0-1	20,000	10	76
DES	0-1.4	4,000	10	66
LSST	0-1.4	20,000	10	80
PAU	0-1	10,000	10	94

But remember complementarity
with other probes ...

Photometric vs. Spectroscopic

Pros for photometric surveys:

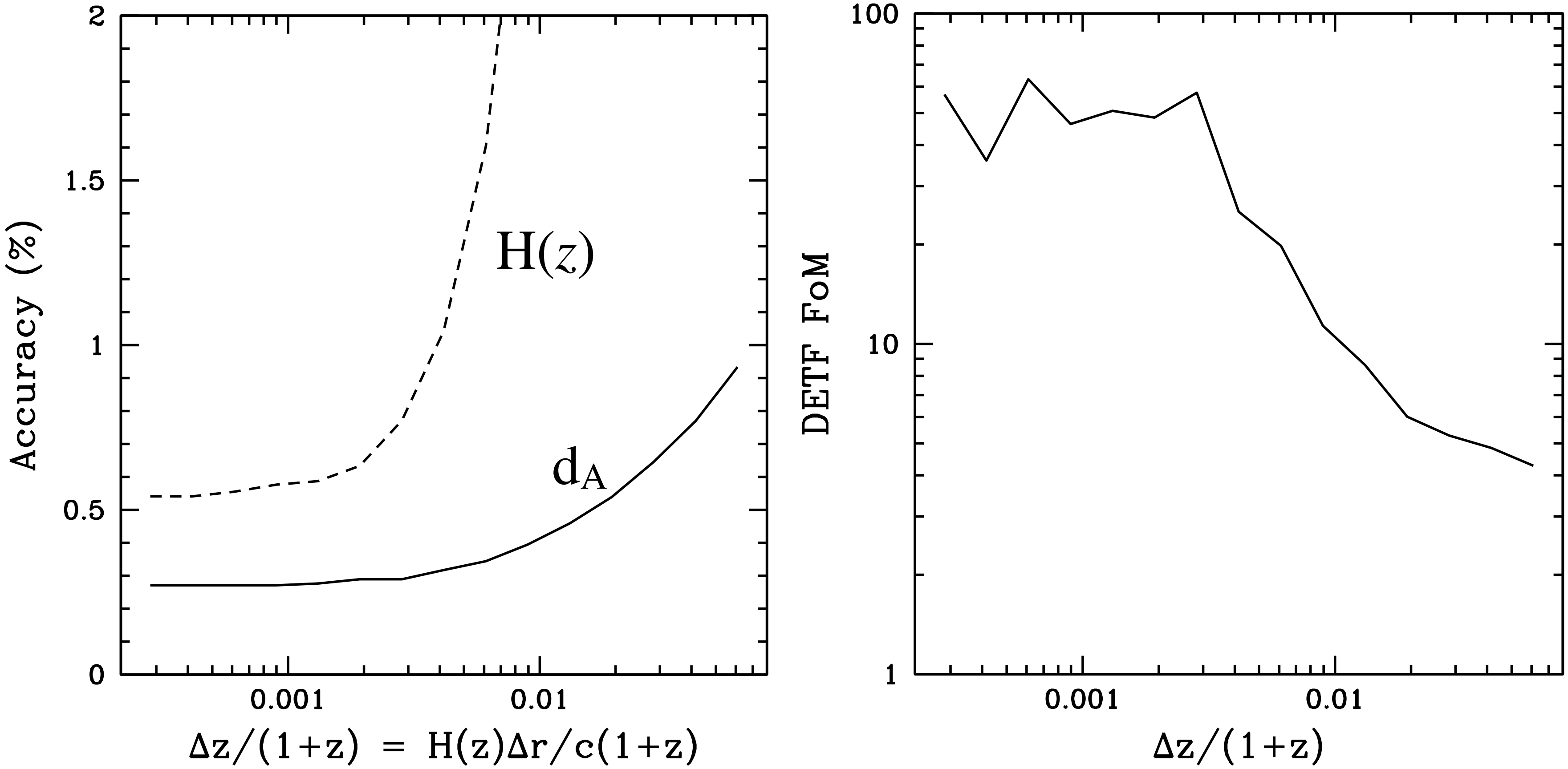
- Much of the science comes “for free”.
  - Not a requirements driver in surveys aiming for weak lensing.
- Easy to cover large areas of sky.
- If have long-wavelength coverage are able to push to high z.

Cons for photometric surveys:

- More susceptible to systematic errors in z determination.
- Fewer modes (2D vs 3D) per unit area
  - Generally takes ~10x as much sky for same constraints on d_A.
- Cannot do line-of-sight correlations [for H(z)].
- Cannot make use of density field reconstruction [at low z].

Photo vs. Spectro redshifts

Spectro redshifts have fewer catastrophic failures and better precision.
Better constraints and allows reconstruction.



Nikhil Padmanabhan

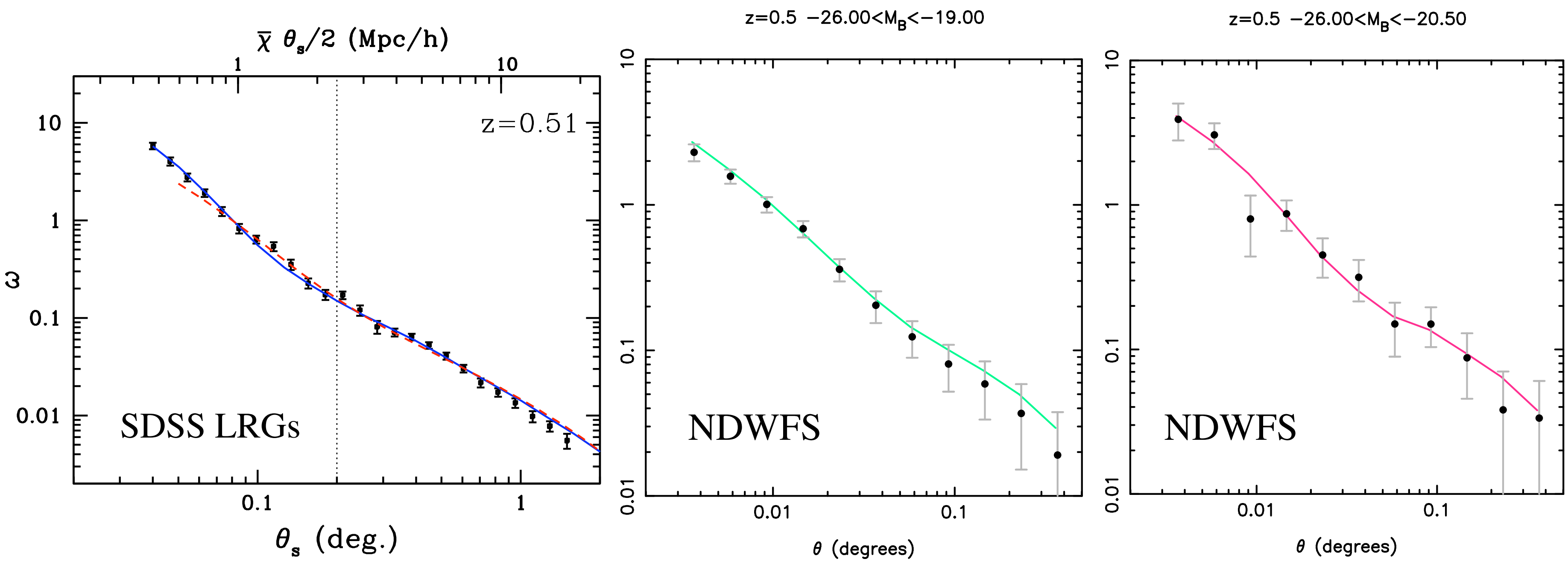
Recent progress: theory

"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." (Dark Energy Task Force)

- Recent progress:
  - Analytic approximations suggested non-linear effects shift the acoustic scale by <0.5-1%
    - Recent numerical calculations find shift of 0.3%. (Seo++08)
    - Acceptable for next-generation experiments, relevant for proposed space-based experiments.
  - Templates including the effects of non-linearity and galaxy bias recover unbiased estimates of *s* when applied to simulated galaxy catalogs.
    - Minimal increase in error bar when marginalizing over nuisance parameters describing galaxy formation.

Recent progress: phenomenology

Now have good models for red galaxies out to z~1.

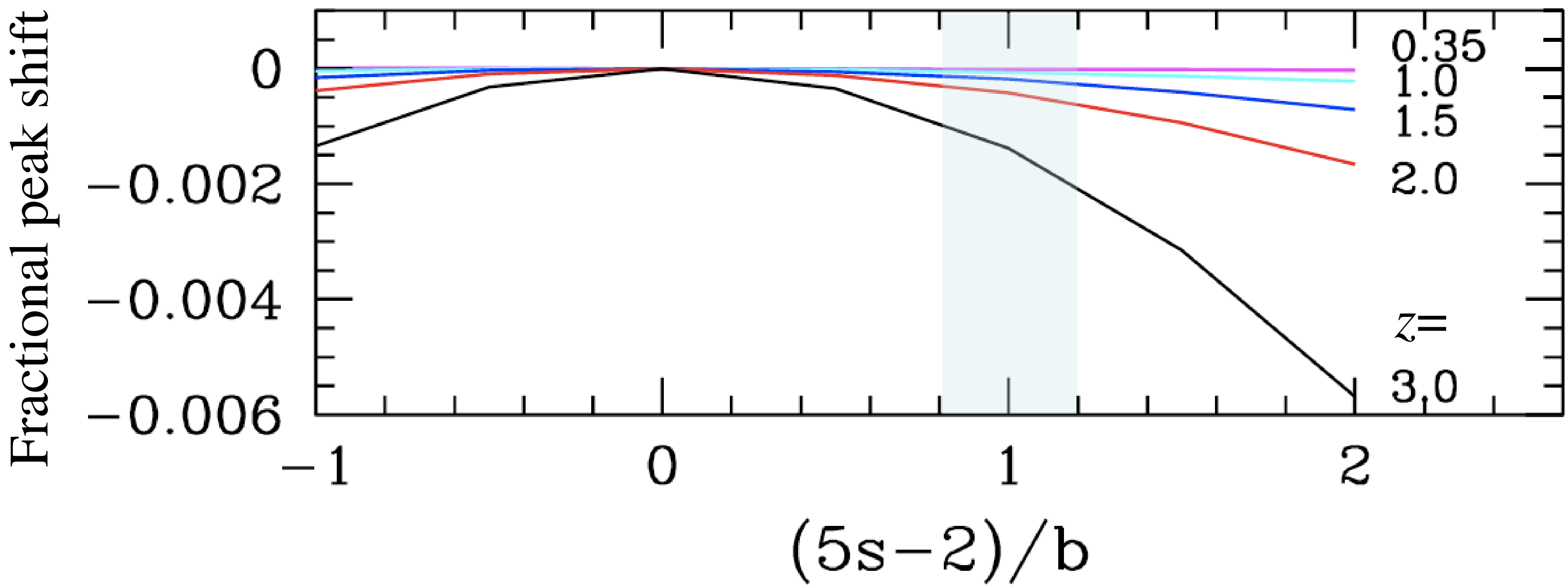


Padmanabhan et al. (2008); Brown et al. (2008); etc.

Recent progress: lensing

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

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

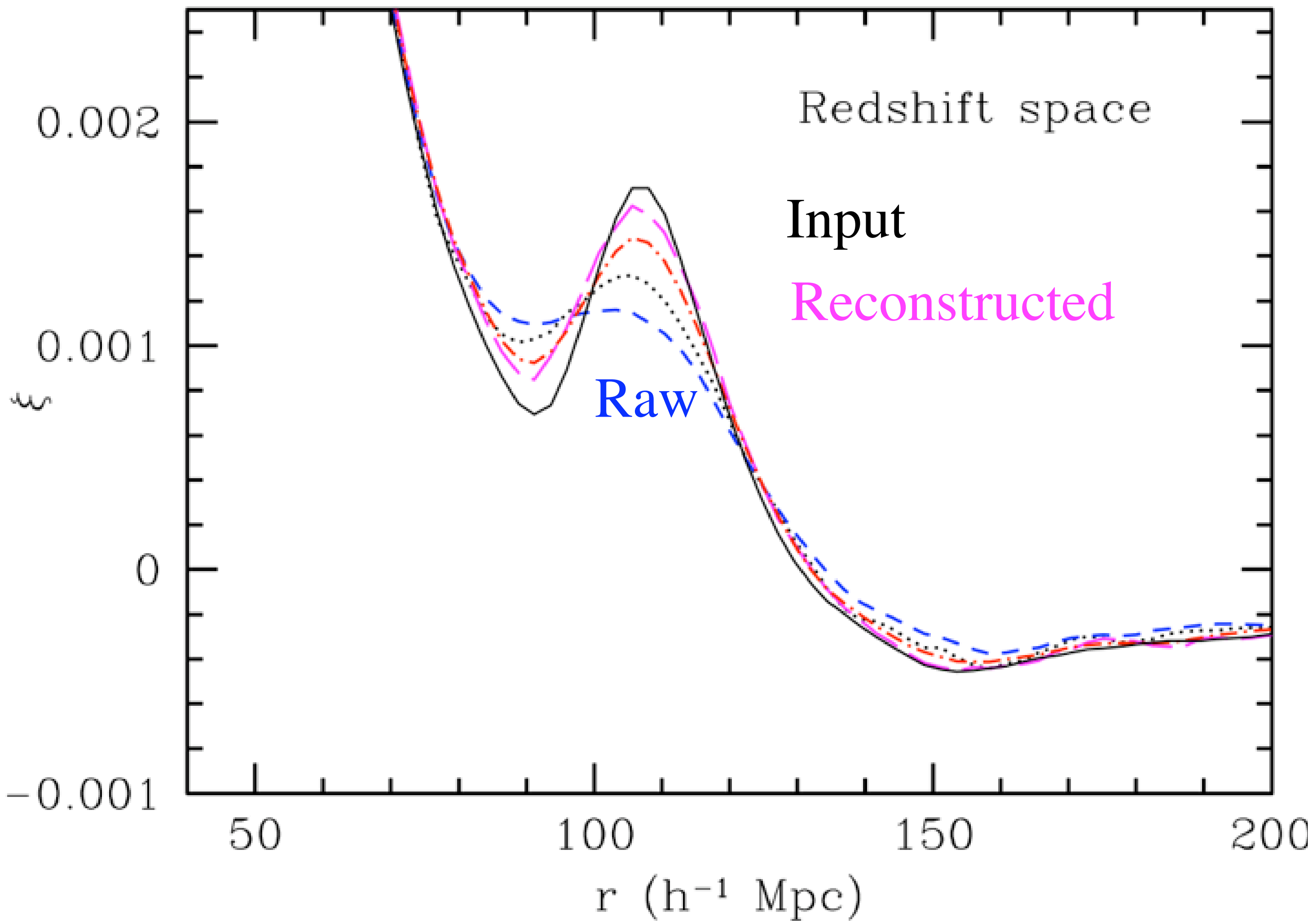


Recent progress: Reconstruction

- The effect of non-linearity is to broaden and slightly shift the peak. Harder to centroid a broad peak.
- The broadening comes from the "tugging" of large-scale structure on the baryon "shell".
  - We measure the large-scale structure and hence the gravity that "tugged".
- Use the observations to "undo" non-linearity

  Eisenstein et al. (2007)
  - Measure $\delta(x)$, infer $\phi(x)$, hence displacement.
  - Move the galaxies back to their original positions.
- Investigations on simulations show it "works", no demonstration on observational data (yet).
- Has potentially large pay-off for low-z experiments.

Reconstruction in simulations



Eisenstein et al. (2006)

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

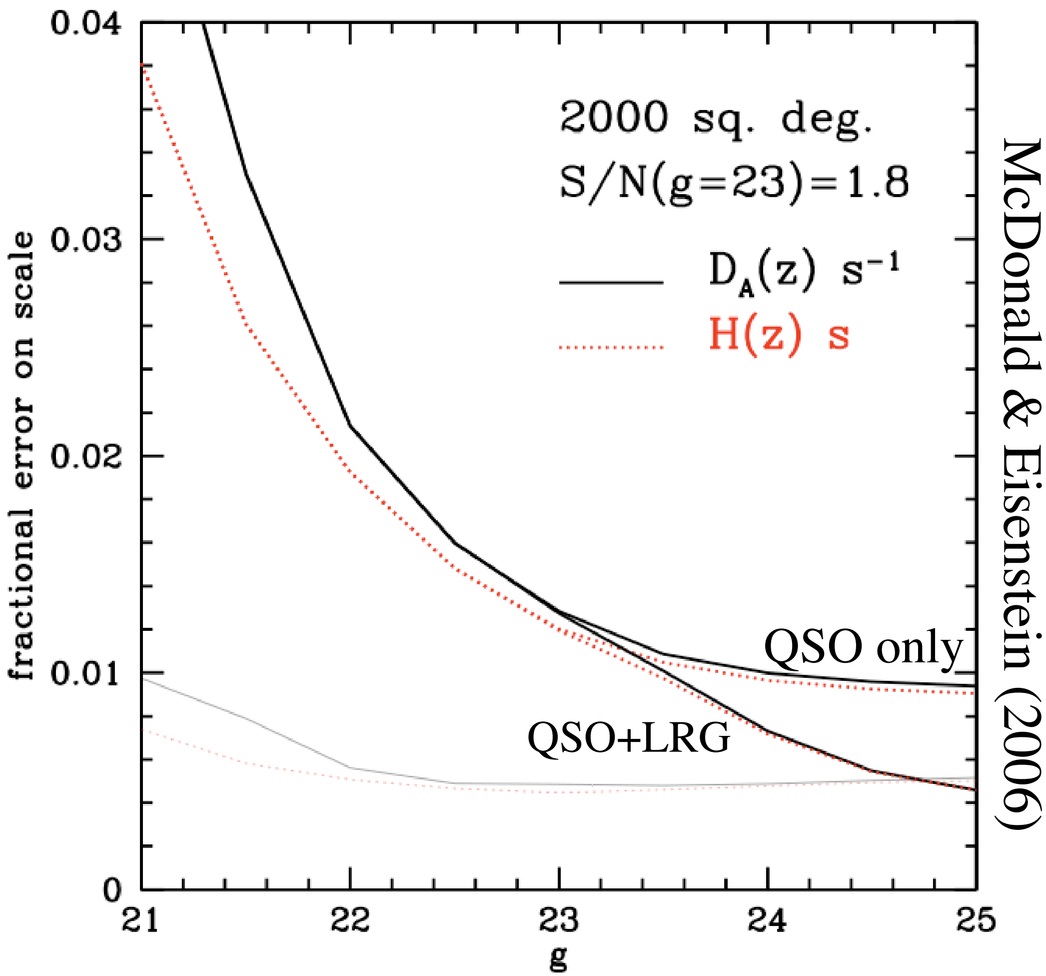
- One requires less sky area per unit volume at high redshift, but it becomes increasingly expensive to obtain spectra (or imaging) of high redshift galaxies.
- Quasars can be seen to very high redshift “easily”.
- Their light is filtered by the intergalactic medium along the line of sight.
  - The fluctuations in the IGM can be seen in QSO spectra
  - These fluctuations contain the BAO signature.
- Thus a dense grid of QSO spectra can (in principle) be used to measure BAO at high z, much more cheaply than with galaxies.
  - 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!



Conclusions

- Method is “simple” and has very low 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, constraining DE.
- Require “only” a large redshift survey - we have >20 years of experience with redshift surveys.
- Exciting possibility of doing high z portion with QSOs.
- We are close to a “turn-key” method for analyzing observations which returns unbiased estimates of s.
- It should be possible to “undo” non-linearity and improve constraints at low z.

The End