Cosmology from Large Scale Structure

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We report on the linear matter power spectrum reconstructed from the Ly\textalpha forest, on baryonic wiggles in the galaxy power spectrum, and on how to measure real space (as opposed to redshift space) power.

1. INTRODUCTION

Much of what I presented at the DARK2002 meeting is contained in \cite{1,2,3,4,5}. To avoid redundancy, I will not repeat what is in those papers, but instead will devote this space to a subset of issues addressed at the meeting, namely the linear matter power spectrum reconstructed from the Ly\textalpha forest, baryonic wiggles in the galaxy power spectrum, and how to measure real space (as opposed to redshift space) power.

2. POWER FROM THE LYMAN ALPHA FOREST

In a remarkable paper, Croft et al. \cite{6} reconstructed the linear matter power spectrum from the measured power spectrum of transmitted flux in the Lyman alpha forests of a sample of 53 Keck spectra of quasars at redshifts $z = 2.2-4.1$. The Ly\textalpha forest offers two advantages over galaxies as a way to access the linear matter power spectrum. First, the scale at which objects are going nonlinear is smaller at high redshift. And second, the Ly\textalpha forest is less biased, or at least we think we understand the bias better, than galaxies.

Some of us were much impressed with Croft’s technique, but at the same time skeptical that it could work so well. The correction from flux power spectrum to linear matter power is large and at least somewhat model-dependent, yet the error bars on the reconstructed matter power spectrum reported in \cite{6} were tiny at the smallest measurable scales.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The linear matter power spectrum inferred from the Ly\textalpha forest, compared to the PSCz \cite{7} galaxy power spectrum and to the $\Lambda$CDM concordance model of \cite{4}, both linear and nonlinearly evolved by the method of \cite{9}.}
\end{figure}
Nick Gnedin and I \cite{1} decided to try to reproduce Croft et al.’s \cite{6} result, and Figure 1 shows the result. We explored a wider range of cosmological parameters, and astrophysical parameters governing the relation between dark matter and transmitted flux. The error bars in Figure 1 on the linear matter power spectrum reconstructed from the Ly \( \alpha \) forest include both statistical and ‘systematic’ errors, the systematic errors being the envelope of uncertainty from differently parametered models that fit the observed power spectrum of transmitted flux. Although our error bars are bigger than those of \cite{6}, we confirm that their procedure seems to work as advertised. Our conclusions in this regard are more optimistic than those of Zaldarriaga et al. \cite{7}.

For comparison, Figure 1 also shows the real space power spectrum of PSCz galaxies measured by \cite{2}, and the ΛCDM concordance model power spectrum of \cite{4}. The linear matter power spectrum reconstructed from the Ly \( \alpha \) forest has been linearly evolved to the present time using the concordance model. The agreement between the power spectrum inferred from the Ly \( \alpha \) forest and the concordance model is quite striking when you consider that the concordance model was obtained without the benefit of the Ly \( \alpha \) data.

### 3. A BARYONIC UNIVERSE?

One of the hottest goals (e.g. \cite{8}) of studies of large scale structure is to detect baryonic wiggles in the galaxy power spectrum. In \cite{10}, the 2 degree Field team reported a tentative detection of baryonic wiggles. Our own analysis \cite{2}, which however is based only on the smaller published 100k data set \cite{11}, finds a similar bump, but does not rate it as a statistically significant detection of baryons.

Nevertheless the bump at \( k \approx 0.05 \ h \ Mpc^{-1} \) is interestingly large. Intriguingly, it lines up nicely with a similar bump in the PSCz power spectrum \cite{12}, as shown in Figure 2. The 2dF and PSCz power spectra in Figure 2 are decorrelated \cite{13}, meaning that the error bars are uncorrelated with each other, so it is legitimate to do chi-by-eye.

For fun, Figure 2 compares the 2dF and PSCz power spectra to a COBE-normalized, flat, adiabatic power spectrum containing a cosmological constant and baryons, \( \Omega_\Lambda = 0.86, \Omega_b = 0.14 \), but no non-baryonic Dark Matter. A large baryonic component not only strengthens baryonic wiggles, but also steepens the power spectrum. To counteract this steepening, the model power spectrum in Figure 2 has a large blue tilt, with primordial spectral index \( n = 2 \).

A comparably decent fit can be obtained without a cosmological constant, but only by dint of increasing the bias factor to the extreme value of \( b \approx 11 \). In other words, in a pure baryonic universe with no cosmological constant, Large Scale Structure fluctuations would predict CMB fluctuations 11 times larger than observed. This discrepancy is of course an ancient result, one of the original motivations for introducing the notion of non-baryonic Dark Matter.

Sadly the Λ-baryon model fails dismally compared with CMB observations: the model predicts a first acoustic peak 5 times larger than observed, and at harmonic number \( l \approx 310 \) way higher than the observed peak at \( l = 210 \).
4. REAL SPACE POWER

The PSCz power spectrum shown in Figure 3 is a real space power spectrum, not a redshift space power spectrum. That is, the effect of pairwise peculiar velocities has been eliminated, at both linear and nonlinear scales.

Quiz question for you: at nonlinear scales, which can you measure more accurately from a galaxy redshift survey, the (angle-averaged) redshift space power spectrum or the real space power spectrum?

The answer is obvious, right? The redshift space power spectrum must be more accurate, because the observations are in redshift space, and to get from redshift space to real space you have to deconvolve the redshift space power spectrum from the effects of pairwise peculiar velocities. Presumably that deconvolution is model-dependent, and liable to the kind of numerical instability that generally attends deconvolution.

Wrong.

Remarkably enough, at nonlinear scales the real space power spectrum can be measured more accurately than the redshift space power spectrum! Which is a wonderful thing, because it is the real space power spectrum that you really want\(^5\). As an added bonus, the distribution of pairwise peculiar velocities (or rather its Fourier transform) emerges as a byproduct of the measurement (Fig. 2 of \(\text{[2]}\)).

The key point that allows this miracle to happen is that peculiar velocities displace galaxies only in the line-of-sight direction in redshift space. This has the consequence that Fourier modes transverse to the line of sight are completely unaffected by redshift distortions. The result is familiar to the executors of angular galaxy surveys, who know that the 3D power spectrum that they extract from an angular survey is a real space power spectrum, not a redshift space power spectrum.

It follows that the real space power spectrum \(P(k)\) is equal to the redshift space power spectrum \(P^s(k_\perp, k_\parallel)\) in the transverse \((k_\parallel = 0)\) direction

\[
P(k) = P^s(k_\perp = k, k_\parallel = 0).
\] (1)

Notice that it is the power spectrum, not the correlation function, for which the relation between real space and redshift space quantities is so sim-
ple, equation (1). If you want to see the mathematics in more detail, look at [2].

Figure 3, from [2], shows a contour plot of the redshift space power spectrum \( P_s(k_\perp, k_\parallel) \) of PSCz, as a function of wavenumbers \( k_\perp \) and \( k_\parallel \) respectively transverse and parallel to the line-of-sight. According to equation (1), the real space power spectrum is equal to the redshift space power spectrum along the transverse axis in Figure 3.

A simple argument demonstrates how it can be that the real space power spectrum is more accurately measurable than the redshift space power spectrum. Take a close pair of galaxies, say 30 \( h^{-1} \) kpc apart. Projected on the sky, the galaxies will appear 30 \( h^{-1} \) kpc apart or less. But thanks to their relative peculiar velocities, the pair will appear typically 3 \( h^{-1} \) Mpc apart in redshift space, a factor of 100 larger. You see that all that wonderful information about close pairs that is in present in the transverse power spectrum is horribly mixed into (100 times, for example) larger scales in the angle-averaged redshift space power spectrum.

5. CONCLUSIONS

Cosmologists now have a Standard Model, a flat \( \Lambda \)CDM model seasoned with baryons. At the DARK2002 conference several speakers reported how data from diverse sources are pointing at the same concordance model.

Figure 4 illustrates one example of this concordance, how the linear power spectrum inferred from the \( \text{Ly} \alpha \) forest is in full agreement with the concordance model.

First results from the new generation of large redshift surveys are emerging. It is probably premature to claim a detection of baryonic wiggles, but there are tantalizing hints of such, Figure 2, and it should not be long before baryonic wiggles in the galaxy power spectrum become an observational reality.

This commentary concluded by bringing attention to the counter-intuitive fact that it is possible to measure the real space power spectrum of galaxies more accurately than the redshift space power spectrum. One hopes that those who analyze redshift surveys will begin to take advantage of this have-your-cake-and-eat-it truth.

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