Numerical Simulations and Baryonic Wiggles

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**Agenda:**

- Baryonic Acoustic Oscillations
- Key Problems in measuring BAO
- BAO and Dark Energy
Baryonic Acoustic Oscillation (BAO)

Baryon acoustic oscillations (BAO) refers to an overdensity or clustering of baryonic matter at certain length scales due to acoustic waves which propagated in the early universe.

Supernovae – Standard Candles

The length of this standard ruler (~150 Mpc comoving) can be measured by looking at the large scale structure of matter using astronomical surveys.

BAO – Standard Ruler

SDSS

Bennett 2006
How does it work?

The scale of the Baryonic Acoustic Oscillations is determined by the size of the sound horizon at recombination.

Given $\Omega_{dm}$ and $\Omega_b$, which can be determined from the CMB we can calculate the sound horizon scale and use BAO as a standard ruler.
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Measuring BAO

Need Large volumes with good statistics
For theoretical comparison we need to understand non-linear physics going into
the formation of BAO peak.

Springel 2006

Eisenstein et al. 2005
Effects that change the form of the galaxy power spectrum on large scales from the prediction of linear perturbation theory:

1. Non-linear fluctuation growth

Angulo 2007
Effects that change the form of the galaxy power spectrum on large scales from the prediction of linear perturbation theory:

2. Redshift Distortions

Bulk motions of large-scale structure toward overdense regions enhance power on large scales.

Virial motions within and among halos create an apparent extension along the line of sight, known as the finger-of-God effect, on small scales.
Effects that change the form of the galaxy power spectrum on large scales from the prediction of linear perturbation theory:

3. Non-linear and scale dependent bias

The power spectrum of dark matter halos in real space compared to a scaled prediction of linear perturbation theory. Effective bias is set by matching the linear theory prediction for the mass spectrum to the measured halo spectrum on large scales.
The Power Spectrum of Galaxies

The power spectrum of various galaxies in real-space, divided by the square of an effective bias and linear power spectrum.

Angulo 2007

Cole 2005
Studying the effects of non-linearity on BAO

Need to use large N-body simulations and semi-analytic models like Galform to populated dark matter halos with galaxies
Non-linear effects in the matter power spectrum

Non-linear growth from mode coupling increases power above the linear growth rate on small scale, resulting in a bigger statistical variance (diluting) underlying initial features.

Seo and Eisenstein 2005
Effects of changing power spectrum on BAO peak:

Non-linear evolution washes out the acoustic oscillations by erasing the higher harmonic peaks leading to the decrease in sharpness of the BAO peak

Sanchez et al. 2008
Galaxies as tracers of BAO:

Populating dark matter halos with galaxies is done with various semi-analytical models and the robustness of this procedure is arguable…

Springel et al 2005
Measuring Dark Energy with BAO

DE eqn of state: \( w_\chi (z) = P_\chi / \rho_\chi @ z \)

\[
\rho_\chi (z) = \rho_\chi (0) \exp \left( 3 \int \frac{1 + w(z)}{1 + z} \, dz \right)
\]

\[
H(z) = H_0 \left( \Omega_m (1 + z)^3 + \Omega_\chi \exp \left( 3 \int \frac{1 + w(z)}{1 + z} \, dz \right) \right)^{1/2}
\]

\[
D_A (z) = \frac{c}{1 + z} \int \frac{dz}{H(z)}
\]

\[
r_\parallel = \frac{c \Delta z}{H(z)} \quad r_\perp = (1 + z) D_A (z) \Delta \theta
\]

Know Measure
Conclusions:

1. Non-linear evolution of dark matter is important even on scales larger than the sound horizon.

2. The distortion of the power spectrum due to peculiar motions is extremely sensitive to the type of object under consideration, being quite different for the cases of dark matter, dark halos and galaxies.

3. Galaxy bias is scale dependent and sensitive to the selection criteria.

4. Numerical simulations are critical in understanding non-linear effects on the BAO detectability.
Thanks!