Estimating the BAO scale

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with S. Anselmi, G. Starkman
Zehavi et al. 2010 (SDSS)
VIPERS (Guzzo et al. 2013)
Complication: Light is a biased tracer

Not all galaxies are fair tracers of dark matter; To use galaxies as probes of underlying dark matter distribution, must understand ‘bias’
Cosmology constraints from geometry (distance-redshift) and dynamics (clustering-redshift), both of which are sensitive to expansion history.

Galaxy formation much less ‘understood’
Cosmology from the same physics imprinted in the galaxy distribution at different redshifts:

Baryon Acoustic Oscillations
CMB from interaction between photons and baryons when Universe was 3,000 degrees (about 300,000 years old)

- Do galaxies which formed much later carry a memory of this epoch of last scattering?
Baryon Oscillations in the Galaxy Distribution

Looking back in time in the Universe
Spike in real space $\xi(r)$ means $\sin(kr_{\text{BAO}})/kr_{\text{BAO}}$ oscillations in Fourier space $P(k)$.

In fact, spike is not delta function because surface of last scattering not instantaneous:

$$e^{-(k/k_{\text{Silk}})^{1.4}} \sin(kr_{\text{BAO}})/kr_{\text{BAO}}$$
BAO in CMB photons on last scattering surface …
... should/are seen in matter distribution at later times
...we need a tracer of the baryons

- **Luminous Red Galaxies**
  - Luminous, so visible out to large distances
  - Red, presumably because they are old, so probably single burst population, so evolution relatively simple
  - Large luminosity suggests large mass, so probably strongly clustered, so signal easier to measure
  - Linear bias on large scales, so *length of rod* not affected by galaxy tracer!
The cosmic web at z~0.5, as traced by luminous red galaxies

SDSS

(M. White 2010)

BOSS

A slice 500h⁻¹ Mpc across and 10h⁻¹ Mpc thick
Can see baryons that are not in stars ...

High redshift structures constrain neutrino mass
BAO in Ly-α forest at z\sim2.4

- Signal from cross-correlating different lines of sight

Slosar, Irsic et al. 2013
• The baryon distribution today ‘remembers’ the time of decoupling/last scattering; can use this to build a ‘standard rod’

• Next decade will bring observations of this standard rod out to redshifts $z \sim 2$ Constraints on model parameters from 10% to 1%
How standard is the rod?
$z=18.3 \ (t=0.21 \text{Gyr})$

Volker Springel (Millenium)

Tuesday, July 17, 2012
Structure formation ‘local’ as nothing moved far
Gastrophysics also local
Typical displacement

We move 600 km/s. What does this mean?

1000 km/s for 10 billion years
= \frac{1000 \text{ km/s}}{c} \times 10^{10} \text{ light years}

1 \text{ Megaparsec} = 3.2 \times 10^6 \text{ light years}

\sim 10 \text{ Mpc}

In CDM nothing has moved much more than 10 Mpc (comoving) since the Big Bang
Zeldovich displacements (further) smear out the BAO spike
Stability of inflection point

• Nonlinear smearing: \( \exp(-k^2 R_{\text{NL}}^2) \sim 1 - k^2 R_{\text{NL}}^2 \)
so correction is like \( k^2 \)

• \( k^2 \) is like a Laplacian

• In real space: \( R_{\text{NL}}^2 [2/r \, d\xi/dr + d^2\xi/dr^2] \)

• At local maximum \( d\xi/dr = 0 \) but second derivative large

At inflection point \( d^2\xi/dr^2 = 0 \), and \( d\xi/dr \) term suppressed by \( (R_{\text{NL}}/r_{\text{BAO}})^2 \sim (10/100)^2 \)
Standard lore

- Gravitational clustering creates nonlinear objects called haloes
- Halo properties (assembly, clustering) correlate most strongly with their mass
- Galaxies form in haloes
- Understand halos to understand galaxies
$k^2$-bias and the inflection point

- $k^2$ from a Laplacian
- In real space: $b_{01} R_h^2 \left[ 2/r \frac{d\xi}{dr} + \frac{d^2\xi}{dr^2} \right]$
- At local maximum $d\xi/dr = 0$ but second derivative large
- At inflection point $d^2\xi/dr^2 = 0$, and $d\xi/dr$ term suppressed by two powers of $(R_h/r_{BAO}) \sim (5/100)$
In practice, BAO feature involves two components of distance across line of sight, and one component along line of sight. So ‘average distance’ is:

\[ D_V(z) \equiv \left[ (1 + z)^2 D_A(z)^2 \frac{cz}{H(z)} \right]^{1/3} \]

In addition, we must convert measured angles/redshifts into comoving distances. We must assume a fiducial cosmology to do so. However,

\[ \xi_0(s_{\text{fid}}(z)/D_V^{\text{fid}}(z)) \simeq \xi_0(s_{\text{true}}(z)/D_V^{\text{true}}(z)) \]
Usual analysis uses shape of $P_k$ in fiducial cosmology to estimate BAO scale.

LP can estimate BAO scale with

- no prejudice about shape of $P_k$.
- no reconstruction.
Usual analysis uses shape of Pk in fiducial cosmology to estimate BAO scale.

LP can estimate BAO scale with

- no prejudice about shape of Pk.
- no reconstruction
- good agreement with published scale