Precise measurement of the radial BAO scale in galaxy redshift surveys

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Based on the work arXiv:1210.6446
In collaboration with: E. Sánchez, F. J. Sánchez, J. García-Bellido and I. Sevilla
Baryon Acoustic Oscillations

- Pressure in b-\(\gamma\) fluid creates sound waves.
- Excess probability at the sound horizon scale (\(r_s \sim 110\) Mpc/h).
- Standard ruler for cosmological constraints.
Radial and angular BAO

- Usual approach to BAO: measure position in the angular-averaged 3-D correlation function $\xi(r)$.
- Alternative: separate measurements in the radial and angular correlation functions.

$$\xi(r) \neq \xi_{||}(\Delta z) + \omega(\theta)$$
Radial and angular BAO

Advantages:
• Only direct observables ($\Delta z$, $\theta$) are involved. No fiducial model needed.
• $\theta_{\text{BAO}}$ and $\Delta z_{\text{BAO}}$ are complementary cosmological probes.

$$\Delta z_{\text{BAO}} = \frac{H(z)}{c r_s}$$

$$\theta_{\text{BAO}} = \frac{r_s}{(1 + z) d_A(z)}$$
Extracting the angular BAO

• Project a redshift bin on the sphere and calculate angular correlation.

Extracting the angular BAO

- Project a redshift bin on the sphere and calculate angular correlation.
- Fit data to the model:
  \[ w(\theta) = A + B\theta^\gamma + C e^{-(\theta - \theta_{\text{FIT}})^2/2\sigma^2} \]
- Correct \( \theta_{\text{FIT}} \) for projection effects to obtain \( \theta_{\text{BAO}} \)

Extracting the angular BAO

\[ \omega(\theta) \]

\[ z=0.4 \]

(arbitrary normalization)
Extracting the angular BAO

- Estimator must be corrected for projection effects.

- The estimator coincides with actual value (to 0.75%) for infinitesimal redshift bins.

- The correction is largely model-independent.
Effect of RSDs

Angular case: effect can be absorbed in offset and amplitude.
Effect of RSDs

Radial case: the shape changes entirely.
Extracting the radial BAO

- Divide your survey into appropriate redshift bins.
- Divide each bin into small angular pixels.
- Correlate galaxy pairs belonging to the same angular pixel.
Extracting the radial BAO

• Fit model

\[ \xi_{\parallel}(\Delta z) = A + B e^{-C \Delta z} - D e^{-E \Delta z} + F^r \exp \left( -\frac{(\Delta z - \Delta z_{BAO})^2}{2\sigma^2} \right) \]

• The BAO scale is given directly by \( \Delta z_{BAO} \).

• Limited interpretation of the other parameters.

• Now, let's see the results...
Pause for commercials: CUTE

- Have loads of objects to correlate? Beware! 2PCF is $O(N^2)$

<table>
<thead>
<tr>
<th>Catalog</th>
<th>#objects</th>
<th>Time for 2PCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSS DR7</td>
<td>80 K</td>
<td>~ 60 s</td>
</tr>
<tr>
<td>DES</td>
<td>~ 20 M (per bin)</td>
<td>~ 40 days</td>
</tr>
<tr>
<td>Simulation</td>
<td>$1024^3$</td>
<td>~ 340 years</td>
</tr>
</tbody>
</table>
Pause for commercials: CUTE

- Have loads (>1 M) of objects to correlate?
- Tired of waiting for ages for a trivial calculation?
- Don't have the dough for a big computer?

GPUs may be that miracle you were praying for...

Try CUTE*!!!

*Correlation Utilities and Two-point Estimation
<table>
<thead>
<tr>
<th><strong>Pause for commercials: CUTE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GPUs</strong></td>
</tr>
<tr>
<td>LOTS of slow(er) nodes for fast graphics rendering.</td>
</tr>
<tr>
<td><strong>Ups</strong></td>
</tr>
<tr>
<td>• Very fast simple computations.</td>
</tr>
<tr>
<td>• Cheap.</td>
</tr>
<tr>
<td><strong>Downs</strong></td>
</tr>
<tr>
<td>• No support for complicated operations.</td>
</tr>
<tr>
<td>• More difficult to code.</td>
</tr>
<tr>
<td><strong>CPUs</strong></td>
</tr>
<tr>
<td>Few(er) fast(er) nodes</td>
</tr>
<tr>
<td><strong>Ups</strong></td>
</tr>
<tr>
<td>• Complicated operations supported.</td>
</tr>
<tr>
<td>• Easy to code.</td>
</tr>
<tr>
<td>• Easy to parallelize.</td>
</tr>
<tr>
<td><strong>Downs</strong></td>
</tr>
<tr>
<td>• Expensive.</td>
</tr>
</tbody>
</table>
Pause for commercials: CUTE

![Graph depicting performance across different device types: Sequential, Laptop-MP, Laptop-GPU, Server-MP, Server-GPU. The x-axis represents the number of objects, and the y-axis represents time (t in s). There are markers indicating performance metrics such as 80 K € and 1 K €. The graph is annotated with various lines and points illustrating the performance comparison.](image_url)
Pause for commercials: CUTE

- x100 faster than sequential code with a high-end GPU.
- x10 faster than sequential code with a gaming GPU.
- Supports: radial, angular, monopole and 3D anisotropic 2PCFs.
- Brute-force, pixels and hybrid algorithms for even faster computation.
- Also parallelized for CPUs (OpenMP).
- Working on optimized P³M algorithm to reduce the $O(N^2)$ scaling.
Pause for commercials: CUTE

Now in stores!!

http://members.ift.uam-csic.es/dmonge/CUTE.html
1st test: theoretical 2PCFs

- Tested on theoretical CFs for 14 different models (including evolving DE).
- The BAO scale is recovered with 0.1% precision in all cases.
2nd test: mock catalog

- Mock catalog from the MICE collaboration.
- Lightcone + RSD effects present.
- 5000 sq-deg, $0.1 < z < 1.5$, 55 M objects.

http://maia.ice.cat/mice/
2nd test: mock catalog
Systematic errors

- Angular pixel size
Systematic errors

- Angular pixel size ~ 0.20%
- Non-linearities ~ 0.10%
- Bias ~ 0.20%
- Fit limits ~ 0.10%

Total systematic error

$$\delta(\Delta z_{\text{BAO}}) < 0.35\%$$
Statistical errors

- Computed theoretically and compared with jacknife.
- Very large volume is needed to suppress cosmic variance.
- Cosmic variance and Poisson errors are comparable.
Statistical errors

\[ \Delta z \]

\[ 0.75 < z < 1.1, \text{ area}=200 \text{ sq-deg} \]
Results

\[ \chi^2 / \text{dof} = 2.622 / 8 \]
\[ \text{Prob} = 0.9558 \]
\[ F = 0.0024 \pm 0.0020 \]
\[ \Delta z_{\text{BAO}} = 0.0463 \pm 0.0021 \]

\[ \chi^2 / \text{ndf} = 7.963 / 15 \]
\[ \text{Prob} = 0.9253 \]
\[ F = 0.0031 \pm 0.0012 \]
\[ \Delta z_{\text{BAO}} = 0.0497 \pm 0.0028 \]

\[ \chi^2 / \text{ndf} = 11.11 / 16 \]
\[ \text{Prob} = 0.8028 \]
\[ F = 0.0030 \pm 0.00077 \]
\[ \Delta z_{\text{BAO}} = 0.0567 \pm 0.0011 \]

\[ \chi^2 / \text{ndf} = 30.72 / 25 \]
\[ \text{Prob} = 0.1984 \]
\[ F = 0.0044 \pm 0.0018 \]
\[ \Delta z_{\text{BAO}} = 0.0716 \pm 0.0047 \]
Results

\[ \Delta Z_{BAO} \]

vs.

\[ Z \]

0.04 0.05 0.06 0.07 0.08

0.2 0.4 0.6 0.8 1.0 1.2 1.4

David Alonso
Seminar @ Université de Genève
Results
Conclusions

- New method to extract the radial BAO scale.
- The method is model-independent.
- Huge volume is needed for a precise determination.
- Robust against systematic uncertainties.
- Important constraints can be obtained from angular + radial BAO.
Coming soon...

- We want to try this method on the latest dataset (DR-9) from SDSS (BOSS).
- Analogous formalism to study RSDs in a model-independent way.
- Study the possible bias on cosmological constraints from the standard BAO analyses.
Thanks!