Anisotropic Clustering Measurements using Fourier Space Wedges and the status of the BOSS DR12 analysis

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Outline

1. Introduction and Motivation
2. Anisotropic Clustering in Fourier Space
3. Covariance Matrices for Cubes and Cut-Sky Catalogs
4. Verification of the new RSD Model
5. BOSS DR12 status
6. Conclusions
**Motivation: Anisotropic Analysis of Galaxy Clustering**

**Aim for the BOSS Analysis**
- Excellent large spectroscopic galaxy sample
- **Baryonic Acoustic Oscillations** imprint in galaxy clustering signal

**Line-of-Sight Decomposition**
- z-space matter clustering is inherently anisotropic
- constrain separately

\[ D_A(z) = \frac{s_\perp}{\Delta \alpha (1 + z)} \]

and \[ H(z) = \frac{c \Delta z}{s_\parallel} \]

source: [F. Montesano]
Extend Clustering Wedges to Fourier Space

The LOS parameter $\mu$

$$\mu = |\cos(\theta)|$$

Power Spectrum Wedges

- $P(\mu, k)$ averaged over wide bins in $\mu$
- harmonized $S/N$
- $P_{\mu_1, \mu_2}(k) \equiv \frac{1}{\mu_2 - \mu_1} \int_{\mu_1}^{\mu_2} P(\mu, k) \, d\mu$
- simple window function description
- transverse projection $P_\perp(k) \equiv P_{0, \frac{1}{2}}(k)$
- line-of-sight projection $P_{\parallel}(k) \equiv P_{\frac{1}{2}, 1}(k)$

$P(k, \mu) = \langle \delta(k, \mu)\delta^*(k, \mu) \rangle$

- bad $\frac{S}{N}$ for fine $\mu$-bins!
Extend Clustering Wedges to Fourier Space

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Power Spectrum Wedges

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- harmonized S/N
- $P_{\mu_1, \mu_2}(k) \equiv \frac{1}{\mu_2 - \mu_1} \int_{\mu_1}^{\mu_2} P(\mu, k) \, d\mu$
- simple window function description
  - $\mu = \cos(\theta)$
- S/N even high enough for three wedges
- $P_{3w, i}(k) \equiv P_{\frac{i-1}{3}, \frac{i}{3}}(k)$

$P(k, \mu) = \langle \delta(k, \mu)\delta^*(k, \mu) \rangle$

bad $\frac{S}{N}$ for fine $\mu$-bins!
Measurements of Anisotropic Clustering

Yamamoto estimator

- pairwise LOS depends on observer and galaxy pair
- double sum over objects
  
  [Yamamoto et al. '05]

- impossible scaling
  \[ N_k (N_{gal}^2 + N_{rnd}^2) \]

  [Samushia et al. '15]
Measurements of Anisotropic Clustering

Yamamoto-Blake estimator

- per-object-LOS approximation instead of pairwise LOS
- single direct sum [Blake et al. '11]
- wide-angle bias for low-z and $\ell \geq 4$ [Samushia et al. '15]

![Graph showing fractional bias in APS (%)]

- $z=0.32$
- $\beta=0.35$

![Diagram illustrating anisotropic clustering]
Yamamoto estimator for Fourier space wedges I

Yamamoto Estimator for Clustering Wedges

- extend Yamamoto estimator to any number of wedges
- replace Legendre polynomials by $\mu$-top-hat functions

wedge (or multipole) overdensity field

$$F_a = \frac{1}{\sqrt{A}} \left[ D_a(k) - \alpha R_a(k) \right]$$

weighted sum over galaxies and randoms ($1/\alpha$ more numerous):

$$D_a(k) = \sum_i w_i e^{i k \cdot x_i} \Theta_a(\mu_{ki}),$$

$$R_a(k) = \sum_j w_j e^{i k \cdot x_j} \Theta_a(\mu_{kj})$$

$\Theta_a(\mu)$: top-hat for this wedge, with argument $\mu_{ki} := \frac{k \cdot x_i}{|k||x_i|}$.

- spoils use of FFTs!?
Yamamoto estimator for Fourier space wedges II

- wedge power spectrum computed as:

\[ P_a(k) = F_a(k)F_0(k)^* - \frac{S_a}{A} \]

- normalization \( A := \alpha \sum_j \tilde{n}_j w_j^2 \) (just as for FKP),
  \( \tilde{n}_j \): the estimated number density of galaxies.
- shot noise \( S_a(k) = \alpha (\alpha + 1) \sum_j w_j^2 \Theta_a(\mu_{kj}) \)

**for polynomial \( \mu \) dependence:**

- fast FFT-scheme for \( P_\ell(\mu) \) developed [Bianchi et al. ’15, Scoccimarro ’15]
- \( \mu^2 = \sum_{ij} \frac{x_i x_j}{x^2} \frac{k_i k_j}{k^2} \rightarrow 6 \) combinations
- unbeatable scaling \( 6 N_{\text{fft}} \log N_{\text{fft}} \) instead of \( N_k (N_{\text{gal}} + N_{\text{rnd}}) \)
FFT-based Clustering Wedges Estimation

- $P_\ell(k)$ by Yamamoto–FFT estimator (*EUCLID comparison project*)
- transform to wedges by

$$P_{\mu_1}^{\mu_2}(k) = \frac{1}{\mu_2 - \mu_1} \sum_{\ell \in \{0, 2, 4\}} P_\ell(k) \int_{\mu_1}^{\mu_2} L_\ell(\mu) \, d\mu$$

Jan Grieb (MPE, Garching)

Fourier Space Wedges

Jul 20th, 2015
A First Look at the Data: BOSS DR12 sample

\[ 0.2 \leq z < 0.5 \]

\[ P_{3w,1}(k) \]

\[ P_{3w,2}(k) \]

\[ P_{3w,3}(k) \]

\[ 0.5 \leq z < 0.75 \]

\[ P_{3w,1}(k) \]

\[ P_{3w,2}(k) \]

\[ P_{3w,3}(k) \]
The Effect of the Window Function

Convolution with wedge window function (assuming isotropy) – in analogy to monopole:

\[
P_{a}^{\text{conv}}(k) = \int d^3k' \left[ P_{a}^{\text{model}}(k') \, W_{a}^2(\|k \hat{e}_z - k'\|) - \frac{W_{a}^2(k)}{W_{0}^2(0)} \, P_{0}^{\text{model}}(k') \, W_{0}^2(k') \right].
\]

(second term: integral constraint)
**Covariance estimation for Clustering Wedges**

- Estimate $P_a(k_i)$-covariance $C_{ab}(k_i, k_j)$ either
  1. theoretically derived (smooth, model required) or
  2. measured from a large set of synthetic catalogues (noisy)

**Full N-body Minerva simulations**

- Verification of covariance estimate (and RSD modelling)
- 100 realizations, $V = 3.37 \ (\text{Gpc}/h)^3$
- HOD galaxies at $z = 0.57$ mimicking CMASS sample (similar $\bar{n}$ and clustering)
The Covariance Matrix for Fourier–Space Wedges

- For a **cubic box**, Fourier modes $P(k, \mu)$ are **uncorrelated** on large scales.
- **Variance** can be constructed by a Gaussian model using an RSD power spectrum
  
  \[ \int k^2 d^3k \ldots \]
Synthetic Catalogues as Covariance Estimate

- noise in covariance propagates to the final constraints [Percival et al. ‘14]
- accurate constraints require $O(10^3)$ of synthetic catalogs (mocks)
- quick generation: non-linear evolution w/ fast approximative schemes
- mimicking full survey including veto regions and fibre collisions
• the survey geometry introduces correlations on the off-diagonals
• fibre collisions also correlate distant bins

\[ \text{C}_{n,m} (k_i, k_j) / \left( \sigma_{P_{3w,n}} (k_i) \sigma_{P_{3w,m}} (k_j) \right) \]
**Verification of the modelling**

**Validation of the new RSD model (to Ariel’s talk)**

- **Verify** the modelling of PS wedges with Minerva simulations
- Smallest possible modes – $k_{\text{max}}$ – to get unbiased parameters?

**unbiased $f\sigma_8$ sets limit**

\[ k_{\text{max}} = 0.2 \, h/\text{Mpc} \]

- **varying the shot noise**
  (prepare for catalogues fits)
  introduces small $\alpha_{\perp,\parallel}$ bias

- **tighter constraints for 3 wedges**
BOSS Mock Challenge

- Model performance compared in a **blind challenge**
- Blind results handed in and **analyzed**

**New Results for Cutsky Mocks**

- Too optimistic choice of $k_{\text{max}}$
- Need to vary the shot noise
Ready to fit the DR12 galaxy catalog

- model predictions using Ariel’s preliminary 2PCF fits
- good agreement between Fourier and configuration space
- be patient until the release!
Conclusions

i) new RSD model for galaxy clustering
- Major improvement, state-of-the art modelling for analysis both in configuration and Fourier space
- Tested and validated with large-scale simulations

ii) BOSS Power Spectrum Wedges
- largest volume probed so far for galaxy clustering analysis, optimized data processing and fitting
- intensive work on final analysis
- highest demands: complementary analysis for multipoles and wedges in conf. and Fourier space
Outlook! Questions?

Outlook

1. Analysis is tremendous team effort
2. Consistency check: configuration and Fourier space
3. Unprecedented accuracy can be expected

- Thank you for your attention!
- Time for all your questions!
References

NOT UP TO DATE!


L. Anderson et al. (BOSS Collaboration),

R. Angulo, C. Baugh, C. Frenk, and C. Lacey,

F. Beutler et al. (BOSS Collaboration)
(2013), arXiv:1312.4611

J. Hartlap, P. Simon, and P. Schneider

Komatsu, E. et al.

L. Samushia, E. Branchini, and W. Percival,
(2015), arXiv:1504.02135

A. G. Sánchez, E. A. Kazin, F. Beutler, et al. (BOSS Collaboration)

A. G. Sánchez, F. Montesano, E. A. Kazin, et al. (BOSS Collaboration)
Angular Diameter Distance and the BAO

- Angular Diameter Distance,
  \[ D_A(z) = c \int_0^z \frac{dz'}{H(z')} \]
- Sound Horizon,
  \[ r_s = \int_0^{t_{\text{dec}}} \frac{c_s(t') \, dt'}{a(t')} \],
  known from CMB measurements \( (r_s = 147 \, \text{Mpc} \, [\text{Komatsu et al. '11}]) \)
- From the BAO position, we can get \( (r_{AB} = r_s) \)
  \[ \theta_{\text{BAO}} = \frac{1}{1 + z} \frac{r_s}{D_A(z)} \]
  \[ \Delta z_{\text{BAO}} = \frac{r_s H(z)}{c} \]
Dependence of Geometry on Cosmology

- Fiducial cosmology of simulations: \( w = w_{\text{true}} = -1 \)
- Assumed cosmology from measurement: \( w_{\text{assumed}} = w_{\text{true}} + \Delta w \)
- Mismatch causes geometry of the late universe to be misinterpreted
- Relates to change \( \alpha = k_{\text{app}} / k_{\text{true}} \) [Angulo et al. ’08]

\[
\begin{align*}
\alpha_\perp &= \frac{D_A(z, w_{\text{assumed}})}{D_A(z, w_{\text{true}})}, \quad \alpha_\parallel = \frac{H(z, w_{\text{true}})}{H(z, w_{\text{assumed}})} \\
\alpha &\approx \alpha_\perp^{-2/3} \alpha_\parallel^{1/3}
\end{align*}
\]

- \( D_A \) angular diameter distance, \( H \) Hubble parameter \( D_A \) and the BAO
- Goals: \( \langle \alpha \rangle = 1 \) (no bias), \( \langle |\Delta \alpha| \rangle \ll 1 \) (high precision)
- \( \Delta \alpha \) and \( \Delta w \) of same magnitude
Estimation of Model Parameters using MCMC

- **Likelihood function** for mean power spectrum wedges $\bar{P}_{||,\perp}(k)$, measured at wavenumber bins $k_i$:

  $$P(\bar{P}|\theta) \propto \exp[-\chi^2(\bar{P}|\theta)/2],$$

  where

  $$\chi^2(\bar{P}|\theta) = \sum_{x,y,i,j} \left[ \bar{P}_x(k_i) - P_{x,rpt}(k_i) \right] C_{xyij}^{-1} \left[ \bar{P}_y(k_j) - P_{y,rpt}(k_j) \right]$$

- covariance matrix estimated from set of realizations

  $$C_{xyij} = \langle \left[ P_x(k_i) - \bar{P}_x(k_i) \right] \left[ P_y(k_j) - \bar{P}_y(k_j) \right] \rangle$$

- inverse corrected for noise [Hartlap et al. '06]

- step through parameter space using **Markov chain Monte Carlo**