Anisotropic Clustering Measurements using Fourier Space Wedges

and the status of the BOSS DR12 analysis

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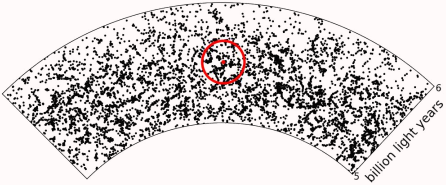
Outline

Motivation: Anisotropic Analysis of Galaxy Clustering

Aim for the BOSS Analysis

- Excellent large spectroscopic galaxy sample
- Baryonic Acoustic Oscillations imprint in galaxy clustering signal

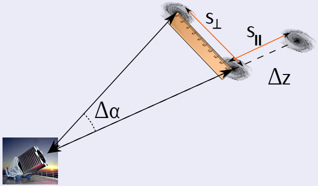


source: [F. Montesano]

- BAO serves as standard ruler
- probe of expansion history

Line-of-Sight Decomposition

- z-space matter clustering is inherently anisotropic



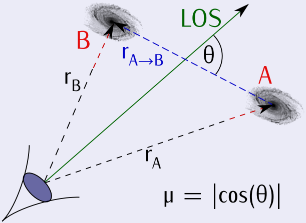
- constrain separately

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

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

Extend Clustering Wedges to Fourier Space

The LOS parameter μ

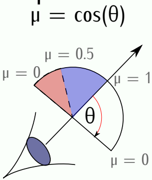


$$P(k,\mu) = \langle \delta(k,\mu)\delta^*(k,\mu)\rangle$$

- bad $\frac{S}{N}$ for fine μ–bins!

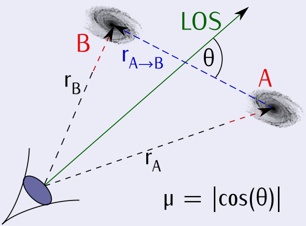
Power Spectrum Wedges

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



Extend Clustering Wedges to Fourier Space

The LOS parameter μ

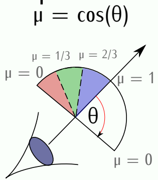


$$P(k,\mu) = \langle \delta(k,\mu)\delta^*(k,\mu) \rangle$$

- bad $\frac{S}{N}$ for fine μ–bins!

Power Spectrum Wedges

- $P(\mu, k)$ averaged over wide bins in μ
- harmonized S/N
- $P_{\mu_1,\mu_2}(k) \equiv \frac{1}{\mu_2 - \mu_1} \int_{\mu_1}^{\mu_2} P(\mu,k)\,\mathrm{d}\mu$
- simple window function description
- S/N even high enough for three wedges
- $P_{3w,i}(k) \equiv P_{\frac{i-1}{3},\frac{i}{3}}(k)$

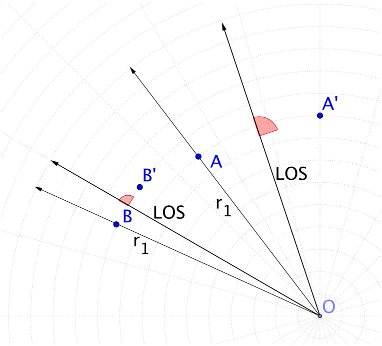


Measurements of Anisotropic Clustering

Yamamoto estimator

- pairwise LOS depends on observer and galaxy pair
- double sum over objects

  [Yamamoto et al. '05]
- *impossible* scaling $N_k \, (N_{\text{gal}}^2 + N_{\text{rnd}}^2)$!

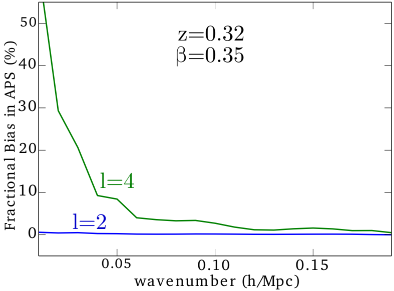


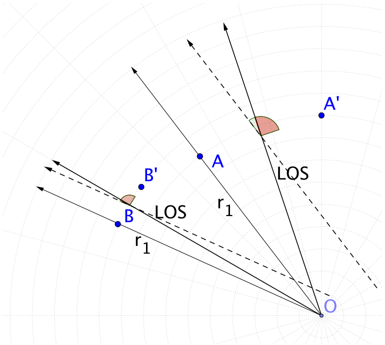
[Samushia et al. '15]

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]





[Samushia et al. '15]

Yamamoto estimator for Fourier space wedges I

Yamamoto Estimator for Clustering Wedges

- extend Yamamoto estimator to any number of wedges
- replace Legendre polynomials by μ–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):

$$D_a(k) = \sum_i w_i \, \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}_i} \, \Theta_a(\mu_{ki}),$$
$$R_a(k) = \sum_j w_j \, \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{x}_j} \, \Theta_a(\mu_{kj})$$

$\theta_a(\mu)$: top–hat for this wedge, with argument $\mu_{ki} := \frac{\boldsymbol{k}\cdot\boldsymbol{x}_i}{|\boldsymbol{k}||\boldsymbol{x}_i|}$.

- *spoils use of FFTs!?*

Yamamoto estimator for Fourier space wedges II

- wedge power spectrum computed as:

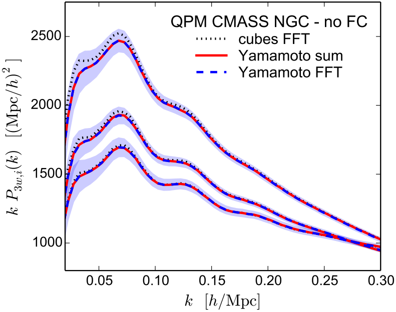
$$P_a(k) = F_a(k)F_0(k)^* - \frac{S_a}{A}$$

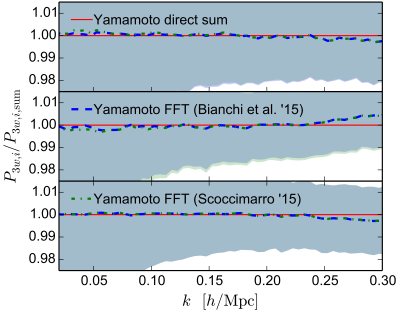
- normalization $A := \alpha \sum_j \bar{n}_j w_j^2$ (just as for FKP),
  $\bar{n}_j$: the estimated number density of galaxies.
- shot noise $S_a(k) = \alpha(\alpha + 1) \sum_j w_j^2 \, \Theta_a(\mu_{kj})$

for polynomial μ dependence:

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

FFT-based Clustering Wedges Estimation

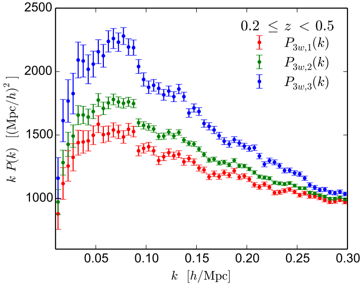


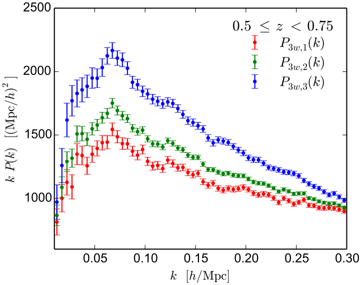


- $P_\ell(k)$ by Yamamoto–FFT estimator (*EUCLID comparison project*)
- transform to wedges by

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

A First Look at the Data: BOSS DR12 sample





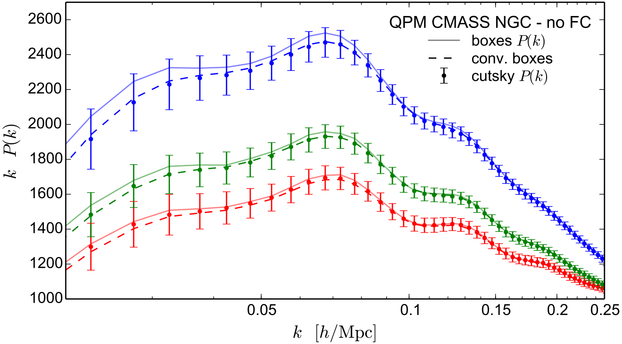
[JG et al. '15b (in prep.)]

The Effect of the Window Function

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

$$P_a^{\mathrm{conv}}(k) = \int \mathrm{d}^3\boldsymbol{k}' \left[P_a^{\mathrm{model}}(k')\, W_a^2(|k\hat{\boldsymbol{e}}_z - \boldsymbol{k}'|) - \frac{W_a^2(k)}{W_0^2(0)} P_0^{\mathrm{model}}(k')\, W_0^2(k') \right].$$

(second term: integral constraint)

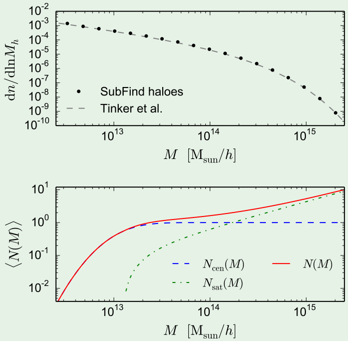


Covariance estimation for Clustering Wedges

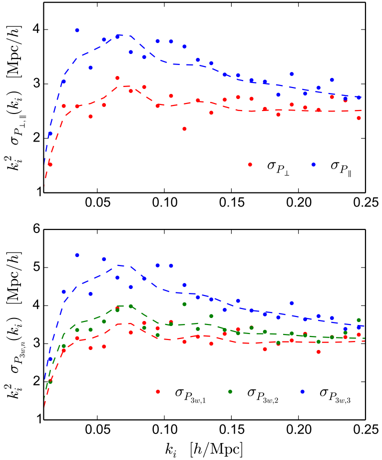
- Estimate $P_a(k_i)$–covariance $C_{ab}(k_i, k_j)$ either
  1. theoretically derived (smooth, model required) or
  2. measured from a large set of synthetic catalogues (noisy)

Full N-body *Minerva* simulations

- Verification of covariance estimate (and RSD modelling)
- 100 realizations, $V = 3.37\ (\mathrm{Gpc}/h)^3$
- HOD galaxies at $z = 0.57$ mimicking CMASS sample (similar $\bar{n}$ and clustering)



The Covariance Matrix for Fourier-Space Wedges

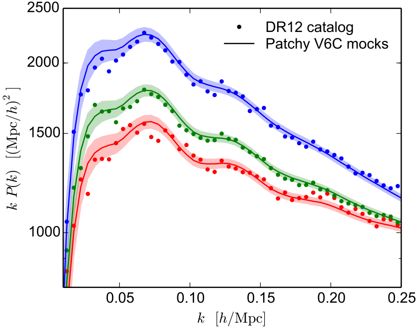


- For a cubic box, Fourier modes $P(k, \mu)$ are uncorrelated on large scales
- Variance can be constructed by a Gaussian model using an RSD power spectrum
  [JG et al. '15a (in prep.)]

- volume-average for each power spectrum bin $\int_{k_1}^{k_2} \mathrm{d}^3k \ldots$

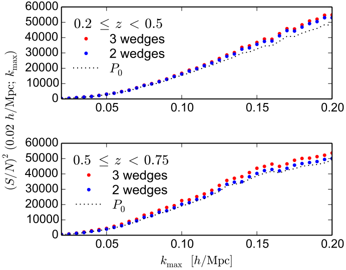
Synthetic Catalogues as Covariance Estimate

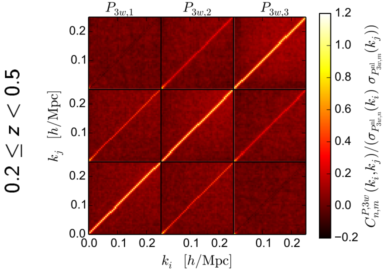
- noise in covariance propagates to the final constraints [Percival et al. '14]
- accurate constraints require $\mathcal{O}\left(10^3\right)$ of synthetic catalogs (*mocks*)
- quick generation: non-linear evolution w/ fast approximative schemes
- mimicking full survey including veto regions and fibre collisions

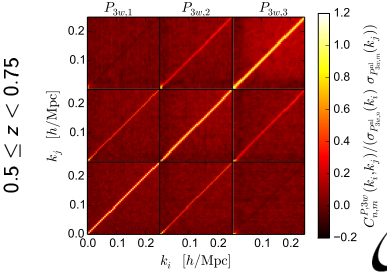


The Covariance Matrix for Fourier–Space Wedges

- the survey geometry introduces correlations on the off–diagonals
- fibre collisions also correlate distant bins



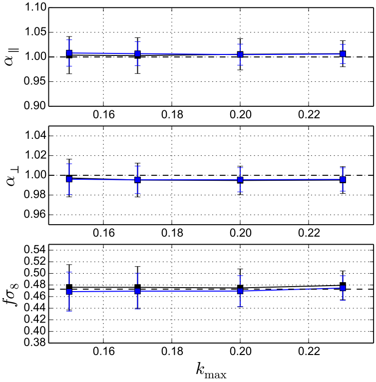




Verification of the modelling

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

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



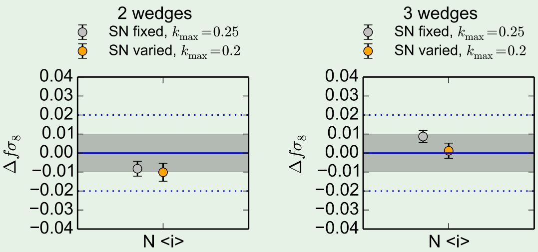
- unbiased $f\sigma_8$ sets limit $k_{\max} = 0.2\ h/\mathrm{Mpc}$
- varying the shot noise (*prepare for catalogues fits*) introduces small $\alpha_{\perp,\parallel}$ bias
- tighter constraints for 3 wedges

BOSS Mock Challenge

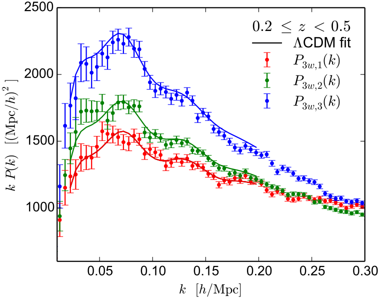
- Model performance compared in a blind challenge
- Blind results handed in and analyzed

- Too optimistic choice of k_{max}
- Need to vary the shot noise

New Results for Cutsky Mocks



Ready to fit the DR12 galaxy catalog



PS fits not ready for the public yet, but...

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

Conclusions

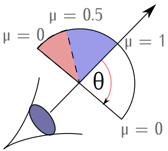
i) new RSD model for galaxy clustering

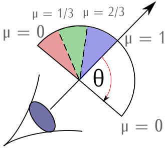
- Major improvement, state-of-the art modelling for analysis both in configuration and Fourier space
- Tested and validated with large-scale simulations

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

$\mu = \cos(\theta)$





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!

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Angular Diameter Distance and the BAO

- Angular Diameter Distance,

$$D_A(z) = c \int_0^z \frac{dz'}{H(z')}$$

- Sound Horizon,

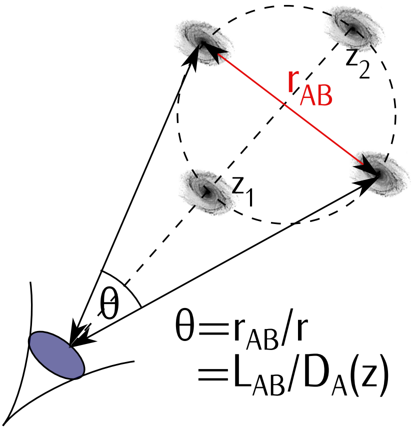
$$r_s = \int_0^{t_{dec}} \frac{c_s(t')\,dt'}{a(t')},$$

known from CMB measurements ($r_s = 147$ Mpc [Komatsu et al. '11])

- From the BAO position, we can get ($r_{AB} = r_s$)

$$\theta_{BAO} = \frac{1}{1+z}\frac{r_s}{D_A(z)}$$

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



go back

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]

$$\alpha_\perp = \frac{D_A(z, w_{\text{assumed}})}{D_A(z, w_{\text{true}})}, \quad \alpha_{||} = \frac{H(z, w_{\text{true}})}{H(z, w_{\text{assumed}})}$$

$$\alpha \approx \alpha_\perp^{-2/3} \alpha_{||}^{1/3}$$

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 Δw of same magnitude

go back

Estimation of Model Parameters using MCMC

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

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

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

- covariance matrix estimated from set of realizations

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

- inverse corrected for noise [Hartlap et al. '06]
- step through parameter space using Markov chain Monte Carlo

go back