Anisotropic Clustering Measurements using Fourier Space Wedges

and the status of the BOSS DR12 analysis

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TR33 Corfu Workshop
Thursday, September 20th, 2015

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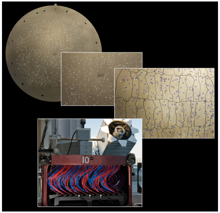
Outline

Introduction: BOSS, a large spec-z galaxy survey

Galaxy clustering with BOSS

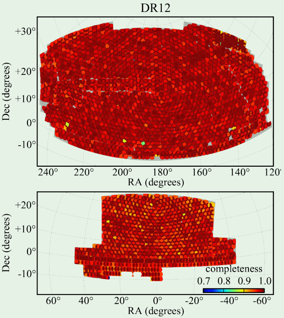
- spectroscopic redshifts
- dense and robust targets:
  - luminous red galaxies (LOWZ) &
  - M_*- and volume limited (CMASS)
- $\bar{n} = 3 \cdot 10^{-4} \left(\frac{h}{\mathrm{Mpc}}\right)^3$
- large volume: 7.4 Gpc^3, $0.2 \leq z \leq 0.75$
- biased tracer of LSS ($b \sim 2$)



source: [lbl.gov]

- rich analysis [Anderson et al. '14, Beutler et al. '14]

DR12 catalogue release



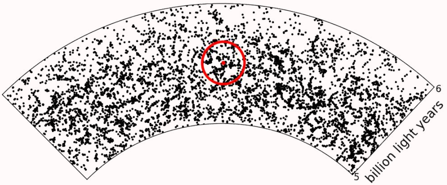
redshifts for 1,372,737 galaxies over 9,376 deg^2

[Reid et al. '15 (in prep.)]

Motivation: anisotropic analysis of galaxy clustering

Aim for the BOSS Analysis

- Baryonic Acoustic Oscillations imprint in galaxy clustering signal

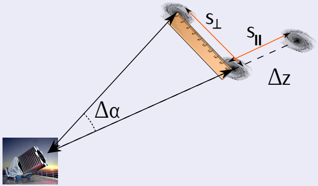


source: [F. Montesano]

- BAO serves as standard ruler
- probe of expansion history

Line-of-Sight Decomposition

- z-space matter clustering is inherently anisotropic



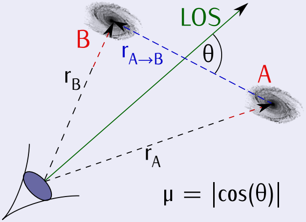
- constrain separately

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

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

Extend clustering wedges to Fourier space

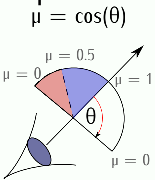
The LOS parameter μ



- analysis of config.-space wedges for BOSS DR11 [Sánchez et al. '13a, Sánchez et al. '13b]

Power Spectrum Wedges

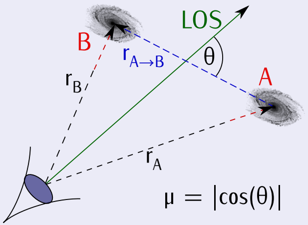
- $P(k,\mu) = \langle \delta(k,\mu)\delta^*(k,\mu) \rangle$
- averaged over wide bins in μ
- $P_{\mu_1,\mu_2}(k) \equiv \frac{1}{\mu_2-\mu_1} \int_{\mu_1}^{\mu_2} P(\mu,k)\,\mathrm{d}\mu$
- *harmonized S/N*
- simple window function description
- transverse projection $P_\perp(k) \equiv P_{0,\frac{1}{2}}(k)$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



- bad $\frac{S}{N}$ for fine μ–bins!

Extend clustering wedges to Fourier space

The LOS parameter μ



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Power Spectrum Wedges

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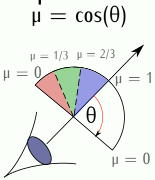
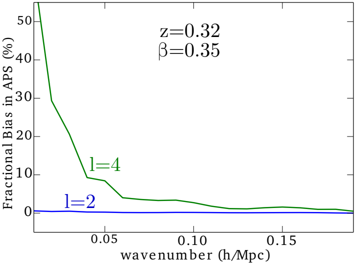
- *harmonized* S/N
- simple window function description
- S/N even high enough for three wedges
- $P_{3w,i}(k) \equiv P_{\frac{i-1}{3},\frac{i}{3}}(k)$

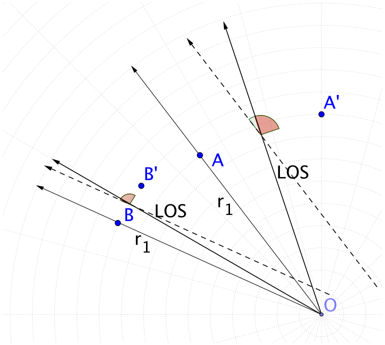


Measurements of Anisotropic Fourier-Space Clustering

Yamamoto-Blake estimator

- per-object-LOS approximation instead of pairwise LOS
- single direct sum (slow) [Yamamoto et al. '06, Blake et al. '11]
- wide-angle bias for low-z and $\ell \geq 4$ [Samushia et al. '15]





[Samushia et al. '15]

Yamamoto-Blake estimator for Fourier space wedges

Yamamoto-Blake estimator for power spectrum multipoles

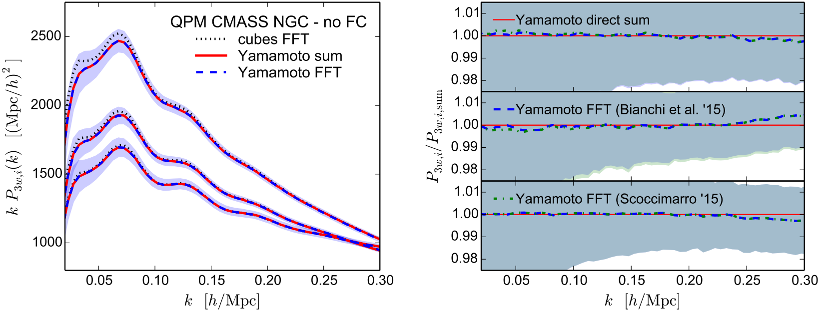
- covariance of density field with multipole field
- apply FKP weights to optimize variance [Feldman et al. '94]
- FFT-scheme for $P_\ell(\mu)$ developed [Bianchi et al. '15, Scoccimarro '15]
- much better scaling $N_{\rm fft} \log N_{\rm fft}$ instead of $N_k\,(N_{\rm gal} + N_{\rm rnd})$

- only works for a polynomial μ dependence
- transform $P_\ell(k)$ to wedges by

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

FFT-based Clustering Wedges Estimation

- Test on 1000 QPM CMASS mocks (NGC, no fibre collisions)



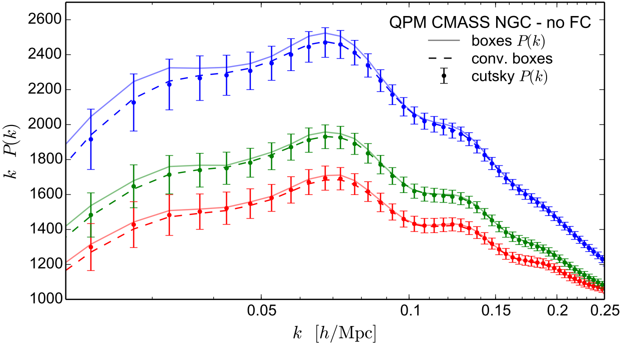
- similar results for covariance matrix

The Effect of the Window Function

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

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

(second term: integral constraint)

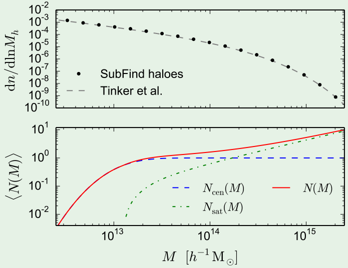


Covariance estimation for Clustering Wedges

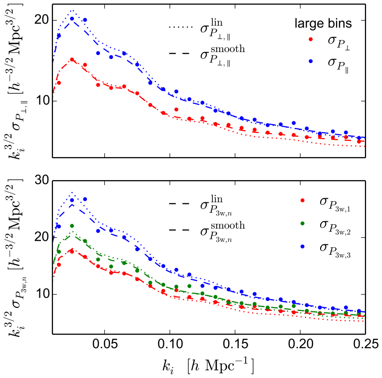
- Estimate for $P_a(k_i)$–covariance $C_{ab}(k_i, k_j)$ either
  1. theoretically derived (smooth, model required) or
  2. measured from a large set of synthetic catalogues (noisy)

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)



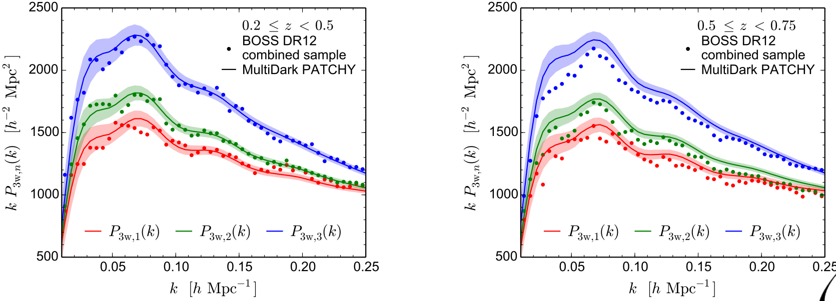
The Covariance Matrix for Fourier-Space Wedges



- Need of a smooth and accurate covariance estimate for verification of RSD modelling
- For a regular cubic simulation, Fourier modes $P(k, \mu)$ are uncorrelated on large scales
- Variance can be constructed by a Gaussian model using an RSD power spectrum
- published together with configuration-space covariance [JG et al. '15a (submitted)]

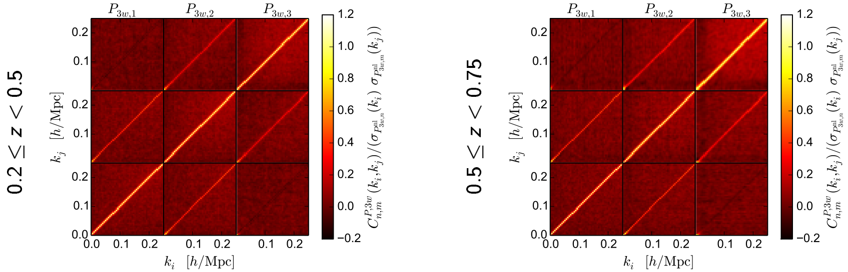
Synthetic Catalogues as Covariance Estimate

- 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



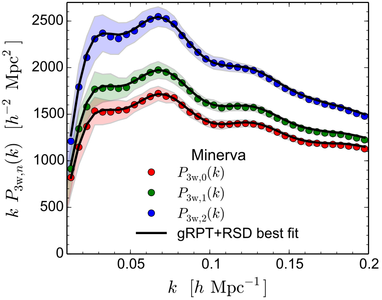
The Covariance Matrix for Fourier-Space Wedges

- the survey geometry introduces correlations on the off-diagonals
- fibre collisions also correlate distant bins
- two sets of mocks: MULTIDARK-PATCHY and QPM



Modelling the Power Spectrum in the trans-linear regime

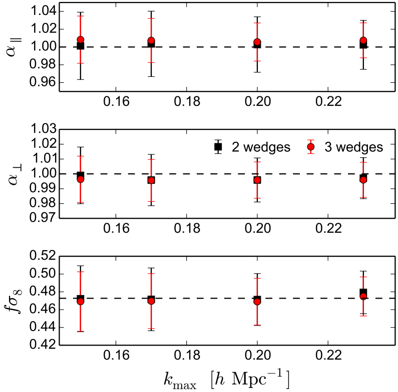
- new approach for renormalized perturbation theory (*gRPT*)
  [Scoccimarro, Crocce et al. '15 (in prep.)]
- linear, non-linear and non-local galaxy bias ($b_1, b_2, \gamma_2, \gamma_3, \sigma_8$)
- RSD using a new concept for the fingers-of-God (a)
- fit of BAO-AP ($\alpha_{||}, \alpha_{\perp}$), and RSD ($f$, growth of structure)
- same model used in, both, configuration and Fourier space



Verification of the modelling

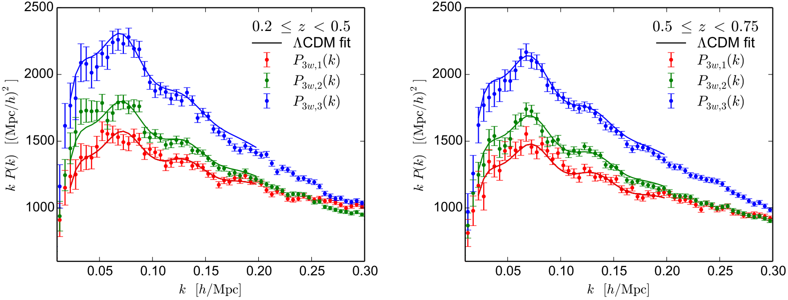
Validation of the RSD modelling

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



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

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

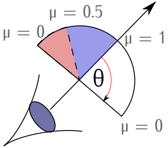
i) new RSD model for galaxy clustering

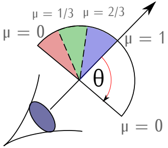
- Major improvement, state-of-the art modelling for analysis both in configuration and Fourier space
- Tested and validated with large-scale simulations

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

$\mu = \cos(\theta)$





References I

- http://newscenter.lbl.gov/2012/08/08/boss-sdss-dr9/
- L. Anderson, É. Aubourg, S. Bailey, F. Beutler, et al. (BOSS Collaboration),
  Mon.Not.Roy.Astron.Soc. **441** 24 (2013), arXiv:1312.4877
- R. Angulo, C. Baugh, C. Frenk, and C. Lacey,
  Mon.Not.Roy.Astron.Soc., **383**, 755 (2008), arXiv:astro-ph/0702543
- F. Beutler, S. Saito, H.-J. Seo, J. Brinkmann, K. Dawson, D. J. Eisenstein, et al. (BOSS Collaboration)
  Mon.Not.Roy.Astron.Soc., **443**, 1065 (2014), arXiv:1312.4611
- D. Bianchi, H. Gil-Marín, R. Ruggeri, W. J. Percival,
  (2015), arXiv:1505.05341
- C. Blake, S. Brough, M. Colless, C. Contreras, W. Couch, et al. ,
  Mon.Not.Roy.Astron.Soc., **415**, 2876 (2011), arXiv:1104.2948 [astro-ph.CO]
- H. A. Feldman, N. Kaiser, J. A. Peacock,
  Astrophys.J., **426**, 23 (1994), arXiv:astro-ph/9304022
- J. N. Grieb, A. G. Sánchez, S. Salazar-Albornoz, C. dalla Vecchia,
  (2015, submitted to MNRAS), arXiv:1509.04293 [astro-ph.CO]
- J. N. Grieb, A. G. Sánchez, F. Montesano, S. Salazar-Albornoz, R. Scoccimarro, M. Crocce et al. ,
  (2015, in prep.)
- J. Hartlap, P. Simon, and P. Schneider
  Astron.Astrophys. (2006), arXiv:astro-ph/0608064
- Komatsu, E. et al.
  ApJS, **192**, 18 (2011), arXiv:1001.4538 [astro-ph.CO]

References II

W. J. Percival, A. J. Ross, A. G. Sánchez, L. Samushia, A. Burden, et al. (BOSS Collaboration), Mon.Not.Roy.Astron.Soc. **439**, 2531 (2014)

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

A. G. Sánchez, E. A. Kazin, F. Beutler, et al. (BOSS Collaboration) Mon.Not.Roy.Astron.Soc. **433** 1202 (2013), arXiv:1303.4396

A. G. Sánchez, F. Montesano, E. A. Kazin, et al. (BOSS Collaboration) Mon.Not.Roy.Astron.Soc. **440** 692 (2013), arXiv:1312.4854

R. Scoccimarro, (2015), arXiv:1506.02729

K. Yamamoto, M. Nakamichi, A. Kamino, B. A. Bassett, H. Nishioka, Publ.Astron.Soc.Jap., **58**, 93 (2006), arXiv:astro-ph/0505115

Angular Diameter Distance and the BAO

- Angular Diameter Distance,

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

- Sound Horizon,

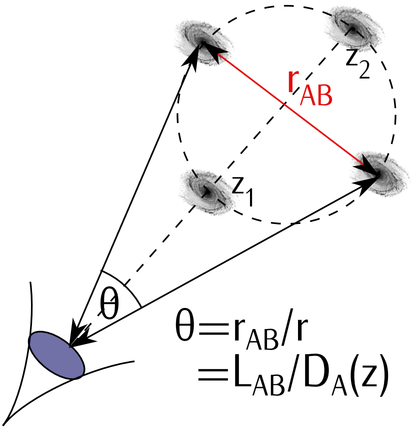
$$r_s = \int_0^{t_{\rm dec}} \frac{c_s(t')\,dt'}{a(t')},$$

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

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

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

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



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

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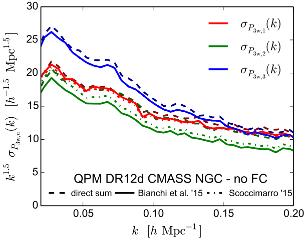
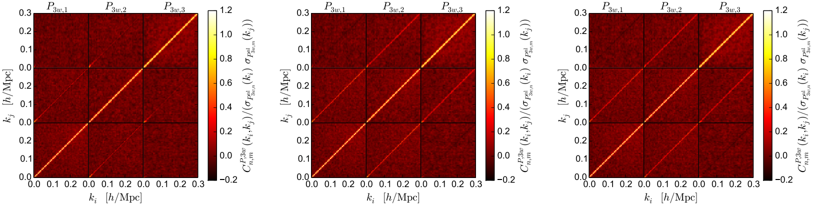
FFT-based Clustering Wedges Estimation – Covariance

- Correlation matrix for 1000 QPM CMASS mocks (NGC, no fibre collision)





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Estimation of Model Parameters using MCMC

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

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

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

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

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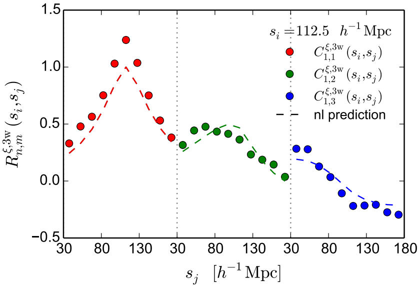
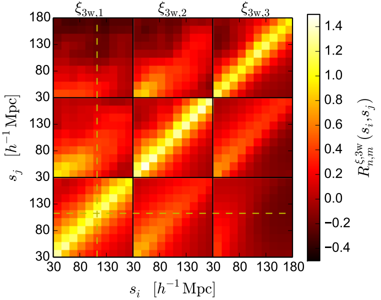
Excursion to Configuration-Space Wedges





upper diag: data / lower diag: theory

- significant correlation because of Fourier transform
- 2PCF variance can be constructed from $\sigma_P^2(k,\mu)$ easily by integration [JG et al. '15a (submitted)]

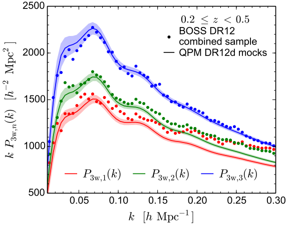
Measurement Noise Level

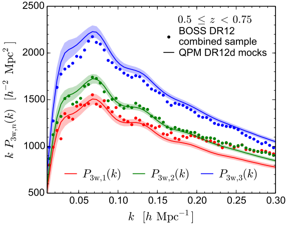
- high level of noise because #bins ≃ #simulations

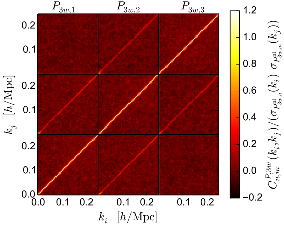
◂ go back

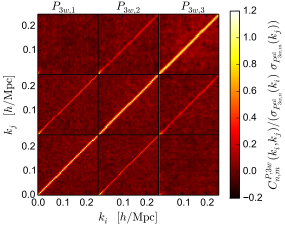
QPM Mocks: PS wedges and their covariance

- low-resolution particle mesh + HOD post-processing, 1000 mocks









Patchy PS wedges
Patchy covariance matrix

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