Measuring RSD in deep redshift surveys

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Outline of my talk

Observational cosmology
  ▶ The galaxy power spectrum
  ▶ Observational effects
  ▶ Redshift space distortions
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Observational cosmology
  - The galaxy power spectrum
  - Observational effects
  - Redshift space distortions

Measuring the redshift space distortions in eBOSS
  - Redshift binning vs redshift weights
  - Optimal redshift weights
  - Preliminary results
Observational cosmology: what does clustering mean?

Clustering strength = number of pairs beyond random

\[ dP = \rho^2 [1 + \xi(r)] dV_1 dV_2 \] (1)
the “probability of seeing structure” can be recast in terms of the overdensity

\[ \delta = \frac{(\rho(x) - \bar{\rho})}{\bar{\rho}} \]  

(2)
Observational cosmology: formal clustering definitions

- the “probability of seeing structure” can be recast in terms of the overdensity

\[ \delta = \left( \rho(x) - \bar{\rho} \right) / \bar{\rho} \]  

(2)

- The correlation function of the field,

\[ \xi(r) = \langle \delta(x)\delta(x + r) \rangle \]  

(3)
the “probability of seeing structure” can be recast in terms of the overdensity

$$\delta = (\rho(x) - \bar{\rho}) / \bar{\rho}$$  \hspace{1cm} (2)

The correlation function of the field,

$$\xi(r) = \langle \delta(x) \delta(x+r) \rangle$$  \hspace{1cm} (3)

or its Fourier analogue, the power spectrum,

$$P(k) = \int d^3r \, \xi(r) e^{-ik \cdot r}$$  \hspace{1cm} (4)

which describes the amplitude of the fluctuations as a function of scale $k$. 
Observational cosmology: the galaxy power spectrum

\[ P_{gal}(k, \mu, z) = k^n T^2(k) D^2(z) [b(z) + f(z) \mu^2]^2 \]

\[ \mu = \mathbf{k} \cdot \hat{n}/k; \quad \hat{n} = \text{line-of-sight} \]
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(5)

Primordial power spectrum

- \( k^n \) (standard inflation)
- \( T^2(k) \rightarrow \Omega_m, m_\nu \ldots \)

Amplitude of clustering

- galaxy bias \( \rightarrow P_g = b(z)P_{dm} \)
- \( D(z) \rightarrow \Omega_m, m_\nu \ldots \)
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**Observational effects** \( \leftrightarrow k, \mu, f(z) \)

- Redshift Space Distortions (RSD)
- Alcock-Paczynksy effect
- (Baryonic acoustic oscillations)
The Baryonic Acoustic Oscillation: standard ruler

BAO as a standard ruler to better understand the nature of the acceleration.

\[ r_s = \left( \frac{1}{H_0 \Omega_m^{1/2}} \right) \int_0^{a_*} \frac{da}{(a + a_{eq})^{1/2}}; \]

\[ k_{bao} = \frac{2\pi}{r_s} \sim 0.06h/Mpc; \]
Galaxy distances are inferred from galaxy redshifts: using a wrong set of fiducial cosmological parameters to convert redshifts into distances introduces \textbf{artificial anisotropy}!

e.g. \( d_p(z) = \int_z^0 dz' \frac{c}{H(z')} \)
The Alcock-Paczynksy test

Galaxy distances are inferred from galaxy redshifts: using a wrong set of fiducial cosmological parameters to convert redshifts into distances introduces artificial anisotropy!

\[ d_p(z) = \int_z^0 dz' \frac{c}{H(z')} \]

Known as Alcock-Paczynski distortion, (Alcock & Paczynski 1979).

- The effect scales differently along and perpendicular to the line-of-sight direction

\[ \alpha_\parallel \propto \frac{H_{\text{fid}}(z)}{H(z)}, \quad \alpha_\perp \propto \frac{D_A(z)}{D_{A,\text{fid}}(z)} \quad (6) \]
The Redshift Space distortions

When making a 3D map of the Universe the radial distance is obtained from observed redshift.

Observed redshift has two components: the Hubble expansion and peculiar motion of galaxies, \( s(r) = r - v_r(r) \hat{r} \).

Line-of-sight selects out a special direction and breaks rotational symmetry of underlying correlations.
Mock real space
2dFGRS
The Redshift Space distortions

**Linear regime** → Coherent infall over-dense regions *squashed* and under-dense regions *stretched* along the line of-sight.

**Non Linear regime** → random (thermal) motion, (fingers-of-god)
The Redshift Space distortions

Linear regime $\rightarrow$ Coherent infall over-dense regions *squashed* and under-dense regions *stretched* along the line of-sight.

Non Linear regime $\rightarrow$ random (thermal) motion, (fingers-of-god)

At large scale the galaxies move because cosmological structure is growing through gravity. This growth is the dominant source of RSD.
Modelling the RSD in the galaxy power spectrum: a simple linear model
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- Mapping, $s(r) = r - v_r(r) \hat{r}$
Modelling the RSD in the galaxy power spectrum: a simple linear model

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- Conservation of the number of galaxies between redshift and real space, \( \bar{n}(s)[1 + \delta^s(s)]s^2 ds = \bar{n}(r)[1 + \delta(r)]r^2 dr. \)
Modelling the RSD in the galaxy power spectrum: a simple linear model

- Mapping, $s(r) = r - v_r(r) \hat{r}$
- Conservation of the number of galaxies between redshift and real space,
  \[ \bar{n}(s)[1 + \delta^s(s)]s^2 ds = \bar{n}(r)[1 + \delta(r)]r^2 dr. \]
- Linear perturbation theory
  \[
  \begin{align*}
  \partial \delta / \partial t + \theta &= 0; \quad \theta = \nabla u \quad (mass\ conservation) \\
  \partial u / \partial t + H u &= -\nabla \phi \quad (momentum\ conservation)
  \end{align*}
  \]
  \[ P^s(k, \mu) = (b + f \mu^2)^2 P(k). \]
Modelling the RSD in the galaxy power spectrum: a simple linear model

- Mapping, $s(r) = r - v_r(r) \hat{r}$
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\partial u / \partial t + \mathcal{H} u &= -\nabla \phi \quad (momentum \ conservation)
\end{align*}

(7)

\begin{equation}
P^s(k, \mu) = (b + f \mu^2)^2 P(k).
\end{equation}

(8)

It is convenient to expand the angular dependence on Legendre Polynomials, e.g. $P_0(k) = (b^2 + \frac{2}{3}bf + \frac{1}{5}f^2) P(k)$,
Modelling the RSD in the galaxy power spectrum: beyond linear approximation;

- Full mapping;
- Non linear perturbation theory

\[
\frac{\partial \delta}{\partial t} + \theta = - \int d^3k_1 d^3k_2 \delta_D(k - k_{12}) \alpha(k_1, k_2) \theta(k_1, t) \delta(k_2, ts) \\
\frac{\partial \theta}{\partial t} + H \theta + 3/2 \Omega_m H^2 \delta = - \int d^3k_1 d^3k_2 \delta_D(k - k_{12}) \\
\times \beta(k_1, k_2) \theta(k_1, \tau) \theta(k_2, \tau)
\]

expand density and velocity fields about the linear solutions;

\[
\delta_n(k) = \int d^3q_1 ... \int d^3q_n \delta_D(k - q_{1...n}) F_n(q_1, ..., q_n) \delta_1(q_1) ... \delta_1(q_n), \\
\theta_n(k) = \int d^3q_1 ... \int d^3q_n \delta_D(k - q_{1...n}) G_n(q_1, ..., q_n) \delta_1(q_1) ... \delta_1(q_n),
\]
Modelling the RSD in the galaxy power spectrum: beyond linear approximation;

\[ P^s(k) = [P_{\delta\delta} + 2f \mu^2 P_{\delta\theta} + f^2 \mu^4 P_{\theta\theta} + A(k\mu) + B(k\mu)]D_{\text{FOG}}[k\mu f\sigma_v]; \]

(see Scoccimarro 2004; Taruya 2010; )
More improvements,

- non linear and non local galaxy bias (see Chan 2012)
- beyond standard perturbation theory
Future and current surveys analysis goals

- Improve the methodology used to analyse data
- Development of fast method to measure anisotropic signal
- **How to combine data from different volumes within the surveys.**
Current constrains from RSD on $f(z)$, $D(z)$, $b(z)$...

Constrain from different redshift bin of redshift evolving quantities

(S. Alam et al. 2016)
How to combine future data from wide redshift ranges
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Redshift-bins splitting with traditional clustering analysis,
- loss of signal across bin boundaries
- computational expensive
- window function effects
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Optimal redshift weights as smoother windows on data,
- compression of the information in the redshift direction
- sensitivity to evolution with redshift
- Fisher prediction $\sim 30\%$ better than actual results
- decrease computational effort for large data sets
The search for optimal weights

Linear compression of a data-set $\mathbf{x}$, Gaussian distributed, with mean $\mu$ and covariance $C$,

$$y = \mathbf{w}^T \mathbf{x}.$$  \hspace{1cm} (9)

For a single parameter $\theta_i$,

$$F_{ii} = \frac{1}{2} \left( \frac{\mathbf{w}^T C, i \mathbf{w}}{\mathbf{w}^T C \mathbf{w}} \right)^2 + \frac{(\mathbf{w}^T \mu, i)^2}{\mathbf{w}^T C \mathbf{w}},$$  \hspace{1cm} (10)

We maximise $F_{ii}$ w.r.t $\mathbf{w}$ assuming $C$ apriori, $C$, $i = 0$ and the only non-trivial eigenvector is $\mathbf{w}^T = \frac{C}{\mathbf{w}} \mu$, $i$, \hspace{1cm} (11)

For $P(\mathbf{x})$, $\mathbf{x}$ is formed by measurements of $\mathbf{2}$. \hspace{1cm}
The search for optimal weights

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We maximise $F_{ii}$ w.r.t $\mathbf{w}$ assuming $\mathbf{C}$ a priori, $C_{i,i} = 0$ and the only non-trivial eigenvector is

$$\mathbf{w}^T = C^{-1} \mu_{i,i}, \quad (11)$$
The search for optimal weights

Linear compression of a data-set \( \mathbf{x} \), Gaussian distributed, with mean \( \mu \) and covariance \( C \),

\[
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\]

(11)

For \( P(k) \), \( \mathbf{x} \) is formed by measurements of \( \delta^2 \).
Cosmological model

- We investigate the $\Omega_m(z)$ relation about $\Lambda$CDM model

$$\frac{\Omega_m(z)}{\Omega_{m,\text{fid}}(z)} = q_0(1 + q_1 y(z) + \frac{1}{2} q_2 y(z)^2),$$

$$y(z) + 1 \equiv \frac{\Omega_{m,\text{fid}}(z)}{\Omega_{m,\text{fid}}(z_p)};$$

- We derive a set of weights to optimally measure $q_0$, $q_1$ and $q_2$
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- $\Omega_m(q_i)$ allows for different deviations from $\Lambda$CDM background: all the standard cosmological parameters can be written in terms of the $q_i$;
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  e.g $f(\Omega_m)$ for modified gravity, the AP parameters through $H(\Omega_m)$ for deviations from a fiducial geometry etc.
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Modelling the observed power spectrum

\[ \mathbf{w}^T = C^{-1} \mu_{,i} \leftrightarrow P_{,i} \] directly gives the form of the weights.
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Redshift weighting assuming known distance-redshift relation

- linear model for redshift space distortions \((b, \sigma_8, f)\)
- bias fiducial model
- \([f \sigma_8]\) only
Modelling the observed power spectrum

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Redshift weighting assuming known distance-redshift relation

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Redshift weighting assuming unknown distance-redshift relation

- combining AP effect with RSD (\(\alpha_\parallel, \alpha_\perp, b, \sigma_8, f\))
Power Spectrum weights, when $D_A$ is assumed known $(b, \sigma_8, f)$

\[ P^s(k) = (b + f\mu_k^2)^2 P(k) \]  

(Kaiser, 1987)

\[ \Omega_m(z, q_0, q_1, q_2) \]
The dependence on the fiducial bias model
Power Spectrum weights, when $D_A$ is unknown

\[ P_{\ell}(k) = \frac{2\ell + 1}{2} \int_{-1}^{1} d\mu \, P(k^t, \mu^t) \mathcal{L}_{\ell}(\mu) \]

(14)
The quasar sample represents an important sample-test to investigate the improvements possible through the optimal weights. Characterized by a wide redshift range, $(0.9 - 2.2)$, and lower density $82.6/\text{deg}^2$;
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Preliminary results: $[f \sigma_8]_{av}$ and $b_{av}$
Preliminary results: $q_0$, $q_1$, $q_2$, $\sigma_v$ and $b$

$$\frac{\Omega_m(z)}{\Omega_{m,fid}(z)} = q_0 \left[ 1 + q_1 y(z) + \frac{1}{2} q_2 y(z)^2 \right] \rightarrow f[\Omega_m(z)], \sigma_8[\Omega_m(z)]$$
Preliminary results: $q_0$, $q_1$, $q_2$, $\sigma_\nu$ and $b$

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Preliminary results: $q_0$, $q_1$, $q_2$, $\sigma_\nu$ and $b$

\[ b(z) = b(z_p) + \frac{\partial b}{\partial z}|_{z_p}(z - z_p) \]
Conclusion

- We investigate departures in $\Omega_m(q_i, z)$ about $\Lambda$ CDM.
- Redshift weights to optimise the measurement of the $q_i$, $(b, \sigma_8, f, \alpha_\parallel, \alpha_\perp)$.
- RSD measurements on the eBOSS data
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**DESI/EUCLID**

- 20 - 30 million objects, $0.5 < z < 3.5$; 15-18,000 $deg^2$;
- Traditional analysis: e.g for DESI, to be repeated on 35 redshift bins, neglecting cross correlation between different volumes.
- Optimal weights technique, as a more efficient and accurate alternative would enhance S/N, considering all galaxy pairs.
- Weighting scheme: the method is flexible and works for other sets of parameters;
Alternative parametrization: Primordial non-Gaussianity from LSS

Scale dependent halo bias $b_{tot} = b + \Delta b$, $\Delta b(k) \propto f_{NL}/\alpha(k)$ (e.g. Dalai et al. 2008) 
Very sensitive at large scales $\rightarrow$ Splitting the survey volume decreases the S/N at large scales
30 – 40% of improvements for eBOSS

Mueller, Percival & Ruggeri (2017)