Precise measures of growth rate from RSD in the void-galaxy correlation

Seshadri Nadathur

Moriond Cosmology, La Thuile
Based on work with Paul Carter and Will Percival

SN & Percival, arXiv:1712.07575

SN, Carter & Percival, due soon
Motivation
Improving modelling of void-galaxy RSD
Problems with measuring void-galaxy RSD
Solutions
Motivation

- Voids might be great tools for Alcock-Paczynski measurement with Stage-IV survey data

  Potentially outperform BAO with Euclid?

  **Lavaux & Wandelt 2012**

But RSD is degenerate with AP distortions, need precise RSD modelling!

- *Environment-dependence* of growth rate! \( f = \frac{d \ln D}{d \ln a} \)
  
  density-dependent screening in modified gravity models …
All simulation results shown in this talk are from custom-made mock void and galaxy catalogues from the Big MultiDark simulation.

The mock galaxies match CMASS galaxies, $z = 0.52$.

Void-finding uses ZOBOV algorithm – though results are quite general.
The void-galaxy correlation function

\[ \xi_{vg}(\mathbf{r}) \]: cross-correlation between void and galaxy positions

(equivalent to the galaxy density profile around a void)
A linear model

Assumption #1: number of void-galaxy pairs conserved

\[(1 + \xi^s(s)) \, d^3 s = (1 + \xi^r(r)) \, d^3 r\]

Assumption #2: RSD due to galaxy motions only

\[s = r + \frac{v \cdot \hat{X}}{aH} \hat{X}\]

Assumption #3: Linear dynamics, governed by void alone

\[v(r) = -\frac{1}{3} f aH \Delta(r) r \equiv v_r \hat{r} ; \quad \Delta(r) \equiv \frac{3}{r^3} \int_0^r \delta(y) y^2 dy\]
A linear model

**Assumption #1 + Assumption #2 + Assumption #3** gives

\[
1 + \xi^s(s) = (1 + \xi^r(r)) \left[ 1 - \frac{f}{3} \Delta(r) - f \mu^2 (\delta(r) - \Delta(r)) \right]^{-1}
\]

Expand to linear order in $\delta$, $\Delta$
Linear model, take 1

\[ \xi^s(r, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r) \]

\[ + f \mu^2 [\delta(r) - \Delta(r)] \]

Cai, Taylor, Peacock, Padilla 2016 (see also Hamaus et al. 2017)

Pro: simple, nice quadrupole-to-monopole estimator for \( f \)

Con: doesn’t work well in void centres
Linear model, take 1

\[ \xi^s(r, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r) + f \mu^2 [\delta(r) - \Delta(r)] \]

Cai, Taylor, Peacock, Padilla 2016  (see also Hamaus et al. 2017)

(simulation) data
Linear model, take 1

\[ \xi^s(r, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r) \]

\[ + f \mu^2 [\delta(r) - \Delta(r)] \]

Cai, Taylor, Peacock, Padilla 2016  
(see also Hamaus et al. 2017)
Linear model, take 1

\[
\xi^s(r, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r) \\
+ f \mu^2 [\delta(r) - \Delta(r)]
\]

Cai, Taylor, Peacock, Padilla 2016  
(see also Hamaus et al. 2017)

residuals (data–model)
Improved linear model

\[ \xi^s(s, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r) (1 + \xi^r(r)) \]

\[ + f \mu^2 [\delta(r) - \Delta(r)] (1 + \xi^r(r)) \]

SN & Percival 2017
Improved linear model

\[ \xi^s(s, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r)(1 + \xi^r(r)) \]

\[ + f \mu^2 [\delta(r) - \Delta(r)] (1 + \xi^r(r)) \]

SN & Percival 2017

Key features:

- \( \xi \delta, \xi \Delta \) are linear order inside voids!
Improved linear model

Key features:

• \( \xi \delta \),

\[
\xi^S (r) = \xi^r (r) + f(r) (1 + \xi r (r))
\]

\[
\xi (s) = \xi (r) + f (r) (1 + \xi r (r))
\]
Improved linear model

\[ \xi^s(s, \mu) = \xi^r(r) + \frac{f}{3} \Delta(r) (1 + \xi^r(r)) \]
\[ + f \mu^2 [\delta(r) - \Delta(r)] (1 + \xi^r(r)) \]

SN & Percival 2017

Key features:

• \( \xi \delta, \xi \Delta \) are linear order inside voids!

• **Coordinate shift** important at linear order!

\[ \xi(r) = \xi(s) + \xi'(s) \frac{f}{3} s \Delta(s) \mu^2 + \ldots \]
Improved linear model

\[ \xi^s (s, \mu) = \xi^r (r) + \frac{f}{3} \Delta(r) (1 + \xi^r (r)) \]

\[ + f \mu^2 \left[ \delta(r) - \Delta(r) \right] (1 + \xi^r (r)) \]

SN & Percival 2017

Key features:

- \( \xi \delta, \xi \Delta \) are \textbf{linear order} inside voids!
- \textbf{Coordinate shift} important at linear order!
  \[ \xi(r) = \xi(s) + \xi'(s) \frac{f}{3} s \Delta(s) \mu^2 + \ldots \]
- Linear galaxy bias \textbf{does not hold}, \( \xi(r) \neq b \delta(r) \)
Improved linear model

Key features:

- $\xi^\varepsilon$ are linear order inside voids!

- $s(s, \mu) = \xi(r) = \xi(s) + \xi_0(s) f_3 s(s) \mu^2 + ...$

- Coordinate shift important at linear order!

- Linear galaxy bias does not hold,

$\xi(r) = \xi(v_g)(r) / b - \Delta(r)$
Improved linear model

*Much* better residuals!

**old model residuals**

**new model residuals**
Why does a linear RSD model fit so well?

Linear theory for velocities in voids is very good:

\[ v_r^{\text{model}}(r) = -\frac{1}{3} \beta a H r \Delta(r) \]
\[ v_r^{\text{model}}(r) = -\frac{1}{3} \beta a H r \bar{\xi}_{vv}(r) \]

\[ v_r^{\text{DM}} \]
\[ v_r^{\text{gal}} \]
Why doesn’t this RSD model fit perfectly?

Dispersion around coherent outflow is large:
Adding velocity dispersion to the model

Allow for a dispersion in los velocities, \( \mathbf{v} = v_r \hat{\mathbf{r}} + v_|| \hat{\mathbf{X}} \), then:

\[
1 + \xi^s(\sigma, \pi) = \int dv_|| P(v_||)(1 + \xi^r(r)) \left| J \left( \frac{s}{r} \right) \right|^{-1}
\]

- Assume Gaussian pdf, can be scale-dependent
- Expand to linear order as before
Adding velocity dispersion to the model

Allow for a dispersion in los velocities, \( \mathbf{v} = v_r \hat{r} + v_\parallel \hat{X} \), then:

\[
1 + \xi^s(\sigma, \pi) = \int dv_\parallel P(v_\parallel)(1 + \xi^r(r)) \left| J \left( \frac{S}{r} \right) \right|^{-1}
\]

Note, not

\[
1 + \xi^s(\sigma, \pi) = \int \frac{(1 + \xi^r(r))}{\sqrt{2\pi}\sigma_v} \exp \left( -\frac{(v_\parallel - v_r(r)\mu)^2}{2\sigma_v^2} \right) dv_\parallel
\]

standard streaming model result does not hold for voids (ask me why later!)

SN & Percival 2017
Improved linear model with dispersion

Even better residuals
Multipole expansion

To linear order, only monopole and quadrupole are non-zero
Multipole expansion

To linear order, only **monopole** and **quadrupole** are non-zero

Completely linear RSD model works well **on all scales**

SN & Percival 2017
Fitting for the growth rate

Fitting requires 3 functions as input:

\[ \xi^r (r), \delta (r), \sigma_{v\parallel} (r) \]

either from simulation OR reconstructed from data

(must be?) calibrated from simulation

Parameter that is fit is \( f \) (not \( f\sigma_8 \))
Fitting for the growth rate

Fitting requires 3 functions as input:

\[ \xi^r(r), \delta(r), \sigma_{v ||}(r) \]

either from simulation OR reconstructed from data

(must be?) calibrated from simulation

\[ f = 0.78 \pm 0.02 \ (2.7\%) \]

using all separation scales

\[ f = 0.77 \pm 0.02 \ (2.8\%) \]

using only scales within mean void scale

\[ (f_{\text{fid}} = 0.761) \]
A major problem

A non-linear transformation of a tracer density field after RSD mapping must have RSD itself, and also a velocity bias

Seljak 2012, 1201.0594

Voids found in redshift-space galaxies have RSD themselves

Chuang et al 2017

This violates assumption #2 (RSD due to galaxy motions alone)!

\( s = r + \frac{v \cdot \dot{X}}{aH} \dot{X} \)

(Also assumption #1 – void numbers not conserved in redshift space)

Modelling will be invalid if voids found using redshift-space galaxies
A major problem can’t be measured? can’t be modelled?

SN, Carter & Percival, in prep.
Solution: reconstruction of real-space galaxy field

Eulerian posn. as Lagrangian posn. + displacement, \( \mathbf{x}(\mathbf{q}, t) = \mathbf{q} + \Psi(\mathbf{q}, t) \)

\[ \nabla \cdot \Psi + \frac{f}{b} \nabla \cdot (\Psi \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} = -\frac{\delta_g}{b} \]

Remove (linear, Kaiser) RSD component of displacement:

\( \Psi_{\text{RSD}} = -f(\Psi \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} \)

Iterate until convergence (2-3 iterations)

Obtain “pseudo real-space” galaxy distribution

SN, Carter & Percival, in prep.
Reconstruction works can be measured! + can be modelled.
Avoiding circularity

Choose parameters $f, b$

Solve for $\Psi_{\text{RSD}}$

Reconstruct pseudo real-space galaxy field

Find voids, measure $\xi^r$

Cross-correlate with redshift-space galaxies; measure multipoles

Calculate theory for given $f$; get $\chi^2$ for fit to data

If not finished, new parameters

If finished, construct likelihood

SN, Carter & Percival, in prep.
Results

Keeping bias fixed, \( f = 0.740^{+0.017}_{-0.012} \) (68% c.l.)

consistent with fiducial at 1-sigma

Marginalising over bias, \( f = 0.732^{+0.016}_{-0.016} \) (68% c.l.)

consistent with fiducial at 2-sigma

SN, Carter & Percival, in prep.
Summary

- Void-galaxy RSD measurements probe interesting physics, not the same as galaxy correlation
- A completely linear RSD model is sufficient on all scales!
- We made major improvements in the modelling
- The improved model allows precise constraints on growth rate in low density regions
- Practical issues with measurement are very important, but can be mostly solved using a reconstruction technique
- Further investigation very much required!
spare slides
The streaming model

\[ 1 + \xi^s(\sigma, \pi) = \int \frac{dr \pi d\gamma}{2\pi} e^{-i\gamma(r\pi - \pi)} Z(if\gamma, r) \]

Galaxy autocorrelation

\[ Z(if\gamma, r) = \langle e^{if\gamma \Delta uz} (1 + \delta(x))(1 + \delta(x')) \rangle \]

Average over all space, so

\[ \langle \delta(x) \rangle = 0 \]

(and in Gaussian approx., all odd cumulants are zero)

etc.

Void-galaxy correlation

\[ Z(if\gamma, r) = \langle e^{if\gamma uz} (1 + \xi^r(r)) \rangle \]

Constrained average

\[ \langle \xi^r(r) \rangle \neq 0 \]

(by definition!)

etc.
changing void centre doesn’t affect conclusions

![Graphs showing density contrast and residual against $r/R_v$](image-url)
changing void centre doesn’t affect conclusions