Anisotropic assembly bias
in theory, simulations and data

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Outline

- Intro: Power spectrum, Redshift-space distortions & bias
- Anisotropic assembly bias (AB)
- Halo AB in simulations
- Galaxy AB in BOSS sample
- Further consequences & Summary
Overview

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• CMB measurements still dominate the constraints on cosmological parameters
• Large-scale Structure is 3D – expected to have more power
• Galaxy redshift surveys – established and promising way further
Large-scale structure

- Overdensity field:
  \[ \delta_m(x) = \frac{\rho_m(x)}{\bar{\rho}_m} - 1 \]
- Power spectrum:
  \[ P_m(k_1, k_2) \propto \langle \delta_m(k_1) \delta_m(k_2) \rangle \]
- Correlation function
  \[ \xi_m(r) = \langle \delta_m(x) \delta_m(x + r) \rangle \]
- Cosmological Principle:
  \[ P(k) \& \xi(r) \]
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\[ \text{Planck, 2018} \]
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- Cosmological Principle:
  \[ P(k) \& \xi(r) \]

- However we neither observe \( x \) nor matter field

Planck, 2018
Redshift-space Distortions

- We observe objects in redshift-space:
  \[ s = x + v \cdot \hat{e}_z / (aH) \]
- Continuity eq: \( \nabla \cdot \mathbf{v} \propto f \delta_m \), \( f \) growth rate
Redshift-space Distortions

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- Linear regime (\( \mu = k_\parallel / k \)):
  \[ \delta_s^m \approx (1 + f\mu^2) \delta_m \]
  \[ P^s_m(k, \mu) \approx (1 + f\mu^2)^2 P_m(k) \]
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  - \( P_s^m(k, \mu) \approx (1 + f \mu^2)^2 P_m(k) \)
- Clustering amplified in radial direction
- RSDs cause anisotropy, sensitive to \( f \)
Galaxies, halos, voids, 21cm, Lyα forest ... all biased tracers of matter in real space

- $\delta_g(k) = b_g \delta_m(k) \iff P_g(k) = b_g^2 P_m(k)$
Linear bias

Galaxies, halos, voids, 21cm, Lyα forest ... all biased tracers of matter in real space

- $\delta_g(k) = b_g \delta_m(k) \iff P_g(k) = b_g^2 P_m(k)$
- $b_g$ scalar linear bias of e.g. galaxies
Linear bias

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- \( b_g \) depends on halo mass & redshift:
  - massive objects more biased
  - objects more biased earlier

Wechsler+, 2018
Linear bias

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- \( b_g \) scalar linear bias of e.g. galaxies
- \( b_g \) depends on halo mass & redshift:
  - massive objects more biased
  - objects more biased earlier
- Equivalence principle \( \Rightarrow \) no velocity bias
  \[ \delta^s_m \approx (1 + f\mu^2) \delta_m \implies \delta^s_g(k, \mu) = (b_g + f\mu^2)\delta_m(k) \]

Wechsler+, 2018
Galaxy power spectrum in redshift-space

- Linear theory: \( P_g^s(k, \mu) = (b_g + f \mu^2)^2 P_m(k) \)
- Use Legendre expansion into multipoles:

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

\[
P_0(k) = \left( b_g^2 + \frac{2}{3} f b_g + \frac{1}{5} f^2 \right) P_m(k)
\]

\[
P_2(k) = \left( \frac{4}{3} b_g f + \frac{4}{7} f^2 \right) P_m(k)
\]

- Measuring \( P_0 \) & \( P_2 \) gives \( b_g \) & \( f \)
- Note quadrupole \( P_2 \propto f \)
- In real-space \( P_2 = 0 \)
Galaxy power spectrum in redshift-space

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Alam+2016
Growth rate $f$

One of the key parameters

- $f \equiv \frac{d \ln D(a)}{d \ln a}$
- GR prediction: $f = \Omega_m(z)^{0.55}$
- Important for:
  - Testing Gravity
  - Constraining neutrino masses
  - Testing dark energy models
  - ...
- Currently $\sim 5 - 10\%$
- Future surveys (DESI, Euclid) expected to reach $\sim 1 - 5\%$ precision

Planck, 2018
Assembly bias

Bias depends on other scalar properties, for fixed halo mass and redshift

- Formation history
- Age
- Spin
- Concentration
- Shape ...

Wechsler+, 2018
Assembly bias

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- Formation history
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Wechsler+, 2018

Detected in simulations, no convincing evidence in data
Non-scalar bias

- There's another term at the linear level of $\delta_m$ – traceless part of the tidal field:

$$\delta_g(k) = (b_g + f\mu^2)\delta_m(k) + b_{ij}s_{ij}(k)$$

$$s_{ij}(k) = (k_i k_j/k^2 - \delta_{ij}/3)\delta_m(k)$$

- Only non-scalar properties can correlate with tidal field
- *Non-scalar* halo properties are correlated with tidal field
Non-scalar bias

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How correlated are halos & tidal field?

We use 1000 Quijote N-body sims (Villaescusa-Navarro+, 2019) to measure cross-correlations

\[ n_{\text{min}} = 100, \ M_h > 6.57 \times 10^{13} \ [h^{-1} \ M_\odot] \]
Non-scalar bias

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• Azimuthal symmetry & $b_q \equiv b_{zz}$

$$\delta_g(k, \mu) = (b_g + f\mu^2)\delta_m(k) + b_{zz}(\mu^2 - 1/3)\delta_m(k)$$
$$= (b_g - b_q/3 + (f + b_q)\mu^2) \delta_m(k)$$
Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\delta_m$$
Anisotropic assembly bias (AB)

\[ \delta^s_g = (b_g + f \mu^2) \delta_m \implies \delta^s_g = (b_g - b_q/3 + (f + b_q) \mu^2) \delta_m \]

- Parameter \( b_q \) is the anisotropic assembly bias

- \( b_q = 0 \) if:
  - Selection independent of halo orientation, e.g. projected size, velocity dispersion, angular momentum
  - or observed tracer and host halo randomly misaligned
Anisotropic assembly bias (AB)

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- Parameter \( b_q \) is the **anisotropic assembly bias**
- Source of anisotropy in the real space power spectrum
Anisotropic assembly bias (AB)

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- Parameter \( b_q \) is the \textbf{anisotropic assembly bias}
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- Additional source of anisotropy in the redshift-space
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- Parameter \( b_{q} \) is the **anisotropic assembly bias**
- Source of anisotropy in the real space power spectrum
- Additional source of anisotropy in the redshift-space
- Note \( b_{q} \) is perfectly degenerate with \( f \)!
Anisotropic assembly bias (AB)

\[ \delta^s_g = (b_g + f\mu^2)\delta_m \quad \Rightarrow \quad \delta^s_g = (b_g - b_q/3 + (f + b_q)\mu^2)\delta_m \]

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Halo selection based on tensor properties

Selection on radial halo extent & velocity dispersion $\sigma_{1D}$ in real space

Halo
High $\sigma_{zz}$
High $I_{zz}$

Halo
Low $\sigma_{zz}$
Low $I_{zz}$

$z$

$s_{zz} < 0$

$s_{zz} > 0$
Halo selection based on tensor properties

Selection on radial halo extent & velocity dispersion $\sigma_{1D}$ in real space

- Real-space $P_2 = f = 0$
- $P_2 \neq 0 \rightarrow b_q \neq 0$
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AO+2019
Halo selection based on tensor properties

Selection on radial halo extent & velocity dispersion $\sigma_{1D}$ in real space

- Real-space $P_2 = f = 0$
- $P_2 \neq 0 \rightarrow b_q \neq 0$
- Halos: $\Delta b_q \approx 1 - 2$
- Redshift-space $f \approx 0.7$

$P_{\ell}^{zz}(k)$ vs $k$ [Mpc$^{-1}$]
What about galaxies?
BOSS DR12 Galaxy sample

- Baryon Acoustic Spectroscopic Survey
- \( \sim 10^6 \) galaxy redshifts
- \( 0.15 < z < 0.7 \)
- Luminous red galaxies
- Ellipticals, \( M_h \sim 10^{13} M_\odot/h \)
- \( b_g \sim 2 \)
- Galaxy samples
  - LOWZ (0.15 < \( z \) < 0.43)
  - CMASS (0.43 < \( z \) < 0.7)
- Galactic Caps
  - North (NGC)
  - South (SGC)
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Reid+, 2016
How we look for AB?

Main idea – split on orientation ($\sigma_*$) → look for differences in anisotropy ($\Delta b_q$)
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  - velocity dispersion \(\sigma_\star\) (1D)
  - stellar mass \(M_\star\)
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- Galaxy Properties from Portsmouth Group
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- Split on $\sigma_\star = $ split on orientation & galaxy mass ($\sigma_\star^2 \propto M_\star$)
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  - velocity dispersion $\sigma_*$ (1D)
  - stellar mass $M_*$
- Split on $\sigma_*$ = split on orientation & galaxy bias $b_g(M_*) \rightarrow$ different $P_0$ & $P_2$
- Use $M_*$ to remove mass ($b_q$) dependence
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- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_*$ (1D)
  - stellar mass $M_*$
- Split on $\sigma_* = \text{split on orientation & galaxy bias } b_g(M_*) \rightarrow \text{different } P_0 & P_2$
- Make subsamples with either
  - high $M_*$, low $\sigma_*$ or
  - low $M_*$, high $\sigma_*$
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- Find subsamples matching \( P_0 \) \& \( n(z) \)!
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- How do we match \( n(z) \)?
  - Need to account for \( z \)-evolution
  - Work with percentiles
  - Compute percentiles in 30 \( z \)-bins
  - Split on percentiles in each \( z \)-bin
  - \( \implies \) matching \( n(z) \)

![Diagram showing distribution of data points with different colors indicating different redshift bins.](image-url)
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  - Grid of 25 \((\sigma_*, M_*\) subsamples
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How do we match monopoles?
- Grid of 25 \((\sigma_*, M_*)\) subsamples
- Measure mean amplitude
- Low \((\sigma_*, M_*)\) – low amplitude
- High \((\sigma_*, M_*)\) – high amplitude
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- How do we match monopoles?
  - Grid of 25 \((\sigma_*, M_*)\) subsamples
  - Measure mean amplitude
  - But we want matching amplitude!
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- How do we match monopoles?
  - Finally select samples with:
    - high \(M_\star\), low \(\sigma_\star\) &
    - low \(M_\star\), high \(\sigma_\star\)
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• What about quadrupoles?
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- Mismatch $P_2$ $\rightarrow$ evidence $\Delta b_q \neq 0$

- Match $P_0$ & $n(z)$ $\rightarrow$ match $P_2$
How we look for AB?

Main idea – split on orientation \((\sigma_*)\) \(\rightarrow\) look for differences in anisotropy \((\Delta b_q)\)

- Subsamples matching \(n(z)\) have matching \(f\)
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Results – CMASS NGC

$10^4 \times n(z) \, [h^3 \text{Mpc}^{-3}]$

$10^3 \, k P^X_\ell \, [h^{-2} \text{Mpc}^2]$
Results – LOWZ NGC

\[ 10^3 \times n(z) [h^3 \text{Mpc}^{-3}] \]

\[ kP_\ell [h^{-2} \text{Mpc}^2] \]

AO+2020
Detection significance

- Use mock galaxy catalogs
- Split each mock in two random subsamples
- Cross-correlate each with full mock
- Find $a_\ell$ which minimizes:

$$\chi^2(a_\ell) = \Delta P_\ell^T C_{a,\ell}^{-1} \Delta P_\ell$$

where

$$\Delta P_\ell = P_{\ell}^{\text{sub},1} - a_\ell P_{\ell}^{\text{sub},2}$$
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- LOWZ & CMASS independent samples
- We combine them
Combined detection significance

$5\sigma$ using $k_{\text{max}} \sim 0.15 \, h\, \text{Mpc}^{-1}$

![Graph showing combined detection significance with $k_{\text{max}}$ vs $\sigma(k_{\text{max}})$]
Discussion

- We present first strong evidence of AB

\[ \Delta b^q \neq 0 \text{ at } > 5 \sigma \text{ confidence} \]

- For BOSS galaxies we find
  \[ \Delta b^q \approx (a^2 - 1) \approx 0.1 - 0.2 \]

- For halos in sims we found
  \[ \Delta b^q \approx 1 - 2 \]

- Misalignment of galaxies and halos decreases the signal

- We can only measure \( \Delta b^q \)

- Important considering \( f \approx 0.7 \)

- Also important for precision on future surveys are...
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- We find no signal when splitting on projected physical size $R_0$ & $M_*$

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- We do FP analysis with $(a, b)$ grid

- Kaiser model for multipoles assuming $b_q = 0$

- Results on AB very sensitive to $(a, b)$ values — Perhaps explaining previous results...
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