Anisotropic assembly bias

in theory, simulations and data

Andrej Obuljen

University of Waterloo, Waterloo Centre for Astrophysics

with Will Percival & Neal Dalal

LBL Research Progress Meeting, October 15th, 2020

arXiv:1906.11823
arXiv:2004.07240

Outline

- Introduction
- Anisotropic halo assembly bias in simulations
- Anisotropic galaxy assembly bias in BOSS sample
- Consequences (for DESI) & Summary

Overview

- We have a very successful ΛCDM model describing the Universe

Overview

- We have a very successful ΛCDM model describing the Universe
- Cosmological information contained in different observables

Overview

- We have a very successful ΛCDM model describing the Universe
- Cosmological information contained in different observables
- Inhomogenities dominant source of information, mainly through 2-point statistics of fluctuations

Overview

- We have a very successful ΛCDM model describing the Universe
- Cosmological information contained in different observables
- Inhomogenities dominant source of information, mainly through 2-point statistics of fluctuations
- CMB measurements still dominate the constraints on cosmological parameters

Overview

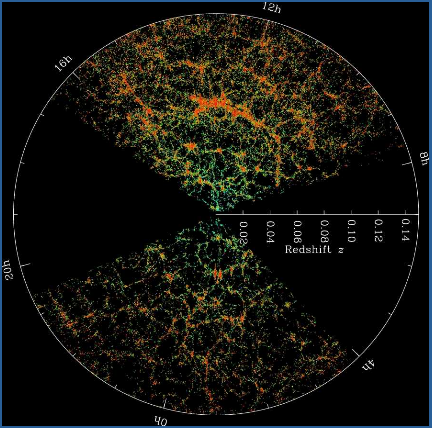
- We have a very successful ΛCDM model describing the Universe
- Cosmological information contained in different observables
- Inhomogenities dominant source of information, mainly through 2-point statistics of fluctuations
- CMB measurements still dominate the constraints on cosmological parameters
- But Large-scale Structure is 3D – expected to ultimately have more constraining power

Overview

- We have a very successful ΛCDM model describing the Universe
- Cosmological information contained in different observables
- Inhomogenities dominant source of information, mainly through 2-point statistics of fluctuations
- CMB measurements still dominate the constraints on cosmological parameters
- But Large-scale Structure is 3D – expected to ultimately have more constraining power
- Upcoming galaxy redshift surveys (DESI, Euclid) will reach unprecedented precision

Large-scale structure

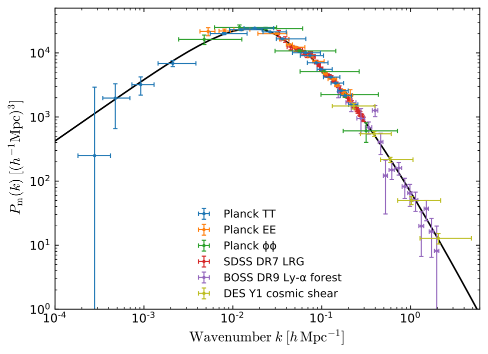
- Overdensity field:
  $\delta_m(\mathbf{x}) = \rho_m(\mathbf{x})/\bar{\rho}_m - 1$
- Power spectrum:
  $P_m(\mathbf{k_1}, \mathbf{k_2}) \propto \langle \delta_m(\mathbf{k_1}) \delta_m(\mathbf{k_2}) \rangle$



SDSS

Large-scale structure

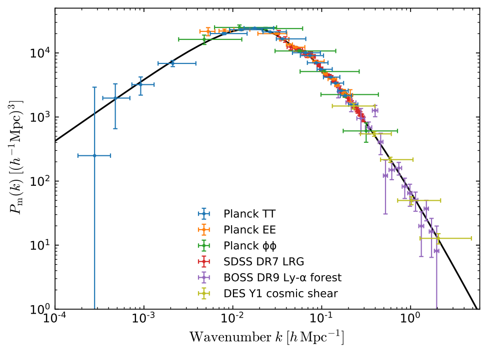
- Overdensity field:
  $\delta_m(\mathbf{x}) = \rho_m(\mathbf{x})/\bar{\rho}_m - 1$
- Power spectrum:
  $P_m(\mathbf{k_1}, \mathbf{k_2}) \propto \langle \delta_m(\mathbf{k_1}) \delta_m(\mathbf{k_2}) \rangle$
- Cosmological Principle: $P_m(k)$



Planck, 2018

Large-scale structure

- Overdensity field:
  $\delta_m(\mathbf{x}) = \rho_m(\mathbf{x})/\bar{\rho}_m - 1$
- Power spectrum:
  $P_m(\mathbf{k_1}, \mathbf{k_2}) \propto \langle \delta_m(\mathbf{k_1}) \delta_m(\mathbf{k_2}) \rangle$
- Cosmological Principle: $P_m(k)$
- However we neither observe dark matter nor real-space positions $\mathbf{x}$

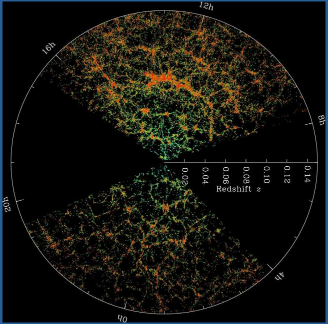


Planck, 2018

Linear bias and redshift-space distortions

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

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

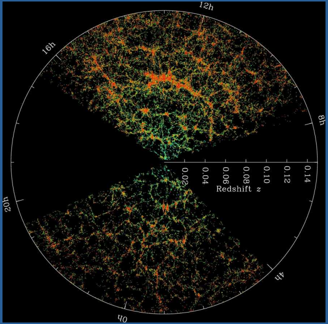


SDSS

Linear bias and redshift-space distortions

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

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

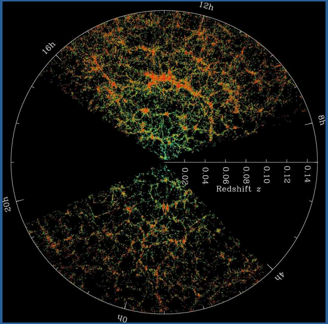


SDSS

Linear bias and redshift-space distortions

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

- $\delta_g(k) = b_g \delta_m(k) \iff P_g(k) = b_g^2 P_m(k)$
- b_g linear scalar bias of e.g. galaxies
- b_g depends on halo mass & redshift:
  - massive objects more biased
  - objects more biased earlier



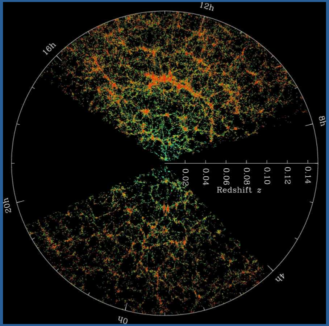
SDSS

Linear bias and redshift-space distortions

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

- $\delta_g(k) = b_g \delta_m(k) \iff P_g(k) = b_g^2 P_m(k)$
- b_g linear scalar bias of e.g. galaxies
- b_g depends on halo mass & redshift:
  - massive objects more biased
  - objects more biased earlier
- In redshift-space, linear theory for matter:

$$\delta_m^s(k,\mu) = (1 + f\mu^2)\,\delta_m(k), \;\; \mu = k_\parallel / k$$



SDSS

Linear bias and redshift-space distortions

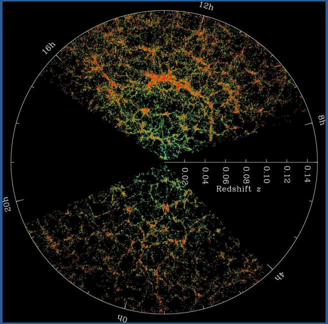
Galaxies, halos, voids, 21cm, Lyα forest ... all biased tracers of matter in real space, observed in redshift-space

- $\delta_g(k) = b_g \delta_m(k) \iff P_g(k) = b_g^2 P_m(k)$
- b_g linear scalar bias of e.g. galaxies
- b_g depends on halo mass & redshift:
  - massive objects more biased
  - objects more biased earlier
- In redshift-space, linear theory for matter:

$$\delta_m^s(k, \mu) = (1 + f\mu^2)\, \delta_m(k), \;\; \mu = k_{\parallel}/k$$

- Equivalence principle $\implies$ no velocity bias

$$\delta_g^s(k, \mu) = (b_g + f\mu^2)\delta_m(k)$$



SDSS

Galaxy power spectrum in redshift-space

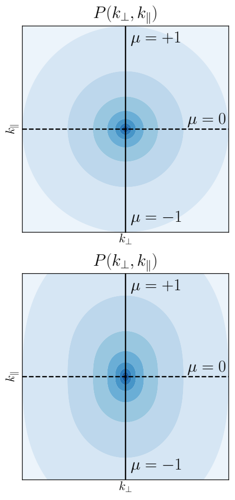
- Linear theory: $P_g^s(k,\mu) = (b_g + f\mu^2)^2 P_m(k)$
- Use Legendre expansion into multipoles:

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

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

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

- 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

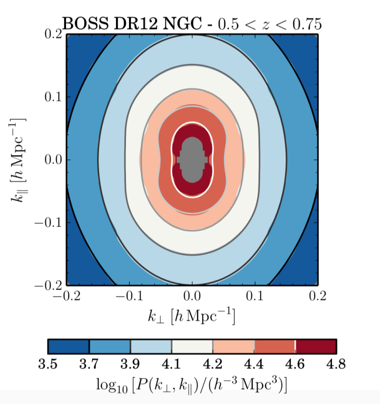
- Linear theory: $P_g^s(k,\mu) = (b_g + f\mu^2)^2 P_m(k)$
- Use Legendre expansion into multipoles:

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

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

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

- Measuring P_0 & P_2 gives b_g & f
- Note quadrupole $P_2 \propto f$
- In real-space $P_2 = 0$

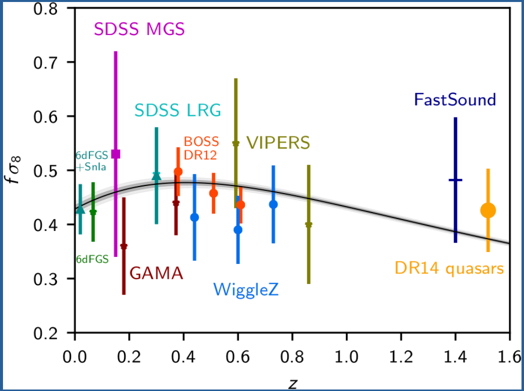


Alam+2016

Growth rate f

One of the key parameters

- $f \equiv \frac{d \ln D(a)}{d \ln a}$
- GR prediction: $f = \Omega_{\rm m}(z)^{0.55}$
- 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

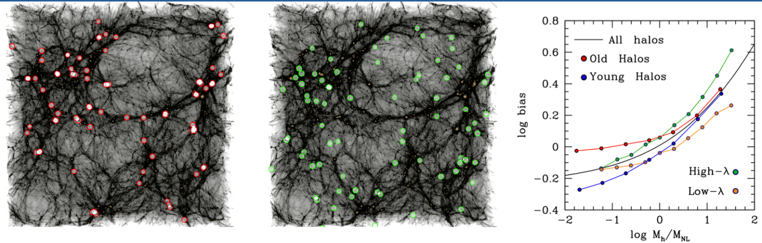


Planck, 2018

Assembly bias

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

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

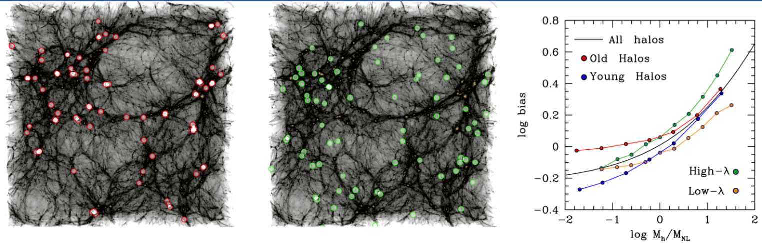


Wechsler+, 2018

Assembly bias

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

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



Wechsler+, 2018

Detected in simulations, no convincing evidence in data

Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$

Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$
- There's another term linear in δ_m – traceless part of the tidal field:

$$s_{ij}(\mathbf{x}) = (\nabla_i \nabla_j \nabla^{-2} - \delta_{ij}/3)\, \delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = (k_i k_j / k^2 - \delta_{ij}/3)\, \delta_m(\mathbf{k})$$

Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$
- There's another term linear in δ_m – traceless part of the tidal field:

$$s_{ij}(\mathbf{x}) = \left(\nabla_i \nabla_j \nabla^{-2} - \delta_{ij}/3\right) \delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = \left(k_i k_j / k^2 - \delta_{ij}/3\right) \delta_m(\mathbf{k})$$

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

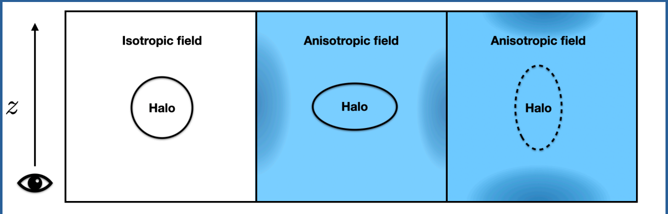
Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$
- There's another term linear in δ_m – traceless part of the tidal field:

$$s_{ij}(\mathbf{x}) = (\nabla_i\nabla_j\nabla^{-2} - \delta_{ij}/3)\,\delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = (k_ik_j/k^2 - \delta_{ij}/3)\,\delta_m(\mathbf{k})$$

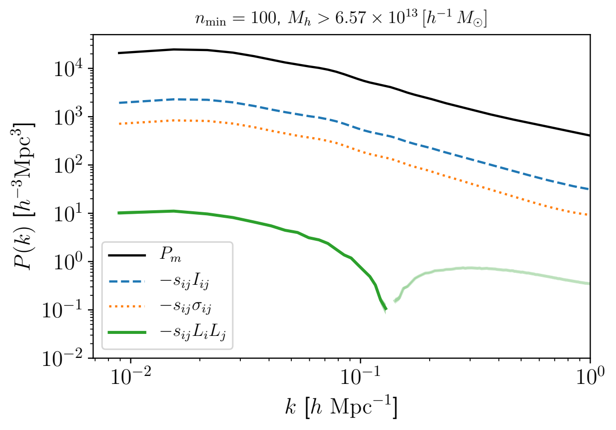
$$\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k) + b_{ij}s_{ij}(\mathbf{k})$$

- Only non-scalar properties can correlate with tidal field
  - projected sizes, velocity dispersion & angular momentum



How correlated are halos & tidal field?

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



AO+2019

Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$
- There's another term linear in δ_m – traceless part of the tidal field:

$$s_{ij}(\mathbf{x}) = (\nabla_i \nabla_j \nabla^{-2} - \delta_{ij}/3)\, \delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = (k_i k_j / k^2 - \delta_{ij}/3)\, \delta_m(\mathbf{k})$$

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

- Only non-scalar properties can correlate with tidal field
  - projected sizes, velocity dispersion & angular momentum

Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$
- There's another term linear in δ_m – traceless part of the tidal field:

$$s_{ij}(\mathbf{x}) = (\nabla_i \nabla_j \nabla^{-2} - \delta_{ij}/3)\, \delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = (k_i k_j / k^2 - \delta_{ij}/3)\, \delta_m(\mathbf{k})$$

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

- Only non-scalar properties can correlate with tidal field
  - projected sizes, velocity dispersion & angular momentum
- Azimuthal symmetry & $b_q \equiv b_{zz}$

$$\begin{aligned}\delta_g(k, \mu) &= (b_g + f\mu^2)\delta_m(k) + b_{zz}(\mu^2 - 1/3)\delta_m(k) \\ &= \left(b_g - b_q/3 + (f + b_q)\mu^2\right) \delta_m(k)\end{aligned}$$

Non-scalar bias

- At the linear level in δ_m we usually assume: $\delta_g(\mathbf{k}) = (b_g + f\mu^2)\delta_m(k)$
- There's another term linear in δ_m – traceless part of the tidal field:

$$s_{ij}(\mathbf{x}) = (\nabla_i \nabla_j \nabla^{-2} - \delta_{ij}/3)\,\delta_m(\mathbf{x}) \iff s_{ij}(\mathbf{k}) = (k_i k_j / k^2 - \delta_{ij}/3)\,\delta_m(\mathbf{k})$$

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

- Only non-scalar properties can correlate with tidal field
  - projected sizes, velocity dispersion & angular momentum
- Azimuthal symmetry & $b_q \equiv b_{zz}$

$$\begin{aligned}\delta_g(k,\mu) &= (b_g + f\mu^2)\delta_m(k) + b_{zz}(\mu^2 - 1/3)\delta_m(k) \\ &= \left(b_g - b_q/3 + (f + b_q)\mu^2\right)\delta_m(k)\end{aligned}$$

- First pointed out by Hirata (2009)

Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = \left(b_g - b_q/3 + (f + b_q)\mu^2\right)\delta_m$$

Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$

- Parameter b_q is the **anisotropic assembly bias**

Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$

- Parameter b_q is the **anisotropic assembly bias**
- Source of anisotropy in the real space power spectrum

Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$

- 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

Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$

- 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 !

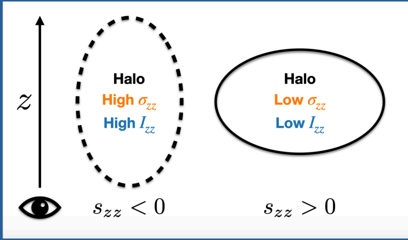
Anisotropic assembly bias (AB)

$$\delta_g^s = (b_g + f\mu^2)\delta_m \implies \delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$

- 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 !
- $b_q = 0$ if:
  - Selection independent of halo orientation, e.g. projected size, velocity dispersion, angular momentum
  - *or* if observed tracer and host halo randomly misaligned

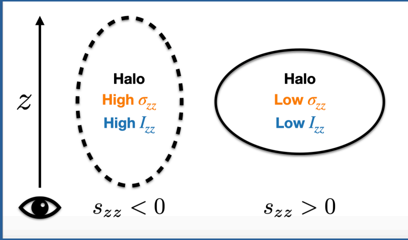
Halo selection based on tensor properties

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



Halo selection based on tensor properties

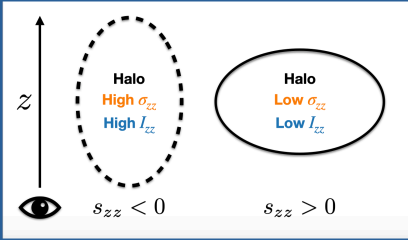
Selection on radial halo extent & velocity dispersion $\sigma_{1\mathrm{D}}$ in **real space**

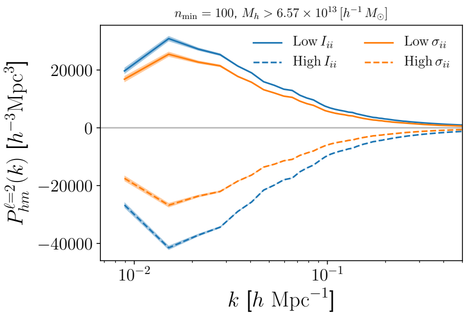


- Real-space $P_2 = f = 0$
- $P_2 \neq 0 \rightarrow b_q \neq 0$

Halo selection based on tensor properties

Selection on radial halo extent & velocity dispersion σ_{1D} in **real space**



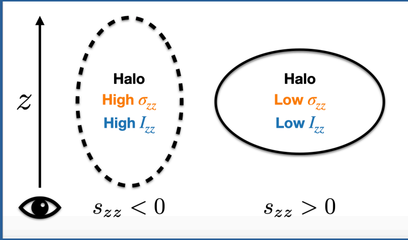


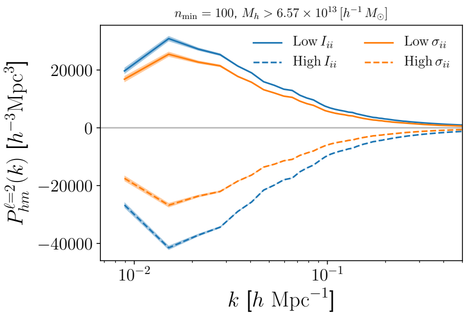
AO+2019

- Real-space $P_2 = f = 0$
- $P_2 \neq 0 \rightarrow b_q \neq 0$

Halo selection based on tensor properties

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





AO+2019

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

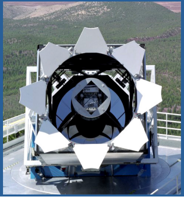
What about real galaxies?

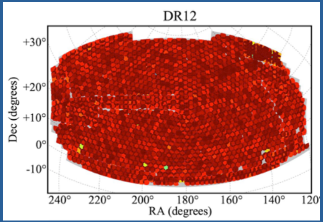
When split on orientation dependent quantities, do galaxies show different clustering strength?

What about real galaxies?

When split on orientation dependent quantities, do galaxies show different clustering strength?

- Baryon Oscillation Spectroscopic Survey **BOSS** DR12 galaxy sample
- $\sim 10^6$ galaxy redshifts
- $0.15 < z < 0.7$
- Luminous red galaxies, $b_g \sim 2$
- Ellipticals, $M_h \sim 10^{13} M_\odot / h$
- Galaxy samples
  - LOWZ $(0.15 < z < 0.43)$
  - CMASS $(0.43 < z < 0.7)$





SDSS

How do we look for AB?

Main idea – split on orientation ($\sigma_\star$) $\rightarrow$ look for differences in anisotropy (Δb_q)

How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f

How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q

How do we look for AB?

Main idea – split on orientation $(\sigma_\star)$ $\rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch P_2 $\rightarrow$ evidence $\Delta b_q \neq 0$

How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Need orientation dependent gal. property

How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

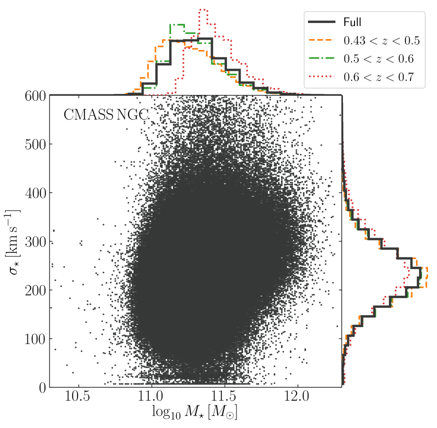
- Need orientation dependent gal. property
- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$

How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$

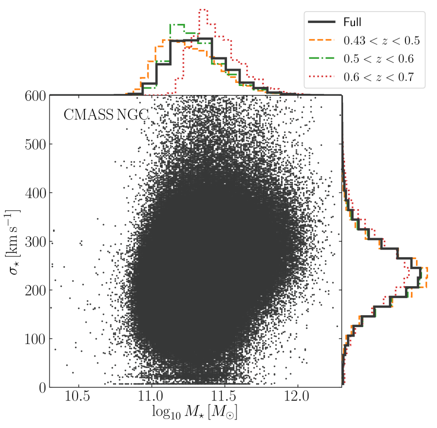


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$
- Split on $\sigma_\star$ = split on orientation & galaxy mass $(\sigma_\star^2 \propto M_\star)$

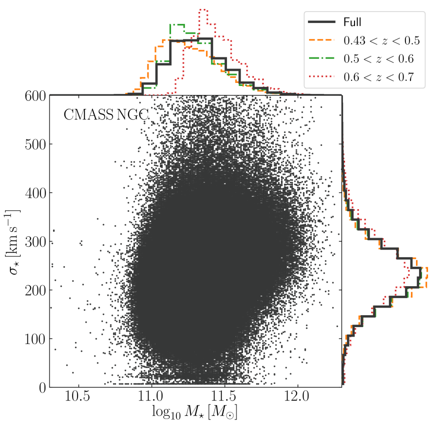


How do we look for AB?

Main idea – split on orientation $(\sigma_\star)$ $\rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$
- Split on $\sigma_\star$ = split on orientation & galaxy bias $b_g(M_\star) \rightarrow$ different P_0 & P_2

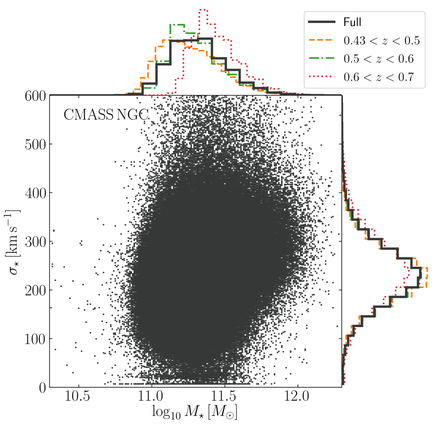


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$
- Split on $\sigma_\star$ = split on orientation & galaxy bias $b_g(M_\star) \rightarrow$ different P_0 & P_2
- Use $M_\star$ to remove mass (b_g) dependence

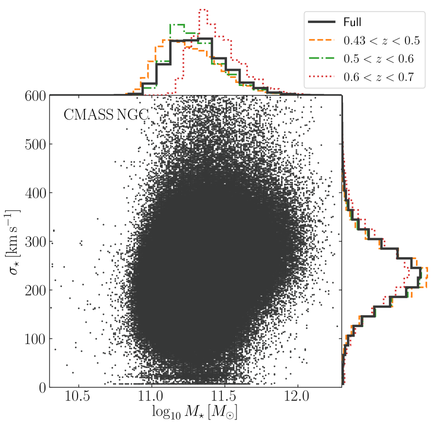


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$
- Split on $\sigma_\star$ = split on orientation & galaxy bias $b_g(M_\star) \rightarrow$ different P_0 & P_2
- Make subsamples with either
  - high $M_\star$, low $\sigma_\star$ *or*
  - low $M_\star$, high $\sigma_\star$

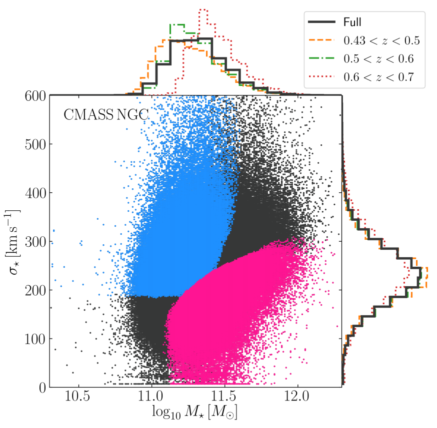


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \to$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \to$ evidence $\Delta b_q \neq 0$

- Galaxy Properties from Portsmouth Group
  - velocity dispersion $\sigma_\star$ (1D)
  - stellar mass $M_\star$
- Split on $\sigma_\star$ = split on orientation & galaxy bias $b_g(M_\star) \to$ different P_0 & P_2
- Make subsamples with either
  - high $M_\star$, low $\sigma_\star$ *or*
  - low $M_\star$, high $\sigma_\star$

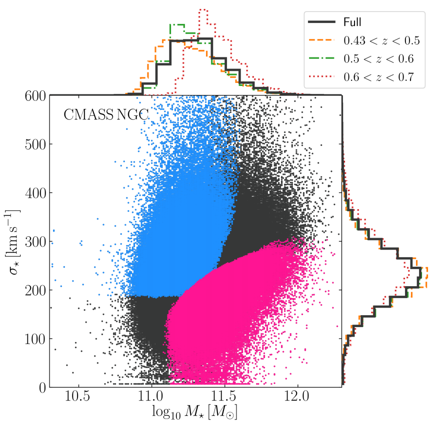


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- 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 $n(z)$



How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

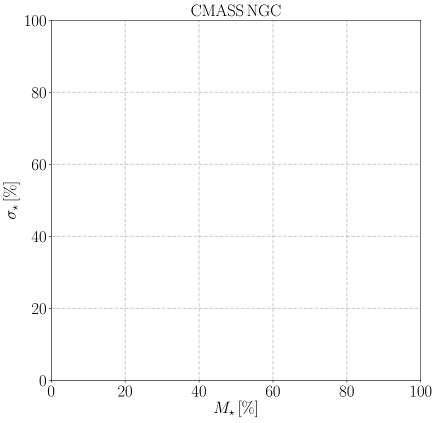
- How do we match monopoles?

How do we look for AB?

Main idea – split on orientation $(\sigma_\star)$ $\rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch P_2 $\rightarrow$ evidence $\Delta b_q \neq 0$

- How do we match monopoles?
  - Grid of 25 $(\sigma_\star, M_\star)$ subsamples

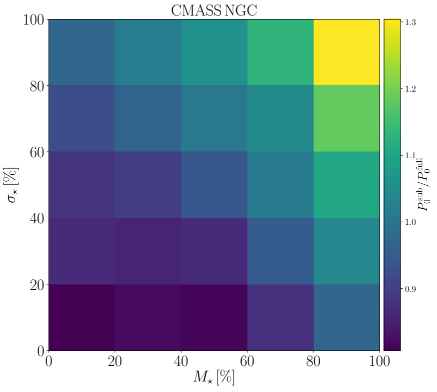


How do we look for AB?

Main idea – split on orientation $(\sigma_\star)$ $\rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- How do we match monopoles?
  - Grid of 25 $(\sigma_\star, M_\star)$ subsamples
  - Measure mean amplitude

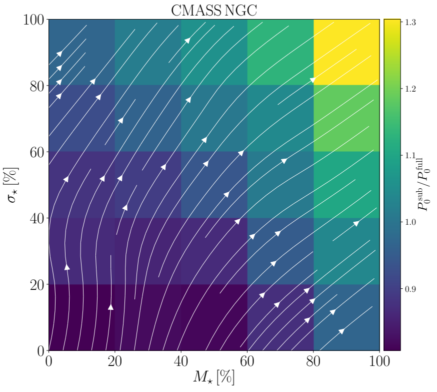


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \to$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \to$ evidence $\Delta b_q \neq 0$

- How do we match monopoles?
  - Grid of 25 $(\sigma_\star, M_\star)$ subsamples
  - Measure mean amplitude
  - Low $(\sigma_\star, M_\star)$ – low amplitude
  - High $(\sigma_\star, M_\star)$ – high amplitude

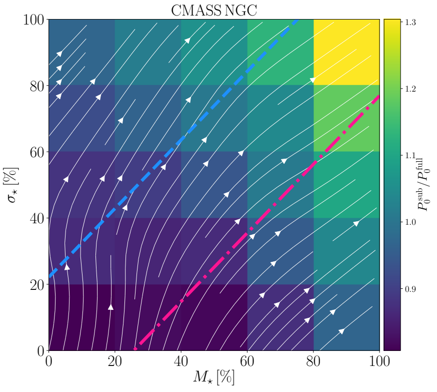


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- How do we match monopoles?
  - Grid of 25 $(\sigma_\star, M_\star)$ subsamples
  - Measure mean amplitude
  - But we want matching amplitude!

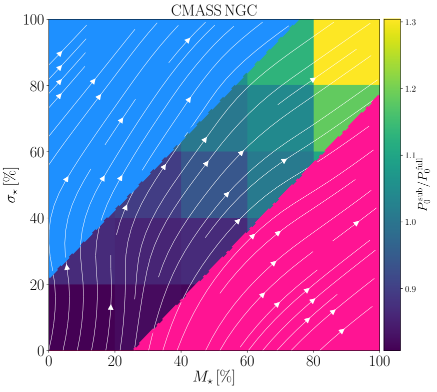


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \to$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \to$ evidence $\Delta b_q \neq 0$

- How do we match monopoles?
  - Finally select samples with:
  - high $M_\star$, low $\sigma_\star$ &
  - low $M_\star$, high $\sigma_\star$

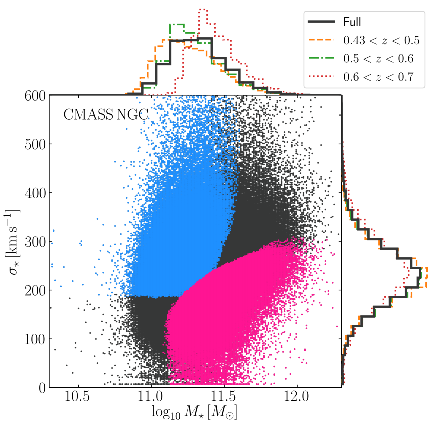


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- How do we match monopoles?
  - Finally select samples with:
  - high $M_\star$, low $\sigma_\star$ &
  - low $M_\star$, high $\sigma_\star$

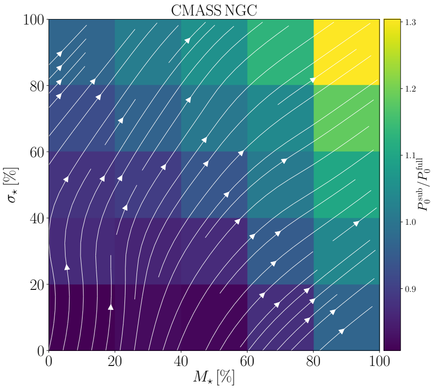


How do we look for AB?

Main idea – split on orientation ($\sigma_\star$) $\rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- What about quadrupoles?

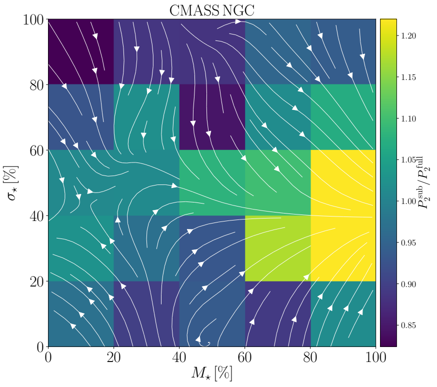


How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \to$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \to$ evidence $\Delta b_q \neq 0$

- What about quadrupoles?



How do we look for AB?

Main idea – split on orientation $(\sigma_\star) \rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch $P_2 \rightarrow$ evidence $\Delta b_q \neq 0$

- Match P_0 & $n(z) \rightarrow$ match P_2

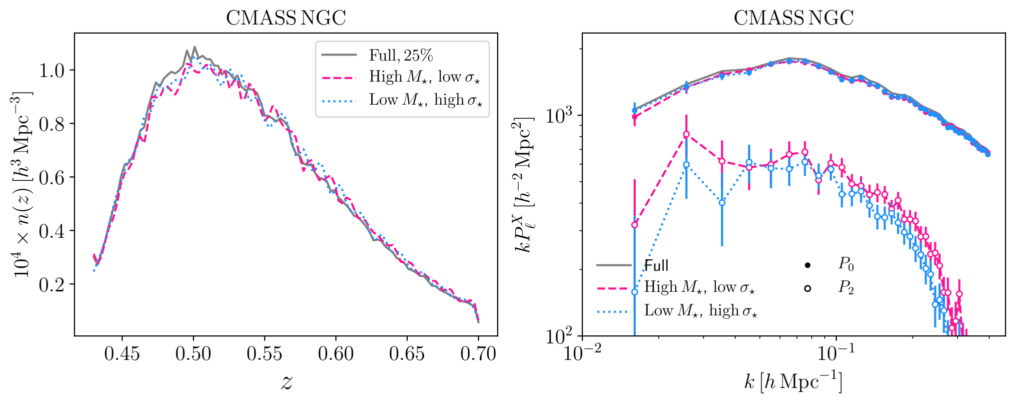
How do we look for AB?

Main idea – split on orientation $(\sigma_\star)$ $\rightarrow$ look for differences in anisotropy (Δb_q)

- Subsamples matching $n(z)$ have matching f
- Subsamples can have different b_g & b_q
- Find subsamples matching P_0 & $n(z)$!
- Mismatch P_2 $\rightarrow$ evidence $\Delta b_q \neq 0$

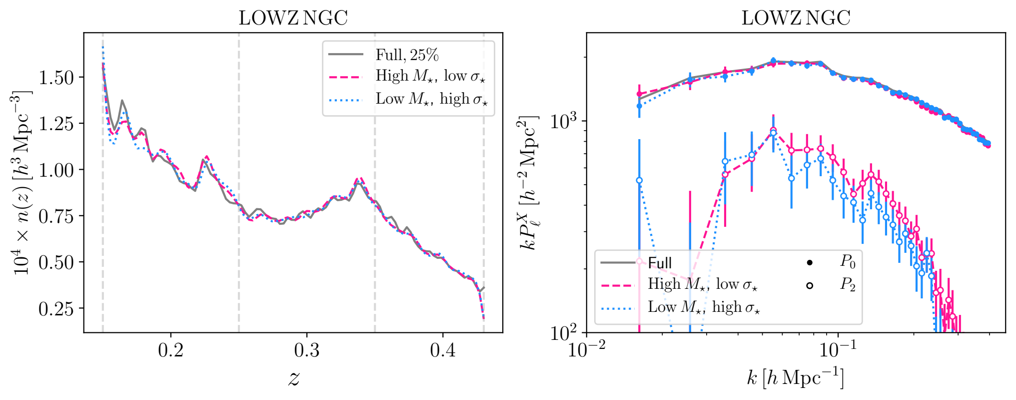
- Match P_0 & $n(z)$ $\rightarrow$ match P_2
- Mismatch P_2 $\rightarrow$ evidence $\Delta b_q \neq 0$

Results – CMASS NGC



AO+2020

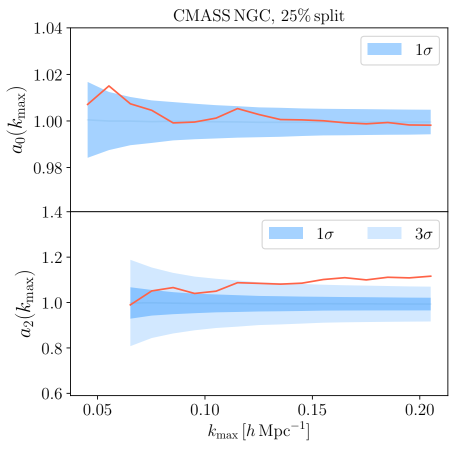
Results – LOWZ NGC



AO+2020

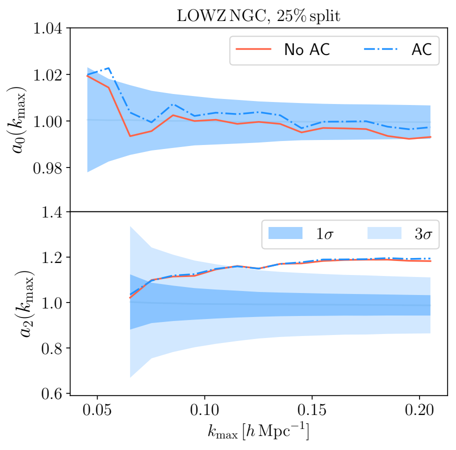
Detection significance

- Use mock galaxy catalogs
- Split each mock in two random subsamples
- Cross-correlate each subsample with full mock
- Minimize $\Delta P_\ell = P_\ell^{\mathrm{sub},1} - a_\ell P_\ell^{\mathrm{sub},2}$
- Matching monopoles – $a_0 \approx 1$
  - within 1σ at all scales
- Different quadrupoles – $a_2 \neq 1$
  - many σ's away!
- $\implies \Delta b_q \neq 0$ between subsamples



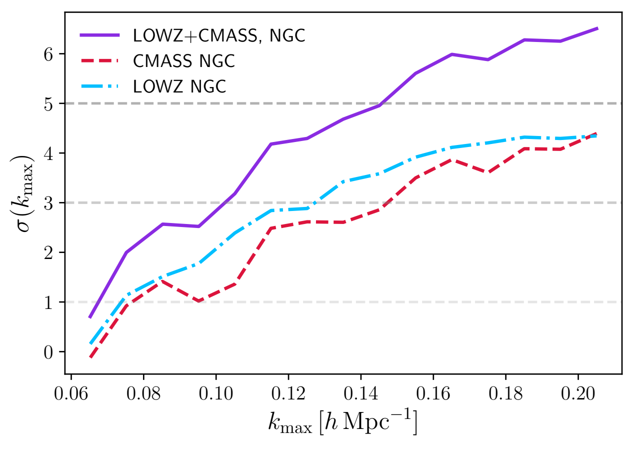
Detection significance

- Use mock galaxy catalogs
- Split each mock in two random subsamples
- Cross-correlate each subsample with full mock
- Minimize $\Delta P_\ell = P_\ell^{\mathrm{sub},1} - a_\ell P_\ell^{\mathrm{sub},2}$
- Matching monopoles – $a_0 \approx 1$
  - within 1σ at all scales
- Different quadrupoles – $a_2 \neq 1$
  - many σ's away!
- $\implies \Delta b_q \neq 0$ between subsamples



Combined detection significance

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



AO+2020

Discussion

- We present significant evidence of AB in BOSS galaxies

Discussion

- We present significant evidence of AB in BOSS galaxies
- We show clustering of galaxies depends on local properties other than halo mass

Discussion

- We present significant evidence of AB in BOSS galaxies
- We show clustering of galaxies depends on local properties other than halo mass
- Our detection is the first to exceed the level of 5σ

Discussion

- We present significant evidence of AB in BOSS galaxies
- We show clustering of galaxies depends on local properties other than halo mass
- Our detection is the first to exceed the level of 5σ
- We only measure Δb_q of subsamples, not the full sample b_q!

Discussion

- We present significant evidence of AB in BOSS galaxies
- We show clustering of galaxies depends on local properties other than halo mass
- Our detection is the first to exceed the level of 5σ
- We only measure Δb_q of subsamples, not the full sample b_q!
- For BOSS galaxies we find subsamples with $\Delta b_q \sim 0.1 - 0.2$

Discussion

- We present significant evidence of AB in BOSS galaxies
- We show clustering of galaxies depends on local properties other than halo mass
- Our detection is the first to exceed the level of 5σ
- We only measure Δb_q of subsamples, not the full sample b_q!
- For BOSS galaxies we find subsamples with $\Delta b_q \sim 0.1 - 0.2$
- For halos in sims we found subsamples with $\Delta b_q \sim 1 - 2$

Discussion

- We present significant evidence of AB in BOSS galaxies
- We show clustering of galaxies depends on local properties other than halo mass
- Our detection is the first to exceed the level of 5σ
- We only measure Δb_q of subsamples, not the full sample b_q!
- For BOSS galaxies we find subsamples with $\Delta b_q \sim 0.1 - 0.2$
- For halos in sims we found subsamples with $\Delta b_q \sim 1 - 2$
- Misalignment of galaxies and halos decreases the signal

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!
  - ELGs contain dust $\implies$ more face-on than edge on galaxies

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!
  - ELGs contain dust $\implies$ more face-on than edge on galaxies
  - However, ELGs aligned weaker than LRGs

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!
  - ELGs contain dust $\implies$ more face-on than edge on galaxies
  - However, ELGs aligned weaker than LRGs
  - We are currently looking into ELG targets to see how big selection effects are

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!
  - ELGs contain dust $\implies$ more face-on than edge on galaxies
  - However, ELGs aligned weaker than LRGs
  - We are currently looking into ELG targets to see how big selection effects are
- DESI Luminous Red Galaxies (LRGs)

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!
  - ELGs contain dust $\Longrightarrow$ more face-on than edge on galaxies
  - However, ELGs aligned weaker than LRGs
  - We are currently looking into ELG targets to see how big selection effects are
- DESI Luminous Red Galaxies (LRGs)
  - Similar to BOSS, better measurement of AB

Consequences for DESI

Main questions: Is target selection of X orientation dependent? Is X aligned with halo?

- DESI Emission Line Galaxies (ELGs)
  - Fiber magnitude vs. model magnitudes
  - Faint galaxies near the detection threshold could be impacted more
  - Faint galaxies are also more numerous!
  - ELGs contain dust $\Longrightarrow$ more face-on than edge on galaxies
  - However, ELGs aligned weaker than LRGs
  - We are currently looking into ELG targets to see how big selection effects are
- DESI Luminous Red Galaxies (LRGs)
  - Similar to BOSS, better measurement of AB
  - Are LRGs dust free?

Other consequences

- Groups/clusters found in redshift-space

Other consequences

- Groups/clusters found in redshift-space
  - ... in simulations exhibit strong AB signal in their clustering

Other consequences

- Groups/clusters found in redshift-space
  - ... in simulations exhibit strong AB signal in their clustering
- Could be an issue for RSD with 21cm Intensity Mapping

Other consequences

- Groups/clusters found in redshift-space
  - ... in simulations exhibit strong AB signal in their clustering
- Could be an issue for RSD with 21cm Intensity Mapping
  - ... due to HI self-absorption, provided HI aligned with halos

Other consequences

- Groups/clusters found in redshift-space
  - ... in simulations exhibit strong AB signal in their clustering
- Could be an issue for RSD with 21cm Intensity Mapping
  - ... due to HI self-absorption, provided HI aligned with halos
- ...

Summary

- Non-scalar halo properties are correlated with large-scale tidal fields
- Orientation dep. selection effects and tidal alignment of halos/galaxies:
$$\delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$
- We find terms like b_q present in simulations and BOSS galaxies
  - Split galaxies based on line of sight velocity dispersion $\sigma_\star$ and $M_\star$
  - Simple test – subsamples matching $P_0 \implies$ matching P_2
- Galaxy clustering depends on other local properties, not just halo mass:
- **First detection of galaxy assembly bias to exceed 5σ!**
- **Problem for RSD since b_q completely degenerate with f!**
- LRGs, ELGs, groups/clusters, 21cm, voids, etc. selection effects?

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \mathrm{const.}$$

with I_0 surface brightness

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \mathrm{const.}$$

  with I_0 surface brightness
  - Martens+18 marginal signal with (I_0, R_0)

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \text{const.}$$

with I_0 surface brightness

  - Martens+18 marginal signal with (I_0, R_0)
  - Singh+20 no signal with full FP

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \mathrm{const.}$$

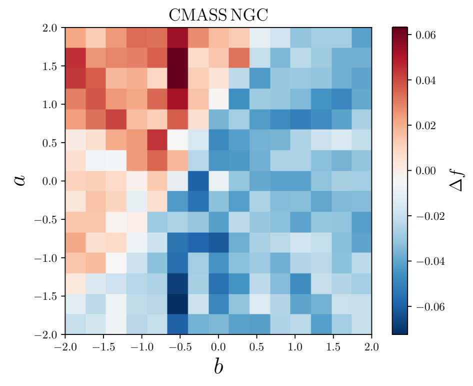
  with I_0 surface brightness
  - Martens+18 marginal signal with (I_0, R_0)
  - Singh+20 no signal with full FP
- We do FP analysis with (a, b) grid

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \text{const.}$$

with I_0 surface brightness
  - Martens+18 marginal signal with (I_0, R_0)
  - Singh+20 no signal with full FP
- We do FP analysis with (a, b) grid
- Kaiser model for multipoles assuming $b_q = 0$



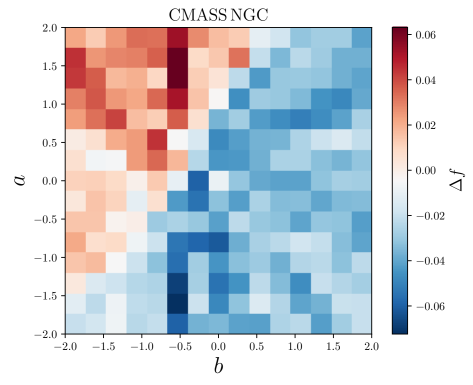
AO+2020

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \text{const.}$$

  with I_0 surface brightness
  - Martens+18 marginal signal with (I_0, R_0)
  - Singh+20 no signal with full FP
- 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



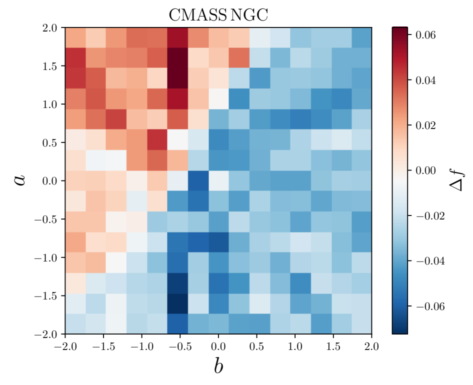
AO+2020

Other splits and approaches

- We find no signal when splitting on projected physical size R_0 & $M_\star$
  - Larger fractional scatter of R_0 compared to $\sigma_\star$
- Previous works used Fundamental Plane (FP):

$$\frac{I_0^b \sigma_\star^a}{R_0} \sim \text{const.}$$

  with I_0 surface brightness
  - Martens+18 marginal signal with (I_0, R_0)
  - Singh+20 no signal with full FP
- 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...



AO+2020

Summary

- Non-scalar halo properties are correlated with large-scale tidal fields
- Orientation dep. selection effects and tidal alignment of halos/galaxies:
$$\delta_g^s = (b_g - b_q/3 + (f + b_q)\mu^2)\,\delta_m$$
- We find terms like b_q present in simulations and BOSS galaxies
  - Split galaxies based on line of sight velocity dispersion $\sigma_\star$ and $M_\star$
  - Simple test – subsamples matching $P_0 \implies$ matching P_2
- Galaxy clustering depends on other local properties, not just halo mass:
- **First detection of galaxy assembly bias to exceed 5σ!**
- **Problem for RSD since b_q completely degenerate with f!**
- LRGs, ELGs, groups/clusters, 21cm, voids, etc. selection effects?